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

Peter Read

University of Oxford, UK

Plan

- Local and global super-rotation in atmospheres around rapidly rotating planets
    - Earth
        - Troposphere?
        - Stratosphere & Mesosphere
    - Mars
        - Global middle atmosphere
        - Tidal jets
    - Gas and ice giants
        - Equatorial jets

Where do we observe super-rotation (and how strong)?

Earth - Annual mean

[zonally averaged] circulation

[As observed - ERA40 - Kallberg et al. 2004]

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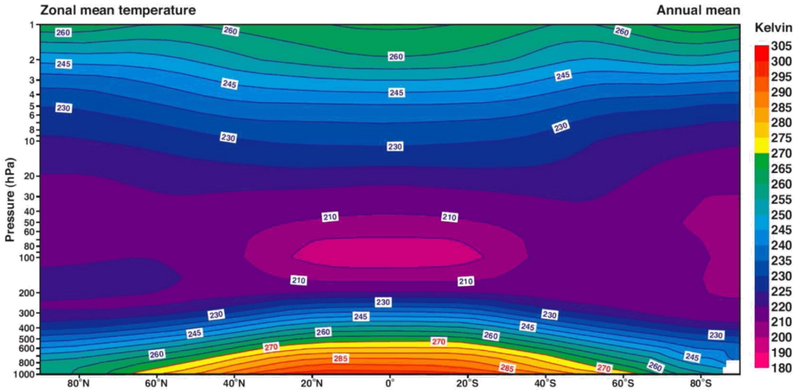

(a)

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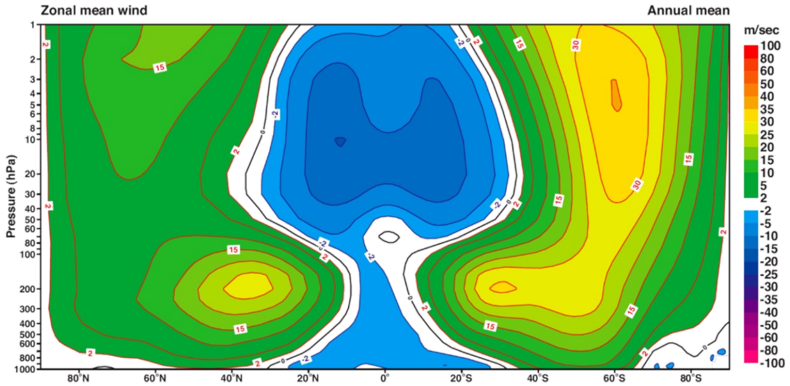

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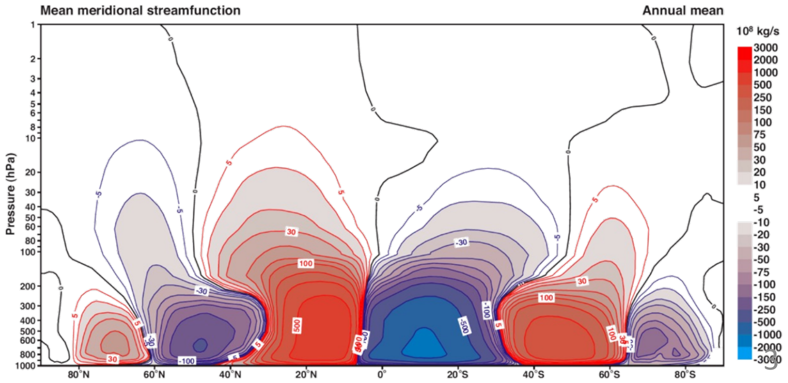

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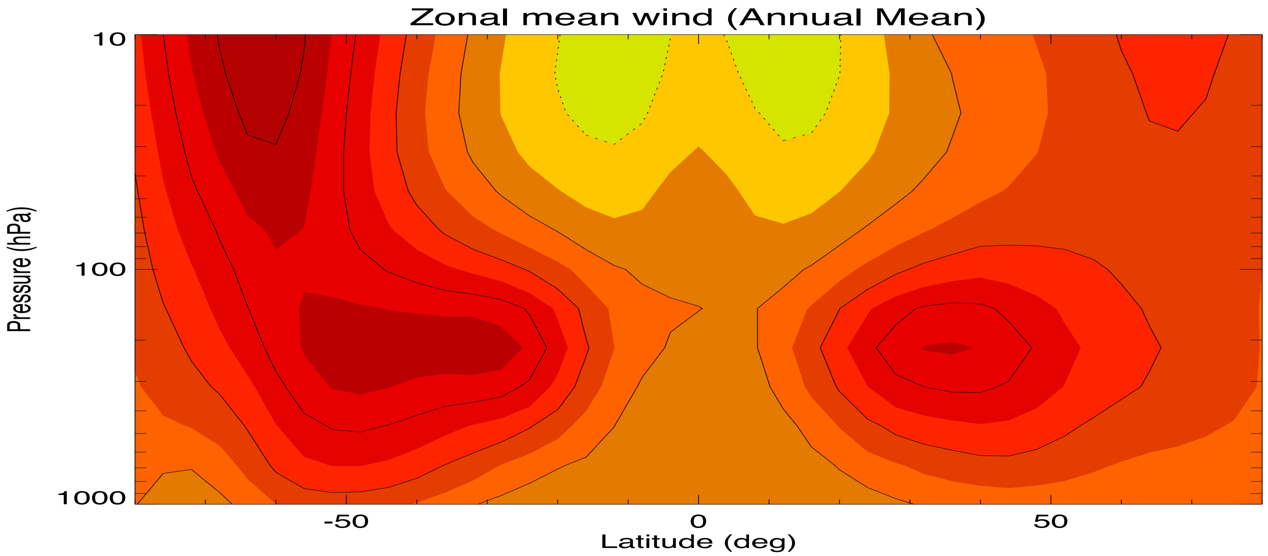
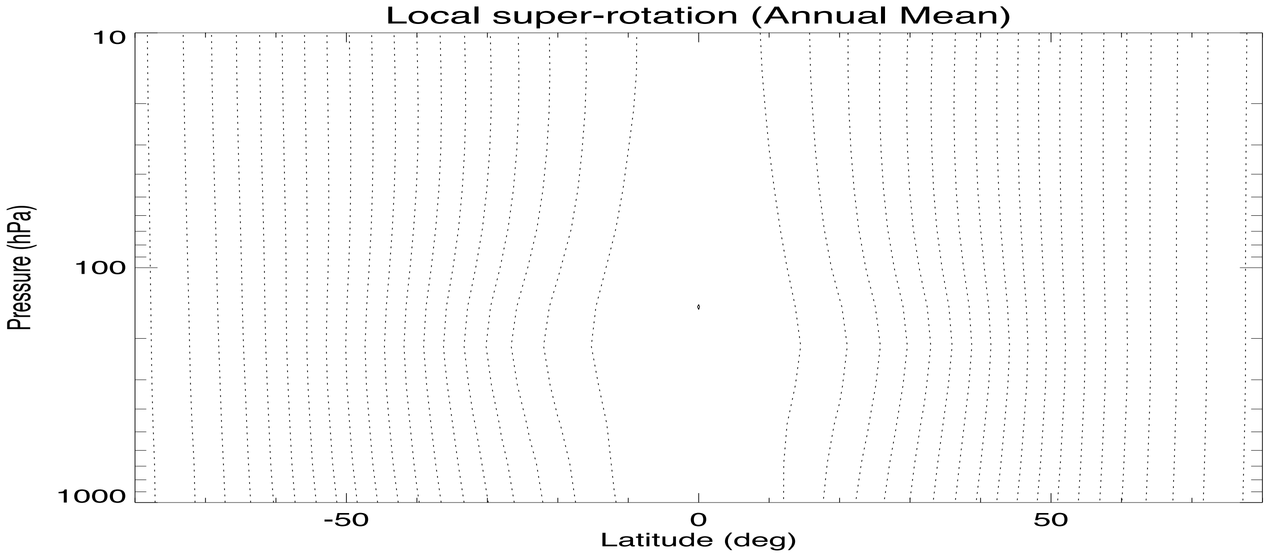
Data credit: Randal et al [2004]

- Earth's troposphere
  - Equatorial values of $s < 0$ most of the time
  - Mass-weighted (compressible) global values of S ~ 0.010-0.017
  - Magnitudes ~ 0.01
- Earth's stratosphere & Mesosphere
  - Annual mean equatorial $\overline{u}$ westward except around 0.1 and 10^{-3} hPa
  - NB Eddy driven!





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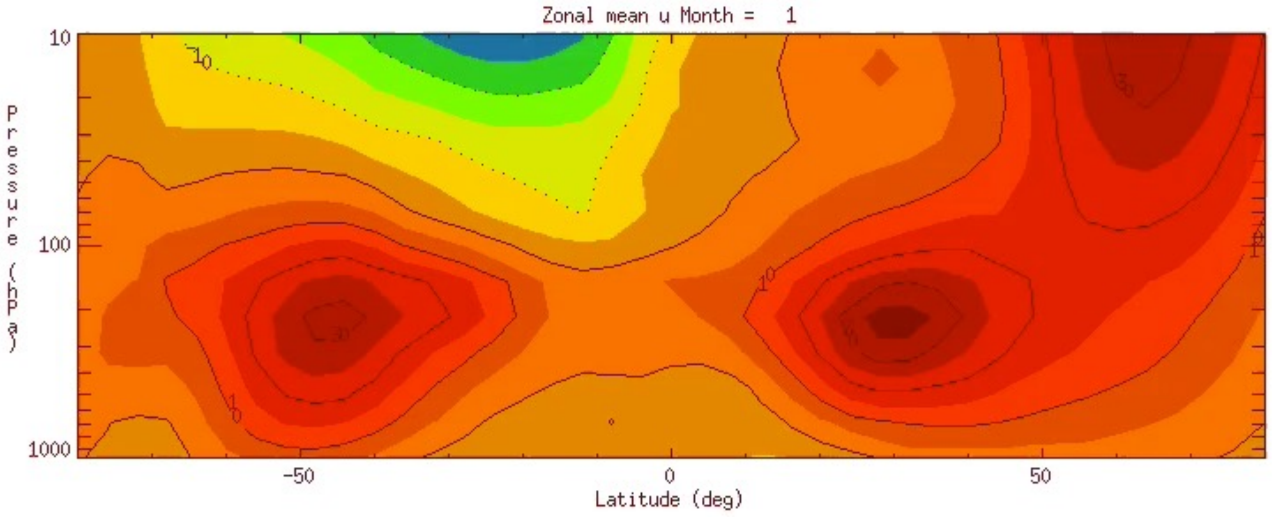
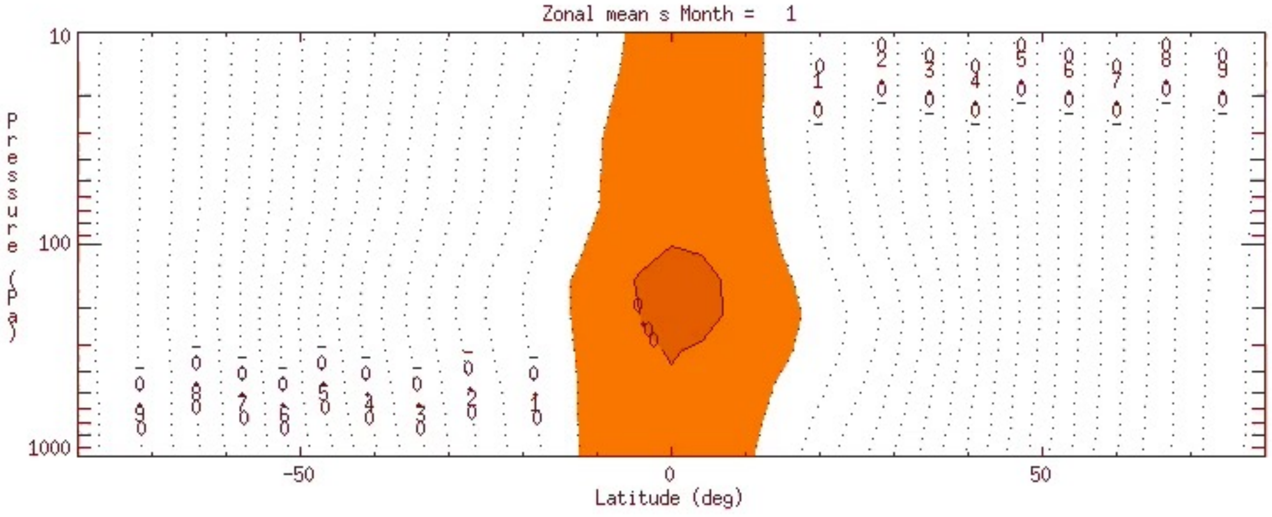
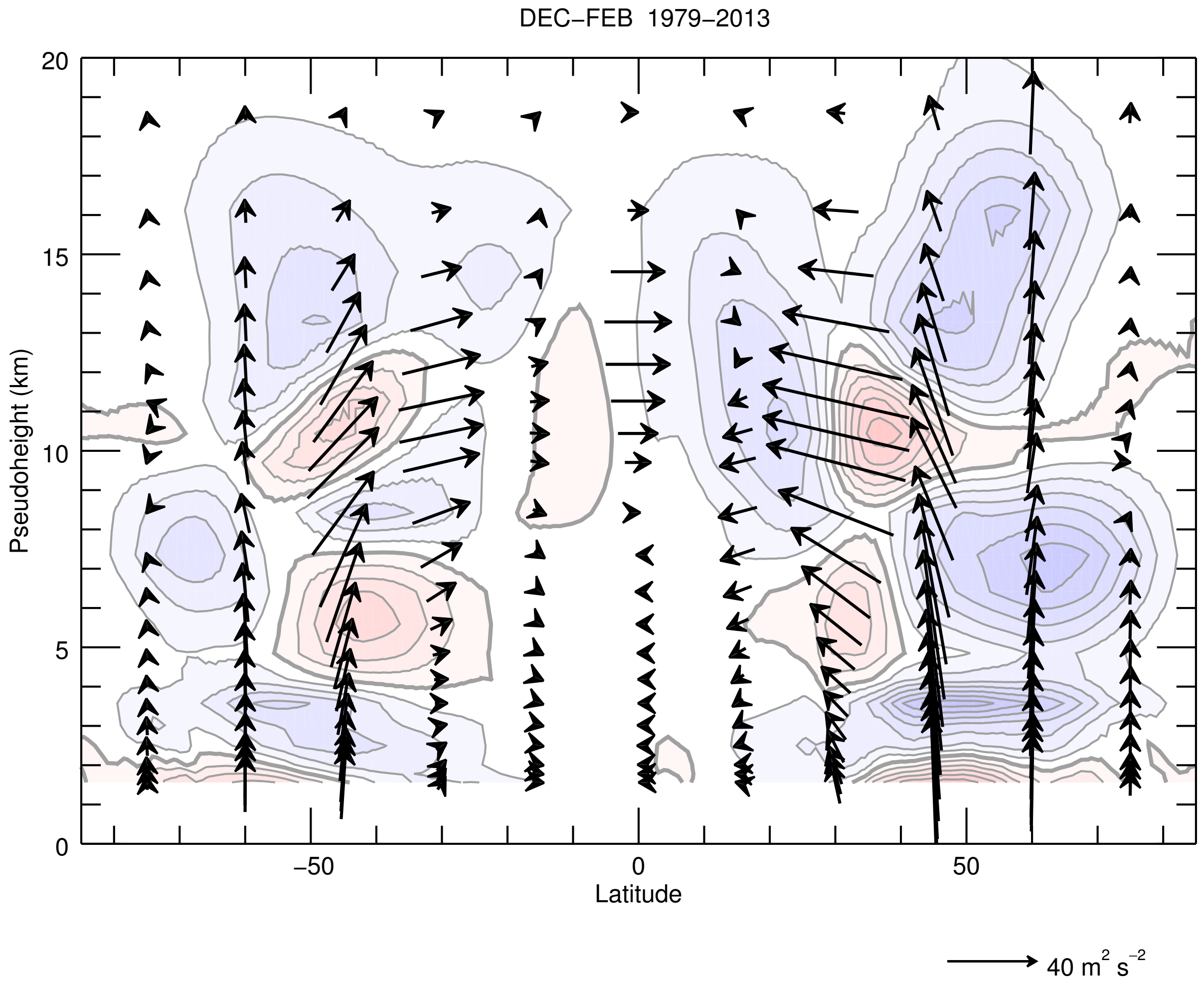




Why doesn't Earth's troposphere super-rotate (locally)?

Image credit: Mitchell et al. [2019]

- Eddy-driven jets mostly driven by (westward-propagating) Rossby waves
- Origin of Rossby waves?
  a) Baroclinic instability in mid-latitudes
     - Forces waves in mid-latitudes [Eastward forcing]
     - Waves dissipate in tropics [Westward forcing]



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  b) Tropical divergence from deep convection
     - Waves launched in tropics [Eastward forcing]
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     - $\frac{\partial \zeta}{\partial t} \approx S = -\boldsymbol{\nabla}.\left(\boldsymbol{v}_{\chi}\zeta\right)$
     - [Sardashmukh & Hoskins 1988]

Image credit: Sardeshmukh & Hoskins [1988]

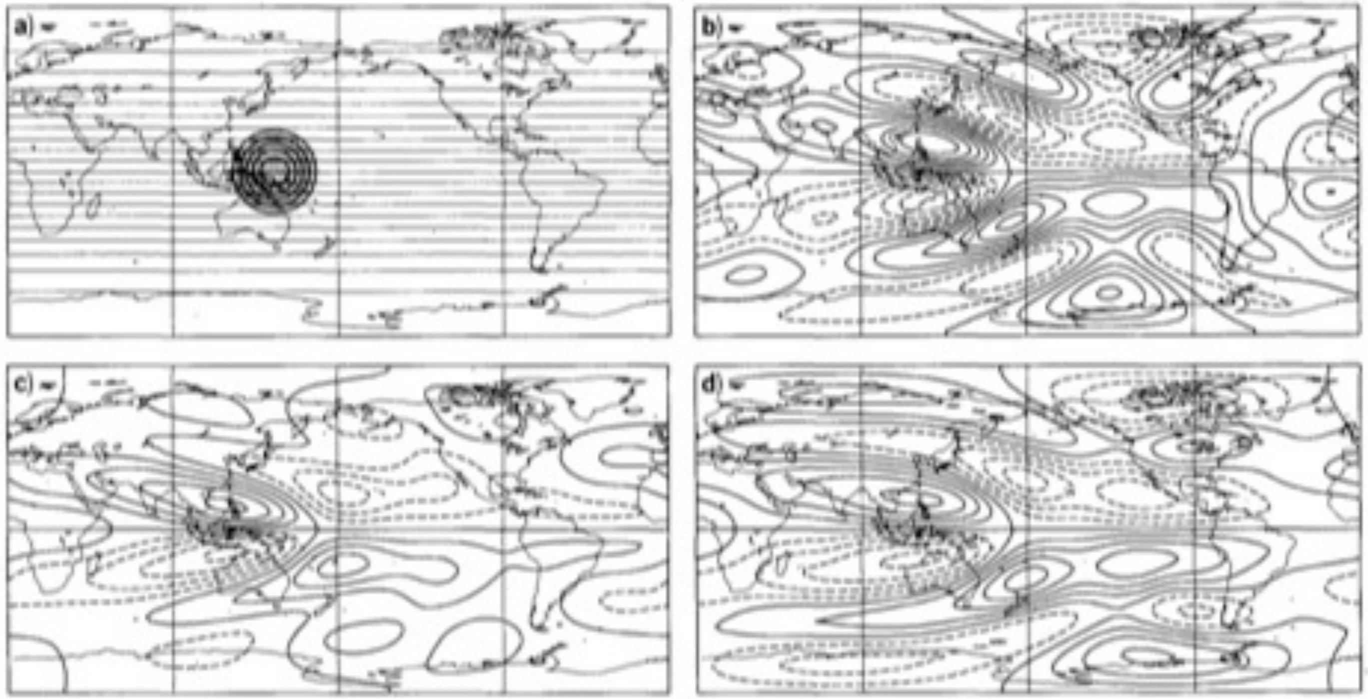

FIG. 1. (a) Basic flow streamfunction (contour interval 10^7 m^2 s^{-1}) and divergence perturbation (shaded; contour interval 10^{-6} s^{-1}). The streamfunction perturbation patterns on day 48 predicted by the linear, partially nonlinear, and fully nonlinear models described in the text are shown in (b), (c) and (d), respectively. The contour interval is 5×10^6 m^2 s^{-1} in all the three panels, and negative values are indicated by dashed contours.

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Image credit: Suarez & Duffy [1992]

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  a) Baroclinic instability in mid-latitudes
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- Transition to equatorial super-rotation as tropical heating is increased
  - Suarez & Duffy [1992]
  - 2-level PE numerical model
  - Additional tropical heat source (~$Q_0 \sin 2\lambda$)

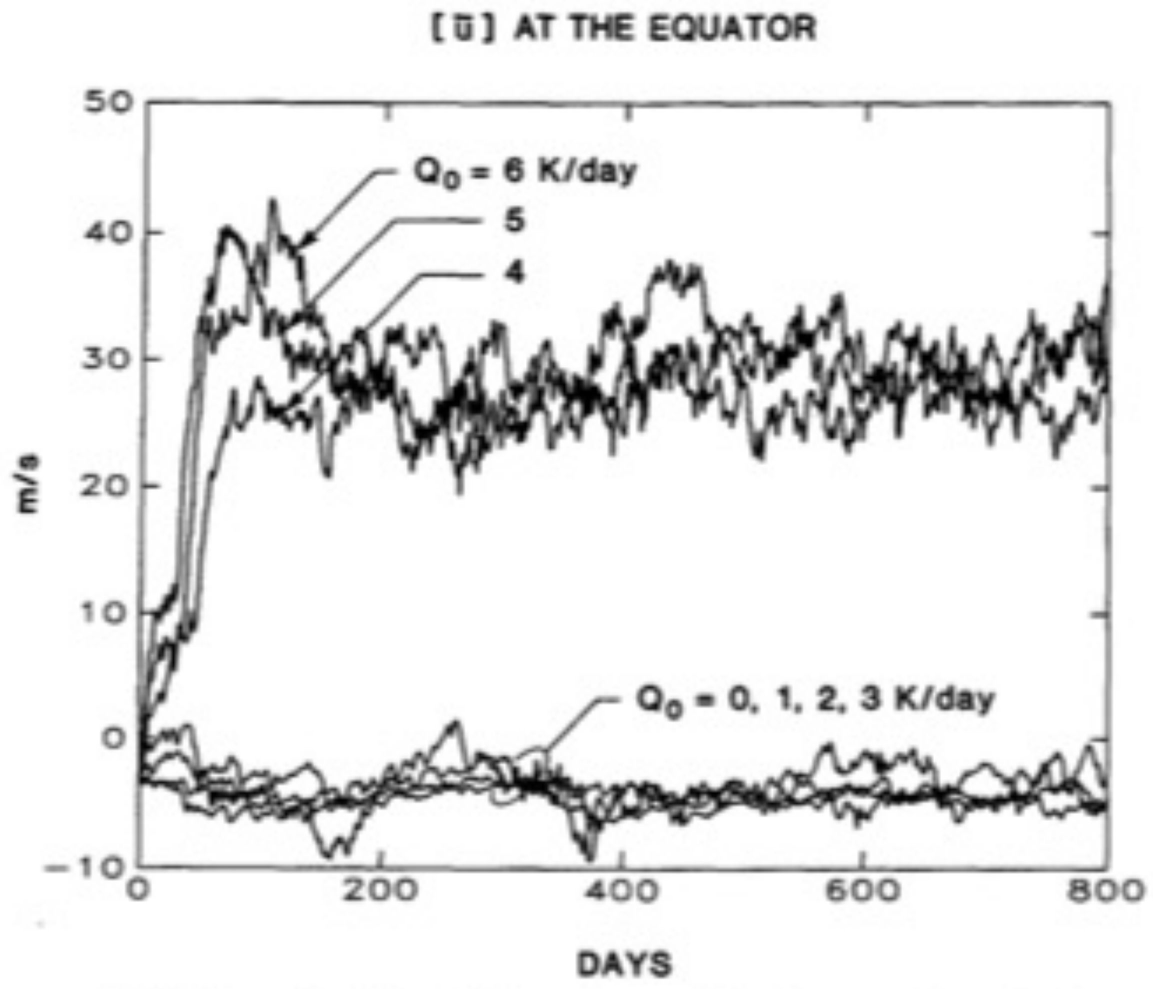

FIG. 2. Temporal evolution of the zonal average of $\bar{u}$ at the equator for various Q_0.

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Barotropic | Baroclinic

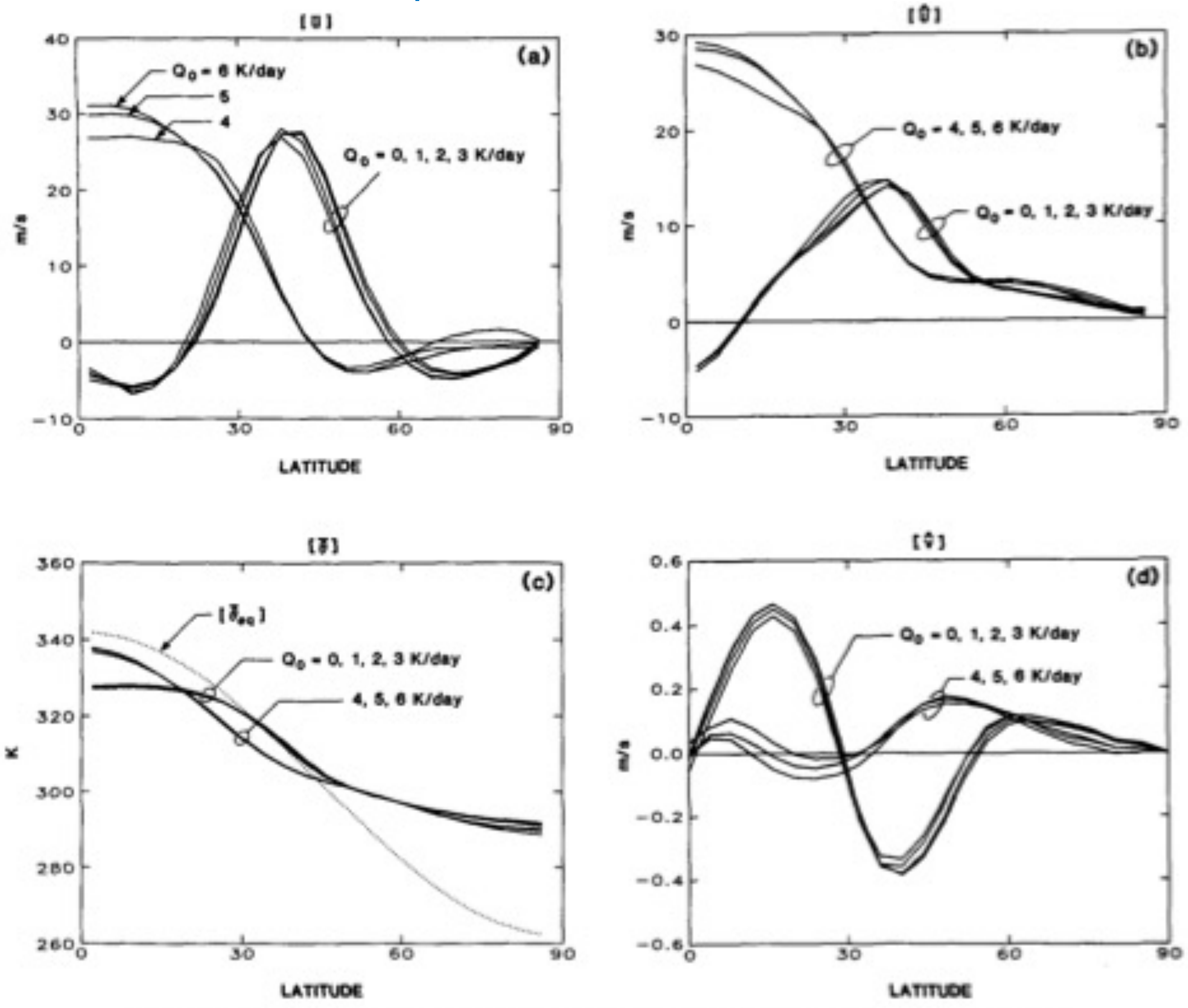

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Image credit: Arnold et al. [2012]

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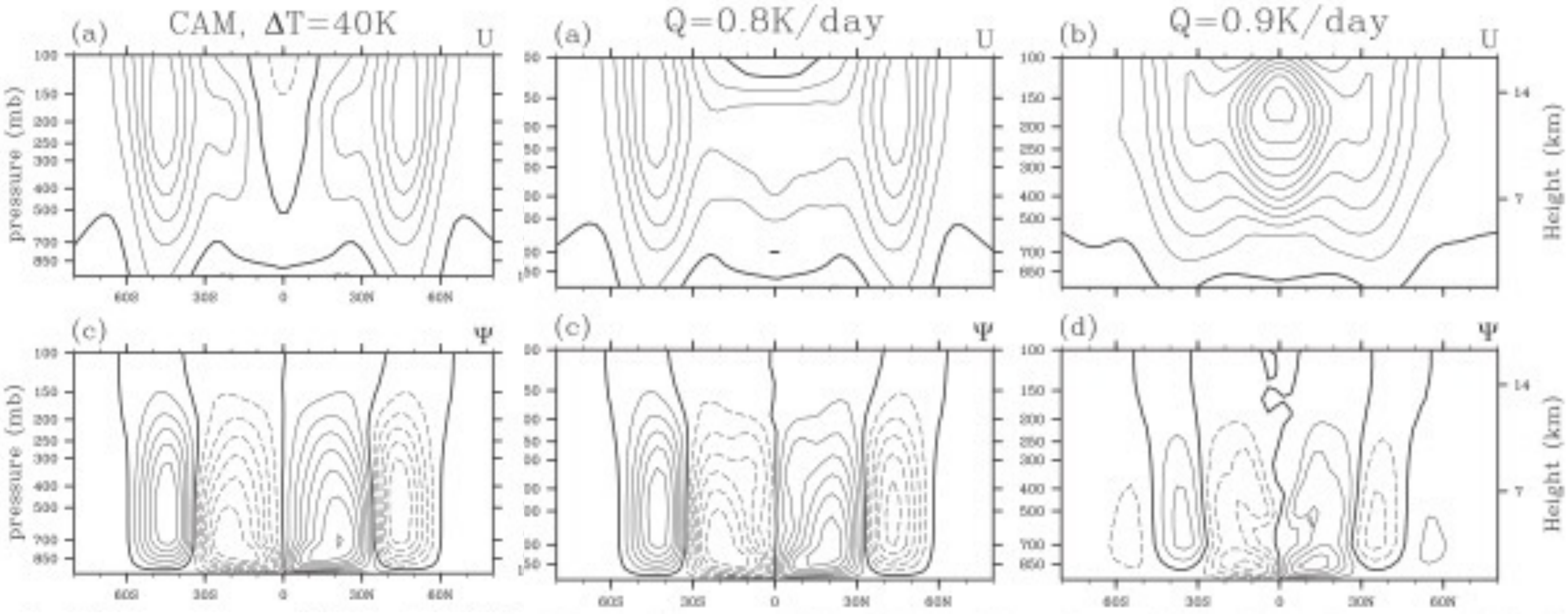
- Transition to super-rotation as tropical heating is increased
  - Non-zonal heating anoma in n-level PE model (CAM,
  - Strong bifurcation associated with equatorial Rossby wave resonance?



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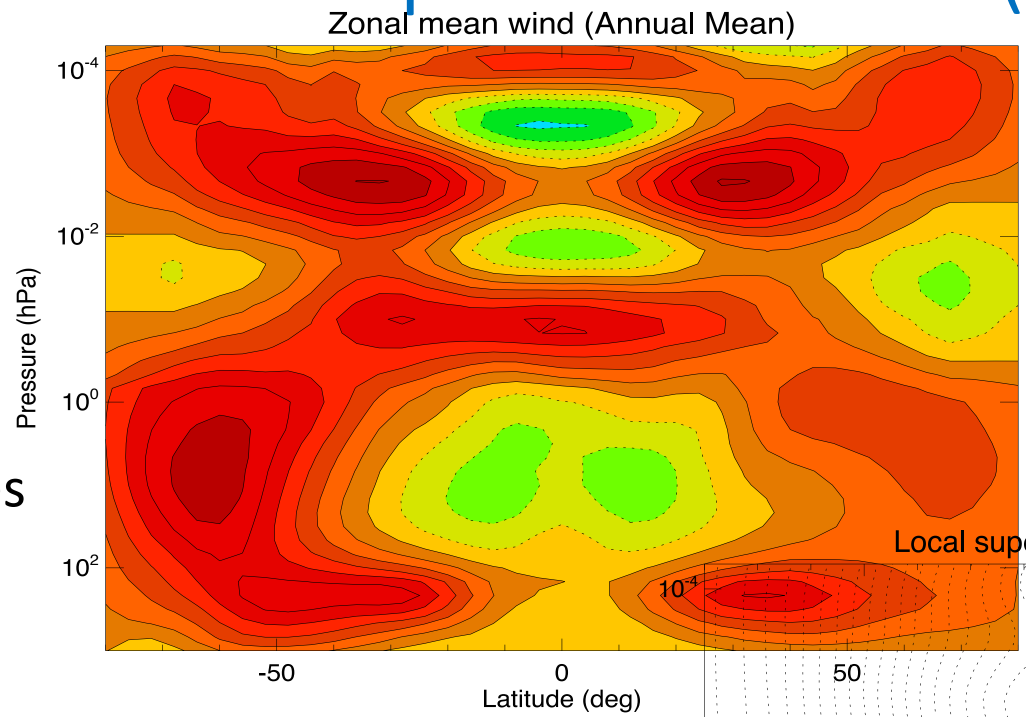

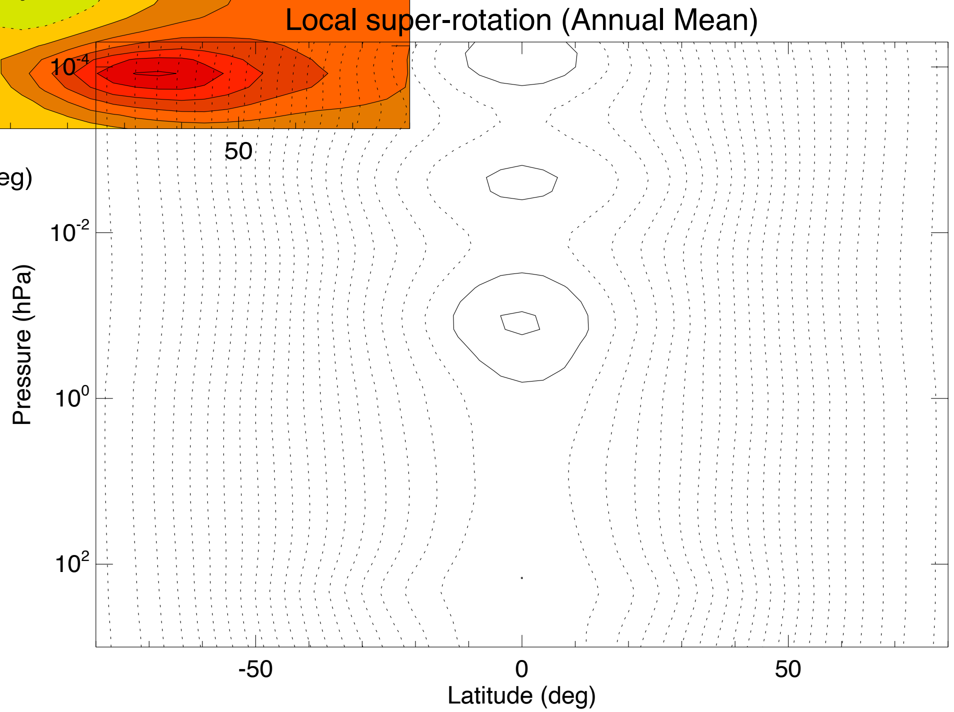

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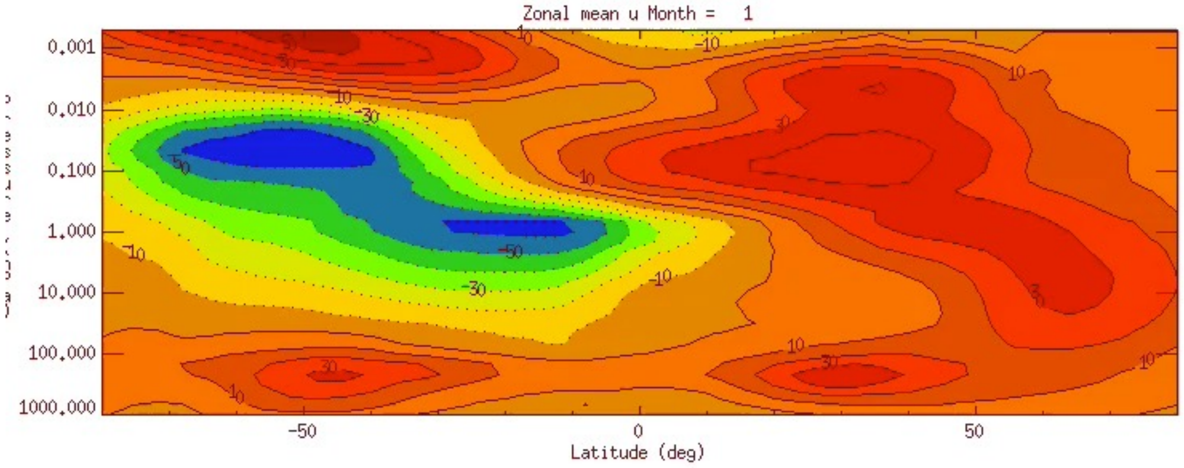

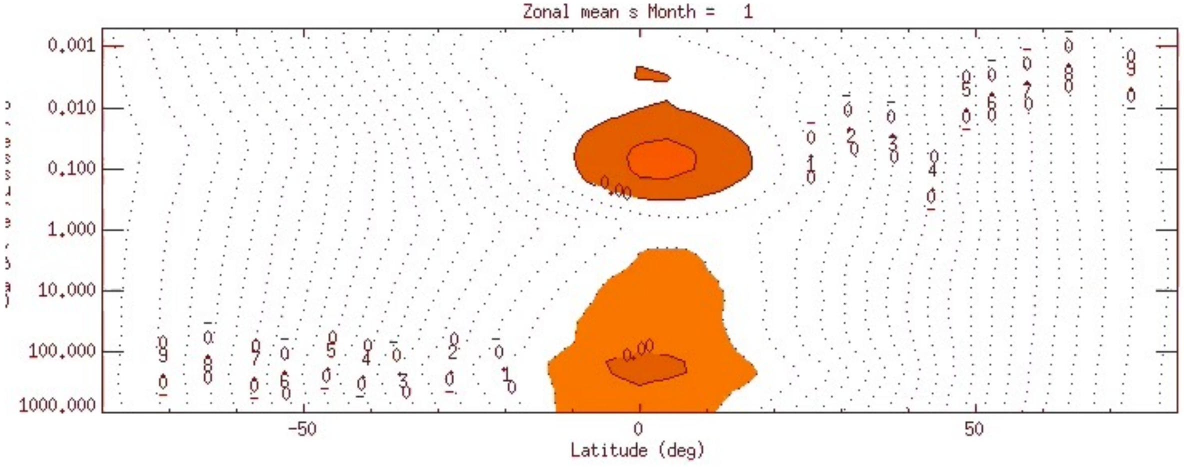

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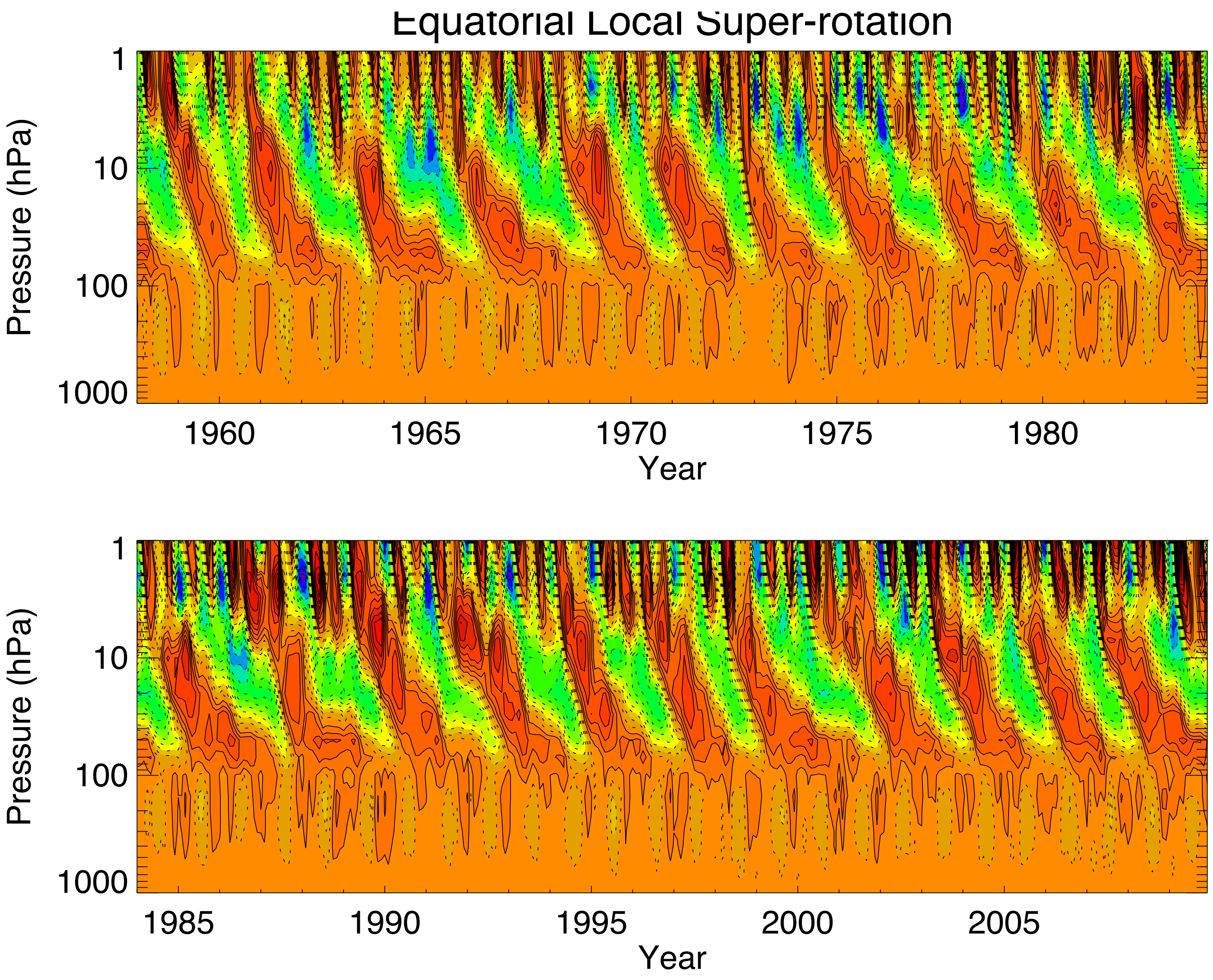
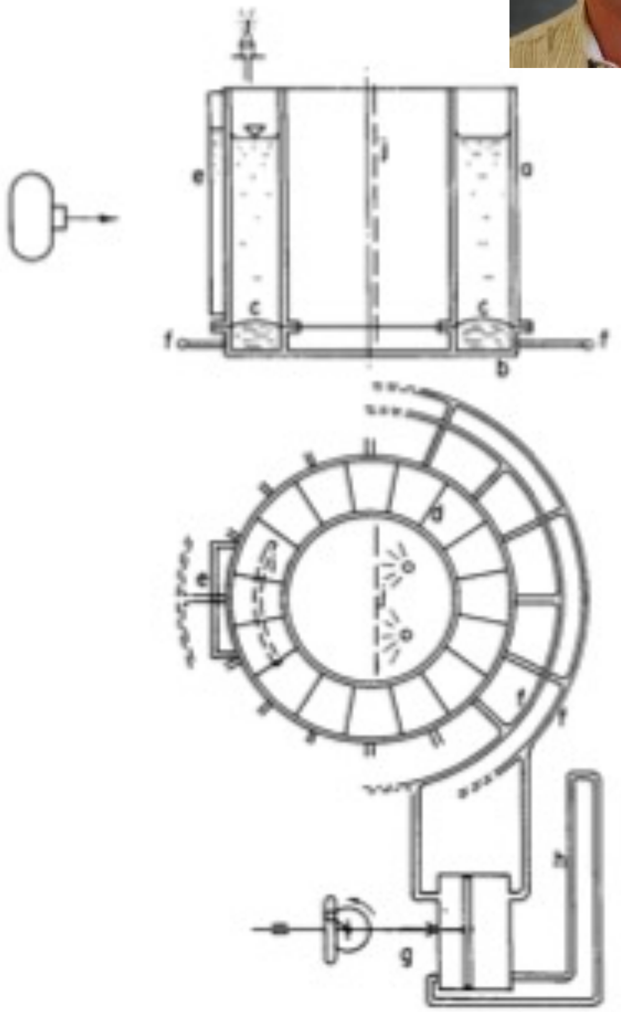
- Earth's stratosphere
  - Equatorial values of *s* range over ±0.14 due to Quasi-Biennial Oscillation and Semi-Annual oscillations
  - NB Eddy driven!



Laboratory experiments: Internal wave streaming with standing wave forcing

- Analogue of the Earth's QBO
  - Plumb & McEwan [1978]
- Interaction of standing internal gravity waves with mean flow (forced from below – or above)
  - Super-position of clockwise and anticlockwise moving waves
- Leads to oscillating mean azimuthal flow as either travelling wave accelerates zonal flow



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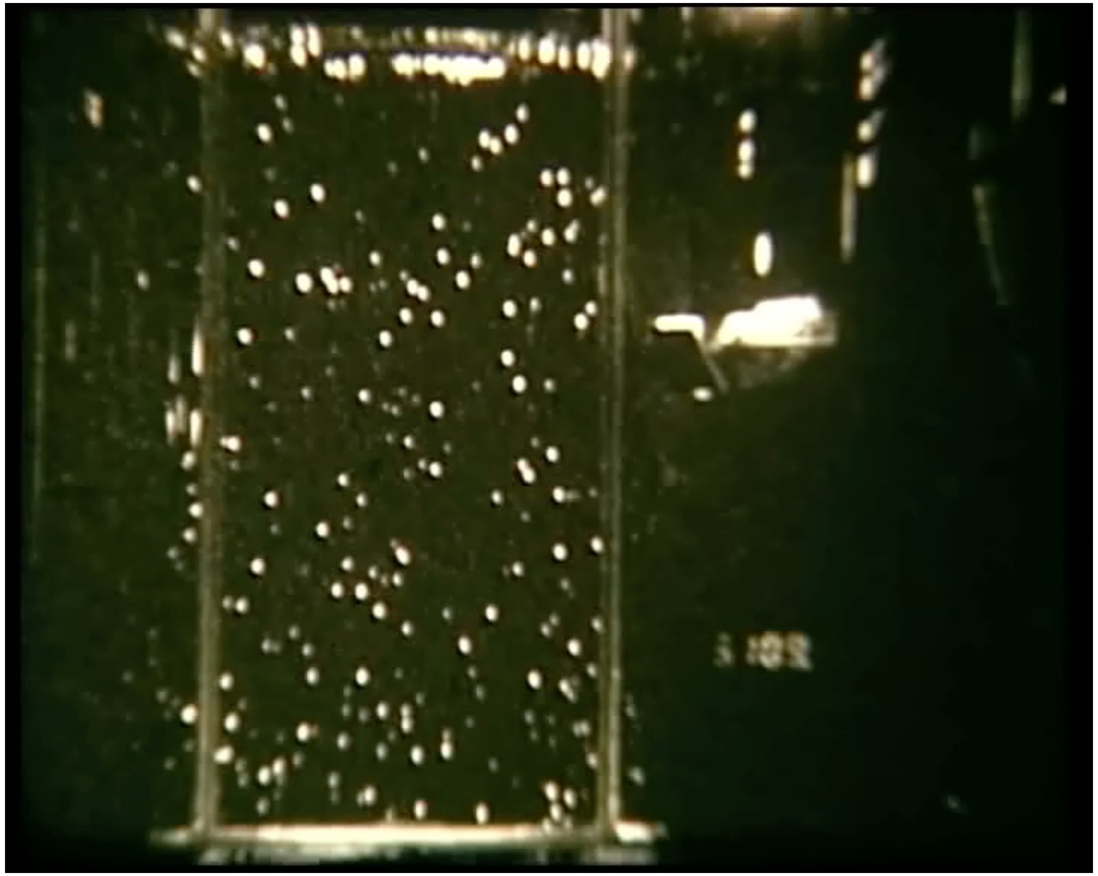

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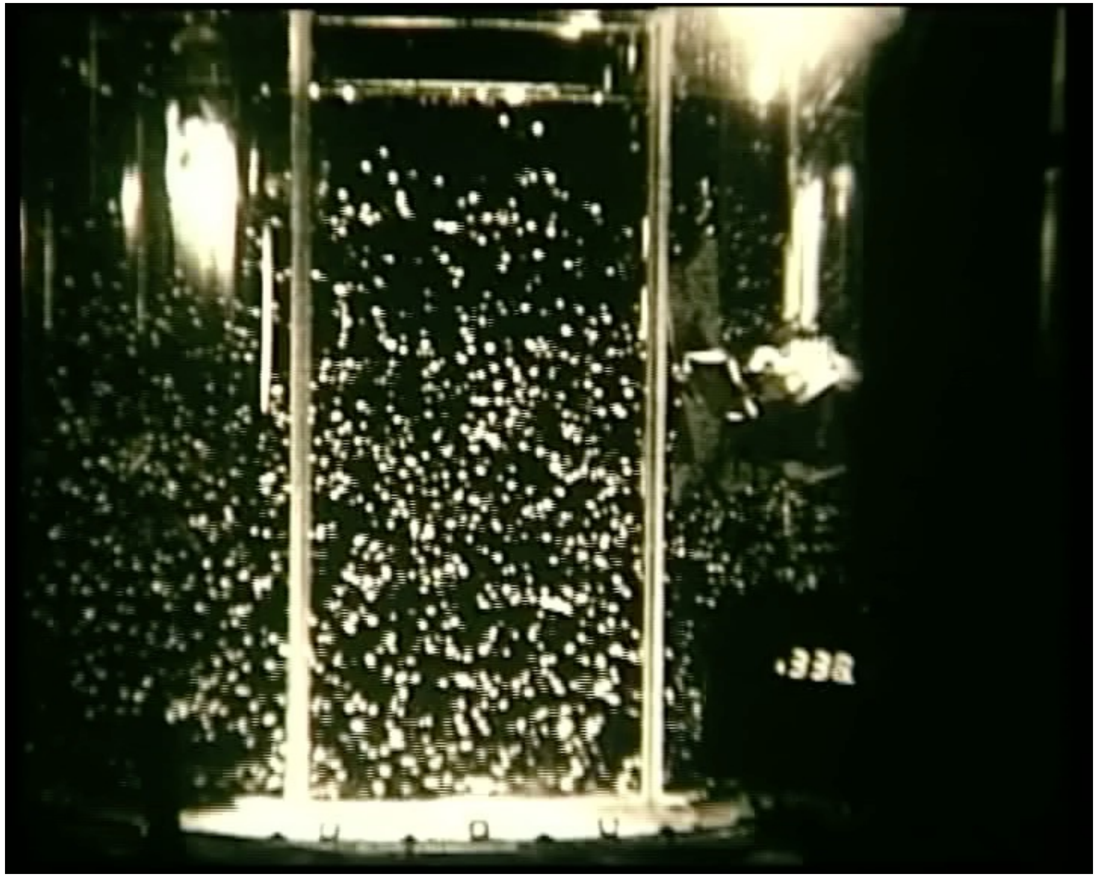
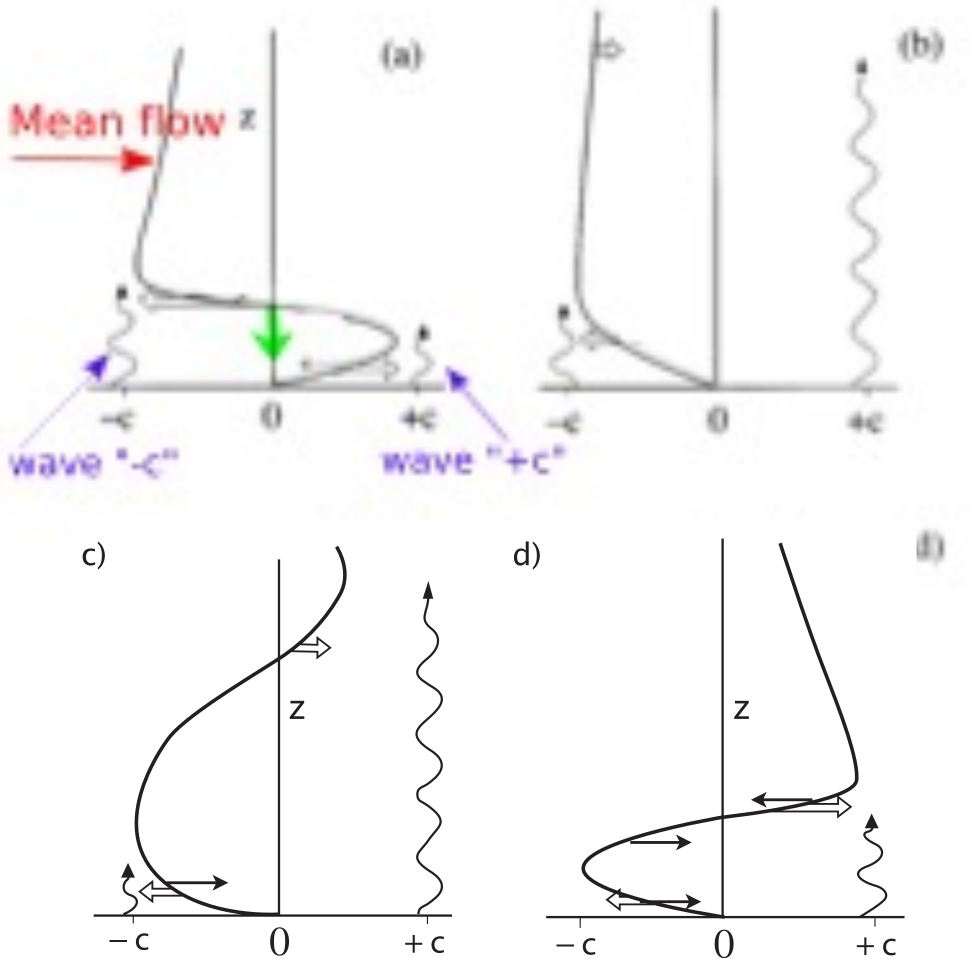
  - NB Needs a minimum forcing amplitude



Laboratory experiments: Internal wave streaming with standing wave forcing

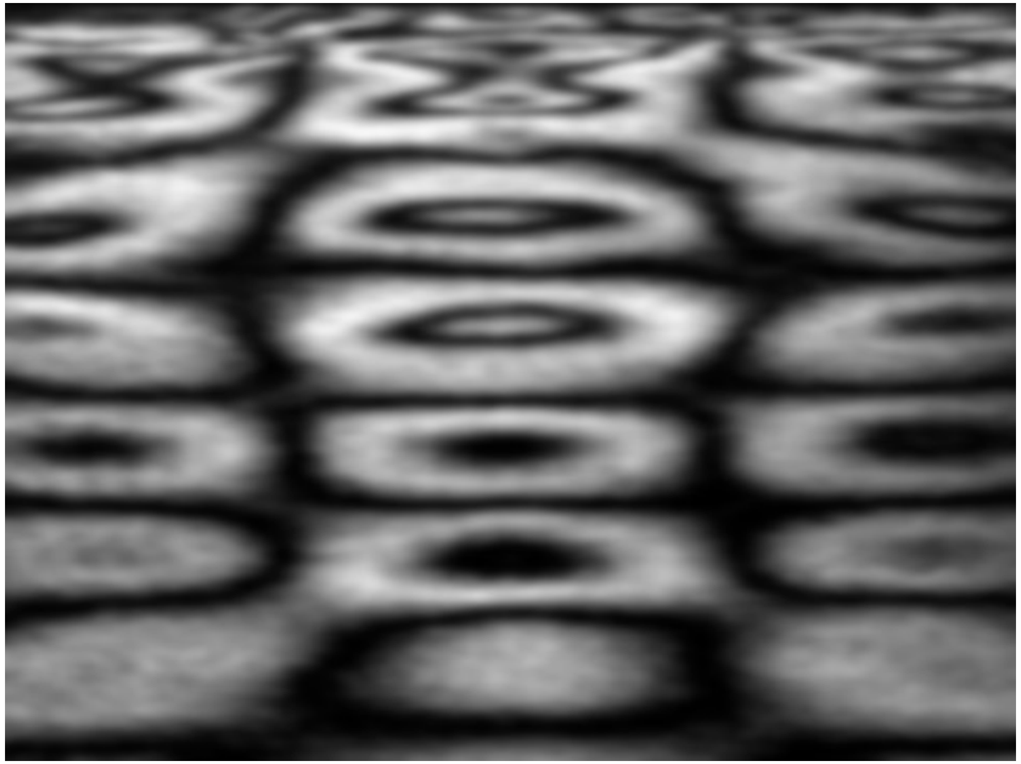
- 2 internal gravity waves with opposite phase velocity in the azimuthal direction
- Dissipation of the waves.

- The transfer of momentum from the wave to the mean flow is more efficient if c and the mean flow V are of the same sign (positive feedback).
- Momentum transfered from a wave to the mean flow can not be transfered above.
- Dissipation of the large mean flow gradient.

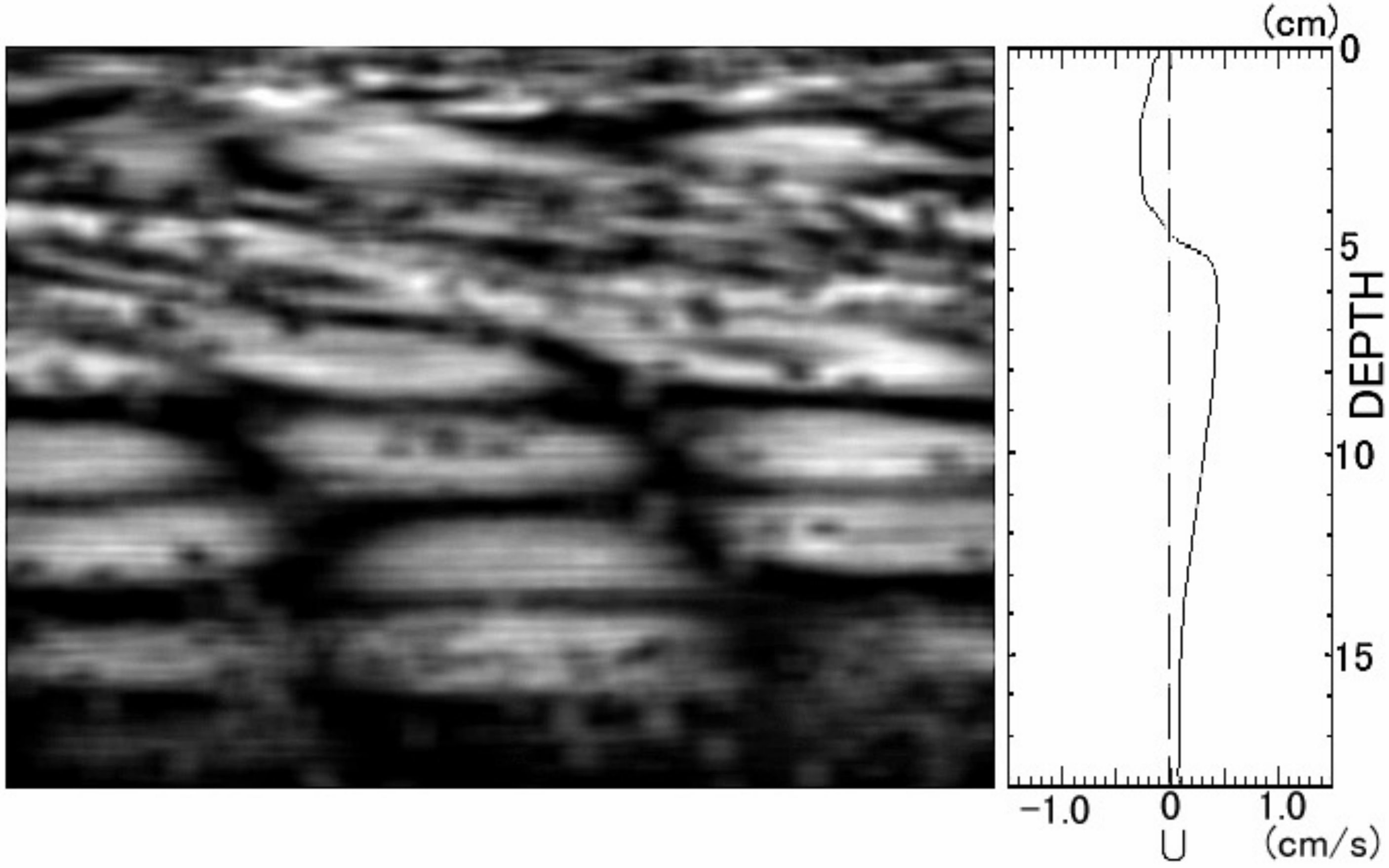


Adapted from Baldwin et al 2001

Laboratory experiments: Internal wave streaming with standing wave forcing



No mean flow
[Credit Otobe et al. 2018]



Mean flow develops and feeds back onto waves

Laboratory experiments: Internal wave streaming with standing wave forcing

Dimensionless model

$$\frac{\partial U}{\partial T} = -\frac{\partial D}{\partial \xi} + \Lambda_1 \frac{\partial^2 U}{\partial \xi^2} - \Lambda_2 U$$

Forcing with two counter-propagating waves:

$$D(\xi) = \exp\left(-\int_0^\xi \frac{1}{(1-U)^4}\mathrm{d}\xi\right) - \exp\left(-\int_0^\xi \frac{1}{(1+U)^4}\mathrm{d}\xi\right)$$

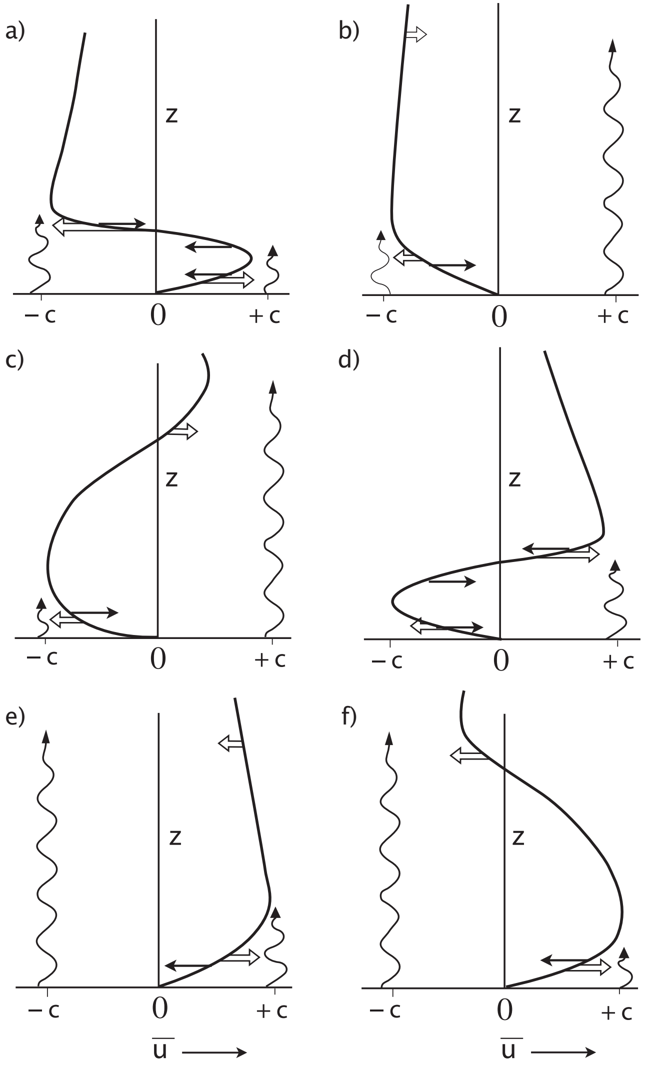
with the scales:

- velocity: $c = \omega / k_x$
- length: dissipation length $d = (k_x c^4)/(N^3 \nu)$
- time: $cd/(F(0))$

and the parameters:

- $\Lambda_1 = \nu c/(F(0)d)$
- $\Lambda_2 = \gamma cd/(F(0))$

This model can be solved semi-analytically close to the threshold.

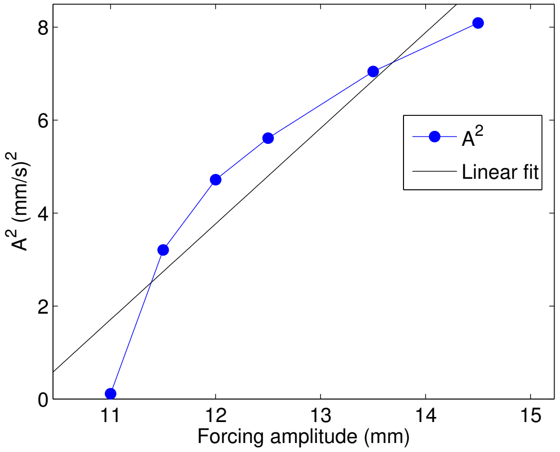


Laboratory experiments: Internal wave streaming with standing wave forcing

Bifurcation

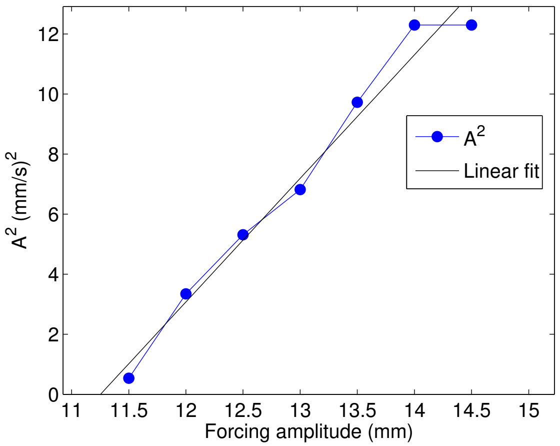
$T = 15$ s, A: vertical average of mean flow amplitude

$N = 1.5 \text{ rad} \cdot \text{s}^{-1}$, NaCl



Subcritical bifurcation

$N = 2.15 \text{ rad} \cdot \text{s}^{-1}$, $MgCl_2$



Supercritical bifurcation

$\Longrightarrow$Nature of the bifurcation depends on the parameters

Yoden and Holton (1988)

- Onset of mean flow oscillation as wave forcing amplitude is increased depends on parameters (e.g. N^2)
  - Small N^2 -> SUB-critical Hopf
  - Larger N^2 -> SUPER-critical Hopf
  - [Semin et al. 2018]

Laboratory experiments: Internal wave streaming with standing wave forcing

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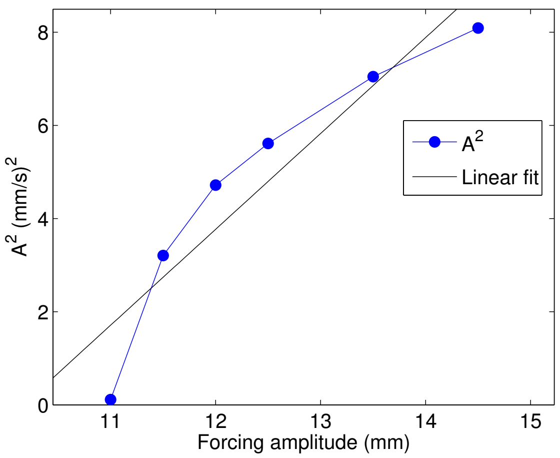

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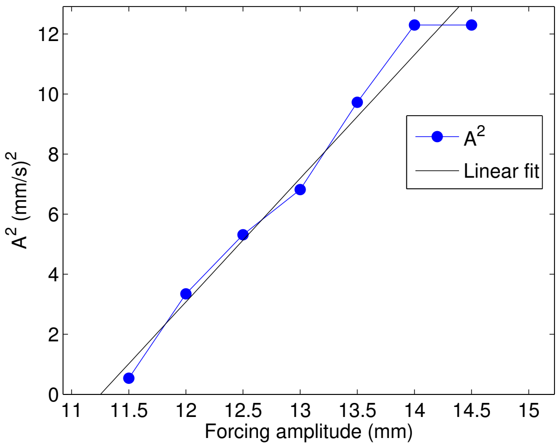

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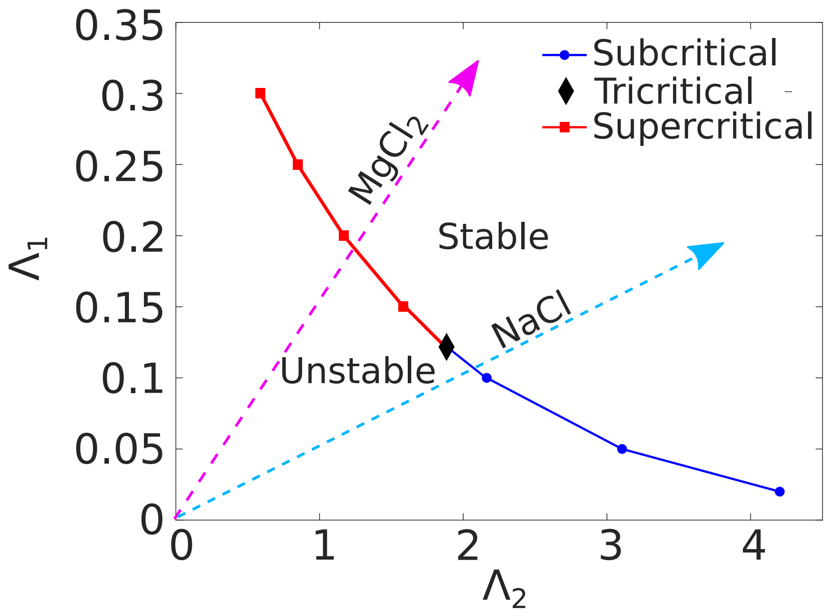


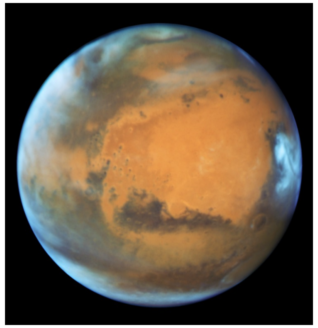
Yoden and Holton 1988

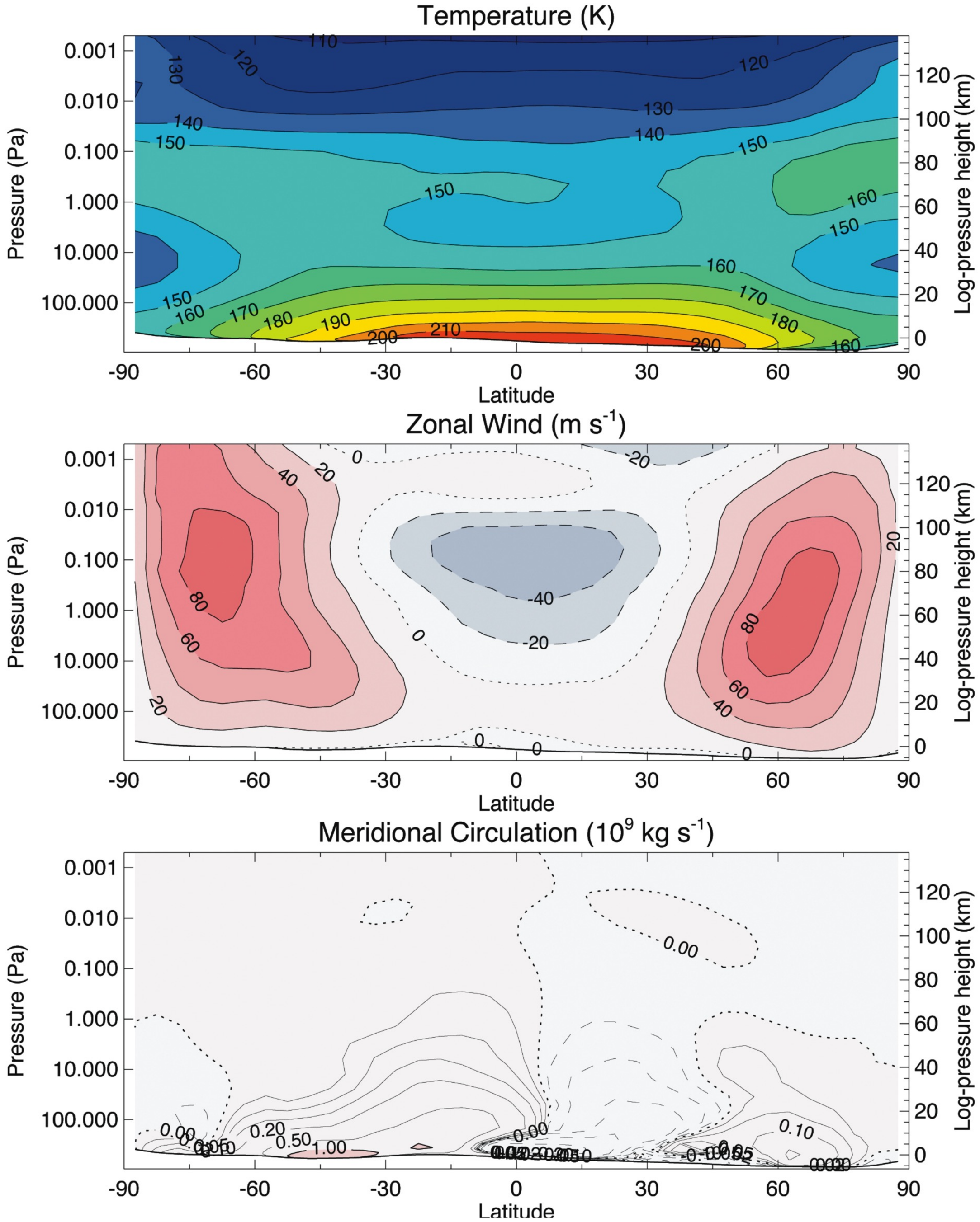
$\Longrightarrow$Hopf bifurcation

$\Longrightarrow$Nature of the bifurcation depends on the form of the dissipation

Where do we observe super-rotation (and how strong)?

- Mars atmosphere
  - Annual mean zonal wind exhibits midlatitude westerly jets and mostly easterly flow in the tropics
  - Weak westerly flow on the equator below 20 km altitude
  - Local super-rotation s peaks at around 0.03
  - Seasonal variations?





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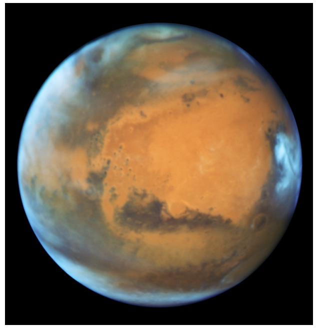

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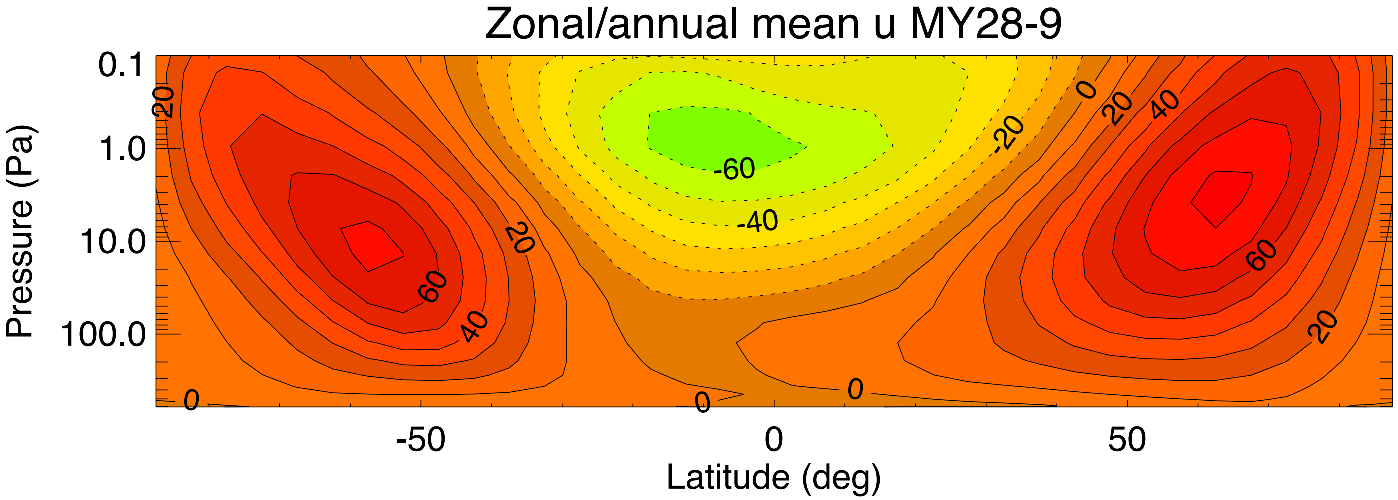

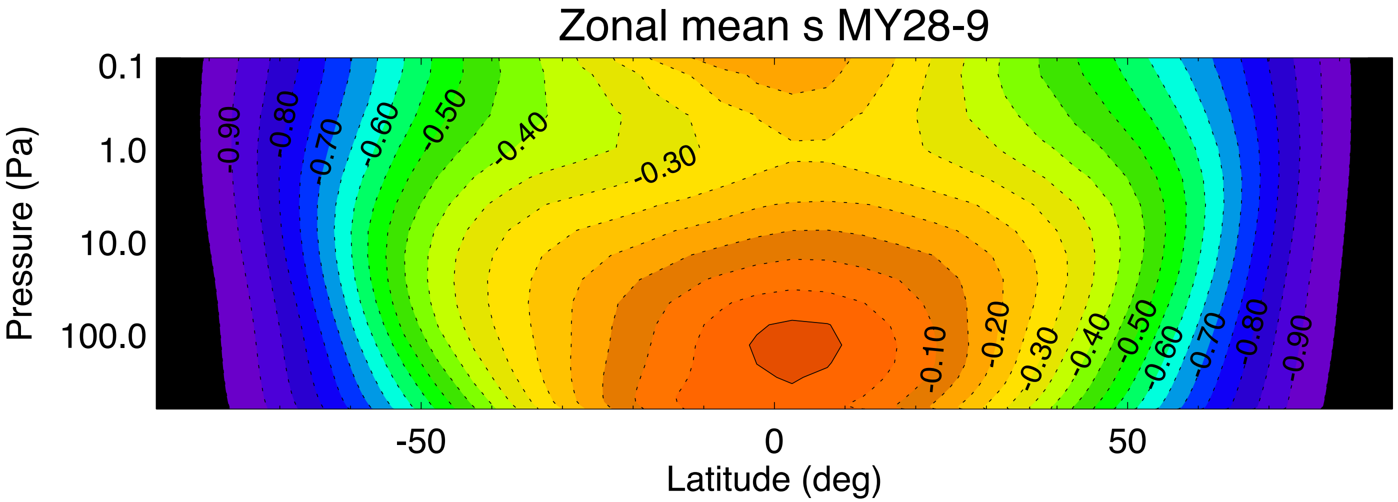

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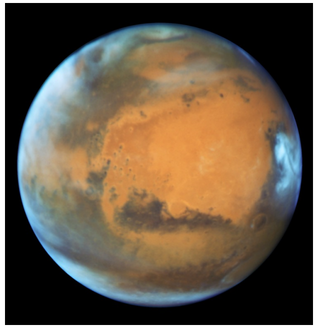

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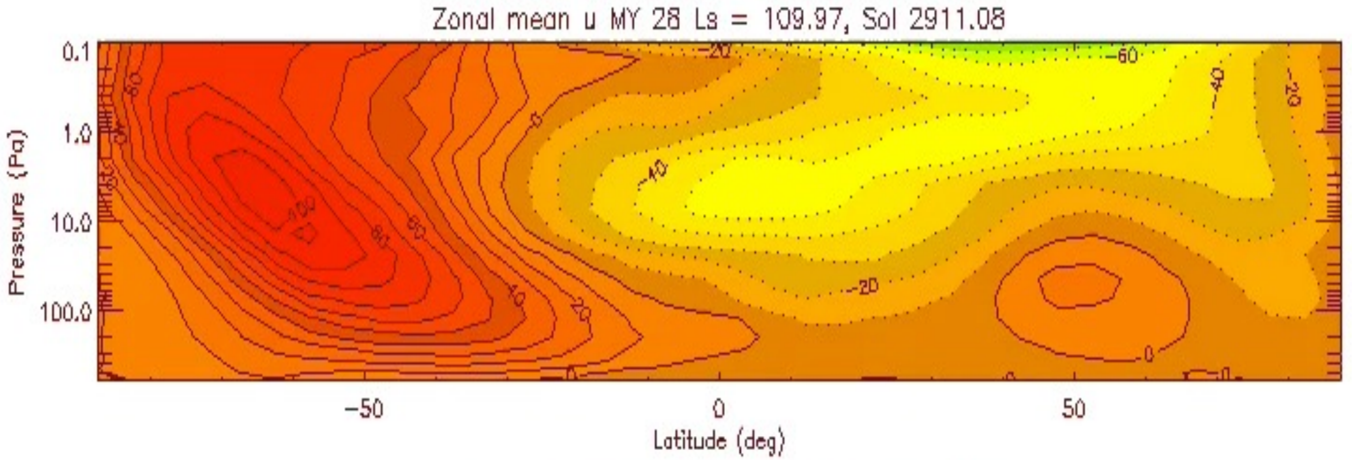

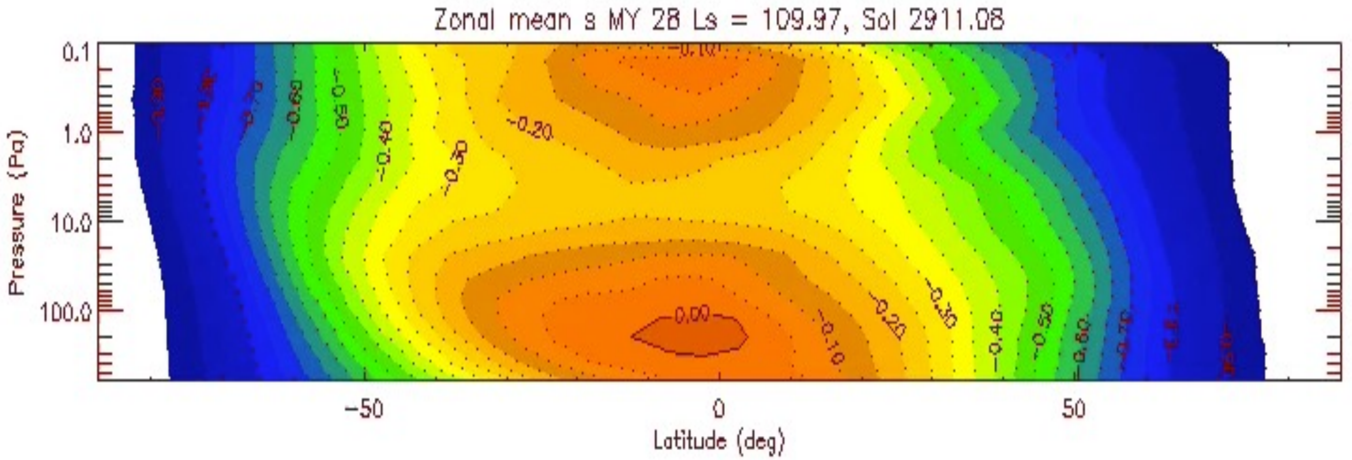

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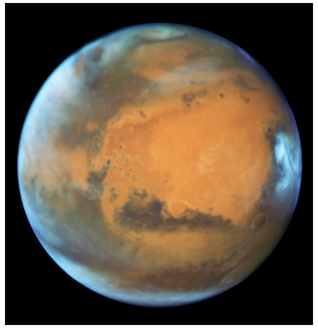

- Mars atmosphere
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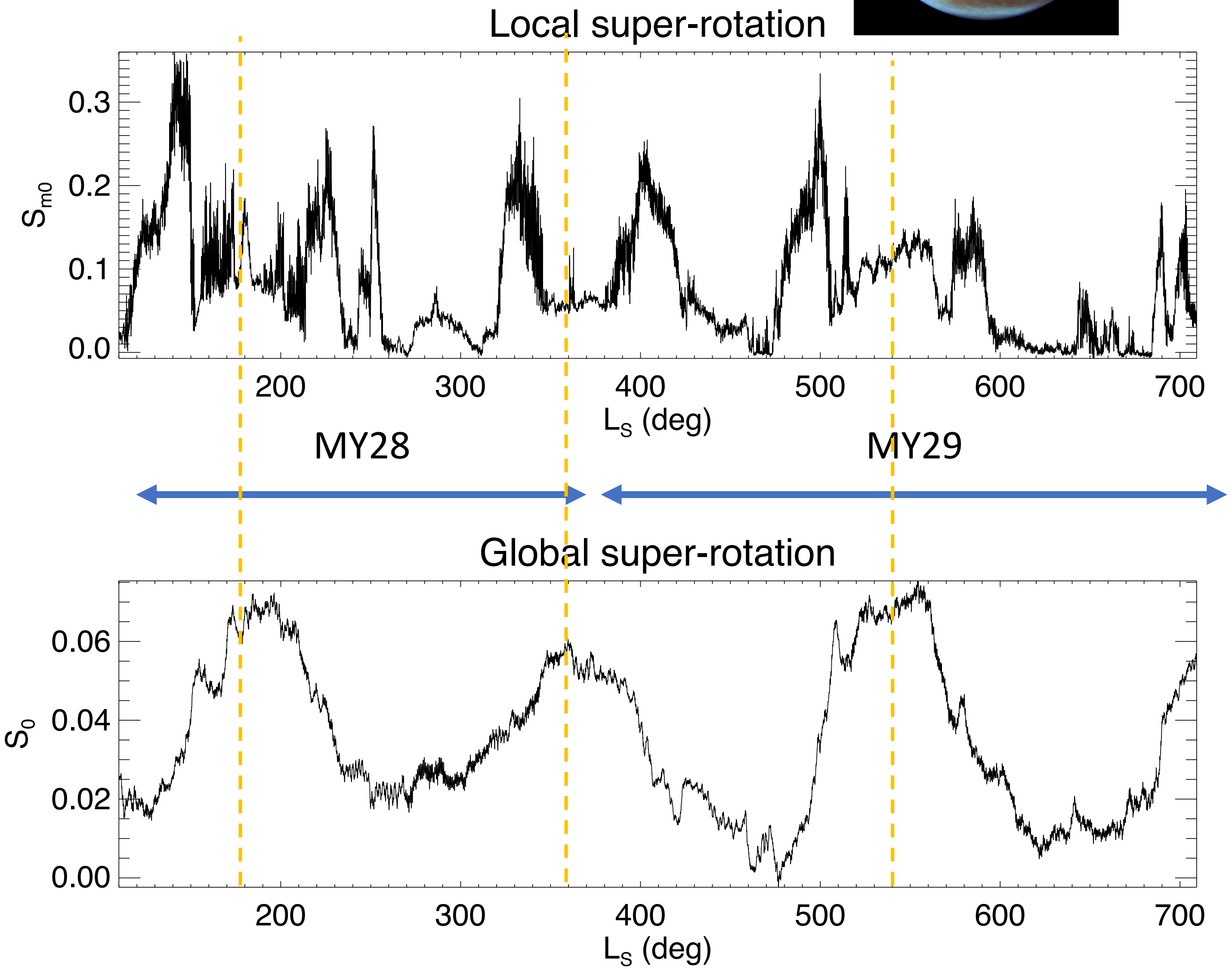
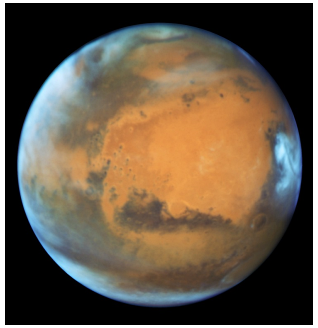
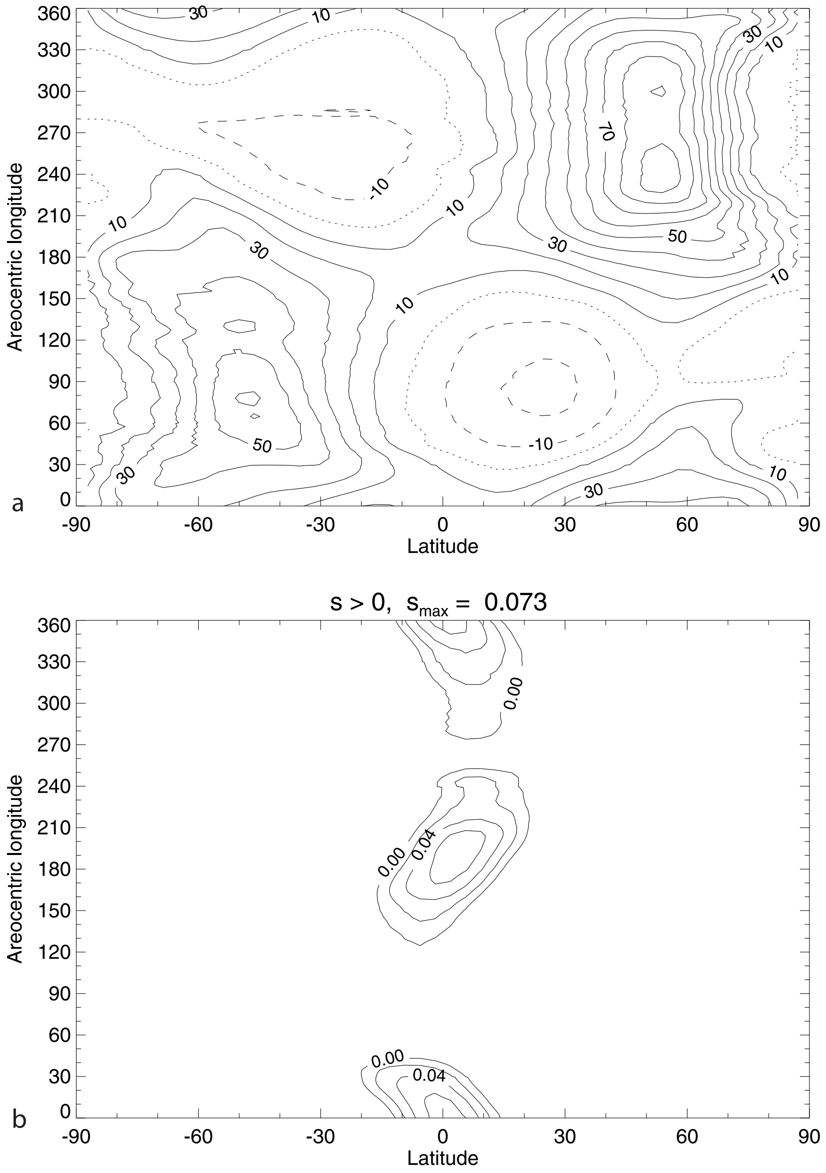
  - Local super-rotation s peaks at around 0.3
  - Seasonal variations?
  - Global super-rotation varies from ~0 to 0.07



Super-rotation in the Martian atmosphere



- Local super-rotation s peaks at around the equinoxes [$L_S \sim 0^o$ and 180^o]
  - [Lewis & Read 2003]



$\bar{u}$ at p = 136 Pa
[z ~ 10 km]

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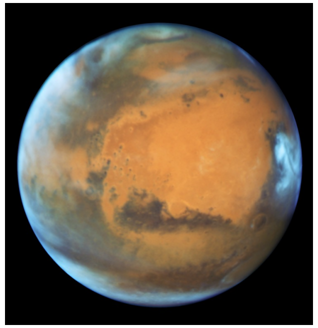

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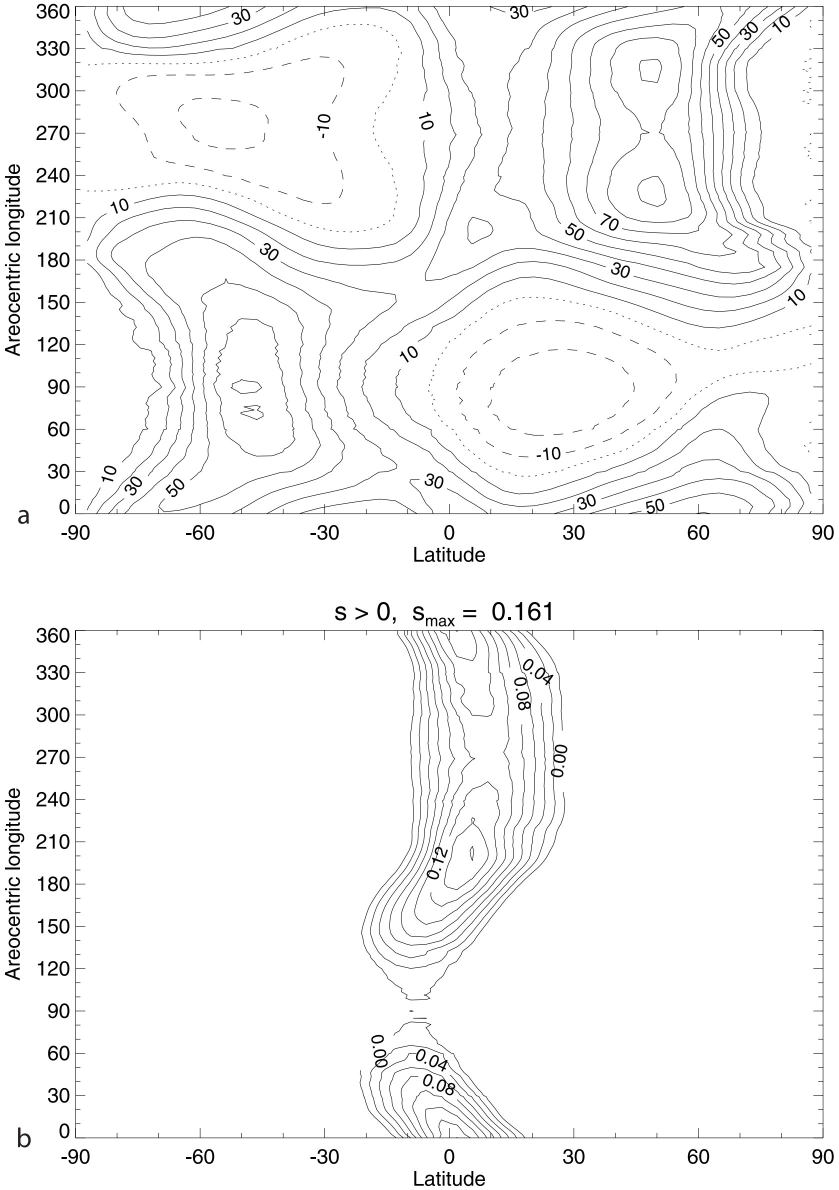

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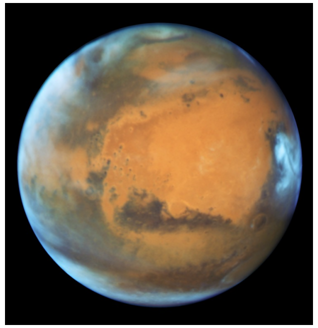

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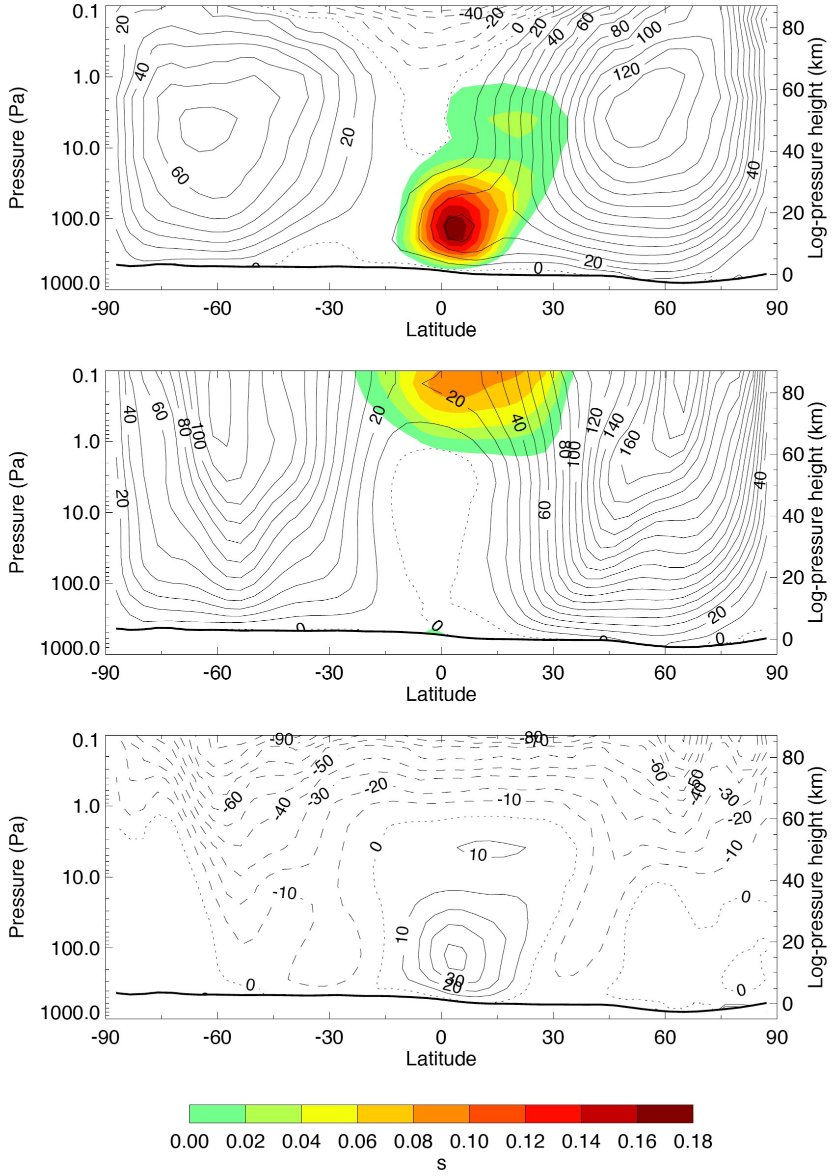
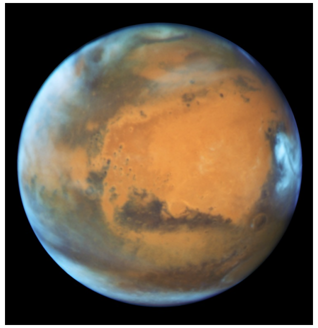


$\bar{u}$ with

and without Diurnal cycle

Difference

Super-rotation in the Martian atmosphere



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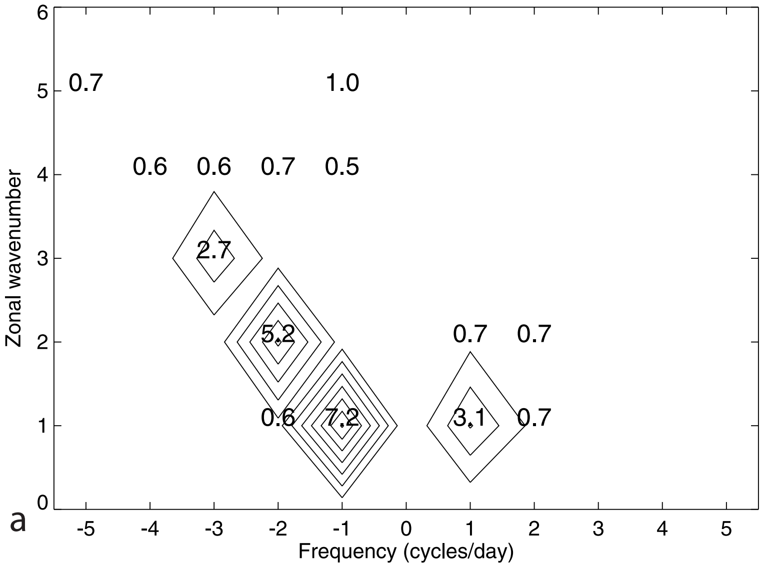
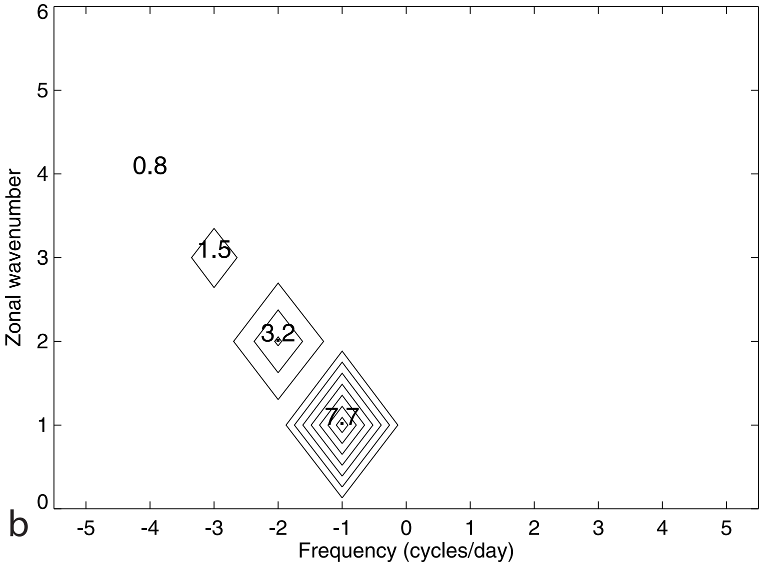
  - [Lewis & Read 2003]
- Enhanced by increased dust loading [x5]
- Role of thermal tides and topography?
  - Easterly tides
  - Interaction with m=2 topography generates westerly Kelvin wave “non-migrating” tide
  - Topography actually REDUCES super-rotation – WHY?



$\overline{T}$ spectra at p = 25 Pa [z ~ *25* km]

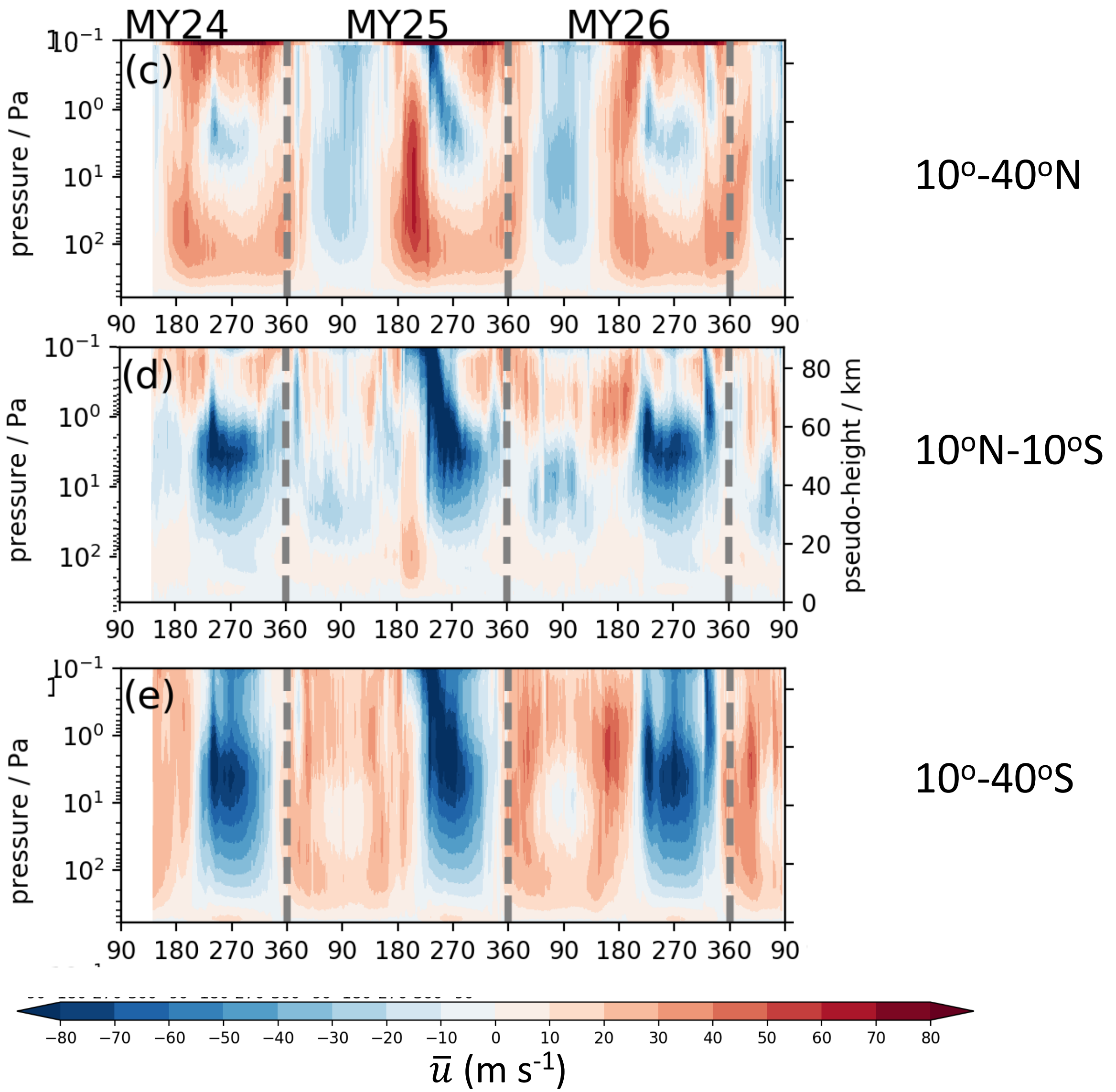
Realistic topography



Flat topography

A super-rotating SAO in the Martian atmosphere

- A semi-annual oscillation in $\bar{u}$ is seen in reanalyses of observations of the Martian middle and lower atmosphere [Ruan et al. 2019 *Icarus*]
- Seen between ±40^o latitude
- Wind doesn't always reverse
- Diagnose forcing using TEM equation for zonal momentum



[Ruan et al. 2015]

A super-rotating SAO in the Martian atmosphere

- Diagnose forcing using TEM equation for zonal momentum

$$\bar{u}_t = \left(f - \frac{(\bar{u}\cos\varphi)_\varphi}{r_0\cos\varphi}\right)\bar{v}^* - \bar{u}_p\bar{\varpi}^* - \frac{1}{r_0\cos^2\varphi}(S_{(\lambda\varphi)}\cos^2\varphi)_\varphi - (S_{(\lambda p)})_p + \bar{X}, \quad (1)$$

1. 2 ← 3 → 4

where $\bar{u}$ is the zonal-mean zonal wind, f is the Coriolis parameter, φ is latitude and r_0 is the radius of the planet, while the residual meridional circulation $(0, \bar{v}^*, \bar{\varpi}^t)$ is defined by

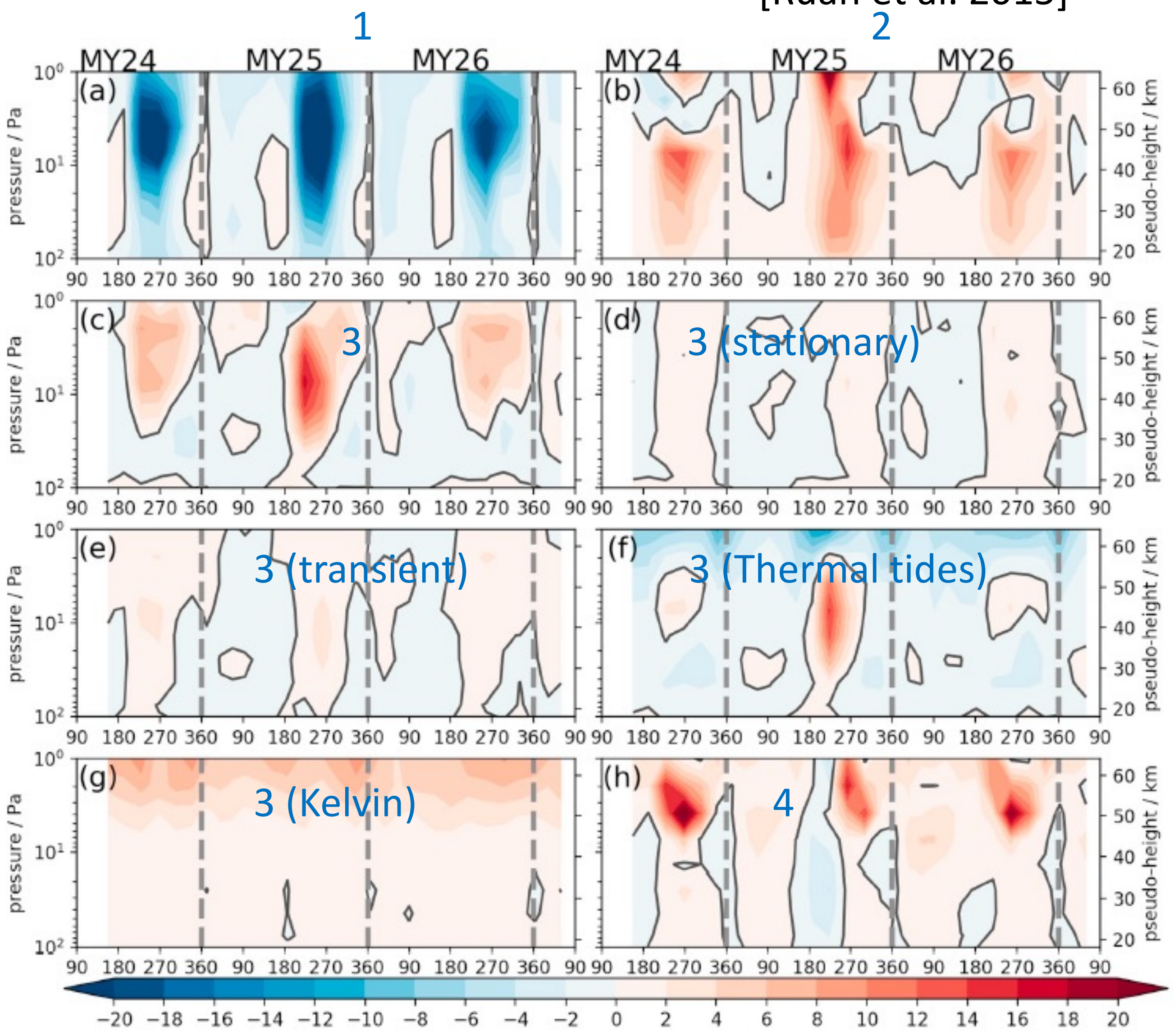
$$\bar{v}^* = \bar{v} - \left(\frac{\overline{v'\theta'}}{\bar{\theta}_p}\right)_p, \qquad \bar{\varpi}^* = \bar{\varpi} + \frac{1}{r_0\cos\varphi}\left(\frac{\overline{v'\theta'}}{\bar{\theta}_p}\cos\varphi\right)_\varphi,$$

and

$$S_{(\lambda\varphi)} = \overline{v'u'} - \bar{u}_p\frac{\overline{v'\theta'}}{\bar{\theta}_p}, \qquad S_{(\lambda p)} = \overline{\omega'u'} + \left(\frac{(\bar{u}\cos\varphi)_\varphi}{r_0\cos\varphi} - f\right)\frac{\overline{v'\theta'}}{\bar{\theta}_p}.$$

- Forcing similar to Earth SAO
  - Westward phase dominated by horiz. adv. [1]
  - Eastward phase dominated by Kelvin modes
  - Plus important role for thermal tides & stationary waves

[Ruan et al. 2015]



Super-rotation in Gas/Ice Giant planet atmospheres

[Credit, Sanchez-Lavega et al. 2019]

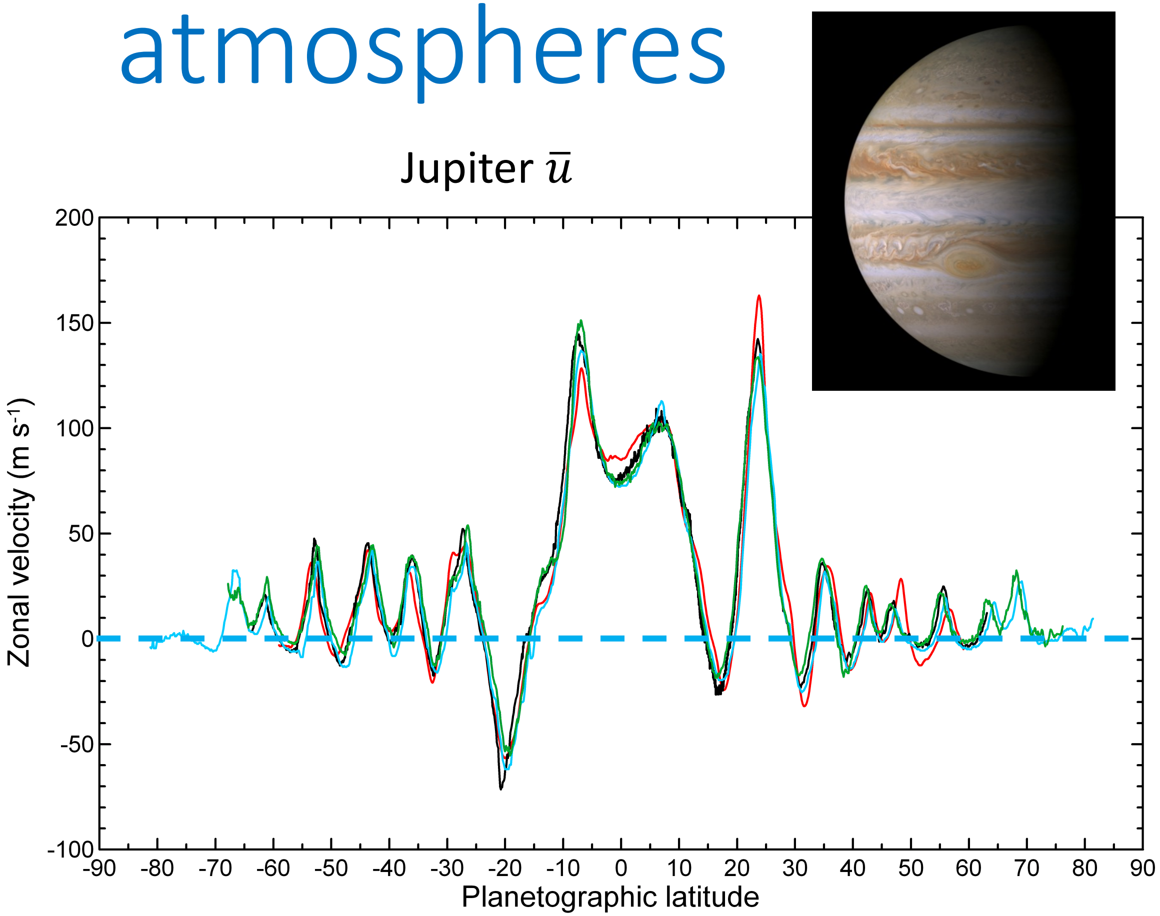


Figure 4.12 Jupiter zonal wind profiles. Red is from Voyager data (Limaye, 1986), black (García-Melendo et al., 2011a) and blue (Porco et al., 2003) are from Cassini data, and green is from HST data (Garcıa-Melendo and Sánchez-Lavega, 2001).

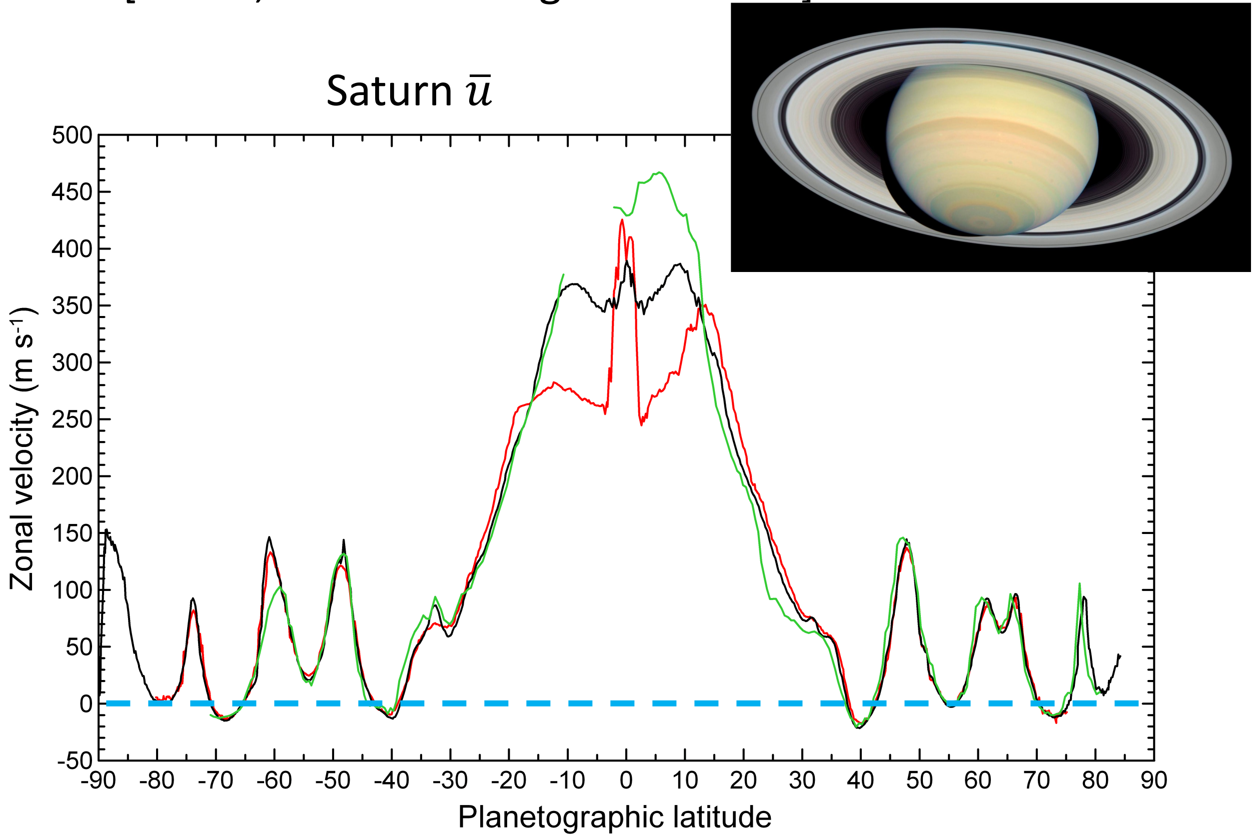
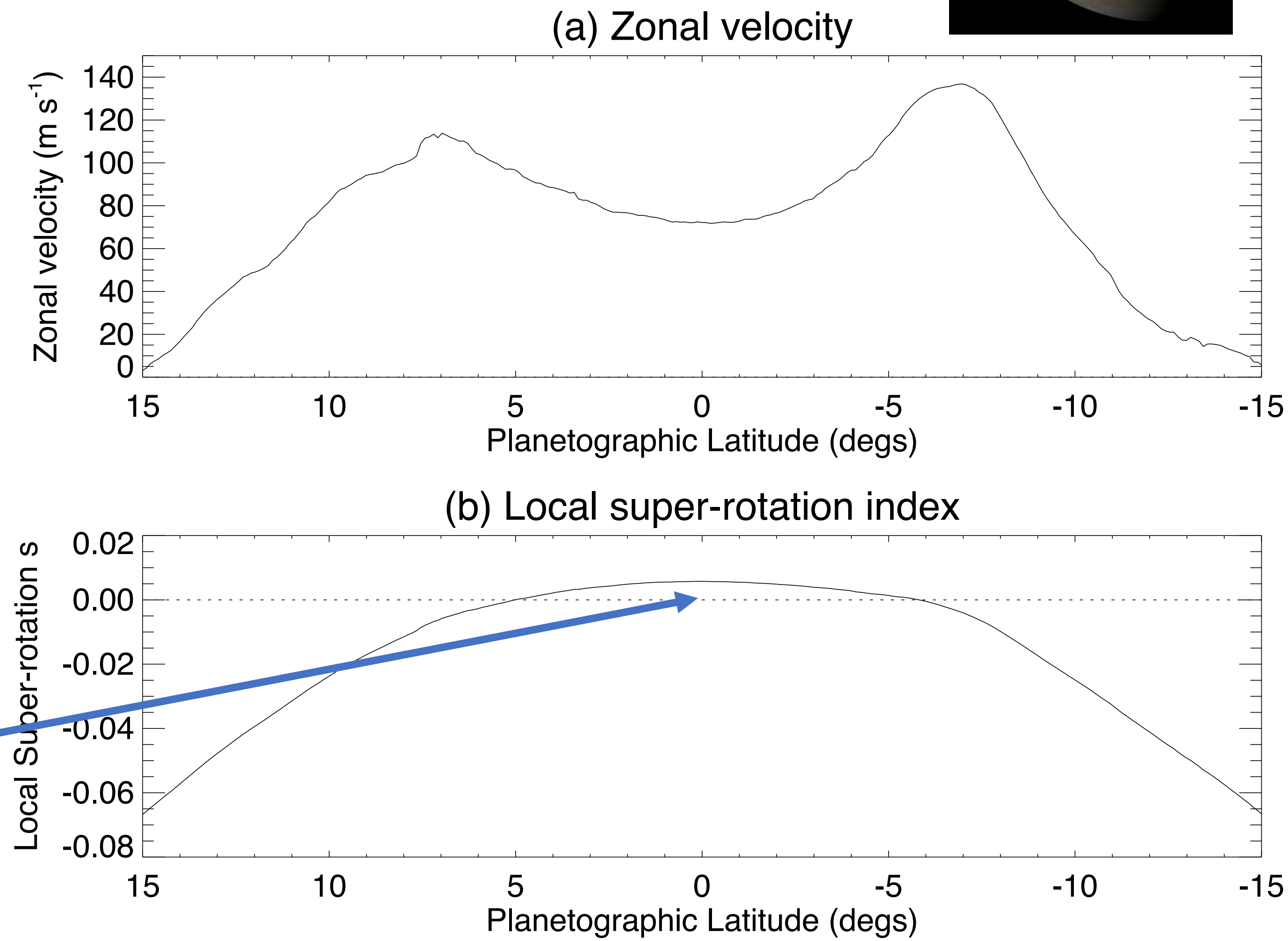


Figure 4.13 Saturn zonal wind profile. Green represents Voyager data (Sánchez-Lavega et al., 2000); black is Cassini imaging data in the continuum (350–500 mbar); red is Cassini imaging data in the strongly absorbing methane band at 890-nm (60–250 mbar) (García-Melendo et al., 2011b).

Where do we observe super-rotation (and how strong)?

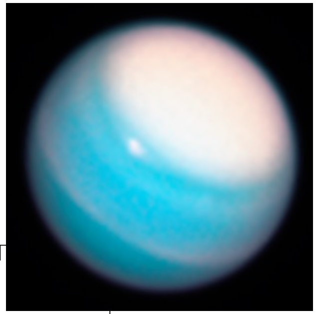
- Jupiter's atmosphere
  - Giant planet ($a \sim 11.a_{Earth}$) rotates rapidly (τ_{rot} = 9.926 hours)
  - Multiple eastward and westward zonal jets in each hemisphere at cloud tops
  - Strong (>100 m s^{-1}) eastward equatorial jet
  - Local super-rotation at cloud tops peaks at around s_{max} = +0.006 at the equator

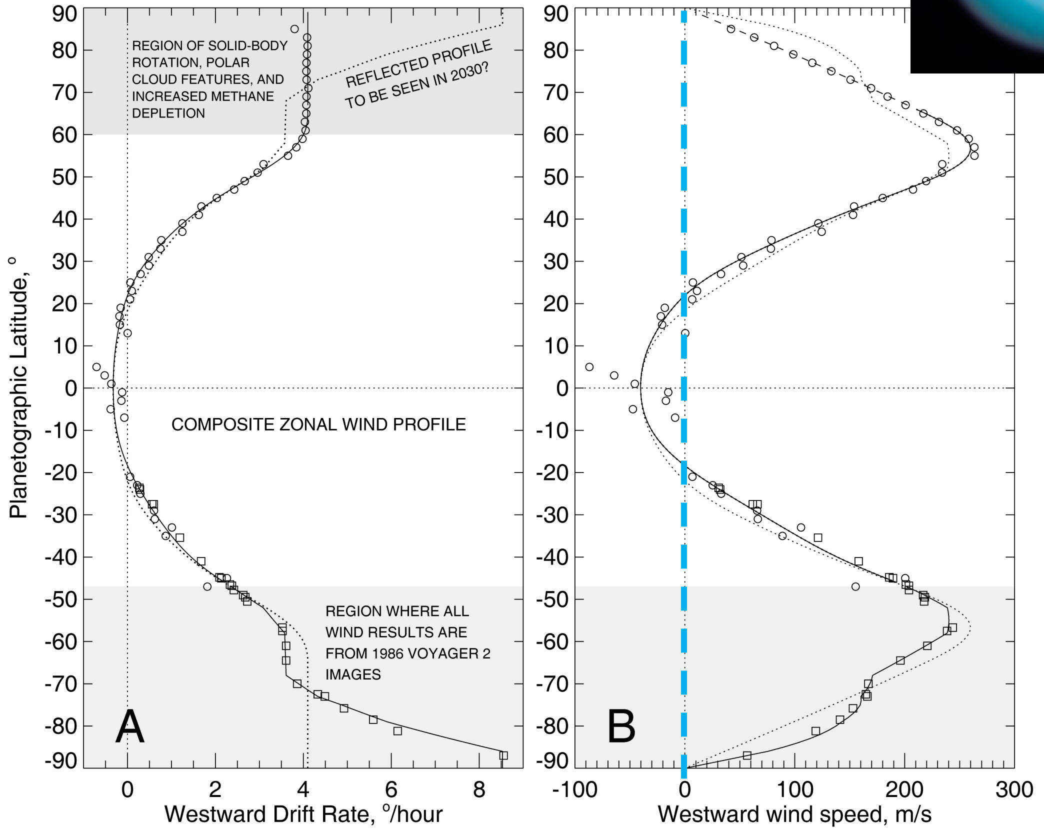


Super-rotation in Gas/Ice Giant planet atmospheres

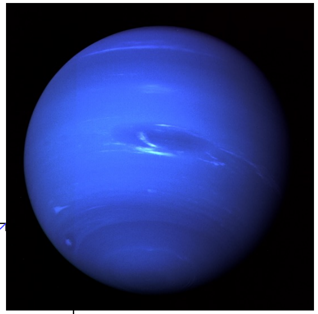
[Credit, Sanchez-Lavega et al. 2019]

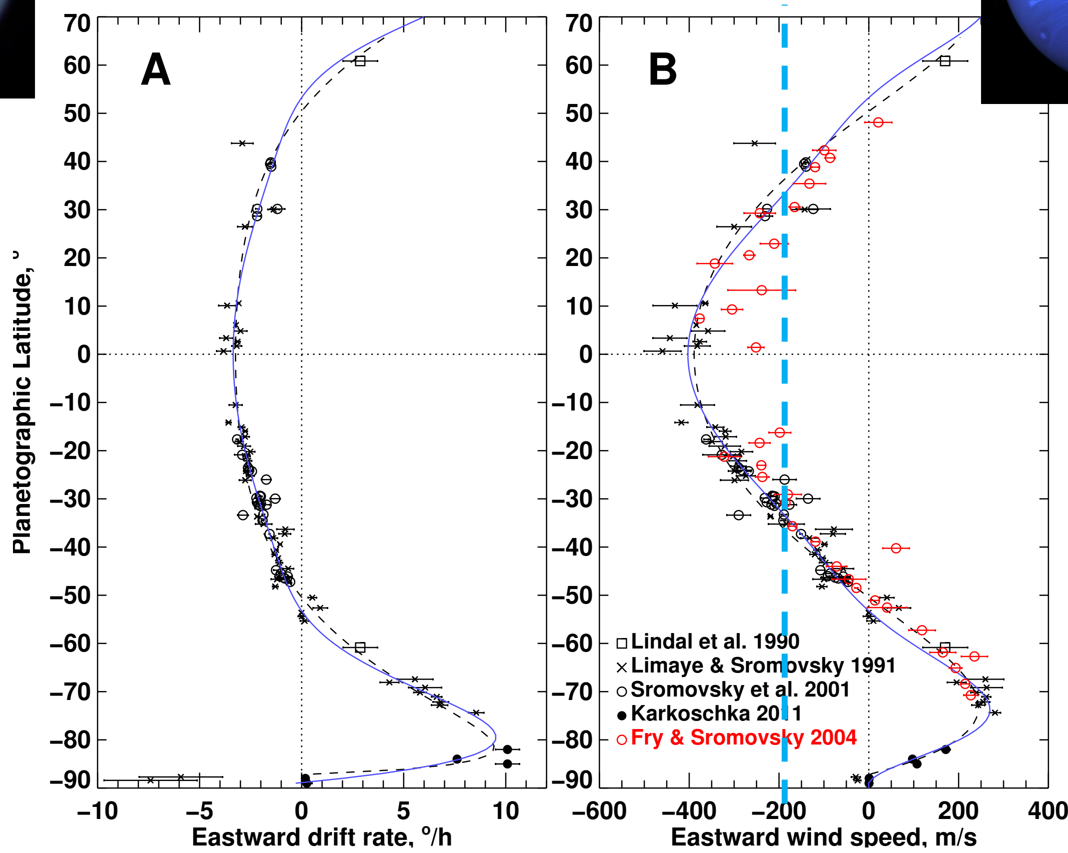
Uranus $\bar{u}$





Neptune $\bar{u}$





NB SUB-rotating equatorial jets

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets?
  - How are they driven?
  - Why are some eastward and others westward?
  - Deep or shallow?
  - Role of eddies vs axisymmetric circulations?
  - Detailed shape (local minima/off-equatorial maxima)….?
- Three basic mechanisms
  1. Vertically propagating/dissipating equatorial planetary waves?
  2. Meridional momentum transport – tropics vs midlatitudes?
  3. Deep convective/thermal Rossby waves….?

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets?
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- Three basic mechanisms
  1. Vertically propagating/dissipating equatorial planetary waves?
  2. Meridional momentum transport – tropics vs midlatitudes?
  3. Deep convective/thermal Rossby waves….?

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 1. Vertically propagating/ dissipating equatorial planetary waves?
  - Cf Gravity wave streaming mechanism [Maxworthy 1975]

T. MAXWORTHY

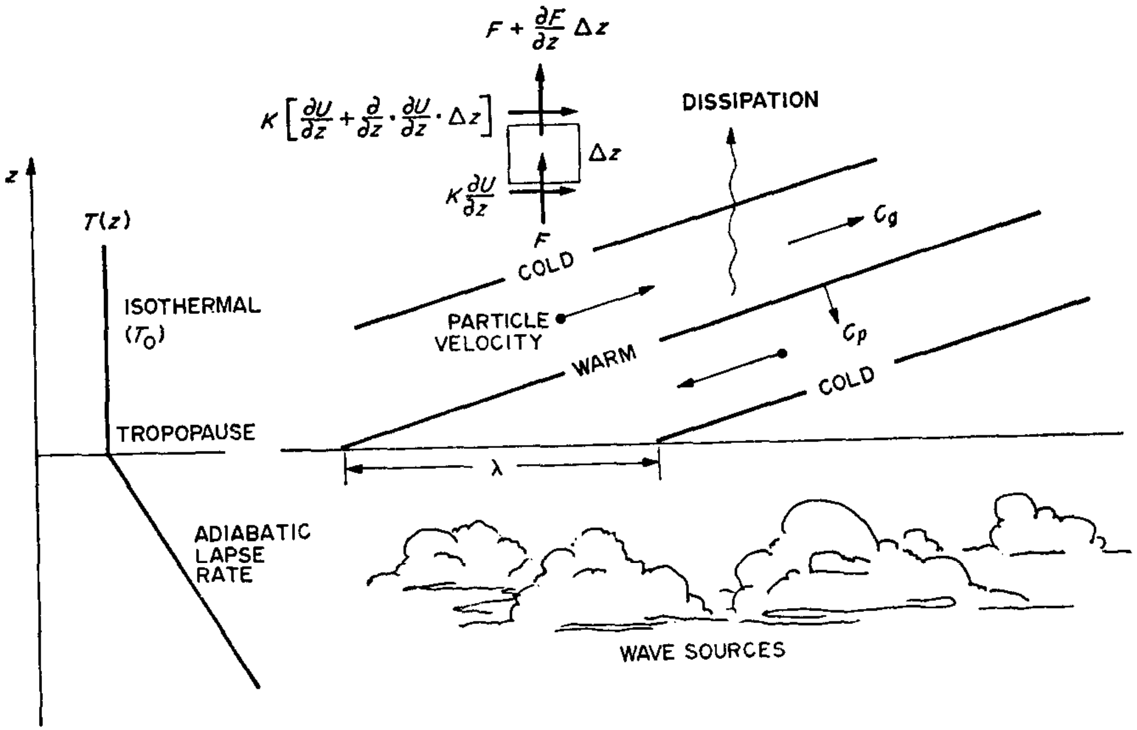


FIG. 1. DIAGRAMMATIC DRAWING OF THE PHYSICAL SITUATION AT THE EQUATOR, SHOWING THE ATMOSPHERIC TEMPERATURE DISTRIBUTION AND THE CHARACTER OF THE INTERNAL KELVIN WAVE PROPAGATING TO THE "EAST."

The motion producing the waves is assumed to be in the troposphere while the visible clouds which are observed to convect at ~100 m/sec extend a small distance into the stratosphere. C_p and C_g are the wave phase and group velocities, respectively, and λ its horizontal wavelength.

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 1. Vertically propagating/ dissipating equatorial planetary waves?
  - Cf Gravity wave streaming mechanism [Maxworthy 1975]
  - Upward propagating equatorial Kelvin waves accelerate $\bar{u}$ where they dissipate toward $\bar{u} \approx c$ (for strong forcing)

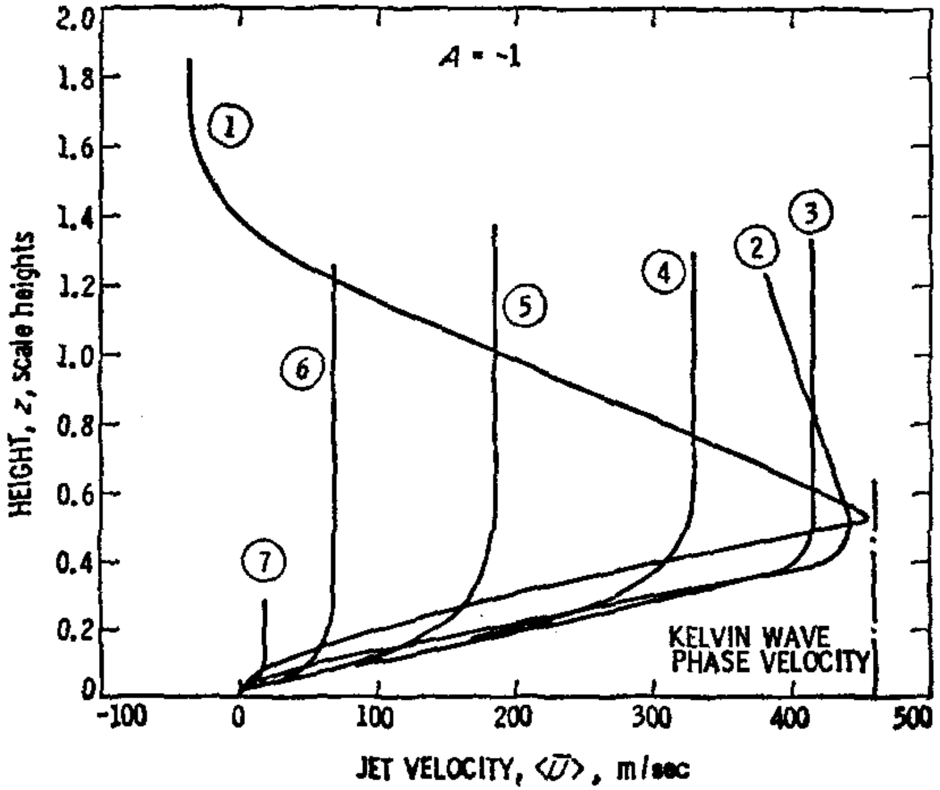


FIG. 2. VELOCITY PROFILES FOR THE CASE $A = -1$ AND A JET HALF-WIDTH OF 12,000 km, i.e. $C_0' = 460$ m/sec, $C_1' = -260$ m/sec.

In this case there is no stress at the tropopause so that the underlying fluid need have no net velocity. For seven values of $K\alpha^2$: (1) 5×10^{-15}; (2) 5×10^{-14}; (3) 5×10^{-13}; (4) 5×10^{-12}; (5) 5×10^{-11}; (6) 5×10^{-10}; (7) 5×10^{-9}.

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 1. Vertically propagating/ dissipating equatorial planetary waves?
    - Demonstrate in idealised numerical models [Yamazaki et al. 2005]
    - Double-peaked profile in φ?
    - Combine with meridional overturning circulation (cf HH80)?

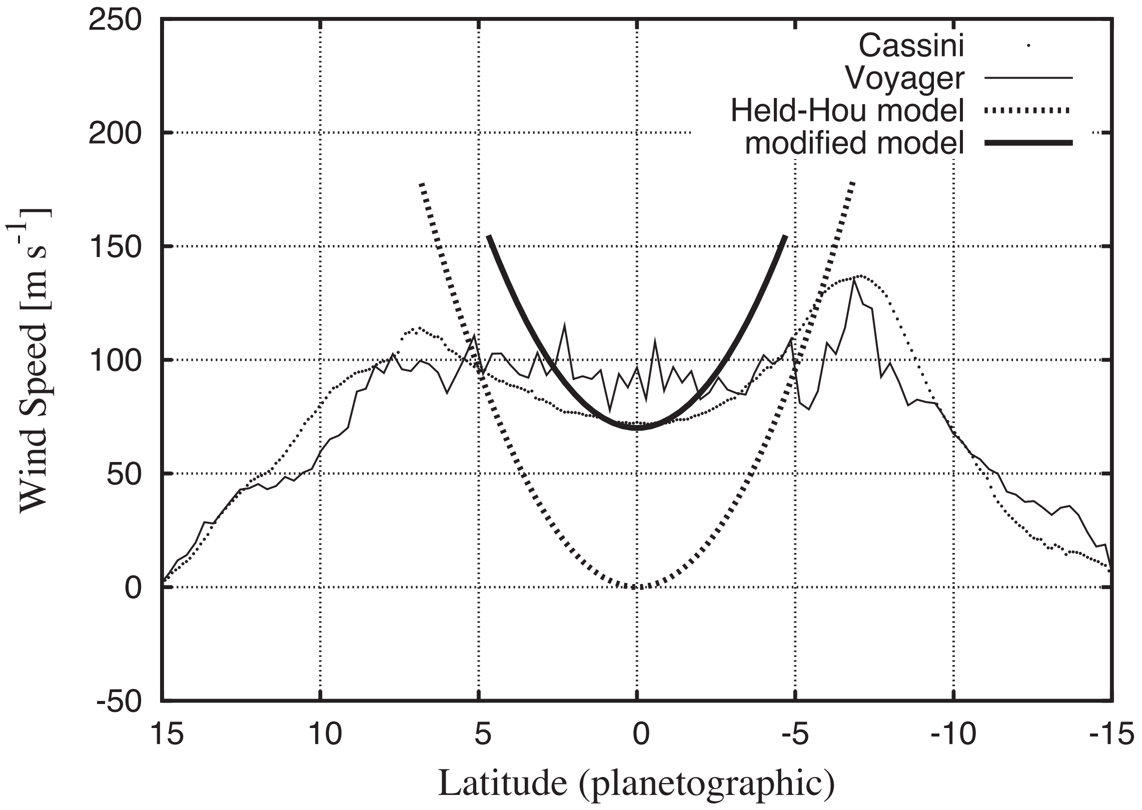
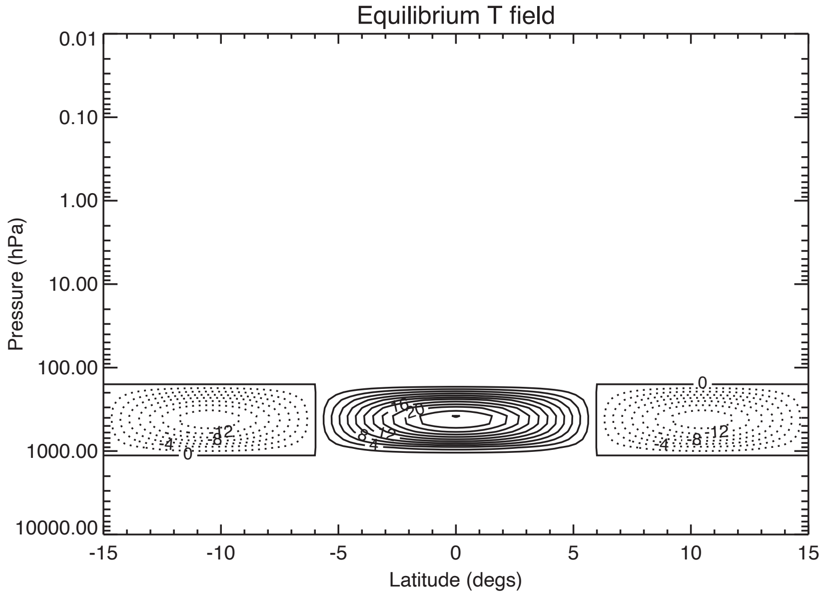


Fig. 2. Jupiter's equatorial winds: observed winds and prediction of simple models of a Hadley-type circulation which assume conservation of angular momentum. Cassini data is the same as that used in Fig. 1; Voyager data cortesy of Dr. A.A. Simon-Miller (see Simon, 1999).

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 1. Vertically propagating/ dissipating equatorial planetary waves?
  - Combine with meridional overturning circulation (cf HH80)?



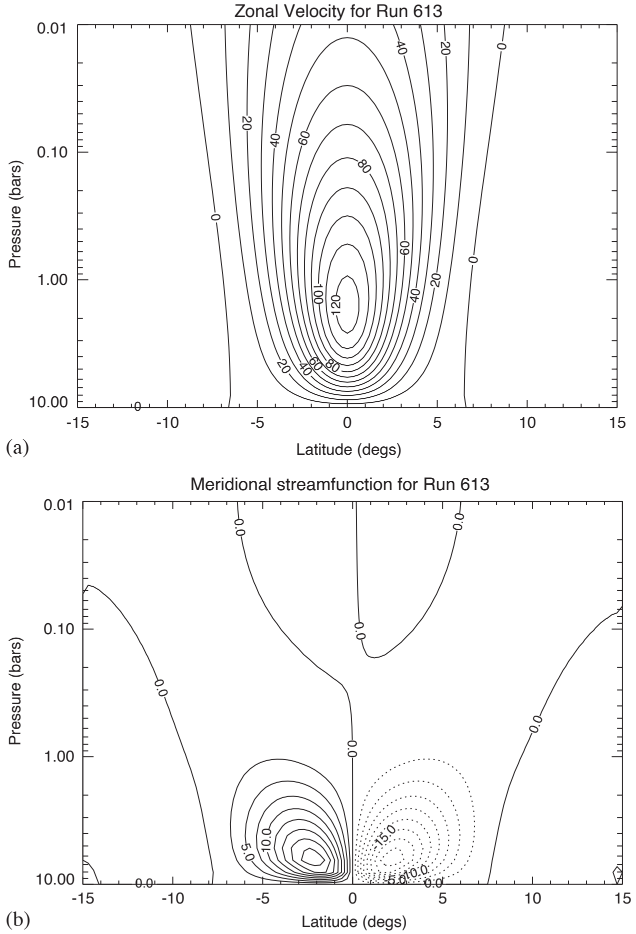


Fig. 6. Latitude–height maps of zonal velocity (a) and meridional streamfunction (b) from a simulation of a flow using the mechanistic model of Li et al. (1997) and Li and Read (2000), for the pure Kelvin wave forcing scenario.

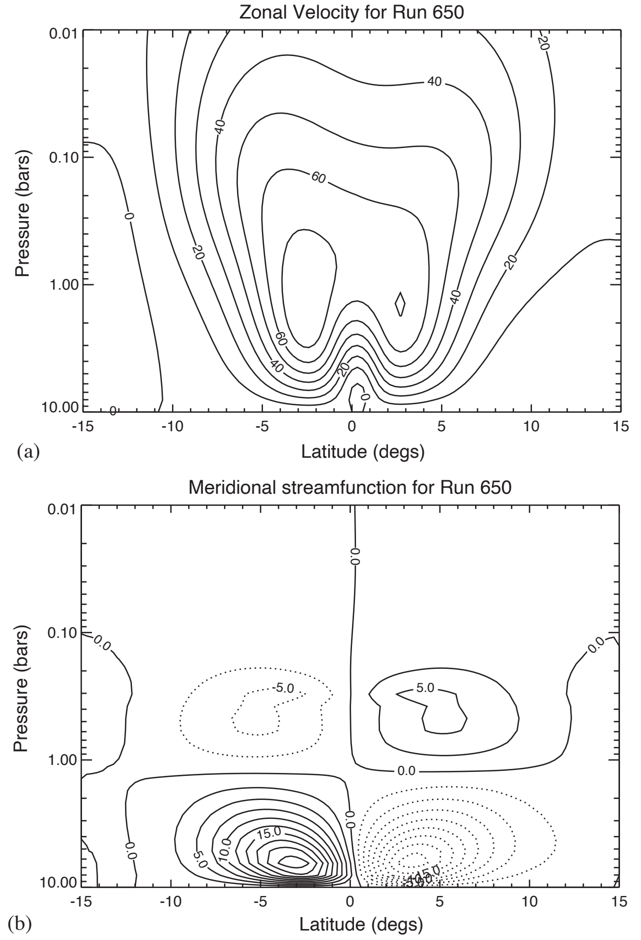


Fig. 7. Latitude–height maps of zonal velocity (a) and meridional streamfunction (b) from a simulation of a flow using the mechanistic model of Li et al. (1997) and Li and Read (2000), for the combined Hadley–Kelvin forcing scenario.

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 1. Vertically propagating/ dissipating equatorial planetary waves?
  - Combine with meridional overturning circulation (cf HH80)?

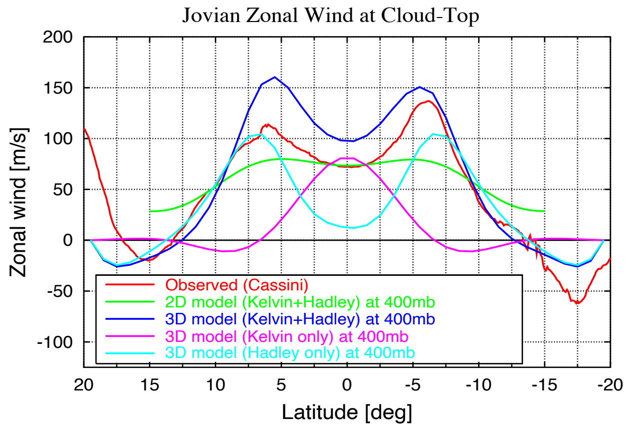


Fig. 11. Comparison of observed and simulated cloud-top winds of Jupiter's equatorial region.

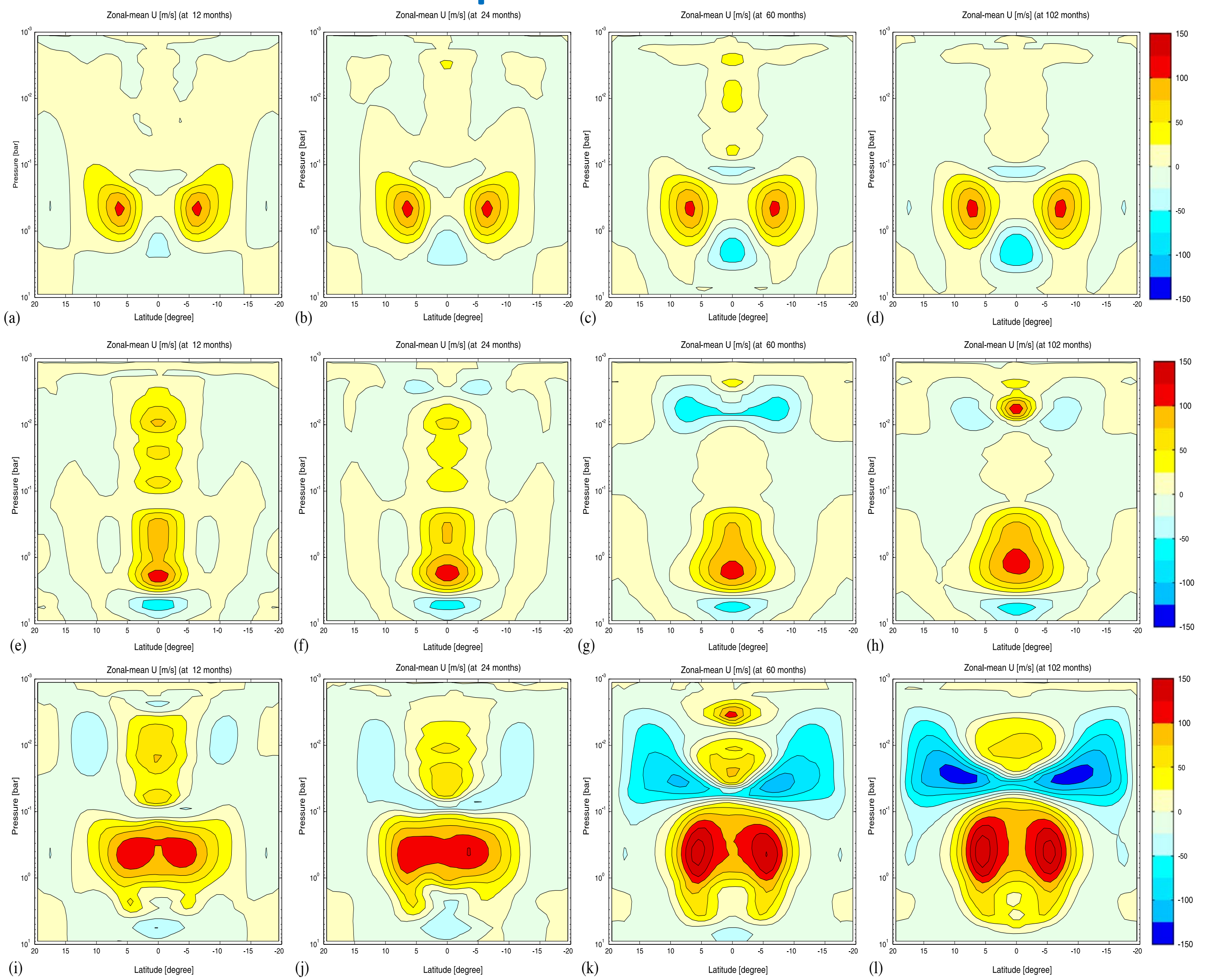
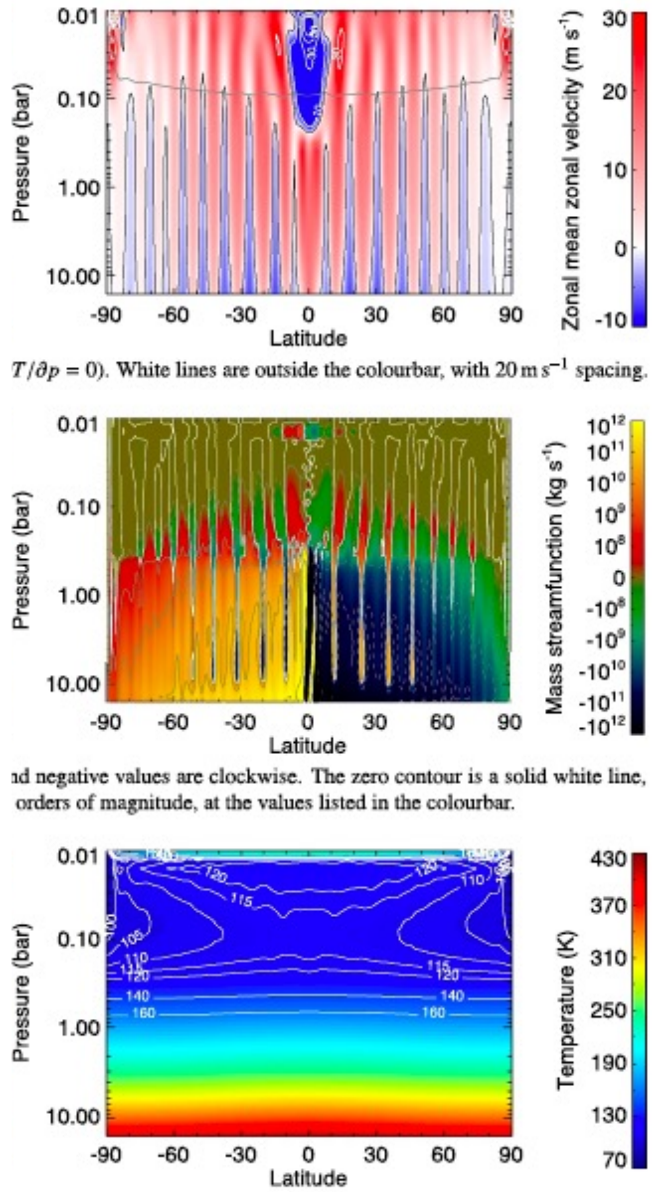


Fig. 10. Evolution of mean zonal winds in GCM experiments: Top, middle and bottom panels show the evolution in the case of Kelvin-only, Hadley-only and combined forcings at 12, 24, 60, and 102 months after the thermal forcing was imposed.

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 2. Meridional momentum transport – tropics vs midlatitudes?
  - Cf Earth's tropics vs super-rotating state?
  - Midlatitude baroclinic forcing vs tropical convection?
  - E.g. Young et al. [2019] Jupiter GCM? – EASTWARD equatorial jet at $p > 1$ bar….



Super-rotation in Gas/Ice Giant planet atmospheres

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  - Cf Earth's tropics vs super-rotating state?
  - Midlatitude baroclinic forcing vs tropical convection?
  - E.g. Young et al. [2019] Jupiter GCM? – EASTWARD equatorial jet at $p > 1$ bar….
  - Driven mainly by horizontal AM eddy flux convergence

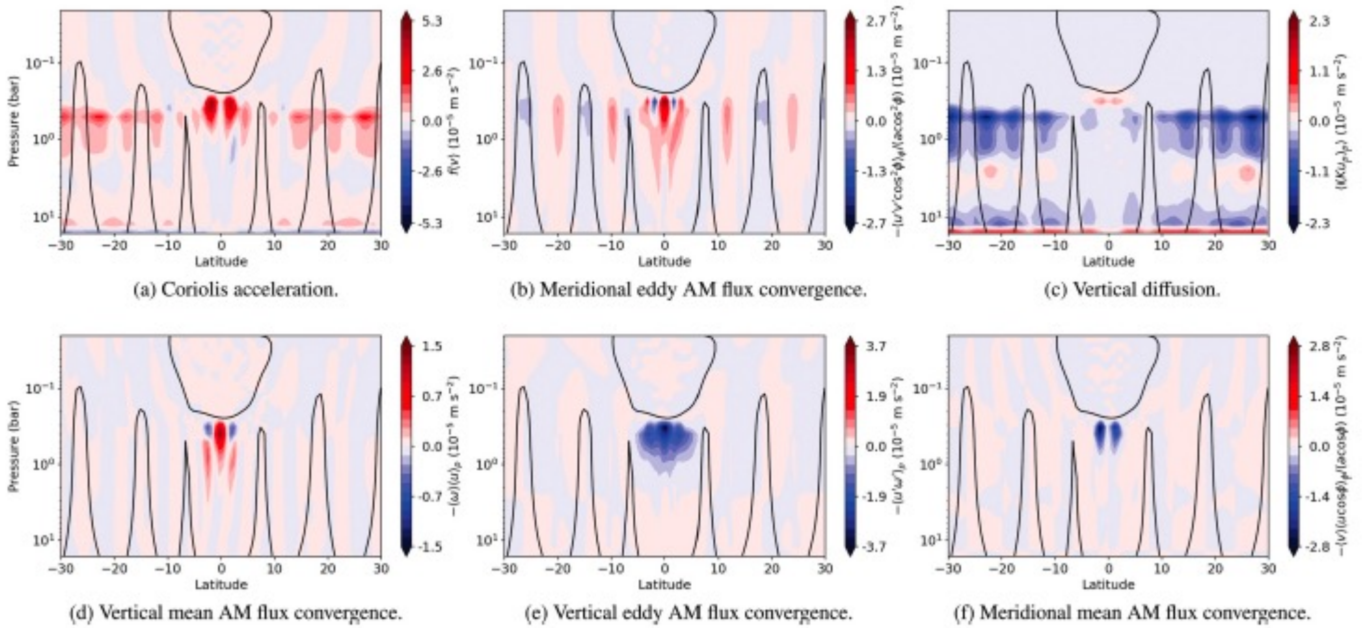
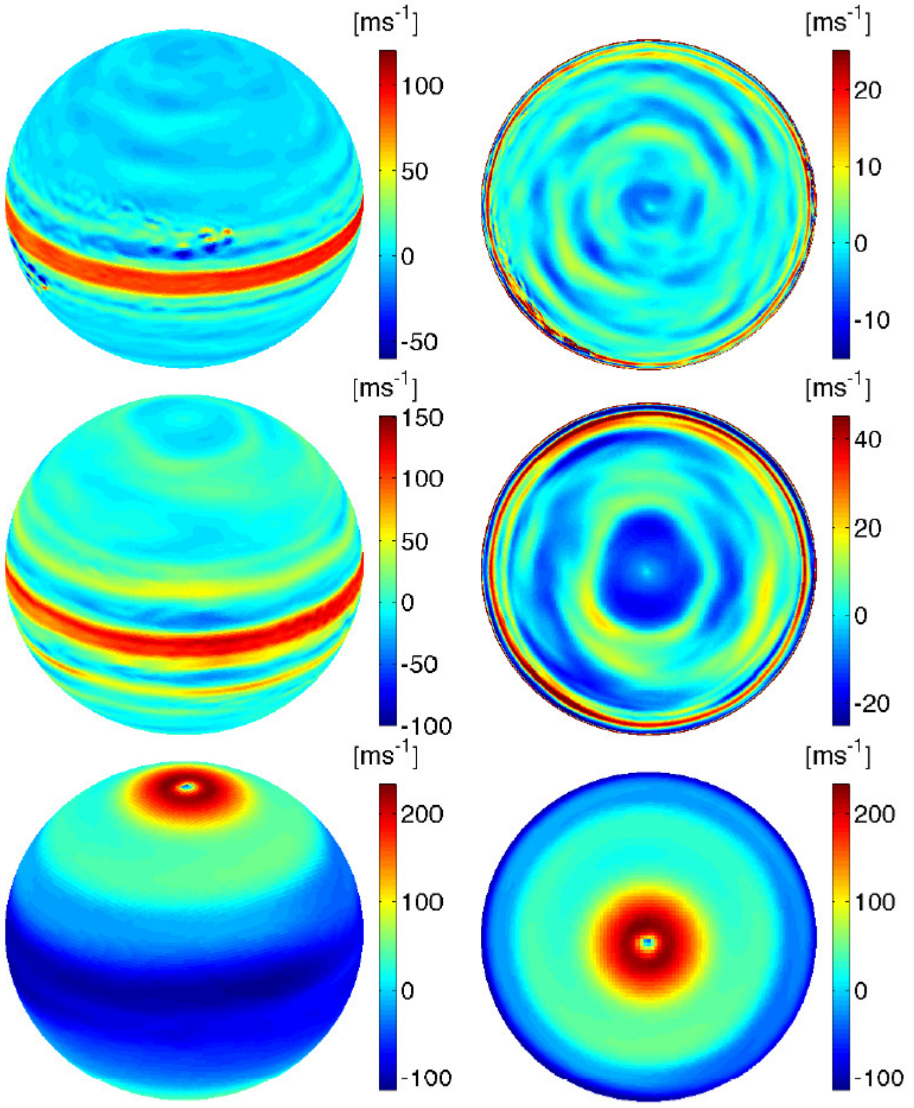


Fig. 24. Forcing terms of $O(10^{-5}\ \mathrm{m\,s^{-2}})$ in the Eulerian mean equation (Eq. 9) for Run B in equilibrium, averaged over 132900–133000 d. The bottom drag, estimate of Shapiro filter, and $\langle v'\partial v'/\partial\lambda\rangle$ terms are omitted; the first two are $O(10^{-6}\ \mathrm{m\,s^{-2}})$ and the latter is $O(10^{-8}\ \mathrm{m\,s^{-2}})$. Supplementary Figure S6 shows all the terms.

Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 2. Meridional momentum transport – tropics vs midlatitudes?
    - Cf Earth's tropics vs super-rotating state?
    - Midlatitude baroclinic forcing vs tropical convection?
    - E.g. Lian & Showman [2010] GCM?
    - Driven mainly by horizontal AM eddy flux convergence
    - Could account for eastward jets on Jupiter & Saturn, but westward jets on ice giants…..?



Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 3. Deep convective/thermal Rossby waves….?
- Deep convection organized parallel to rotation axis
- Propagates like Rossby waves in DEEP spherical shell – i.e. EASTWARD
- E.g. Heimpel et al. [2005] GCM?
- Driven mainly by horizontal AM eddy flux convergence

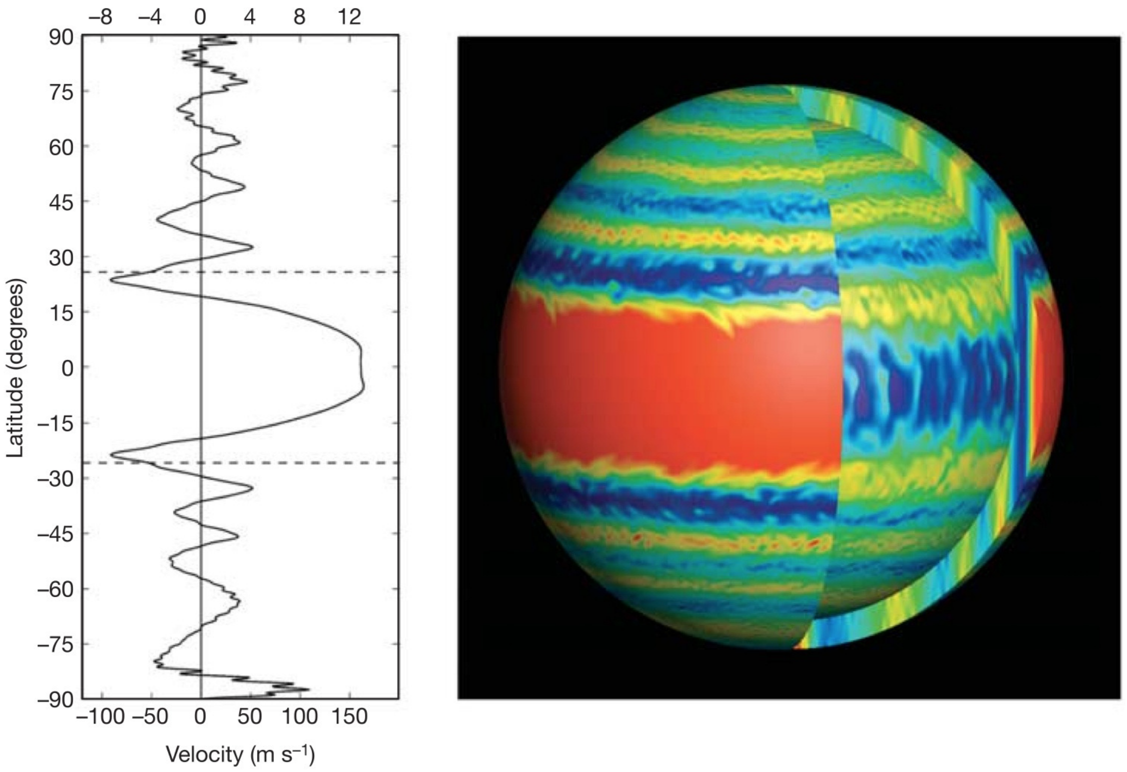
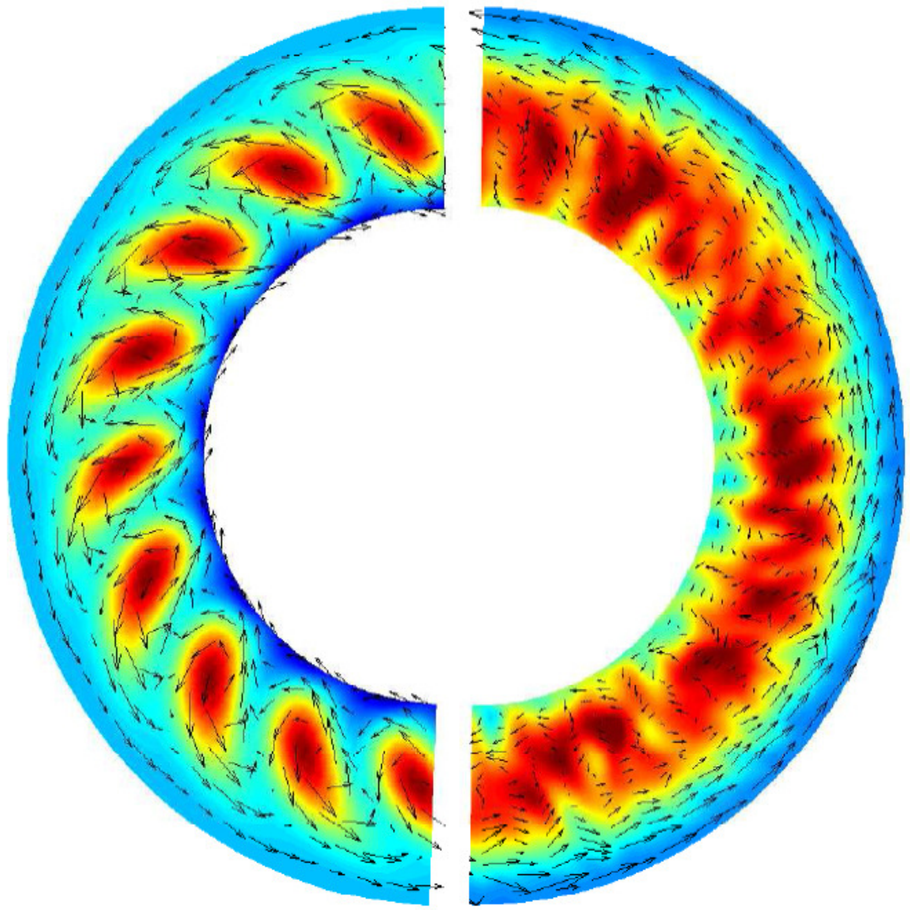


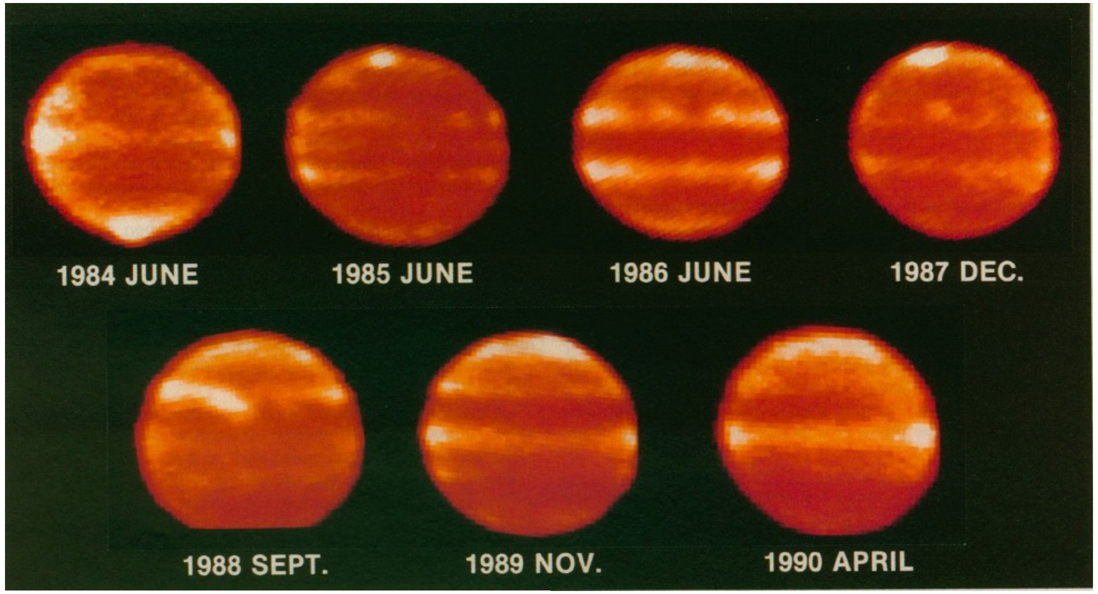
Figure 4.30 Zonal winds in a three-dimensional model of convection in a thin spherical shell from Heimpel et al. (2005). The ratio of the inner and outer radii in the model is 0.9. The model is Boussinesq and thus ignores the increase of mean density with depth that occurs on the giant planets. Equatorial superrotation and multiple off-equatorial jets emerge, qualitatively similar to those on Jupiter.

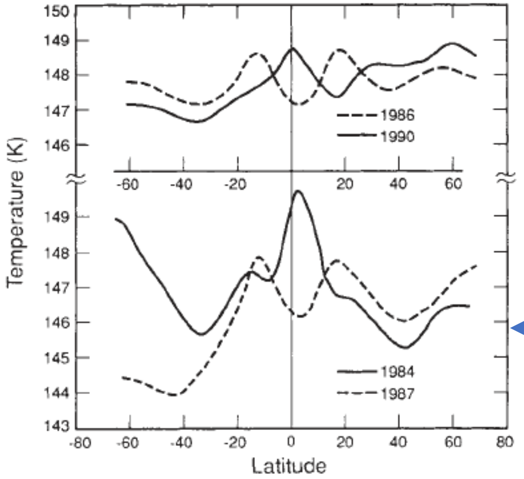
Super-rotation in Gas/Ice Giant planet atmospheres

- Origin of equatorial jets: 3. Deep convective/thermal Rossby waves….?
- Deep convection organized parallel to rotation axis
- Propagates like Rossby waves in DEEP spherical shell – i.e. EASTWARD
- E.g. Showman et al. [2011] GCM?
- Driven mainly by horizontal AM eddy flux convergence in laterally tilted vortices
  - Eastward u where dissipated.

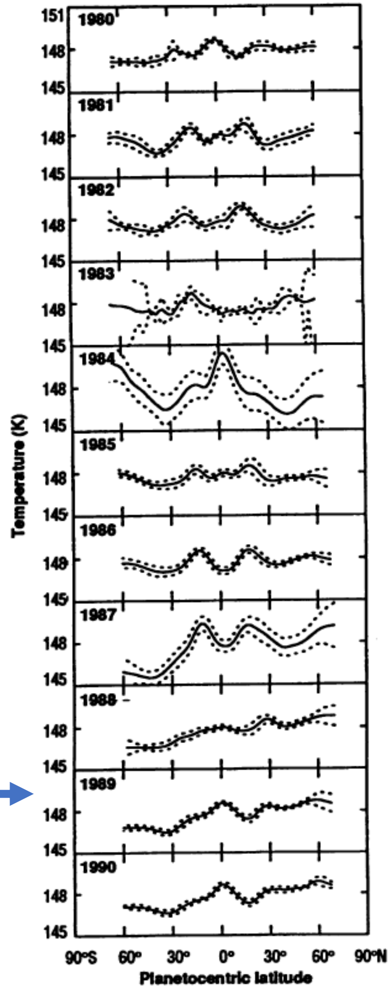


Jupiter's Quasi-Quadrennial Oscillation (QQO)



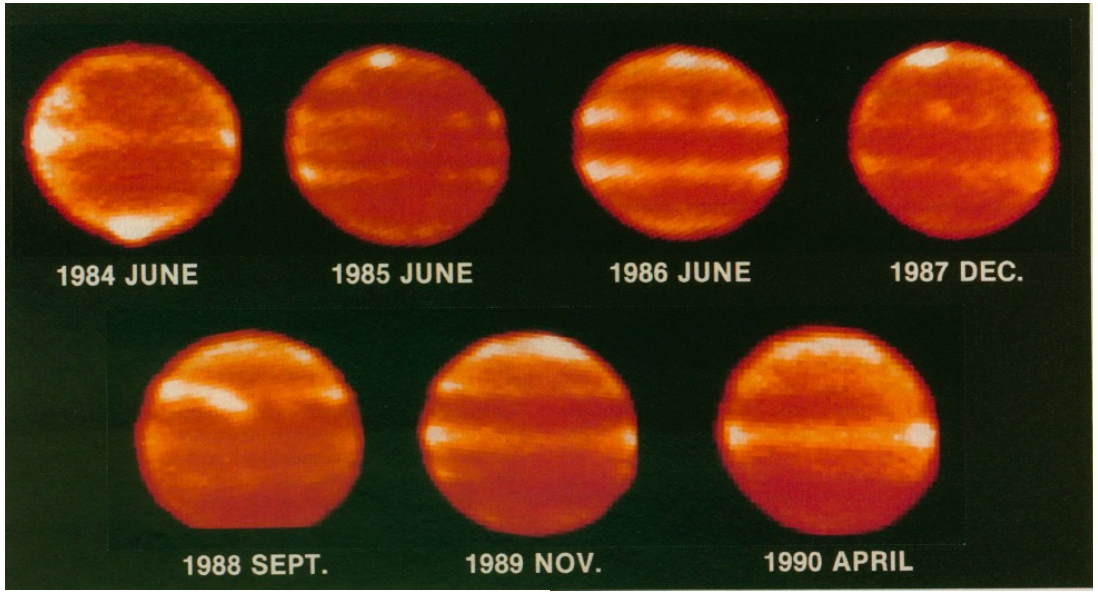


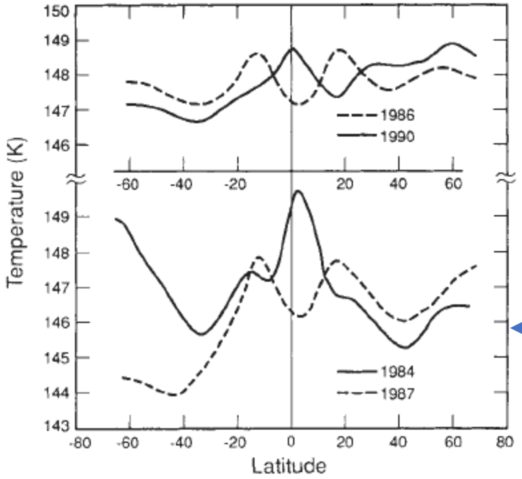
- IRTF observations over 11years of T at ~20 hPa
- See Orton et al. (1991) *Science* & Leovy et al. (1991) *Nature*



- Discovery in 1991 by Glenn Orton & colleagues of temperature $(\bar{T})$ oscillations in Jupiter's stratosphere
  - Period ~ 4 Earth years
  - Analogue of QBO in Earth's stratosphere?
- Oscillations driven by upward propagating equatorially trapped waves?

Jupiter’s Quasi-Quadrennial Oscillation (QQO)





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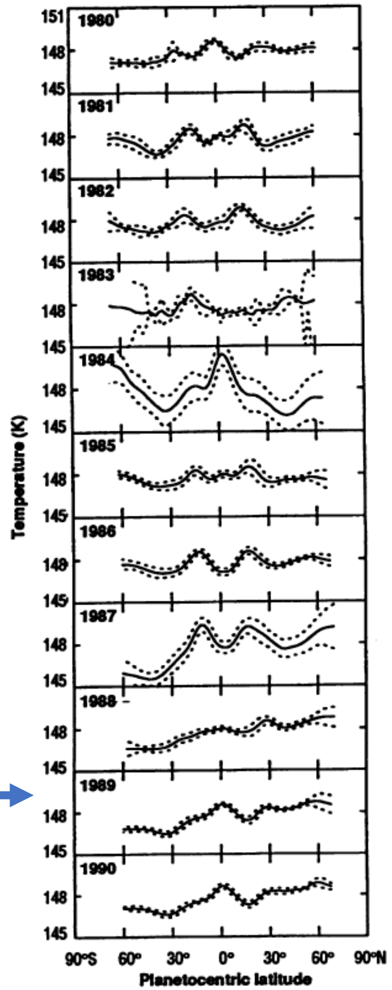
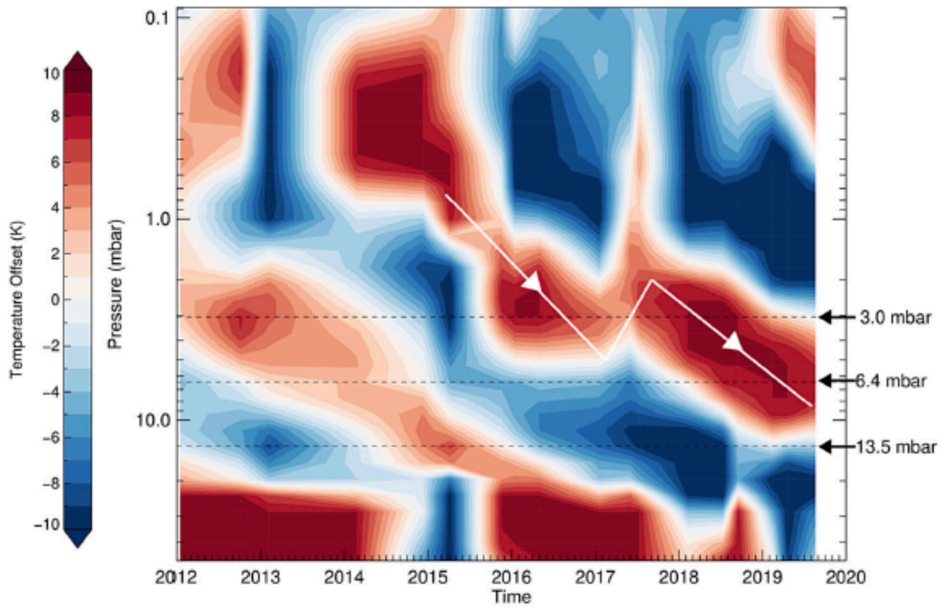
- See Orton et al. (1991) *Science* & Leovy et al. (1991) *Nature*



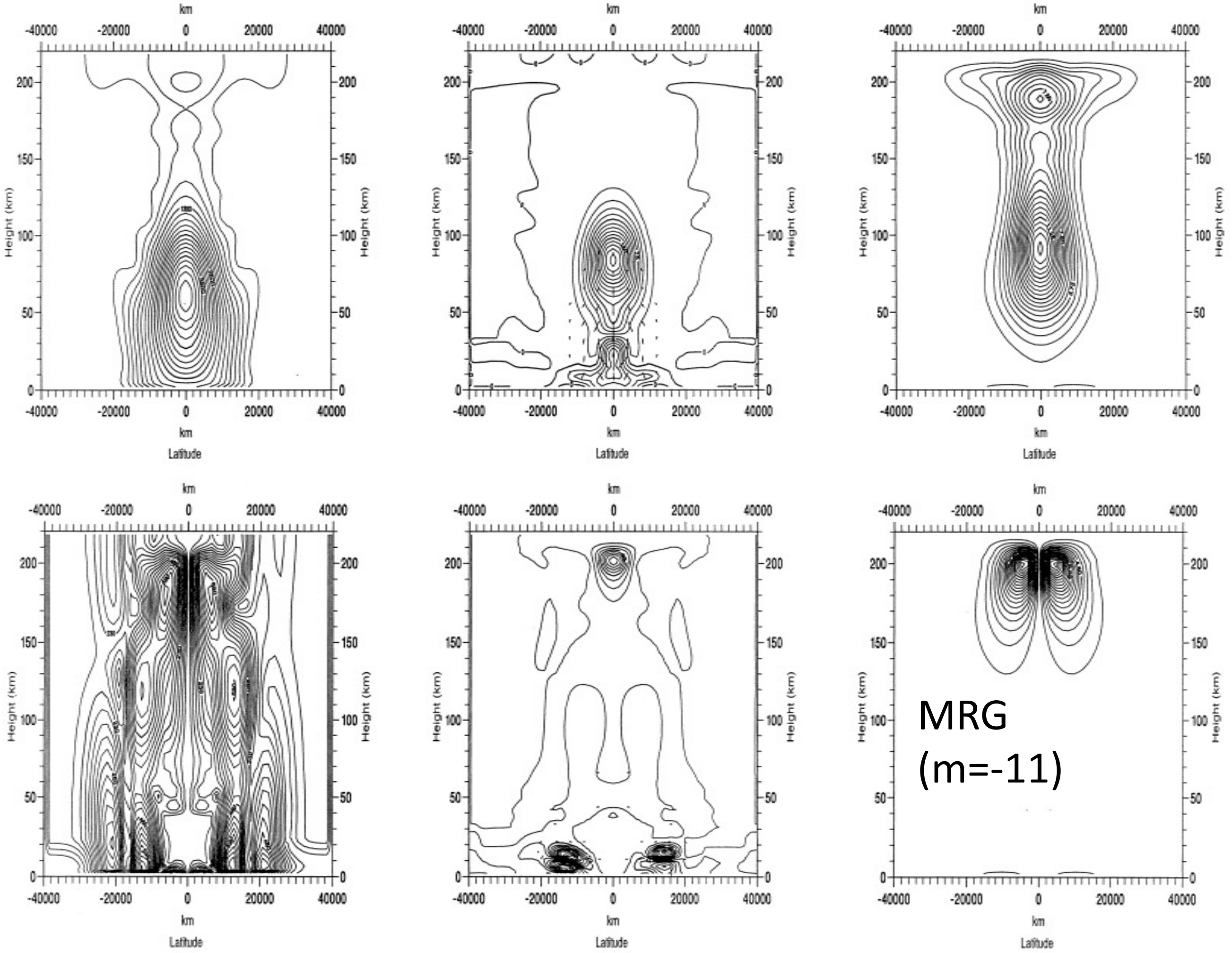
TEXES IRTF temperature measurements [Credit: Giles et al. 2020]



Models of QBO and QQO

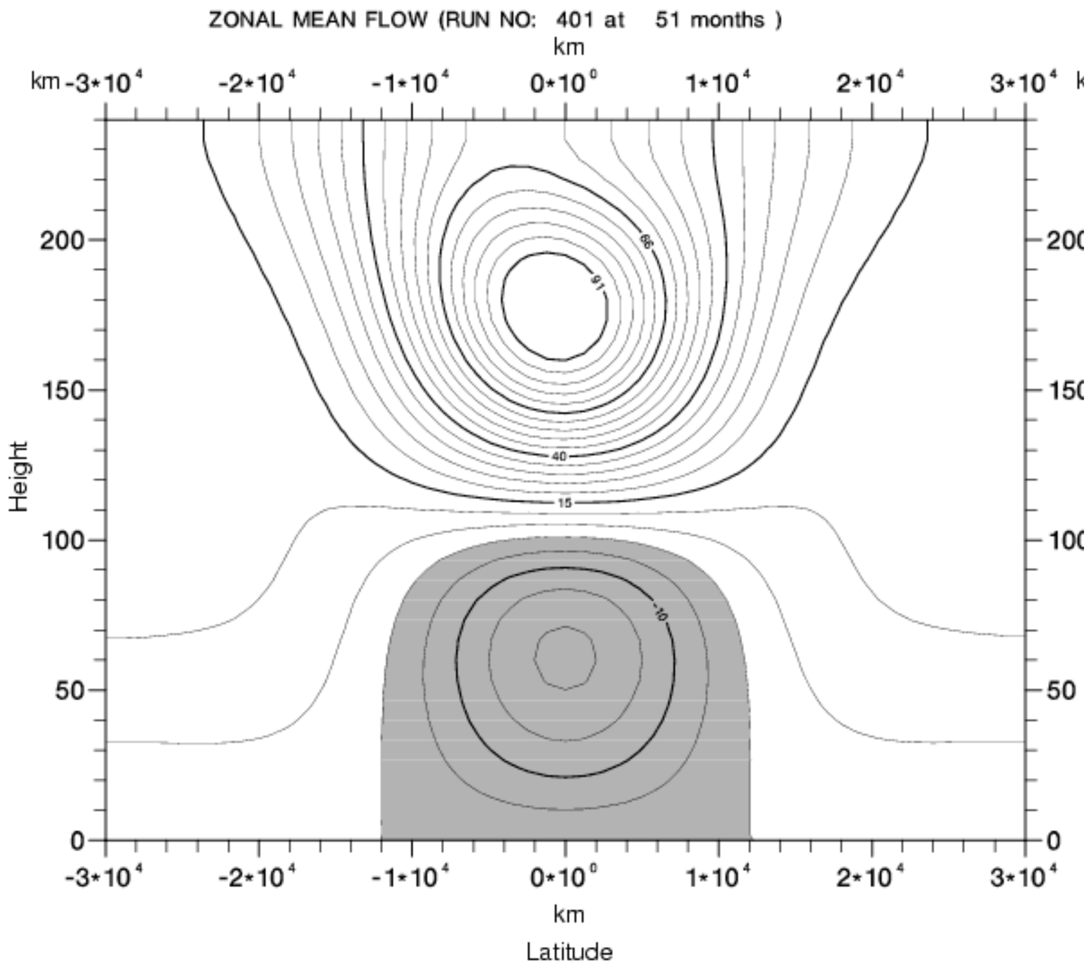
- Quasi-linear wave models
  - (a) analytical and
  - (b) numerical mechanistic models of equatorial waves and QBO-like oscillations
- Based on TEM formalism
  - Solve for structure of equatorial waves with $\bar{u}(y,z)$
  - Evolve $\bar{u}(y,z)$ with time in response to ∇.(EP flux) due to each wave mode

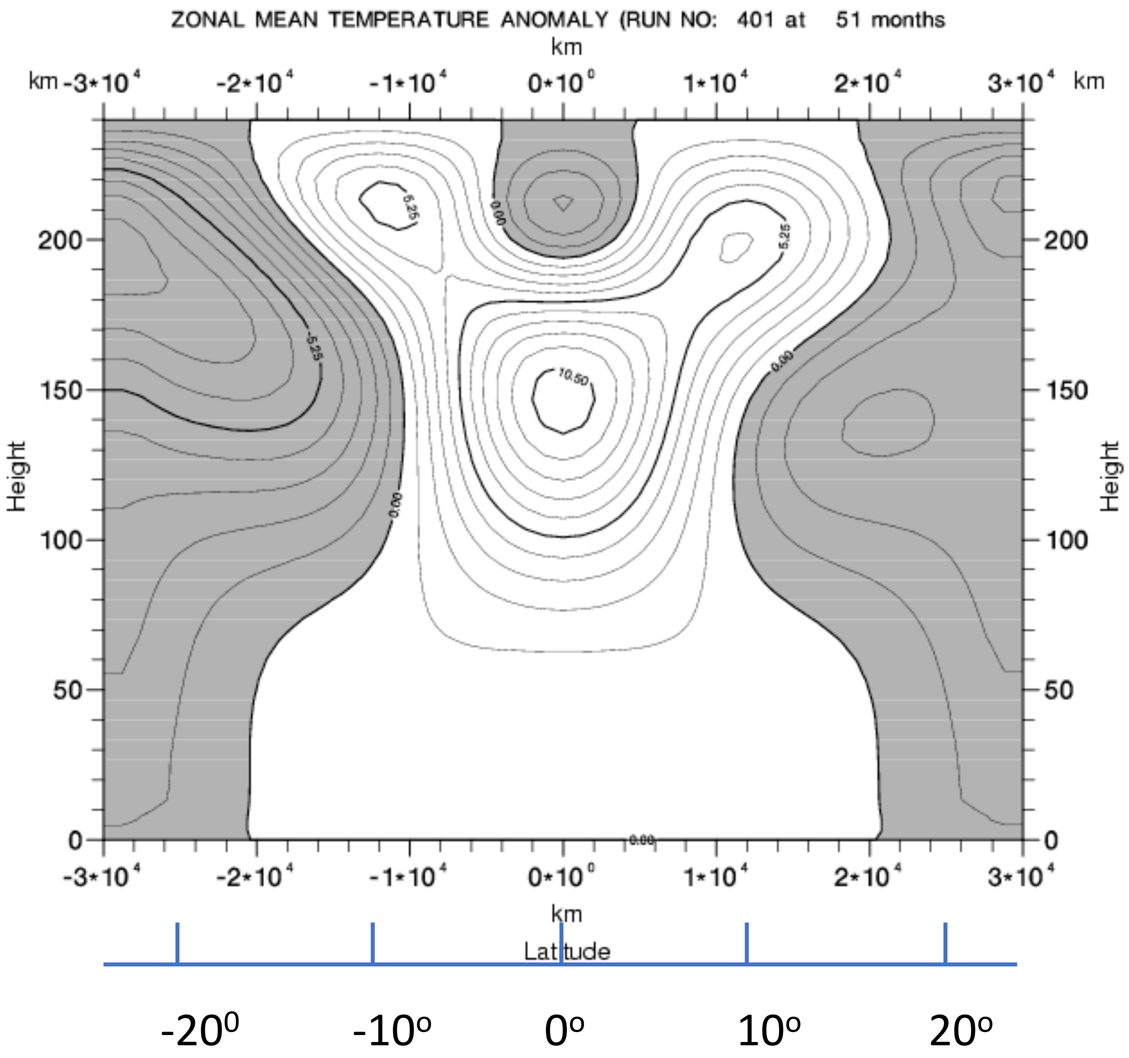
Kelvin
(m=2)



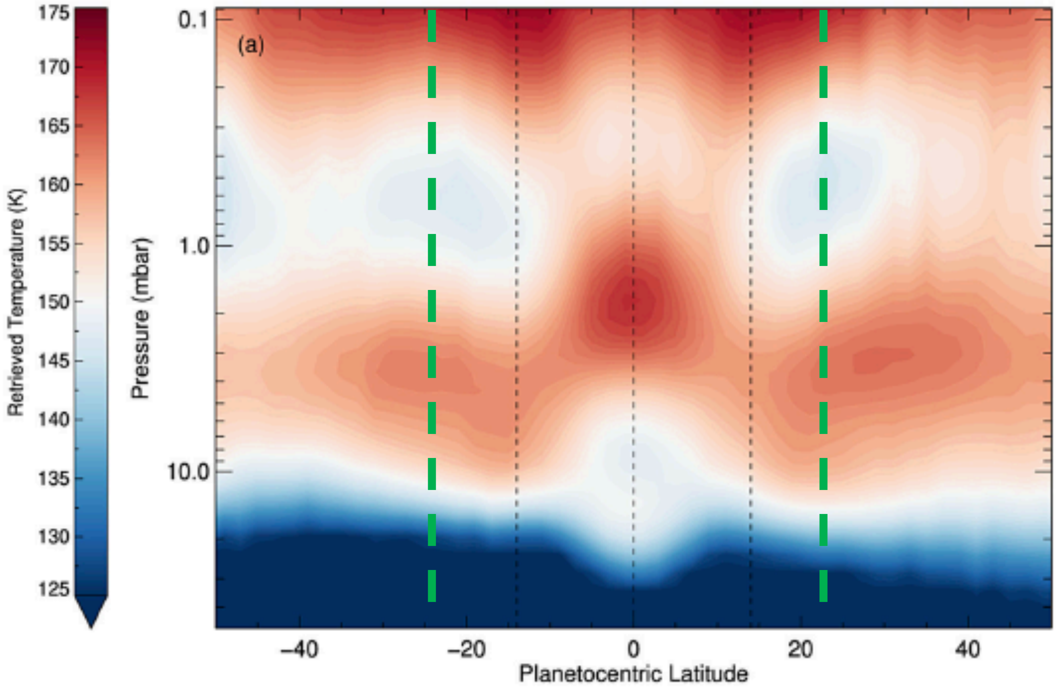
$\Phi'(y,z)$ $\nabla.\boldsymbol{F}$ $T'(y,z)$

Simulated QQO [Li & Read (2000) PSS]

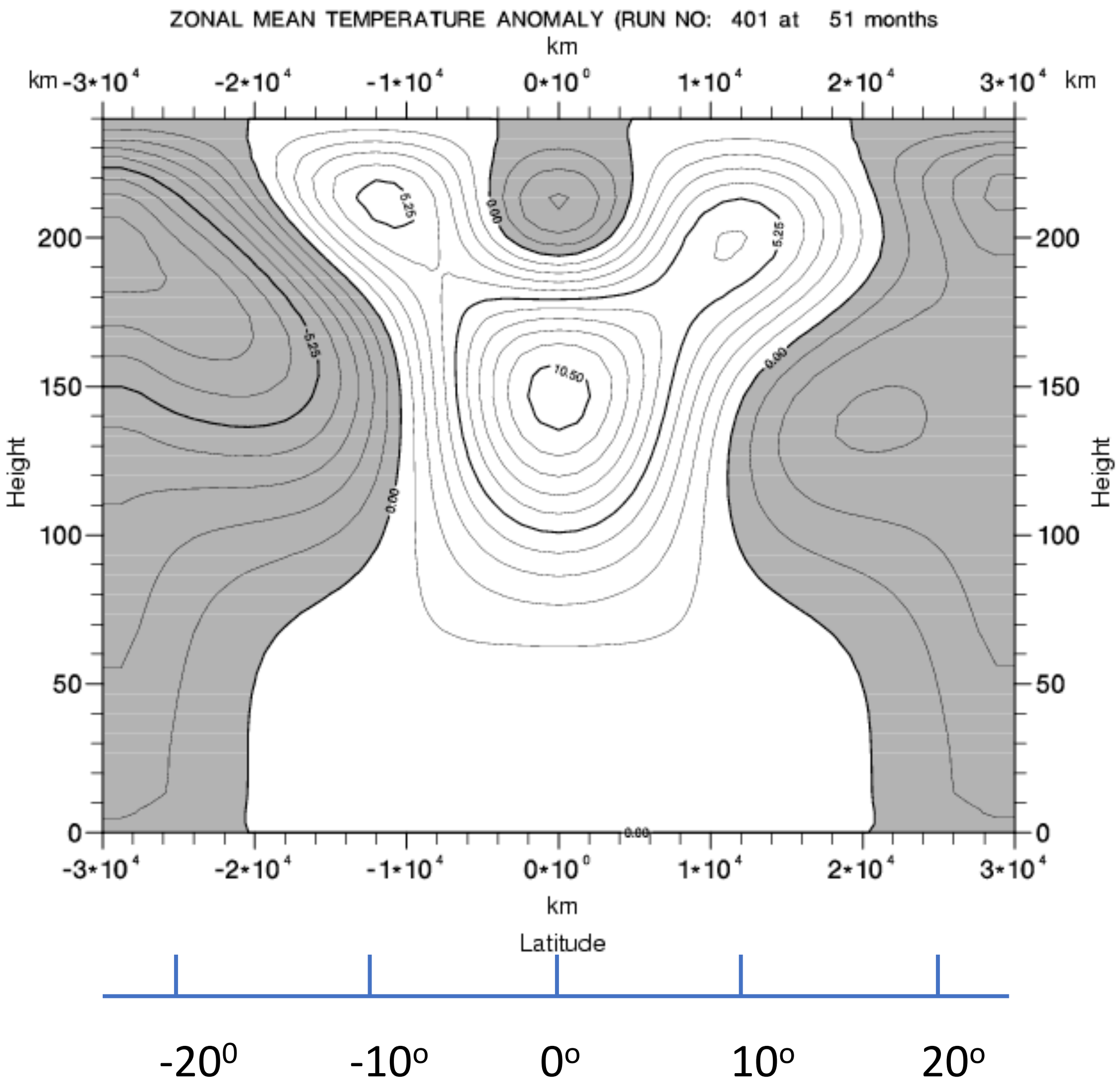




Simulated QQO [Li & Read (2000) PSS]

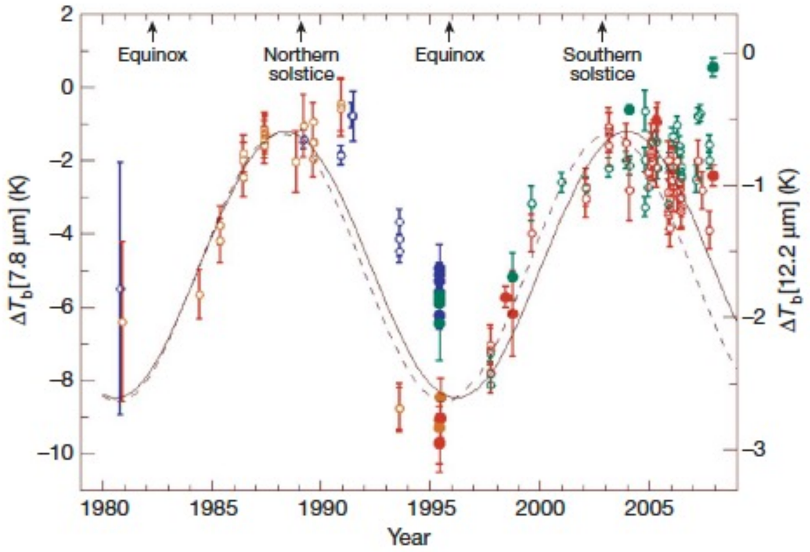


TEXES IRTF temperature measurements
[Credit: Giles et al. 2020]

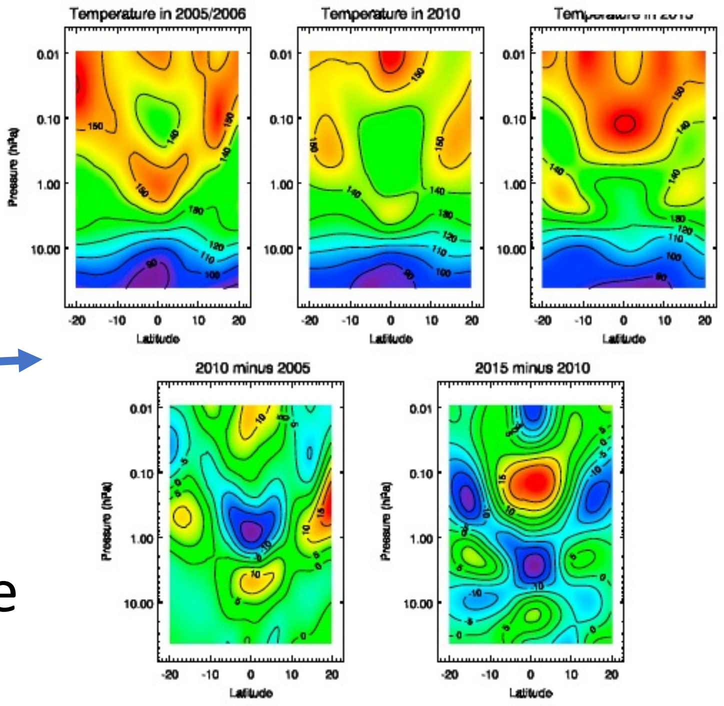


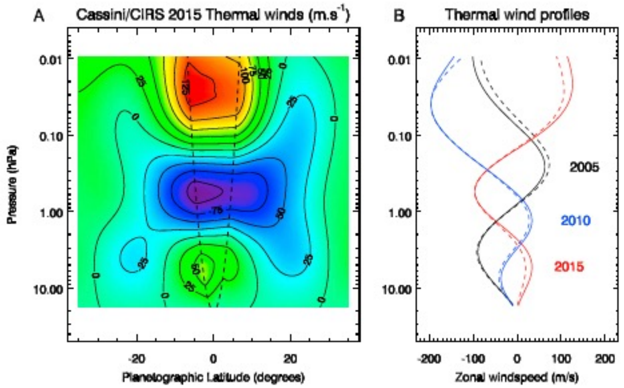
Saturn's Equatorial Oscillation (SEO)

- Discovered in 2008 by Orton et al. (2008 Nature) in IRTF measurements of stratospheric temperatures



- Period ~15 Earth years [~ 0.5 Saturn years]
  - a semi-annual oscillation cf SAO?
- Confirmed in detailed Cassini observations [Guerlet et al. (2020) JGR]





- Driven by equatorial waves?
  - Only n=1 equatorial Rossby mode identified in observations…..

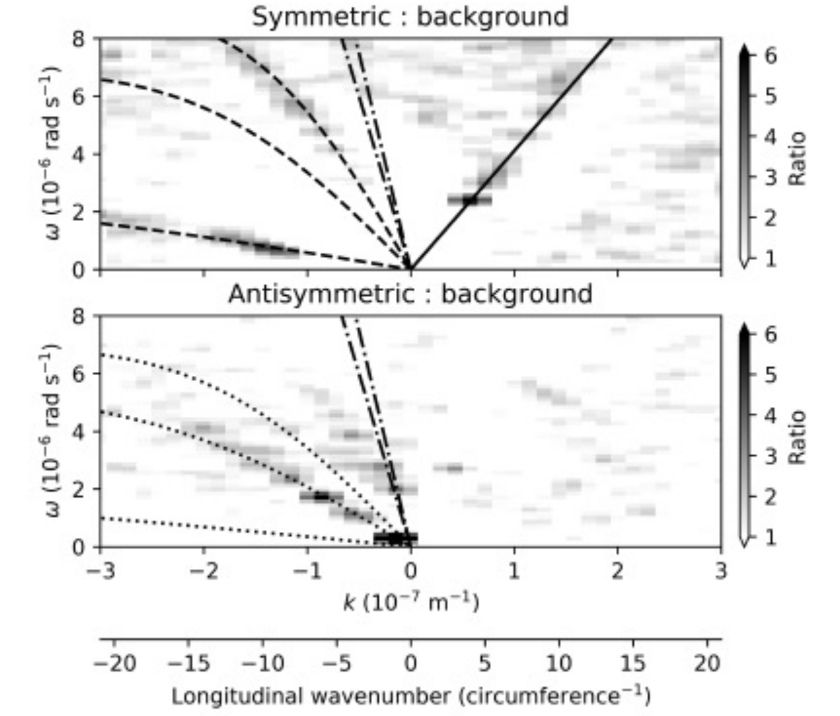
QQO in GCM simulations?

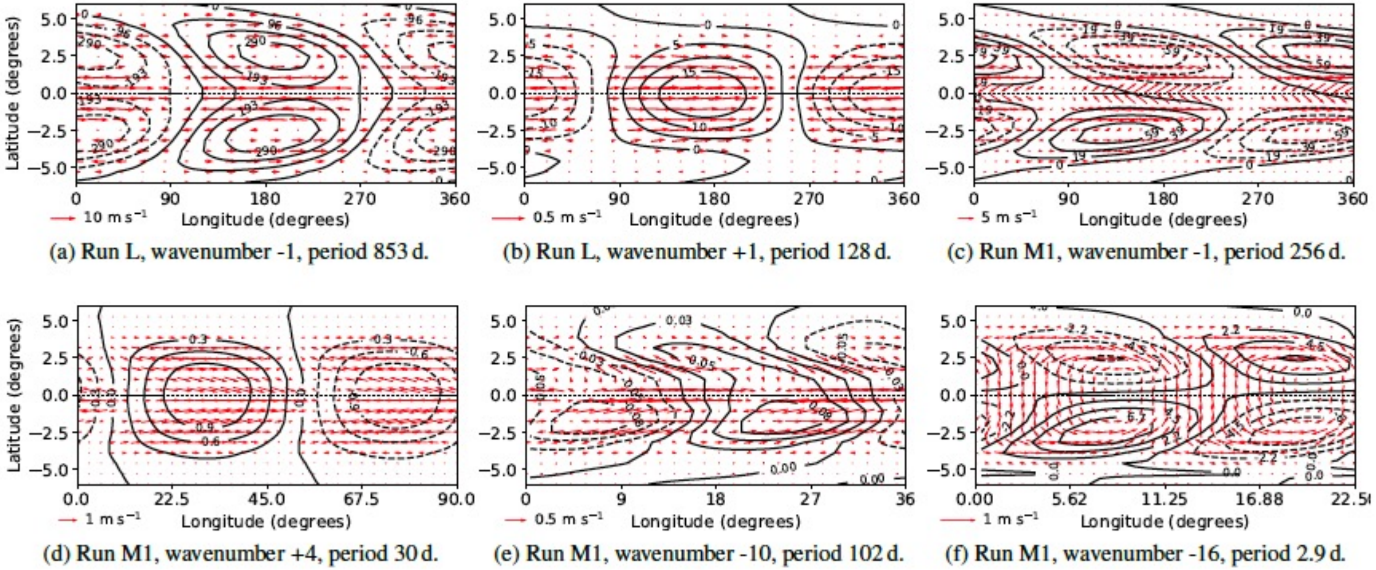
Stratospheric oscillation in the Oxford Jupiter GCM

Configuration: Solar heating, 5.7 W m^{-2} interior heating, active water cycle
512 x 256 x 33 resolution (~0.7 deg). Frame rate = 960 days / second
Temperature and zonal velocity: Zonal mean and anomaly from 5000d mean

Roland M. B. Young and Peter L. Read
AOPP, Department of Physics, University of Oxford

QQO in GCM simulations?





(a) Run L, wavenumber -1, period 853 d. (b) Run L, wavenumber +1, period 128 d. (c) Run M1, wavenumber -1, period 256 d. (d) Run M1, wavenumber +4, period 30 d. (e) Run M1, wavenumber -10, period 102 d. (f) Run M1, wavenumber -16, period 2.9 d.

Figure 5: Reconstructions of single wave modes in runs L and M1 at 1 bar. Each plot shows the horizontal velocity (red arrows) and geopotential height above 18 bar (black contours, dashed contours are negative). The dotted line is the equator, and note the longitude axis runs from 0 to 360/|*m*|.

- Wave modes in the stratosphere (p<1 bar) include (Young & Read 2023 *Icarus* submitted)

Run		Wave	n	H (m)	$c = \sqrt{gH}$ (m s^{-1})	L_{eq} (km)	Peak mode	$c_p = \omega/k$, peak mode (m s^{-1})	Circumequator time (d)
M1	$*$	ER (Antisymmetric)	2	450	110	3300	-1	-22	240
M1	$*$	K	-1	65	41	2000	+4	41	120
M1		ER (Symmetric)	1	1300	180	4300	-8	-53	96
M1	$*$	ER (Symmetric)	1	12	18	1300	Around -10	-5.7	880
M1	$*$	?ER$_T$/MRG? (Antisymmetric)	0	∞	∞	∞	Around -16	-130	41

Newly discovered Jovian stratospheric jet

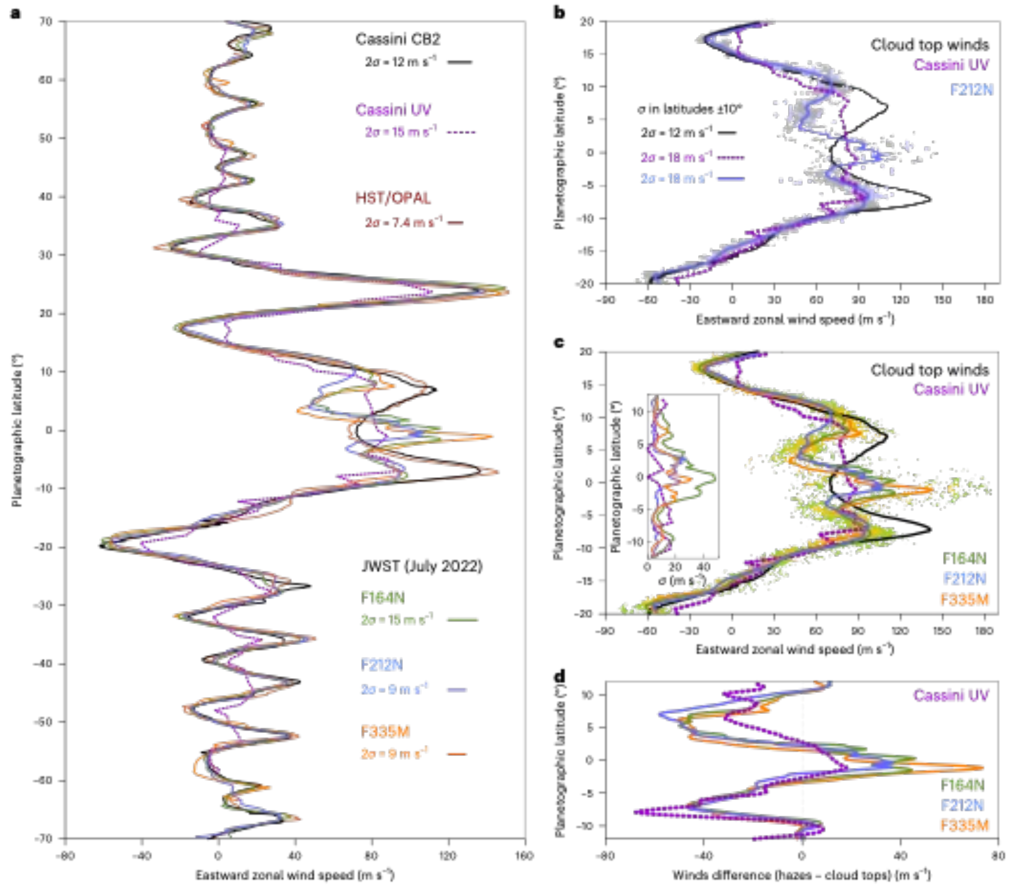


Fig. 4 | Jupiter's zonal wind profile. Zonal winds from JWST images are compared with zonal winds measured on Cassini UV images, on continuum filters at cloud level, and on HST images acquired in 2019 and analysed following the procedure in ref. 39. **a**, Mean zonal winds. **b**, Zonal winds at the equator. A black line shows the average of Cassini data from the year 2000 and HST data from 2019. The blue line is the F212N zonal mean winds. Grey symbols correspond to measurements of F212N images using the cloud correlation software. Blue circles correspond to cloud features visually tracked in F212N images. Mean error bars from twice the standard deviation (2σ) are shown as segments for each wind profile in **a** and for the ±10° latitudes in **b**. **c**, Zonal winds in the F164N, F212N and F335M filters in the equator compared with cloud-top winds and winds measured on Cassini UV images. Dots are individual measurements from the correlation software and lines are mean zonal winds. The inset shows the standard deviation of zonal winds in each filter considering latitudinal bins of width 0.3°, except for the Cassini UV data, which used latitudinal bins of 1°. **d**, Wind difference between the different filters sampling the hazes and the clouds tops. A dotted grey line shows the zero value.

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An intense narrow equatorial jet in Jupiter's lower stratosphere observed by JWST

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The atmosphere of Jupiter has east–west zonal jets that alternate as a function of latitude as tracked by cloud motions at tropospheric levels. Above and below the cold tropopause at ~100 mbar, the equatorial atmosphere is covered by hazes at levels where thermal infrared observations used to characterize the dynamics of the stratosphere lose part of their sensitivity. James Webb Space Telescope observations of Jupiter in July 2022 show these hazes in higher detail than ever before and reveal the presence of an intense (140 m s^{-1}) equatorial jet at 100–200 mbar (70 m s^{-1} faster than the zonal winds at the cloud level) that is confined to ±3° of the equator and is located below stratospheric thermal oscillations that extend at least from 0.1 to 40 mbar and repeat in multiyear cycles. This suggests that the new jet is a deep part of Jupiter's Equatorial Stratospheric Oscillation and may therefore vary in strength over time.

Summary

- Super-rotation on Earth troposphere is weak, mainly because eddy forcing dominated by midlatitude baroclinic instability
- Could be accelerated by enhanced divergent generation of Rrossby waves in tropics
- Role of thermal tides affect super-rotation of Mars lower atmosphere
- Quasi-biennial/QQ oscillations in stratospheres due to upward propagating waves
- Equatorial jets opn gas giants?
    - Several different possible mechanisms…