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

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Background and motivation The longevity of the richly-instrumented Cassini mission permitted an exceptionally detailed characterization, and monitoring over the changing seasons, of Saturn's a) latest Great White Spot[1] and associated stratospheric warming[2,3]; b) mid-latitude convective storms[4] and vortices[5,6]; c) stable hexagonal polar jet[7] and central turbulent polar vortex[8]; d) equatorial stratospheric oscillation of temperature, with jets stacked along the vertical, in Saturn's stratosphere[9] with semi-annual periodicity[10]; e) possible meridional transport of stratospheric hydrocarbons[11,12]. Cassini mapping of Jupiter's and Saturn's banded tropospheric jets in the cloud layer demonstrated the high rate of conversion of energy from eddies to banded jets[13,14] and detailed the structure of macroturbulence and vorticity[15,16], which strongly suggests that large-scale tropospheric banded jets emerge from forcing by smaller-scale eddies and waves arising from hydrodynamical instabilities. This harvest of Cassini observations has been complemented by Earth-based space telescopes[17], which enabled to monitor e.g. Jupiter's "quasi-quadriennal" equatorial oscillation[18]. Inserted in Jupiter's orbit in July 2016, the Juno spacecraft is currently acquiring, for the first time, microwave radiometry maps of water abundance and convective cloud opacity below Jupiter's visible cloud level (in the deep troposphere, at pressures exceeding 100 bars), high-order gravity measurements to infer the depth at which banded jets extend[19], and high-resolution images of Jupiter's Great Red Spot and polar regions. Cassini's Grand Finale in 2017 will also perform the latter two measurements for Saturn.

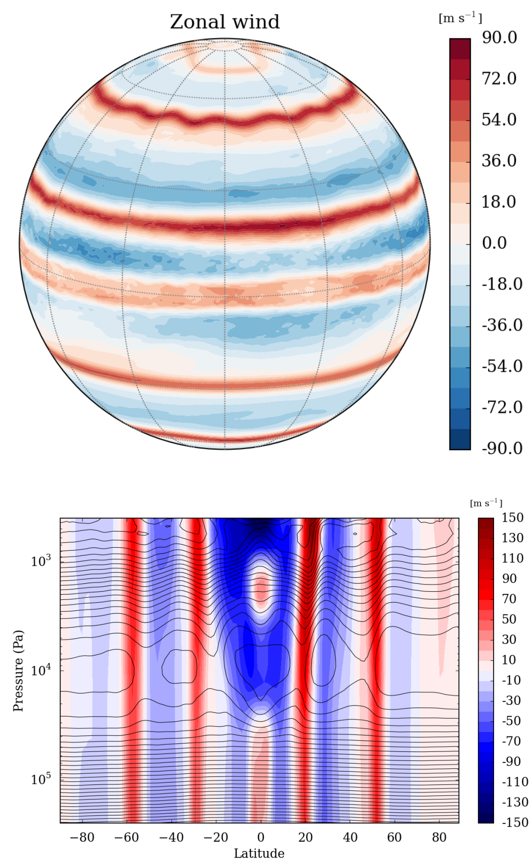

Figure 1: *[Top] Tropospheric 1.5-bar zonal wind obtained in the ninth simulated year ($L_s = 0°$) with our Saturn GCM. [Bottom] Pressure-latitude section of zonal-mean zonal winds for the same season and Saturn GCM simulation, with zonal-mean temperature contours superimposed.*

A new GCM for gas giants To address the new questions raised by those recent measurements, we built a new GCM for gas giants, both versatile and powerful enough to resolve the eddies arising from hydrodynamical instabilities and forcing the planetary-scale jets, to extend from the troposphere to the stratosphere with good enough vertical resolution, and to use optimized radiative transfer to predict seasonal tendencies over decade-long giant planets' years. To that end, we coupled our seasonal radiative model tailored for Saturn[20], and recently adapted to Jupiter as well[21], with DYNAMICO, the next state-of-the-art dynamical core for Earth and planetary climate studies in our lab, using an original icosahedral mapping of the planetary sphere which ensures excellent conservation and scalability properties in massively parallel resources[22].

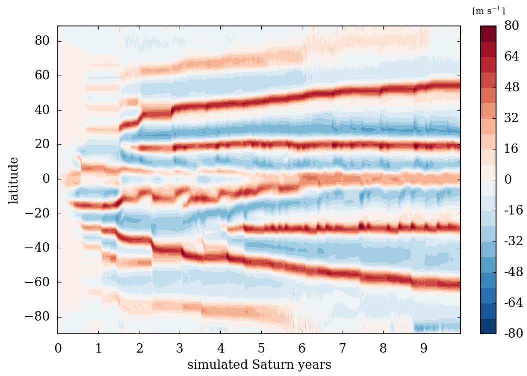

Figure 2: *The evolution of zonal-mean tropospheric zonal jets from our 10-year-long Saturn GCM simulation.*

1/2° Saturn GCM simulations Our GCM simulations for Saturn reproduce tropospheric mid-latitude jets bearing similarities with the observed jet system (numbering, intensity, width, see Figure 1). They also predict eastward-propagating Rossby-gravity (Yanai) waves at the equator, and high-wavenumber waves in mid-latitudes, as well as vortices. In contrast to observations, in our GCM simulations the equatorial jet is only weakly super-rotating and the polar jet is strongly destabilized by meandering. Our model predicts stacked stratospheric eastward and westward jets, but raising the model top is needed to address the equatorial oscillation. We find that jets are eddy-driven with a conversion rate from eddies to mean flow in agreement with Cassini estimates. Before reaching equilibrium, mid-latitude jets experience poleward migration (Figure 2), which can be ascribed to a self-destabilization of the jets by baro-tropic/-clinic instabilities. Our GCM simulations exhibit a stratospheric meridional circulation from one tropic to the other, with seasonal reversal, suggesting dynamical control on the observed variations of hydrocarbons.

Perspectives for Saturn and Jupiter We also carried out 1/4° and 1/8° Saturn GCM simulations with a "test" configuration (sponge layer and high dissipation). The simulated midlatitude jets' strengths are closer to observed values – and a more complete spectrum of eddies, waves, and vortices is resolved. Refining the vertical resolution is also considered as a path forward. Our Saturn GCM is only a first step towards a GCM system able to simulate all giant planet environnements: preliminary Jupiter GCM simulations will be presented to discuss measurements from JUNO and the (future) JUICE missions.

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