High-resolution Global Climate Modeling of Saturn's and Jupiter's tropospheric and stratospheric circulations

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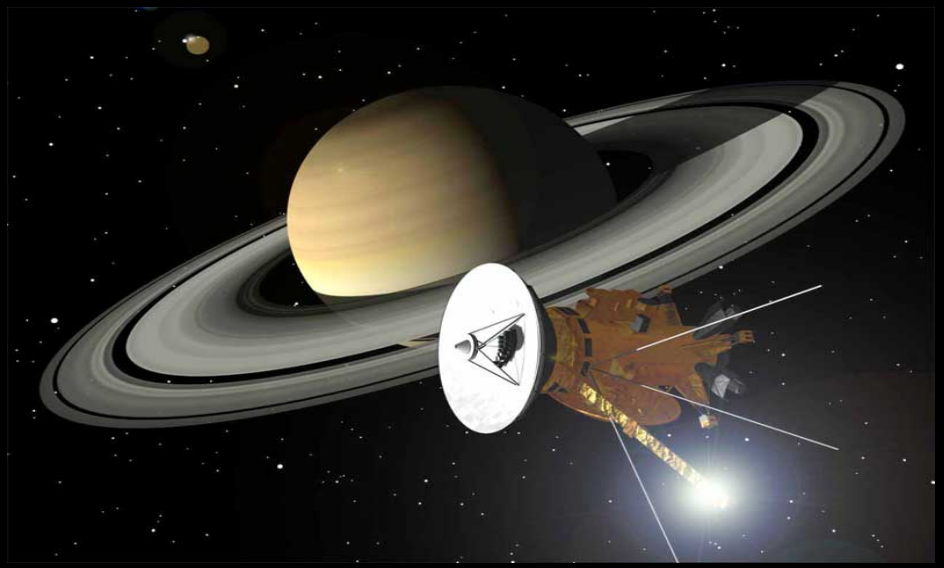
EPSC (Riga) September 20, 2017

Outline

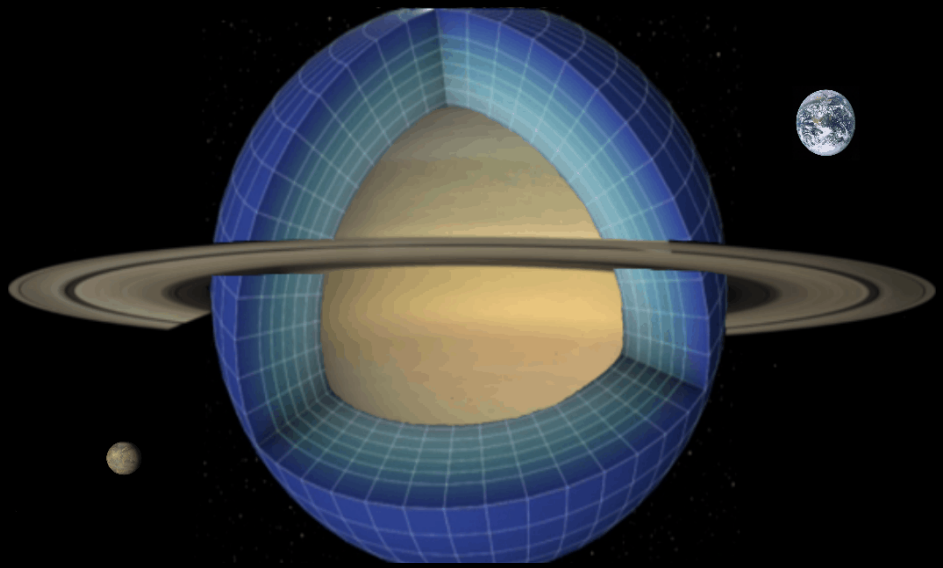
Outline

Exploring Saturn's atmosphere

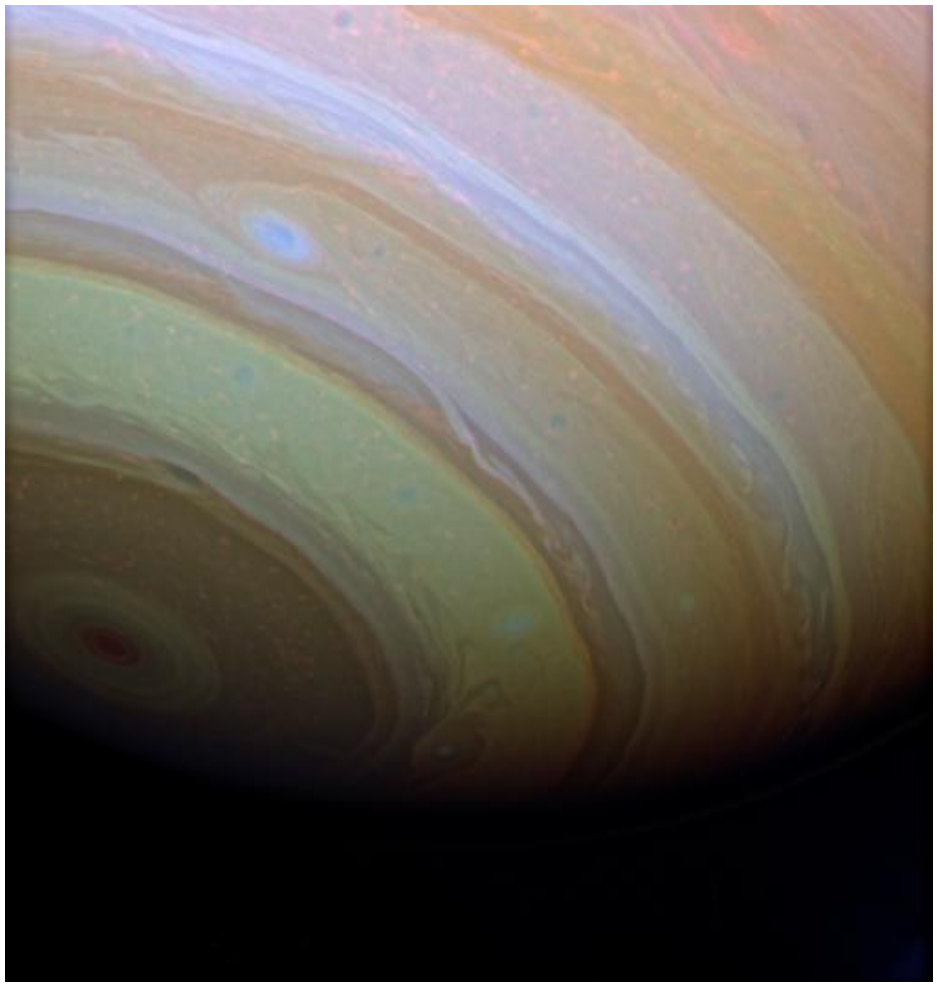
. . . with instruments

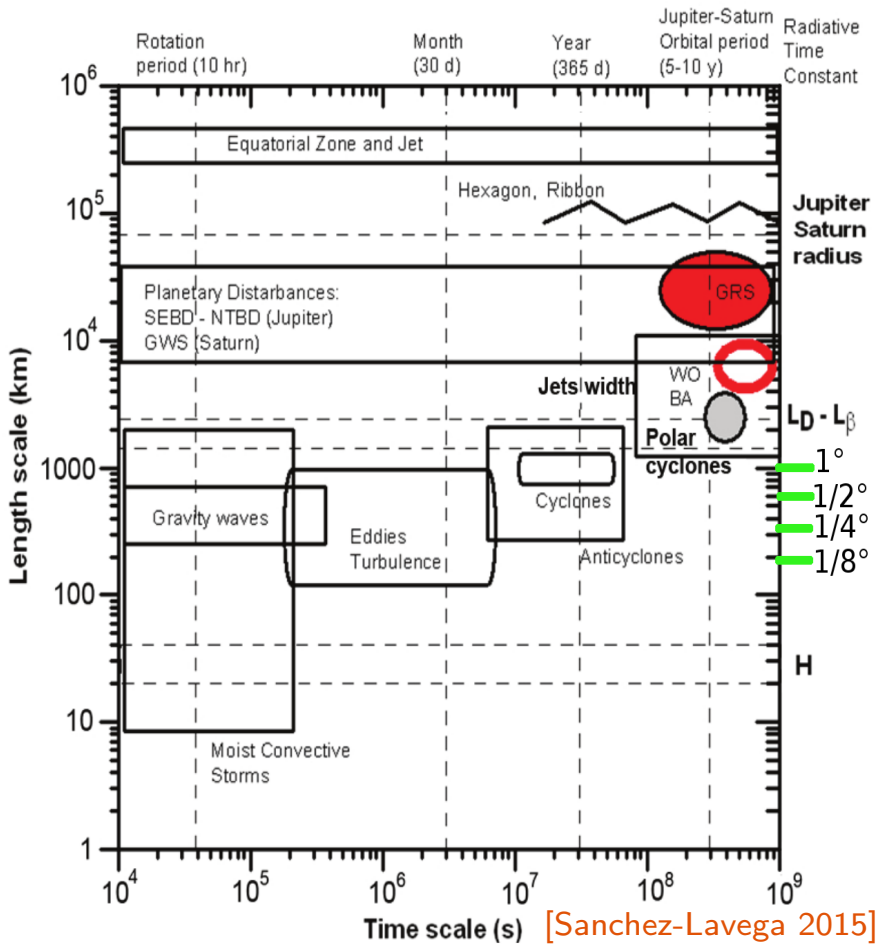


. . . with computers



Scales involved in giant planets



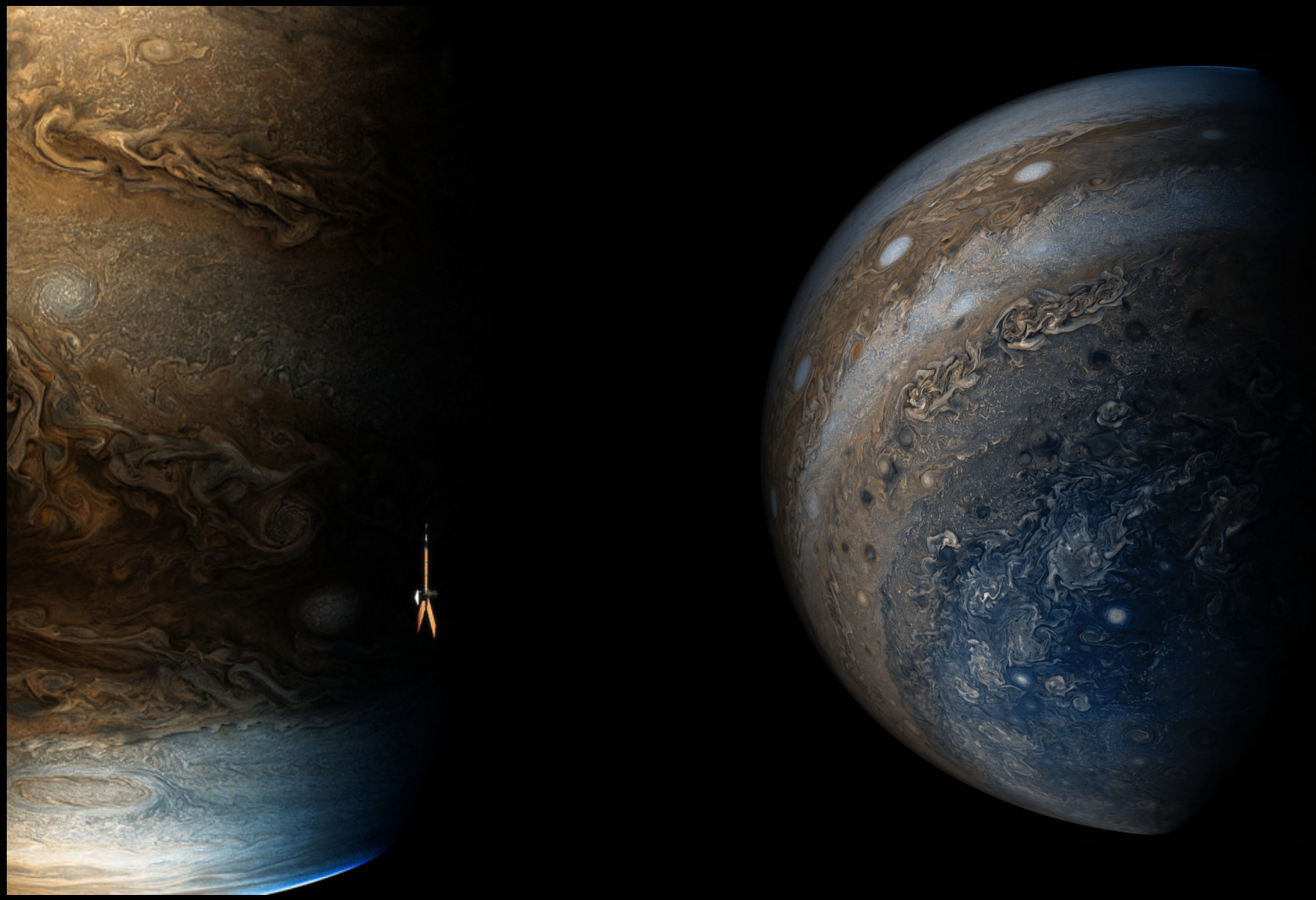


[Sanchez-Lavega 2015]

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

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

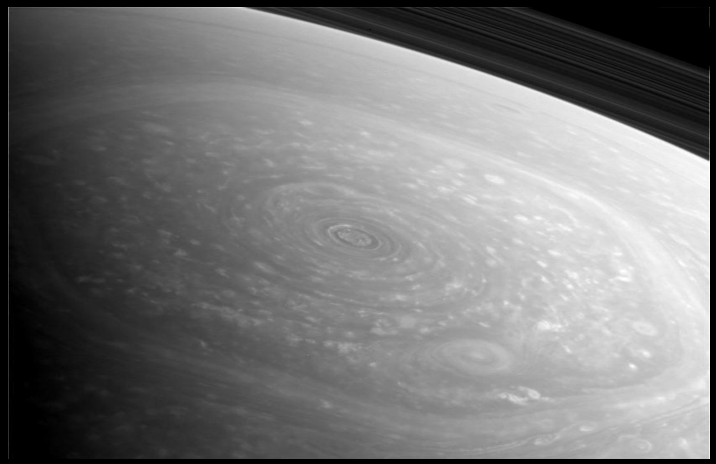
Juno at Jupiter



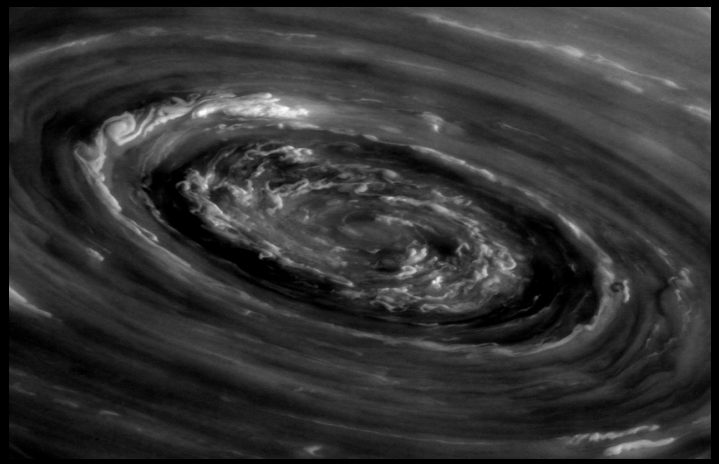
[NASA / SwRI / MSSS / Gerald Eichstädt / Seán Doran, Model by NASA/JPL-Caltech]

Shallow-water simulations of the hexagonal jet

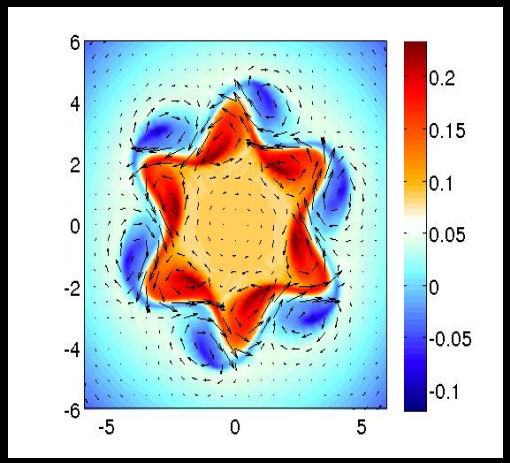
Hexagonal jet



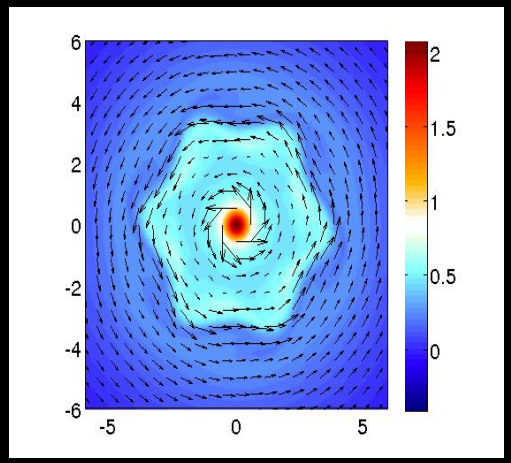
Turbulent vortex at center



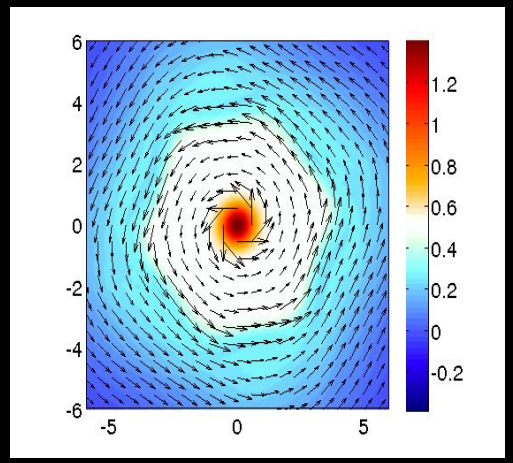
Jet @ 150 f_0^{-1}



Jet+vortex @ 150 f_0^{-1}



Jet+vortex @ 1000 f_0^{-1}



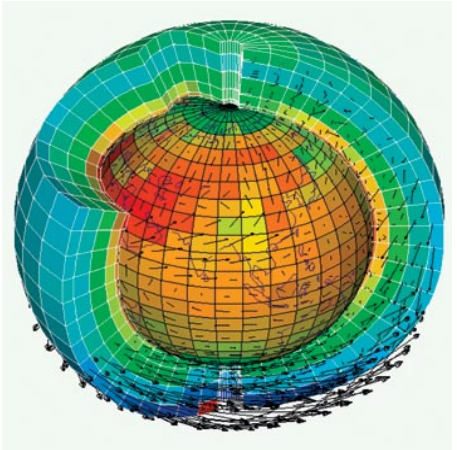
[Rostami et al. submitted to Icarus]

Outline

A new Global Climate Model for Saturn

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

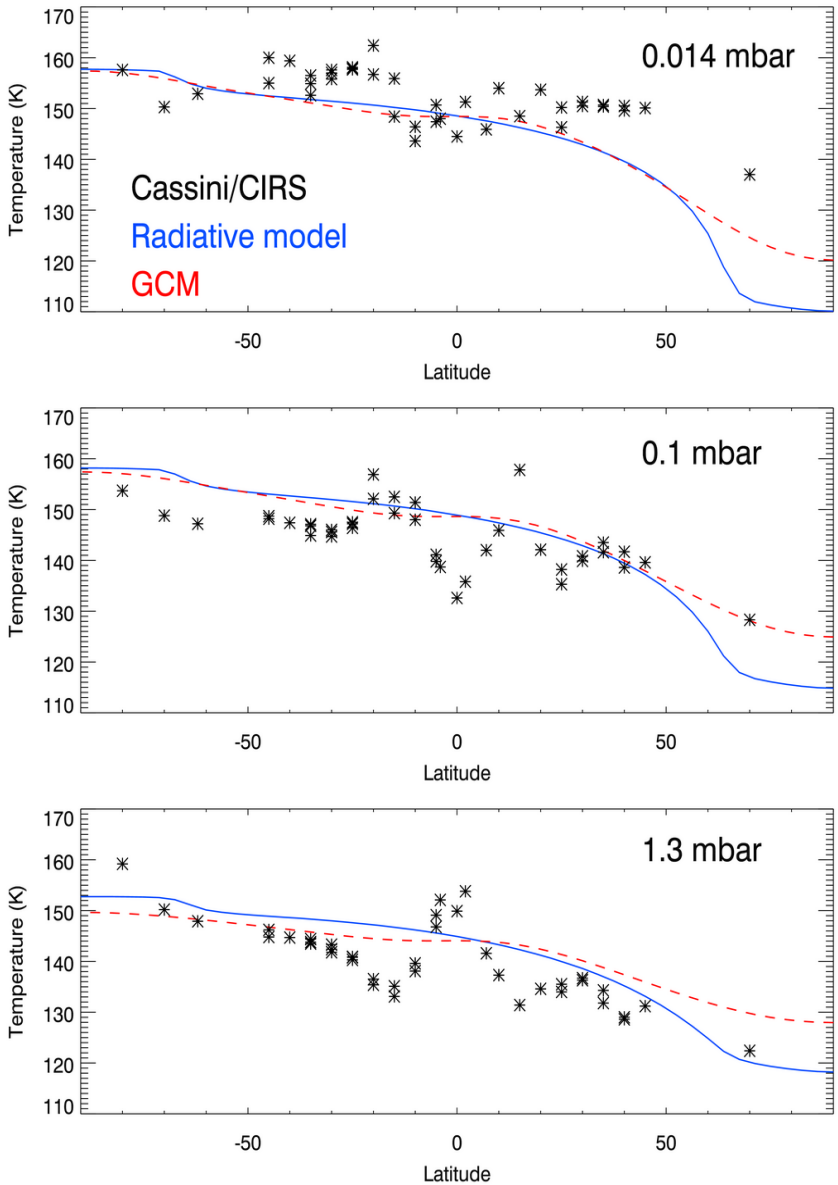
Parallel LMDz solver [Hourdin et al. 2006, 2012]

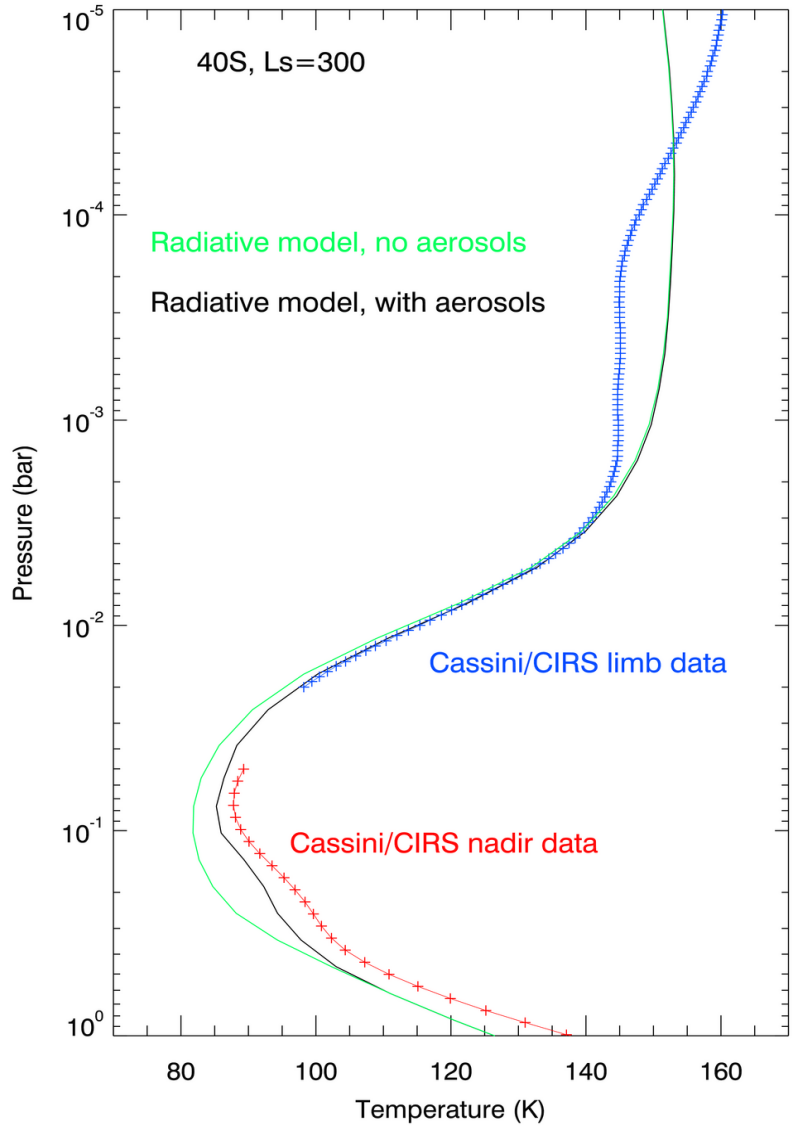


Physical parameterizations ⇒ 1D computations of forcings on each grid point

- ☞ 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
    - stratospheric haze layer $1 - 30$ mbar / $\tau \sim 0.1$ / $r = 0.1\mu$m
  - free bottom surface with internal heat flux
  - incoming flux: ring shadowing, oblateness
- ☞ Turbulent diffusion + dry convective adjustment [Hourdin et al. 1993]

Saturn radiative model vs. CIRS measurements

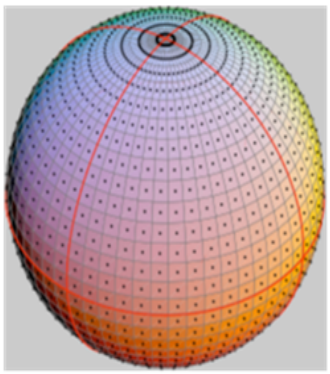


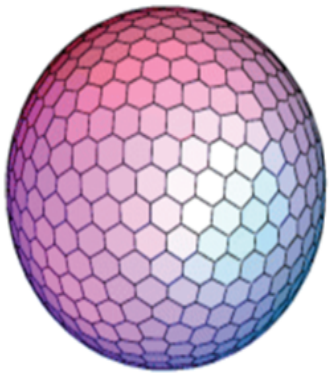


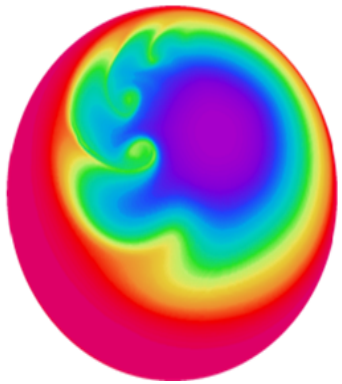
[Guerlet et al. Icarus 2014]

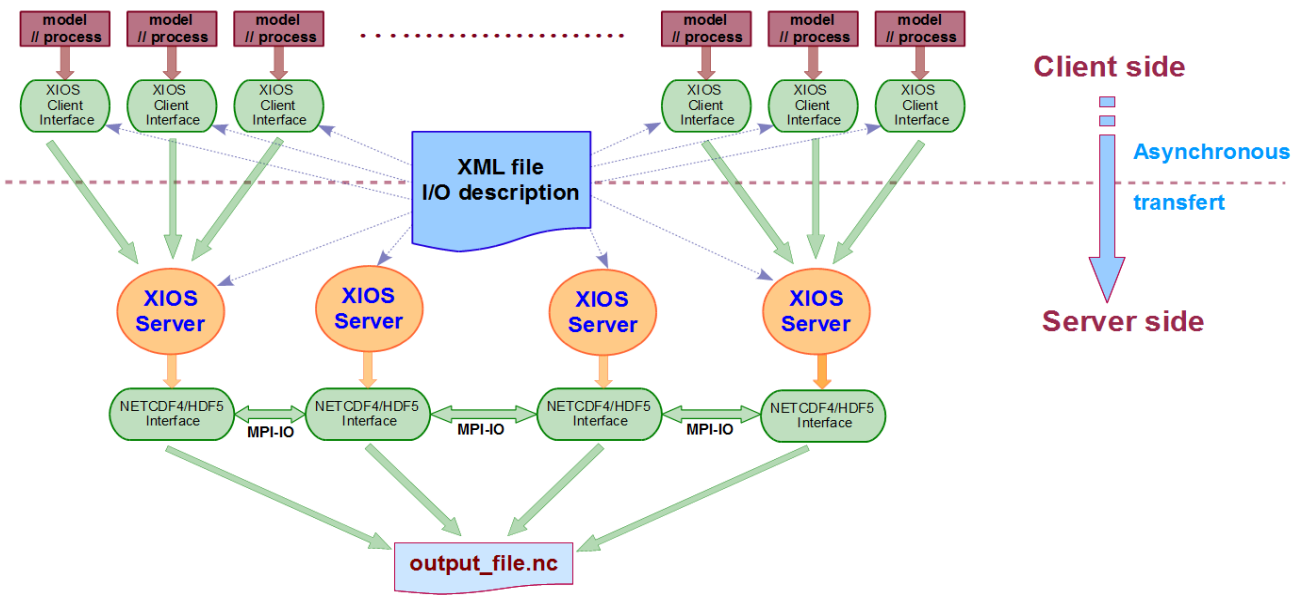
DYNAMICO: new icosahedral dynamical core

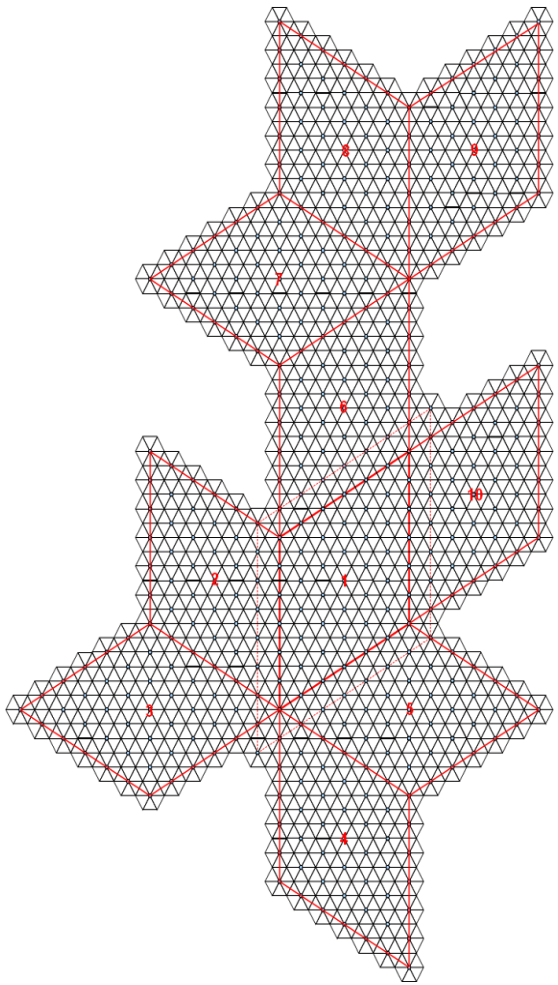
Scientific PI: Thomas Dubos (LMD) ; Technical PI: Yann Meurdesoif (LSCE)











[DYNAMICO reference publication : Dubos et al. Geoscientific Model Development 2015]

Saturn GCM simulations

Grid

- Horizontal resolution: $1/2^\circ$ ($+$ tests $1/4^\circ$ & $1/8^\circ$)
- Vertical levels: 32 levels from 3 bars to 1 mbar (no sponge layer)

Boundary conditions

- Initial: steady-state temperature from 1D run, no winds
- Dissipation (SGS): from 500 (very strong) to 50000 (very weak); reference: 10000
- Bottom drag $|\lambda| > 33^\circ$ / 10° with $\tau = 9$ / 90 / 900 Edays [Liu and Schneider JAS 2010]

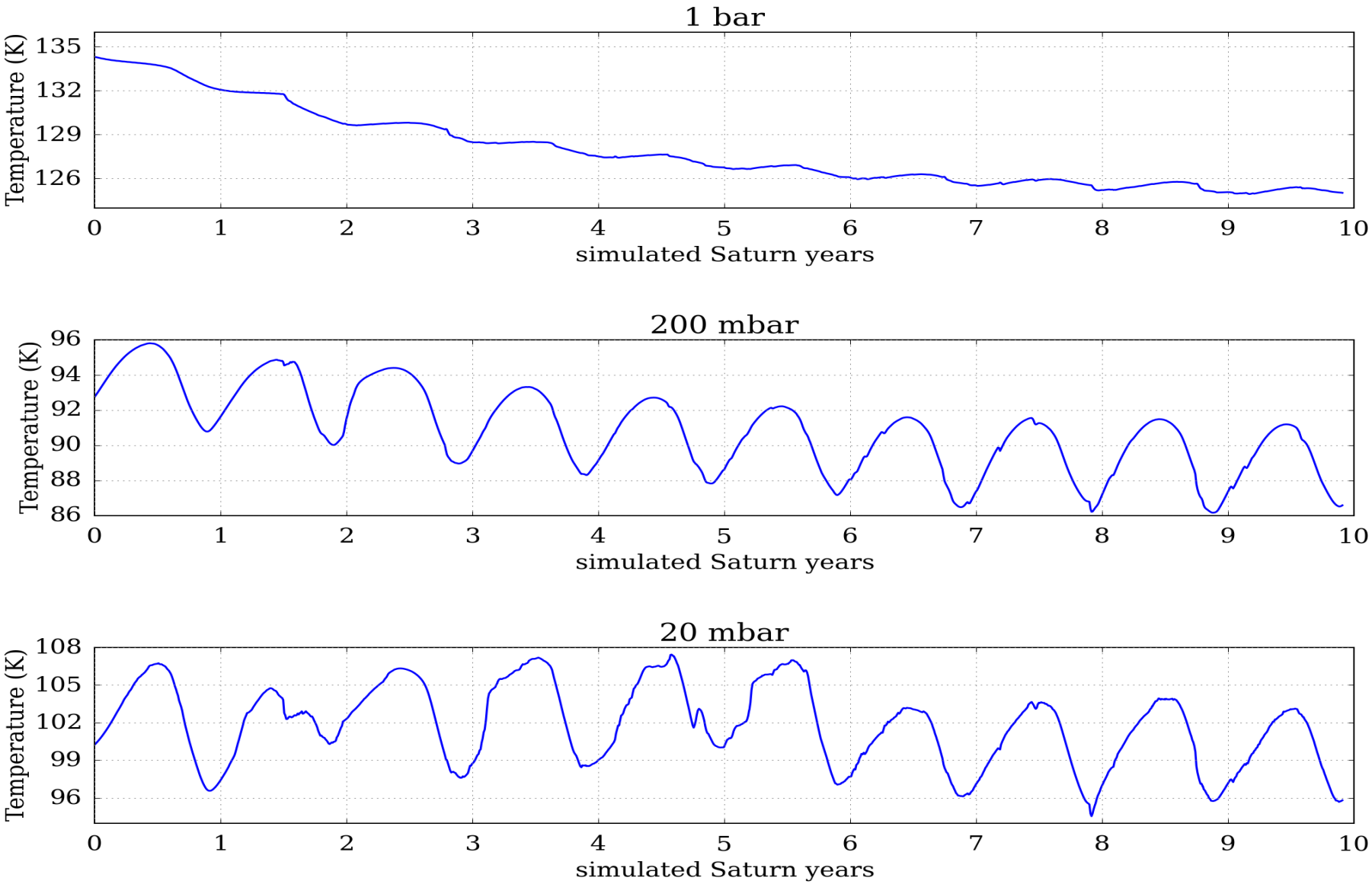
Machinery

- MPI+openMP code run on Occigen cluster in CINES
- cores: 1200 ($1/2^\circ$), 9000 ($1/4^\circ$), 11520-30000 ($1/8^\circ$)

Outline

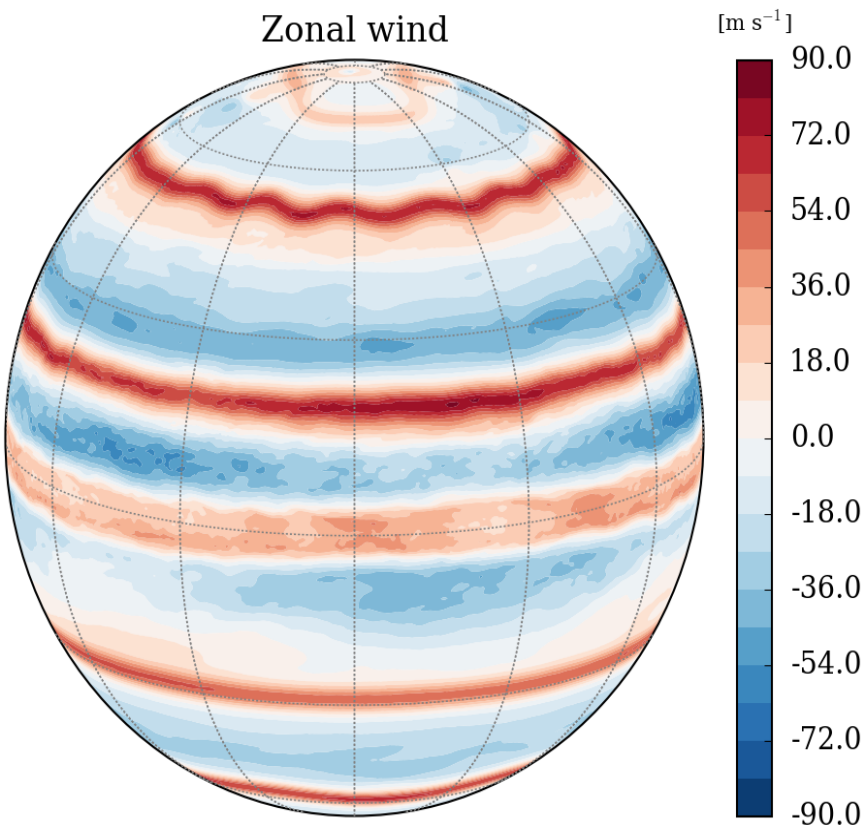
Outline

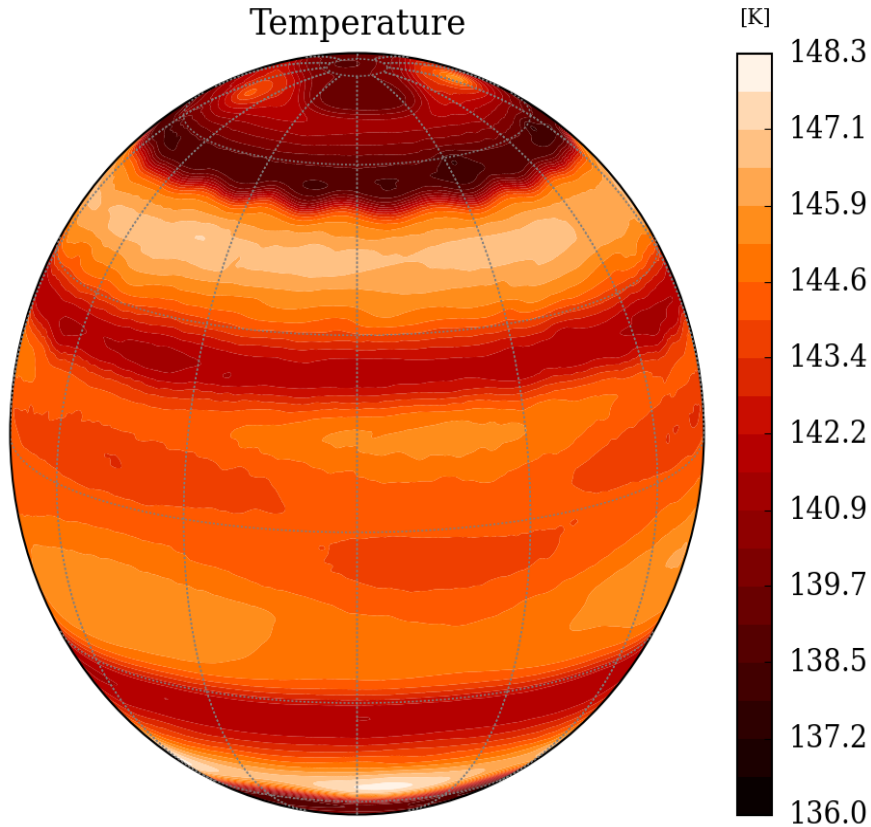
Evolution of zonal-mean temperature (20 – 40°N)



Saturn GCM with 1/2° horizontal resolution

Results at 1.5 bar after 8 simulated Saturn years

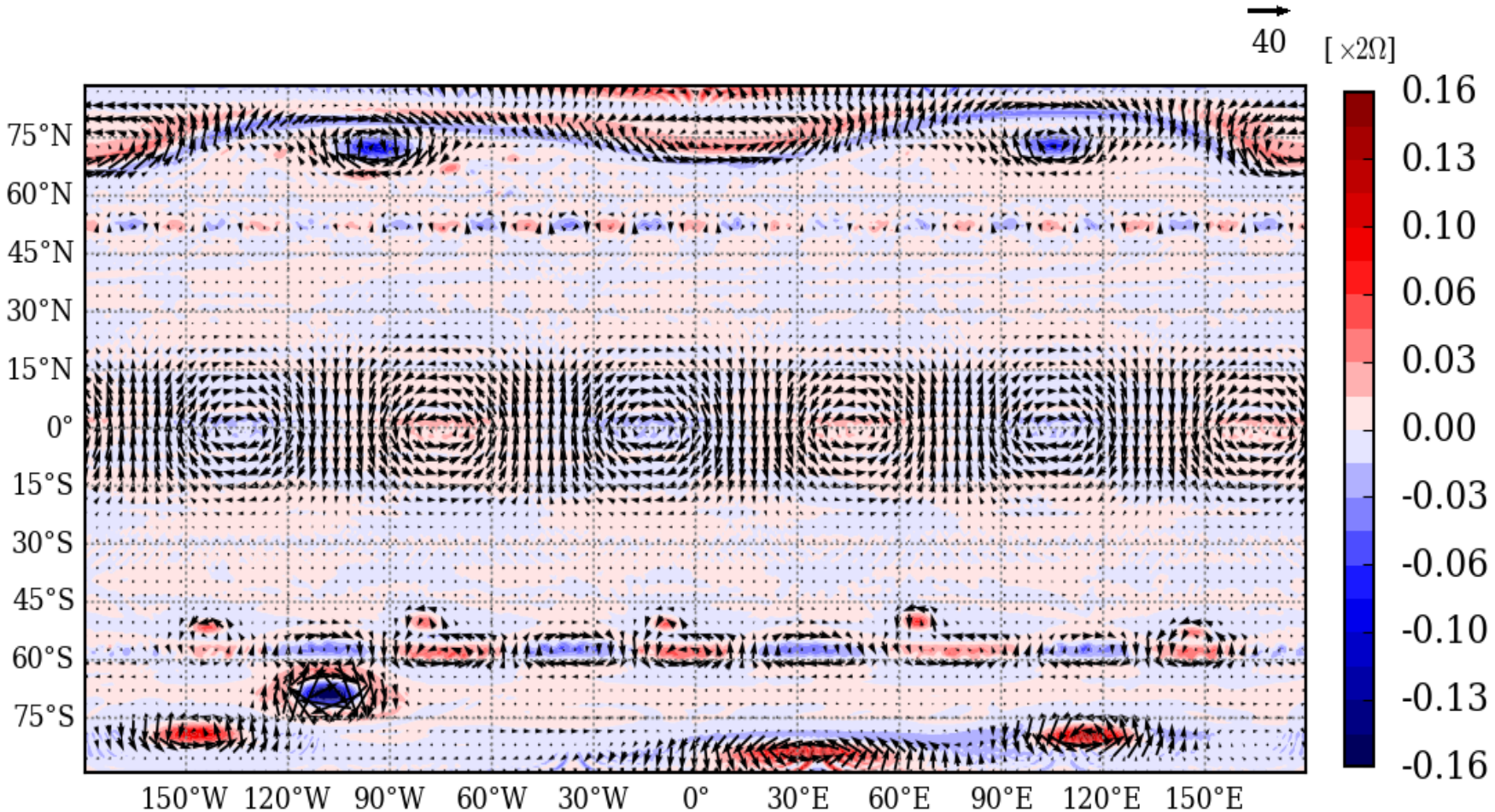




[Spiga et al. in preparation for Icarus]

Vorticity at 1.5 bar after 8 simulated Saturn years

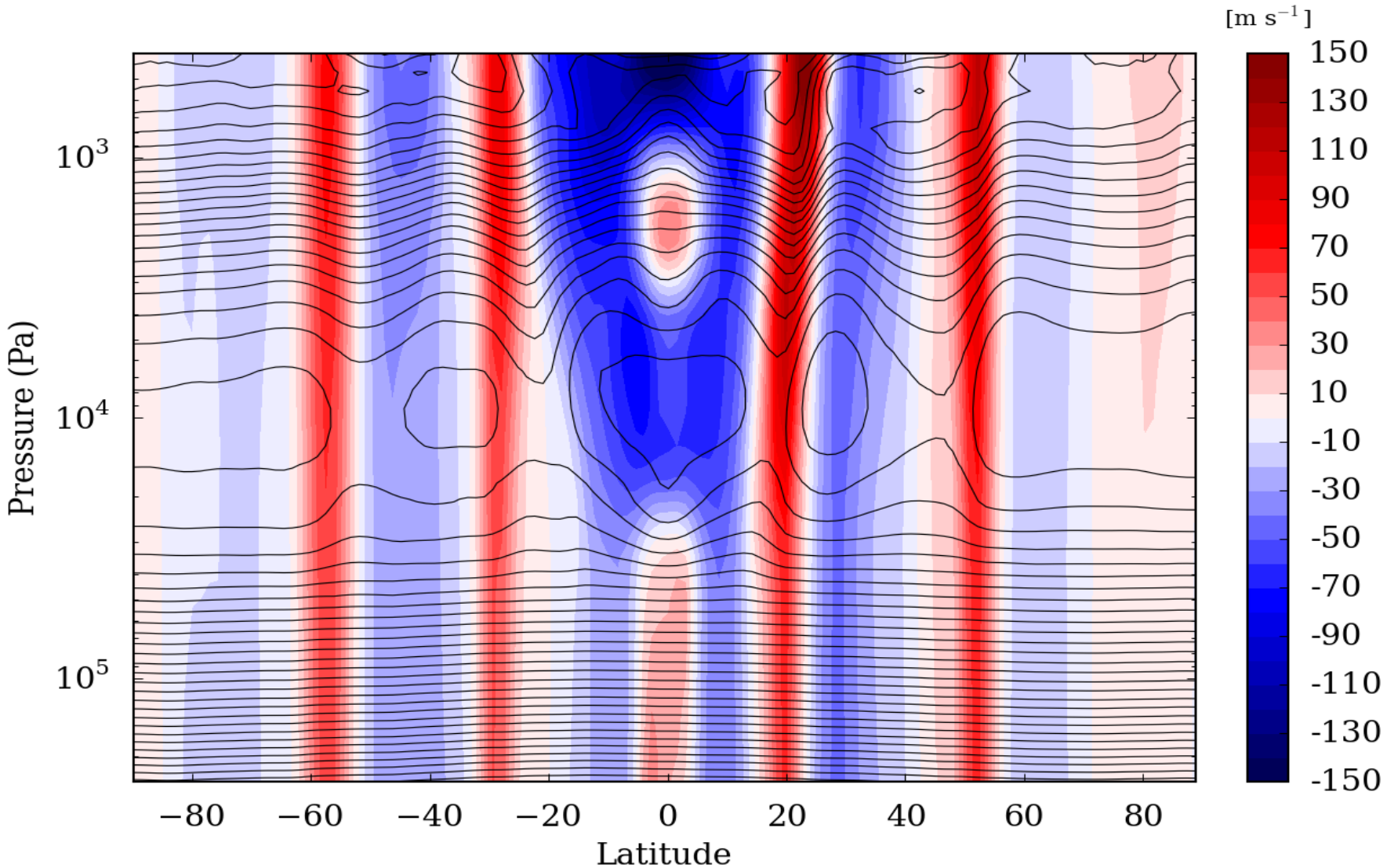
with perturbation winds superimposed



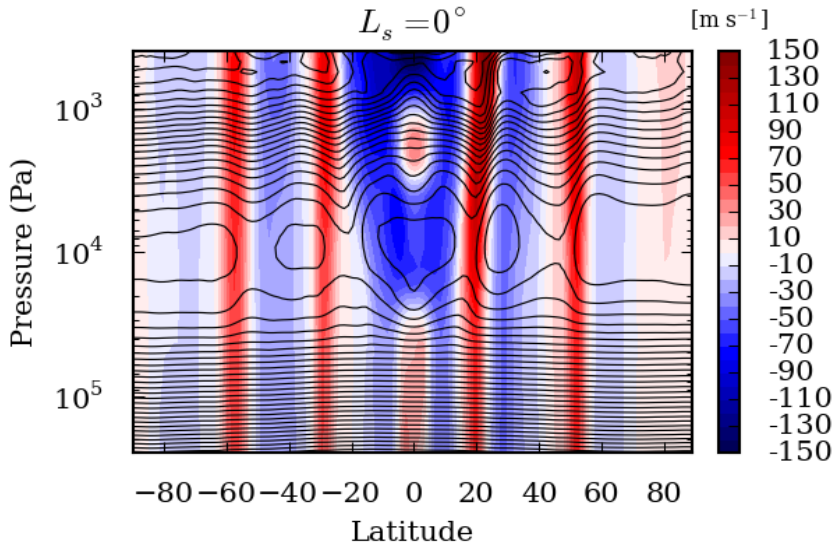
[Spiga et al. in preparation for Icarus]

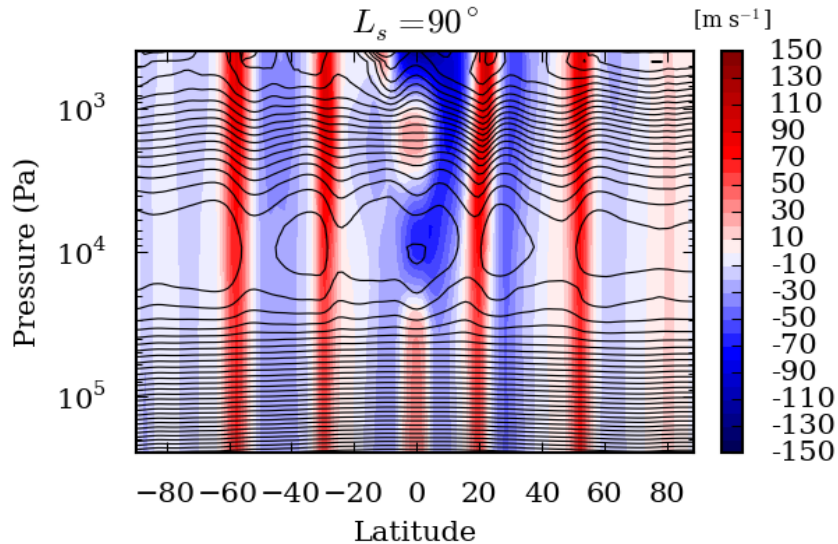
Zonal-mean zonal winds – year 8 ($L_s = 0°$)

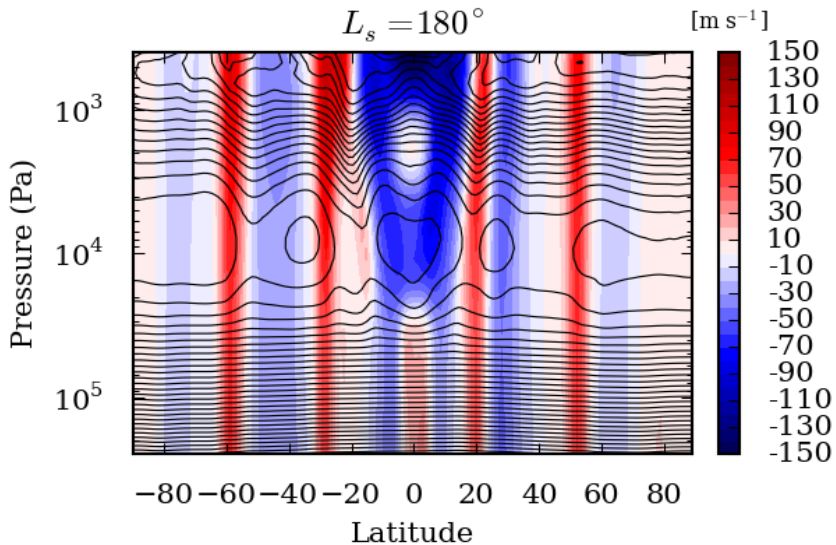
with temperature contours

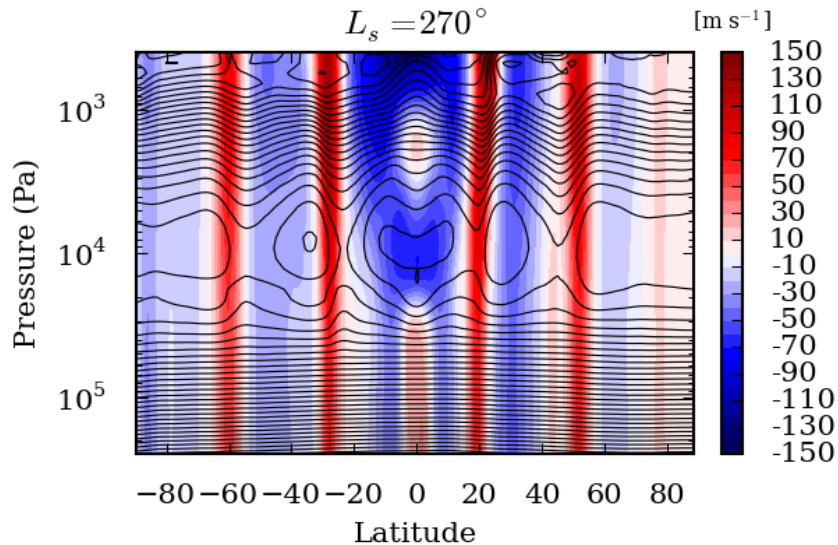


Zonal-mean zonal winds – seasonal evolution







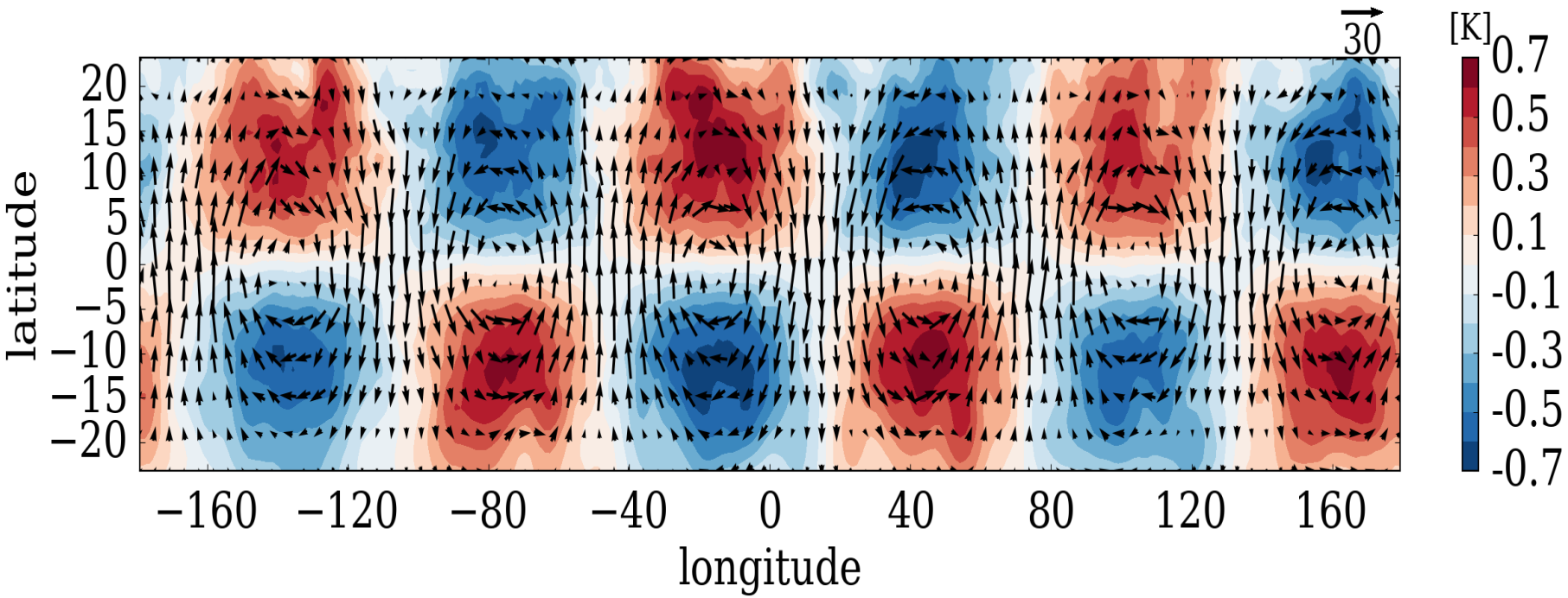


Outline

Equatorial mixed Rossby-Gravity wave

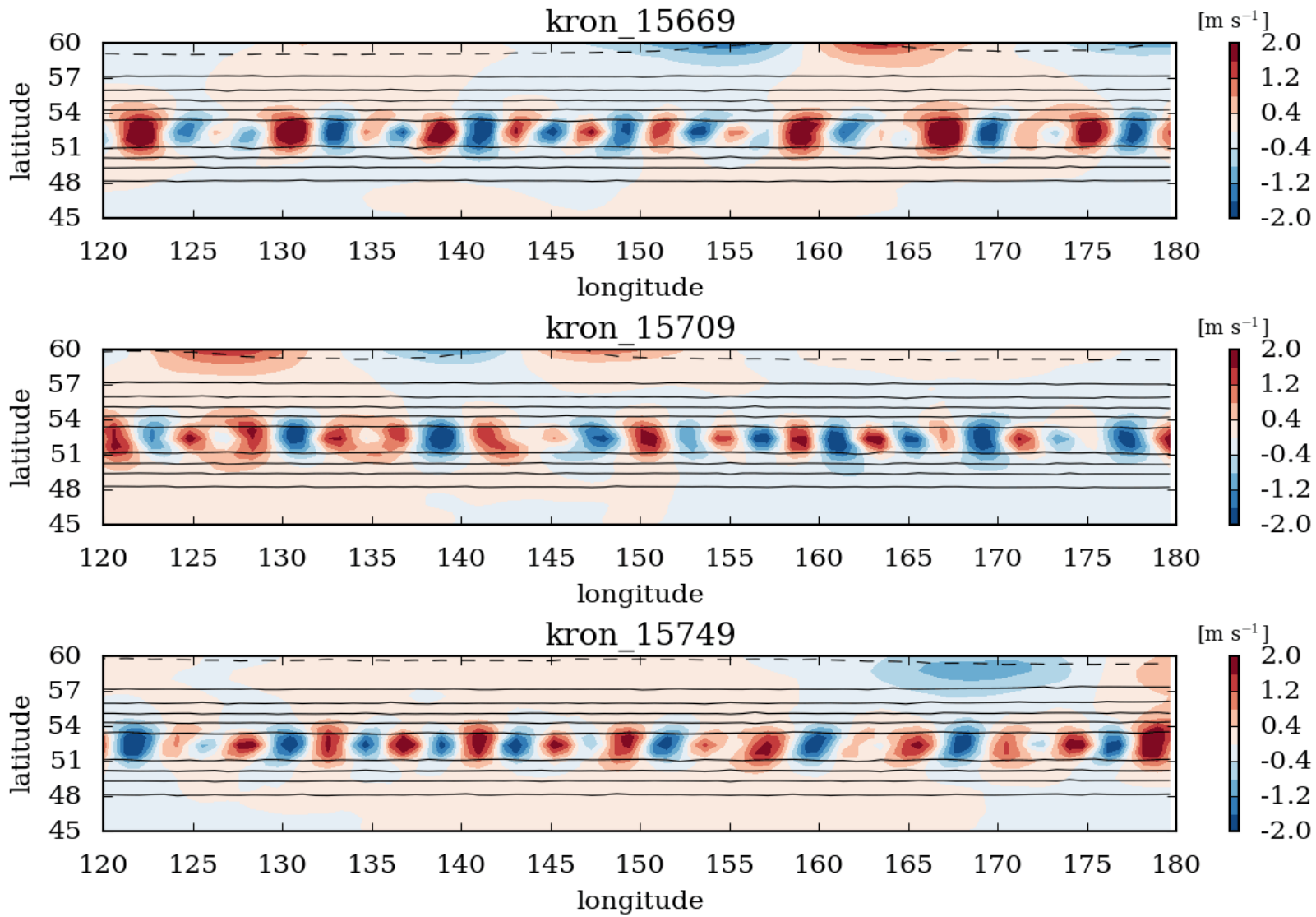
eastward-propagating wavenumber-3, period 230 days

perturbations of T (colours) and u, v (vectors) from zonal mean



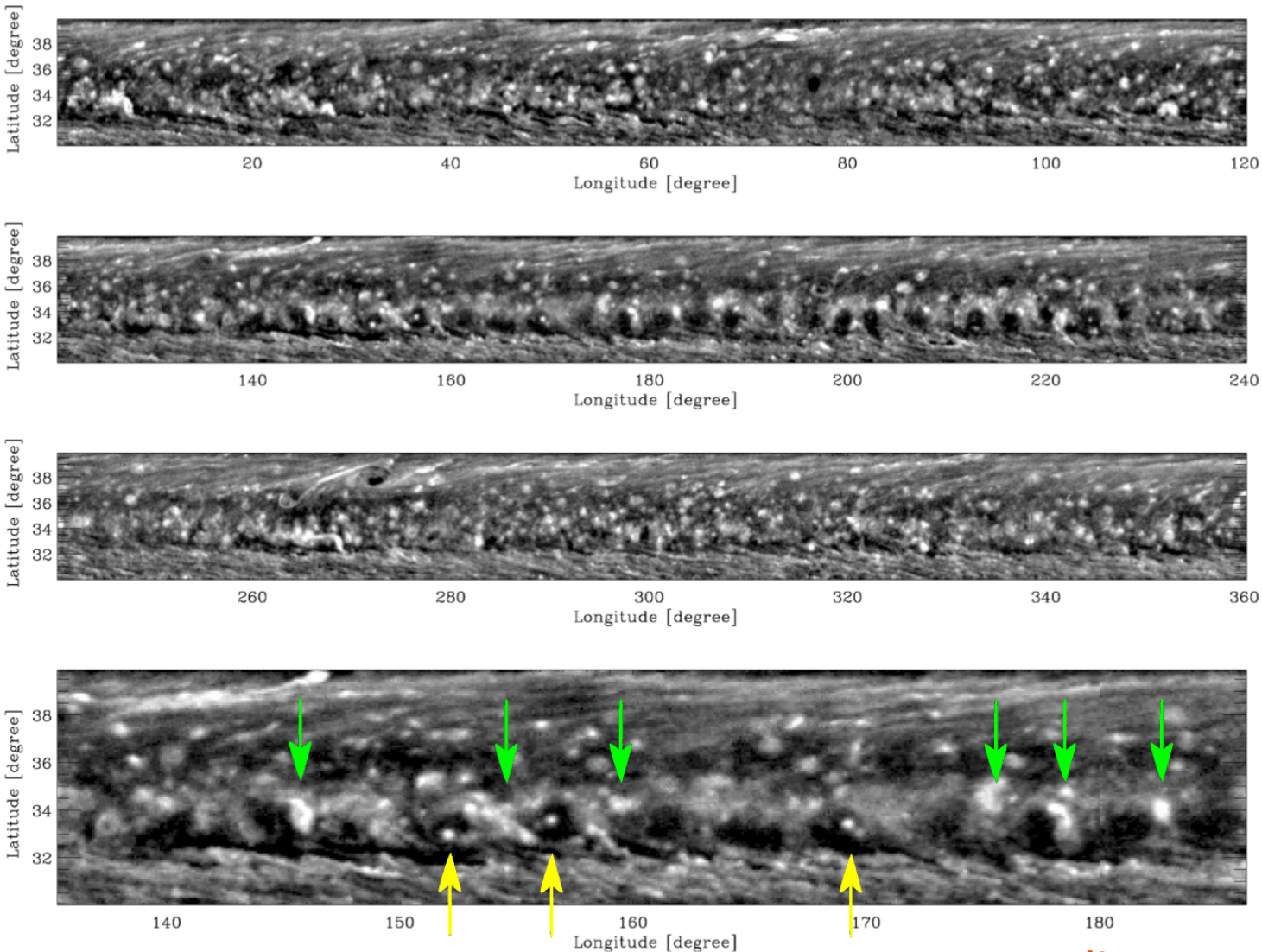
High-wavenumber wave within a midlatitude jet

Meridional wind. Fourier analysis: wavenumber 86, -1.8°/day (period: 200 krons)



Saturn's String of Pearls

IR bright spots, VIS darks spots, -2.26°/day, no merging

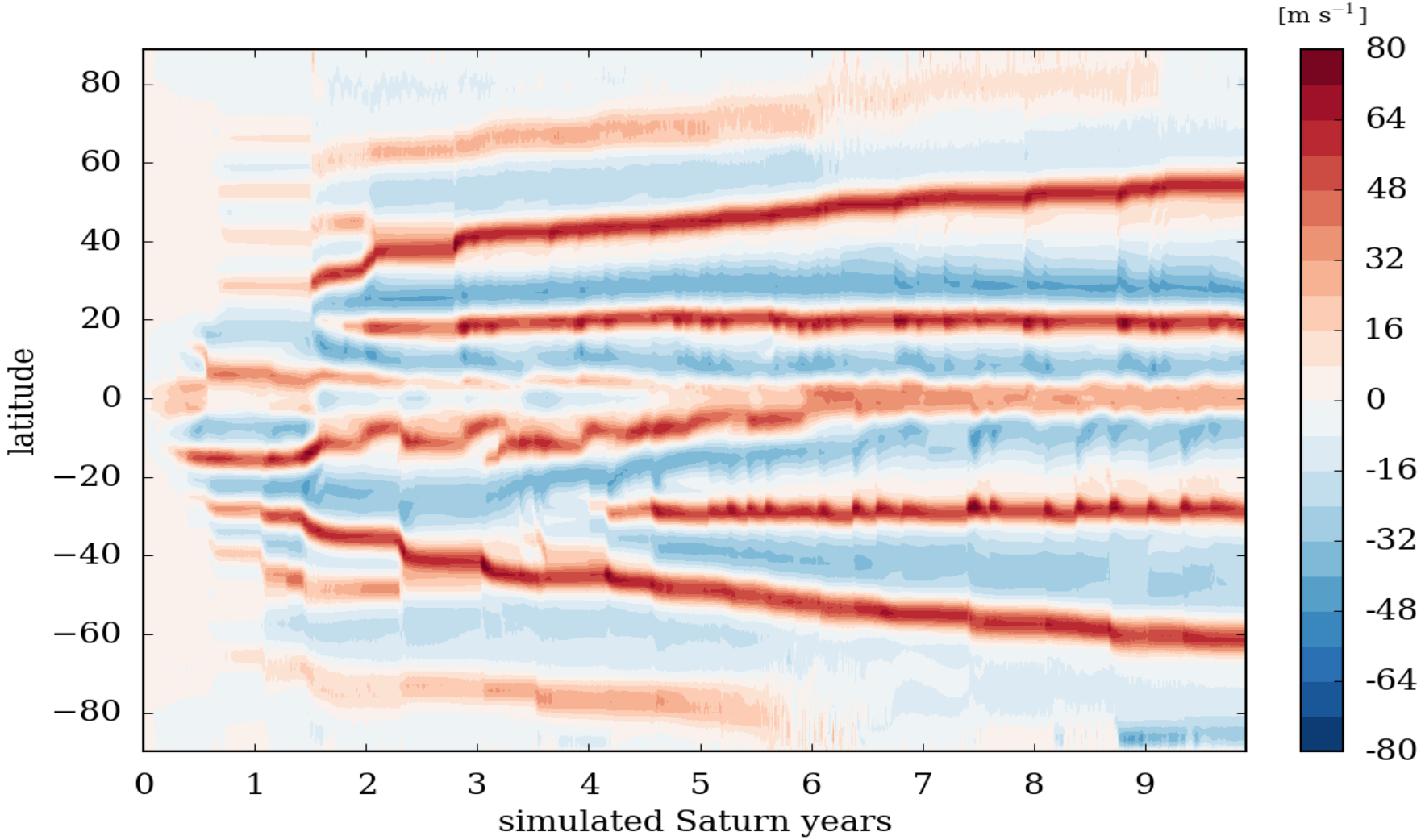


[Sayanagi et al. Icarus 2014]

Outline

Evolution of zonal-mean zonal winds at 1 bar

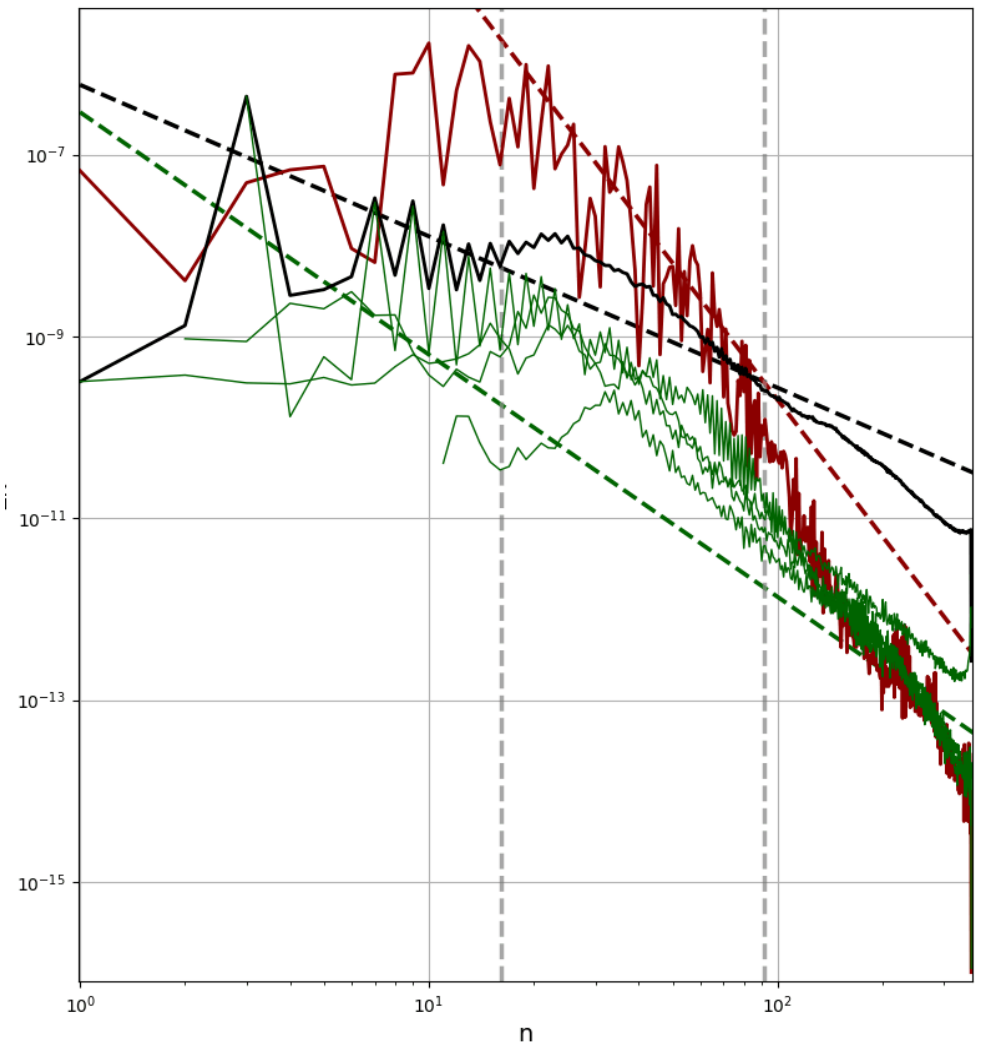
horizontal resolution 1/2°



[Spiga et al. in preparation for Icarus]

Energy spectra on spherical harmonics

from our Saturn GCM 1/2° wind field at 1.5 bars



- zonal energy spectra (m=0); line: $E_z(n) = C_z \beta^2 n^{-5}$
- residual energy spectra (m>1); line: $E_R(n) = C_K \epsilon^{2/3} n^{-5/3}$
- individual modes energy spectra (m)

☞ $E_z(n)$ peaks at Rhines scale n_R

☞ $E_z(n)$ and $E_R(n)$ intersects at n_β

[Vallis & Maltrud 1993, Boer & Shepherd 1983, Galperin et al. 2014, Young & Read 2017]

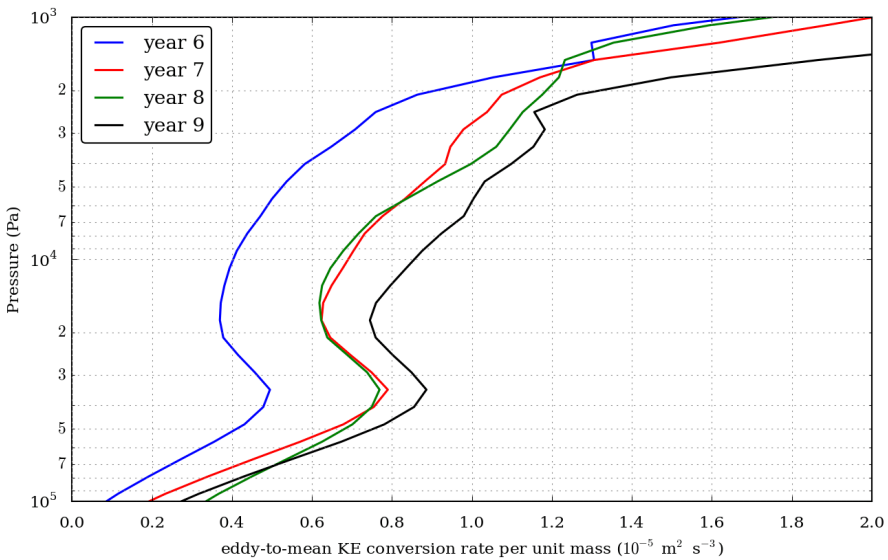
Energy conversion from Eddies to Mean Zonal wind

20 – 60°N, from winter to summer solstice

eddy kinetic energy $\leftrightarrow$ zonal-mean kinetic energy

$$\xi = \underbrace{\overline{u'v'}}_{\text{eddy mom. transp.}} \frac{\partial \overline{u}}{\partial y} \qquad \boxed{> 0 : \quad E \Rightarrow ZM}$$

Cassini: high values: $\xi \sim 1 \times 10^{-5}$ m^2 s^{-3} (or W kg^{-1}) [Del Genio and Barbara 2012]



- $\xi \downarrow z$ in our Saturn GCM
  (as in Liu and Schneider 2010)
- $\xi \uparrow z$ in observations
  ($\xi \sim 4 \times 10^{-5}$ m^2 s^{-3} deeper tropo)
- Missing source of tropospheric eddies: moist convection?

Jet acceleration by eddies e.g. Andrews et al. JAS 1983

ψ function & residual mean circulation $\overline{v}^*$

$$\psi = -\overline{v'T'} \Big/ \left(\frac{R\,\overline{T}}{c_p\,p} - \frac{\partial \overline{T}}{\partial p} \right) \qquad \overline{v}^* = \overline{v} - \frac{\partial \psi}{\partial p}$$

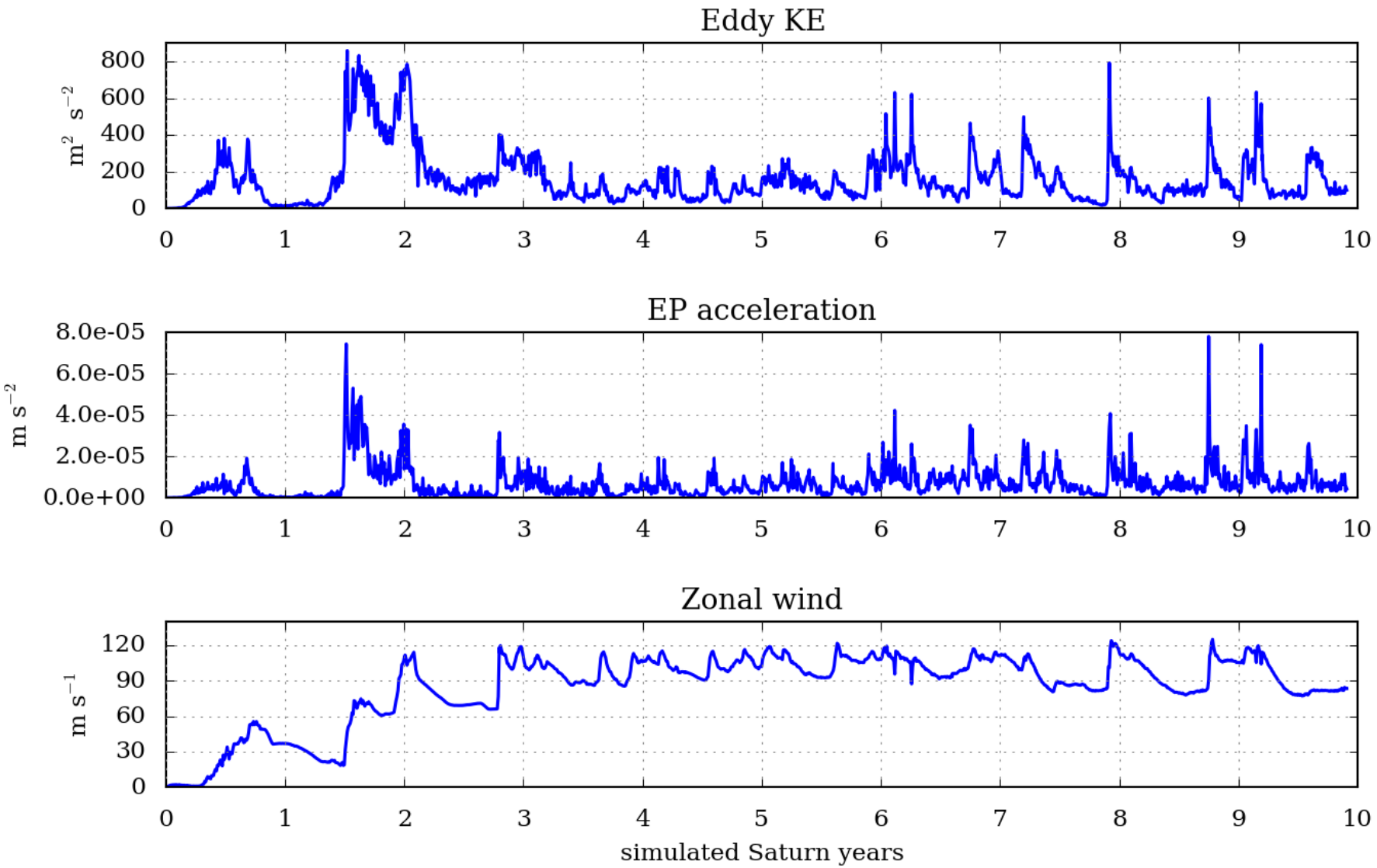
Eliassen-Palm Flux (zonal acceleration = divergence of F_φ)

$$F_\varphi = a\,\cos\varphi \left(-\overline{u'v'} + \psi \frac{\partial \overline{u}}{\partial p} \right)$$

Acceleration term by divergence of EP flux

$$\frac{\partial \overline{u}}{\partial t} = \frac{1}{a^2\,\cos^2\varphi} \frac{\partial F_\varphi\,\cos\varphi}{\partial \varphi}$$

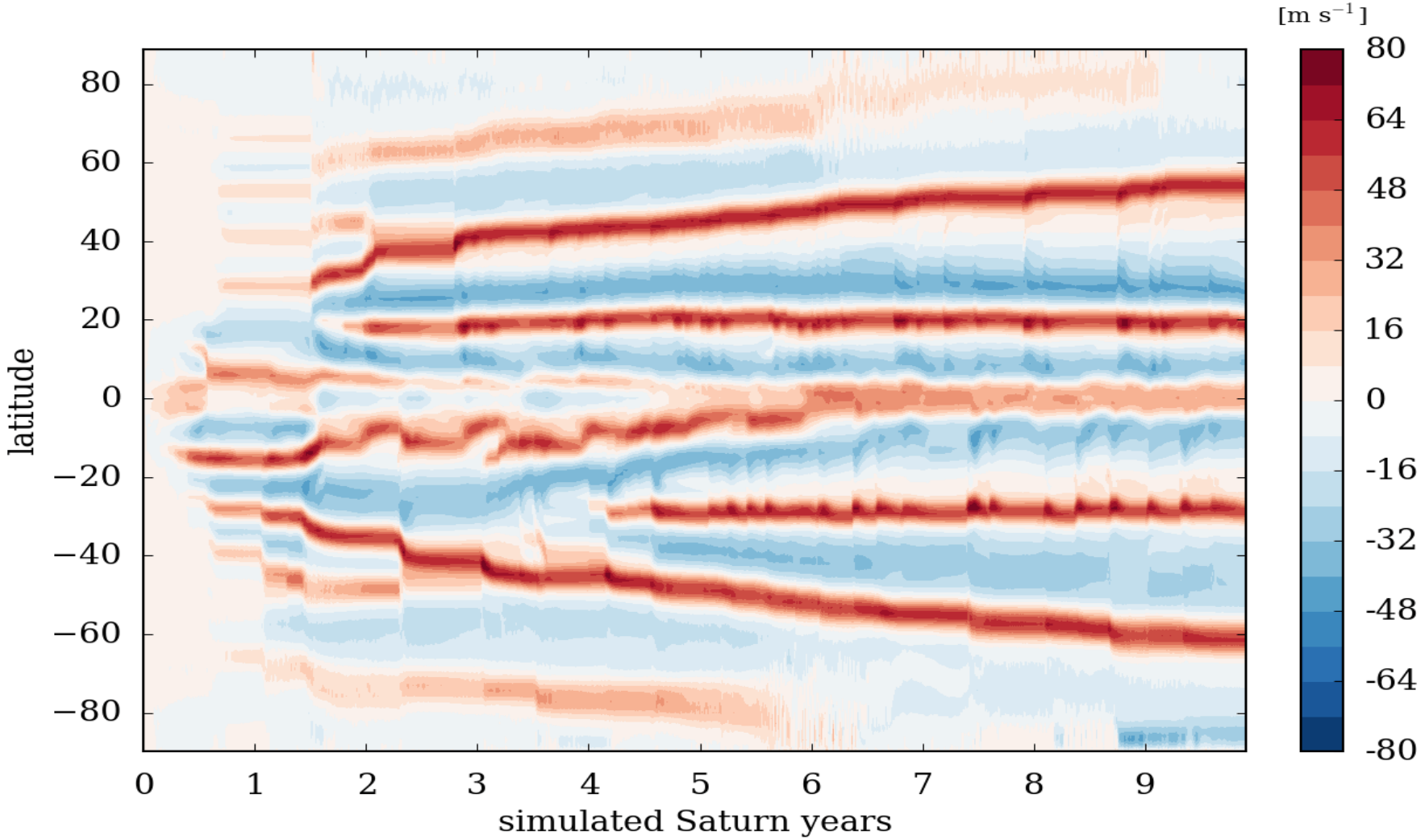
Evolution of barotropic zonal-mean jets (max $30-60^{\circ}$N)



[Spiga et al. in preparation for Icarus]

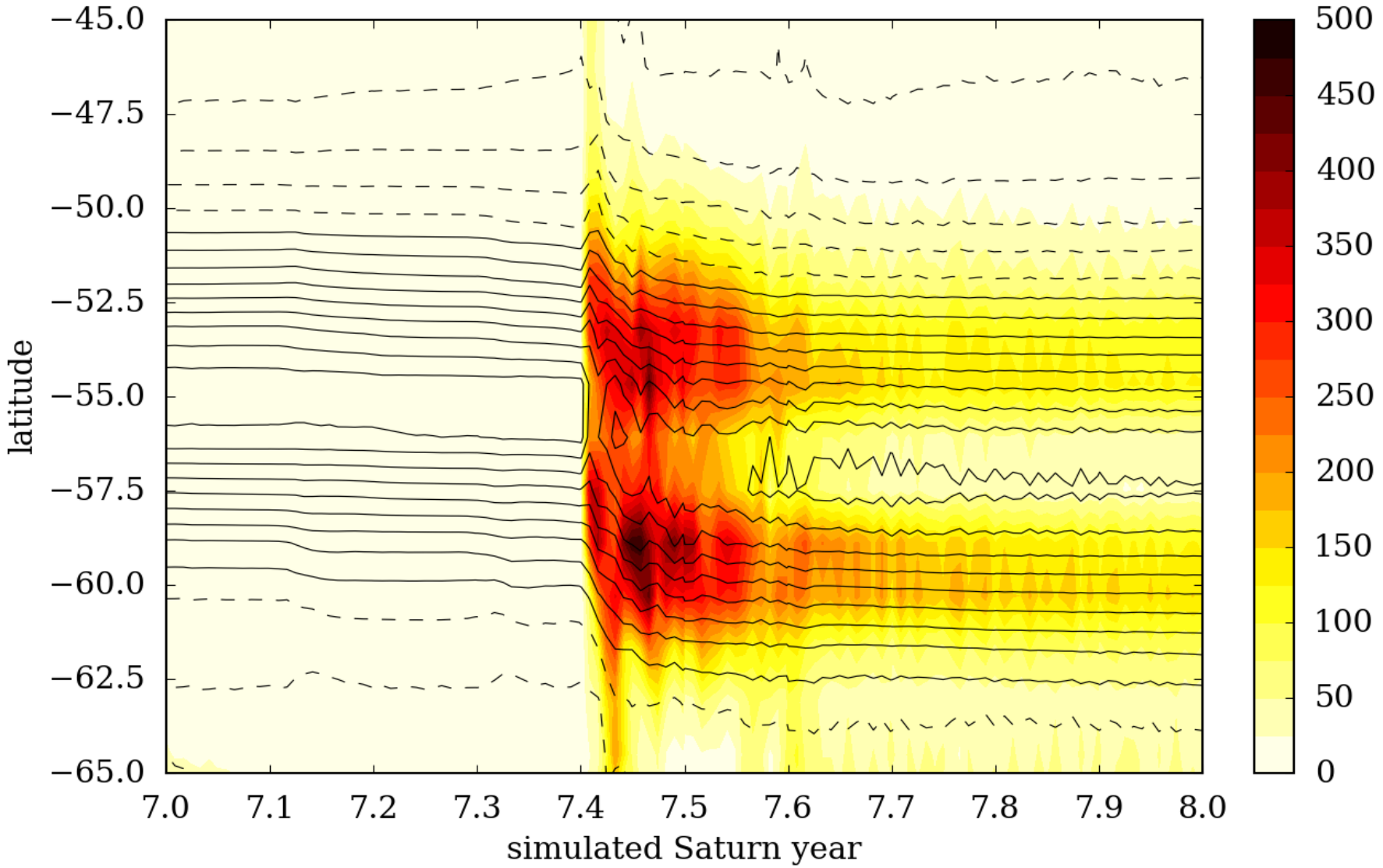
Evolution of zonal-mean zonal winds at 1 bar

horizontal resolution 1/2°

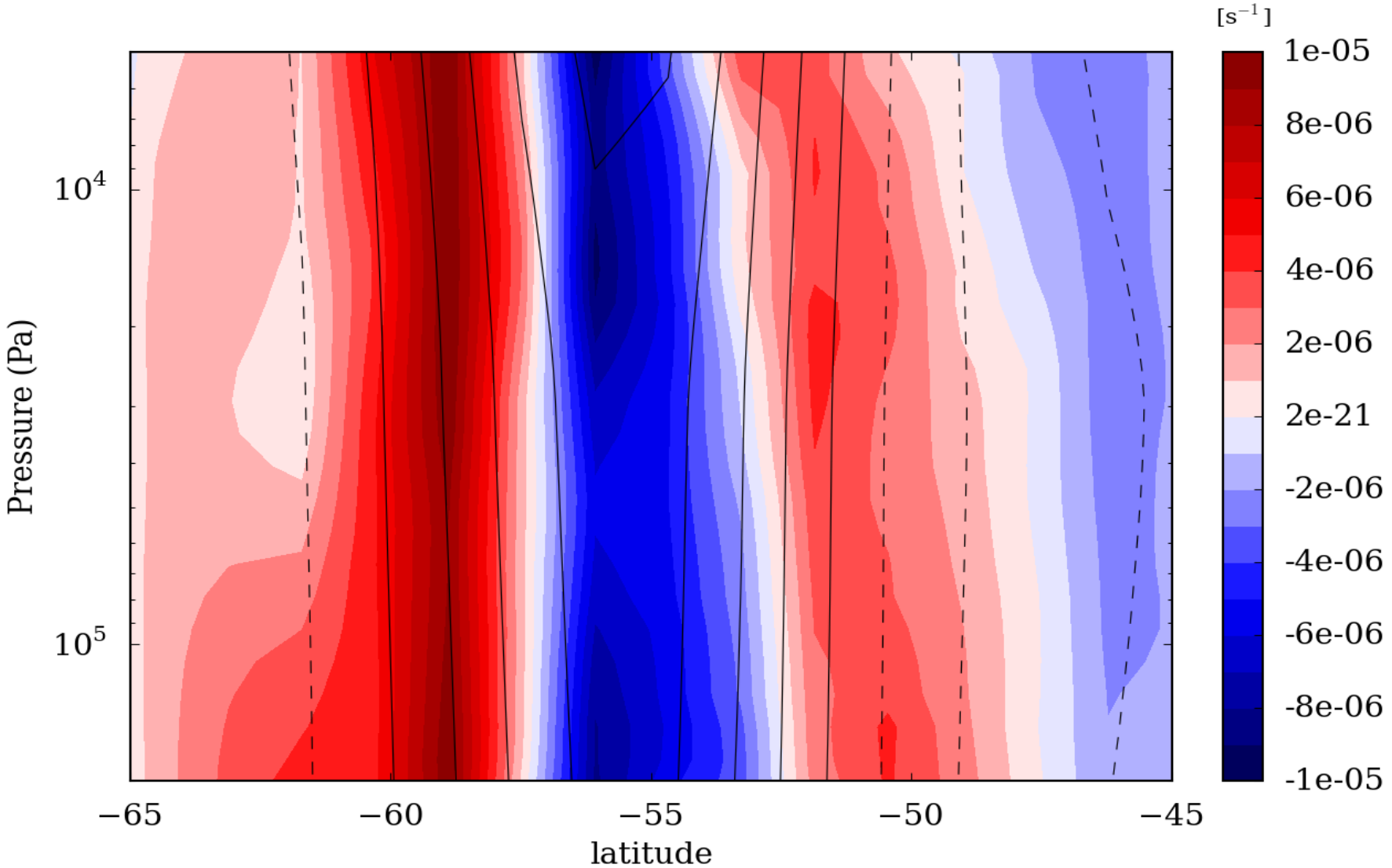


[Spiga et al. in preparation for Icarus]

Zonal jet and Eddy Kinetic Energy $\frac{1}{2}\left(u'^2 + v'^2\right)$



Zonal jet and divergence of EP flux

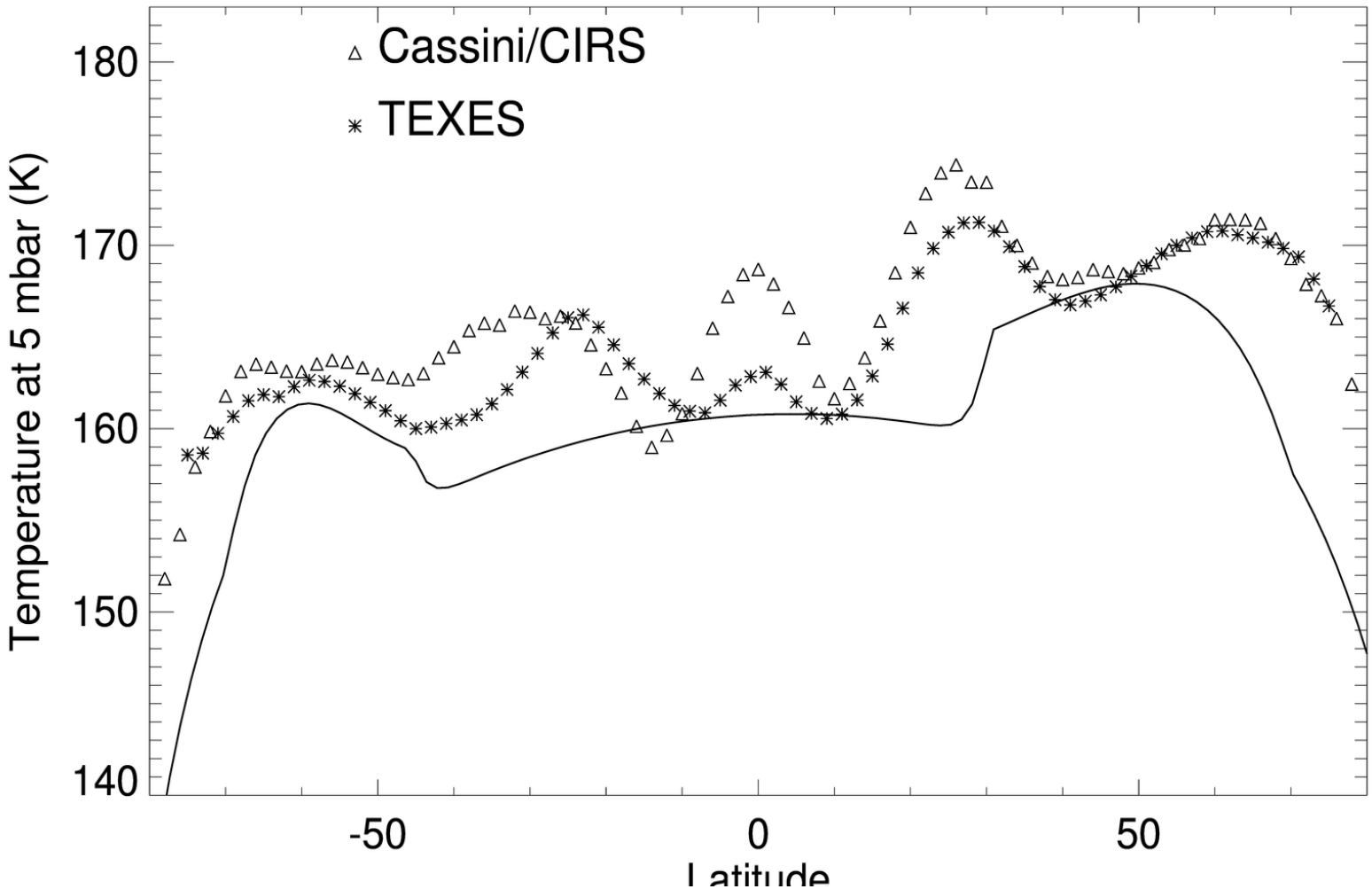


Outline

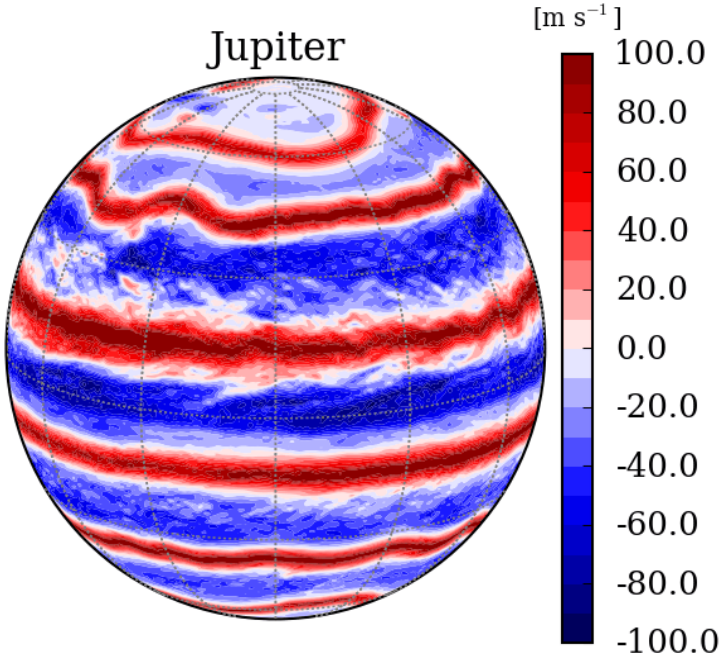
Optimized radiative transfer for Jupiter

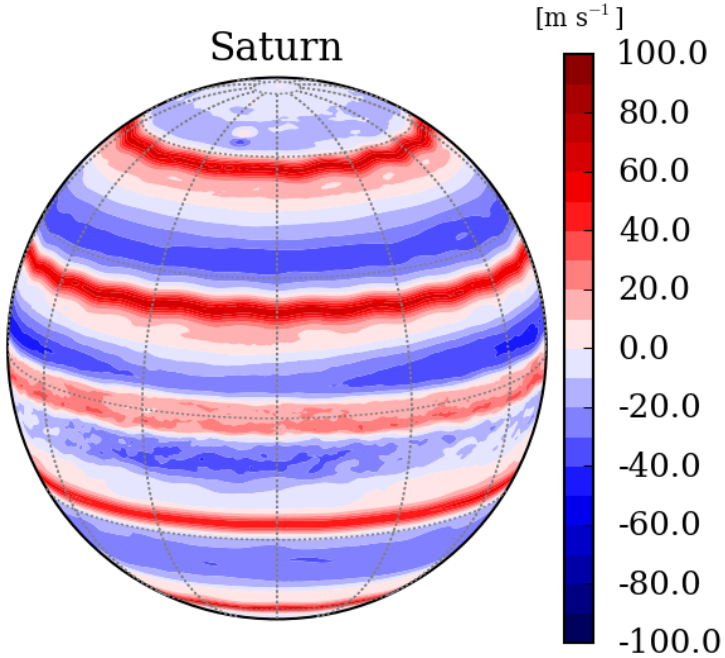
Guerlet et al. 2014 for Saturn, adapted to Jupiter [in prep]

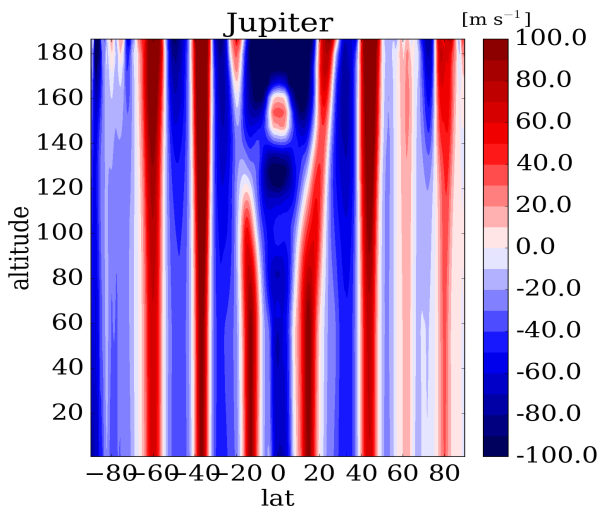
Comparison between radiative modeling and observations at 5 mb

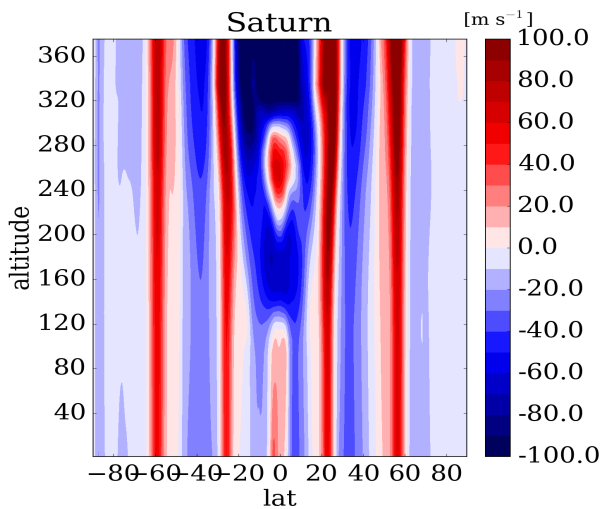


LMD DYNAMICO for gas giants (1/2°)









Take-home messages [Contact: aymeric.spiga@upmc.fr]

A new GCM for gas giants' troposphere and stratosphere

- Icosahedral dynamical solver DYNAMICO [Dubos et al. 2015]
- Complete & optimized physical packages [Guerlet et al. 2014]

Encouraging first results for Saturn ($1/2^\circ$) [soon submitted]

- ✔ wave & eddy activity, eddy-driven tropo & strato jets
- ✗ strong equat. super-rotation and oscillation, north hexagon

Future work

- ☞ Energy spectra analysis
- ☞ Simulations with Jupiter
- ☞ Add a moist convective scheme
- ☞ Exploration at $1/4^\circ$ resolution & more vertical levels