An exploration of Saturn's dynamics through Global Climate Modeling

A. Spiga
S. Guerlet, M. Indurain, E. Millour,
T. Fouchet, M. Sylvestre,
Y. Meurdesoif (LSCE/CEA), T. Dubos

Les Houches workshop March 2, 2015

A word of caution

Work in progress: unpublished & open for discussions

Outline

1. Questions and perspectives

2. Building a model and testing it at intermediate resolutions
   - Emphasis on radiative transfer
   - Tests with relaxation towards observed jets

3. Tests at higher resolution

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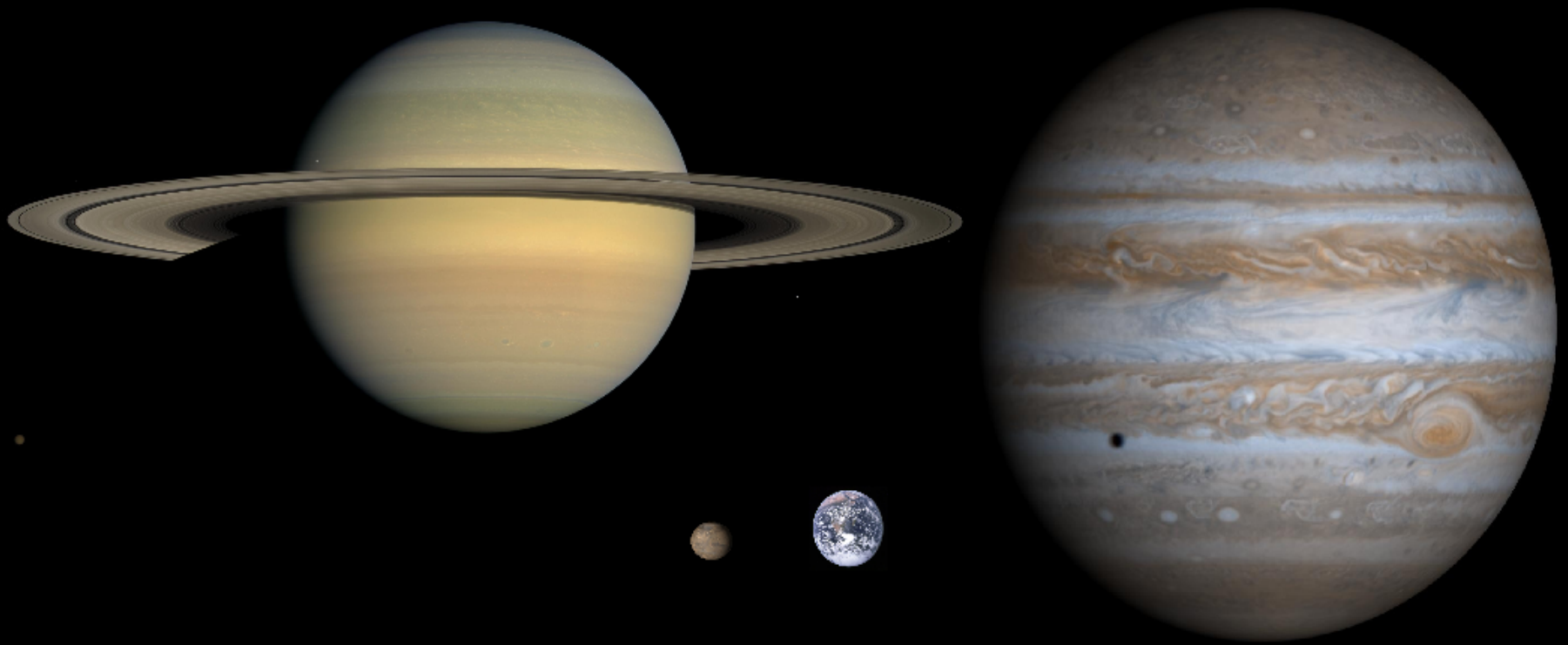
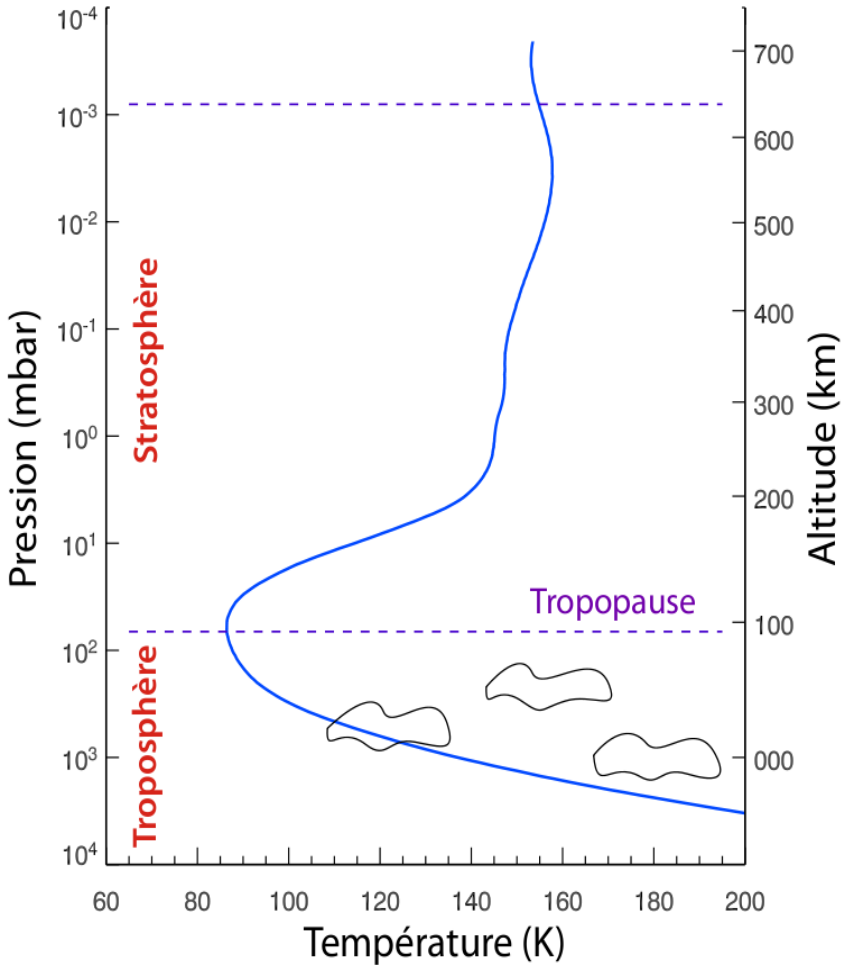
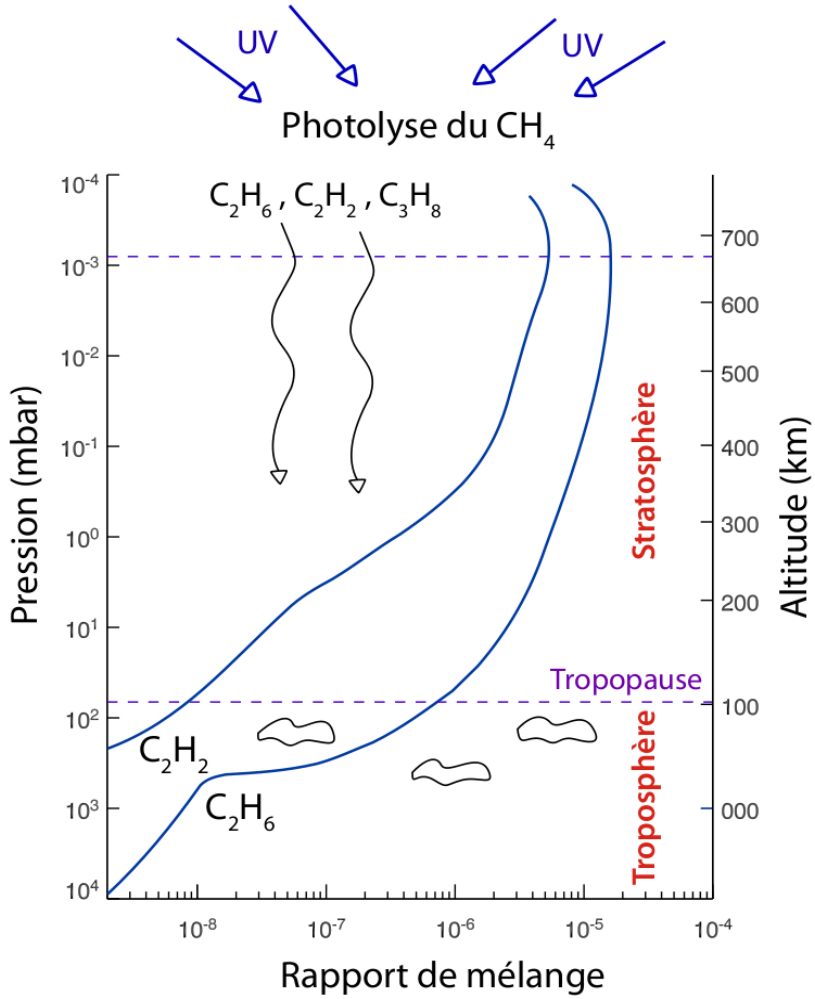
A geophysical approach for astronomical objects



Saturn: thermal structure and hydrocarbons

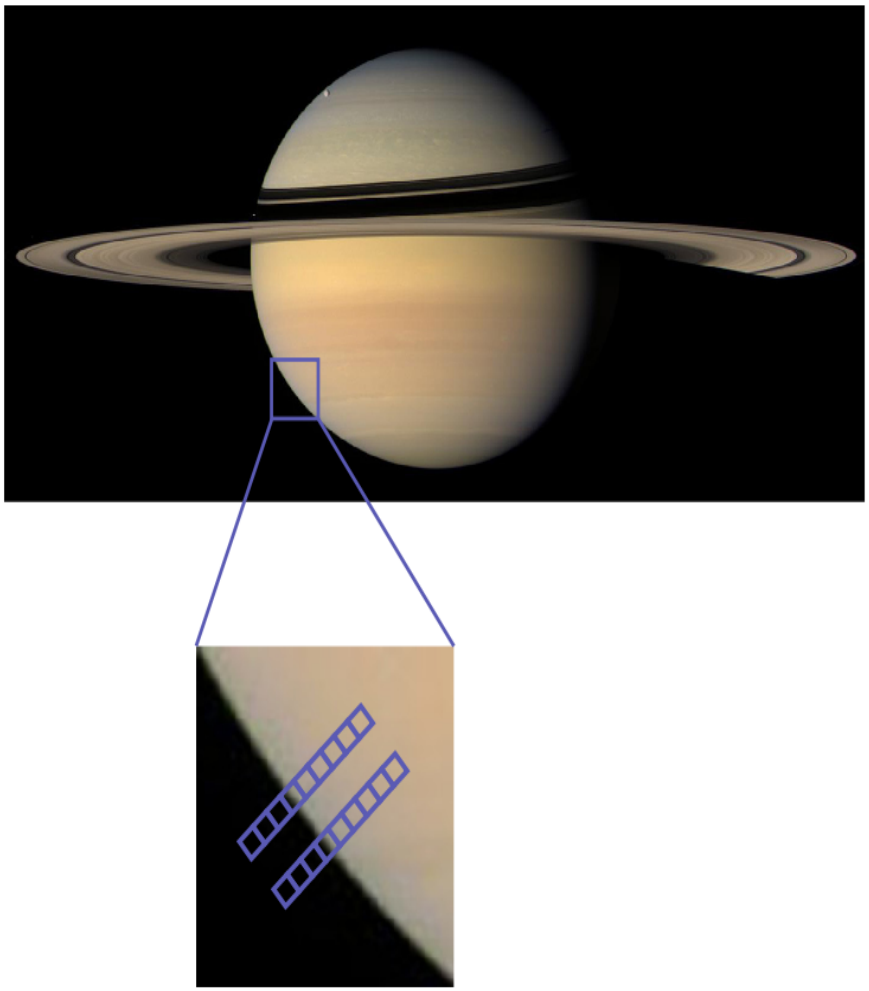


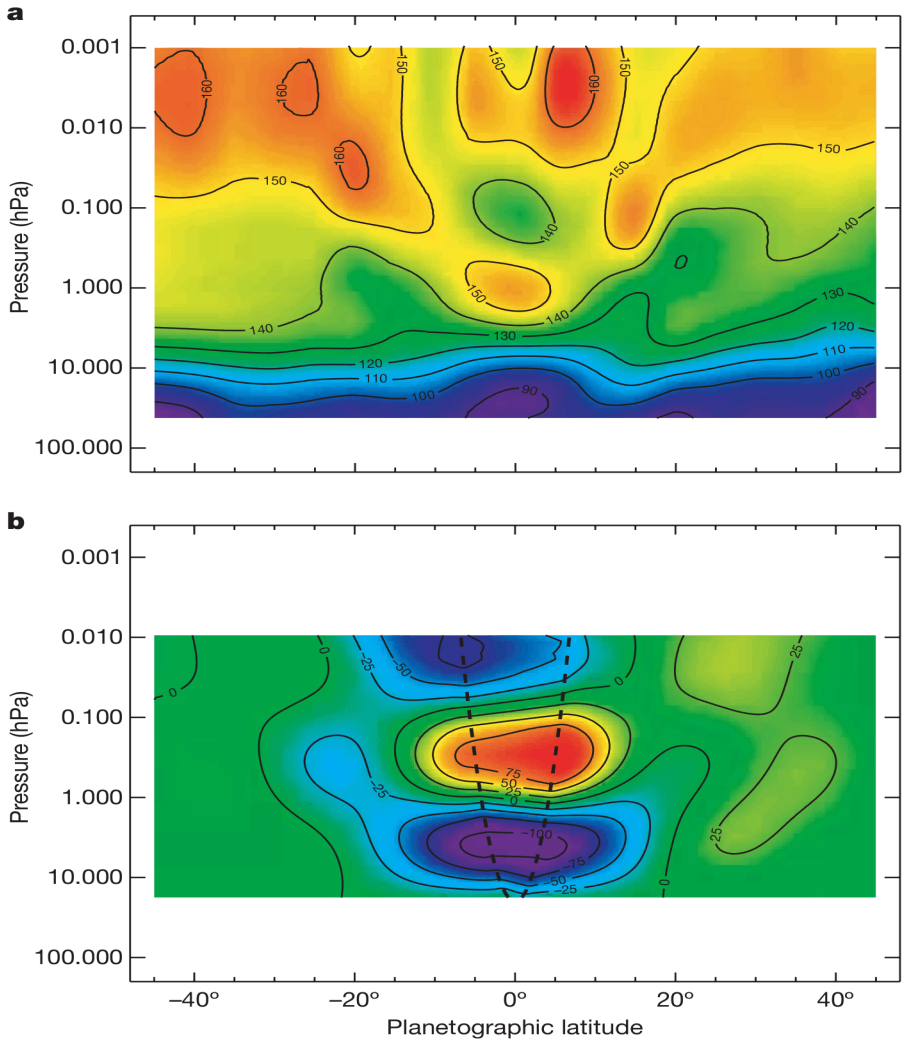


[Courtesy of S. Guerlet]

An equatorial oscillation in Saturn's stratosphere

Cassini / CIRS thermal profile and thermal wind

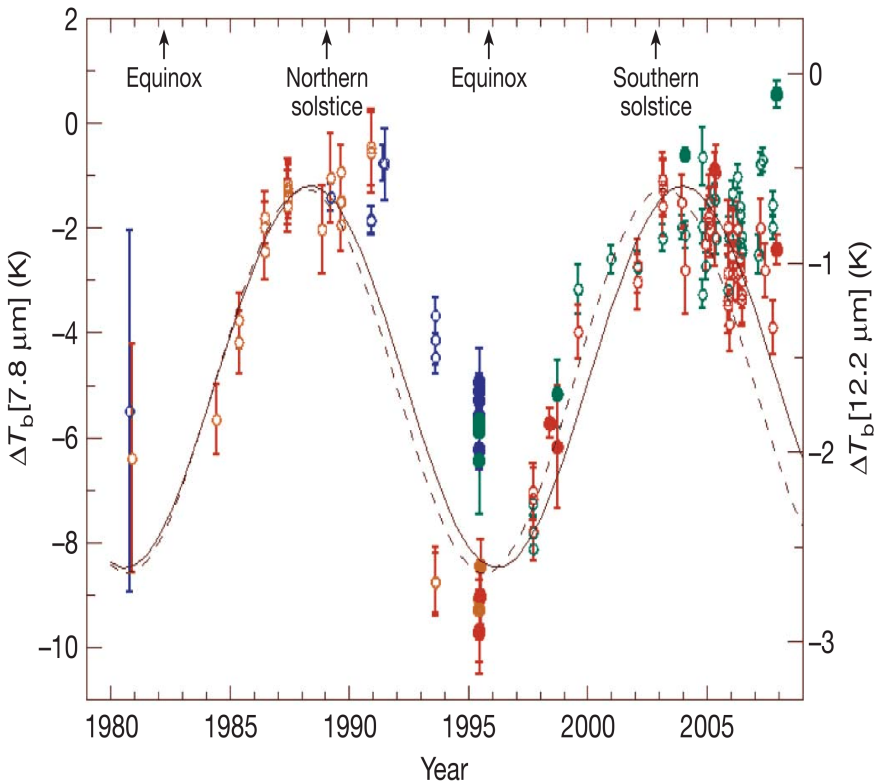




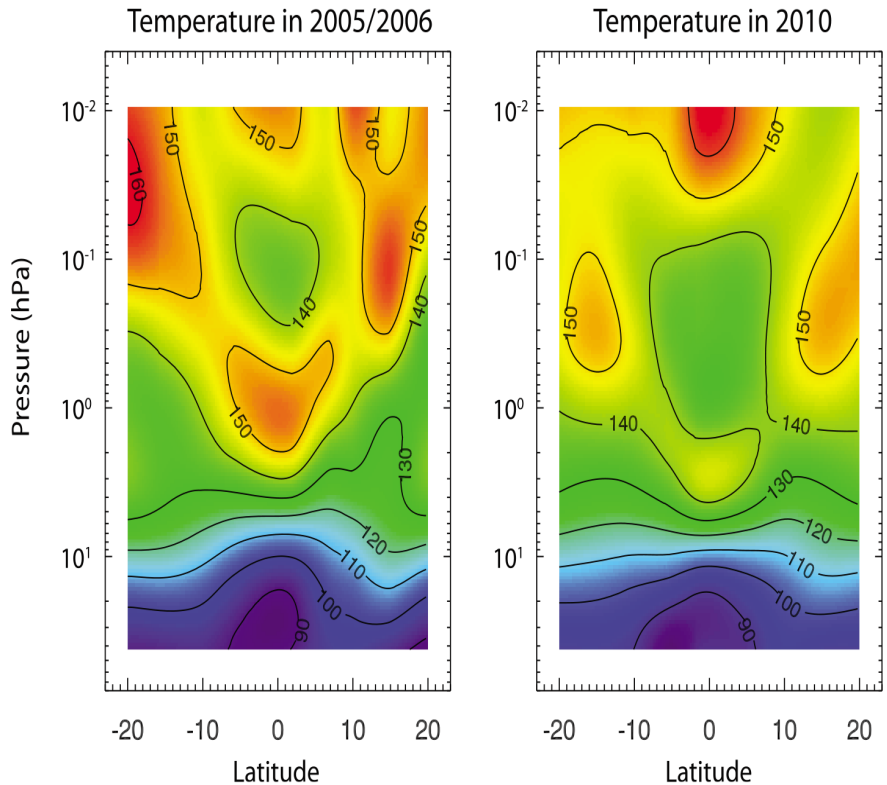
[Fouchet et al. Nature 2008]

An equatorial oscillation in Saturn's stratosphere

Evolution with time with CIRS and ground-based observations

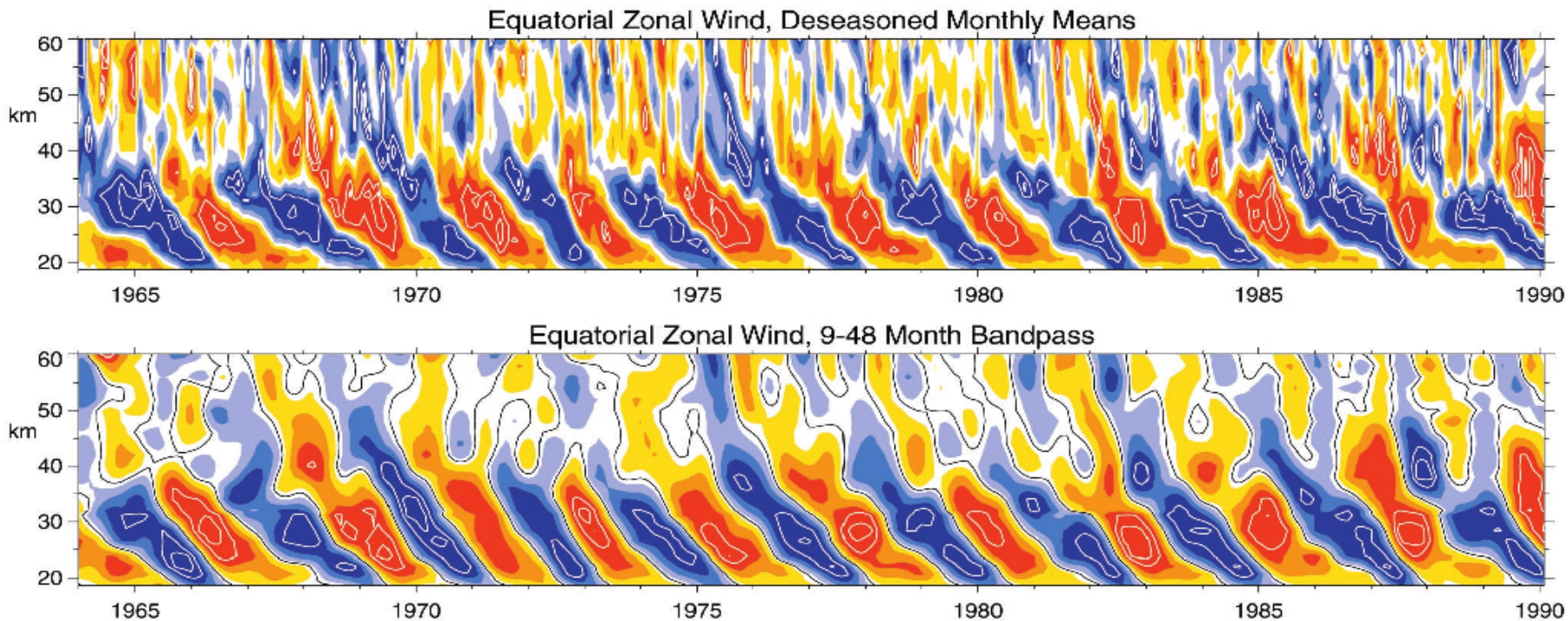


[Orton et al. Nature 2008]



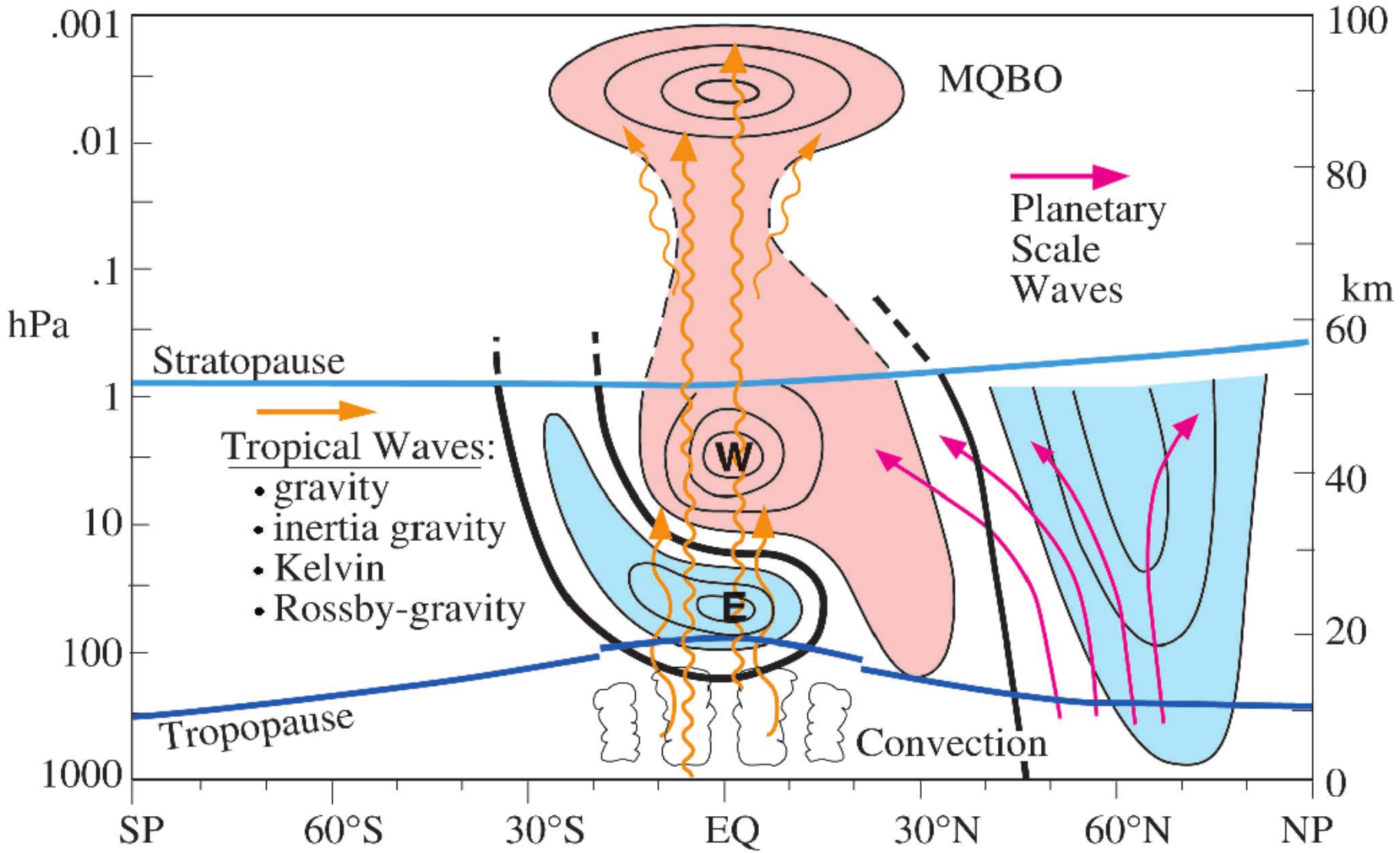
[Fouchet et al. Nature 2008 ; Guerlet et al. GRL 2011]

Quasi-Biennal Oscillation, Earth's stratosphere



[Baldwin et al. Review of Geophysics 2001]

Quasi-Biennal Oscillation, Earth's stratosphere

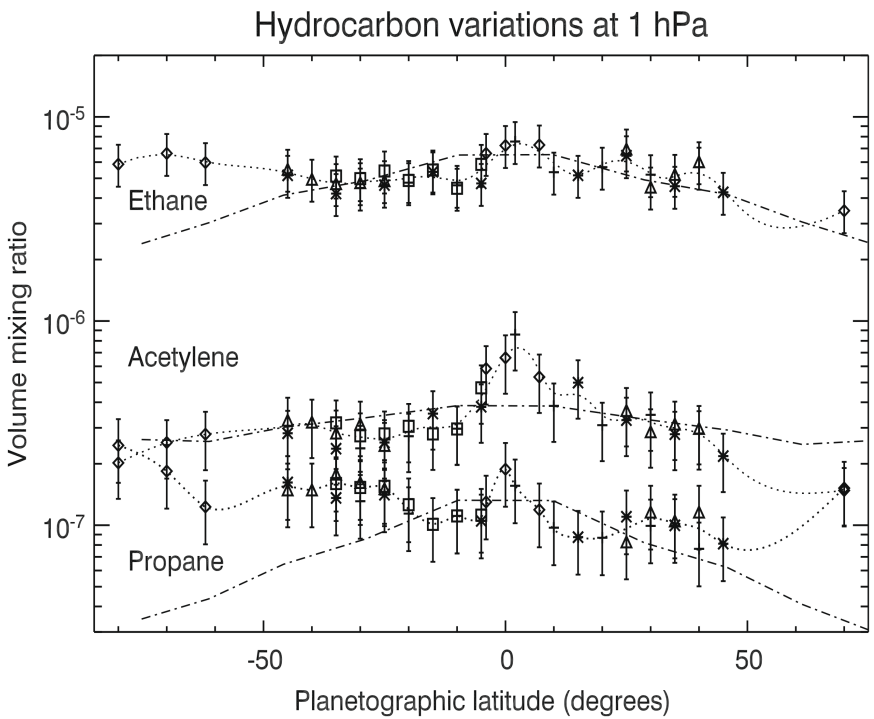


[Baldwin et al. Review of Geophysics 2001]

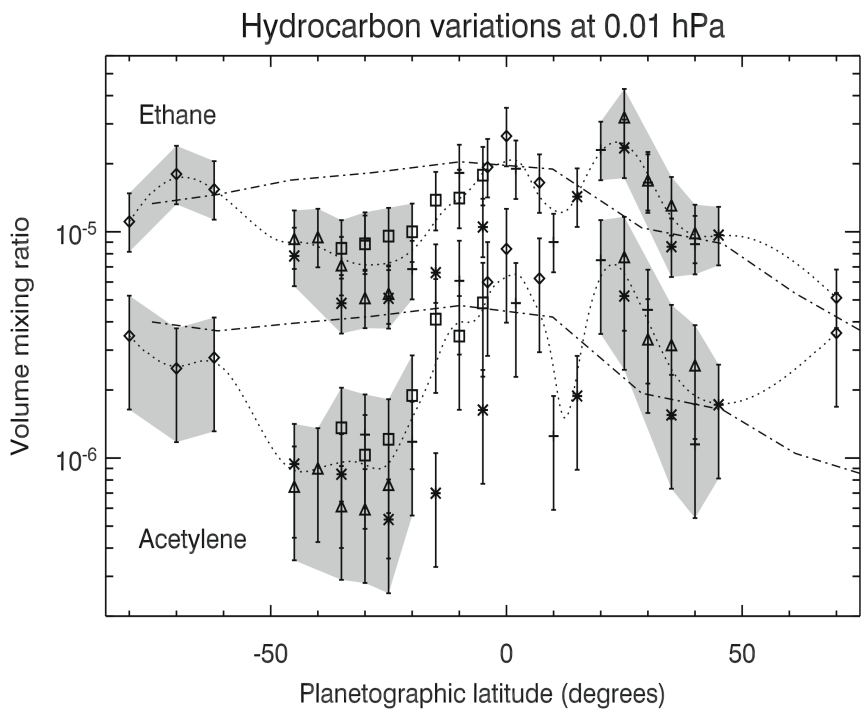
Departures from 1D photochemical model

CIRS observations of hydrocarbons (C_2H_6 and C_2H_2)

Low stratosphere



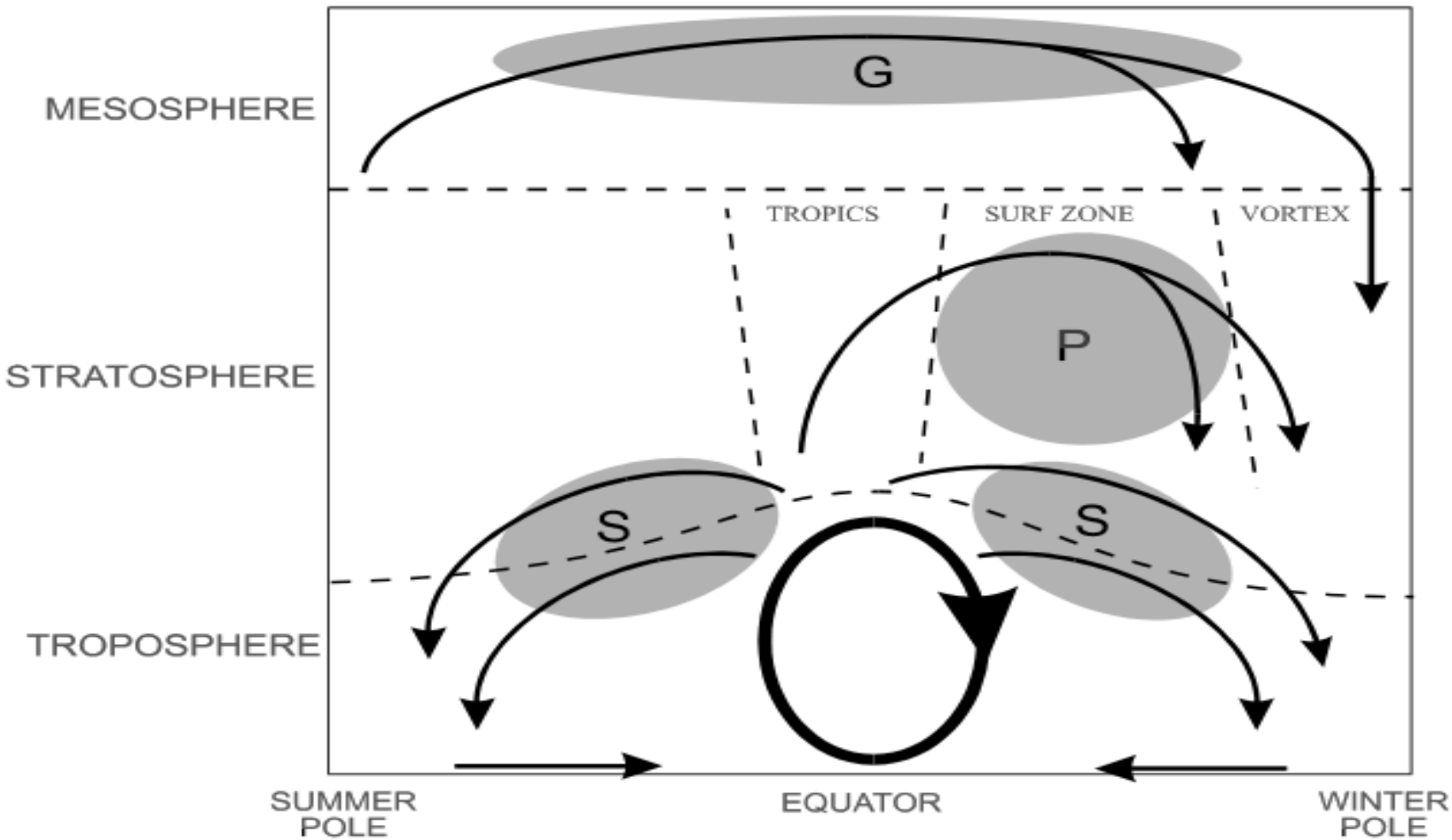
High stratosphere



[Guerlet et al. Icarus 2009]

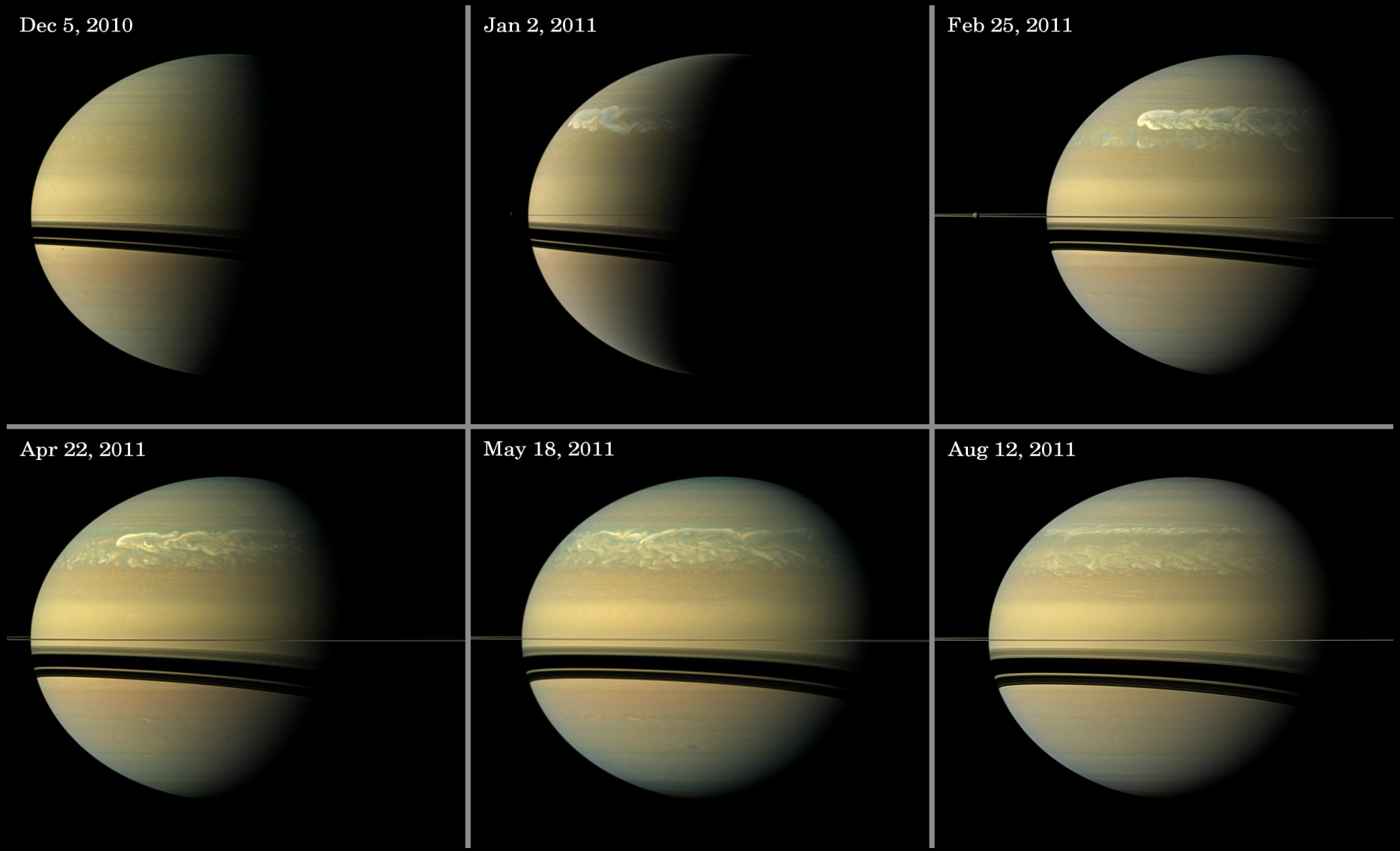
Brewer-Dobson circulation

Wave-driven transport in the Earth's stratosphere and mesosphere



[Plumb J. Meteor. Soc. Japan 2002]

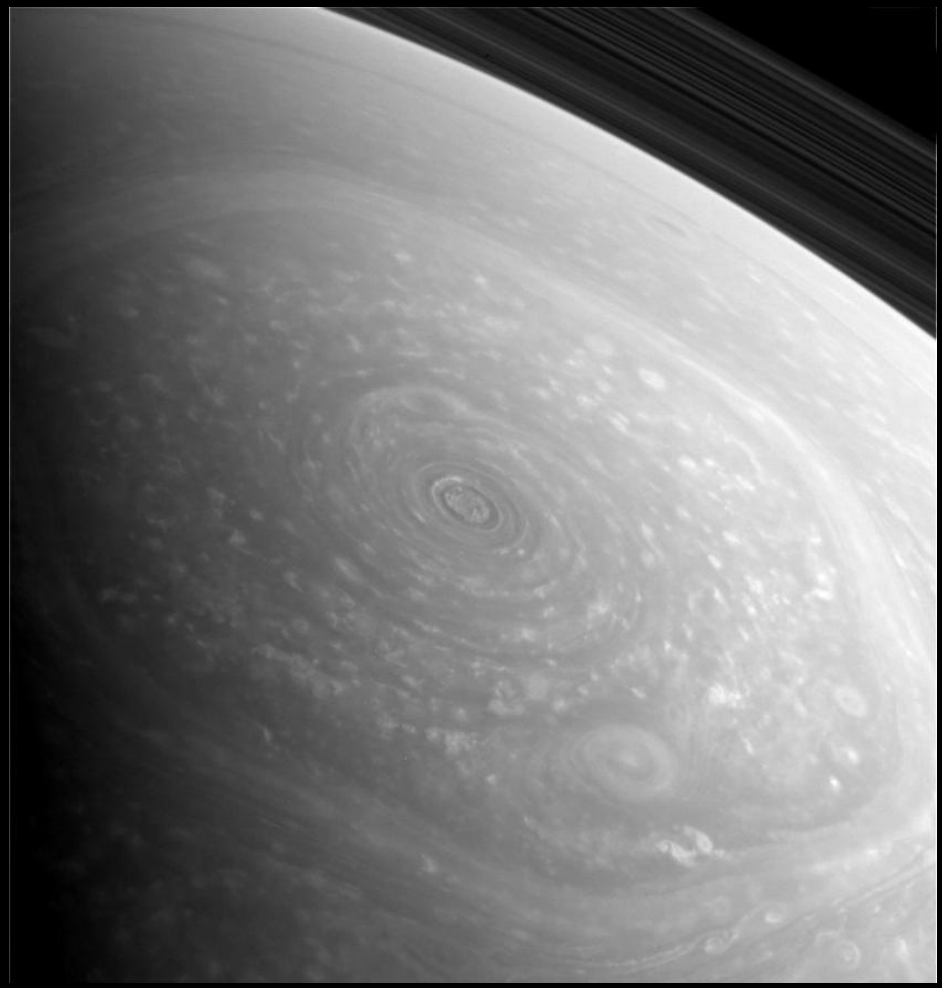
Les orages géants sur Saturne *Great White Spots*



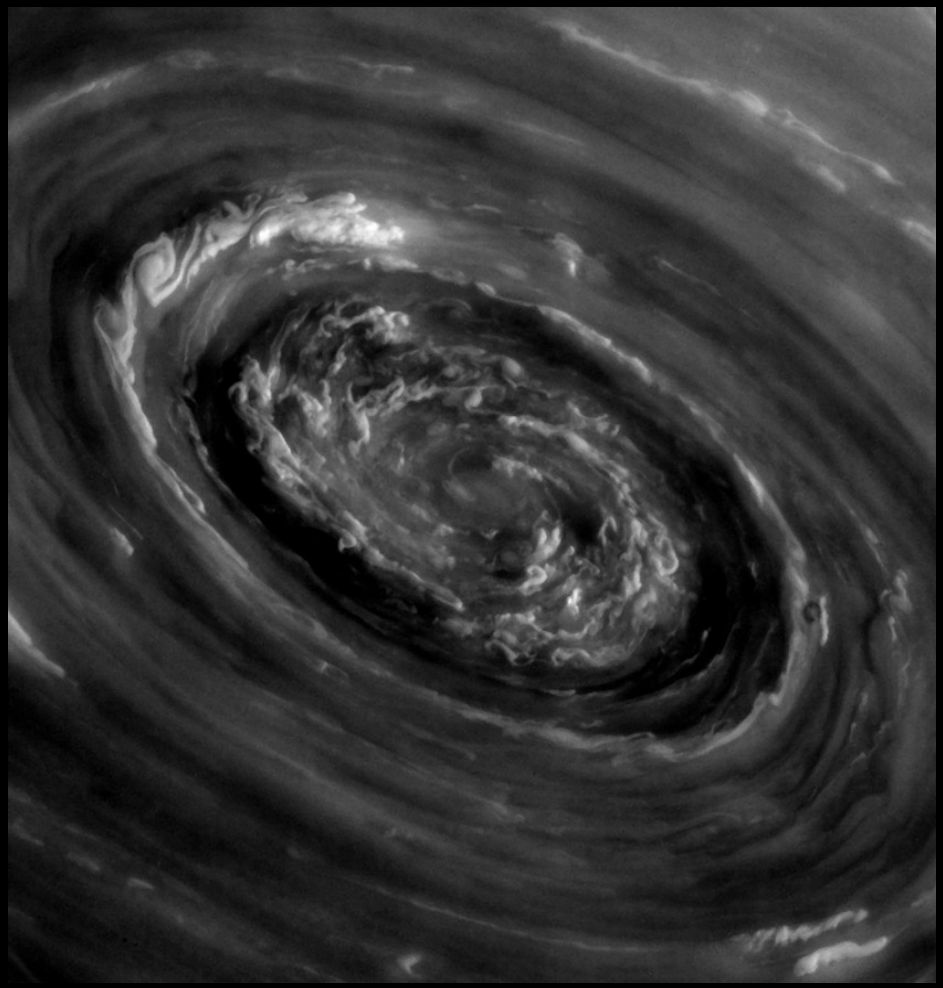
[Images Cassini-Huygens PIA14905]

Saturn polar vortex

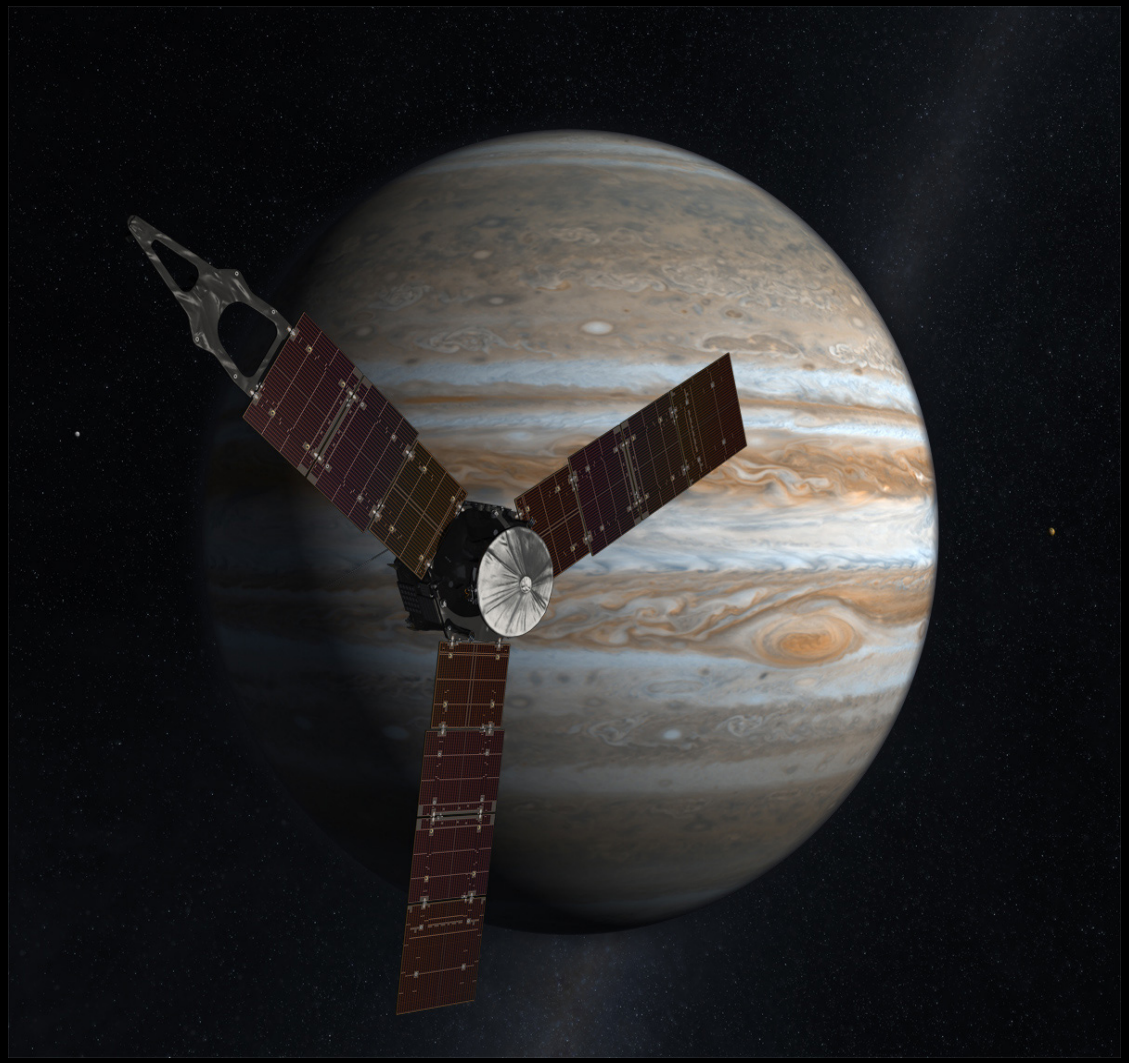
Hexagonal jet

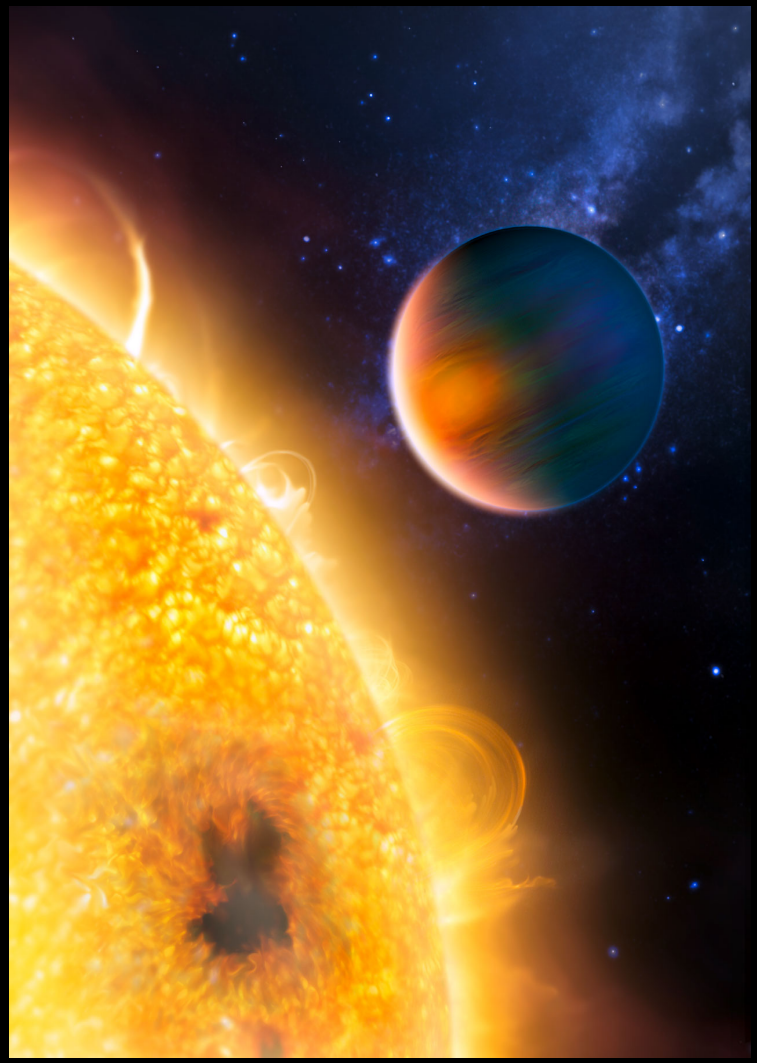


Turbulent vortex at center



Saturn. . . and beyond





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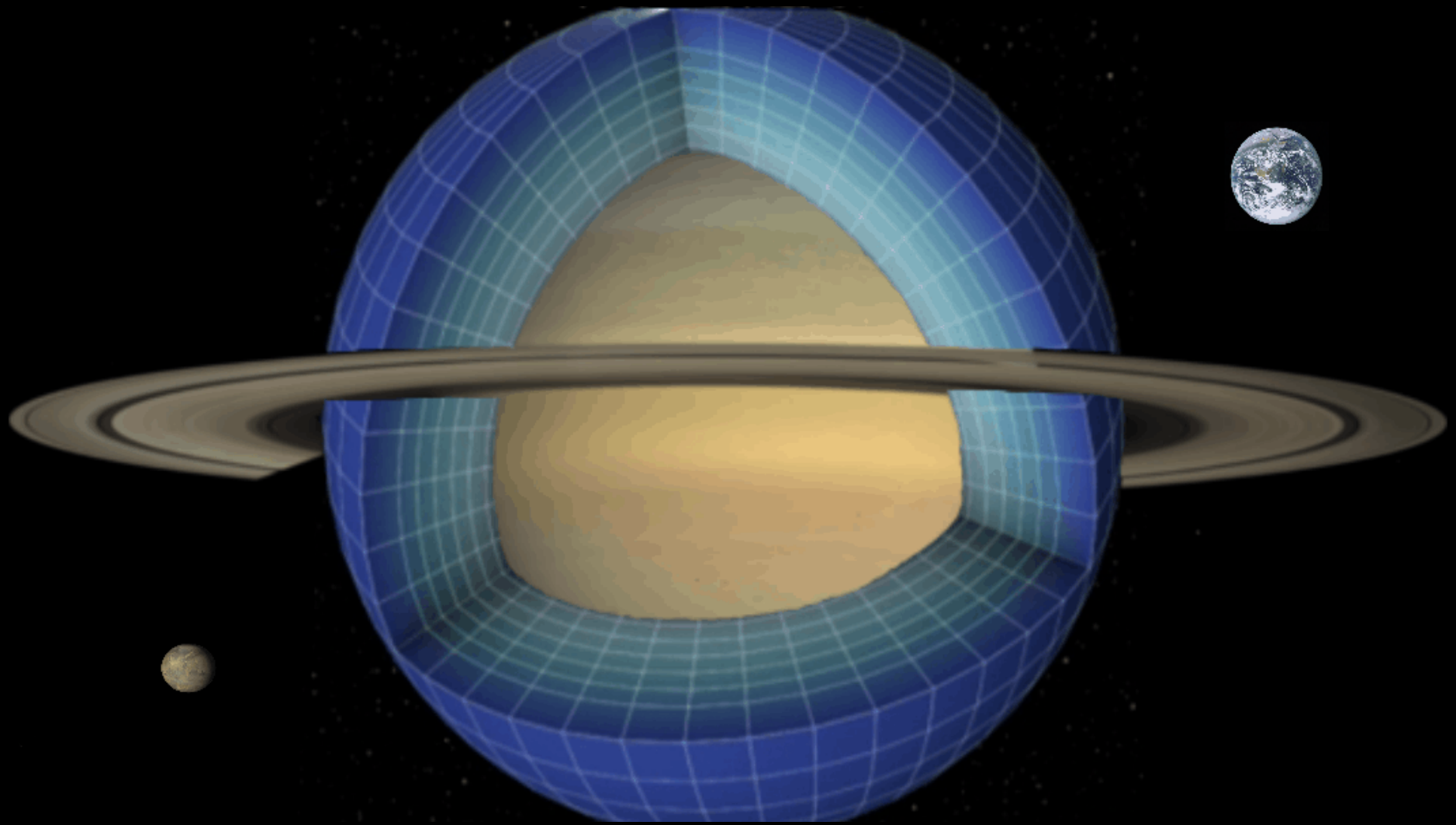
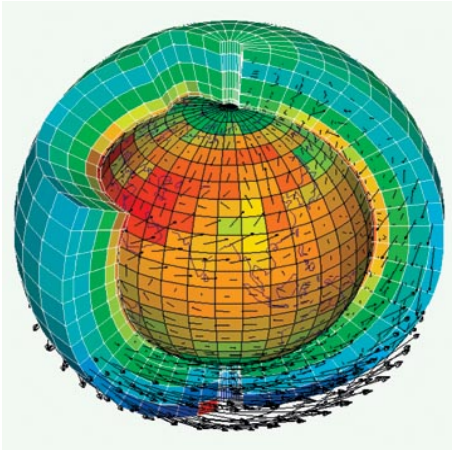
A GCM for Saturn



A new Global Climate Model for Saturn

Dynamical core ⇒ 3D geophysical fluid dynamics
(conservation laws of momentum, mass, energy, tracers)

Parallel LMDz solver [Hourdin et al. 2006, 2012]



Physical parameterizations ⇒ 1D computations of forcings on each grid point

- ☞ Radiative transfer ⇒ Guerlet et al. Icarus 2014
  - correlated-k scheme for IR and VIS heating rates [Wordsworth et al. 2010]
  - gases CH_4, C_2H_6, C_2H_2 with optimized spectral discretization
  - HITRAN 2012 database + Karkoschka and Tomasko 2010 for CH_4 around 1μm
  - collision-induced absorption H_2-H_2 and H_2-He [Wordsworth et al. 2012]
  - Rayleigh scattering H_2, He
  - simple two-layer aerosol model [constrained by Roman et al. 2013]
    - tropospheric haze layer $180 - 660$ mbar / $\tau \sim 8$ / $r = 2\mu$m
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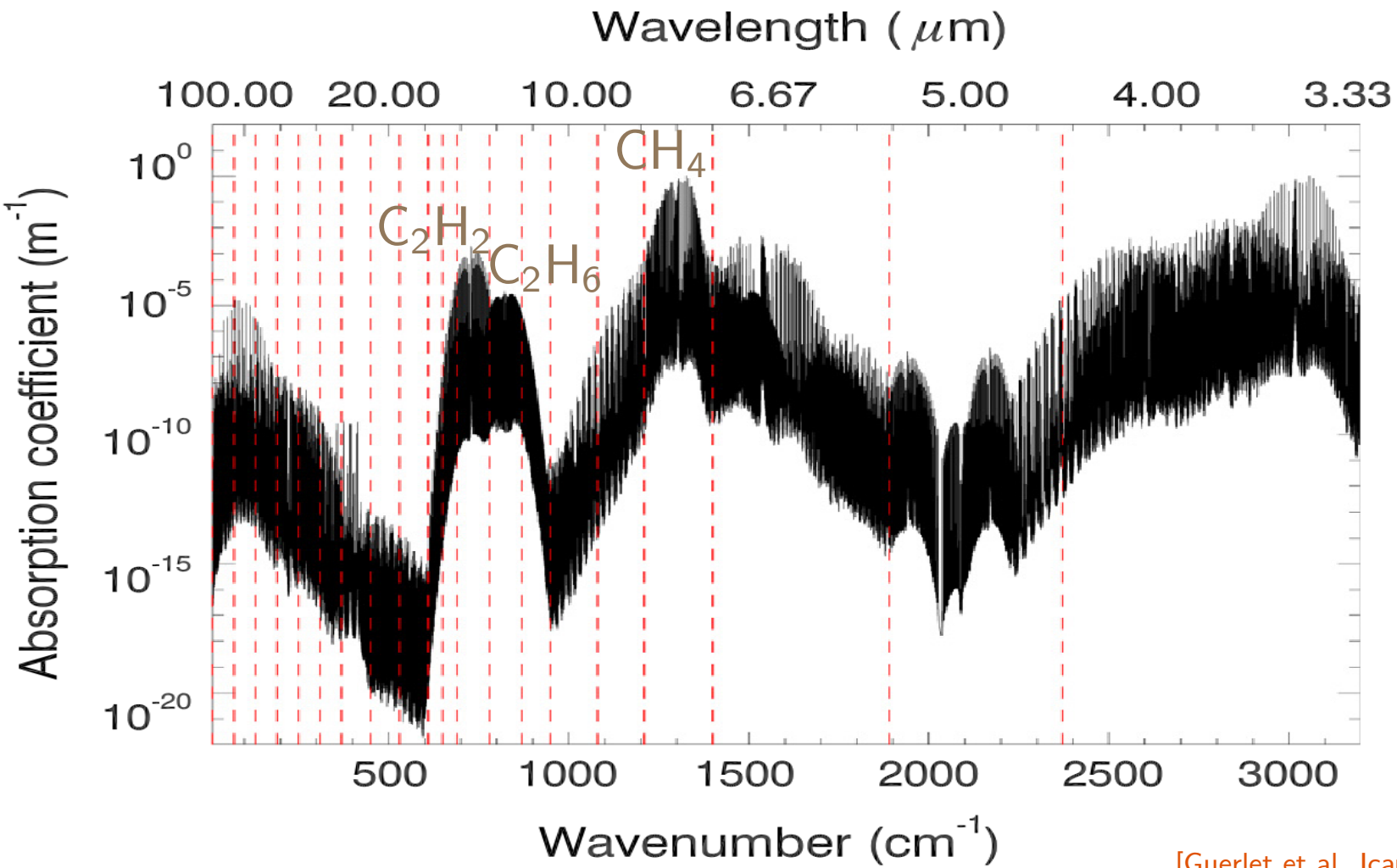
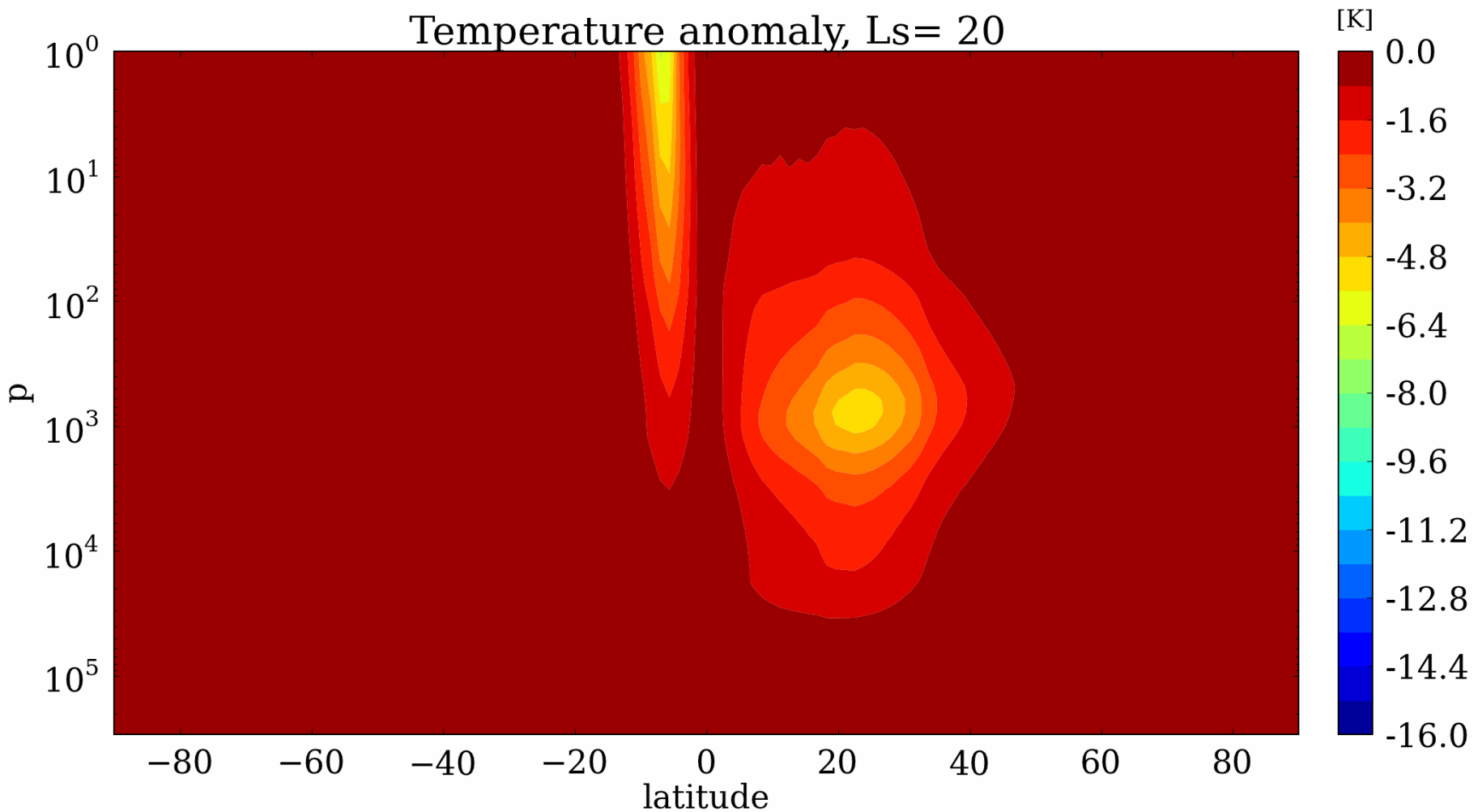
  - free bottom surface with internal heat flux
  - incoming flux: ring shadowing, oblateness
- ☞ Turbulent diffusion + dry convective adjustment [Hourdin et al. 1993]

IR spectral discretization – correlated-k scheme



[Guerlet et al. Icarus 2014]

Saturn's rings shadowing and temperatures



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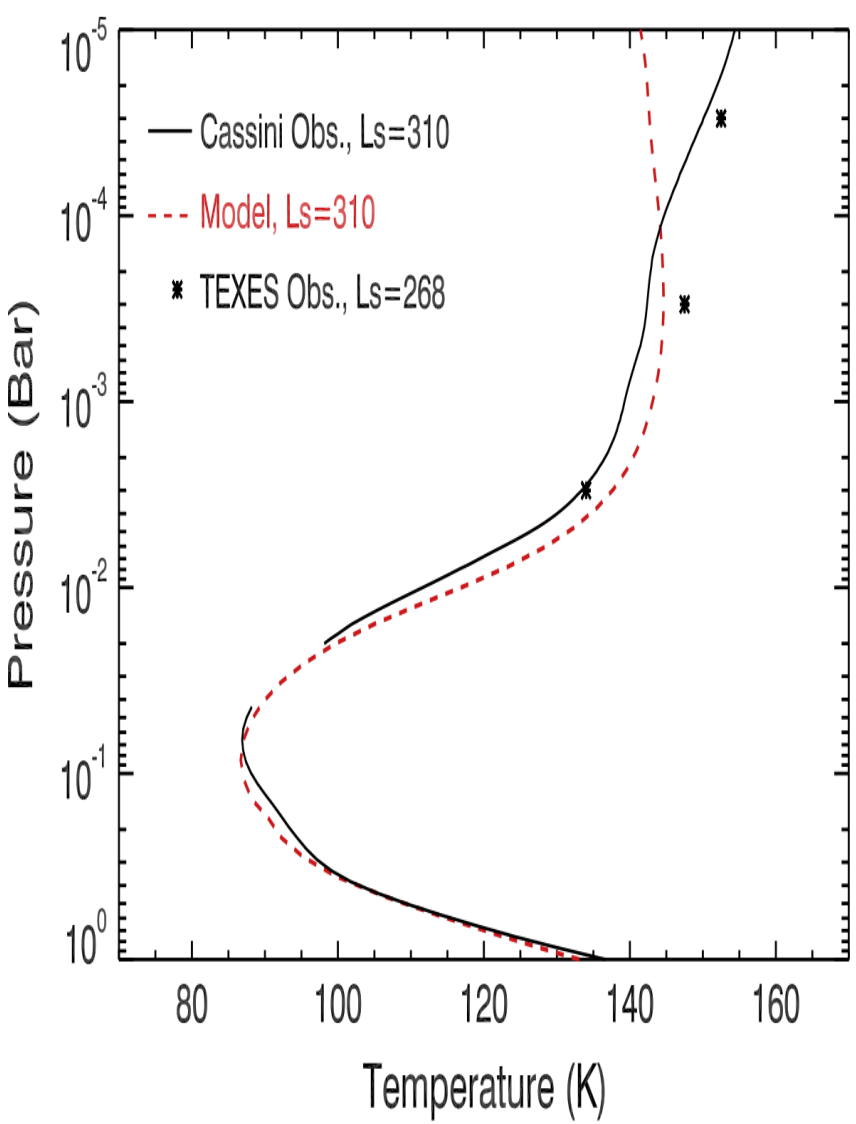
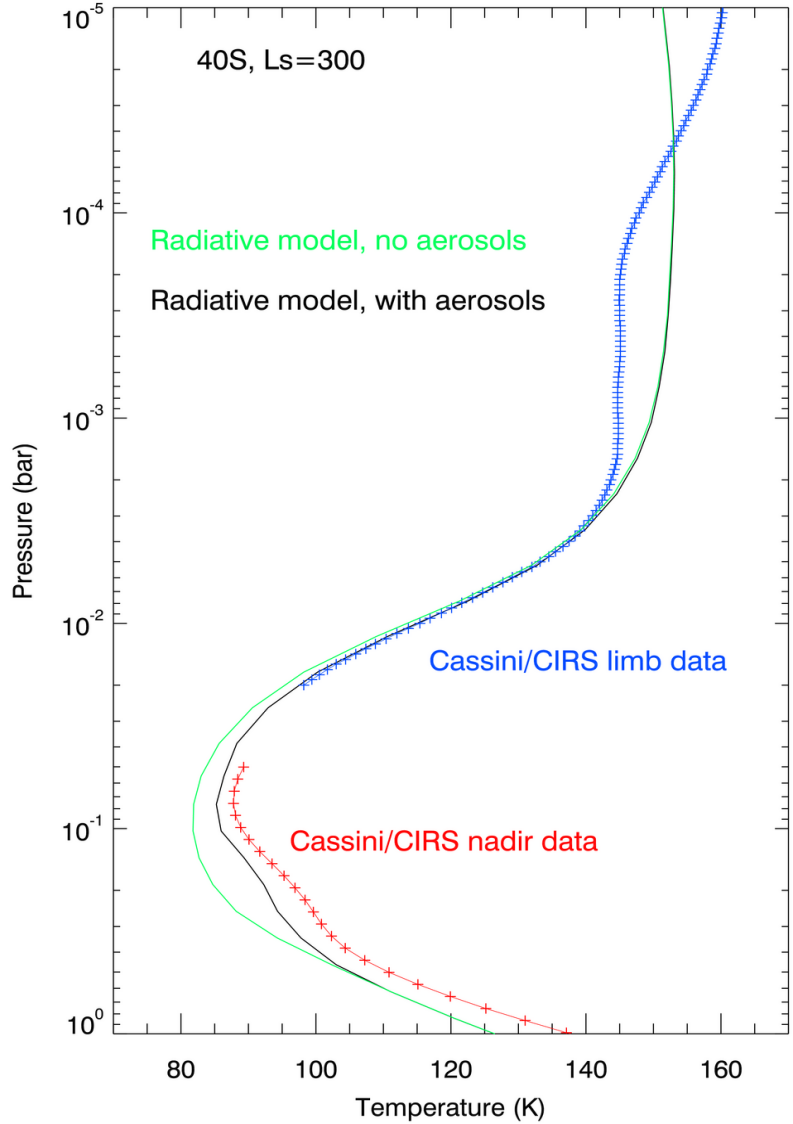
3D radiative model vs. profile measurements

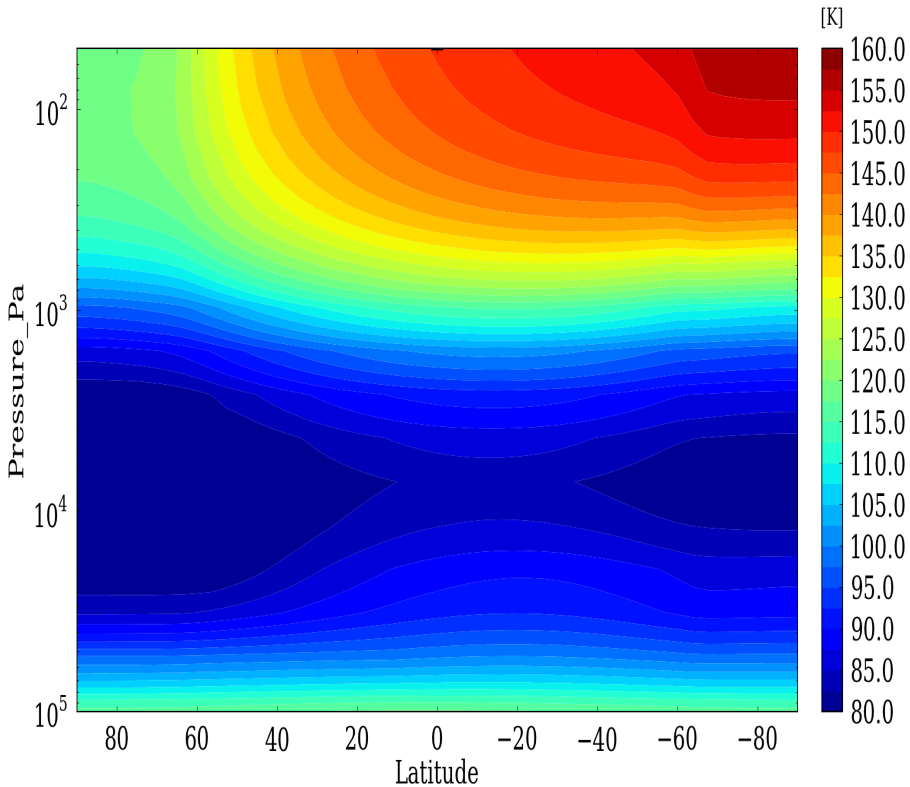


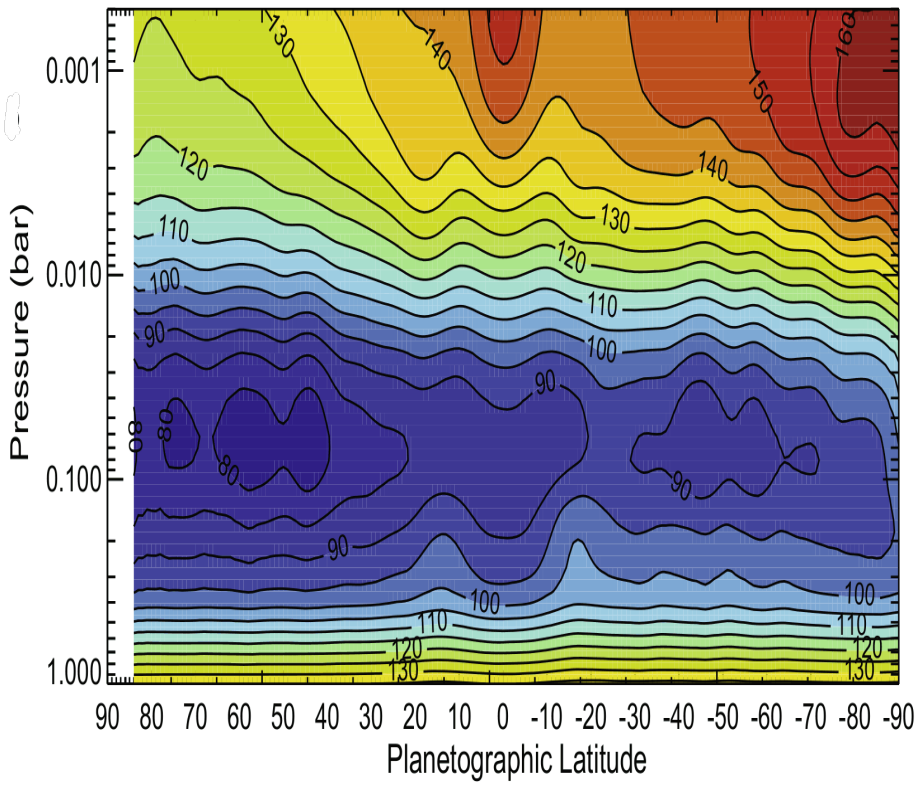


[Guerlet et al. Icarus 2014]

Saturn GCM (nodyn) vs. CIRS [Fletcher et al. 2010]

Year 2005. $L_s = 300°$





[Guerlet et al. Icarus 2014]

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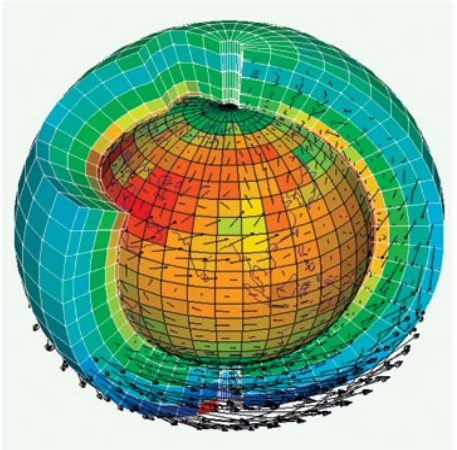

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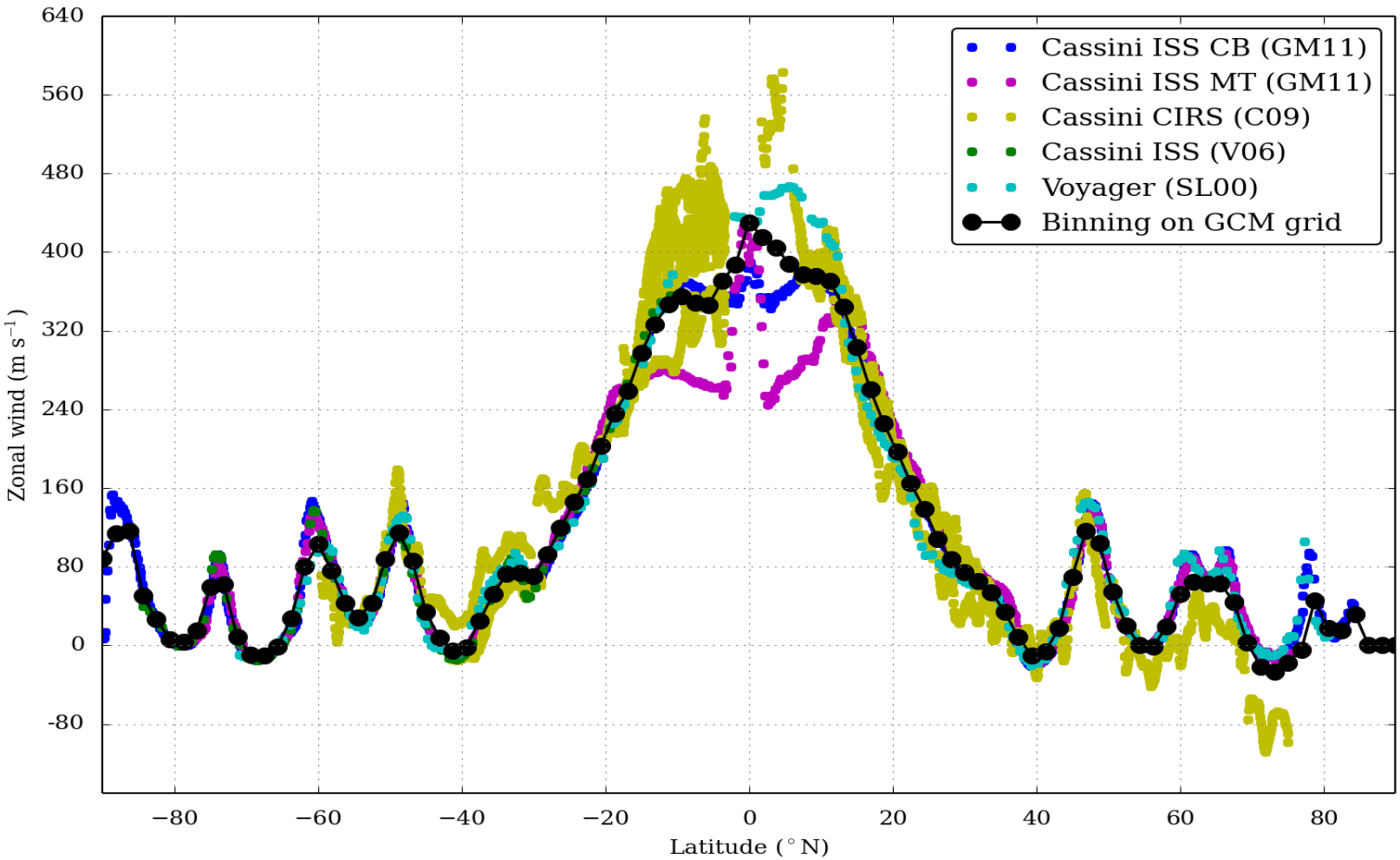
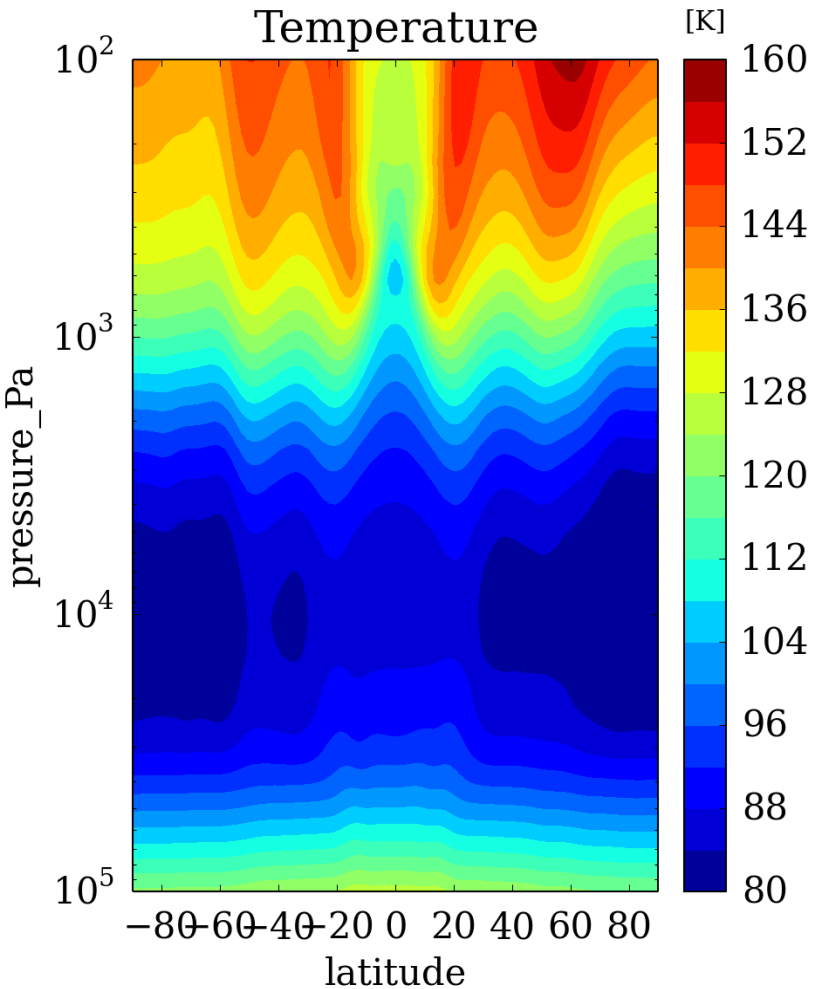
Relaxation towards observed wind structure

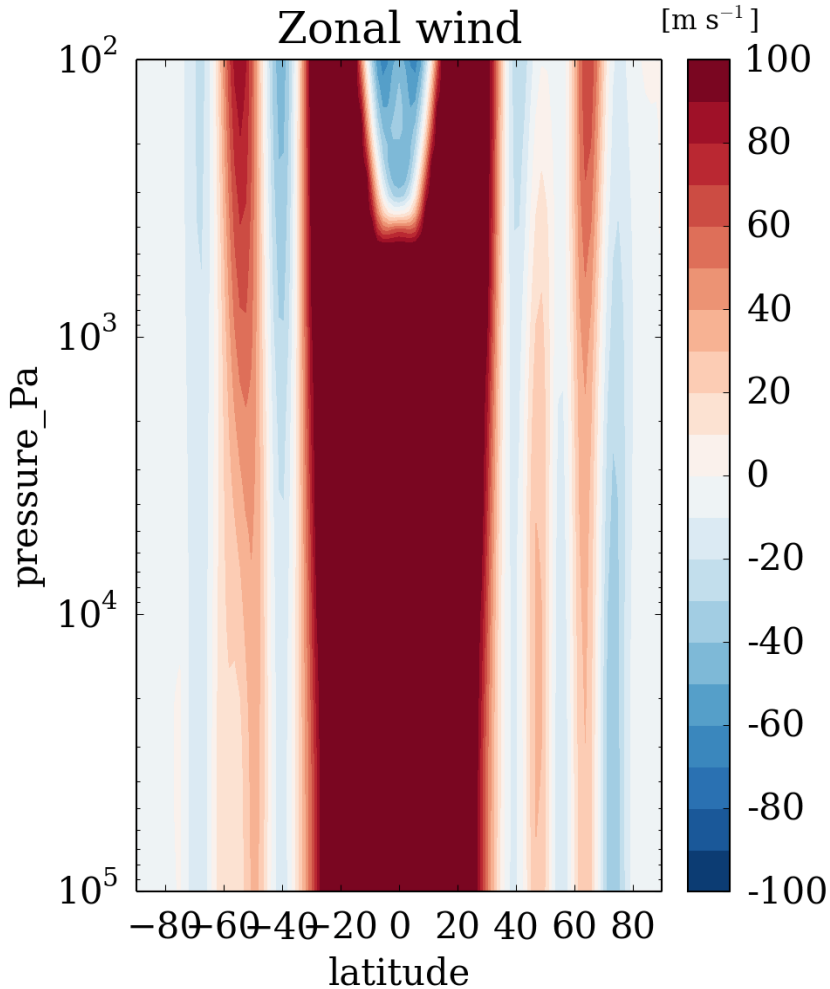
Additional tendency $\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{u - u_{\mathrm{ref}}}{\tau_u}$ in lowermost two levels



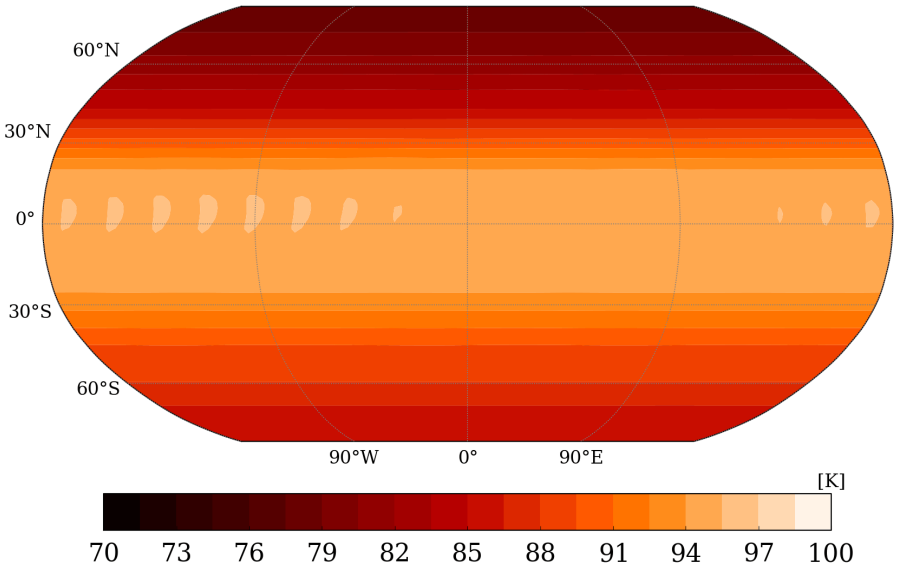
Zonal-mean structure. 1.5° simulation.

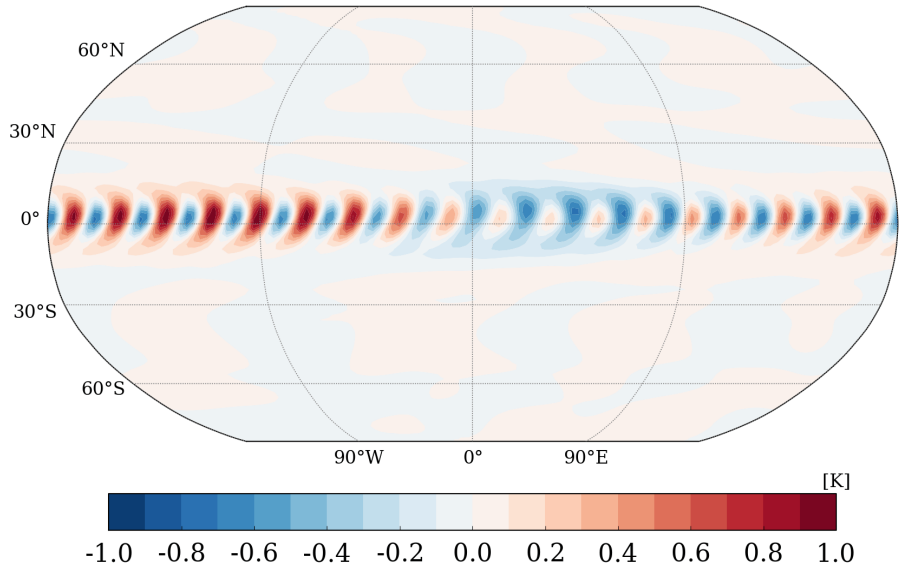
Winds are 'nudged' towards observed values at the bottom of simulation domain

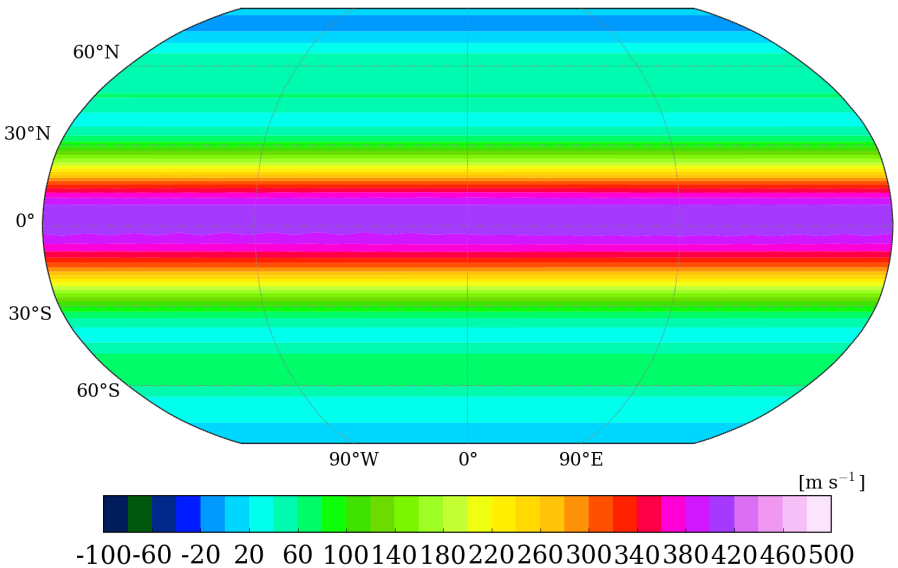


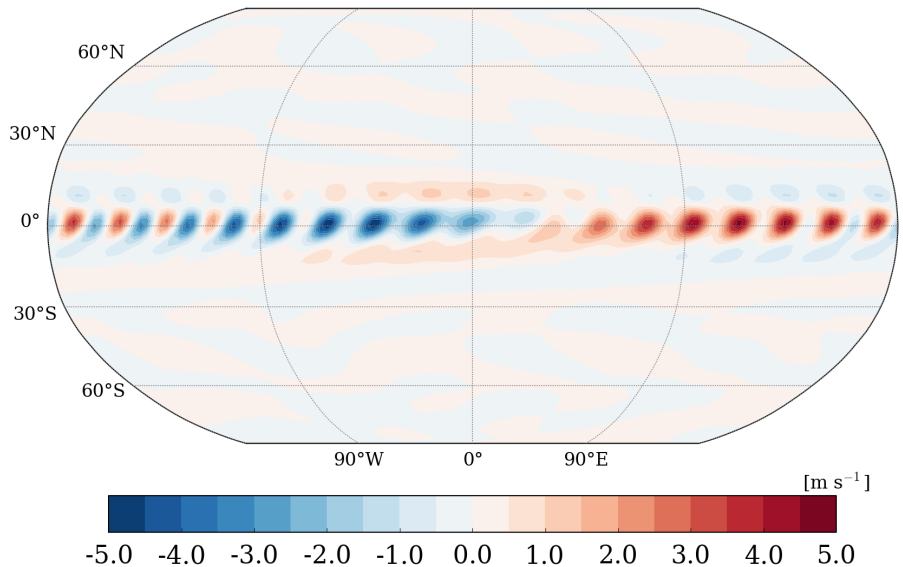


Equatorial waves, upper troposphere (100 mbar)





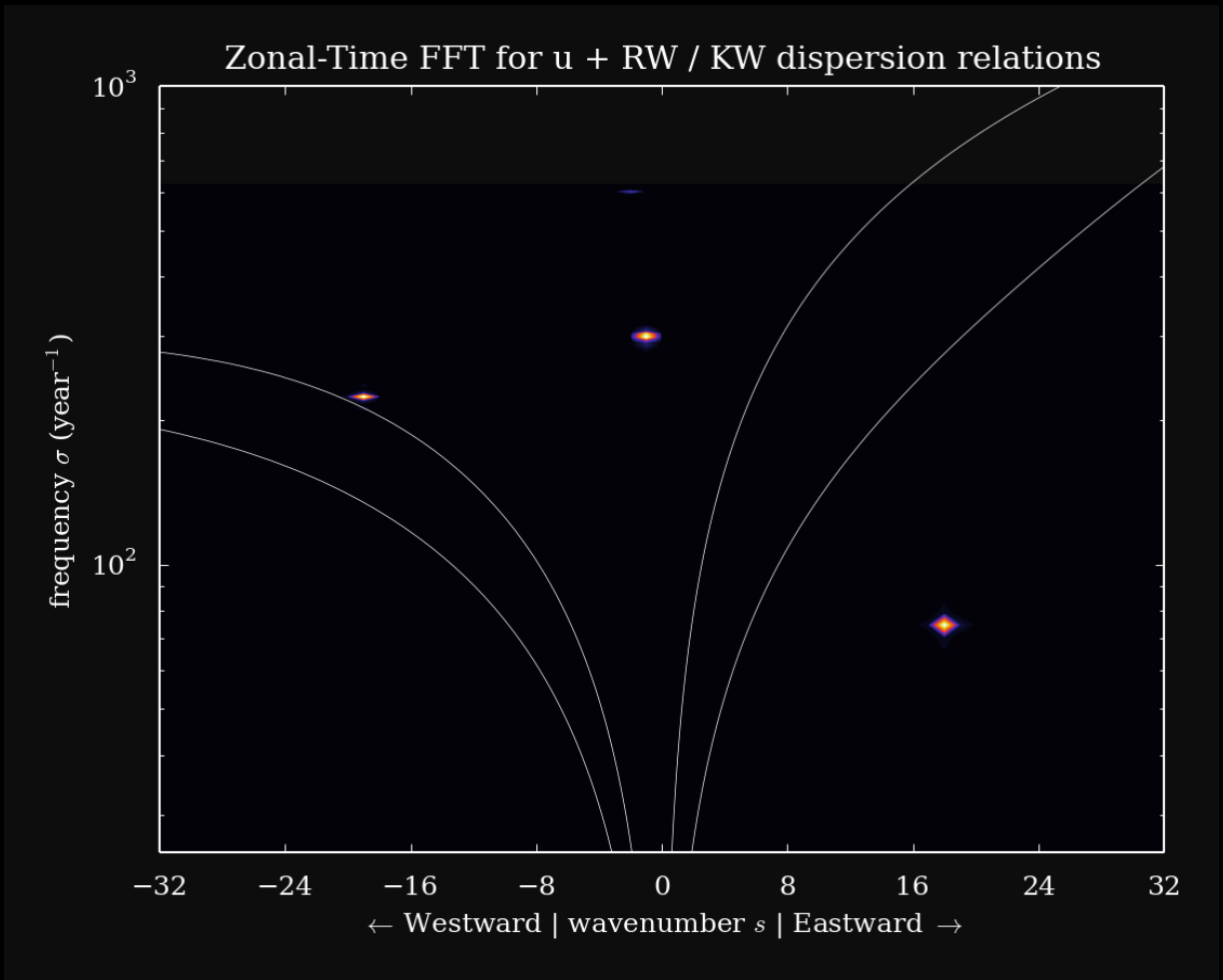




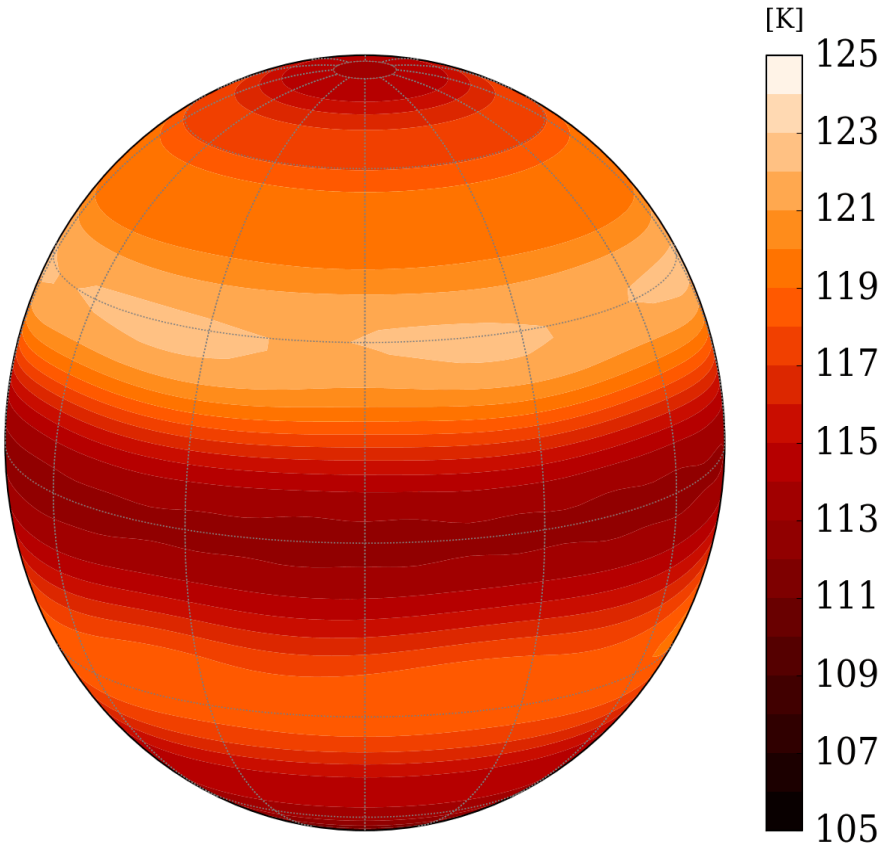
Spectral characterization of equatorial waves

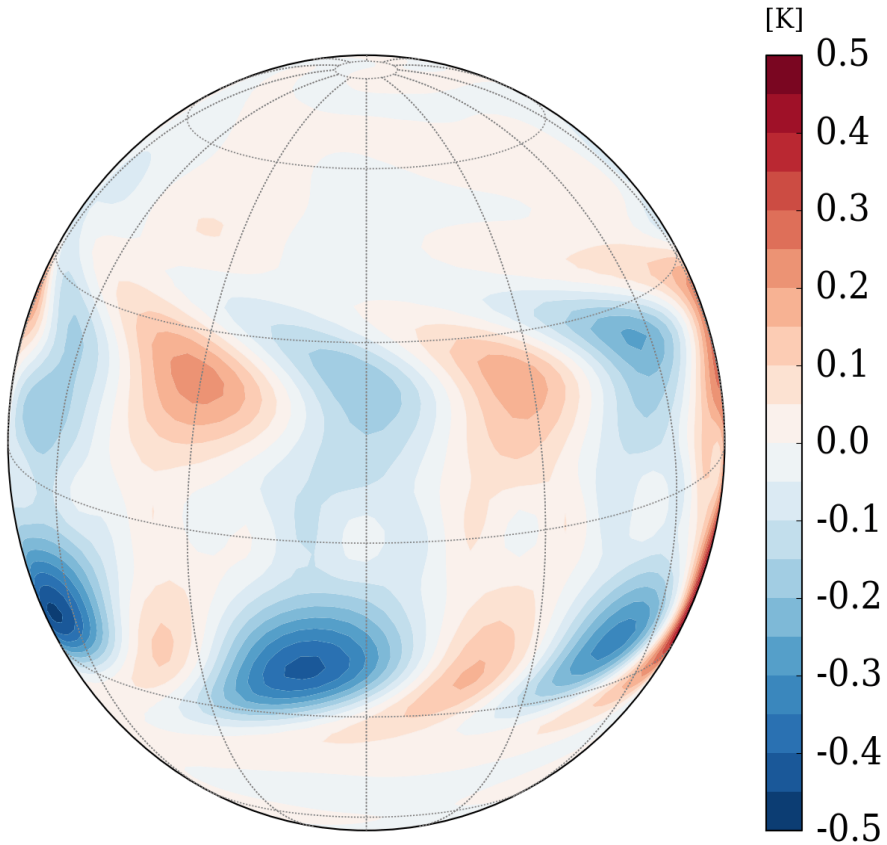
Rossby: $\nu = +1, +2, \ldots$; Rossby-gravity: $\nu = 0$; Kelvin: $\nu = -1, -2, \ldots$

$$\boxed{\sqrt{\gamma}\,(2\,\nu + 1) = \gamma\,\sigma^2 - s^2 - s/\sigma} \quad \text{with} \quad \frac{\gamma\,N^2}{4\,a^2\,\Omega^2} = \left(\frac{2\,\pi}{\lambda_z}\right)^2 + \left(\frac{1}{2\,H}\right)^2$$



Midlatitudes waves, lower stratosphere (10 mbar)

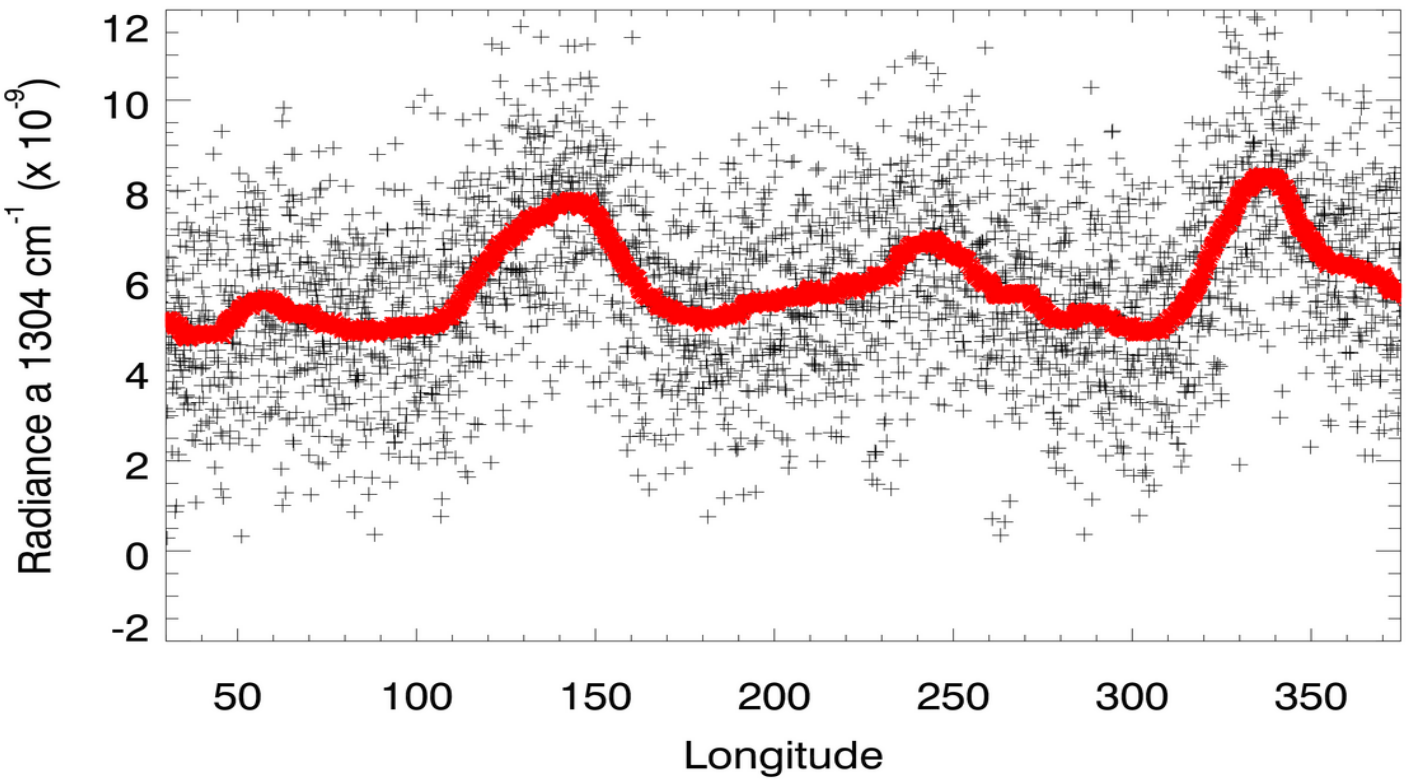




Longitudinal variations of temperature

CIRS nadir 1304 cm^{-1} CH_4 Q-branch at latitude $42 - 43°S$ (dec 2011, $L_s \sim 30°$)

(Rough) analysis: correspond to wave amplitude of 2.5 K at 2mbar.

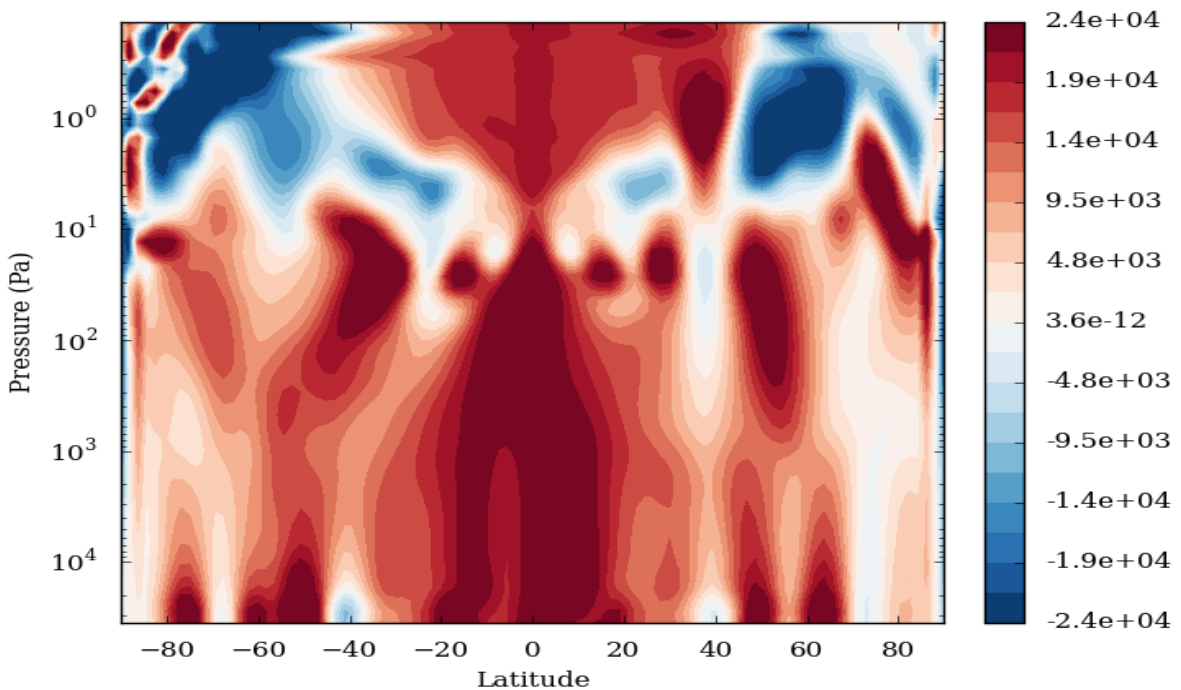


[S. Guerlet (unpublished)]

Baroclinic instability?

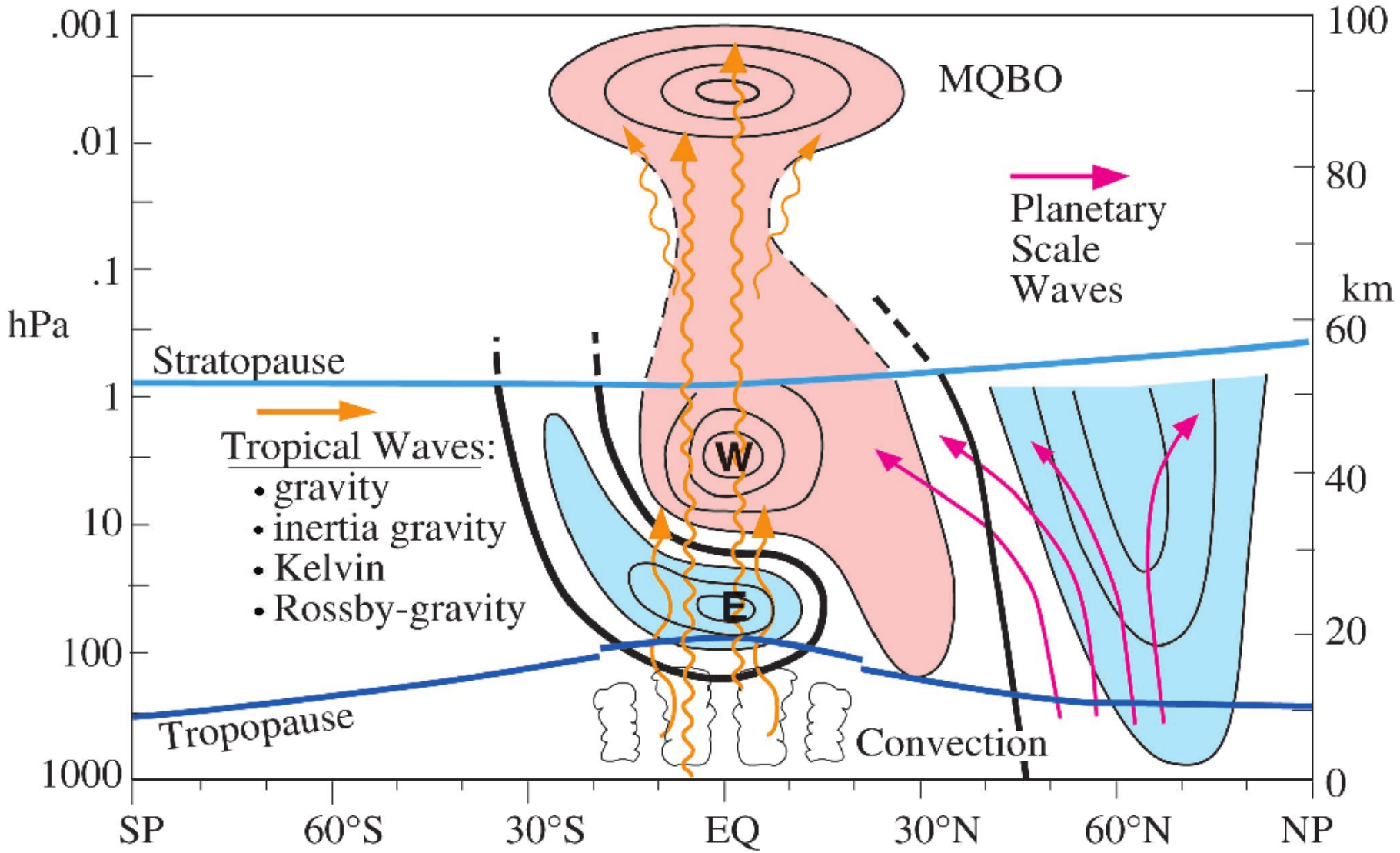
Charney-Stern criterion: vanishing of

$$\mathcal{Q}_\phi = 2\,\Omega\,a\,\cos\phi - \left[\frac{1}{\cos\phi}\left(\cos\phi u\right)_\phi\right]_\phi - \frac{4\,\Omega^2\,a^2}{p}\,\sin^2\phi\,\left[\frac{p}{N^2}\,u_z\right]_z$$



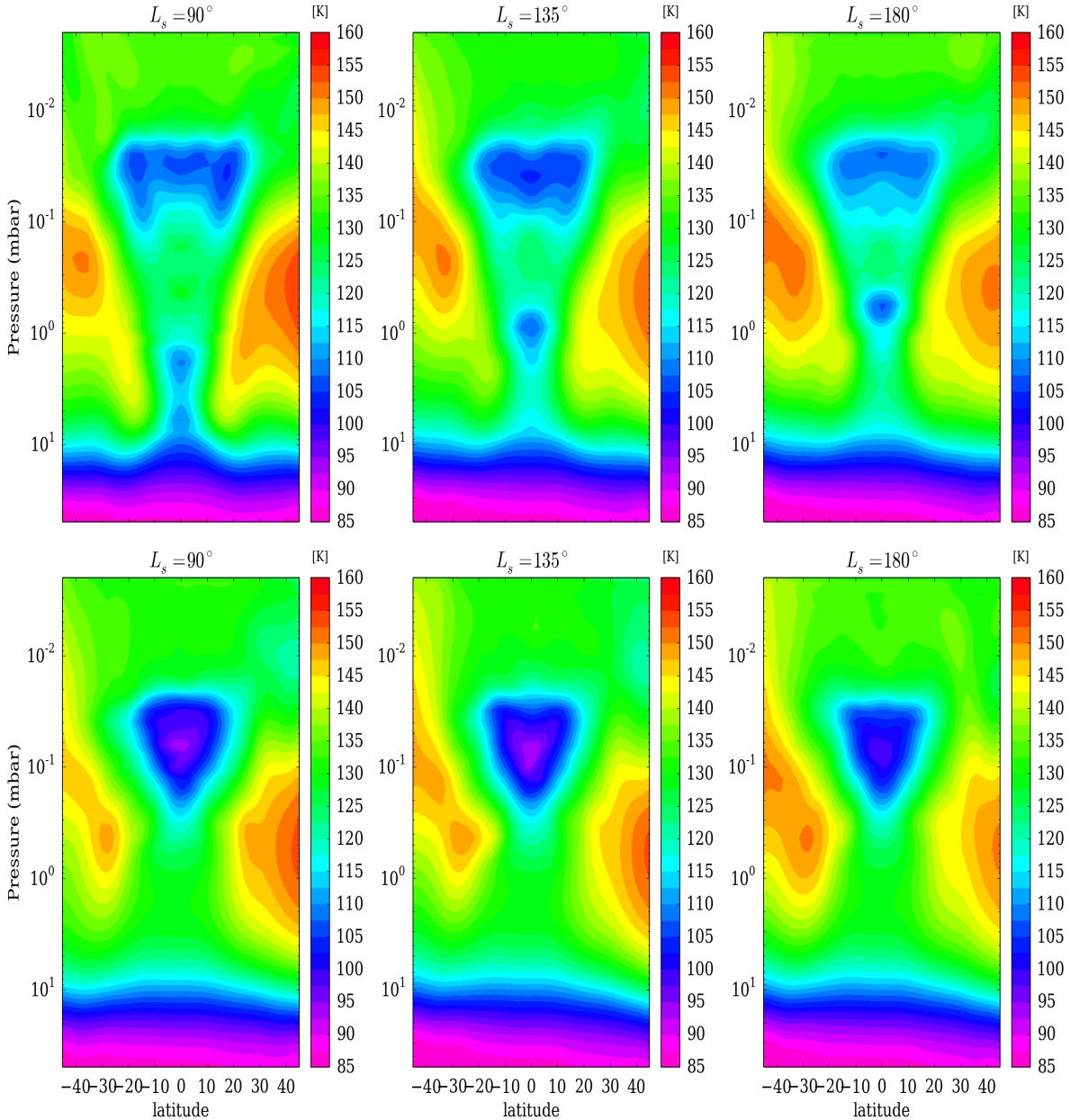
(necessary condition derived from QG equations of motion for an atmosphere of infinite extent)

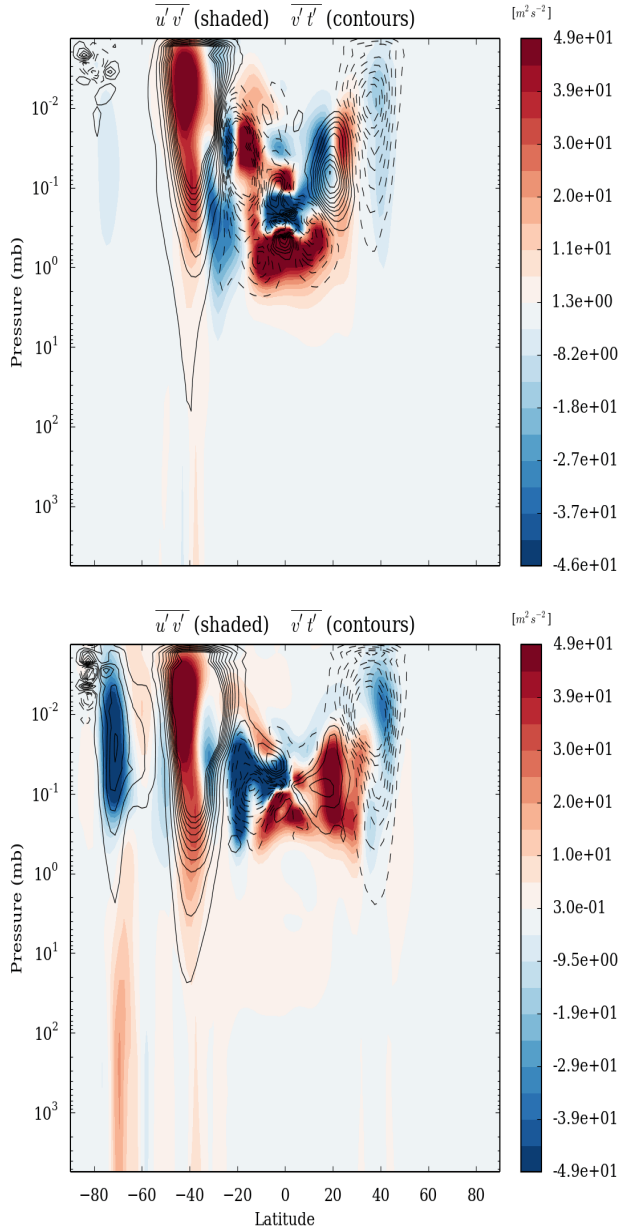
Quasi-Biennal Oscillation, Earth's stratosphere



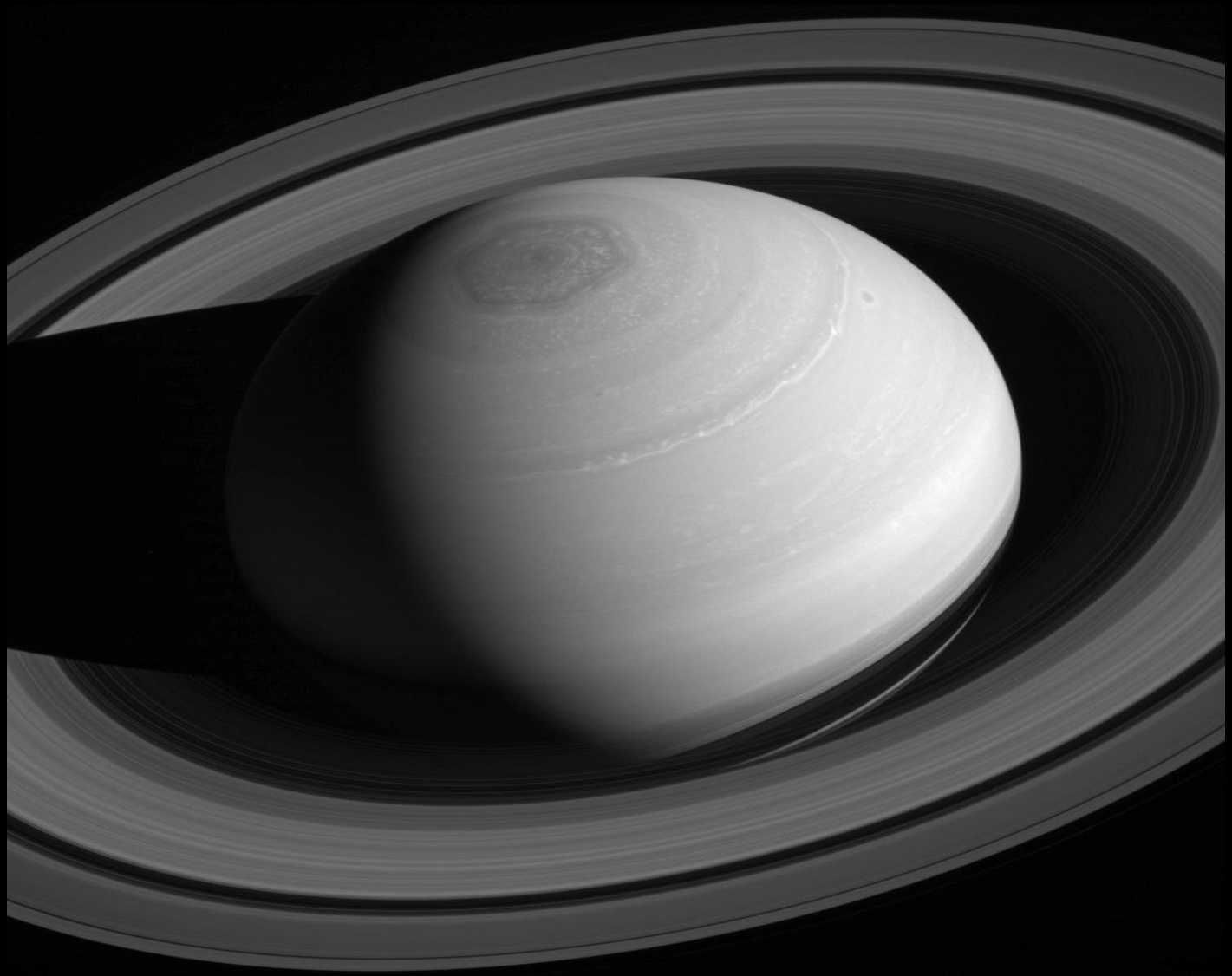
[Baldwin et al. Review of Geophysics 2001]

Any equatorial oscillation?





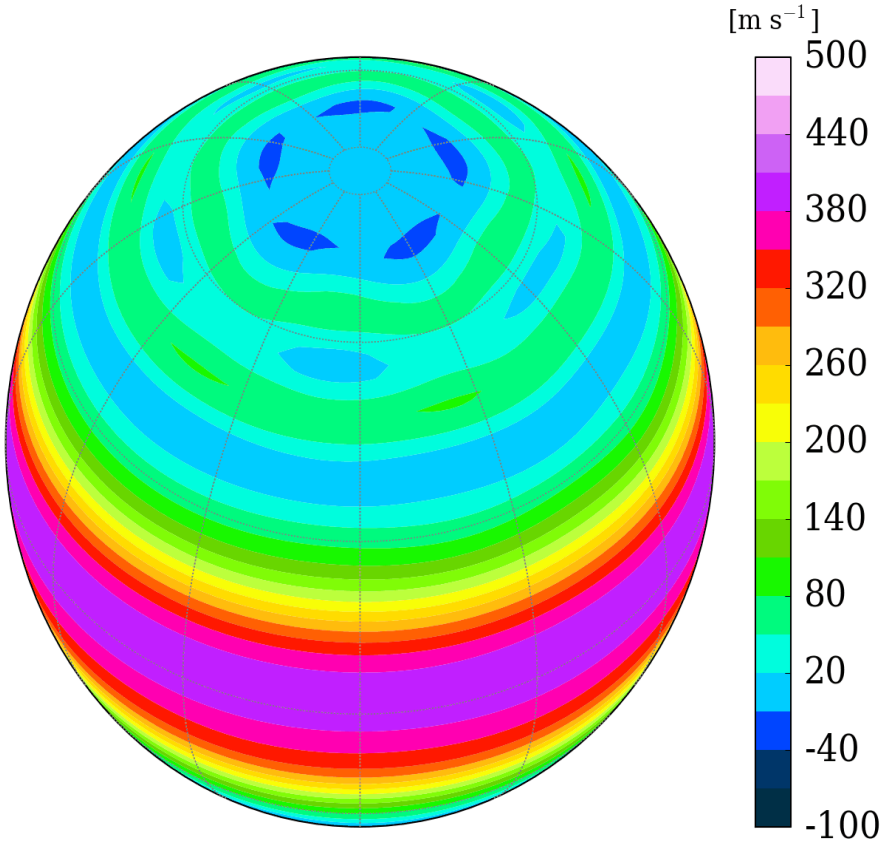
Saturn's hexagon

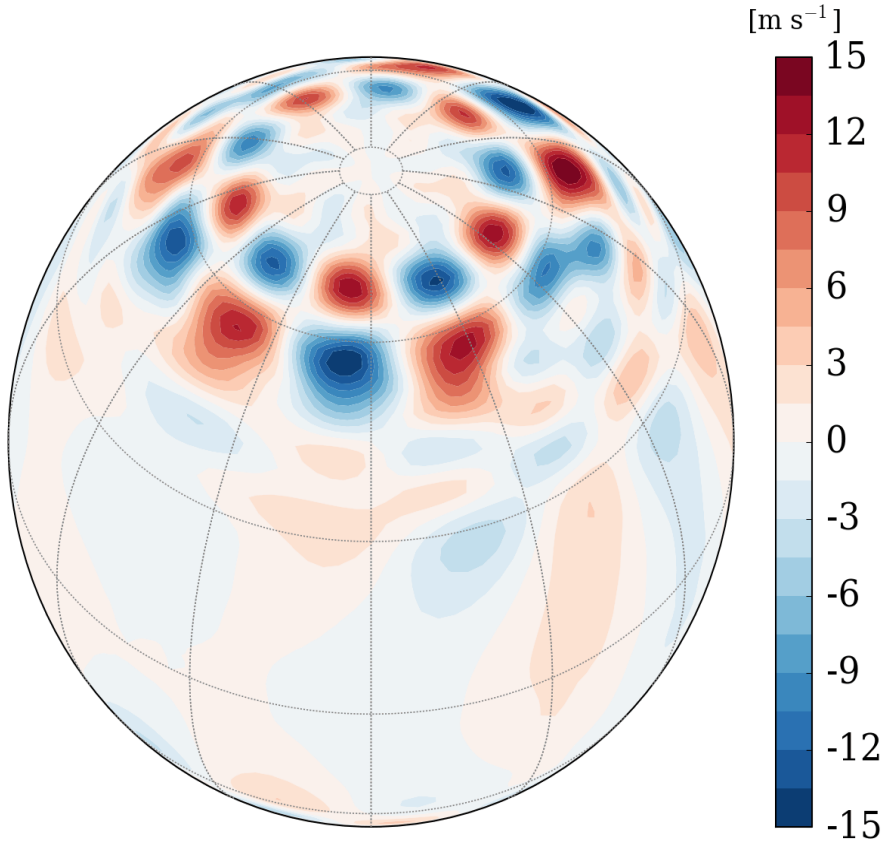


[PIA18278]

Polar jets

Zonal wind and perturbations to zonal mean





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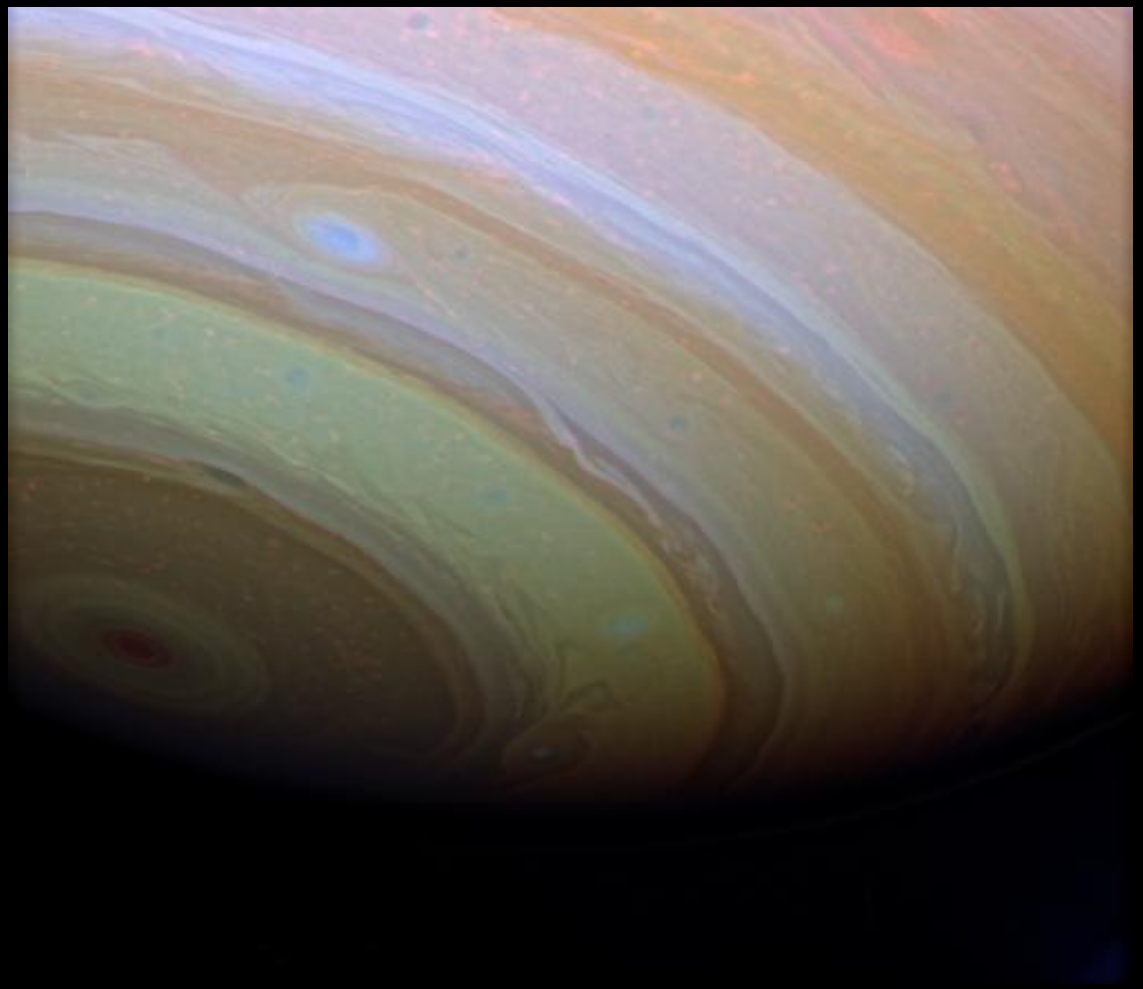
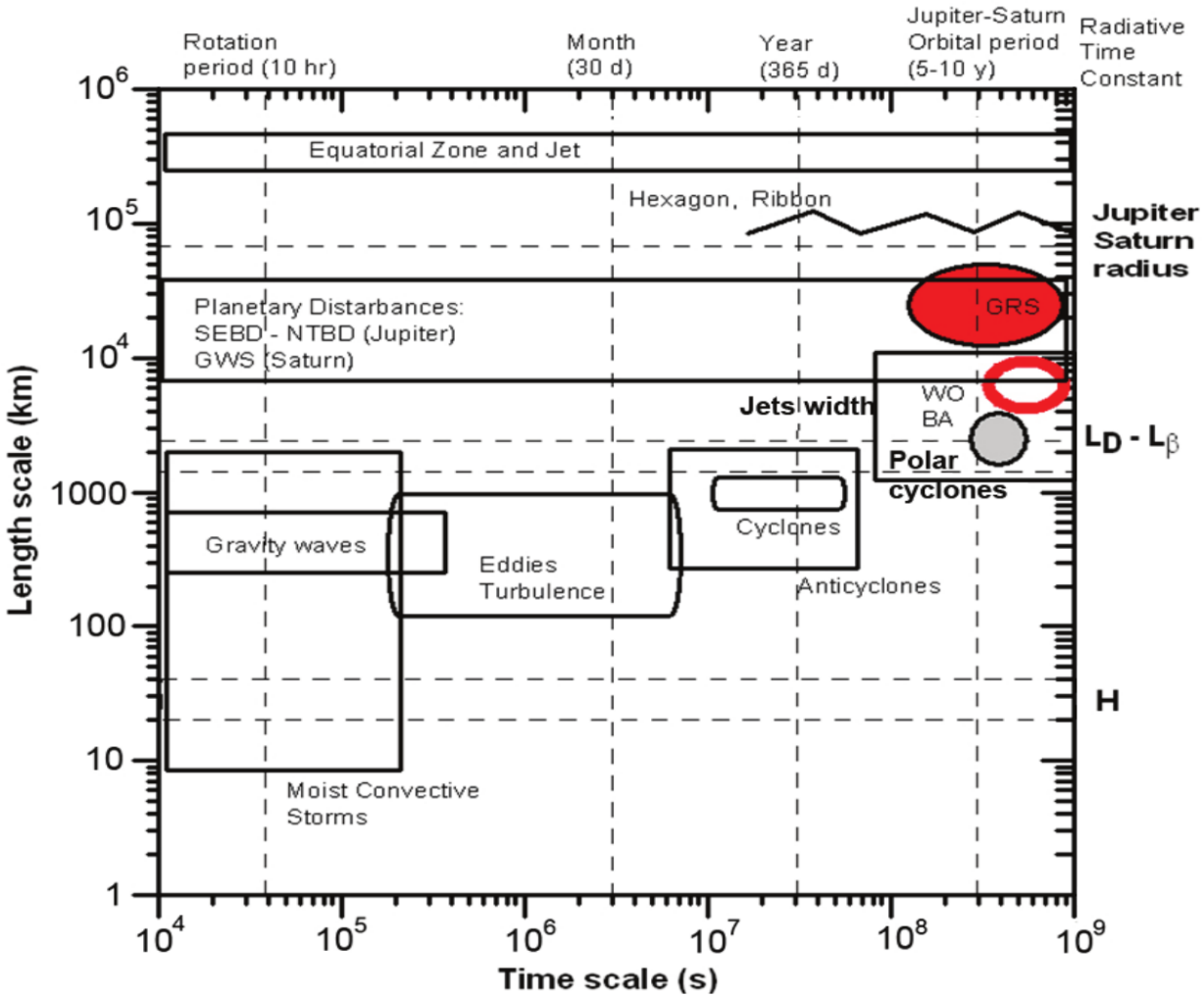
Towards fine-scale simulations



[Cassini image]

Scales involved in giant planets

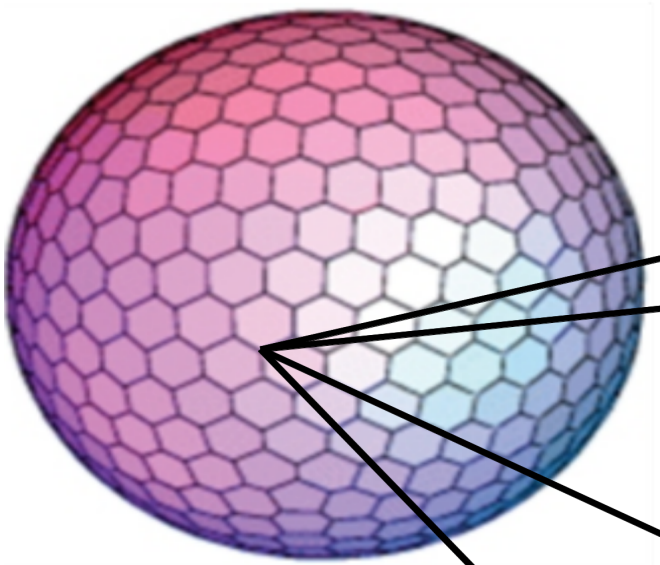


[Sanchez-Lavega 2015]

Rhines scale $\sim$ energy-containing eddy length scale

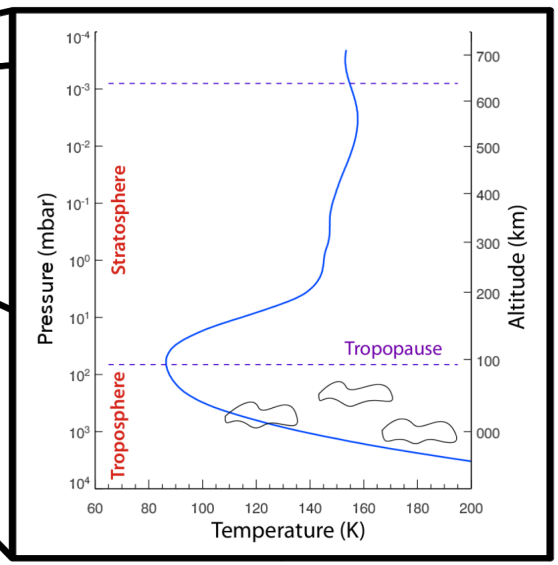
Rossby radius of deformation $\sim$ length scale of the baroclinically most unstable linear waves

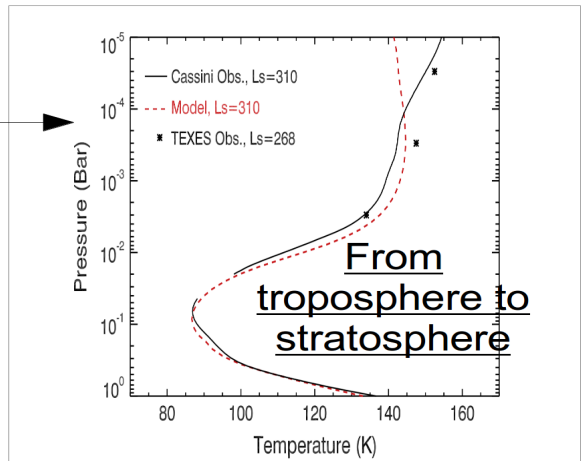
A new GCM for giant planets



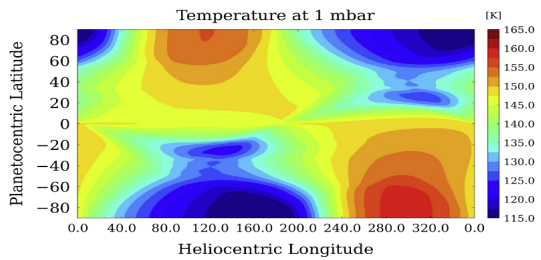
DYNAMICAL CORE
icosahedral-grid
high-performance
DYNAMICO model
[Dubos et al. 2015]

PHYSICAL PACKAGES
radiative-convective model
[Guerlet et al. 2014]
+ magnetic drag (Goal 2.1)
+ photochemistry (Goal 2.2)

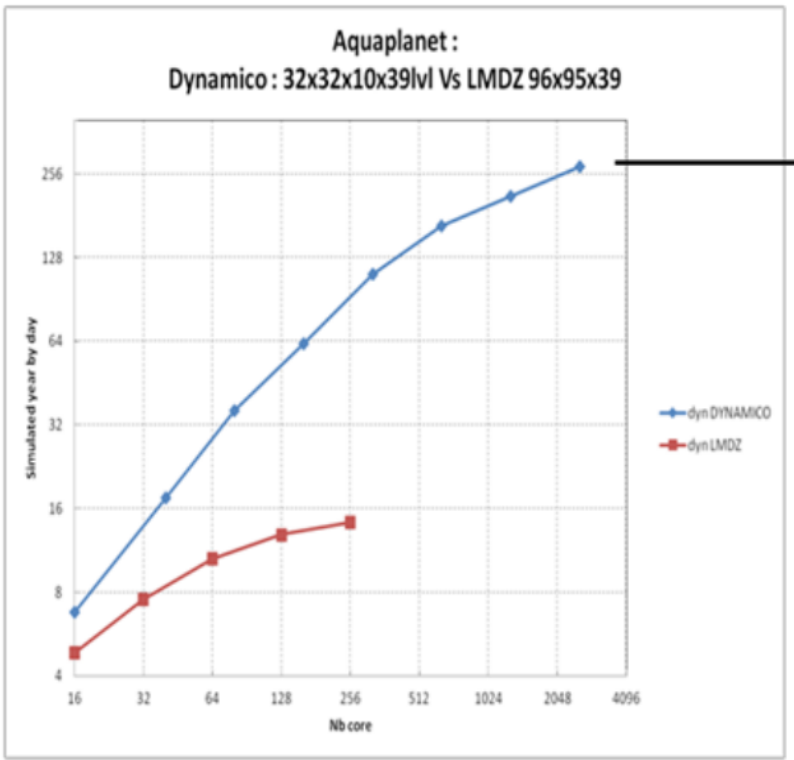




Predicted seasonal evolution



DYNAMICO (icosahedral) vs. LMDz (lat-lon)

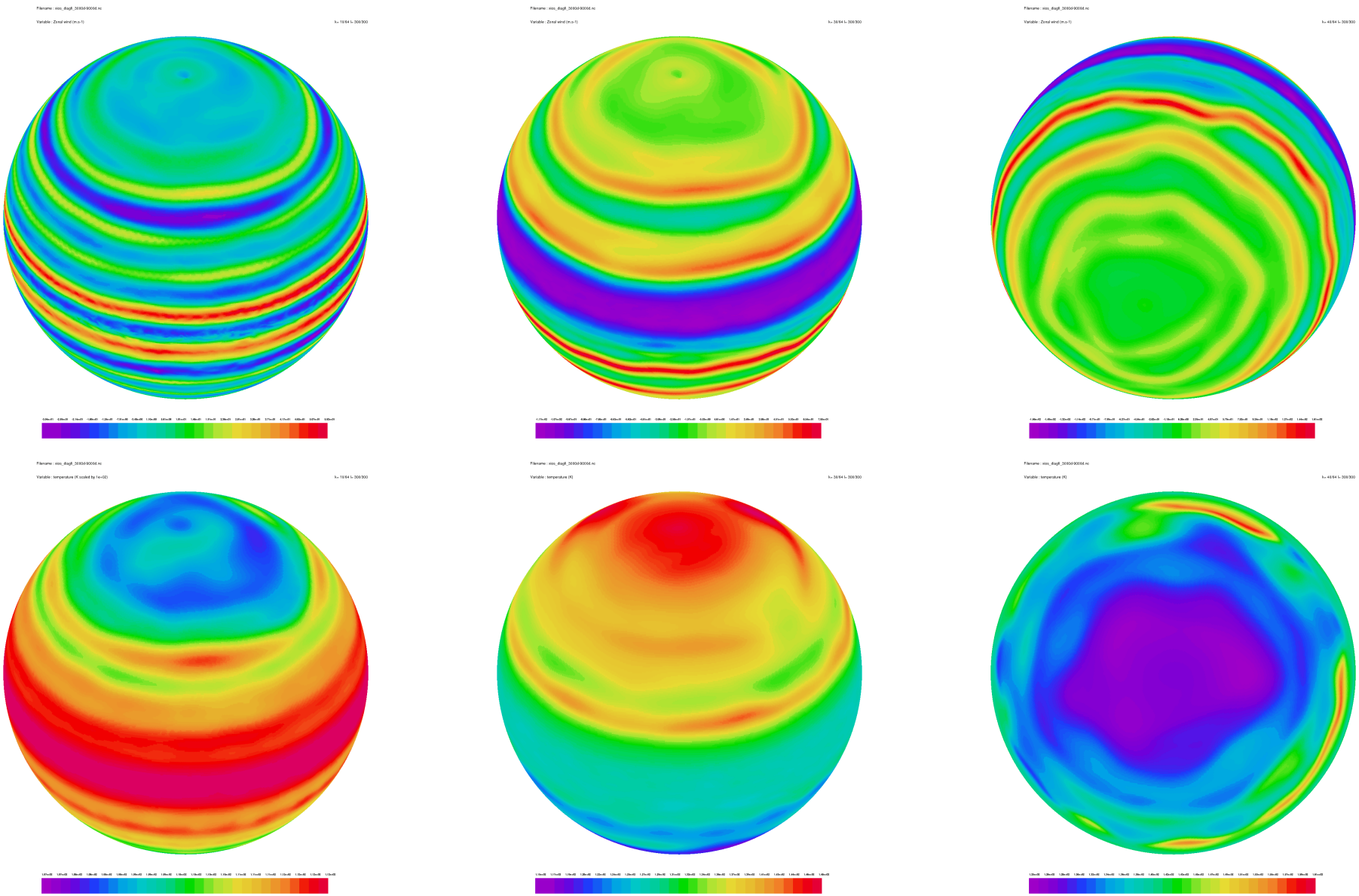


Résolution (degré ~ km)	Nombre de coeurs	Années / jours	
3° ~ 300 km	2 560	272 (x20)	mesuré
1° ~ 100 km	20 480	85	
1/2° ~ 50 km	82 000	42	extrapolé
1/3° ~ 33 km	184 000	28 (x40)	
1/4 ° ~ 25 km	328 000	21	
1/8° ~ 12 km	1 300 000	10	

Comparaison de la scalabilité entre l'ancien cœur dynamique LMDz (en rouge) et le nouveau coeur dynamique DYNAMICO candidat au grand challenge (en bleu). L'echelle est en log-log. Dans le tableau, le nombre d'années simulées (en année terrestre) par jour. En vert, sont indiqués les résultats mesurés, le reste étant extrapolé en supposant une scalabilité faible parfaite.

Demonstration test. HD $1/2^\circ$ about 500 km resolution.

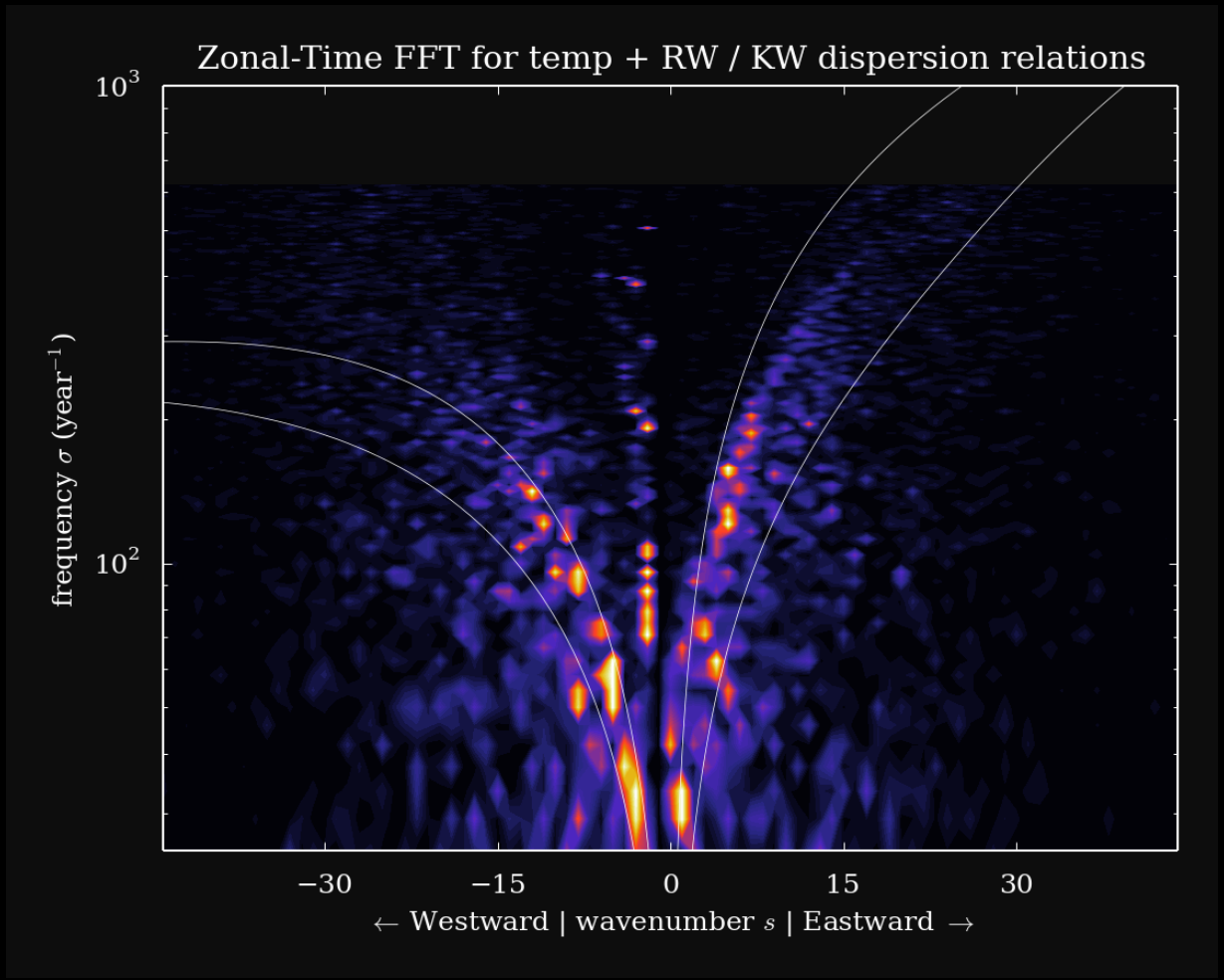
Icosahedral dynamical core. 0.5° simulation.



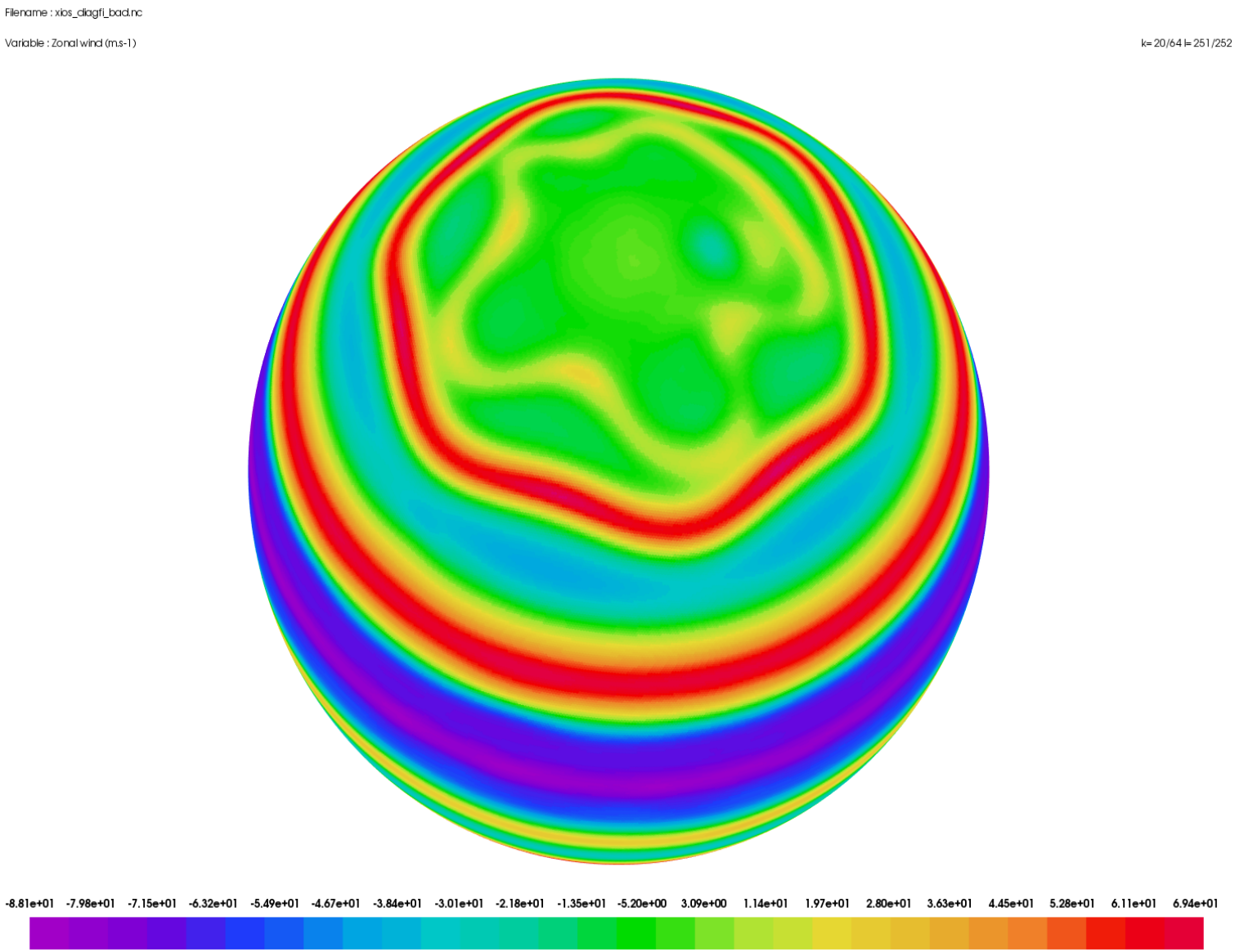
Spectral characterization of equatorial waves

Rossby: $\nu = +1, +2, \ldots$; Rossby-gravity: $\nu = 0$; Kelvin: $\nu = -1, -2, \ldots$

$$\boxed{\sqrt{\gamma}\,(2\,\nu + 1) = \gamma\,\sigma^2 - s^2 - s/\sigma} \quad \text{with} \quad \frac{\gamma\,N^2}{4\,a^2\,\Omega^2} = \left(\frac{2\,\pi}{\lambda_z}\right)^2 + \left(\frac{1}{2\,H}\right)^2$$

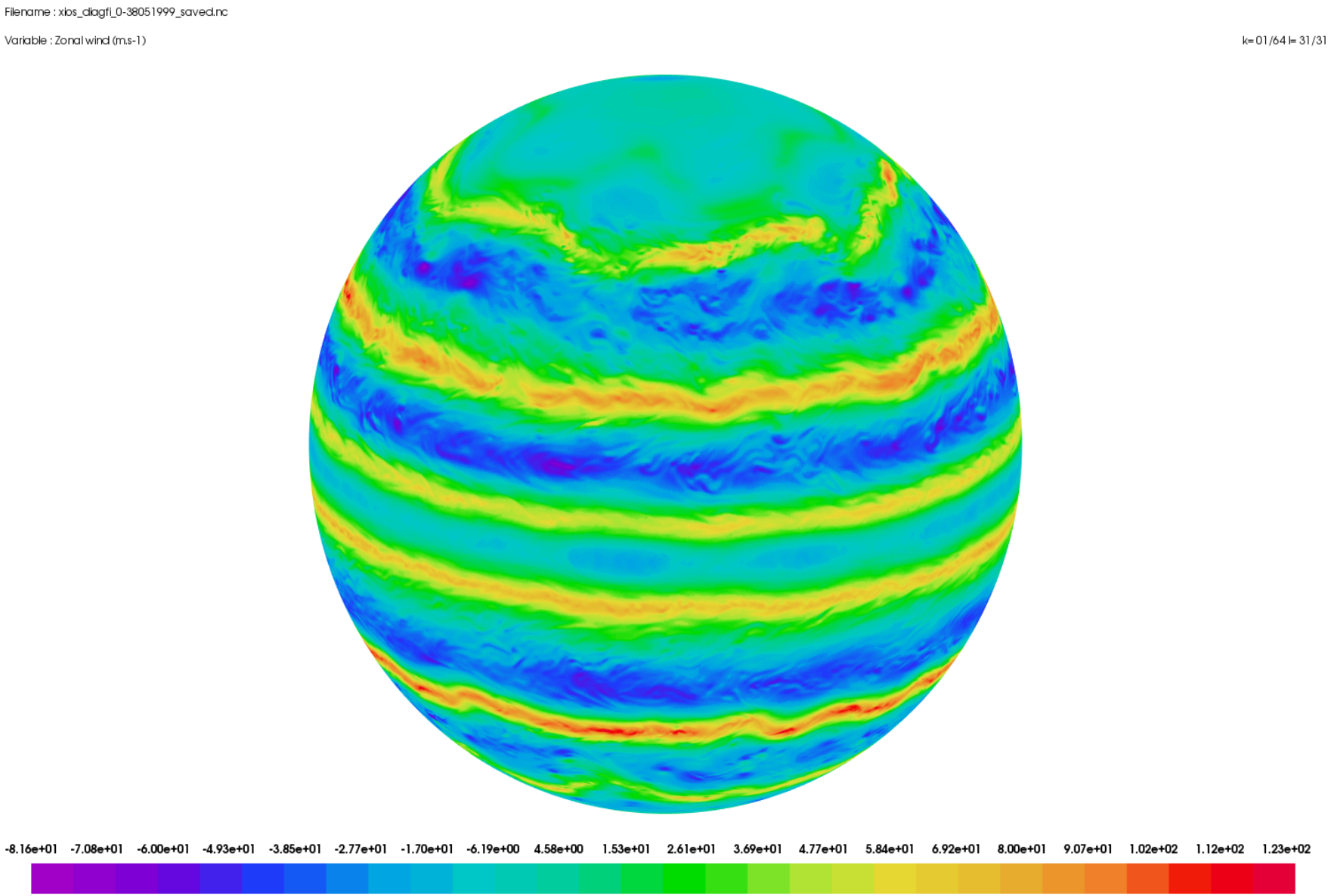


$1/2^\circ$ after one year. Zonal winds (upper tropo).



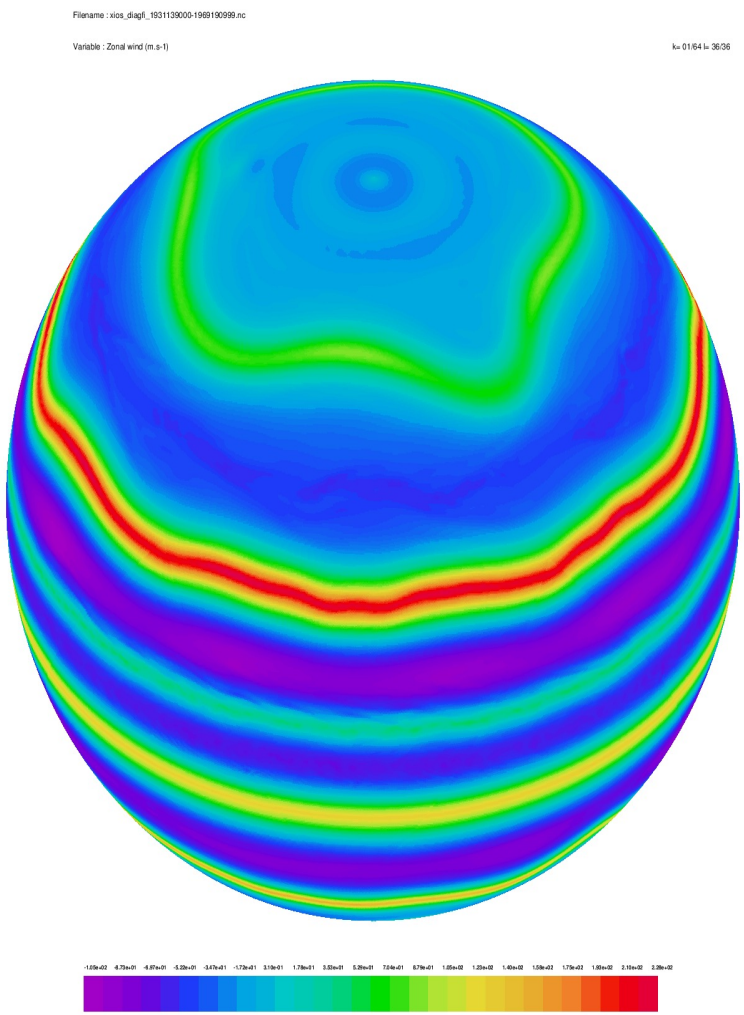
Demonstration test. UHD $1/4^\circ$ about 250 km resolution.

1/4° after 500 days. Zonal winds at 3 bars.

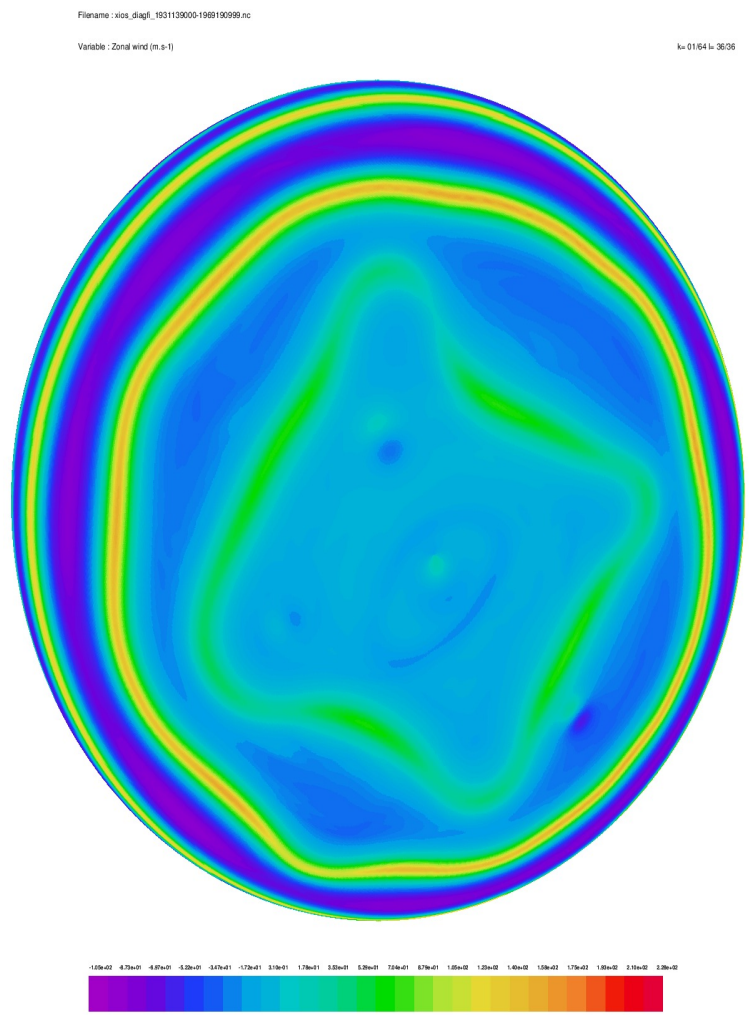


1/4° after two years. Zonal winds at 3 bars.

North pole

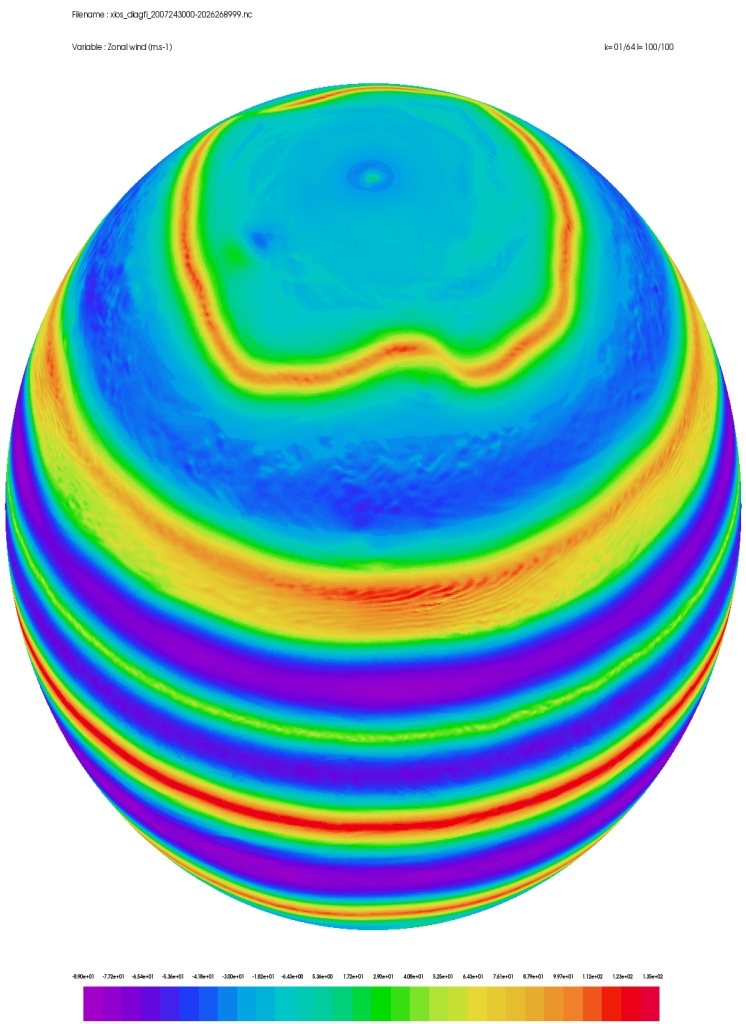


South pole

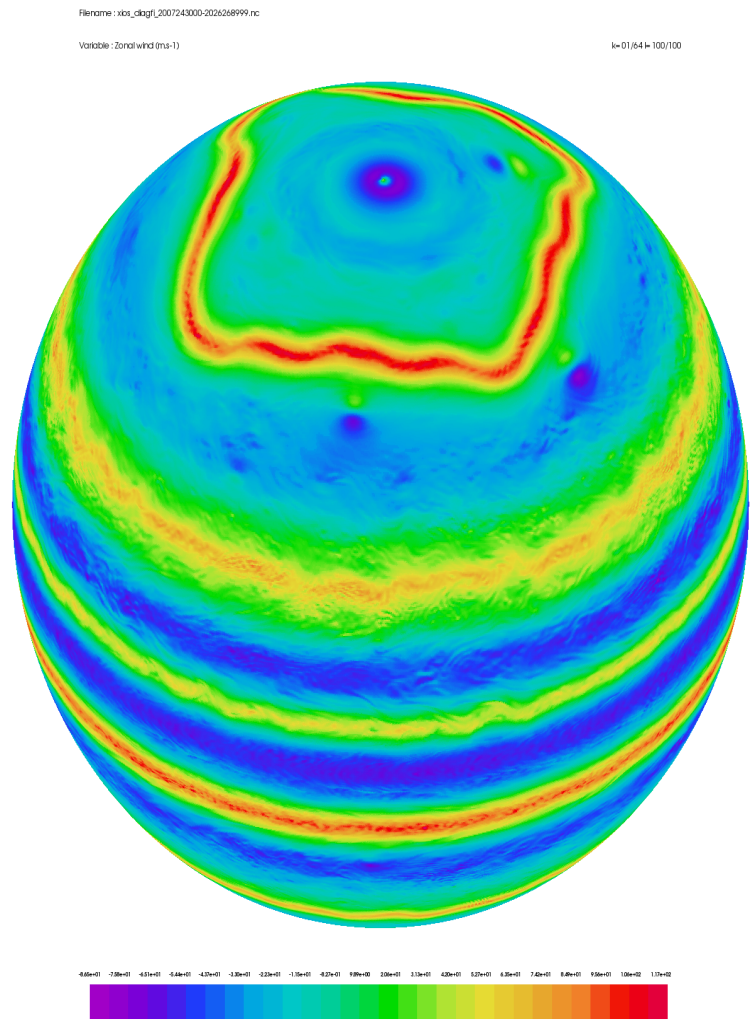


$1/4^\circ$ + 2000 days with a different dissipation.

$2\times$ weaker

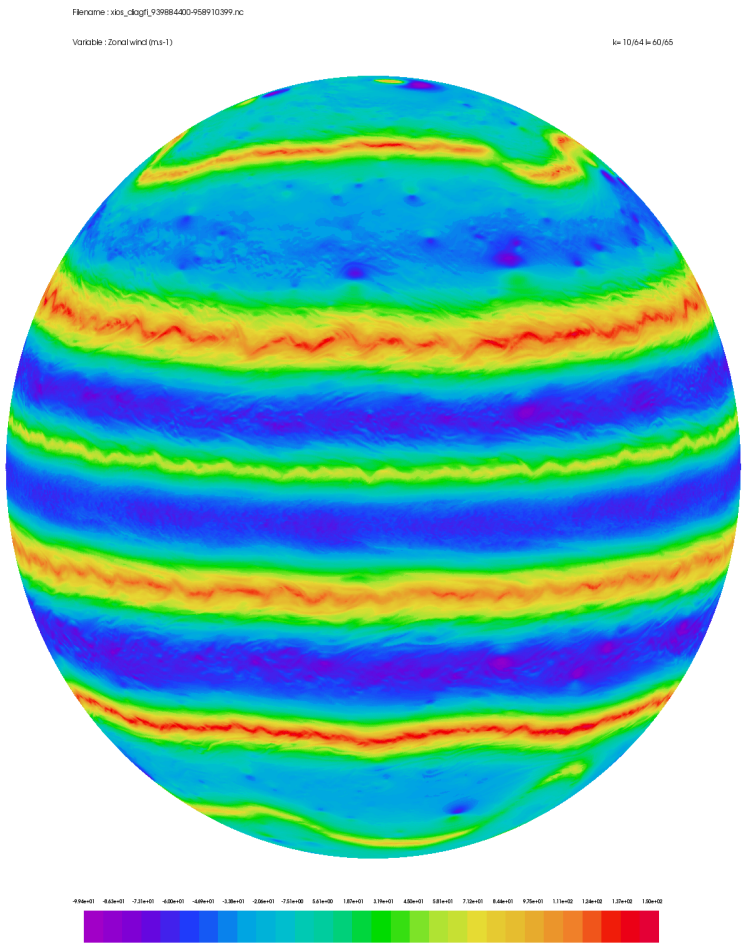


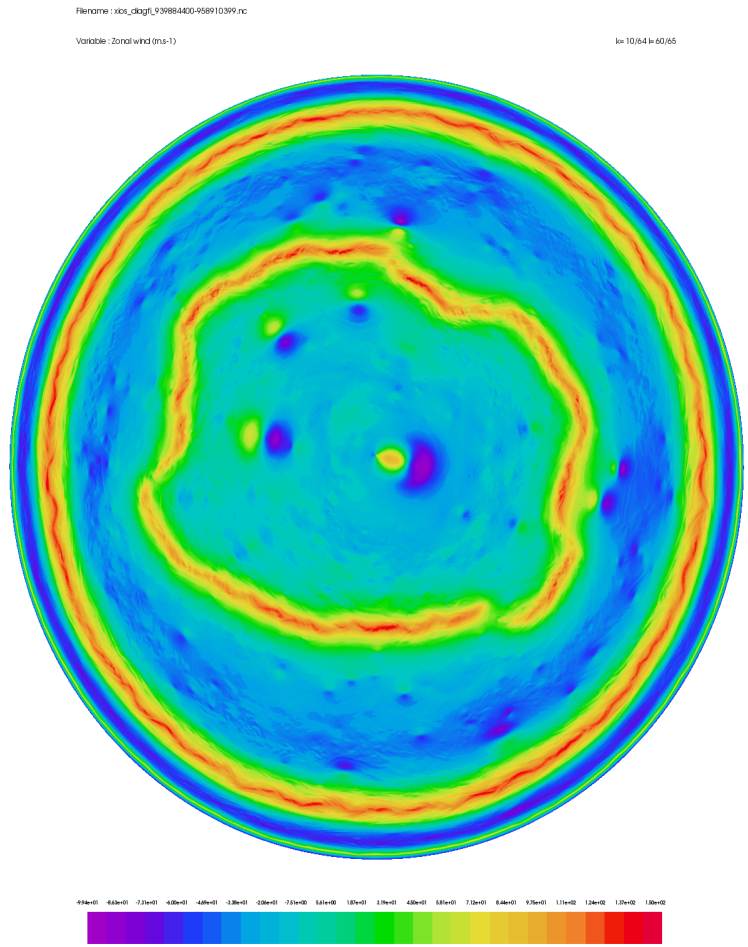
$4\times$ weaker



Demonstration test. UXD $1/8^\circ$ about 125 km resolution

1/8° after 500 days. Zonal winds at 500 mbars.



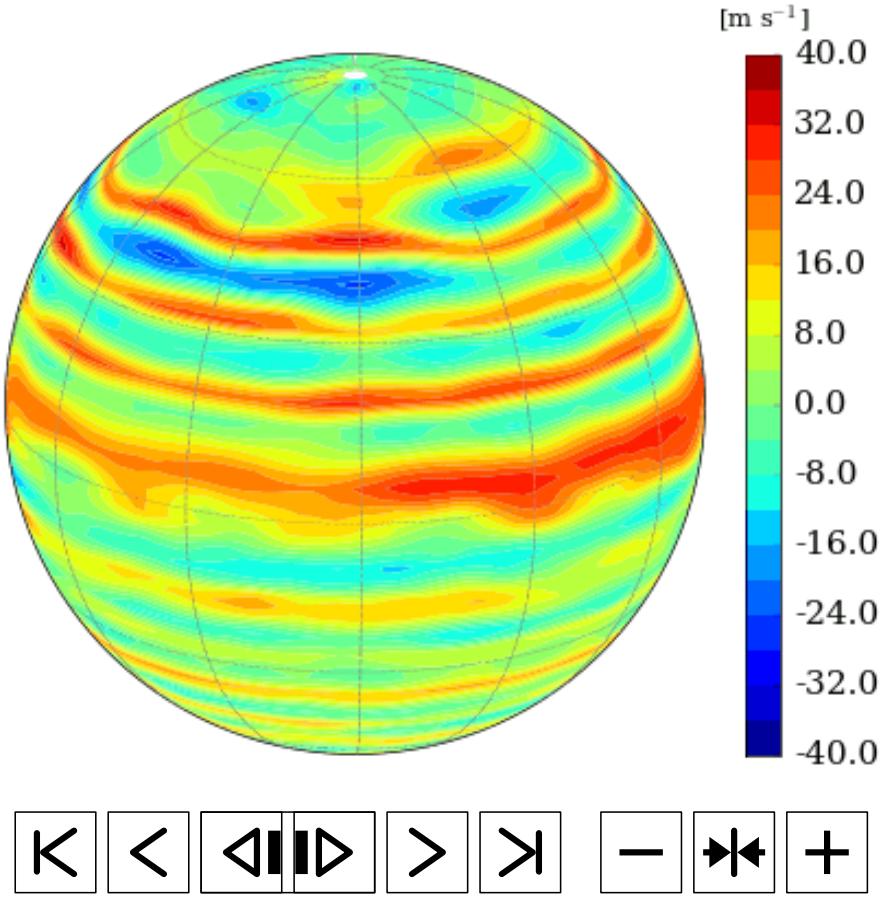


Saturn GCM @ LMD

- ☞ Optimized radiative transfer (Guerlet et al. Icarus 2014)
- ☞ Testing icosahedral dynamical core: massively parallel runs

Preliminary results

- ☞ Chasing Rossby, Kelvin waves
- ☞ Equatorial oscillation?
- ☞ Somewhat-gonal polar jets
- ☞ **Much more to come!**



Email: aymeric.spiga@upmc.fr
Twitter: @aymeric_spiga

A word of caution

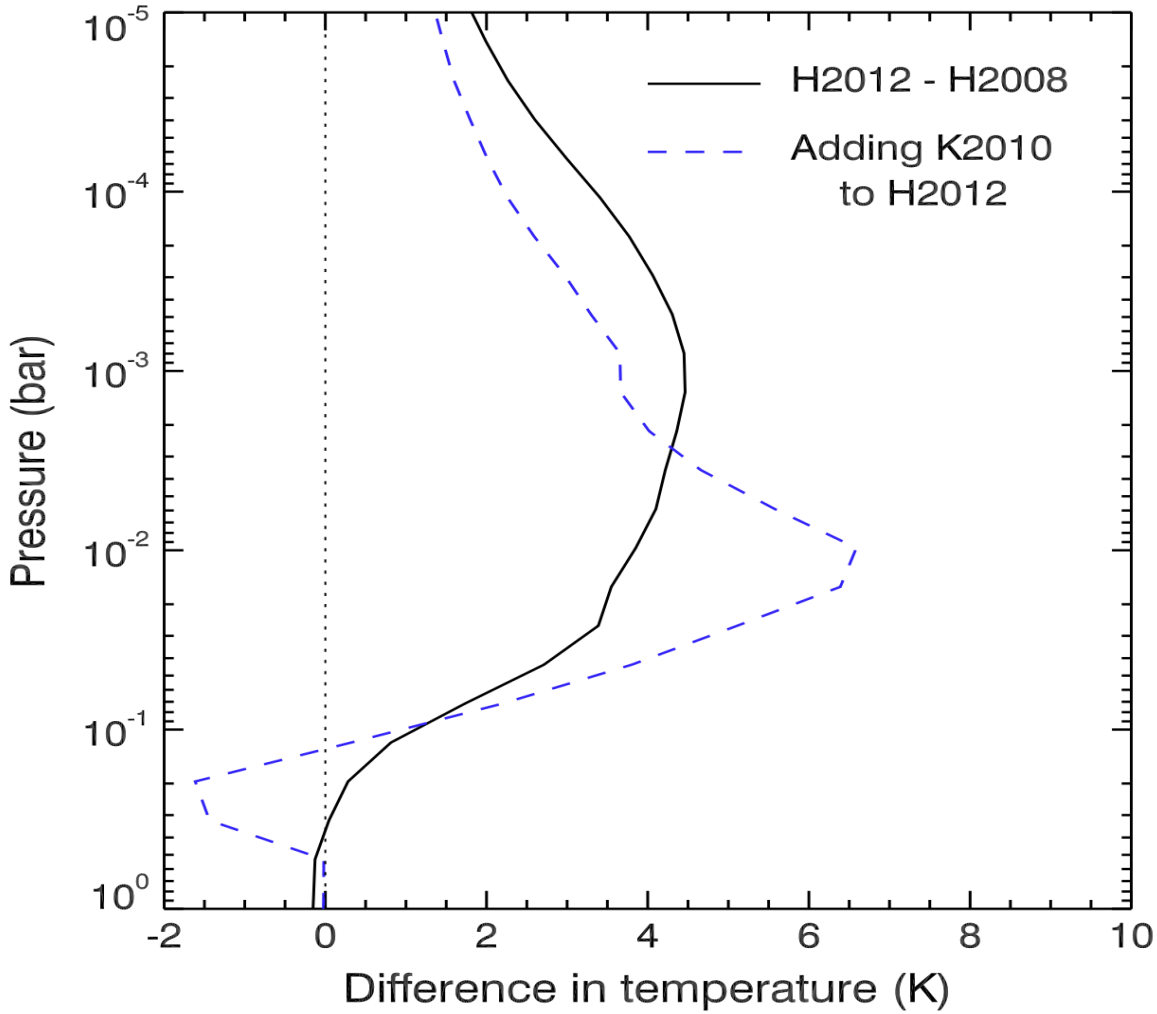
Work in progress: unpublished & open for discussions

We hire!

- ☞ 18mo post-doc (LMD, Paris)
- ☞ Saturn+Jupiter simulations
- ☞ dynamical analysis: instabilities, eddies, ...

Antichambre

Effects of recent radiative transfer improvements

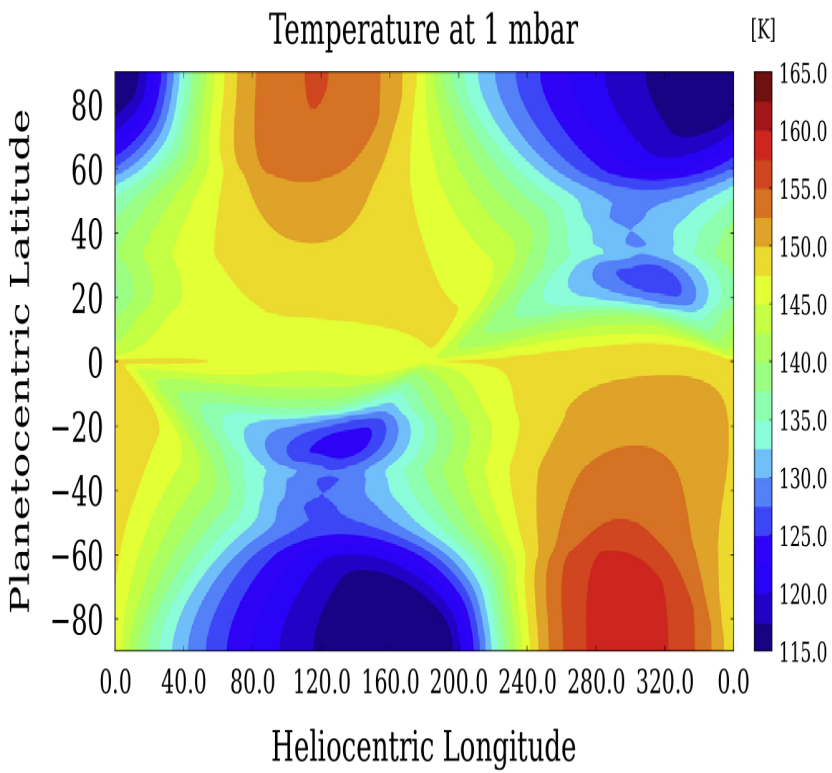


[Guerlet et al. Icarus 2014]

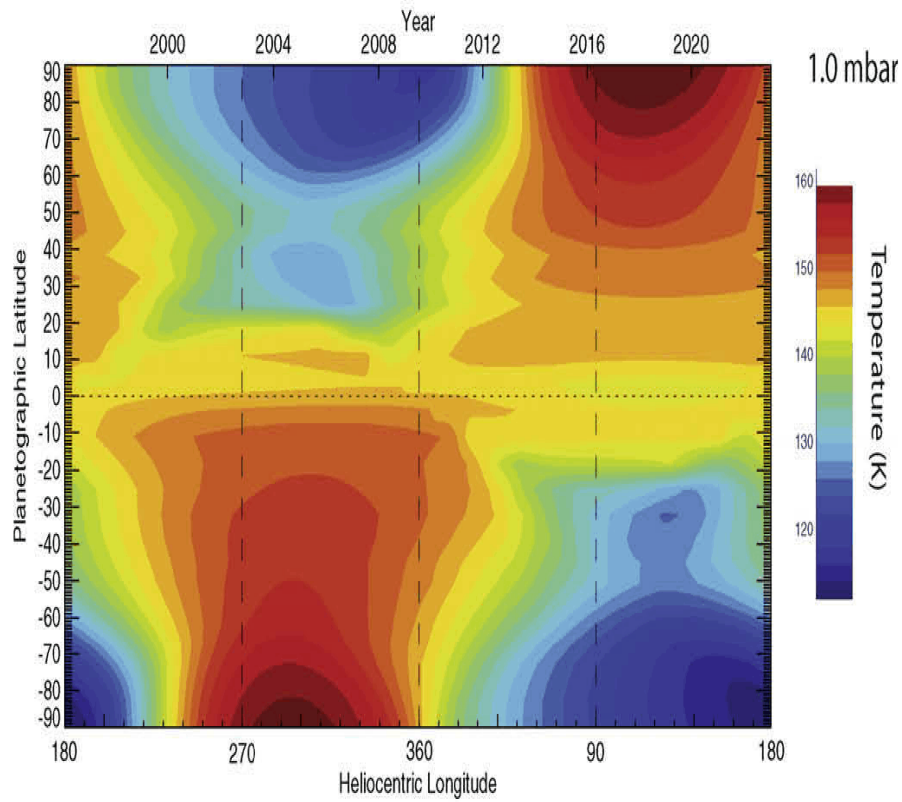
Seasonal variations of 1 mbar temperature

Predicted by radiative-convective models

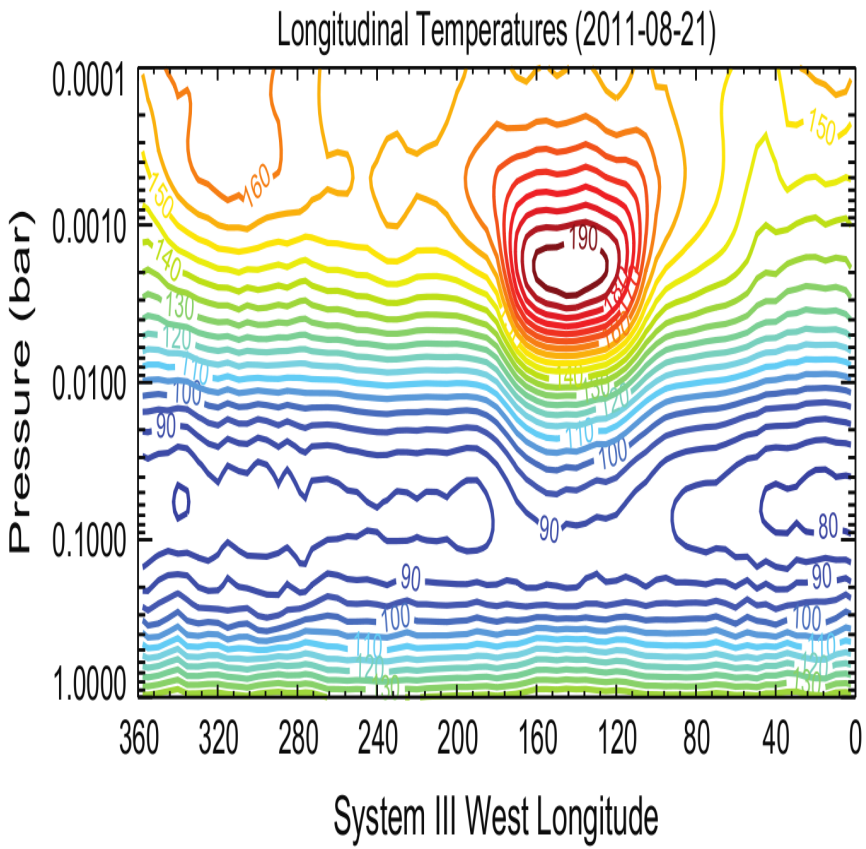
Our model Guerlet et al. 2014



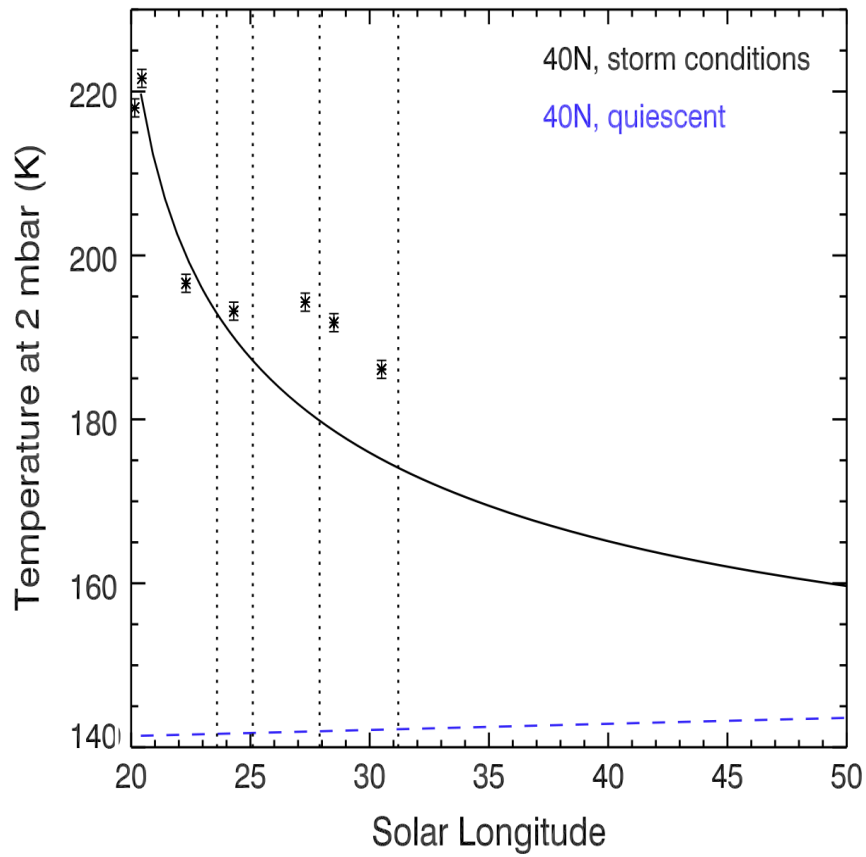
Greathouse model in Fletcher et al. 2010



Cooling the 2010 storm stratospheric warm beacon



[CIRS measurements: Fletcher et al. Icarus 2012]



[Radiative model: Guerlet et al. Icarus 2014]

1/4° temperature trends in the stratosphere.