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Waves and eddies simulated by high-resolution Global Climate Modeling of Saturn's troposphere and stratosphere

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Context The Cassini spacecraft, orbiting the Saturn's system since 2004, opened a new era for giant planets' exploration (1), and recently revealed that Saturn's hazy atmosphere is as dynamically active as Jupiter's colorful one. The longevity of the mission permitted a detailed analysis of tropospheric storms (2); an exceptionally detailed coverage of Saturn's great northern storm of 2010-2011, which eventually encircled the entire planet for months, and caused a sudden warming in the stratosphere (3); an assessment of the remarkable stability of the hexagonal polar jet (4); the seasonal monitoring of Saturn's equatorial oscillation (5), helping to build the analogy with the Quasi-Biennal Oscillation in the Earth's stratosphere (and a putative Quasi-Quadriennal Equatorial Oscillation in the jovian equatorial atmosphere). Those puzzling signatures in the stratosphere add to the outstanding questions related to the alternated jets structure in Saturn's troposphere: do jets' extent and forcing are deep in the interior, or confined to the weather layer? Are jets driven by sunlight or internal heat? Why such a strong prograde equatorial jet in Saturn?

Modeling challenges Based on the experience of telluric planets, the best step forward is to build a Global Climate Model for giant planets, obtained by coupling a solver for the Navier-Stokes equations for the atmospheric fluid on the sphere ("dynamical core") with realistic models for external forcings on the fluid: radiation, phase changes, chemistry ("physical packages"). Despite recent efforts which provided insights into the importance of wave-driven processes both in the troposphere and the stratosphere (6; 7; 8; 9), a Global Climate Model for giant planets complete enough to adress the theoretical challenges opened by observations is yet to emerge, for one or several of the following difficulties could not be overcome. ($\mathcal{D}_1$) ***Dynamical accuracy*** Through an inverse energy cascade named geostrophic turbulence, planetary-scale jets are forced by smaller-scale eddies arising from hydrodynamical instabilities. Relevant interaction scales (e.g. Rossby deformation radius) are 20° longitude on Earth but only 1° in giant planets, making eddy-resolving global simulations there 4 orders of magnitude more computationally expensive. ($\mathcal{D}_2$) ***Vertical extent*** Terrestrial experience shows that models need to extend from the troposphere to the stratosphere with sufficient vertical resolution to resolve the vertical propagation of waves responsible for large-scale structures in both parts of the atmosphere. ($\mathcal{D}_3$) ***Radiative computations*** The radiative transfer calculations necessary to predict the evolution of atmospheric temperature must be optimized for integrations over decade-long giant planets' years, while still keeping robustness against observations. ($\mathcal{D}_4$) ***Upper & lower boundaries*** Climate models do not extend deep enough to predict how tropospheric jets interact with interior convective fluxes and magnetic dynamo, and not high enough to model the photochemistry of key hydrocarbons impacting stratospheric winds and temperatures.

Our modeling efforts We started to build a Global Climate Model for Saturn which will be both versatile and powerful enough to overcome the four $\mathcal{D}_{1\to4}$ difficulties and address the outstanding questions and dynamical mysteries opened by Cassini and previous observational campaigns. Note that we leave apart here $\mathcal{D}_4$ which warrants further investigation on deep interior processes and upper atmosphere photochemistry. To address $\mathcal{D}_2$ and $\mathcal{D}_3$, we developed for Saturn an optimized seasonal radiative package validated against measurements (10). Our model's radiative computations are based on a versatile correlated-k method, suitable for any planetary composition (11) with k-coefficients derived from detailed line-by-line computations with the latest spectroscopic databases. The spectral discretization of the model was optimized for Saturn, with additional computations corresponding to this environment: aerosol layers, ring shadowing, internal heat flux. To address $\mathcal{D}_1$ and $\mathcal{D}_2$, we use

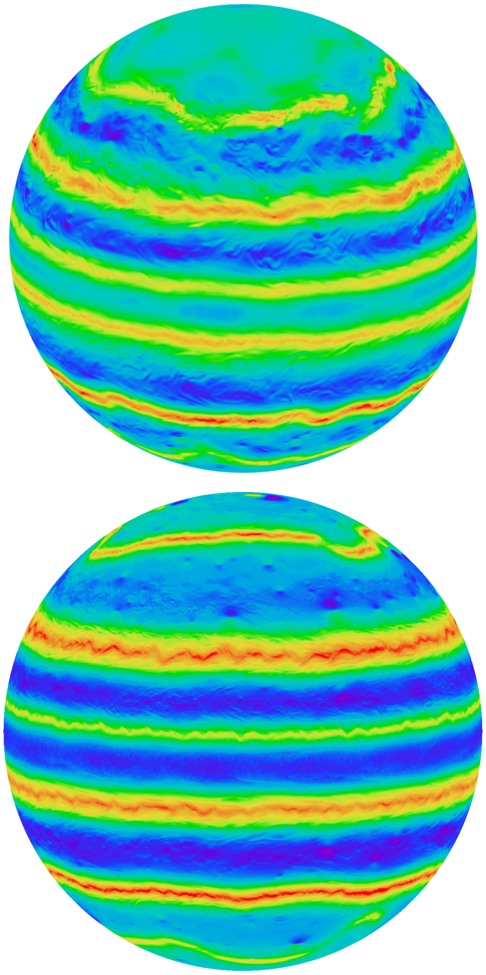

Figure 1: *Zonal winds predicted at 0.5 bar (yellow/red: prograde jets, blue/violet: retrograde jets) by our Global Climate Model for Saturn. Our simulations used the unprecedented horizontal resolutions of* $1/4^\circ$ *(top) and* $1/8^\circ$ *(bottom) longitude and* 64 *vertical levels from troposphere to stratosphere. In the top plot, jets' instabilities and filamentation can be noticed; in the bottom plot, the even finer horizontal resolution allows the model to reproduce the propagation of gravity waves on the flanks of the jets, as well as the possible emergence of traveling vortices (cf. blue/green spots in the northern hemisphere).*

DYNAMICO, developed in LMD as the next state-of-the-art dynamical core for Earth and planetary climate studies. DYNAMICO is tailored for massively parallel High-Performance Computing resources, thanks to an original icosahedral mapping of the planetary sphere which ensures excellent conservation and scalability properties up to 10^5 cores (12).

Results and perspectives An exceptional allocation on a new petaflops acquisition by the French inter-university computing center (CINES) allowed us to run our Global Climate Model for Saturn down to unprecedented resolutions of $1/4^\circ$ and $1/8^\circ$ (Figure 1). Our high-resolution Global Climate Model runs for Saturn show a detailed view into a striking variety of eddies and vortices, as well as the arising of alternated banded jets, the formation of a polar vortex, the deformation of the polar jet into polygonal structures (though not a stable hexagon). We will discuss during the EPSC conference the characteristics of both eddies and eddy-driven features, both in the troposphere (jets) and in the stratosphere (equatorial oscillations). Through spectral analysis, we determine the nature of the waves (Rossby, Kelvin, …); through dynamical analysis, the instabilities which give birth to those disturbances (e.g. barotropic or baroclinic). We will describe how close our simulations are to the observed features by Cassini and other observational campaigns, and assess which processes are in need to be improved in our Global Climate Model. Our high-resolution simulations for Saturn not only open new perspectives for fundamental knowledge of atmospheric waves and instabilities, but also offer a step forward to the overarching goal of providing the community with a model capable to interpret past and future observations of gas giants' atmospheres.

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