High-resolution Global Climate Modeling for giant planets

Aymeric SPIGA, S. Guerlet
Y. Meurdesoif (LSCE/CEA), M. Indurain,
E. Millour, M. Sylvestre,
T. Dubos, and T. Fouchet

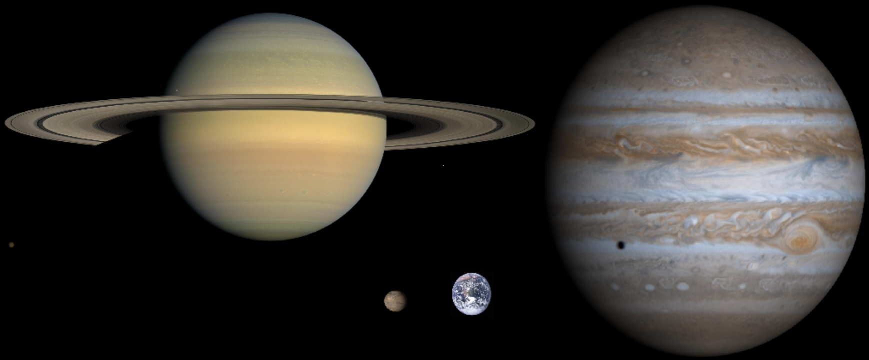
SF2A meeting June 17, 2016

Outline

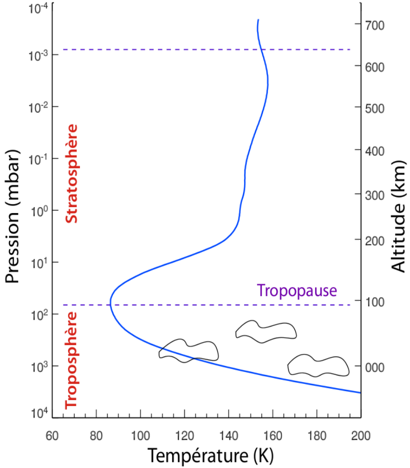
1. Context
2. Global Climate Model
3. Results with $1/2^\circ$ resolution
   - Instantaneous view
   - Multi-annual evolution
   - Eddy-driven jets
4. Experiments with $1/4^\circ$ and $1/8^\circ$

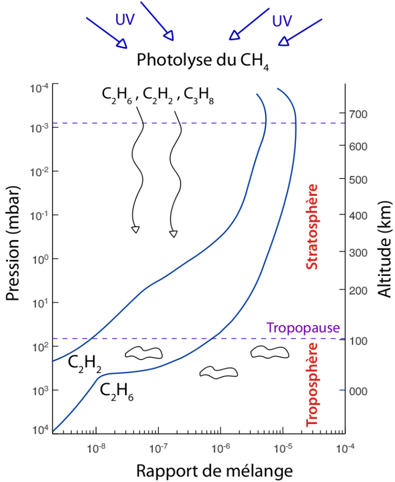
Outline

A geophysical approach for astronomical objects



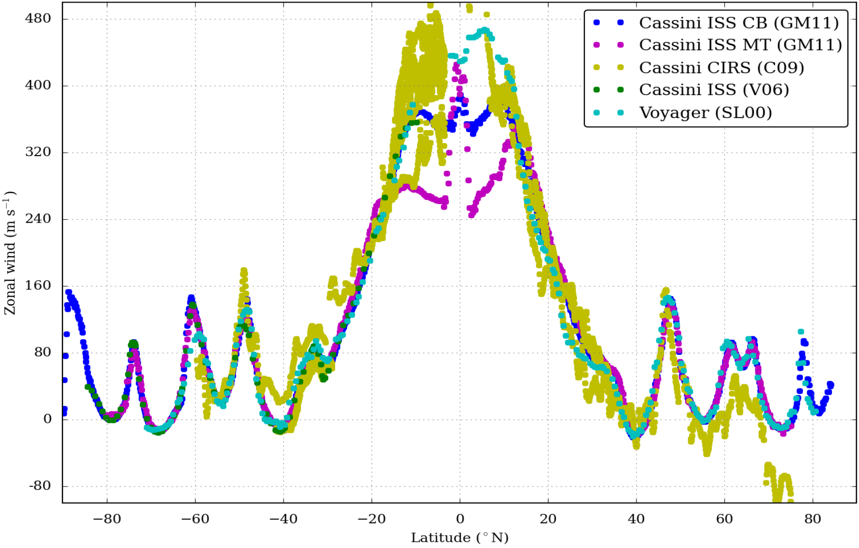
Saturn: thermal structure and hydrocarbons



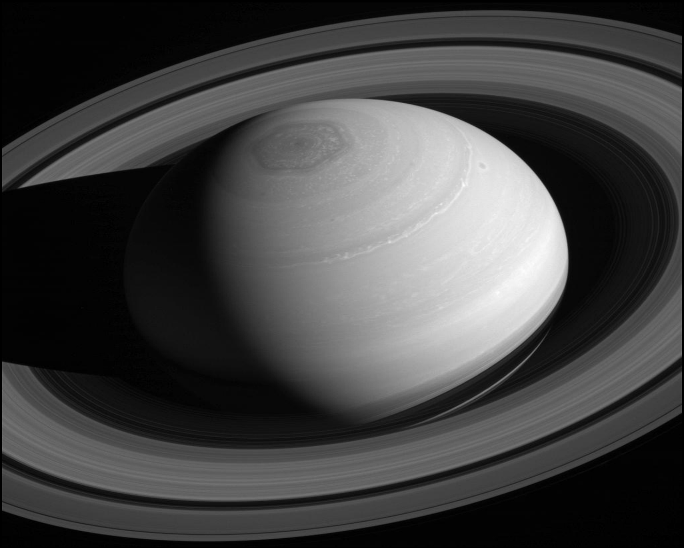


[Courtesy of S. Guerlet]

Observed tropospheric zonal winds on Saturn



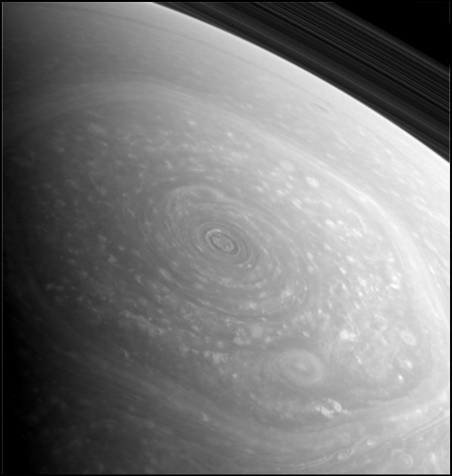
Saturn's hexagon



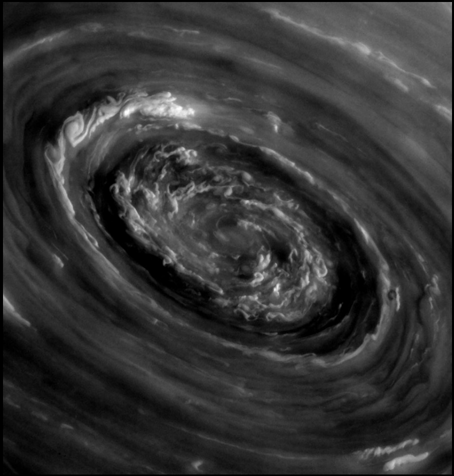
[PIA18278]

Saturn polar vortex

Hexagonal jet

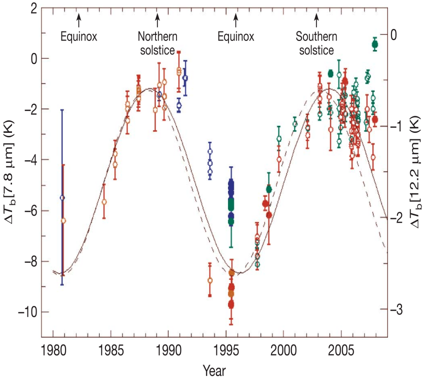


Turbulent vortex at center

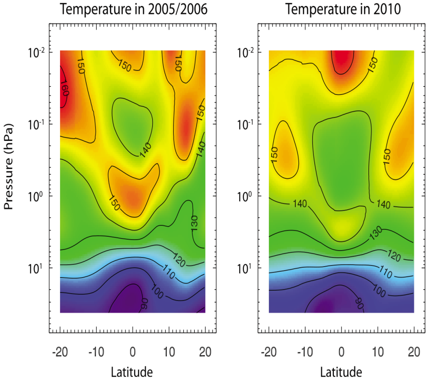


An equatorial oscillation in Saturn's stratosphere

Evolution with time with CIRS and ground-based observations

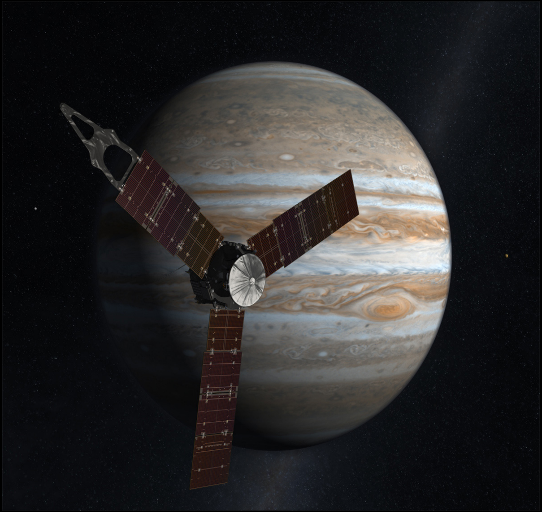


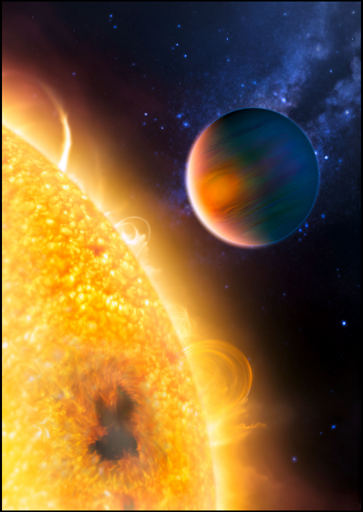
[Orton et al. Nature 2008]



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

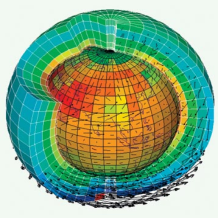
Saturn. . . and beyond





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]

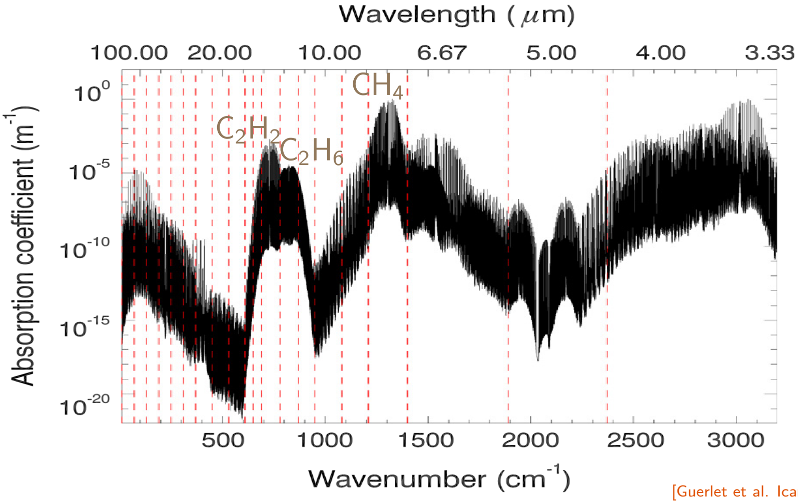
Physical parameterizations ⇒ 1D computations of forcings on each grid point

☞ 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

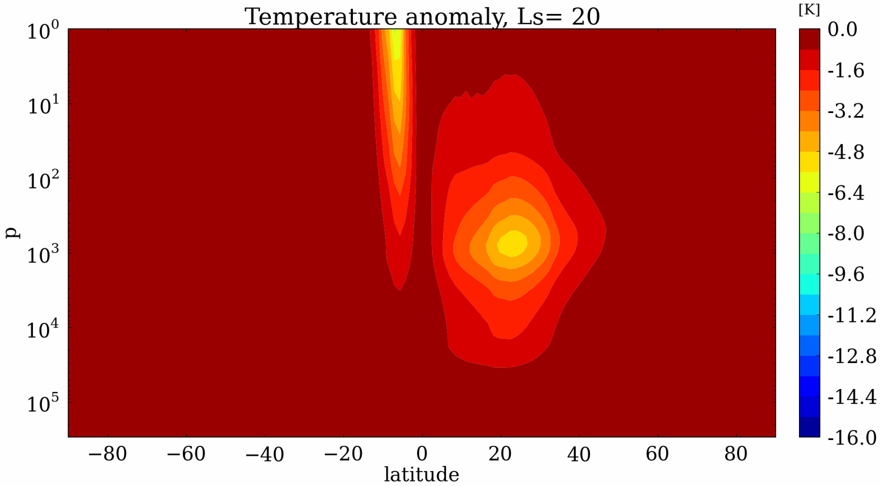
☞ Turbulent diffusion + dry convective adjustment [Hourdin et al. 1993]

IR spectral discretization – correlated-*k* scheme



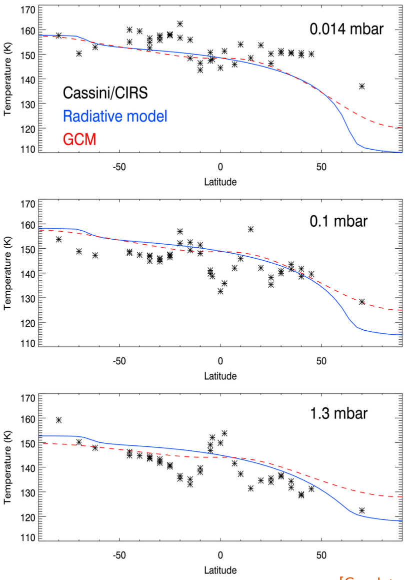
[Guerlet et al. Icarus 2014]

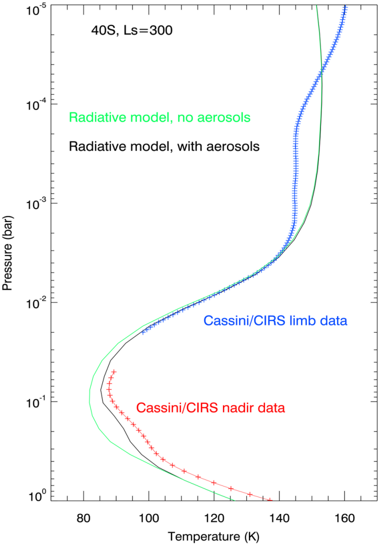
Saturn's rings shadowing and temperatures



[Guerlet et al. Icarus 2014]

3D radiative model vs. CIRS measurements

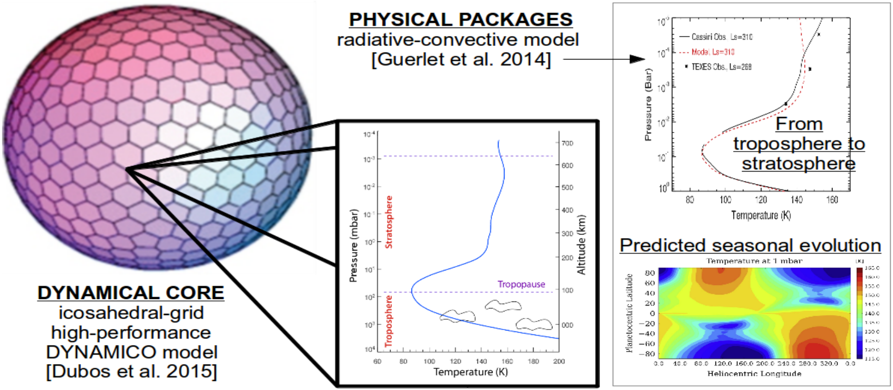




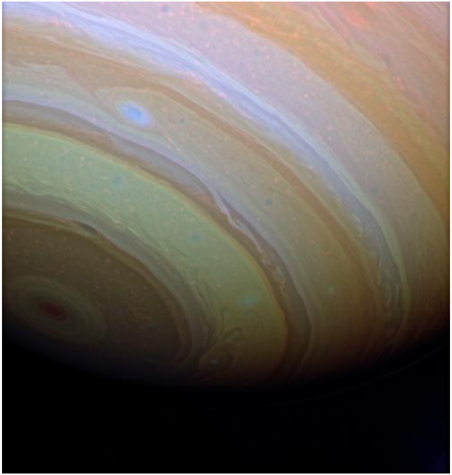
[Guerlet et al. Icarus 2014]

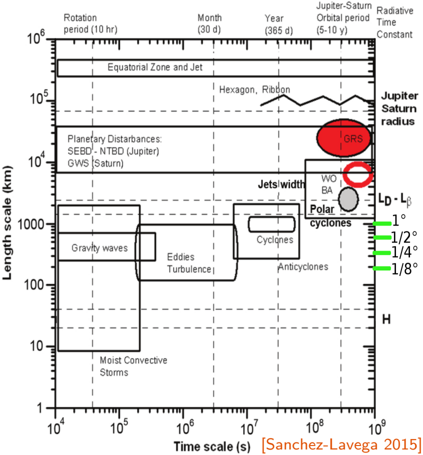
A new GCM for giant planets

Dubos, T., Dubey, S., Tort, M., Mittal, R., Meurdesoif, Y., and Hourdin, F. (2015).
DYNAMICO, a hydrostatic icosahedral dynamical core designed for consistency and versatility.
submitted to Geoscientific Model Development, doi:10.5194/gmdd-8-1749-2015.



Scales involved in giant planets



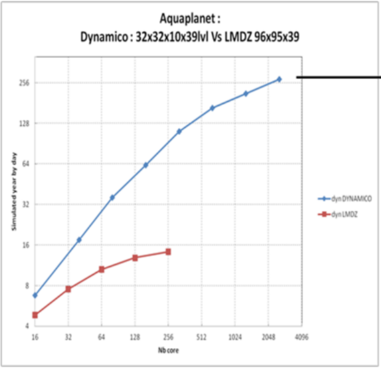


[Sanchez-Lavega 2015]

Rhines scale ∼ energy-containing eddy length scale

Rossby radius of deformation ∼ length scale of the baroclinically most unstable linear waves

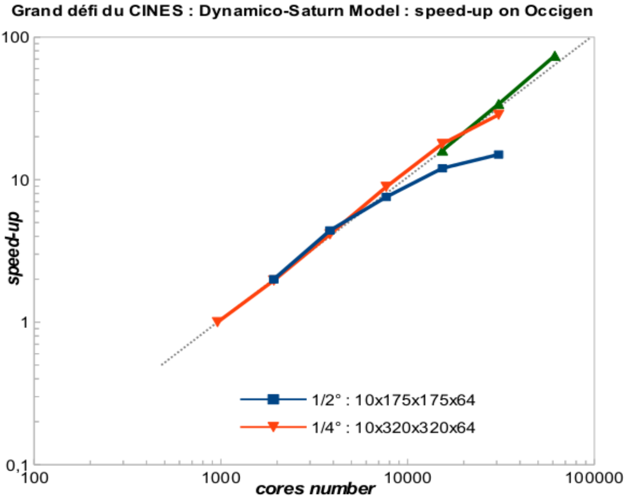
DYNAMICO (icosahedral) vs. LMDz (lat-lon)



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

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.

Scaling of the DYNAMICO hydrodynamical solver



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

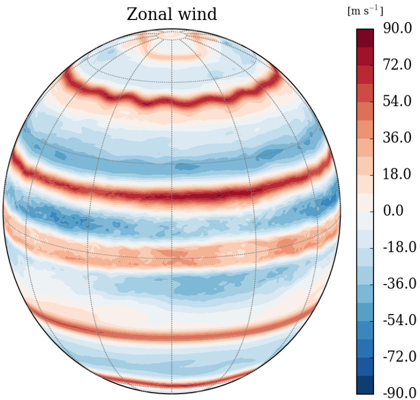
- MPI+openMP code run on Occigen cluster in CINES
- cores: 1200 ($1/2^\circ$), 9000 ($1/4^\circ$), 11520-30000 ($1/8^\circ$)

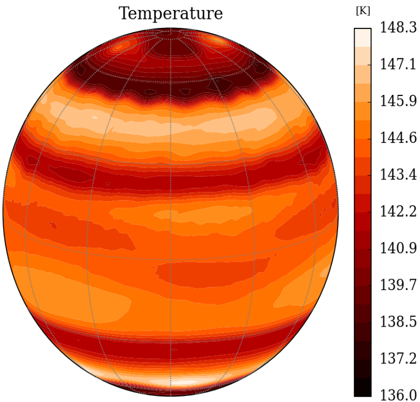
Outline

Outline

Results at 1.5 bar after 8 simulated Saturn years

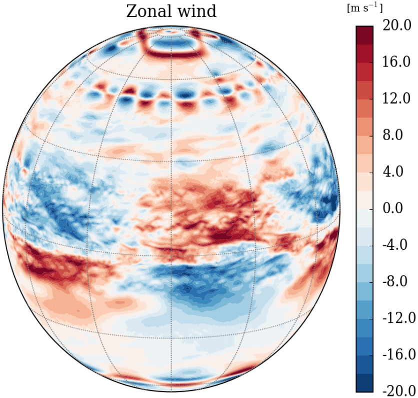
drag 90 Edays / dissipation 10000

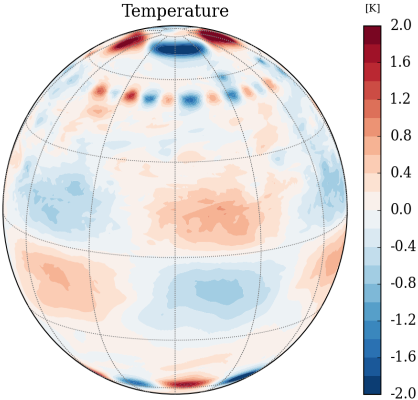




Results at 1.5 bar after 8 simulated Saturn years

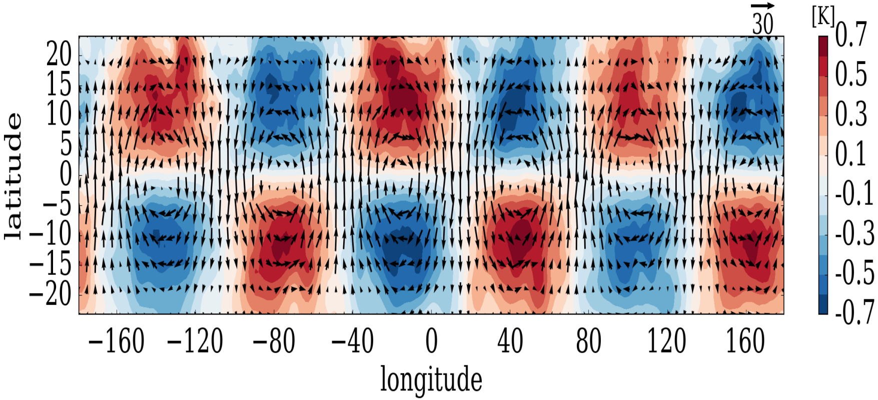
drag 90 Edays / dissipation 10000





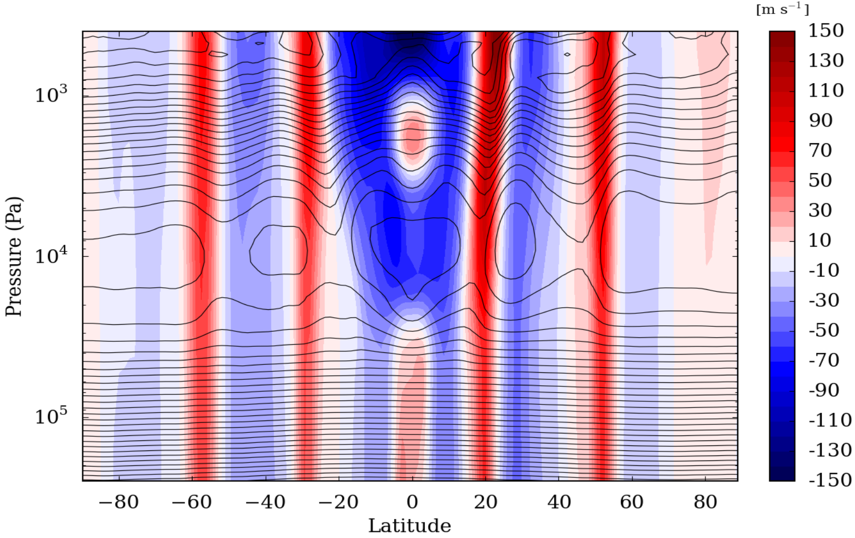
Equatorial mixed Rossby-Gravity wave

eastward-propagating, period 230 days



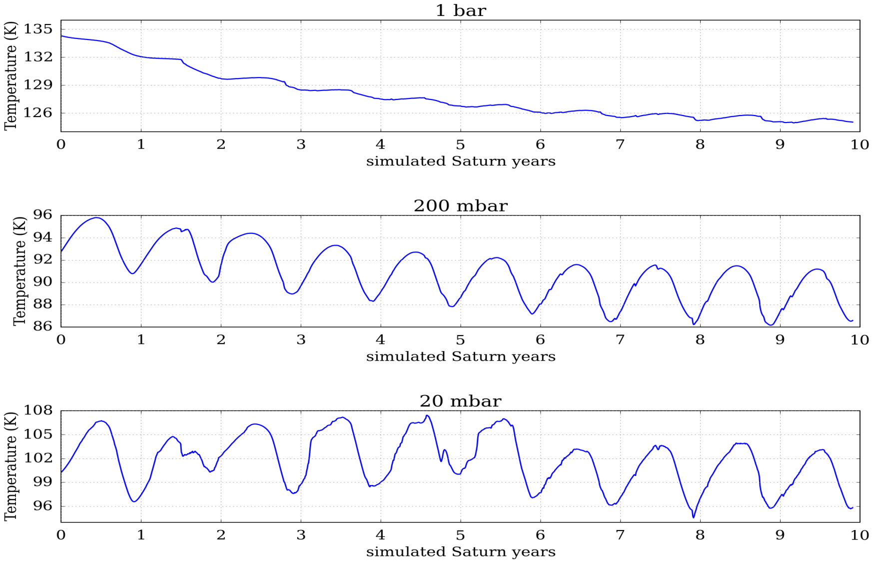
Zonal-mean zonal winds – year 8 ($L_s = 0°$)

with temperature contours

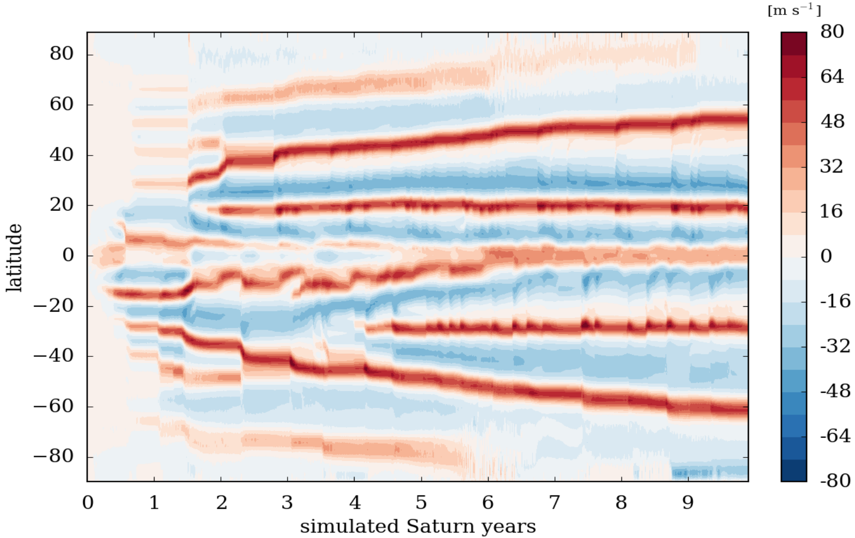


Outline

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



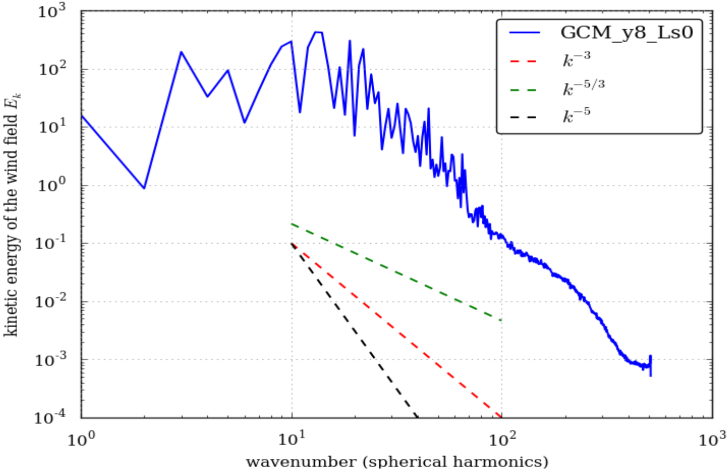
Evolution of zonal-mean zonal winds at 1 bar



Outline

Energy spectra on spherical harmonics

instantaneous wind field at 1.5 bars



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

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

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

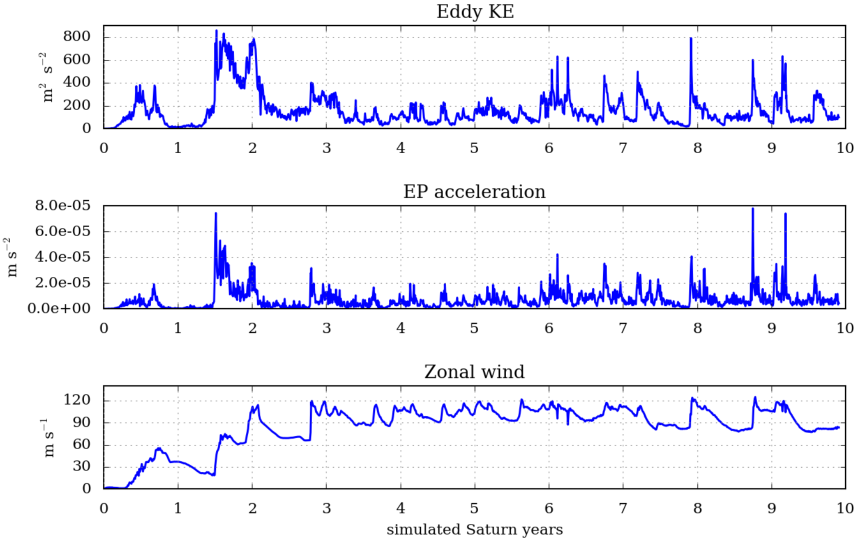
Eliassen-Palm Flux (zonal acceleration = divergence of F_φ)

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

Acceleration term by divergence of EP flux

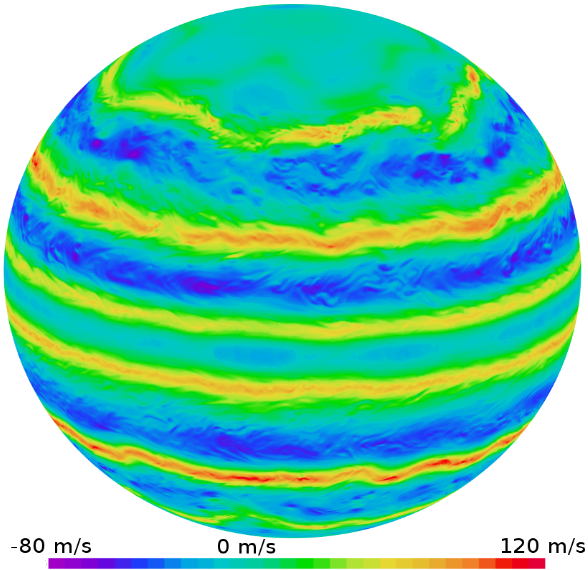
$$\frac{\partial \overline{u}}{\partial t} = \frac{1}{a^2 \cos^2\varphi} \frac{\partial F_\varphi \cos\varphi}{\partial \varphi}$$

Evolution of barotropic zonal-mean jets (max 30 – 60°N)

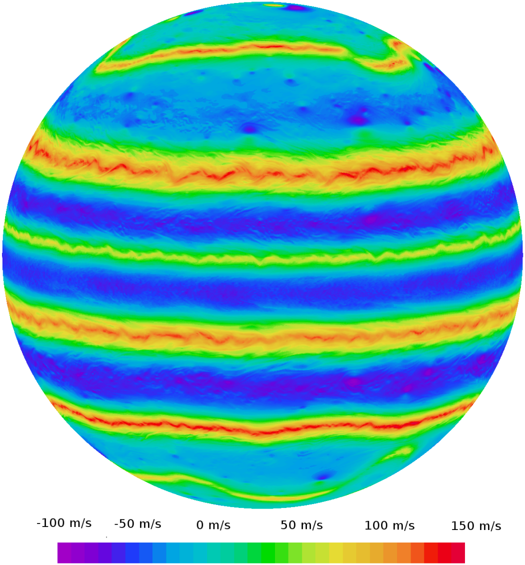


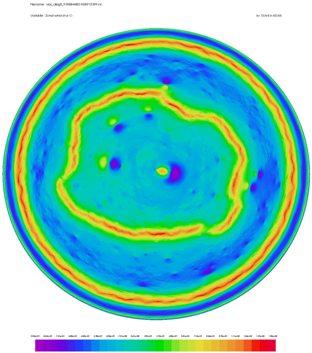
Outline

$1/4^\circ$ after 500 days. Zonal winds at 2 bars.



$1/8^\circ$ after 500 days. Zonal winds at 500 mbars.





Movie

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

A new GCM for Saturn's troposphere and stratosphere

- Icosahedral dynamical solver [Dubos et al. 2015]
- Excellent scalability on massively parallel clusters
- Complete & optimized physical packages [Guerlet et al. 2014]

Encouraging first results

- ✔ wave & eddy activity
- ✔ eddy-driven tropospheric jets &stratospheric circulations

Perspectives for future studies (we have ideas)

- ✗ weak equatorial super-rotation, no clear equatorial oscillation
- ✗ no hexagonal jet in the north pole