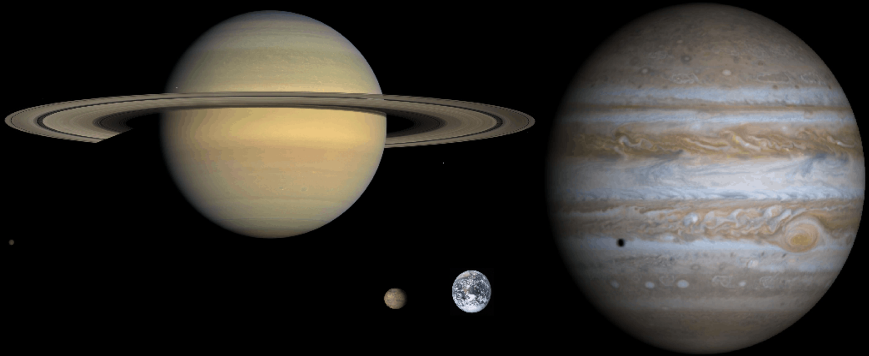
Modéliser la dynamique atmosphérique à fine échelle: de Mars aux planètes géantes

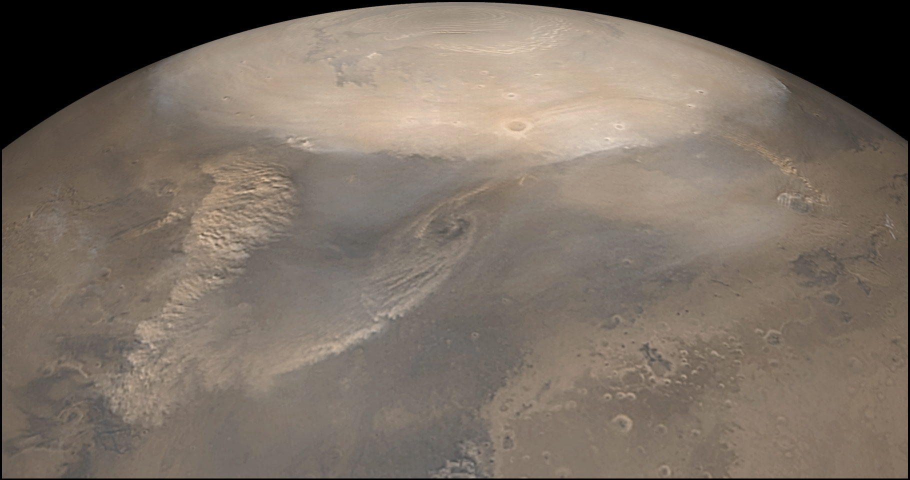
Aymeric Spiga

Astrosim ENS Lyon October 11, 2018

A geophysical approach for astronomical objects



Fronts poussérieux et ondes baroclines



[Image MOC sur Mars Global Surveyor 2002 (printemps nord martien)]

Modèles météorologiques planétaires

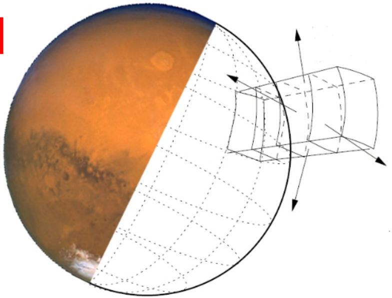
3D "DYNAMICAL CORE"

Geophysical fluid dynamics computations → conservation laws for momentum, mass, energy, tracers

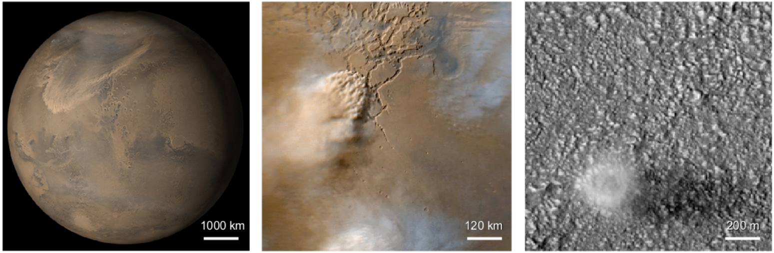
1D "PHYSICS"

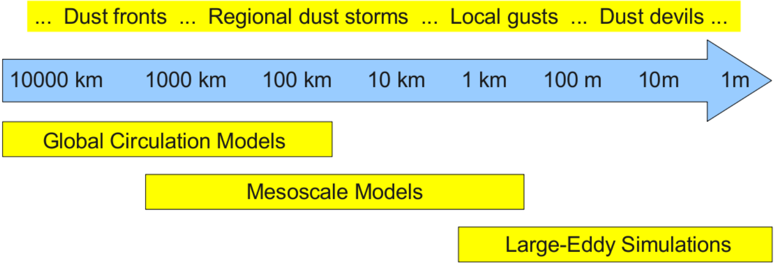
Radiative transfer, heat exchanges	Subgrid-scale schemes (mixing, gravity waves)
microphysics, chemistry, lifting/sedimentation	

$$\begin{cases} \dfrac{\mathrm{D}\boldsymbol{v}}{\mathrm{D}t} = -2\,\underset{*}{\boldsymbol{\Omega}} \wedge \boldsymbol{v} - \dfrac{1}{\rho}\,\boldsymbol{\nabla}\, p + \underset{*}{\boldsymbol{g}} + \boxed{\mathbf{F}} \\ \dfrac{1}{\rho}\dfrac{\mathrm{D}\rho}{\mathrm{D}t} + \boldsymbol{\nabla}\cdot\boldsymbol{v} = 0 \\ \boxed{\dfrac{\mathrm{Q}}{\mathrm{T}}} = \dfrac{c_p}{\underset{*}{\theta}}\,\dfrac{\mathrm{D}\theta}{\mathrm{D}t} \\ \dfrac{\mathrm{D}\,q_i}{\mathrm{D}t} = \boxed{(\mathrm{S}_i - \mathrm{P}_i)} \\ p = \rho\,\underset{*}{\mathrm{R}}\,\mathrm{T} \end{cases}$$



Scales and Models




... Dust fronts ... Regional dust storms ... Local gusts ... Dust devils ...

10000 km 1000 km 100 km 10 km 1 km 100 m 10m 1m

Global Circulation Models

Mesoscale Models

Large-Eddy Simulations

[Spiga and Lewis, Mars Journal 2010]

Mars Global Climate Model: LMD-MGCM

LMDz dynamical core

integration of conservation laws for momentum, mass, energy, tracers

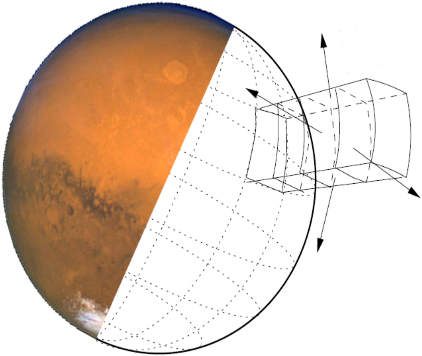
LMD Mars physics

radiative transfer (dust and CO_2), soil model, vertical mixing, microphysics (H_2O and CO_2), lifting/sedimentation, chemistry

MGS dataset

topography, thermal inertia, albedo
dust scenario

Grid spacing $\sim$ 200 km



[Forget et al., JGR 1999]

Mars Mesoscale Model: LMD-MMM

WRF dynamical core

integration of conservation laws for momentum, mass, energy, tracers

LMD Mars physics

radiative transfer (dust and CO_2), soil model, vertical mixing, microphysics (H_2O and CO_2), lifting/sedimentation, chemistry

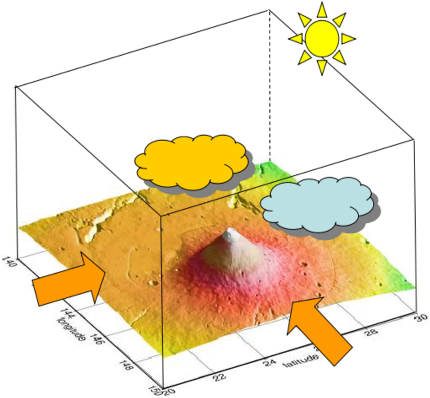
LMD Mars GCM fields

initial and boundary conditions

MGS hi-res dataset

topography, thermal inertia, albedo
dust scenario

Grid spacing $\sim 10 - 1$ km



[Spiga and Forget, JGR 2009]

Mars Large-Eddy Simulations: LMD-LES

WRF dynamical core

integration of conservation laws for momentum, mass, energy, tracers

LMD Mars physics

radiative transfer (dust and CO_2), soil model, vertical mixing, microphysics (H_2O and CO_2), lifting/sedimentation, chemistry

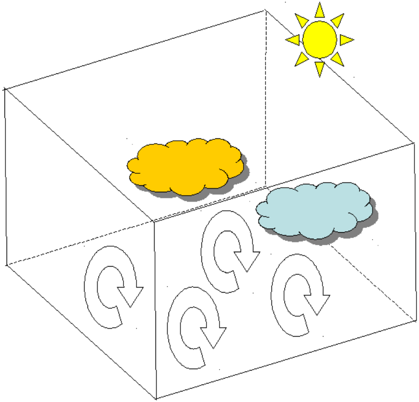
LMD Mars GCM fields

initial profiles only, periodic boundaries

MGS hi-res dataset

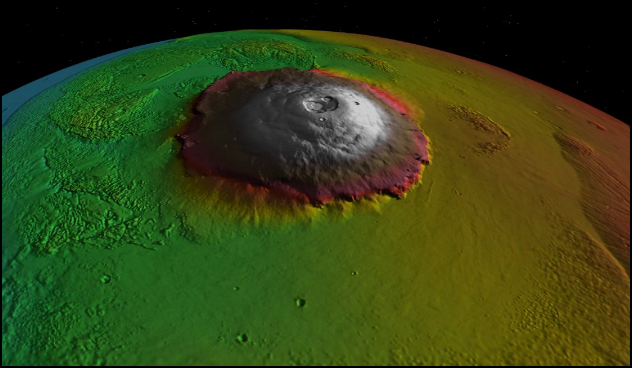
topography, thermal inertia, albedo
prescribed dust scenario

Grid spacing $\sim 100 - 10$ m



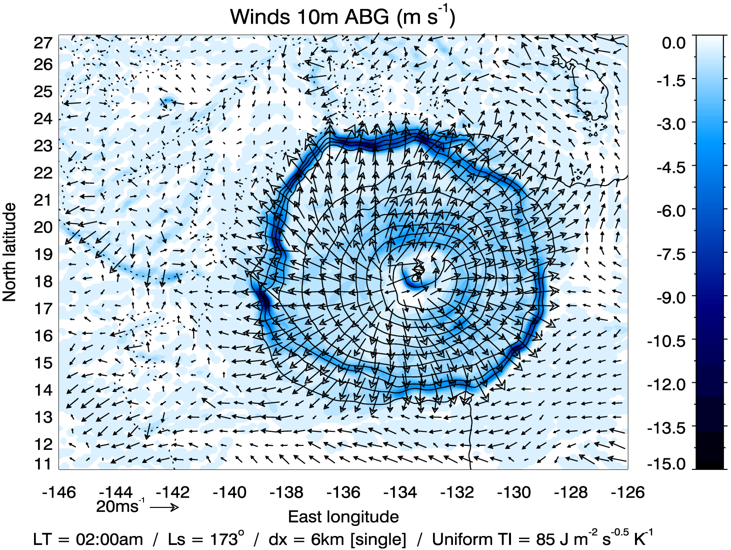
[Spiga et al., QJRMS 2010]

WRF-ARW	MM5
• Terrain-following hydrostatic pressure vertical coordinate	• Terrain-following height (sigma-z) vertical coordinate
• Arakawa C-grid	• B-grid
• 3rd order Runge-Kutta split-explicit time integration	• 1st order (time-filtered) Leapfrog time integration
• Conserves mass, momentum, entropy, and scalars using flux form prognostic equations	• Advective formulation (no conservation properties)
• 5th order upwind or 6th order centered differencing for advection	• 2nd order centered differencing for advection



Olympus Mons

Katabatic winds over Olympus Mons

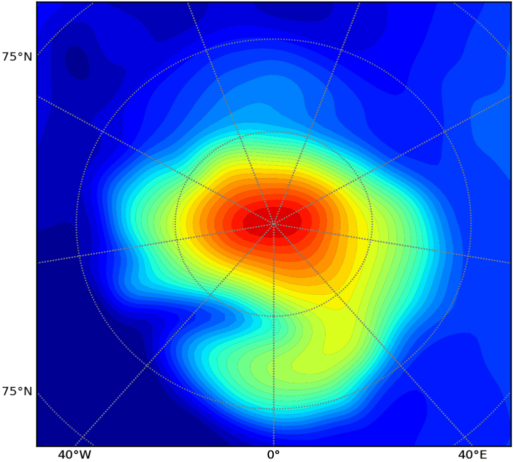


[Spiga and Forget, JGR 2009; Spiga et al., Icarus 2011]

The northern polar cap on Mars

Five nested domain zooming in one polar trough!

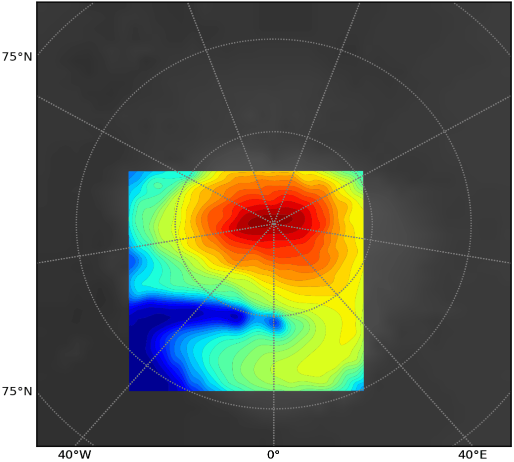
Horizontal resolutions: 20 km



[Spiga and Smith Icarus 2018]

Five nested domain zooming in one polar trough!

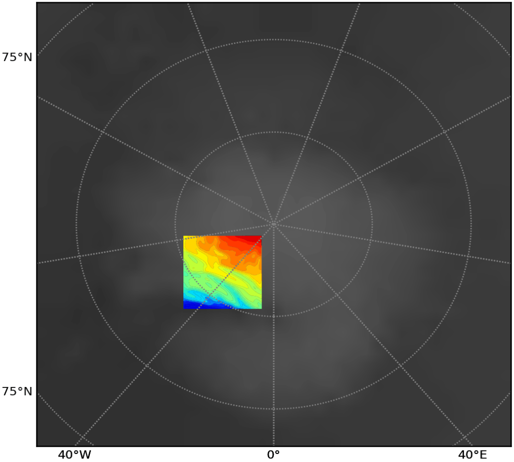
Horizontal resolutions: 20 km / 6.7 km



[Spiga and Smith Icarus 2018]

Five nested domain zooming in one polar trough!

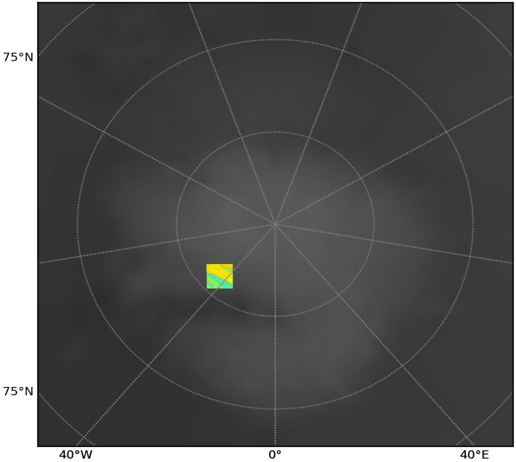
Horizontal resolutions: 20 km / 6.7 km / 2.2 km



[Spiga and Smith Icarus 2018]

Five nested domain zooming in one polar trough!

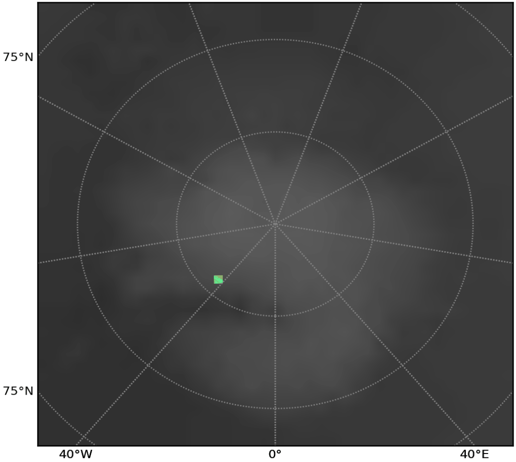
Horizontal resolutions: 20 km / 6.7 km / 2.2 km / 740 m



[Spiga and Smith Icarus 2018]

Five nested domain zooming in one polar trough!

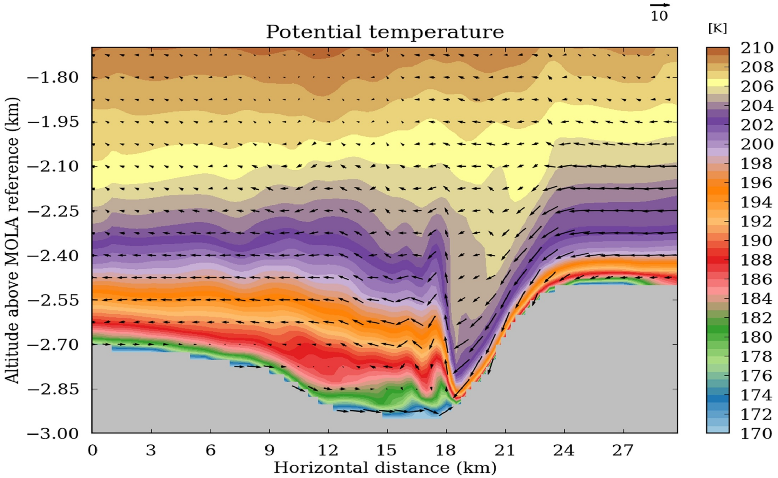
Horizontal resolutions: 20 km / 6.7 km / 2.2 km / 740 m / 250 m



[Spiga and Smith Icarus 2018]

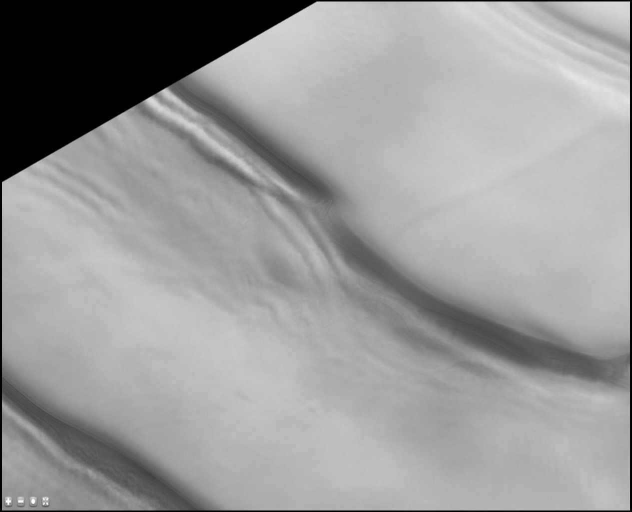
Hi-res modeling of katabatic jumps in troughs

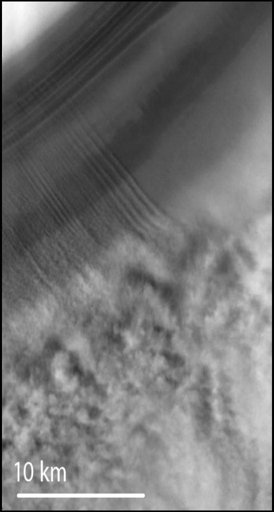
Potential temperature (traces adiabatic motions)



[Spiga and Smith Icarus 2018]

Polar trough clouds on Mars



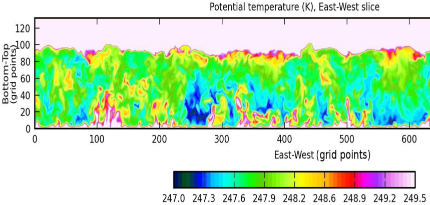


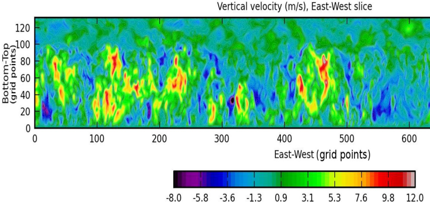
[Smith and Holt Nature 2010, Smith et al. JGR 2013]

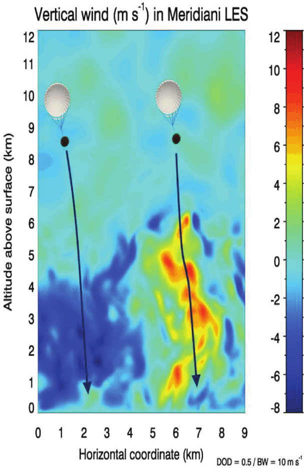
Planetary Boundary Layer

Turbulent convection in daytime boundary layer

Simulated through Large-Eddy Simulations [LES]


Potential temperature (K), East-West slice


Vertical velocity (m/s), East-West slice

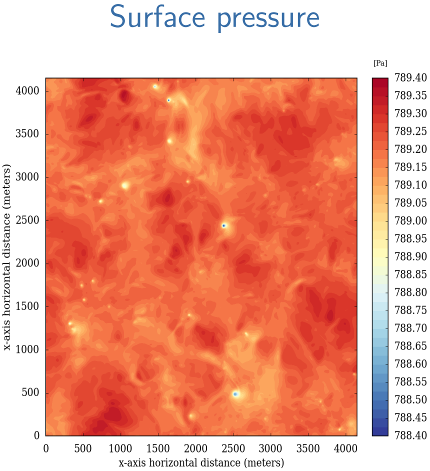

Vertical wind ($m\ s^{-1}$) in Meridiani LES

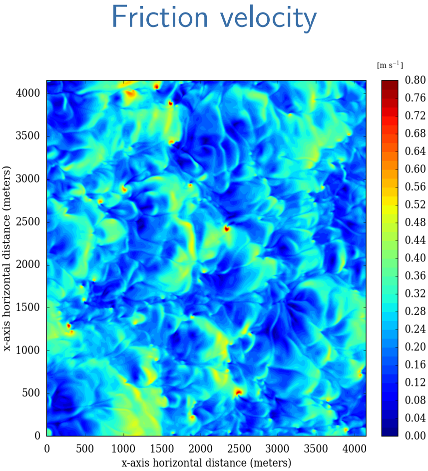
Animation: *xz* section showing tracer transport

[Spiga et al. QJRMS 2010; Colaitis et al. JGR 2013]

Large-Eddy Simulations for Insight

horizontal resolution 10 m, results at local time 9AM





[Spiga et al. Space Science Reviews 2018]

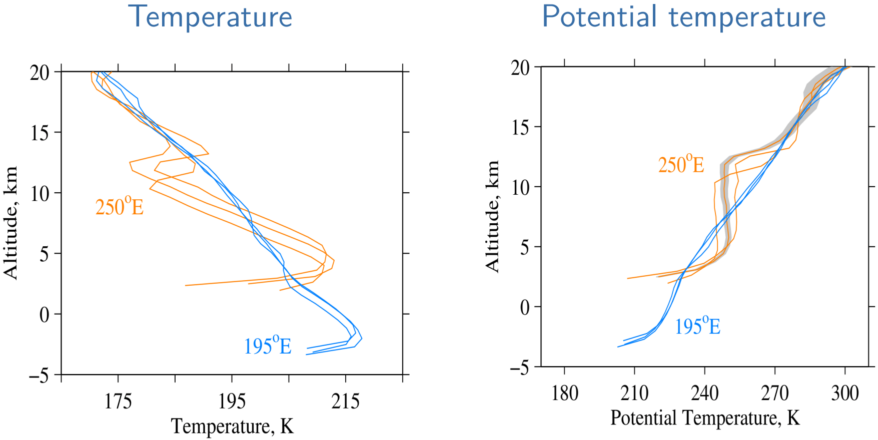
InSight within the Martian PBL

[Extract from an original drawing by Manchu]

Mars' water-ice clouds

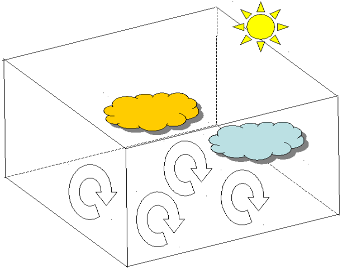
MGS nighttime radio-occultations

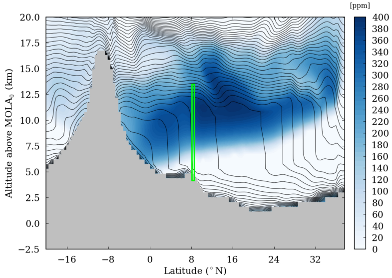
Amazonis (blue) vs. Tharsis (orange). Lat $20-25°$N. Local time 4am. $L_s = 140°$



[Hinson et al. Icarus 2014]

Large-eddy simulations to study water-ice clouds



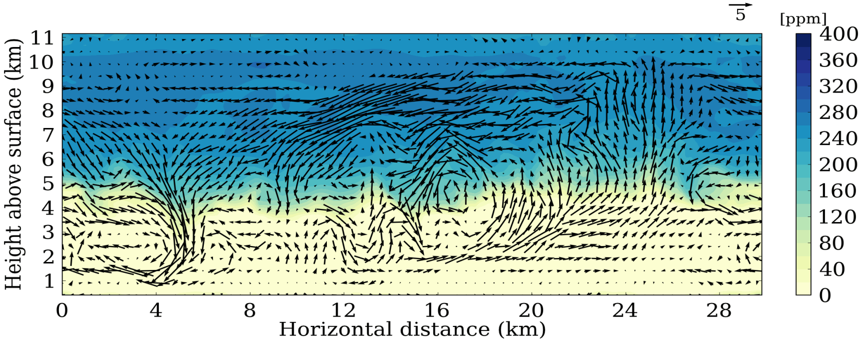


- ✎ LMD-MMM based on WRF; positive definite advection [*Spiga et al.* QJRMS 2010]
- ✎ Dust and Water ice radiative transfer & 2-moment scheme [*Madeleine et al.* JGR 2011, GRL 2012]
- ✎ Cloud microphysics [*Navarro et al.* JGR 2014]

- ✎ 151 × 151 × 81 grid points
- ✎ $\Delta x = 200$ m, $\Delta z \sim 200$ m, $z_{\mathrm{max}} = 15$ km
- ✎ $L_s = 120°$
- ✎ Initial MCD profile

Ice microbursts [a.k.a. turbulent "snowstorms"]

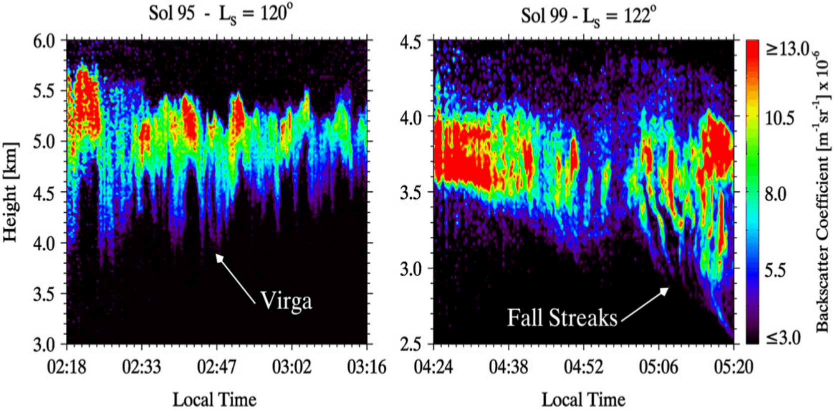
Large-Eddy Simulations of radiatively active clouds



[Spiga et al., Nature Geoscience 2017]

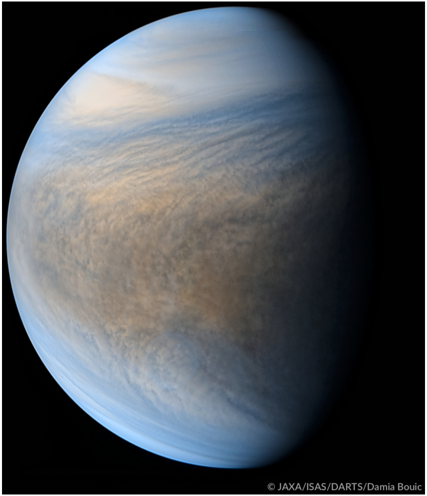
Virga & Fall streaks below water-ice clouds

LIDAR measurements onboard Mars Phoenix lander (68°N)

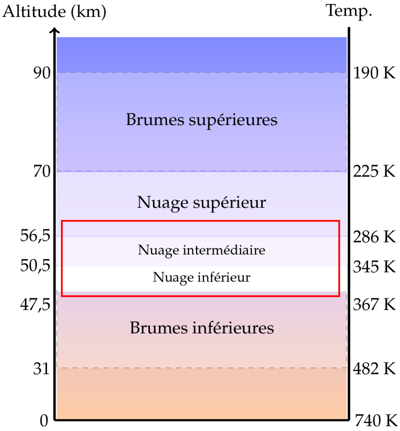


[Whiteway et al. Science 2009, Dickinson et al. GRL 2010, Dickinson et al. PSS 2011]

Introduction : Small-scale activity


© JAXA/ISAS/DARTS/Damia Bouic

Main convective layer



LES Physics configuration

Heating rates decomposed in 3 different contributions :

-2 radiative ones : Solar and IR
- Dynamics: associated with global dynamics : Hadley cell (Adiabatic warming/cooling)

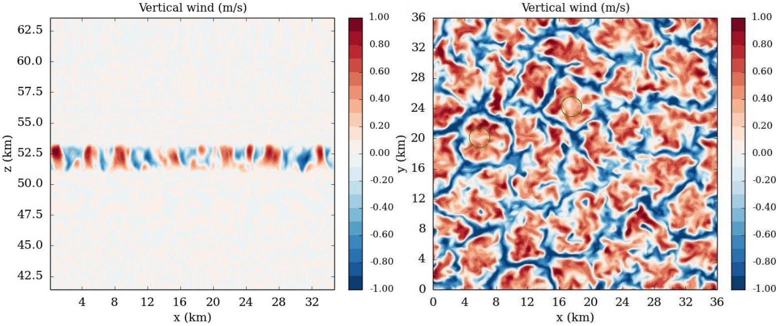
	Off-line (Lefèvre et al., 2017)	On-line (Lefèvre et al., 2018)
Solar	Constant	LMD Venus radiative transfer
IR	Constant	LMD Venus radiative transfer
Dynamics	Constant	Constant
Resolution	200 m	400 m
horizontal domain	36x36 km	60x60 km
vertical level	181	300
vertical domain	40 to 70 km	surface to 100 km
computational time	less than one day	~50 days

No wind shear is imposed

Input from GCM Simulations

Off-line mode

Equator noon



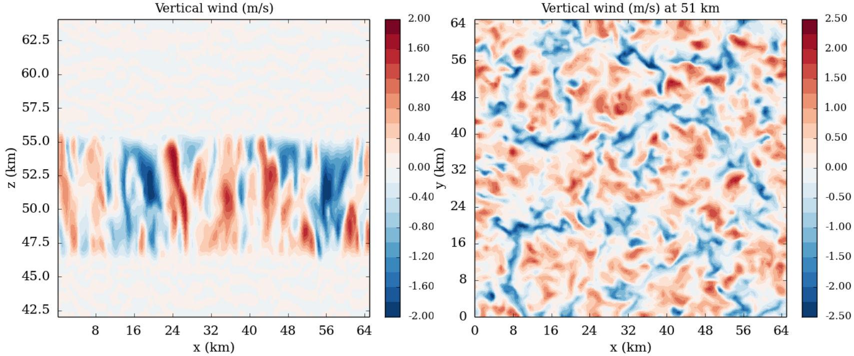
Lefèvre et al, 2017

First insight of the 3D organization

Convective layer of few kilometers. Weaker than the observations

On-line mode

Equator noon



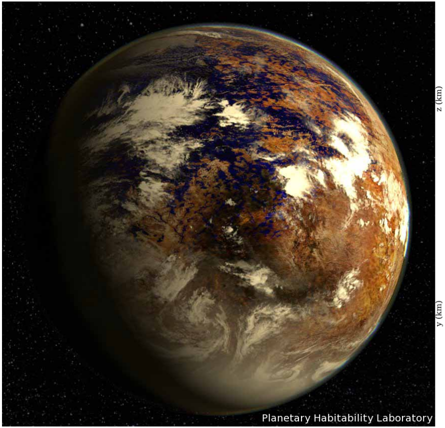
Lefèvre et al, 2018

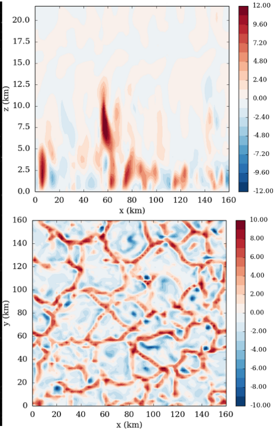
Vertical wind between ±2.5 m/s, consistent with observations

Convective cell of 20 km of diameter

Exoplanetary Applications

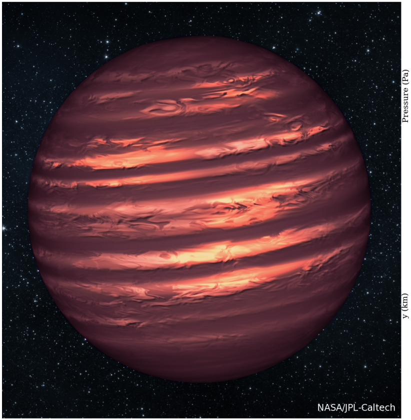
Convection in synchronous planets with M. Turbet (LMD)

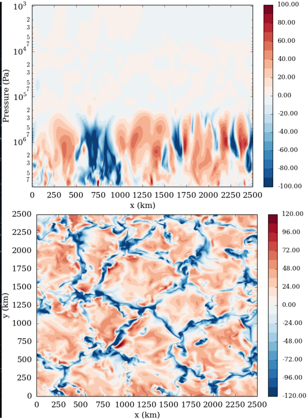




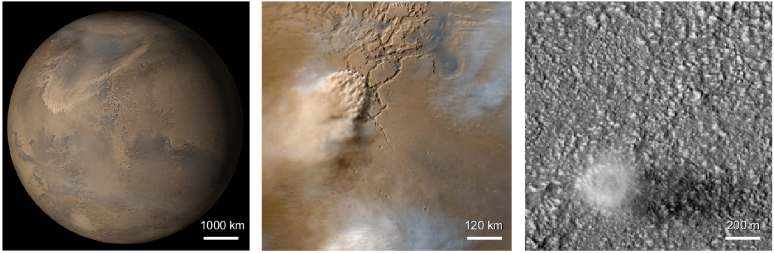
Exoplanetary Applications

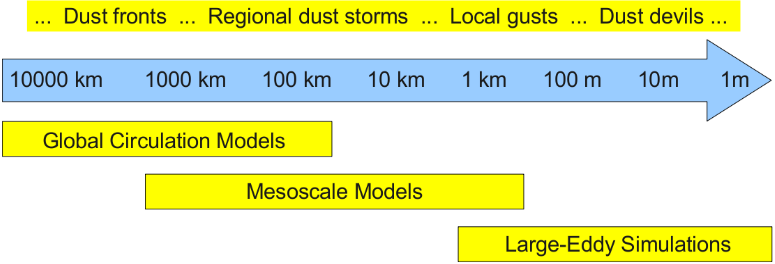
Brown dwarfs and Young Giant with B. Charnay (LESIA)


NASA/JPL-Caltech



Scales and Models





... Dust fronts ... Regional dust storms ... Local gusts ... Dust devils ...

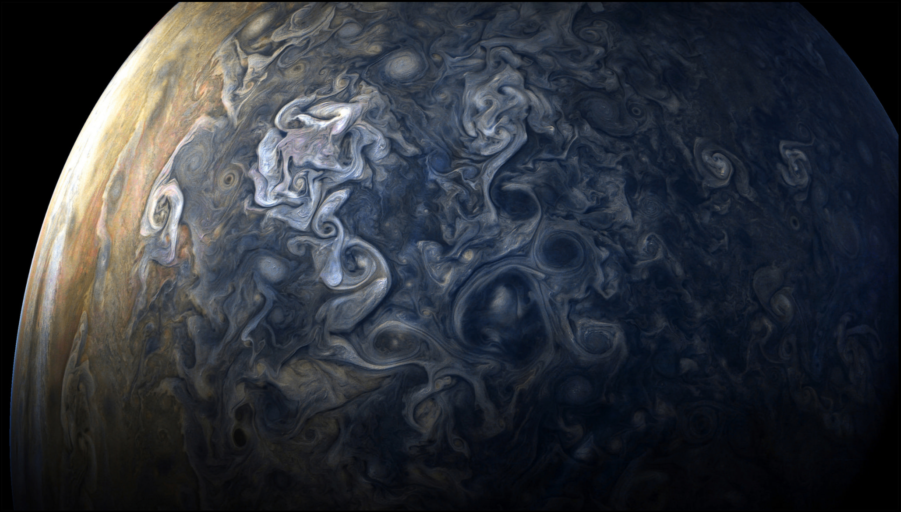
10000 km 1000 km 100 km 10 km 1 km 100 m 10m 1m

Global Circulation Models

Mesoscale Models

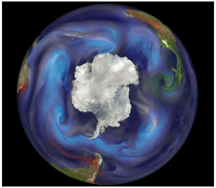
Large-Eddy Simulations

[Spiga and Lewis, Mars Journal 2010]

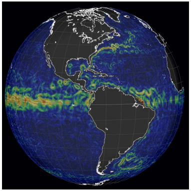


Modeling planetary flow zonation

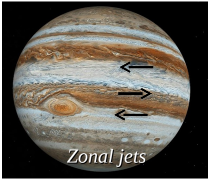
South pole circulation



Oceanic circulation

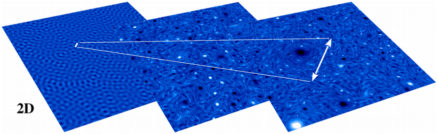


Jupiter zonal jets

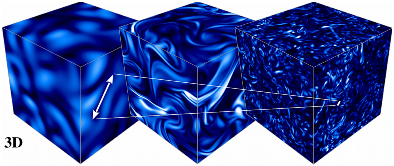


- **Gas giants set an asymptotic zonostrophic regime.**

2D – Turbulent inverse cascade

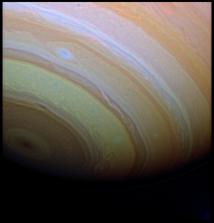


3D – Turbulent dissipation

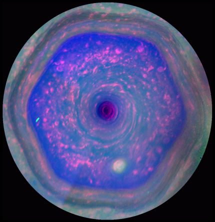


Atmospheric activity in Saturn

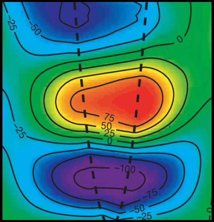
Jets



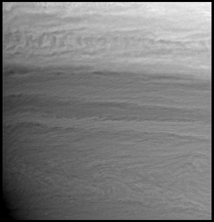
Hexagon



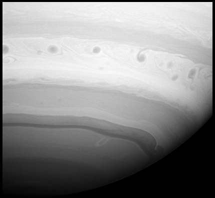
QBO



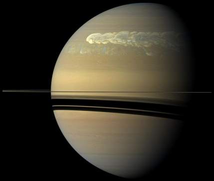
Eddies



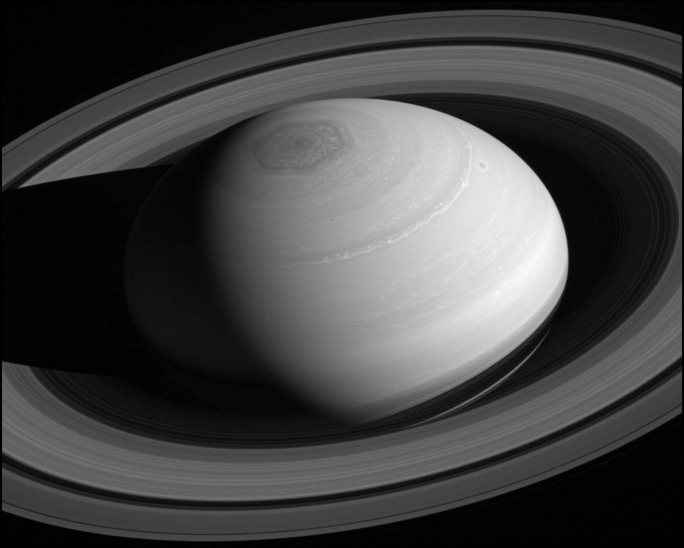
Vortices



Storms



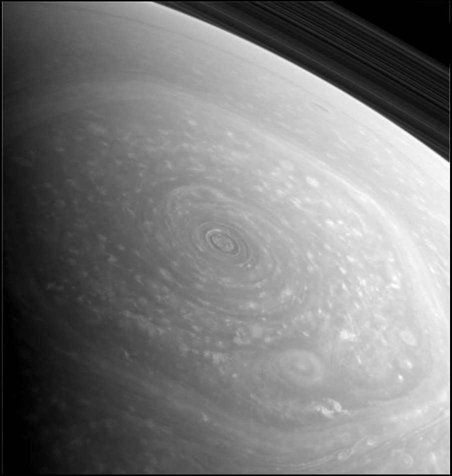
Saturn's hexagon



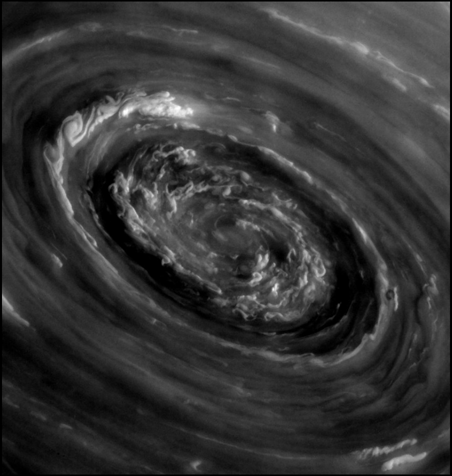
[PIA18278]

Saturn polar vortex

Hexagonal jet

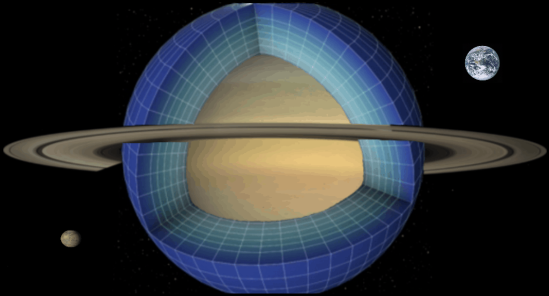


Turbulent vortex at center

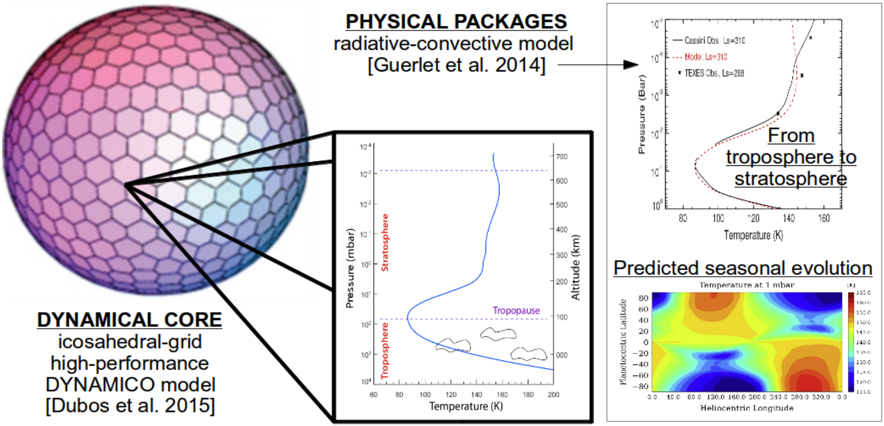


A GCM for gas giants: technical barriers

- $\mathcal{C}_1$ Radiative transfer computations over decade-long giant planets' years
- $\mathcal{C}_2$ Relevant interaction scales for smaller-scale hydrodynamical eddies are only 1° latitude-longitude in gas giants vs. 20° on the Earth
- $\mathcal{C}_3$ Extent from troposphere to stratosphere with fine vertical resolution
- $\mathcal{C}_4$ Coupling with interior convective and magnetic fluxes



A new GCM for giant planets



PHYSICAL PACKAGES
radiative-convective model
[Guerlet et al. 2014]

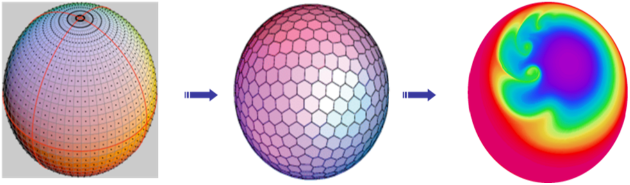
From troposphere to stratosphere

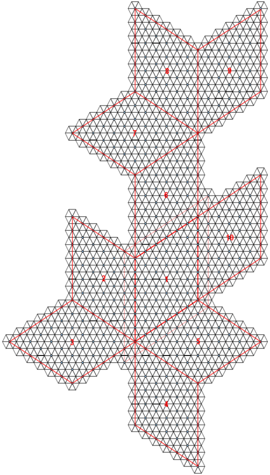
Predicted seasonal evolution

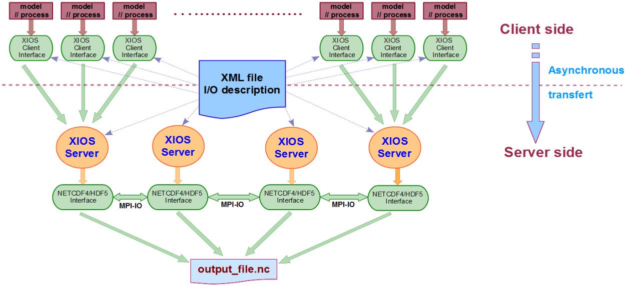
DYNAMICAL CORE
icosahedral-grid
high-performance
DYNAMICO model
[Dubos et al. 2015]

DYNAMICO: new icosahedral dynamical core

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







model // process

XIOS Client Interface

XML file I/O description

XIOS Server

NETCDF4/HDF5 Interface

MPI-IO

output_file.nc

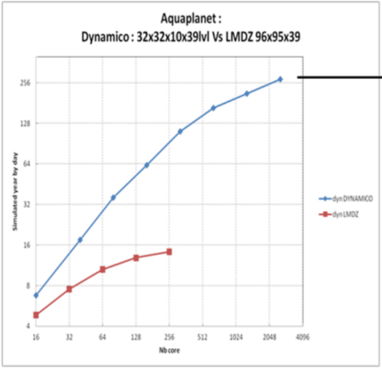
Client side

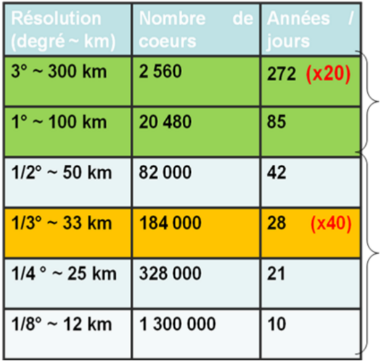
Asynchronous transfert

Server side

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

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





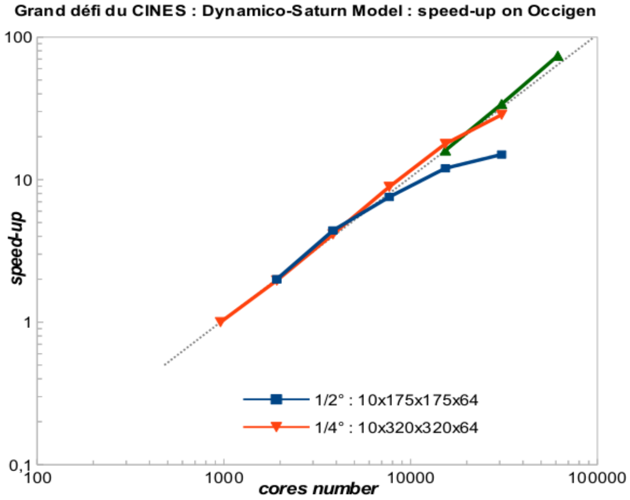
Résolution (degré ~ km)	Nombre de coeurs	Années / jours
3° ~ 300 km	2 560	272 (x20)
1° ~ 100 km	20 480	85
1/2° ~ 50 km	82 000	42
1/3° ~ 33 km	184 000	28 (x40)
1/4 ° ~ 25 km	328 000	21
1/8° ~ 12 km	1 300 000	10

mesuré

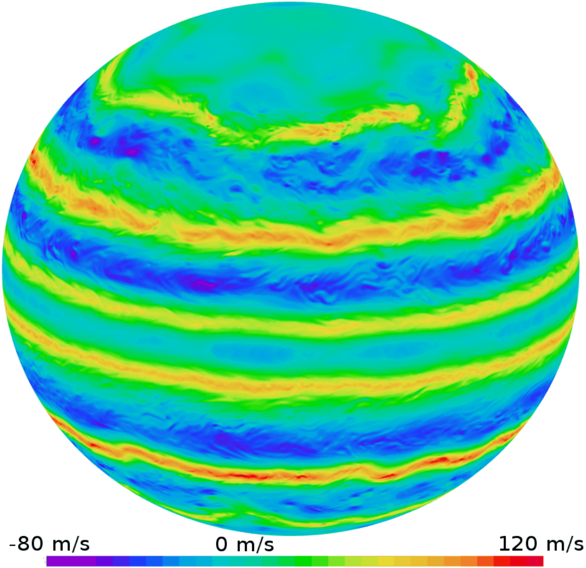
extrapolé

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.

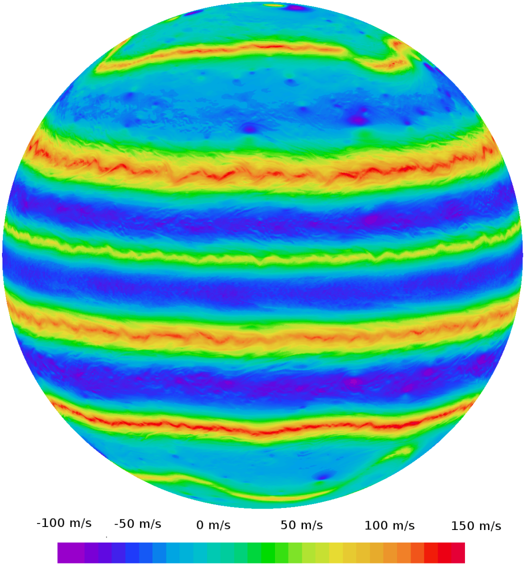
Scaling of the DYNAMICO hydrodynamical solver

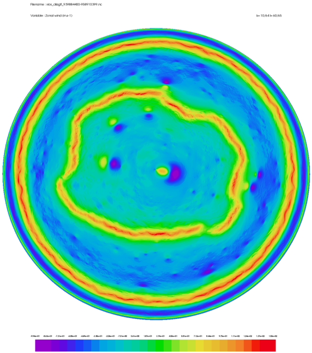


$1/4^\circ$ after 500 days. Zonal winds at 2 bars.



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



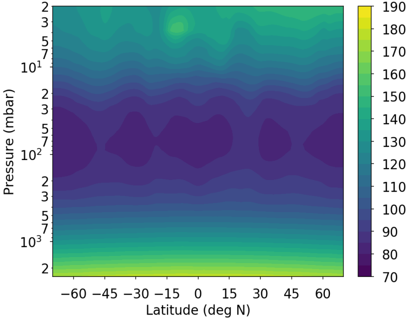


Movie

Saturn's thermal structure

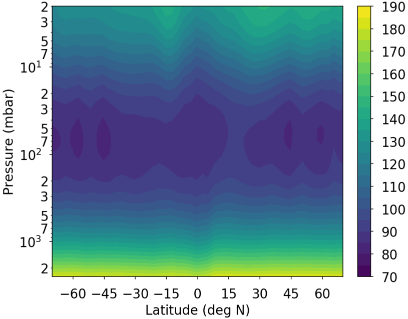
GCM temperature at $L_s \sim 70^\circ$

(zonal-mean, ninth simulated year)

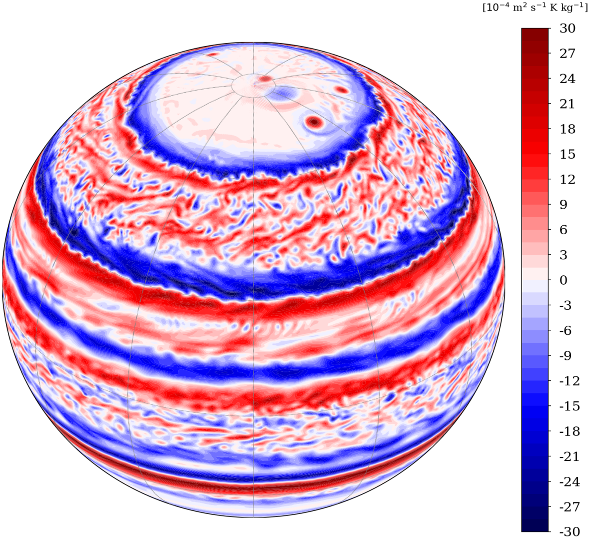


CIRS temperature at $L_s \sim 70^\circ$

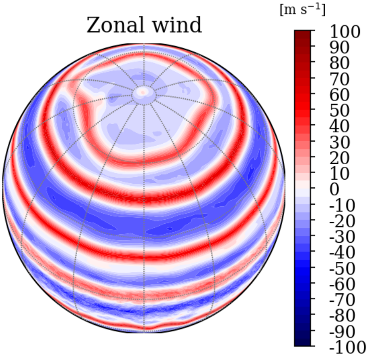
(2015 nadir, best: 500-70 mb & 5-0.5 mb)

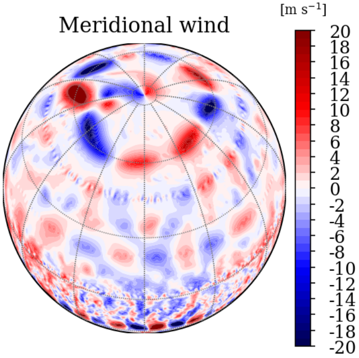


Eddies and vortices in a $1/2^\circ$ Saturn GCM

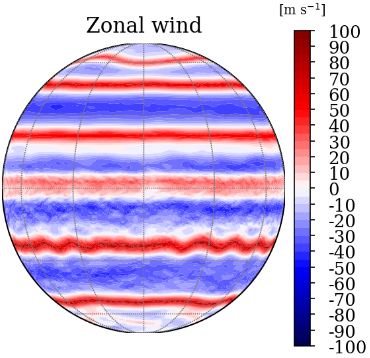


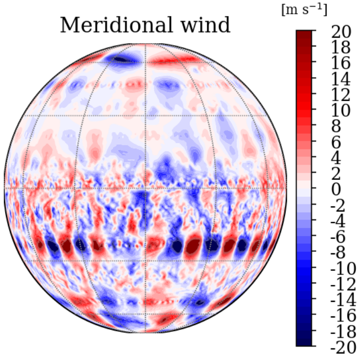
Saturn 1/2° GCM after 3.5 simulated Saturn years





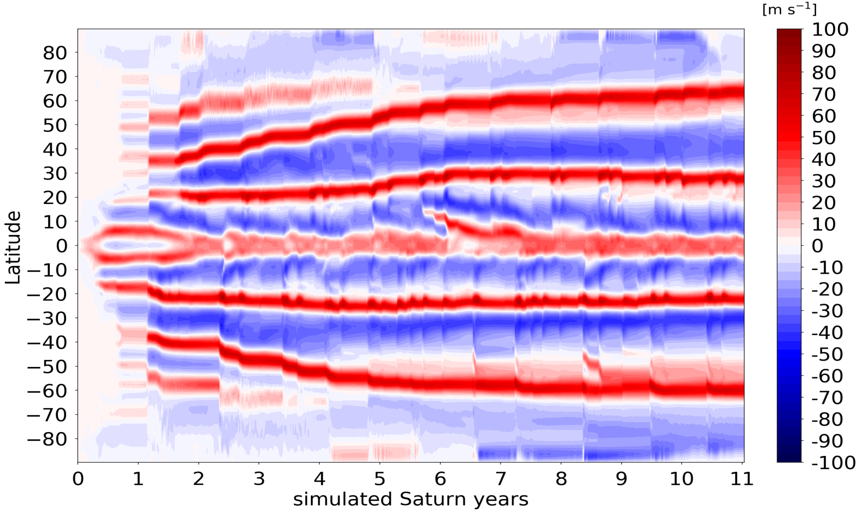
Saturn 1/2° GCM after 3.5 simulated Saturn years





JETS: 11 years of 1/2° Saturn GCM

zonal-mean zonal winds at 800 mbar



[Spiga et al. in preparation for Icarus]

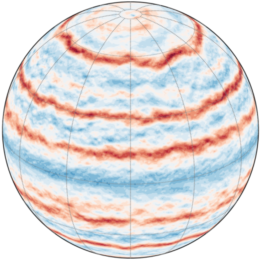
Gas giants: jets & eddies

Jupiter

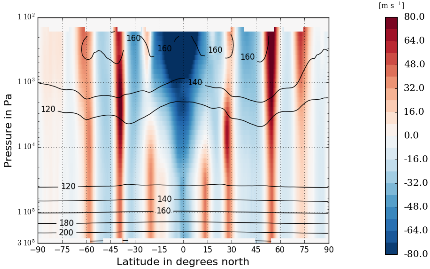
Saturn

Zonal wind after a 4 jovian years run

Zonal wind



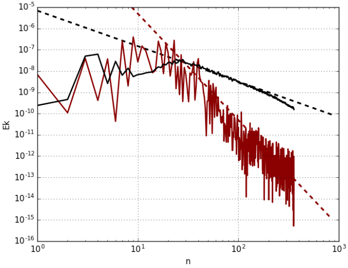
Zonal mean zonal wind



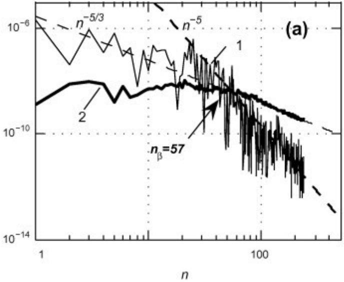
- About 13 Jets
- Alternately prograde and retrograde
- Equatorial jet is subrotating
- Speeds have good order of magnitude

Energy spectra

Model



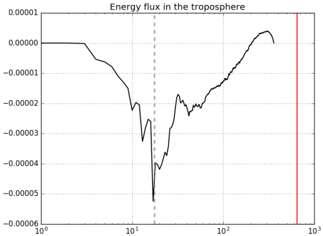
Observation



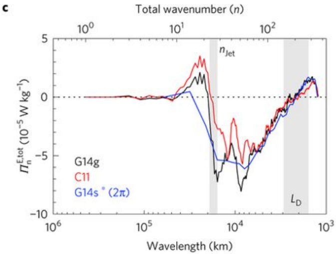
The model, despite the wrong number of jets, reproduces the correct energy distribution and dynamical regime (cf. *Galperin et al, Icarus, 2014*).

Energy fluxes

Model



Observation



Spectral energy flux is also in good agreement with the observations (cf. *Young et al, Nature Physics, 2017*). The model reproduces an inverse cascade of energy from small scales to the jet scale.

Summary

- Modeling to explore, discover, interpret
- Mesoscale simulations for Mars: slope circulations, . . .
- LES for turbulence: PBL & clouds: Mars, Venus, exoplanets!
- A “global mesoscale” model for gas giants: Saturn & Jupiter

IUF
cnes CENTRE NATIONAL D'ÉTUDES SPATIALES
AGENCE NATIONALE DE LA RECHERCHE ANR
ACAV+
îledeFrance

Vision actuelle

- ☞ Tendance 1: vers la haute résolution
- ☞ Tendance 2: physique sophistiquée

Problèmes

- ☞ Funding is mission-driven
- ☞ *Publish or perish*: frein au code
- ☞ Pérennisation des codes

Solutions

- ☞ Engineers, mésocentres et grands défis
- ☞ Echange de bonnes pratiques
- ☞ Brute-force? Machine learning?