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1 Global climate modeling of Saturn's atmosphere.
2 Part IV: stratospheric equatorial oscillation.

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11 **Abstract**

The Composite InfraRed Spectrometer (CIRS) on board Cassini revealed an equatorial oscillation of stratospheric temperature, reminiscent of the Earth's Quasi-Biennial Oscillation (QBO), as well as anomalously high temperatures under Saturn's rings. To better understand these predominant features of Saturn's atmospheric circulation in the stratosphere, we have extended to the upper stratosphere the DYNAMICO-Saturn global climate model (GCM), already used in a previous publication to study the tropospheric dynamics, jets formation and planetary-scale waves activity. Firstly, we study the higher model top impact on the tropospheric zonal jets and kinetic energy distribution. Raising the model top prevents energy and enstrophy accumulation at tropopause levels. The reference GCM simulation with $1/2^\circ$ latitude/longitude resolution and a raised model top exhibits a QBO-like oscillation produced by resolved planetary-scale waves. However, the period is more irregular and the downward propagation faster than observations. Furthermore, compared to the CIRS temperature retrievals, the modeled QBO-like oscillation underestimates by half both the amplitude of temperature anomalies at the equator and the vertical characteristic length of this equatorial oscillation. This QBO-like oscillation is mainly driven by westward-propagating waves; a significant lack of eastward wave-forcing explains a fluctuating eastward phase of the QBO-like oscillation.

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We also show that the seasonal cycle of Saturn is a key parameter of the establishment and the regularity of the equatorial oscillation. At 20°N and 20°S latitudes, the DYNAMICO-Saturn GCM exhibits several strong seasonal eastward jets, alternatively in the northern and southern hemisphere. These jets are correlated with the rings' shadowing. Using a GCM simulation without rings' shadowing, we show its impact on Saturn's stratospheric dynamics. Both residual-mean circulation and eddy forcing are impacted by rings' shadowing. In particular, the QBO-like oscillation is weakened by an increased drag caused by those two changes associated with rings' shadowing.

12 *Keywords:* Saturn, Atmosphere, dynamics, stratosphere

13 **1. Introduction**

14 The longevity of the Cassini mission permitted an unprecedented spatial
15 and seasonal coverage of Saturn's stratosphere. In particular, the Composite In-
16 fraRed Spectrometer (CIRS) instrument on board Cassini revealed stratospheric
17 phenomena analogous to ones occurring in Earth's and Jupiter's stratospheres
18 ([Dowling, 2008](#)).

19 Firstly, seasonal monitoring of hydrocarbons in Saturn's stratosphere sug-
20 gests a conceivable inter-hemispheric transport of stratospheric hydrocarbons
21 ([Guerlet et al., 2009, 2010](#); [Sinclair et al., 2013](#); [Fletcher et al., 2015](#); [Sylvestre
22 et al., 2015](#)), similar to the Earth's Brewer-Dobson circulation which affects
23 the stratospheric ozone distribution ([Murgatroyd and Singleton, 1961](#); [Dunkert-
24 ton, 1979](#); [Solomon et al., 1986](#); [Butchart, 2014](#)). The Cassini mission further
25 revealed a lack of temperature minimum under the rings' shadow (that was
26 expected by the radiative balance [Fletcher et al. \(2010\)](#); [Friedson and Moses
27 \(2012\)](#); [Guerlet et al. \(2009, 2010, 2014\)](#)), which is an additional hint of subsi-
28 dence motion in the winter hemisphere.

29 Secondly, a crucial discovery is that temperatures retrieved from thermal
30 infrared spectra in Saturn's stratosphere exhibit an equatorial oscillation with
31 semi-annual periodicity ([Orton et al., 2008](#); [Fouchet et al., 2008](#)). During the

32 13-Earth-years cruise of Cassini around Saturn, CIRS and radio occultations
33 measurements permitted to characterize this equatorial oscillation of tempera-
34 ture and its downward propagation over seasonal timescales (Guerlet et al., 2011;
35 Li et al., 2011; Schinder et al., 2011; Guerlet et al., 2018). Alternatively east-
36 ward and westward stacked jets are associated with the temperature signatures
37 detected by Cassini, according to the thermal wind equation. This oscillation
38 is called Saturn “Quasi-Periodic Oscillation” or “Semi-Annual Oscillation”, due
39 to its half-Saturn-year periodicity. Equatorial oscillations appear to be common
40 phenomena in planetary stratospheres. Observations of Jupiter’s stratosphere
41 revealed an equatorial oscillation of temperature (Leovy et al., 1991; Orton et al.,
42 1991) associated with a wind propagation reversal (Friedson, 1999; Simon-Miller
43 et al., 2007). This oscillation exhibits a period of 4.4 Earth years and has been
44 designated as the jovian Quasi-Quadrennial Oscillation. Equatorial oscillations
45 are also suspected on Mars (Kuroda et al., 2008; Ruan et al., 2019). Those
46 equatorial oscillations in planetary atmospheres are reminiscent of the Earth’s
47 stratospheric Quasi-Biennial Oscillation (QBO) and Semi-Annual Oscillation
48 (SAO) (Lindzen and Holton, 1968; Andrews et al., 1983; Baldwin et al., 2001).

49 Earth’s Quasi-Biennial Oscillation (QBO) results from wave-mean flow inter-
50 actions (Reed et al., 1961; Andrews et al., 1983; Baldwin et al., 2001). The QBO
51 is driven by the vertical propagation of tropospheric waves – both planetary-
52 scale and mesoscale waves – to stratospheric altitudes where they break either
53 by becoming convectively unstable or by encountering critical level (depending
54 on vertical and horizontal wavelengths, wave phase speeds and vertical shear
55 (Lindzen and Holton, 1968; Dunkerton, 1997)). Critical levels play a central
56 role in driving the alternate eastward/weastward QBO phases by zonal mo-
57 mentum transfer. Radiative and mechanical damping of the waves also induce
58 wave absorption by the mean flow, as suggested by Holton and Lindzen (1972).
59 Equatorially trapped waves carry eastward and westward momentum. During
60 wave breaking, momentum is transferred to the mean flow, changing the large-
61 scale zonal wind field and driving an axisymmetric meridional circulation. The
62 observed Earth’s QBO displays a vertical stack of warm and cold anomalies

63 due to this meridional circulation: adiabatic warming in the subsidence region
64 produces warm anomalies and adiabatic cooling in the upwelling region pro-
65 duces cold anomalies (Plumb and Bell, 1982). The induced large-scale thermal
66 perturbations, and zonal wind reversal, oscillate with an average period of 28
67 months and a mean downward propagation rate of 1 km per month on Earth
68 (Reed et al., 1961; Mayr and Lee, 2016). The eastward and westward phases
69 of the Earth’s equatorial oscillation are of similar amplitude and are created
70 by a diversity of eastward- and westward-propagating wave sources (Dunker-
71 ton, 1997; Hamilton et al., 2001; Giorgetta et al., 2002; Ern and Preusse, 2009).
72 The terrestrial QBO’s eastward phase is produced by the wave breaking of
73 eastward-propagating gravity waves (from tropospheric moist convection) and
74 Kelvin waves. Kelvin waves contribute to about 30% of the eastward forcing
75 (Ern and Preusse, 2009), whereas mesoscale gravity waves contribute to 70%
76 of the eastward forcing (Dunkerton, 1997). The westward phase of the Earth’s
77 QBO is induced by Rossby and mixed Rossby-gravity waves’ breaking, as they
78 carry westward momentum. Furthermore, inertia-gravity waves transport east-
79 ward and westward zonal momentum, thus are involved in both the eastward
80 and westward phases of the QBO (Baldwin et al., 2001).

81 Despite differences in their periods, Jupiter’s and Saturn’s equatorial oscilla-
82 tions share similarities with the Earth’s (Dowling, 2008), which raises questions
83 about the driving mechanisms of the gas giants’ equatorial oscillations. Building
84 on tools developed throughout the long history of Earth’s atmospheric modeling,
85 numerical models of global circulation on Jupiter and Saturn have been devel-
86 oped for almost 20 years. Stratospheric oscillations on gas giants have been
87 previously addressed by a handful of those models. Three studies employed a
88 quasi-two-dimensional modeling framework that only resolves meridional and
89 vertical structure and parameterizes longitudinal forcing. On the one hand,
90 Li and Read (2000) demonstrated that the major contribution to a QBO-like
91 oscillation in Jupiter’s atmosphere was planetary-scale waves (Rossby, mixed
92 Rossby-gravity and Kelvin waves). On the other hand, Friedson (1999) and
93 Cosentino et al. (2017) showed that a parameterization of mesoscale gravity

94 waves enabled to reproduce the observed jovian equatorial oscillation – with no
95 need to invoke planetary-wave forcing.

96 Regardless of the nature of waves invoked in these studies, QBO-like oscilla-
97 tions are phenomena resulting from wave propagation in longitude, latitude and
98 on the vertical that cannot be fully resolved by 2D models: the 3D propagation
99 of waves, and their impact on global circulation, must be parameterized in 2D
100 models. Thus, to better understand the wave-mean flow interactions leading to
101 the observed gas giants’ equatorial oscillations, atmospheric models must solve
102 the three-dimensional dynamics. A fully three-dimensional model to study in
103 detail the global troposphere-to-stratosphere circulation in gas giants has only
104 been recently developed, because of the huge computational resources required
105 to resolve eddies arising from hydrodynamical instabilities that putatively force
106 equatorial oscillations. [Showman et al. \(2019\)](#) were the first to show the devel-
107 opment of a QBO-like oscillation in an idealized 3D global primitive-equation
108 model for gas giants and brown dwarfs. Their model uses a random wave forc-
109 ing parameterization at the radiative-convective boundary to drive equatorial
110 oscillations, and a Newtonian scheme to represent radiative heating/cooling in
111 the thermodynamics energy equation. A stack of eastward and westward jets
112 that migrate downward over time is created in the stratosphere of [Showman
113 et al. \(2019\)](#)’s model, analogous to Earth’s QBO, with a range of periods simi-
114 lar to Jupiter’s and Saturn’s equatorial oscillations. Nevertheless, the QBO-like
115 oscillations depicted in their model occur at higher pressure (between 10^5 and
116 10^3 Pa) than the observations (Saturn’s equatorial oscillation extends from 10^3
117 to 1 Pa).

118 To gain further insights on Saturn’s equatorial oscillation, this work aims
119 at adopting the three-dimensional approach of [Showman et al. \(2019\)](#) with a
120 more realistic representation of radiative transfer and wave dynamics in Saturn’s
121 stratosphere. The present paper is part IV of a series of papers about global
122 climate modeling of Saturn. In part I, [Guerlet et al. \(2014\)](#) built a complete
123 seasonal radiative model for Saturn. In part II, [Spiga et al. \(2020\)](#) coupled this
124 radiative model to a new hydrodynamical core ([Dubos et al., 2015](#)) to obtain

125 the DYNAMICO-Saturn Global Climate Model (GCM). Using this GCM tai-
126 lored for Saturn, [Spiga et al. \(2020\)](#) simulated Saturn’s atmosphere from the
127 troposphere to the lower stratosphere for 15 Saturn years at fine horizontal
128 resolution, without any prescribed sub-grid-scale wave parameterization. The
129 DYNAMICO-Saturn GCM simulation described in [Spiga et al. \(2020\)](#) produced
130 consistent thermal structure and seasonal variability compared to Cassini CIRS
131 measurements, mid-latitude eddy-driven tropospheric eastward and westward
132 jets commensurate to those observed (and following the zonostrophic regime –
133 see section 3 for details – as is argued in the part III paper by [Cabanès et al.](#)
134 [\(2020\)](#)), and planetary-scale waves such as Rossby-gravity (Yanai), Rossby and
135 Kelvin waves in the tropical waveguide. While the simulations in [Spiga et al.](#)
136 [\(2020\)](#) exhibited stacked eastward and westward jets in the equatorial strato-
137 sphere, those jets were not propagating downwards, contrary to the observed
138 equatorial oscillation. The likely reason for this is that the model top was too
139 low and the vertical resolution too coarse to address the question of a QBO-like
140 oscillation in the stratosphere.

141 In this paper, we use the DYNAMICO-Saturn model as in [Spiga et al. \(2020\)](#)
142 with a top of the model extended to the higher stratosphere. As in the part
143 II paper, the simulations presented here include neither a gravity-wave drag
144 nor the bottom thermal forcing invoked in [Showman et al. \(2019\)](#). Planetary-
145 scale waves involved in the equatorial dynamics are triggered by both baroclinic
146 and barotropic instabilities associated to tropospheric jets in our DYNAMICO-
147 Saturn GCM ([Spiga et al., 2020](#)). We describe here the benefits on the strato-
148 spheric dynamics of using a wider vertical extent in our GCM. In section 2,
149 we describe briefly our DYNAMICO-Saturn GCM. Section 3 presents, through
150 comparison between [Spiga et al. \(2020\)](#) and our results, the impact on dynamical
151 spectral regime of raising the model top. Section 4 focuses on the stratospheric
152 dynamics and wave-mean flow interactions producing a QBO-like oscillation in
153 our Saturn GCM. We also tested the Saturn annual cycle influences in its equa-
154 torial oscillation periodicity in section 5. In addition, a strong seasonal wind
155 reversal is obtained at 20°N and 20°S. We study this phenomenon and discuss

156 the impact of the rings' shadowing on the stratospheric tropical dynamics in
157 section 6. Summary, conclusions and perspectives for future improvements are
158 explained in section 7.

159 2. DYNAMICO-Saturn

160 A complete description of the DYNAMICO-Saturn is available in [Spiga et al.](#)
161 [\(2020\)](#). A Global Climate Model (GCM) is composed of two parts: a dynamical
162 core to resolve the Navier-Stokes equations on planetary scales and a physical
163 package which is an ensemble of parameterizations to describe sub-grid-scale
164 processes. The Saturn GCM developed at Laboratoire de Météorologie Dy-
165 namique employs DYNAMICO, a dynamical core using an icosahedral grid that
166 ensures conservation and scalability properties in massively parallel resources
167 ([Dubos et al., 2015](#)). It solves the primitive hydrostatic equations assuming a
168 shallow atmosphere. Our DYNAMICO-Saturn features an optional absorbing
169 (“sponge”) layer with a Rayleigh drag acting on the topmost model layers. As
170 in [Spiga et al. \(2020\)](#), we did not use it in simulations presented in this paper
171 since previous studies ([Shaw and Shepherd, 2007](#); [Schneider and Liu, 2009](#); [Liu](#)
172 [and Schneider, 2010](#)) show that using such an absorbing layer poses problems
173 of angular momentum conservation.

174 The physical package used in our DYNAMICO-Saturn is tailored for Saturn,
175 particularly regarding radiative transfer (this is fully detailed in the part I paper
176 by [Guerlet et al. \(2014\)](#)). Radiative transfer computations use correlated-k ta-
177 bles, tabulated offline from detailed line-by-line computations. Methane, ethane
178 and acetylene are included in radiative contributions, as well as H₂-H₂ and H₂-
179 He collision-induced absorption and aerosol layers in the troposphere and the
180 stratosphere. Rings’ shadowing is taken into account in radiative computa-
181 tions. The internal heat flux prescribed at the bottom of the model is used
182 as a boundary condition for radiative transfer calculations. Possible unstable
183 temperature lapse rates, induced after radiative transfer calculations, are mod-
184 ified by a convective adjustment scheme: the vertical profile of temperature is
185 instantaneously brought back to the dry adiabat.

186 Most simulation settings in this part IV paper are analogous to those adopted
187 in the part II paper by [Spiga et al. \(2020\)](#). For our *reference simulation*, we
188 employ DYNAMICO-Saturn with an approximate horizontal resolution of 1/2°

189 in longitude/latitude. The time step of calculations is 118.9125 seconds, with
190 physical packages called every half a Saturn day and radiative computations
191 done every 20 Saturn days, because of the long radiative timescales in tropo-
192 sphere and stratosphere of gas giants. The values of all parameters detailed in
193 Table 1 of [Spiga et al. \(2020\)](#) are set similarly in the simulations of this paper.
194 The major difference between [Spiga et al. \(2020\)](#) (Part II) and the present Part
195 IV reference simulation is the inclusion of 61 levels in the vertical dimension,
196 extending from the troposphere $p_{bottom} = 3.10^5$ Pa (or 3 bars) to the upper
197 stratosphere $p_{top} = 10^{-1}$ Pa (1 μ bar).

198 In this study, we opt for a reasonable yet not particularly high vertical dis-
199 cretization. Unlike [Showman et al. \(2019\)](#), we do not attempt to test the sen-
200 sitivity of the modeled equatorial oscillation to vertical resolution. We choose,
201 instead, to make a simulation long enough to reach a steady state in the tro-
202 posphere (at least 8 simulated Saturn years, see [Spiga et al. \(2020\)](#)) and to
203 simulate several cycles of the equatorial oscillation in the stratosphere. This
204 is crucial to obtain interactions between the troposphere and the stratosphere,
205 and create a conceivable and stable equatorial oscillation. This choice of mod-
206 eling strategy does not allow us to attest that the results presented here are
207 vertically convergent, which is deferred to another study. It is possible that a
208 simulation with twice as many levels over the same pressure range would give
209 quantitatively different results.

210 Simulations using our DYNAMICO-Saturn are initialized at every horizontal
211 grid point with a vertical profile of temperature computed by a 1D radiative-
212 convective equilibrium model of Saturn’s atmosphere ([Guerlet et al., 2014](#)),
213 using the same physical parameterizations than our DYNAMICO-Saturn GCM.
214 The single-column simulation starts with an isothermal profile and runs for
215 twenty Saturn years to reach the annual-mean steady-state radiative-convective
216 equilibrium. The initial zonal and meridional winds are set to zero in our
217 simulations. DYNAMICO-Saturn simulations requires radiative and dynamical
218 spin-up of about five simulated Saturn years for the tropopause levels to ensure
219 a dynamical steady-state ([Spiga et al., 2020](#)). In what follows, we present 13-

220 Saturn-year-long simulations to study Saturn’s stratospheric dynamics.

221 **3. Impact of the extended model top on Saturn’s atmospheric dy-** 222 **namics**

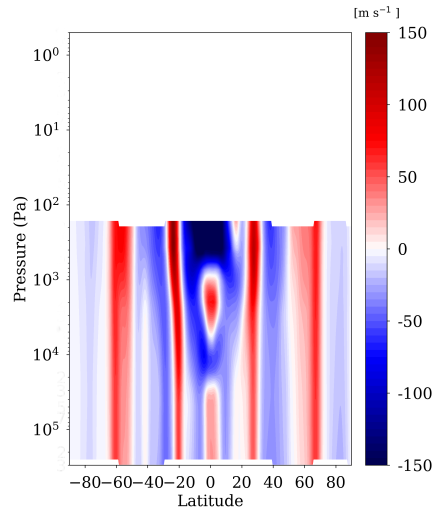
223 Saturn’s atmosphere is dominated by zonal jets, invariant in the longitudinal
224 direction (i.e. flow axisymmetry) and alternatively prograde (eastward) and
225 retrograde (westward) in latitude. The spherical curvature of the planetary fluid
226 layer acts to channel kinetic energy into the zonal direction via the so-called β -
227 effect, where the parameter $\beta = 2\Omega\cos\varphi/a$ is the variation of the Coriolis force
228 with Saturn’s radius a , rotation rate Ω and latitude φ . This dynamical regime is
229 referred to as zonostrophic macroturbulence (Sukoriansky et al., 2002; Galperin
230 et al., 2014). Further discussions on this topic can be found in the Part III
231 paper Cabanes et al. (2020).

232 Here, we present a comparison of tropospheric and stratospheric jets as sim-
233 ulated by Spiga et al. (2020) versus the present work, to check that the dy-
234 namical regime is conserved with the new vertical grid. Figure 1 displays alti-
235 tude/latitude sections of zonal-mean zonal wind after 11 years of simulation for
236 each vertical grid. Both simulations present similar results in the troposphere,
237 although with some notable differences. The 32-vertical-level simulation (Spiga
238 et al. (2020), Figure 1(a)) exhibits about 10 jets, over latitude, each one extend-
239 ing from 3×10^5 Pa (or 3 bars) to the model top (10^2 Pa or 1 mbar) except the
240 equatorial one. At the equator, there is a stacking of eastward and westward
241 jets between 2×10^4 Pa and the model top. With an extended vertical range
242 (Figure 1(b), model top at 10^{-1} Pa), we now distinguish 14 jets into the tropo-
243 sphere and 9 jets in the stratosphere. The equatorial stacking of wind seen in
244 32-level simulation is now clearly localized between 2×10^4 Pa (tropopause) and
245 the model top. Contrary to previous GCM works (Lian and Showman, 2008,
246 2010; Schneider and Liu, 2009), we remark that some of eastward jets of the
247 61-level simulation, particularly ones closer to the equator, decay with altitude,
248 which is not the case in the 32-level one (except for the equatorial jet). In

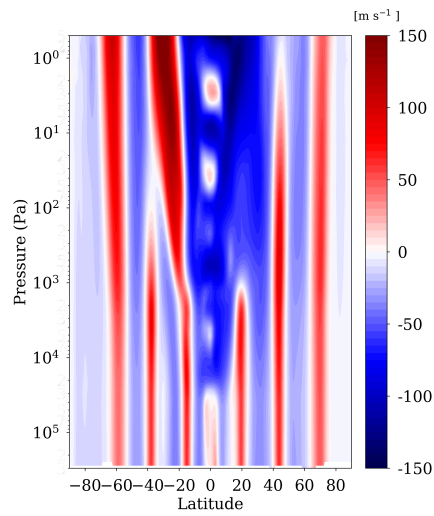
249 both simulations, the jets beyond 60° latitudes do not exhibit this decay with
250 altitude. Thus the behavior of our 61-level troposphere-to-stratosphere simula-
251 tion is more consistent with observations for the lower latitudes (Fletcher et al.,
252 2019). We also note that the equatorial tropospheric eastward jet is less intense
253 in our reference (61-level) simulation than in the 32-level simulation of Spiga
254 et al. (2020).

255 We now extend our comparison by computing the spherical harmonic de-
256 composition of horizontal velocity maps from our 61-level simulation, using the
257 same tools as in the Part III paper (Cabanès et al., 2020) for the 32-level simu-
258 lation. When spherical harmonic functions are invoked, energy spectra depend
259 on non-dimensional total and zonal indices n and m respectively (Boer, 1983).
260 The axisymmetric flow component defines the jets and corresponds to the zonal
261 index $m = 0$. The non-axisymmetric flow component, or residual, defines waves
262 and eddies and corresponds to all other indices $m \neq 0$. We report on Figure 2
263 the time evolution of the total energy integrated over all indices, for the upper
264 troposphere and the lower stratosphere. The general tendency shows that the
265 total energy in the troposphere is similar in our 61-level simulation and in the
266 32-level simulation of Spiga et al. (2020). However, the stratosphere is more
267 energetic than the troposphere and the energetic intensity reduces by a factor
268 of two when we extend the model top in the 61-level simulation.

269 We show the temporal average of the spectral quantities at steady state in
270 the upper troposphere in Figure 3 and the lower stratosphere in Figure 4. A
271 common feature of the 32-level and 61-level simulations is that the energetic
272 magnitude of the zonal jets (i.e. axisymmetric spectra in red) is bounded by
273 the $0.5\beta^2 n^{-5}$ spectral law of the zonostrophic theory coined by Sukoriansky
274 et al. (2002). The energetic maximum is well estimated by the Rhines typical
275 index $n_R = a(\beta/2U)^{1/2}$ (Rhines, 1977), which sets typical jets' size to $\sim 38,000$
276 km in the troposphere and $\sim 44,000$ km in the stratosphere (see details in
277 Figure 3). At Rhines scale, the energy of the jets is two orders of magnitude
278 higher than the residual energy spectra, namely the energy contained in waves
279 and eddies. To disclose the dynamical transfers underlying this jet-dominated



(a)



(b)

Figure 1: Altitude/latitude cross sections of the zonal-mean zonal wind, at the northern spring equinox, comparing [Spiga et al. \(2020\)](#) results (32 vertical levels, 1(a)) and our results using 61 vertical levels (1(b)).

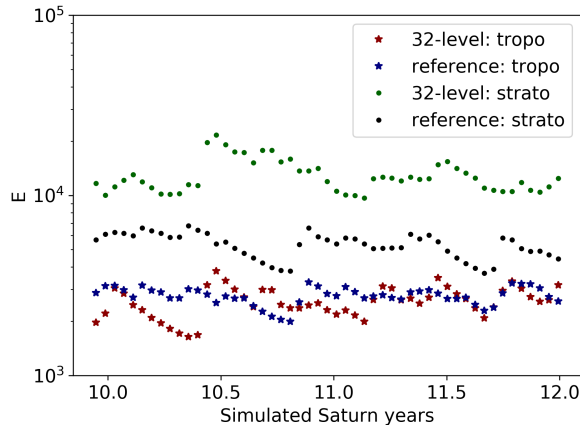


Figure 2: Time evolution of the total energy ($\text{m}^2 \text{s}^{-2}$) in the two last simulated Saturn years for each simulation. Red and green curves correspond to the 32-level simulation at $p \sim 1.9 \times 10^4$ Pa and $p \sim 4.9 \times 10^2$ Pa respectively. Blue and black curves correspond to the reference simulation at $p \sim 1.9 \times 10^4$ Pa and $p \sim 4.9 \times 10^2$ Pa respectively.

280 flow, we also report in Figures 3 and 4 the spectral fluxes of energy and en-
 281 strophy. In all simulations, spectral fluxes clearly show the predominance of an
 282 inverse cascade of energy at large scale and a direct cascade of enstrophy at
 283 small scale. This energy-enstrophy double cascade scenario is a well-known fea-
 284 ture of quasi-two-dimensional (2D) turbulence, when a turbulent flow is made
 285 quasi-2D by confinement to a shallow atmosphere and under rapid planetary
 286 rotation (Pouquet and Marino, 2013; Cabanes et al., 2020). For the 32-level
 287 simulation, Cabanes et al. (2020) showed that the inverse cascade of energy
 288 results from the barotropization of baroclinic eddies at small scales and drives
 289 the large scale atmospheric flow.

290 What Figures 3 and 4 also show is that the eddy spectra is different in our
 291 61-level simulation compared to the 32-level simulation analyzed in Spiga et al.
 292 (2020) and Cabanes et al. (2020). In the 32-level simulation, the tropospheric
 293 residual spectrum barely fits the well-known Kolmogorov-Kraichnan (KK) law
 294 $\epsilon^{2/3} n^{-5/3}$ (Kraichnan, 1967a) evocative of the inverse turbulent cascade with the
 295 energy transfer rate $\epsilon = 2 \times 10^{-6} \text{ W Kg}^{-1}$. Conversely, in the 61-level reference

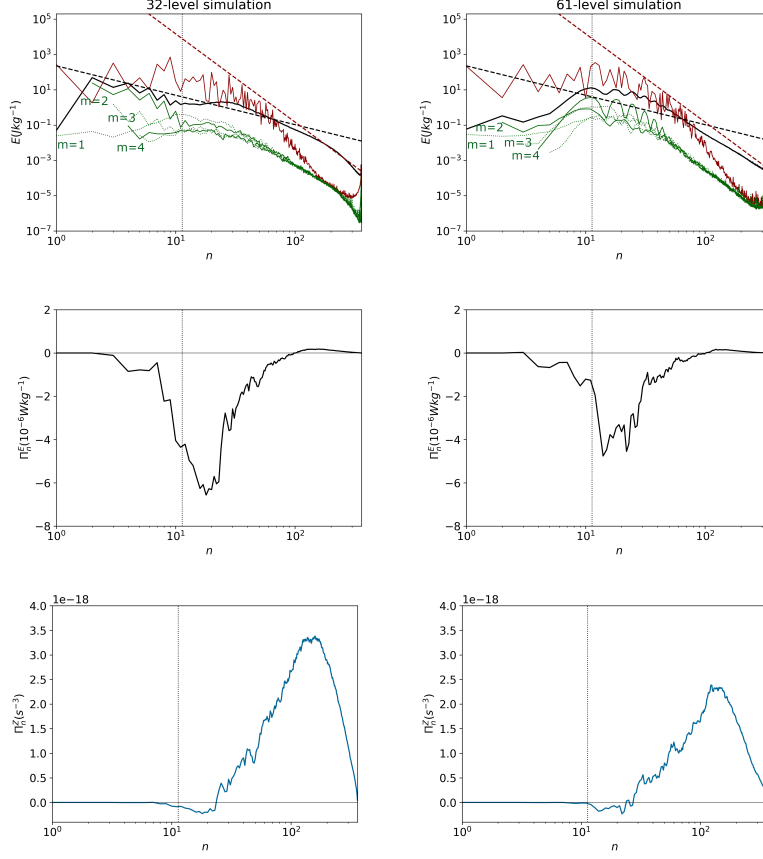


Figure 3: Comparative spectral analysis of the 32-level simulation (left) and the reference simulation (right) in the upper tropospheric level $p \sim 1.9 \times 10^4$ Pa. Spectral quantities are averaged in time, over the tenth to twelfth simulated Saturn years, and in altitude, over pressure levels $(1.7 < p < 2) \times 10^4$ Pa. Top panels show kinetic energy spectra: the zonal spectra in red (i.e. axisymmetric $m = 0$ mode), the residual spectra in black (i.e. sum over all non-axisymmetric $m \neq 0$ modes shown separately), the modal spectra are shown for zonal modes $m = 1$ to 5 in green. Middle and bottom panels represent the spectral energy and enstrophy fluxes respectively. Positive fluxes corresponds to downscale energy/enstrophy transfers (a “direct” cascade) and negative fluxes are upscale energy/enstrophy transfers (an “inverse” cascade). All spectral quantities are function of the total indices n . At any typical length scale in latitude L , one can attribute a typical index by the relation $n = 2\pi a/L$. Dashed lines are (black) the theoretical Kolmogorov-Kraichnan law $6\epsilon^{2/3}n^{-5/3}$ with the energy transfer rate $\epsilon = 2 \times 10^{-6} \text{ W kg}^{-1}$ (Kraichnan, 1967b) and (red) the theoretical zonostrophic law $0.5\beta^2 n^{-5}$. The vertical dotted lines are the Rhines indices $n_R = a(\beta/2U)^{1/2}$, with U the square root of the total energy presented in Figure 2. It corresponds to the typical length scale $\sim 32,000$ km for both simulations. All our calculation consider a parameter $\beta = 4 \times 10^{-12} \text{ m}^{-1} \text{ s}^{-1}$ estimated at mid-latitude $\varphi = 45^\circ$.

296 simulation, the $-5/3$ KK slope does not apply to the residual spectrum that
 297 shows an energetic bump at intermediate indices (i.e. $10 < n < 100$). The 32-
 298 level simulation also features very energetic non-axisymmetric modes $m = 1, 2, 3$
 299 (see modal spectra in green) that dominate in the residual spectrum beyond the
 300 Rhines index ($n < n_R$) and extend the $-5/3$ slope to small indices (i.e. down to
 301 $n \sim 2$). Such modes or waves are absent in the 61-level simulation and energy of
 302 the residual spectrum decreases at indices smaller than the Rhines index. It is
 303 likely that the energetic $m = 1, 2, 3$ modes enforced in the 32-level simulation are
 304 artifacts of the shallow geometry. By extending the model top, we also release
 305 part of the flow confinement in the vertical that promotes a quasi-2D flow. This
 306 release might explain the reduction of the energy and enstrophy fluxes in the
 307 61-level simulation compared to the 32-level simulation. The raise of model
 308 top towards stratospheric levels appears to significantly impact the statistical
 309 properties of the tropospheric flow. Saturn’s direct observations, akin to those
 310 used for Jupiter in [Young and Read \(2017\)](#), are required to further validate our
 311 model.

312 Statistical properties are mostly similar in the upper troposphere and in
 313 the lower stratosphere (Figure 4). The 32-level simulation preserves a $-5/3$
 314 residual spectrum that prevails at all indices in the lower stratosphere. In the
 315 61-level simulation, the residual spectrum is substantially steepened and spectral
 316 energy piles up in the range $n > n_R$, to decrease beyond Rhines index. In both
 317 simulations, the integrated total energy in the stratosphere is more energetic
 318 than in the troposphere (Figure 2), with energy fluxes one order of magnitude
 319 higher in the stratosphere. This might result from the growth of baroclinic
 320 instabilities that preferentially form in the stratosphere ([Cabanès et al., 2020](#)).
 321 The integrated total energy also show that the 32-level simulation predicts a
 322 flow at stratospheric levels more energetic by a factor of 2 than in the 61-level
 323 simulation. In the former simulation, the top of the model is close to the lower
 324 stratosphere, therefore an energy accumulation likely produces these high values
 325 of total energy – and might also create wave reflection leading to energetic non-
 326 axisymmetric modes $m = 1, 2, 3$.

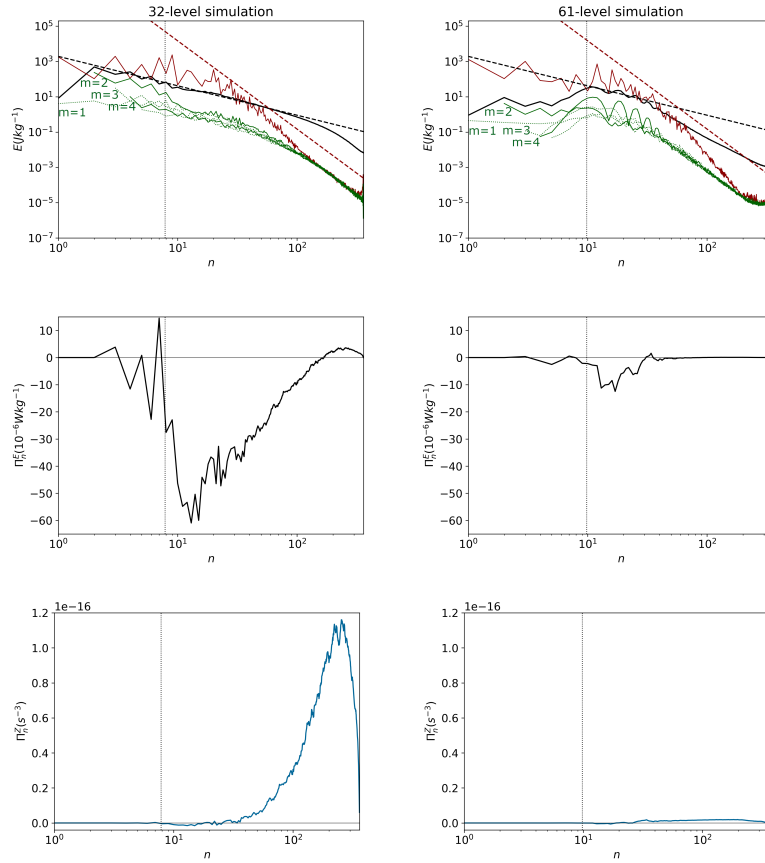


Figure 4: Comparative spectral analysis of the 32-level simulation (left) and the reference 61-level simulation (right) in the stratospheric level $p \sim 4.9 \times 10^2$ Pa. Spectral quantities are averaged in time, over the tenth to twelfth simulated Saturn years, and in altitude, over pressure levels $(4.7 < p < 6) \times 10^2$ Pa. The dashed black lines are the KK-law with the energy transfer rate $\epsilon = 5 \times 10^{-5} \text{ W kg}^{-1}$ (Kraichnan, 1967b). The Rhines typical indices correspond to a typical length scale of $\sim 47,000$ and $\sim 37,000$ km for the 32-level and 61-level simulations respectively. All other spectral quantities are similar to the caption of Figure 3

327 Finally, we propose in Figure 5 a spectral analysis similar to those of Figure 3
 328 and 4 for the stratospheric level 25 Pa of our 61-level simulation, left unresolved
 329 in the previous Part II and III papers. At the smallest resolved scales, the
 330 zonal kinetic spectrum depicts a -5 slope with estimated values of $\epsilon=8\times 10^{-6}$
 331 W kg^{-1} , two orders of magnitude less than the residual kinetic spectrum. As
 332 in the troposphere (Figure 3, right top row), the large scales are driven by a
 333 strong zonal anisotropy linked to zonostrophic turbulence. In the stratosphere,
 334 our simulation indicates that the modes $m = 2$ and 4 are dominant in the
 335 residual spectrum, suggesting that strongly-energetic waves propagate in the
 336 zonal direction. The spectral flux of energy depicts huge negative values for
 337 moderate n , contrary to tropospheric results in Figure 3. The inverse energy
 338 cascade, from the small scales to the large scales, is operating in the stratosphere
 339 for most intermediate scales between $n = 3$ and $n = 10^2$. At both the largest
 340 and the smallest resolved scales, the energy flux becomes positive denoting a
 341 direct energy cascade (energy is transferred from the large to the small scales).
 342 Aside from the positive peak around $n = 3$, the global trend of energy flux is
 343 equivalent in the troposphere and the stratosphere. The enstrophy flux confirms
 344 the dynamical regime of the stratosphere (bottom row of Figure 5): it is positive
 345 for n higher than 10, which suggests the existence of an inverse cascade.

346 4. Equatorial stratospheric dynamics with the DYNAMICO-Saturn

347 4.1. Global stratospheric zonal wind

348 The temporal evolution of the zonal-mean stratospheric zonal wind over
 349 the whole 13-year duration of our DYNAMICO-Saturn simulation is shown in
 350 Figure 6 at the pressure level of 40 Pa. Before turning to low latitudes, we
 351 note that at high and mid-latitudes, zonal jets undergo a poleward migration
 352 due to bursts of eddies induced by baroclinic instabilities. This migration was
 353 already witnessed by Spiga et al. (2020) in the troposphere and is thought to be
 354 partly caused by baroclinicity at the bottom of the model (3×10^5 Pa), where the
 355 meridional gradient of temperature is slightly overestimated compared to the

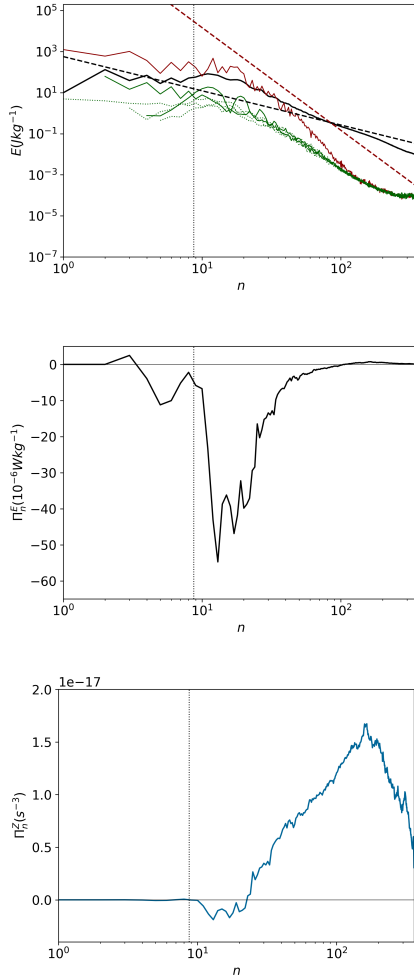


Figure 5: Spectral analysis of the reference simulation in the stratospheric level $p \sim 25$ Pa. Spectral quantities are averaged in time, over the tenth to twelfth simulated Saturn years, and in altitude, over pressure levels $21 < p < 27$ Pa. The dashed black lines are the KK-law with the energy transfer rate $\epsilon = 8 \times 10^{-6} \text{ W kg}^{-1}$ (Kraichnan, 1967b). The Rhines typical indices correspond to a typical length scale of $\sim 42,000$ km. All other spectral quantities are similar to the caption of Figure 3

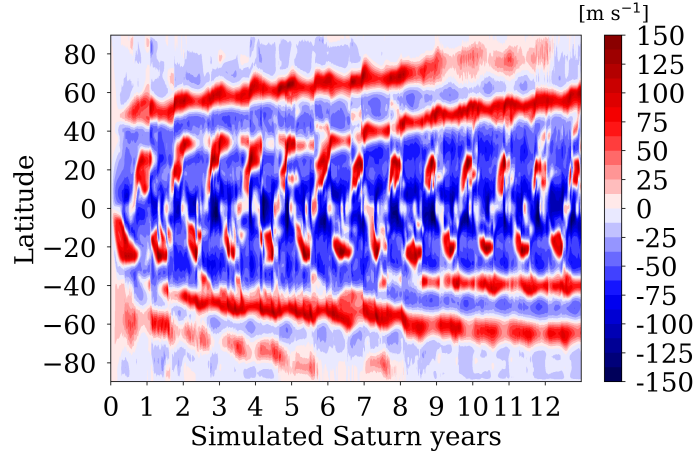


Figure 6: Time evolution of the zonal-mean zonal wind in Saturn’s stratosphere (40 Pa) within the whole 13-years duration of our DYNAMICO-Saturn simulation. The wind structure at this pressure level is typical of conditions between the tropopause and the model top in the upper stratosphere.

356 observations. Furthermore, [Chemke and Kaspi \(2015\)](#) show that the poleward
 357 migration of baroclinic eddy-driven jets is consistent with an asymmetry in the
 358 baroclinic growth around the jet’s core: the poleward flank of the jet can be
 359 slightly more baroclinically unstable than the equatorward flank. The baroclinic
 360 growth precedes the increase of the eddy momentum flux convergence, causes
 361 the eddy forcing to be shifted slightly poleward of the jet peak, and thus drives
 362 the poleward migration of the jets.

363 Now, turning to the low latitudes simulated in our reference 61-level Saturn
 364 simulation, we notice in [Figure 6](#) two key features in the temporal evolution of
 365 the stratospheric zonal-mean zonal wind:

- 366 • an alternatively eastward and westward wind direction at the equator,
 367 with a sub-annual periodicity, appearing in the second simulated year and
 368 maintained for the rest of the 13 simulated years;
- 369 • an alternatively eastward and westward wind direction at 20°N and 20°S,

370 with an annual periodicity and a phase opposition between the northern
371 and the southern hemisphere.

372 These two features are discussed in detail in the following sections.

373 *4.2. Equatorial stratospheric zonal jets*

374 By making an altitude/time section of the zonal-mean zonal wind at the
375 equator (Figure 7), for the four last years of our 13-years simulation, the down-
376 ward propagation with time of the stacked stratospheric eastward-westward jets
377 is well visible. At a given pressure level, the zonal wind alternates between east-
378 ward and westward direction, with a westward phase more intense – about -100
379 m s^{-1} (Figure 9 in Showman et al. (2019) shows a similar behaviour) – than
380 the eastward one (only 60 m s^{-1}). In addition, at a given pressure level, the
381 westward phase lasts longer than the eastward one. The equatorial eastward
382 phases of the oscillation seem to be unstable and disturbed compared to west-
383 ward phases. For this reason, the period of the resulting equatorial oscillation
384 is irregular in time.

385 As is reminded in the introduction, a pattern of alternatively eastward and
386 westward jets stacked on the vertical, with a downward propagation, reminds
387 both the Quasi-Biennial Oscillation (QBO) on Earth and the QBO-like oscil-
388 lation evidenced in Cassini observations (Fouchet et al. (2008), Guerlet et al.
389 (2011), Li et al. (2011), Orton et al. (2008), Guerlet et al. (2018)). We tracked
390 the equatorial jets to calculate the periodicity and the downward propagation
391 rate of the modeled QBO-like oscillation. Our DYNAMICO-Saturn produces a
392 QBO-like oscillation with a period in the range 0.3-0.7 Saturn year. The cor-
393 responding stacked jets’ downward propagation rate is respectively between 73
394 and 60 km per Saturn month. In Fletcher et al. (2017), Cassini observations
395 were used to estimate a period of 0.50 ± 0.03 Saturn year and a downward prop-
396 agation speed of (42 ± 2) km per Saturn month. Guerlet et al. (2018) estimated
397 a downward propagation of 24.5 km per Saturn month at 500 Pa and 49 km
398 per Saturn month at 10 Pa. Hence, the DYNAMICO-Saturn simulation exhibit
399 an equatorial oscillation periodicity of the right order of magnitude compared

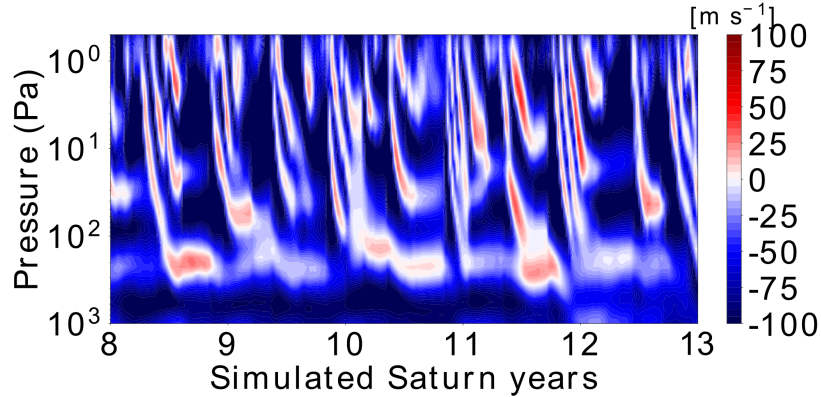


Figure 7: Altitude/time section at the equator of the zonal-mean zonal wind in Saturn's stratosphere for the 5 last years of our 13-years DYNAMICO-Saturn simulation.

400 to the observations, but more irregular. Moreover, the stacked zonal jets in
 401 our simulation propagate downward 1.5 times too fast compared to the obser-
 402 vations. The irregularity in both the oscillating period and the downward rate
 403 propagation could be due to the absence of sub-grid-scale waves parameteriza-
 404 tion, which, as is explained in introduction, contribute to 70% of the eastward
 405 phase forcing in the Earth's QBO.

406 The second notable feature in Figure 6 is the strong alternating eastward
 407 and westward jets at around 20°N and 20°S , with a seasonal phase opposition
 408 between the northern and southern hemispheres. Compared to a time evolution
 409 of the incoming solar radiation (Figure 8), we remark that each eastward jets
 410 emerge during the winter and seem to be correlated to the rings' shadowing.
 411 Those tropical eastward and westward jets both have an amplitude of about
 412 100 m s^{-1} , contrary to the QBO-like equatorial oscillation which exhibits an
 413 eastward phase weaker than the westward phase. This pattern exhibits a regular
 414 one-Saturn-year periodicity without downward propagation: the jets shown in
 415 Figure 6 at 40 Pa extend from 10^3 Pa to the model top (Figure 9).

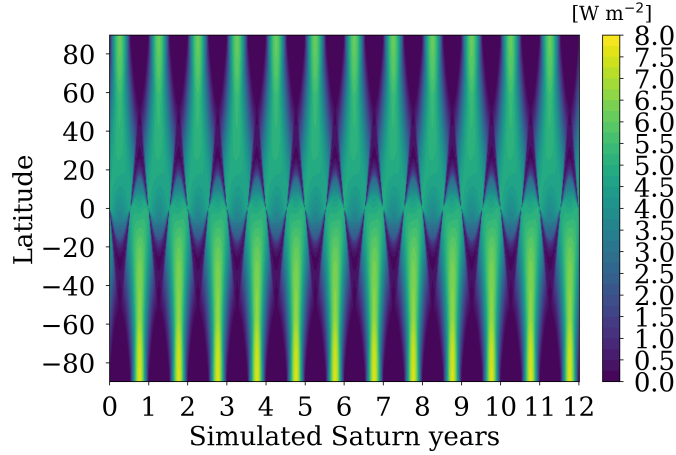
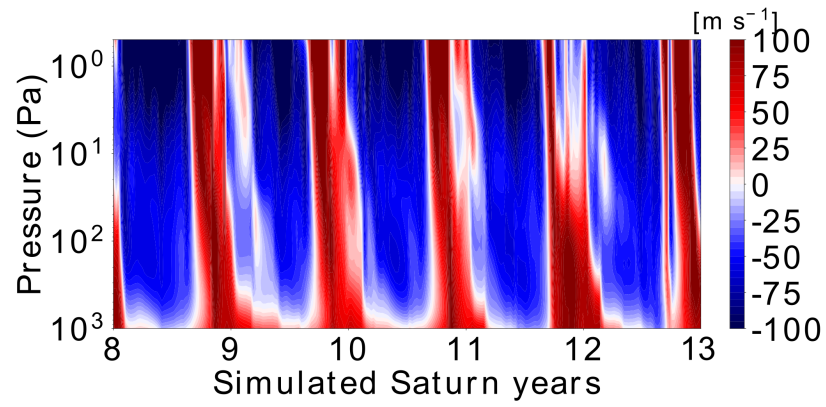


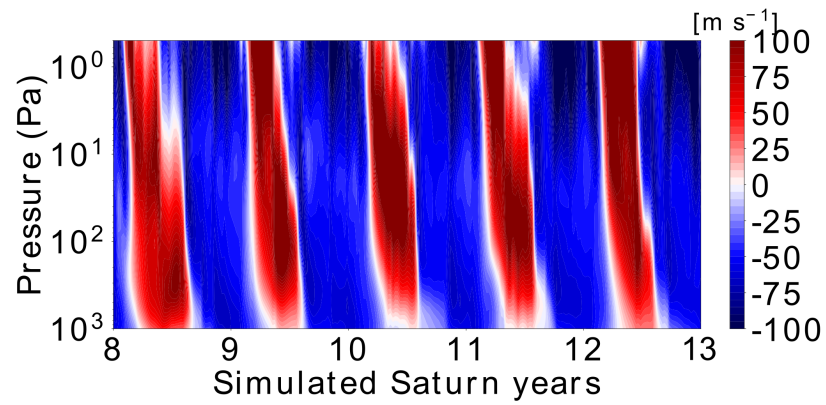
Figure 8: Temporal evolution of the incoming solar radiation in Saturn’s atmosphere on the whole 12-year DYNAMICO-Saturn simulation

416 *4.3. Equatorial stratospheric thermal structure*

417 In this section, we compare our DYNAMICO-Saturn simulations with the
 418 observations of Saturn’s equatorial stratosphere by Cassini/CIRS. Stratospheric
 419 winds have never been measured; rather, the CIRS instrument on-board the
 420 Cassini spacecraft allowed the retrieval of stratospheric temperature vertical
 421 profiles and stratospheric winds were calculated using thermal wind balance.
 422 It is therefore relevant to compare the observed and simulated stratospheric
 423 temperatures. Figure 10 represents altitude/latitude section of temperature
 424 simulated by DYNAMICO-Saturn in the stratosphere. Between 8°N and 8°S,
 425 this meridional section exhibits a stack of local maxima (around 148 K) and
 426 minima (130 K) of temperature from 10^2 Pa to the top of the model. The
 427 pattern of alternating temperature extrema propagate downward with time.
 428 Temperature oscillates with a 10 K-magnitude around 140 K with a period
 429 and a descent rate equivalent to the wind’s. Moreover, temperature extrema
 430 at the equator are anti-correlated to those occurring in the tropics. At a given
 431 pressure level, the cold equator regions are flanked by warmer tropical regions



(a)



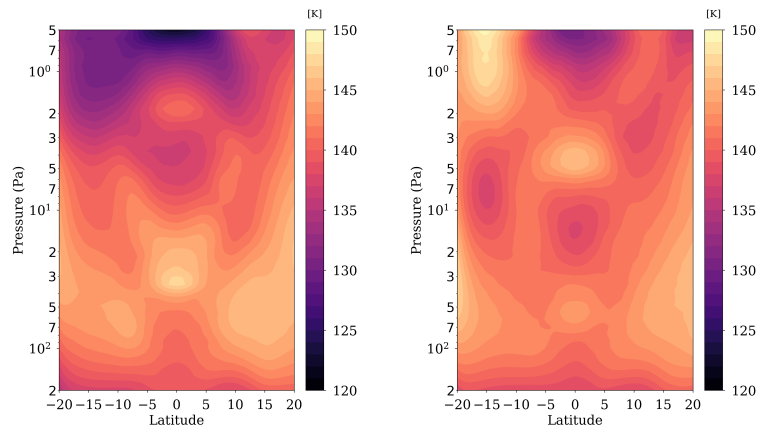
(b)

Figure 9: Altitude/time section at 20°N (9(a)) and 20°S (9(b)) of the zonal-mean zonal wind in Saturn's stratosphere for the 5 last years of our 13-years DYNAMICO-Saturn simulation.

432 at 10 to 15°N and at 10 to 15°S. Using the thermal-wind equation applied
433 assuming a geostrophically balanced flow, this significant meridional gradient
434 of temperature confirms the presence of a significant vertical shear of the zonal
435 wind at the equator.

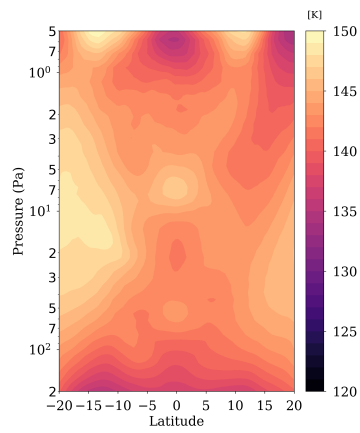
436 To compare our simulation to CIRS observations, we re-mapped altitude vs
437 latitude sections of modeled and observed temperatures with the same temper-
438 ature range. GCM results are mapped in Figure 11 and CIRS limb observations
439 (acquired in 2005, 2010 and 2015) in Figure 12, focused on high stratospheric
440 levels. To carry out this comparison, we used CIRS data already processed in
441 [Guerlet et al. \(2018\)](#). Our DYNAMICO-Saturn simulation produces a temper-
442 ature field qualitatively consistent with observations, with alternative maxima
443 and minima of temperature stacked on the vertical in the stratosphere. There
444 are between 3 and 4 temperature extrema in our DYNAMICO-Saturn model
445 whereas there are only 2 (2010) or 3 (2005 and 2015) temperature extrema in
446 CIRS temperature retrievals. Moreover, observations show a temperature oscil-
447 lation from 170 K to 120 K, with a 20 K-magnitude, hence twice as much as in
448 our Saturn GCM simulations.

449 To highlight the anomalies temperature resulting of the modeled and ob-
450 served Saturn equatorial oscillation, we map temperature differences between
451 two half-period-separated dates. Figure 13 displays altitude/latitude sections
452 of temperature differences between the dates 8.53 and 8.5 years (top left) and
453 between the dates 8.6 and 8.53 years (bottom left) of Figure 11. Comparison
454 with CIRS measurements (right rows of Figure 13) shows the similarities and
455 differences in the modeled and observed QBO-like oscillations. Temperature
456 differences underline a stack of positive and negative anomalies of temperature,
457 with Saturn-DYNAMICO underestimating the amplitude by a factor of 2 com-
458 pared to the observations. The characteristic vertical size of the DYNAMICO-
459 Saturn QBO-like oscillations is two times smaller than the observed one. Our
460 DYNAMICO-Saturn underestimates the temperature maximum by around 20 K
461 and underestimates the magnitude of the temperature anomalies by 10 K. An-
462 other difference between the Cassini observations and the GCM-modeled equato-



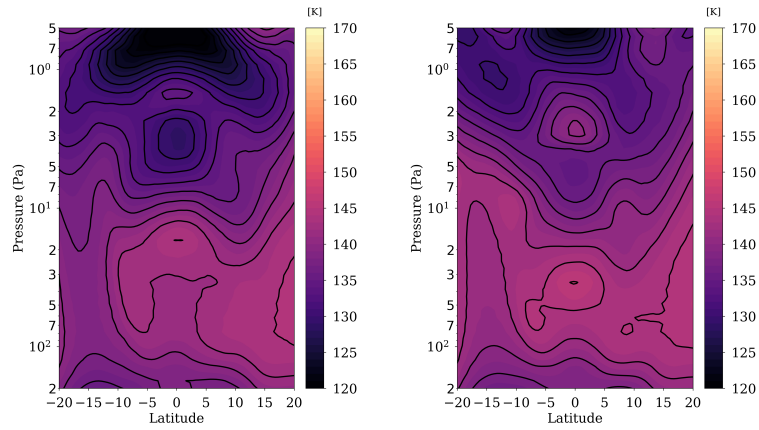
(a)

(b)



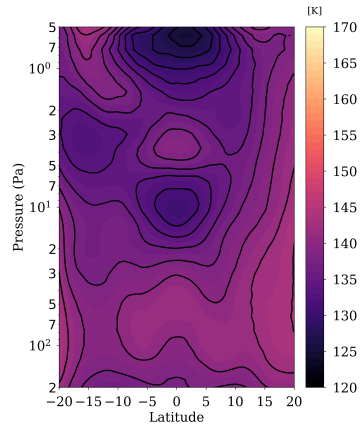
(c)

Figure 10: Altitude/latitude sections of zonal-mean temperature in Saturn's stratosphere at three dates of simulation: 10(a) at 10.45 years, 10(b) at 10.55 years and 10(c) at 10.60 years.



(a)

(b)



(c)

Figure 11: Altitude/latitude sections of zonal-mean temperature in Saturn's stratosphere at the 8.5 (11(a)), 8.53 (11(b)) and 8.6 (11(c)) years to compare with CIRS measurements (Figure 12). Contour lines are separated by 2 Kelvin.

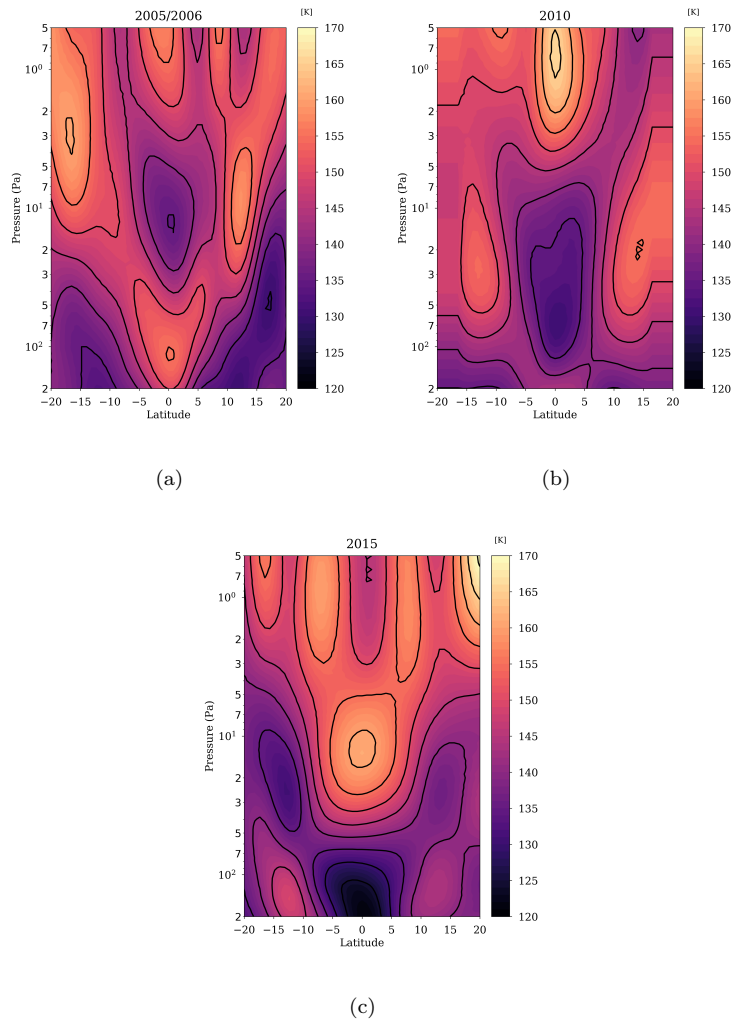


Figure 12: Altitude/latitude sections temperature measured by Cassini CIRS instrument at 2005/2006, 2010 and 2015 (analogous to Guerlet et al. (2018) Figure 3 top row but focused here on high stratospheric levels). Contour lines are separated by 5 Kelvin.

463 rial oscillation is the vertical extent of the temperature anomalies at the equator.
464 Cassini radio occultation data showed that the descending temperature minima
465 and maxima extend down to the tropopause level, around 100 hPa (Schinder
466 et al., 2011) whereas in the Saturn-DYNAMICO simulations there is no more
467 equatorial-oscillation signal below the 1-2 hPa level.

468 We can also compare our simulations to the idealized work of Showman et al.
469 (2019). In their idealized simulation, they obtain a temperature oscillation of
470 about ~ 10 K that migrate downward over time (Figure 8 of Showman et al.
471 (2019)), as in our simulation. Moreover, we obtain a stack of temperature ex-
472 tremes spatially close to each other on the vertical, contrary to their simulation,
473 where the extremes of temperature are half a decade (in pressure) apart from
474 each other by a constant temperature zone. In our and their simulations, op-
475 posite extremes of temperature (at a given pressure level), centered between 10
476 and 15 latitude degrees (both north and south), are generated. There is, in the
477 two simulations, an anti-correlation between temperature extremes at the equa-
478 tor and those occurring off the equator. With DYNAMICO-Saturn, compared
479 to the CIRS observations, we obtain a more realistic patterns of temperature
480 anomalies at the equator than the idealized work of Showman et al. (2019), but
481 there are still some notable differences with the CIRS observations.

482 Another feature of Saturn’s stratosphere observed by Cassini/CIRS is the
483 anomalously high temperatures under the rings’ shadows (Fletcher et al., 2010).
484 Previous radiative simulations of Saturn’s atmosphere failed to reproduce these
485 temperature anomalies (Guerlet et al., 2014), hence dynamical heating was con-
486 sidered to explain this feature.

487 In our simulations, there is an interplay between the tropical eastward jets
488 and temperature evolution, displayed in Figure 14. In wintertime, at 20° lat-
489 itude, the temperature starts by cooling rapidly (from 150K to 140K), which
490 is likely due to the ring’s shadow radiative effect. Then, when the eastward
491 jet increases in strength, this low temperature region is significantly reduced,
492 there is an increase of temperature from 140K to 145K. This is true only near
493 the core of the eastward jet, at 20° . Indeed, at 30° latitude, the temperature

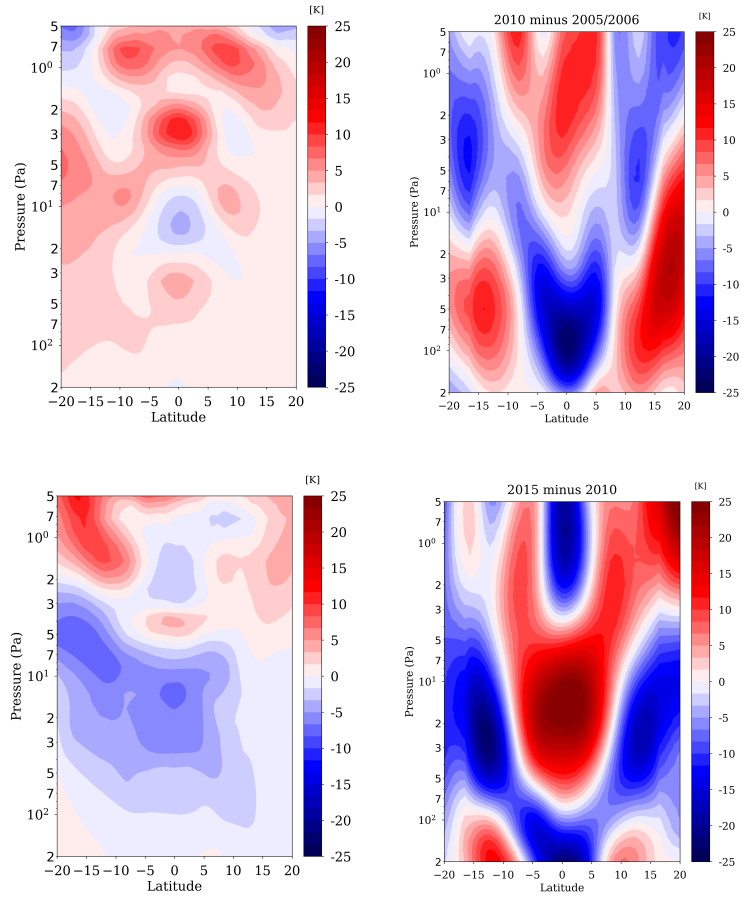


Figure 13: Altitude/latitude sections of temperature differences between two half-period-separated dates (left: DYNAMICO-Saturn results and right: as derived from CIRS measurements, analogous to [Guerlet et al. \(2018\)](#) Figure 3 bottom row) in Saturn's stratosphere. The modeled temperature oscillation underlines a vertical characteristic length twice as small as the observed one and a amplitude differences weaker than derived from CIRS measurements.

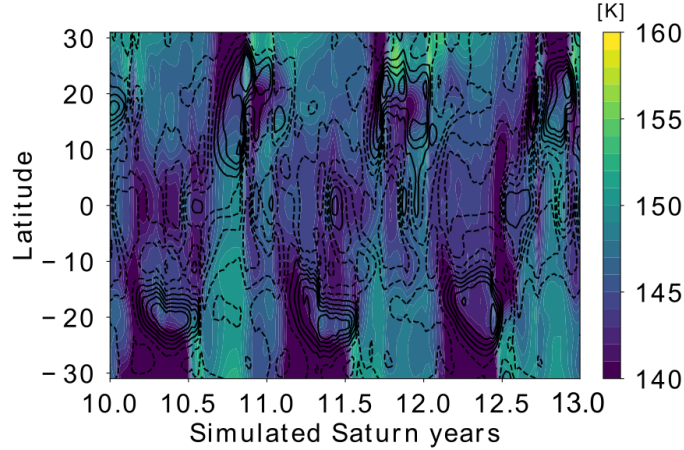


Figure 14: Time evolution of the zonal-mean temperature (color) and the zonal-mean zonal wind (contours spacing by 25 m s^{-1} between -100 m s^{-1} and 100 m s^{-1}) in Saturn's stratosphere (40 Pa) of our 13-years DYNAMICO-Saturn simulation.

494 remains very cold (140K) throughout wintertime. We will assess in more detail
 495 the dynamical impact of ring shadowing in the stratosphere in section 6.

496 4.4. Equatorial stratospheric planetary-scale waves

497 According to the terrestrial experience, equatorial oscillation results from
 498 both planetary-scale waves and mesoscale waves forcing. In our DYNAMICO-
 499 Saturn GCM simulation, the oscillation at the low latitudes can only result
 500 from resolved motions, therefore planetary-scale waves, because there is no sub-
 501 grid scale parameterization or bottom thermal forcing in our model. To study
 502 those waves, we performed a two-dimensional Fourier transform of the sym-
 503 metric and antisymmetric components of temperature and zonal wind fields,
 504 following Wheeler and Kiladis (1999) method, as in Spiga et al. (2020) section
 505 3.3.1. We applied the two-dimensional Fourier analysis on a specific 1000-day-
 506 long run, with daily output frequency, after 270000 simulated Saturn days as
 507 in Spiga et al. (2020). The spectral mapping in the wavenumber s and fre-
 508 quency σ space enables to evidence and characterize the planetary-scale waves

509 driving the stratospheric equatorial oscillation. Symmetric component of tem-
510 perature (about the equator) T_S shows Rossby, inertia-gravity and Kelvin waves
511 and antisymmetric component of temperature T_A shows Yanai (Rossby-gravity)
512 waves.

513 The results of the two-dimensional Fourier transform for the stratospheric
514 temperature and zonal wind fields at the 20-Pa pressure level are shown in
515 Figure 15 and in Table 1. The spectral analysis demonstrates, both in the anti-
516 symmetric component of temperature and zonal wind fields, that the dominant
517 wavenumber-2 is a westward-propagating Rossby-gravity wave with a period
518 of 6 days and a frequency of 60° longitude per day. Westward-propagating
519 Rossby and internal-gravity waves with wavenumber $s = -1$ are the secondary
520 prominent mode in temperature, with a period of 100 Saturn days. There are
521 two other westward-propagating modes with wavenumbers $s = -2$ and $s = -$
522 3, and respectively a period of 6 and 34 Saturn days. Finally, there are only
523 two eastward-propagating Kelvin waves (identified both in the temperature and
524 wind field) with $s = +3$ and $s = +4$, with a 5 Saturn days and 6 Saturn days
525 periodicity. The zonal wind field indicates westward-propagating Rossby waves
526 with $s = -1$ to $s = -10$, exhibiting long periods of several tens of Saturn days
527 and frequencies of about fifteen degrees longitude per day.

528 It is worth noticing that there are numerous westward-propagating modes
529 versus only two eastward-propagating mode, both in temperature and zonal
530 wind components. The resolved QBO-like oscillation in our DYNAMICO-
531 Saturn reference GCM simulation is thus characterized by an imbalance in
532 eastward- and westward-wave forcing. This may be symptomatic of the ab-
533 sence of sub-grid scale waves parameterization, which contribute of almost 3/4
534 of the eastward momentum forcing in the equatorial oscillation of Earth. Indeed,
535 the smaller the eastward-wave forcing is, the smaller the eastward momentum
536 carried by waves to critical levels is. This lack of eastward momentum in the
537 resolved dynamics could explain why, as noticed in section 4.2, the eastward
538 phase of the equatorial oscillation seems to be unstable in time compared to
539 the westward phase. A plausible explanation is that the eastward momentum

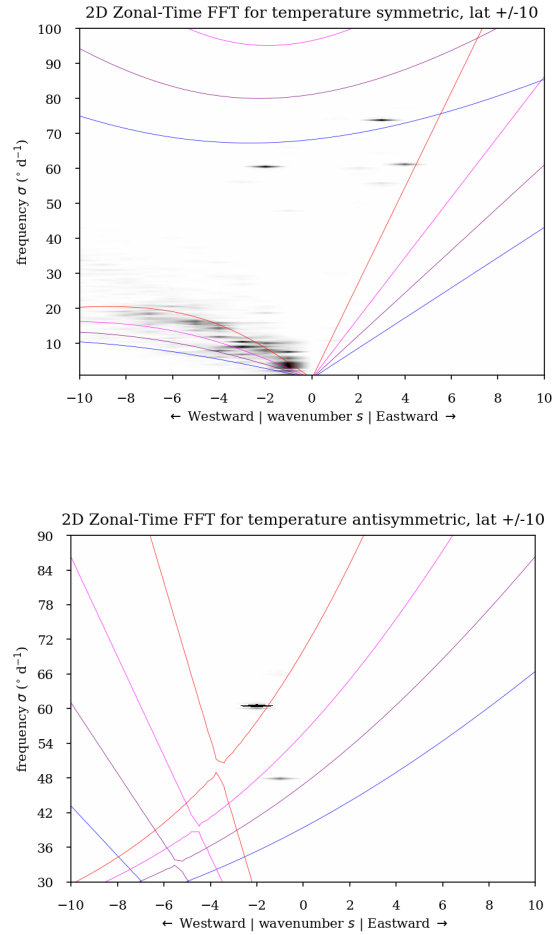


Figure 15: Two-dimensional Fourier transforms of the symmetric component of temperature field, following [Wheeler and Kiladis \(1999\)](#) method, to highlight the equatorial waves produced by our DYNAMICO-Saturn in dynamical steady-state at the 40th pressure-level (43 Pa). Grey shaded areas depict the waves identified by the spectral analysis. The colored curves correspond to the dispersion relation from the linear theory. Four values of equivalent depths are included into the linear theory: 5 km in blue, 10 km in purple, 20 km in magenta and 50 km in red.

Dominant modes in T_s			
s	σ ($^\circ$ /d)	period (d)	$\log(\text{SP})$
-1	3.6	100	9.6
-2	60.5	6	9.4
-3	10.4	34	9.2
+3	73.8	5	8.9
-4	7.9	45	8.7
+4	61.2	6	8.7
-5	16.2	22	8.7

Dominant modes in u_s			
s	σ ($^\circ$ /d)	period (d)	$\log(\text{SP})$
-1	4.0	91	11.9
-2	7.9	45	11.9
-3	11.2	32	11.3
-7	13.7	26	11.3
+3	73.8	5	11.3
-4	8.3	43	11.2
-5	10.4	34	11.1
-10	17.3	21	11.0
-6	16.2	22	11.0
+4	61.2	6	11.0

Dominant modes in T_A, u_A, v_S			
s	σ ($^\circ$ /d)	period (d)	$\log(\text{SP})$
-2	60.5	6	11.3

Table 1: Spectral modes detected by Fourier analysis and depicted in Figure 15. SP means spectral power and d Saturn days.

540 deposition of Kelvin wave is too low on its own to balance the westward phase
 541 induced by the Rossby-gravity, Rossby and inertia-gravity waves.

542 4.5. Eddy-to-mean interactions driving the equatorial stratospheric oscillation

543 To determine the eddy-to-mean interactions within the flow, we use the
 544 Transformed Eulerian Mean (TEM) formalism. In terrestrial atmospheric stud-
 545 ies, it is commonly employed to investigate momentum and heat transfers by
 546 wave-mean flow interactions (Andrews et al., 1983).

547 In all the following equations (1 to 4), the overline denotes the zonal-mean of
 548 each field, the prime symbol denotes the eddy component, i.e. departures from
 549 the zonal mean. By defining the transformed zonal-mean velocities as follows

$$\overline{v^*} = \overline{v} - \frac{\partial}{\partial P} \left(\frac{\overline{v'\theta'}}{\overline{\theta_P}} \right) \quad (1)$$

550

$$\overline{\omega^*} = \overline{\omega} + \frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} \left(\frac{\cos \phi \overline{v'\theta'}}{\overline{\theta_P}} \right) \quad (2)$$

551 we obtain the momentum equation in the Transformed Eulerian Mean formal-
 552 ism:

$$\frac{\partial \overline{u}}{\partial t} = \overline{X} - \underbrace{\left[\frac{1}{a \cos \phi} \frac{\partial(\overline{u} \cos(\phi))}{\partial \phi} - f \right]}_I \overline{v^*} - \overline{\omega^*} \frac{\partial \overline{u}}{\partial P} + \underbrace{\frac{1}{a \cos \phi} \overline{\nabla \cdot \vec{F}}}_{II} \quad (3)$$

553 where \overline{X} is the zonal-mean non-conservative friction and $\vec{F} = (F^\phi, F^P)$ is the
 554 Eliassen-Palm flux, which components are defined in equation 4 below.

$$\begin{aligned} F^\phi &= \rho_0 a \cos \phi \left(\frac{\overline{v'\theta'} \frac{\partial \overline{u}}{\partial P}}{\frac{\partial \overline{\theta}}{\partial P}} - \overline{u'v'} \right) \\ F^P &= \rho_0 a \cos \phi \left(\frac{\overline{v'\theta'}}{\frac{\partial \overline{\theta}}{\partial P}} \left(f - \frac{1}{a \cos \phi} \frac{\partial(\overline{u} \cos \phi)}{\partial \phi} \right) - \overline{u'\omega'} \right) \end{aligned} \quad (4)$$

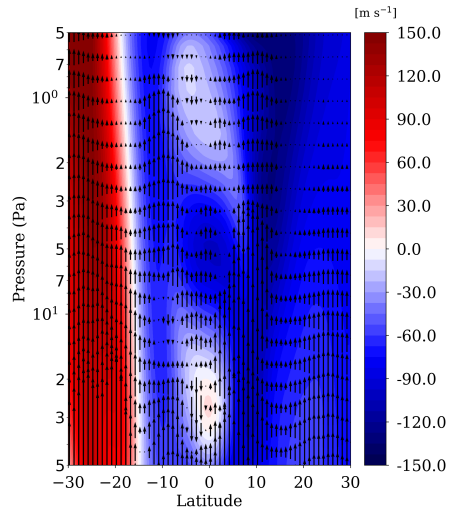
555 The Eliassen-Palm flux is defined as a wave momentum flux: it depicts both
 556 interactions between eddies and the mean flow (a momentum stress on the mean
 557 flow) and eddy propagation, as a wave activity. It allows one to link the merid-
 558 ional flux of heat $\overline{v'\theta'}$ and zonal momentum $\overline{u'v'}$ (due to waves forcing) to a
 559 horizontal F^ϕ and vertical F^P flux of momentum on the mean flow (into Equa-
 560 tion 3). In equation 3, the term I is the residual-mean acceleration and the term

561 II is the Eliassen-Palm flux divergence, i.e. the eddy forcing in momentum on
562 the mean flow acceleration (named eddy-induced acceleration in the following).
563 Studying the Eliassen-Palm flux, as well as its divergence, makes it possible to
564 identify the regions of greatest interaction between the eddies and the mean
565 flow, and to visually determine the propagation of eddy-induced momentum
566 from one region of the atmosphere to another.

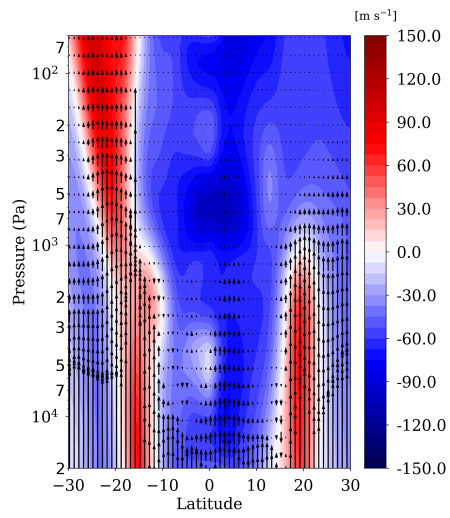
567 In the following analysis, we separate the lower stratosphere (2×10^4 Pa to
568 6×10^1 Pa) and the upper stratosphere (6×10^1 Pa to 5×10^{-1} Pa) to clarify the
569 analysis. For each stratospheric regions, the two components of the Eliassen-
570 Palm vectors are scaled by their own averaged values which are distinct in the
571 two stratospheric regions.

572 We ran an additional, specific 1000-day-long GCM simulations with a daily
573 output frequency, restarted at a time of a strong reversal of wind direction from
574 the westward to the eastward direction (at $L_s = 140^\circ$ during the eighth simu-
575 lated Saturn years). Figure 16 displays the time-average of the Eliassen-Palm
576 flux diagram (vectors) superimposed on the zonal-mean zonal wind (color). The
577 Eliassen-Palm flux essentially comes from the high troposphere in tropical re-
578 gions, particularly the strong eastward jets located at $\pm 20^\circ$ of latitude. In
579 the southern hemisphere, the Eliassen-Palm flux vectors is significant between
580 2×10^4 Pa and 6×10^2 Pa in the lower stratosphere (Figure 16(b)) and between
581 5×10^1 Pa and 1×10^1 in the upper stratosphere (Figure 16(a)). The eddy mo-
582 mentum transferred to the upper stratospheric layers mainly comes from the
583 strong eastward jet correlated to the rings shadow (centered at 25° S). Compari-
584 son between northern and southern tropical regions shows that the largest eddy
585 momentum forcing is correlated to this strong eastward jet, even in the highest
586 stratospheric layers, where the forcing is greatly reduced. Furthermore, there
587 is an inversion of the Eliassen-Palm vectors' direction at the equator (down-
588 ward) compared to the two tropical regions (upward). We deduce that there is
589 a conceivable cell of eddy flux on both sides of the equatorial stacked jets, which
590 suggests an eddy forcing of the equatorial oscillation.

591 Eddy-to-mean interactions are indeed involved in the downward propagation



(a)



(b)

Figure 16: Altitude/latitude sections of the zonal mean zonal-wind (color) and the Eliassen-Palm flux in equatorial regions at $L_s = 140^\circ$ during the eighth simulated Saturn years, focused on high stratospheric levels (16(a)) and low stratospheric levels (16(b)). Vectors scale is arbitrary for each section.

592 of the terrestrial equatorial oscillation. We investigate those interactions in the
 593 case of our simulated Saturn equatorial oscillation by choosing a representative
 594 case study, the downward propagation of the equatorial eastward zonal jets
 595 between $L_s = 185^\circ$ and $L_s = 188^\circ$ on simulated year 8. For this test case, to
 596 diagnose the wave-induced forcing on the mean flow, we report the temporal
 597 evolution of zonal wind profiles, waves and the divergence of the Eliassen-Palm
 598 flux in Figure 17. Additionally, to investigate the types of waves involved in this
 599 forcing, we perform two related spectral analysis, one in the interval $L_s = 181-$
 600 185° and the other in the interval $L_s = 185-188^\circ$, each one over 250 simulated
 601 Saturn days.

602 At $L_s = 185^\circ$, zonal wind profile shows an intense westward jet (almost -
 603 75 m s^{-1}) between 50 and 15 Pa, a weak eastward jet between 15 and 9 Pa
 604 (only 10 m s^{-1}) and the lower part of a second intense westward jet (from
 605 9 Pa to the top of the figure). At 21 Pa, between $L_s=181^\circ$ and 188° , there is
 606 a small eastward eddy-induced acceleration, of about 0.3 m s^{-2} . Our spectral
 607 analysis shows that this is associated to a decrease of both Rossby and Kelvin
 608 waves activity at this pressure level. The eastward eddy-induced acceleration,
 609 correlated to the Kelvin waves activity at 21 Pa, forces the wind direction to
 610 eastward propagation and tends to “push” the eastward jet down. So, at $L_s =$
 611 188° , this eastward jet is located from 20 to 12 Pa, close to the weak eastward
 612 eddy-induced acceleration. At 10 Pa, the temporal average of the Eliassen-Palm
 613 flux divergence demonstrates a significant westward eddy-induced acceleration,
 614 associated to a great enhancement of Rossby waves and a vanishing of Kelvin
 615 waves activity in spectral analysis. During the 500 Saturn days around the date
 616 $L_s = 185^\circ$, at 10 Pa, the westward waves transfer westward momentum to the
 617 mean flow, the large westward acceleration changes the wind direction and at-
 618 tenuates the eastward jet. As a result, the westward jet, located between 9 Pa
 619 to the top of the figure at $L_s = 185^\circ$, downs to 11 Pa at $L_s = 188^\circ$. At this
 620 pressure level, we observe the transition from the eastward phase to the west-
 621 ward phase of the equatorial oscillation. Eastward and westward accelerations
 622 occur just below eastward and westward jets, respectively: this may be due

623 to the location of critical levels. Approaching a critical level from below, the
624 wave vertical group velocity and vertical wavelength both decrease, facilitating
625 the momentum exchange with the mean flow, although the maximum transfer
626 of momentum can occur somewhere before encountering the critical level (e.g.
627 through radiative damping). This could explain the downward propagation of
628 the stacked jets causing the QBO-like oscillation.

629 **5. Saturn seasonal cycle to synchronize its equatorial oscillation**

630 Idealized terrestrial QBO simulations show that the seasonal cycle could lock
631 the equatorial oscillation period to an integer multiple of the annual cycle period
632 (Rajendran et al., 2016). In our reference simulation, the QBO-like oscillation
633 period is nearly the observed mean period, namely about half a Saturn year.
634 This raises a new question: does Saturn’s annual seasonal cycle synchronize the
635 period of the equatorial oscillation? To address this question, we performed an
636 alternate simulation (named hereinafter the “no-season” simulation) in which
637 the seasonal cycle of the incoming solar radiation is neglected: the planet’s po-
638 sition around the Sun is fixed at $L_s=0^\circ$. As a consequence, there is no ring
639 shadowing in this simulation to avoid any singularities in the radiation at the
640 equator. All other settings are similar to the DYNAMICO-Saturn reference sim-
641 ulation described previously. This “no-season” simulation starts with an initial
642 state derived from the reference simulation after 7 simulated Saturn years. In
643 this alternate simulation, the DYNAMICO-Saturn GCM is run for six simulated
644 years: three years to reach a dynamical steady-state (a spin-up phase) and three
645 additional years to compare the results with the eleventh to the thirteenth years
646 of our reference simulation.

647 Figure 18 shows the time evolution of the zonal-mean zonal wind vertical
648 structure at the equator for the six simulated Saturn years of the “no-season”
649 simulation. Compared to the reference simulation (Figure 7), two conclusions
650 emerge from the “no-season” simulation:

- 651 • During the spin-up phase, the eastward wind intensity is higher and the

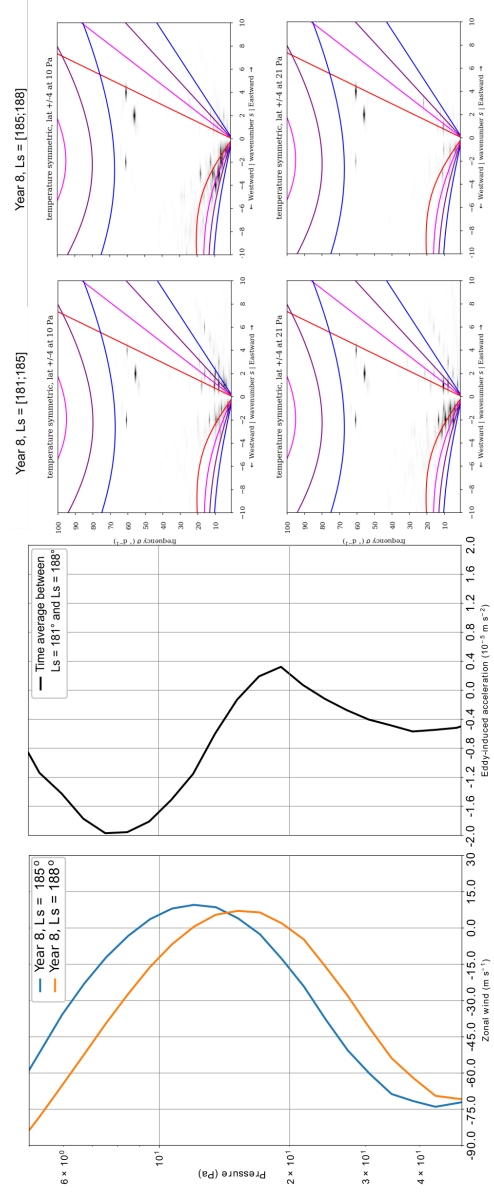


Figure 17: Left panel: Zonal-mean zonal wind profiles at Ls = 185° (blue line) and Ls = 188° (orange line). Middle panel: zonal-mean eddy-induced acceleration (term II of Equation 3, black line), average over 500 days around Ls = 185°. Each profiles are average over ± 5 degrees of latitude. Right panel: two-dimensional Fourier transforms of the symmetric component of temperature field, following Wheeler and Kiladis (1999) method, over two time intervals (Ls = 181-185° and Ls = 185-188°) and at 21 and 10 Pa.

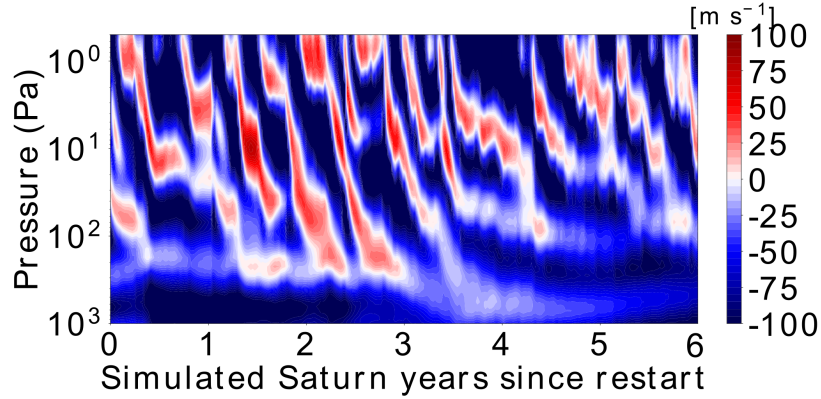


Figure 18: Altitude/time section at the equator of the zonal-mean zonal wind in Saturn’s stratosphere for the no-season DYNAMICO-Saturn simulation.

652 eastward phase of the equatorial oscillation is more regular and longer
 653 duration than in the reference simulation.

- 654 • after three simulated Saturn years, the oscillation begins to disappear in
 655 the lower stratosphere, toward 5×10^1 Pa.

656 There is an interconnection between the stratospheric jets (mean flow) and
 657 the eddies that force the equatorial oscillation. The presence of established
 658 jets, coming from the reference simulation, at the beginning of the “no-season”
 659 simulation influences the eddies activity, maintaining a seasonal signature for
 660 about three years. Jets and eddies are intimately coupled: once the seasonal
 661 cycle is removed, the equilibrium between jets and eddies is slightly disturbed,
 662 the effect of which is only noticeable after three simulated years.

663 After spin-up, the equatorial oscillation disappears in the lower stratosphere,
 664 between 10^3 and 5×10^1 Pa, but it is maintained between 5×10^1 Pa to the model
 665 top with a different periodicity than in the reference simulation. At any pres-
 666 sure level, from the fourth simulated Saturn year to the end of the “no-season”
 667 simulation, we notice only 3 or 4 stratospheric eastward jets. We obtain, in this
 668 “no-season” simulation, a periodicity of about 0.7 simulated Saturn year which
 669 is less consistent with observations than the reference simulation. This is con-

670 sistent with one of the conclusions of [Rajendran et al. \(2016\)](#): the annual cycle
671 can regulate an equatorial oscillation by enhancing the eddies forcing induced
672 by the seasonality of atmospheric waves.

673 We conclude from our “no-season” simulation that the seasonal cycle of
674 Saturn is a key parameter to establish and regulate the stratospheric equato-
675 rial oscillation modeled by our DYNAMICO-Saturn GCM. Both eddy activity
676 and residual-mean circulations are impacted by seasons in such a way that the
677 periodicity of the equatorial oscillations is “locked” close to a semi-annual pe-
678 riodicity. How much which effect dominates over the other is left for a future
679 study.

680 **6. Impact of the rings on Saturn’s stratospheric dynamics**

681 *6.1. Zonal wind in the tropical regions*

682 To determine Saturn’s rings contribution to the atmospheric dynamics in
683 the tropical channel, we performed an alternate simulation named the “no-
684 ring” simulation, in which the rings’ shadowing of the incoming solar radiation
685 is neglected, all other settings being equal with the DYNAMICO-Saturn refer-
686 ence simulation described previously. Contrary to the “no-season” simulation,
687 a seasonal cycle is simulated in the “no-ring” simulation: it is different from the
688 reference simulation since the shadow of the rings is removed. This “no-ring”
689 simulation starts with an initial state derived from the reference simulation after
690 8 simulated Saturn years. The DYNAMICO-Saturn GCM is run for five simu-
691 lated years: three years devoted to spin-up to reach a dynamical steady-state
692 (see section 5) and two additional years to compare the results with the eleventh
693 and the twelfth years of our reference simulation.

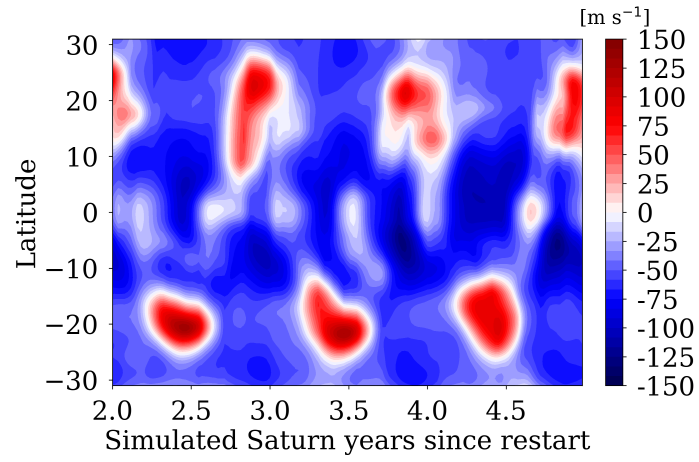
694 Figure 19 compares the two Saturn GCM simulations. In the no-ring simula-
695 tion compared to the reference simulation, we note a disturbance of the structure
696 of the zonal-mean zonal wind at the tropics, as well as an enhancement of the
697 zonal wind intensity at the equator. Eastward jets at the tropics in the no-ring
698 simulation split in several weaker eastward jets in the northern hemisphere. In

699 the southern tropics, eastward jets even disappear after 3.5 Saturn years of sim-
700 ulation. Hence, rings' shadowing (or the absence thereof) impacts equatorial
701 and tropical dynamics.

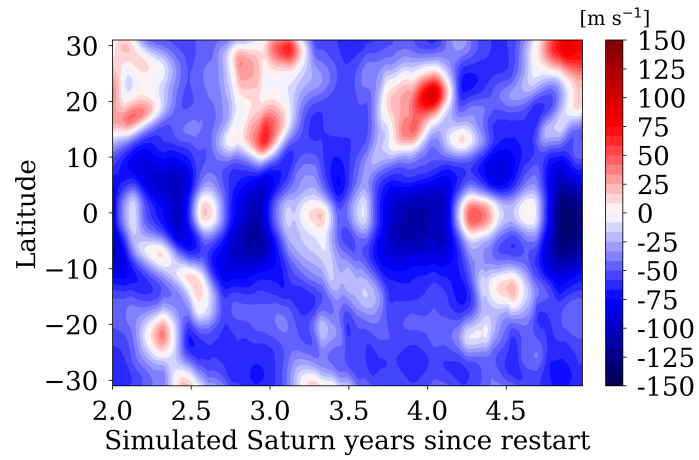
702 We present in Figure 20 the vertical structure of the stratospheric equatorial
703 oscillation resulting from the no-ring simulation. As in the reference simulation,
704 the eastward phase of this QBO-like oscillation is irregular compared to the
705 westward phase. However, eastward stratospheric jets in the no-ring simulation
706 are larger in amplitude compared to the reference simulation (see Figure 7),
707 and the eastward phase of the equatorial oscillation lasts longer in the no-ring
708 simulation than in the reference simulation. Eastward and westward phases are
709 less contrasted. Neglecting the ring shadowing, we obtain an eastward phase of
710 the simulated Saturn QBO-like oscillation enhanced by around 25 m s^{-1} and a
711 periodicity between 0.4 and 0.5 simulated Saturn years.

712 6.2. Temperature field in the tropical region

713 Figure 21 compares at the 40-Pa pressure level the reference DYNAMICO-
714 Saturn simulation, the no-ring DYNAMICO-Saturn simulation, with radiative-
715 convective 2D seasonal modeling *à la* Guerlet et al. (2014), and the 2005 CIRS
716 limb observations (Guerlet et al., 2009). This comparison is carried out at
717 $L_s = 300^\circ$ in southern summer, when rings shadowing occurs at $20\text{-}25^\circ\text{N}$. As
718 mentioned previously, the radiative-convective model fails to reproduce the lo-
719 cal temperature maximum under the rings' shadow (between 20 and 30°N).
720 It predicts instead a temperature $\sim 12 \text{ K}$ colder than the CIRS observations.
721 Besides, the reference GCM simulation presents higher temperatures at these
722 latitudes, which are still $\sim 5 \text{ K}$ too cold compared to measurements. At north-
723 ern mid-latitudes in the winter hemisphere, the modeled temperature decreases
724 from 20°N to 40°N , that we can associate with the signature of the rings shadow.
725 Even if the dynamics of the DYNAMICO-Saturn GCM raises temperature un-
726 derneath the ring, there remains a failure to replicate hot anomalies in the
727 shadows. The no-ring simulation also exhibits warm temperature between 20°N
728 and 30°N ; however, these temperatures are higher than the reference simulation



(a)



(b)

Figure 19: Two-month running mean evolution of the zonal-mean zonal wind in Saturn's stratosphere (40 Pa) between 30°N and 30°S of our DYNAMICO-Saturn comparative simulations: 19(a) with rings' shadow (reference simulation) and 19(b) without rings' shadow. The two first simulated years of the alternate simulation are not shown (model spin-up).

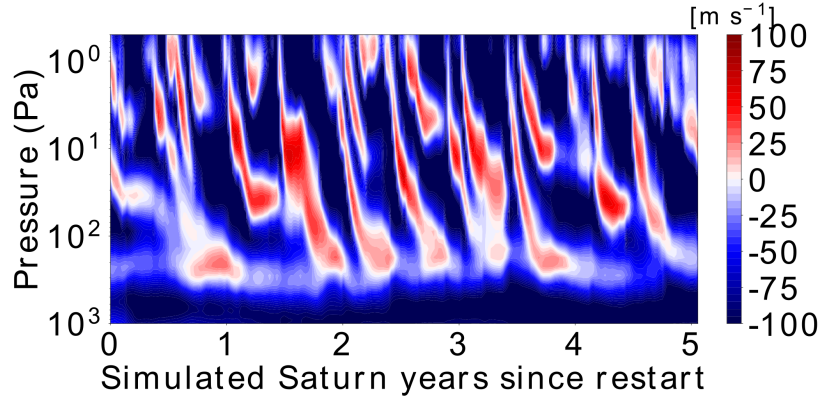


Figure 20: Altitude/time section at the equator of the zonal-mean zonal wind in Saturn's stratosphere for the no-ring DYNAMICO-Saturn simulation.

729 (probably because the tropical eastward jets are impacted by the lack of ring
 730 shadowing) and too warm compared to the observations for the whole north-
 731 ern hemisphere except between 30-35°N. Hence Figure 21 suggests a possible
 732 dynamical origin of the unexpected high temperature below Saturn's rings, but
 733 this dynamics is not fully addressed by DYNAMICO-Saturn *with* rings shadow.
 734 We defer the detailed study of the seasonal circulation to a future work.

735 6.3. Eddy-to-mean interactions in the tropical region

736 Ring shadowing impacts the tropical eastward jets. Those jets are forced
 737 by the residual-mean circulation and the eddy-to-mean interactions. To further
 738 characterize the impact of ring shadowing on those two contributions, we use
 739 the TEM formalism (Equation 3).

740 In the two simulations, eddy-induced (term II of Equation 3) and mean-
 741 circulation-induced (term I of Equation 3) accelerations are of the same order
 742 of magnitude. It is also of the same order of magnitude between both simu-
 743 lations (Figure 22). The presence of the tropical southern eastward jet in the
 744 reference simulation is associated with a significant eddy-induced acceleration
 745 that disappears completely when ring shadowing is not included (Figure 22
 746 top rows). The equatorial behavior of eddy-induced acceleration is of opposite

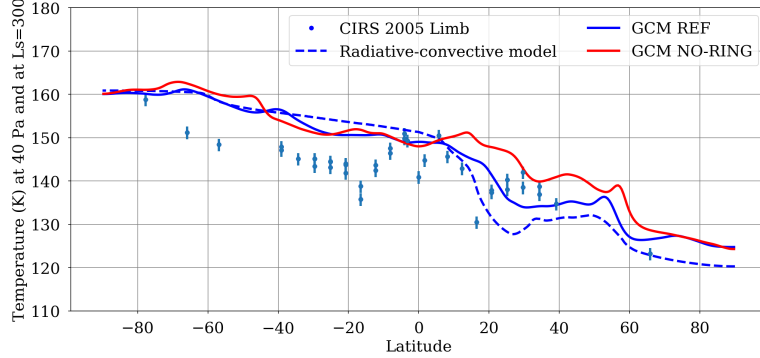


Figure 21: Temperature comparison between CIRS 2005 limb data (blue dots), reference simulation (blue line), NO-RING simulation (red line) and the radiative-convective model *à la Guerlet et al. (2014)* (blue dashed line) at the 40 Pa pressure level. Errorbars for the CIRS data contain the error due to the measurement noise and also related to the uncertainty of the CH_4 abundance.

747 sign at the top of the stratosphere in the no-ring simulation compared to the
 748 reference simulation.

749 The acceleration due to the mean circulation is shown at the bottom of Fig-
 750 ure 22. Without rings shadowing, acceleration induced by the mean circulation
 751 is mainly positive in the north and negative in the south. With ring shadow-
 752 ing, this pattern is disturbed both in the southern hemisphere (where a reduced
 753 acceleration is seen at the location of the tropical eastward jet) and in the oppo-
 754 site hemisphere as well. Indeed, in the northern hemisphere, the acceleration is
 755 now mainly negative in the range 2 – 100 Pa when ring shadowing is taken into
 756 account. A similar behavior is observed during southern summer (not shown).

757 The amplification of the eddy-induced acceleration just below rings shad-
 758 owing presents the same periodicity than the Saturn seasonal cycle. We map
 759 the time evolution of the acceleration due to eddies in the reference simulation
 760 (Figure 23(a)) and the no-ring simulation (Figure 23(b)). In the reference sim-
 761 ulation, eddy-induced acceleration is enhanced at the tropics when eastward
 762 tropical jets are present. There is a strong deceleration due to eddies at the

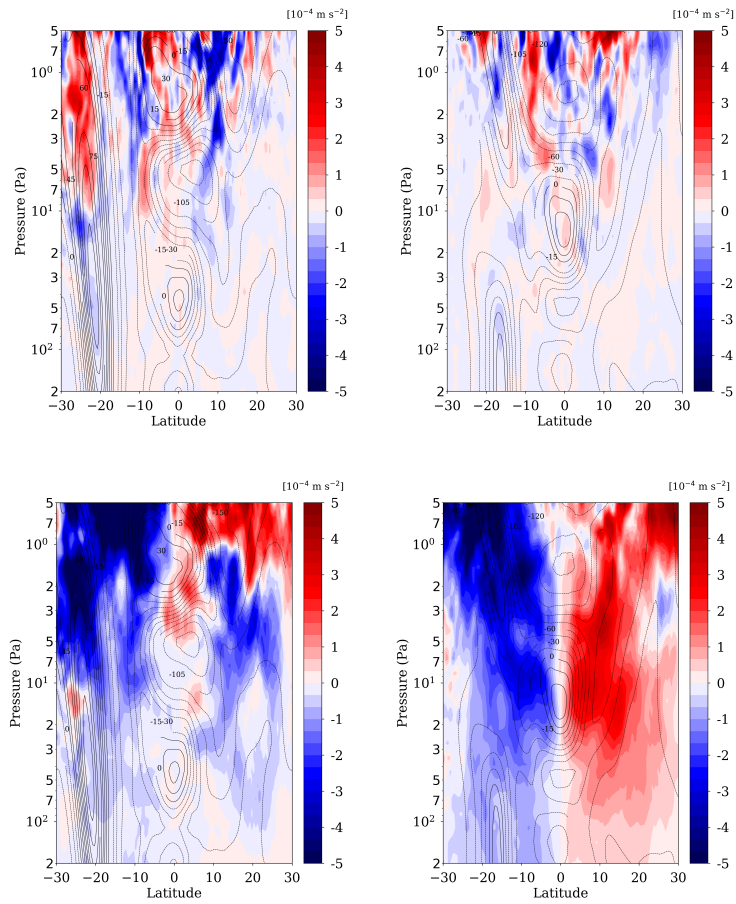
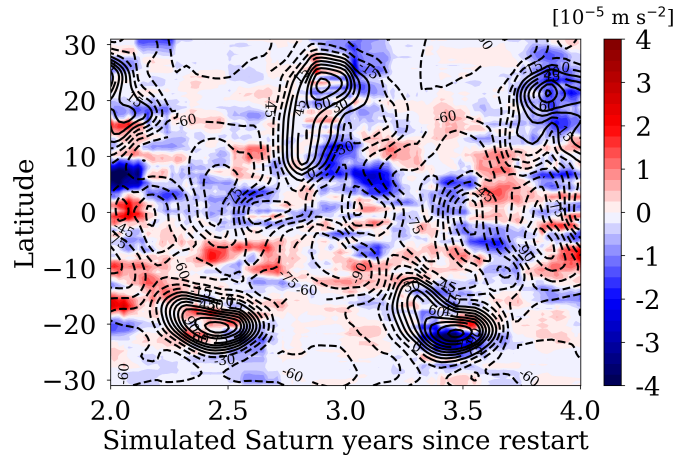


Figure 22: Comparative meridional sections of zonal-mean zonal wind (contours, solid lines depict eastward jets and dashed lines depict westward jets), eddy-induced acceleration (color, top rows) and mean-circulation-induced acceleration (color, bottom rows) in TEM formalism between rings- (left columns) and no-ring- (right columns) simulations at the 3.5 simulated Saturn year since restart. This dates correspond to the northern summer: rings' shadow takes place at around 20°S and produces a strong eastward jet centered at 25°S .

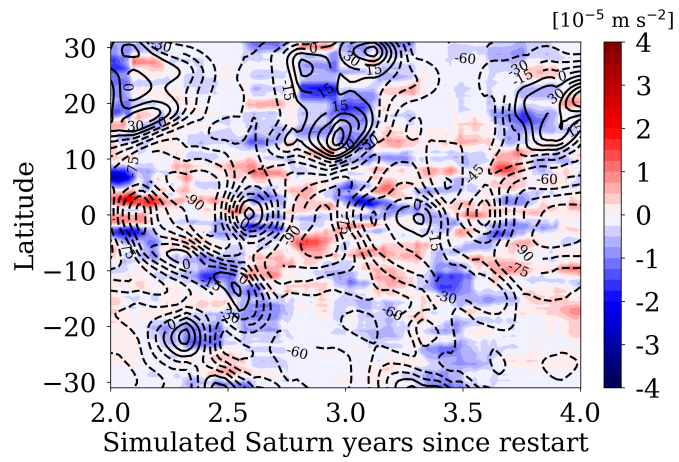
763 location of the tropical eastward jets (except for the jets located at 20°S at 2.5
764 simulated Saturn year). The winter tropics, where the rings' shadow occurs
765 and eastward jets are produced, are associated with an intense interaction be-
766 tween eddies and the mean circulation, which induces a significant deceleration
767 due to eddy activity. Regarding the no-ring simulation, the eddy-induced ac-
768 celeration is halved compared to the reference simulation at the location of the
769 eastward jets. The seasonality of the eddy-to-mean interaction persists at the
770 tropics without the rings shadowing, but the intensity of the eddy forcing in the
771 mean flow is reduced. In this case, the whole tropical channel is driven by ho-
772 mogeneous absolute values of acceleration and deceleration (about $1.5 \times 10^{-5} \text{m}$
773 s^{-2}).

774 To summarize the conclusions of this section 6, rings' shadowing affects the
775 stratospheric dynamics of Saturn. Rings shadowing impacts the thermal struc-
776 ture of the tropical regions with a seasonal periodicity. This causes seasonally-
777 varying tropical eastward jets underneath the shadows, through two distinct
778 dynamical interactions. First of all, there is an enhancement of the eddy-induced
779 acceleration at the location of the shadow. Secondly, there is a reversal of sign
780 of the acceleration (positive in the case without ring shadow to negative sign
781 in the case with rings shadow) due to the residual-mean circulation in summer
782 hemisphere (opposite of the "rings shadow" hemisphere). Moreover, the strong
783 meridional gradients of wave activity disturb the eastward phase of the equa-
784 torial oscillation (and the overall periodicity of it) by producing low-intensity
785 eastward jets.

786 A putative impact of the ring's shadow on Saturn's stratospheric dynamics
787 was already suspected by previous authors, based on the observation of a lo-
788 cal maximum in hydrocarbons and anomalously high temperatures under the
789 ring's shadow in northern winter, disappearing at the spring equinox (Guerlet
790 et al., 2009; Sylvestre et al., 2015). Upward motion at summer mid-latitudes
791 associated with a tropical adiabatic subsidence in the winter hemisphere could
792 explain heat transport under the ring shadowing, as well as the observed hydro-
793 carbon abundances asymmetries (Guerlet et al. (2009), Guerlet et al. (2010)).



(a)



(b)

Figure 23: Two-month running mean evolution of the zonal-mean eddy-induced acceleration (colors) and the zonal wind (contours) in Saturn's stratosphere (40 Pa) between 30°N and 30°S of our DYNAMICO-Saturn comparative simulations: 23(a) with rings' shadow (reference simulation) and 23(b) without rings' shadow.

794 With our study, we show that such interpretations of anomalies seen in obser-
795 vations invoking upward and downward motions may reflect a too simplistic
796 view. Rather, eddy forcings might play a role as much as significant as the
797 residual-mean circulation in shaping Saturn's stratospheric temperatures and
798 dynamics.

799 7. Conclusions and perspectives

800 We use a troposphere-to-stratosphere Saturn GCM without any prescribed
801 wave parameterization to study the equatorial stratospheric dynamics, espe-
802 cially the stratospheric equatorial oscillation. Concerning the global atmo-
803 spheric dynamics, spherical harmonic decomposition of the horizontal velocity
804 shows that statistical properties are similar in the tropospheric and stratospheric
805 levels. These properties differ when we extend the model top toward higher
806 stratospheric levels, but still predict a stratosphere more energetic than the tro-
807 posphere. However, the 32-level simulation shows energetic non-axisymmetric
808 modes $m = 1, 2, 3$ at large scale (i.e. small indices n) that vanish in our refer-
809 ence simulation. These modes likely results from energy accumulation at the
810 model top which artificially enforces large-scale waves in the 32-level simula-
811 tion of [Spiga et al. \(2020\)](#). Our spectral analysis emphasizes a currently open
812 question: does the statistical framework of 2D-turbulence with a β -effect apply
813 to energy spectra of Saturn’s atmosphere, and more generally to 3D planetary
814 macroturbulence? If [Spiga et al. \(2020\)](#) simulation retrieves the well-known
815 KK-law of quasi-2D turbulence, the $-5/3$ slope does not apply when we raise
816 the model top in our reference simulation. These statistical predictions of our
817 Saturn climate model have now to be validated by direct observations of the
818 Saturn’s atmospheric flow.

819 Regarding the lower latitudes, our DYNAMICO-Saturn GCM reproduces an
820 almost semi-annual equatorial oscillation with contrasted eastward and west-
821 ward phases. This oscillation shows a similar behavior in temperature than the
822 Cassini/CIRS retrievals, with alternatively local maxima and minima of temper-
823 ature stacked on the vertical at the equator. The DYNAMICO-Saturn signal
824 exhibits a two times smaller vertical characteristic size of the oscillation and
825 underestimates by a factor of two the amplitude of the temperature anomalies,
826 compared with CIRS observations. Regarding the zonal-mean zonal wind, we
827 determined an irregular period of wind reversal and a downward propagation
828 rate faster than observations. Spectral analysis at the equator demonstrated

829 that this QBO-like oscillation is produced by planetary-scale waves. The equa-
830 torial oscillation in the DYNAMICO-Saturn GCM is mainly driven by strong
831 westward-propagating waves, such as Rossby, Rossby-gravity and inertia-gravity
832 waves, which deposit westward momentum in the stratosphere. There are only
833 two eastward-propagating modes (Kelvin waves) in the spectral analysis with
834 a weaker impact in the stratospheric dynamics than the westward-propagating
835 waves. This lack of eastward waves prevents the eastward momentum depo-
836 sition in the mean zonal wind and explains the erratic behavior of the east-
837 ward phase of the modeled QBO-like oscillation. Using the Transformed Eu-
838 lerian Mean formalism to determine how the eddy-to-mean interactions drives
839 the Saturn equatorial oscillation, we are able to conclude that the maximum
840 of eddy forcing comes from the high-troposphere tropical regions. Moreover,
841 we demonstrate the wave forcing origin of the vertically-stacked stratospheric
842 eastward and westward jets that propagate downward with time to form the
843 equatorial oscillation. At the equator, in the stratosphere, the eddy-induced
844 eastward acceleration maximum is located just under the eastward jets and the
845 eddy-induced westward acceleration maximum is located just under the west-
846 ward jets at every step of the downward propagation of this Saturn QBO-like
847 equatorial oscillation. A control experiment, using a perpetual equinox radiative
848 forcing, demonstrate that the seasonal cycle of Saturn plays a significant role to
849 establish and regulate the stratospheric equatorial oscillation modeled by our
850 DYNAMICO-Saturn GCM. Both eddy activity and residual-mean circulations
851 are impacted by seasons in such a way that the periodicity of the equatorial
852 oscillations is “locked” close to a semi-annual periodicity.

853 For future improvements of the modeling of the QBO-like oscillation in Sat-
854 urn’s equatorial stratosphere, we will draw inspiration from Earth’s atmospheric
855 modeling. Adequate vertical resolution is needed to obtain a more realistic
856 Quasi-Biennial Oscillation in Earth models ([Richter et al. \(2014\)](#), [Hamilton et al.
857 \(2001\)](#)). We plan to refine the vertical resolution in the stratosphere both to lead
858 to a downward propagation rate of the oscillating zonal wind consistent with
859 the observations, and a large-enough amplitude of Kelvin and Rossby-gravity

360 waves to enhance the westward and eastward forcing of the Saturn equatorial
361 oscillation phases. Furthermore, the Earth’s QBO eastward phase is primarily
362 induced by gravity waves, triggered by tropospheric convection (around 70%
363 of the total eastward forcing) and Kelvin waves for the remaining 30% (Bald-
364 win et al., 2001). To overcome the lack of eastward momentum in our Saturn
365 stratospheric modeling, we plan to add a stochastic gravity wave drag param-
366 eterization (Lott et al., 2012) in our DYNAMICO-Saturn GCM. This is ex-
367 pected to produce a more realistic wave spectrum (with equivalent eastward-
368 and westward-propagating waves), which would strongly impact the simulation
369 of the equatorial oscillation and the downward propagation of winds.

370 Another main result of this study is the impact of ring shadowing on the
371 stratospheric dynamics. In our DYNAMICO-Saturn reference simulation we
372 obtained strong tropical eastward jets, which are seasonally periodic, and cor-
373 related with Saturn rings’ shadow. With an additional simulation not includ-
374 ing rings’ shadowing, we show that the tropical eastward jets are caused by
375 rings’ shadowing in the stratosphere. Without rings’ shadowing, the tropi-
376 cal eastward jets disappear after 3 simulated Saturn years. Comparisons be-
377 tween temperature predicted by our dynamical GCM simulations, computed
378 with radiative-convective equilibrium, and measured from Cassini/CIRS obser-
379 vations also suggests a dynamical impact of rings’ shadowing in the stratosphere.
380 The transformed Eulerian mean formalism shows that the dynamical impact of
381 ring shadowing on tropical eastward jets is strong both on the eddy-induced
382 acceleration and the residual-mean-induced acceleration. In presence of rings’
383 shadowing, eddy-induced acceleration is increased in the tropical channel and
384 there is a reversal of the residual-mean-induced acceleration in the opposite
385 hemisphere to the rings. Wave activity is correlated with rings’ shadowing: the
386 seasonality of the eddies is enhanced by rings’ shadowing, which contributes to
387 the annual periodicity of the strong eastward tropical jets. Dynamics in the
388 equatorial region, in particular the QBO-like oscillation, is also influenced by
389 rings’ shadowing.

390 Stratospheric winds have never been measured on Saturn and were deter-

891 mined using the thermal wind balance from the CIRS retrievals of stratospheric
892 temperatures. Obviously, the tropical eastward jets could be a particularity
893 of our DYNAMICO-Saturn GCM. Because of the small vertical wind shear
894 associated with these tropical jets, there is no specific temperature signature
895 associated to it. In other words, we cannot invalidate their existence with the
896 available observations of the temperature field. Future measurements of winds
897 in Saturn's stratosphere would help to validate the predictive scenario drawn
898 by our model.

899 Future studies using the DYNAMICO-Saturn GCM could adopt a wider
900 analysis scope and study the global meridional circulation in the stratosphere.
901 Results presented here are focused on the tropical regions, while the GCM extent
902 is global. For instance, we could further characterize heat transport under the
903 ring shadows, as well as the observed asymmetries of hydrocarbon abundances
904 (Guerlet et al. (2009), Guerlet et al. (2010)). More generally, a complete study
905 on the possible Brewer-Dobson-like circulation in the stratosphere of Saturn,
906 and its impact on the hydrocarbons distribution, is warranted. A subsequent
907 coupling of DYNAMICO-Saturn with photochemical models would then allow
908 to refine this picture.

909 Sudden stratospheric warming on Earth's high and mid-latitude regions are
910 associated with downward wind propagation anomalies of the Quasi-Biennial
911 Oscillation (Lu et al., 2008). Is it possible that the extremely warm stratospheric
912 disturbance in the aftermath of the Great White Storm of 2010-2011 (Fletcher
913 et al., 2011, 2012; Fouchet et al., 2016) is due to a disruption of the downward
914 propagation of the equatorial oscillation on Saturn? Conversely, Cassini obser-
915 vations showed that the occurrence of this huge storm disturbed the equatorial
916 oscillations (Fletcher et al., 2017). Global stratospheric dynamical simulations
917 by DYNAMICO-Saturn could help to address these questions in future studies.

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929 **References**

- 930 Andrews, D.G., Mahlman, J.D., Sinclair, R.W., 1983. Eliassen-Palm Diag-
931 nostics of Wave-Mean Flow Interaction in the GFDL "SKYHI" General
932 Circulation Model. *Journal of the Atmospheric Sciences* 40, 2768–2784.
933 doi:[10.1175/1520-0469\(1983\)040<2768:ETWATM>2.0.CO;2](https://doi.org/10.1175/1520-0469(1983)040<2768:ETWATM>2.0.CO;2).
- 934 Baldwin, M.P., Gray, L.J., Dunkerton, T.J., Hamilton, K., Haynes, P.H.,
935 Randel, W.J., Holton, J.R., Alexander, M.J., Hirota, I., Horinouchi, T.,
936 Jones, D.B.A., Kinniersley, J.S., Marquardt, C., Sato, K., Takahashi, M.,
937 2001. The quasi-biennial oscillation. *Reviews of Geophysics* 39, 179–229.
938 doi:[10.1029/1999RG000073](https://doi.org/10.1029/1999RG000073).
- 939 Boer, G.J., 1983. Homogeneous and isotropic turbulence on the sphere. *Journal*
940 *of the Atmospheric Sciences* 40, 154–163. doi:[10.1175/1520-0469\(1983\)](https://doi.org/10.1175/1520-0469(1983)040$<$0154:HAITOT$>$2.0.CO;2)
941 [040\\$<\\$0154:HAITOT\\$>\\$2.0.CO;2](https://doi.org/10.1175/1520-0469(1983)040$<$0154:HAITOT$>$2.0.CO;2).
- 942 Butchart, N., 2014. The Brewer-Dobson circulation. *Reviews of Geophysics* 52,
943 157–184. doi:[10.1002/2013RG000448](https://doi.org/10.1002/2013RG000448).
- 944 Cabanes, S., Spiga, A., Young, R.M.B., 2020. Global Climate Modelling of
945 Saturn’s atmosphere. Part III: Global statistical picture of zonostrophic tur-
946 bulence in high-resolution 3D-turbulent simulations. *Icarus* 345, 113705.
947 doi:[10.1016/j.icarus.2020.113705](https://doi.org/10.1016/j.icarus.2020.113705).
- 948 Chemke, R., Kaspi, Y., 2015. Poleward migration of eddy-driven jets. *Jour-*
949 *nal of Advances in Modeling Earth Systems* 7, 1457–1471. doi:[10.1002/](https://doi.org/10.1002/2015MS000481)
950 [2015MS000481](https://doi.org/10.1002/2015MS000481).
- 951 Cosentino, R.G., Morales-Juberías, R., Greathouse, T., Orton, G., Johnson, P.,
952 Fletcher, L.N., Simon, A., 2017. New Observations and Modeling of Jupiter’s
953 Quasi-Quadrennial Oscillation. *Journal of Geophysical Research (Planets)*
954 122, 2719–2744. doi:[10.1002/2017JE005342](https://doi.org/10.1002/2017JE005342).
- 955 Dowling, T.E., 2008. Planetary science: Music of the stratospheres. *Nature*
956 453, 163–164. doi:[10.1038/453163a](https://doi.org/10.1038/453163a).

- 957 Dubos, T., Dubey, S., Tort, M., Mittal, R., Meurdesoif, Y., Hourdin, F.,
958 2015. DYNAMICO-1.0, an icosahedral hydrostatic dynamical core designed
959 for consistency and versatility. *Geoscientific Model Development* 8, 3131–
960 3150. doi:[10.5194/gmd-8-3131-2015](https://doi.org/10.5194/gmd-8-3131-2015).
- 961 Dunkerton, T.J., 1997. The role of gravity waves in the quasi-biennial oscillation.
962 *Journal of Geophysical Research* 102, 26053–26076. doi:[10.1029/96JD02999](https://doi.org/10.1029/96JD02999).
- 963 Dunkerton, T., 1979. On the Mean Meridional Mass Motions of the Strato-
964 sphere and Mesosphere. *Journal of the Atmospheric Sciences* .
- 965 Ern, M., Preusse, P., 2009. Quantification of the contribution of equatorial
966 Kelvin waves to the QBO wind reversal in the stratosphere. *Geophysical*
967 *Research Letters* 36, L21801. doi:[10.1029/2009GL040493](https://doi.org/10.1029/2009GL040493).
- 968 Fletcher, L.N., Achterberg, R.K., Greathouse, T.K., Orton, G.S., Conrath, B.J.,
969 Simon-Miller, A.A., Teanby, N., Guerlet, S., Irwin, P.G., Flasar”, F., 2010.
970 ”seasonal change on saturn from cassini/cirs observations, 2004–2009”. *Icarus*
971 208, 337 – 352. URL: [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S0019103510000412)
972 [pii/S0019103510000412](http://www.sciencedirect.com/science/article/pii/S0019103510000412), doi:[https://doi.org/10.1016/j.icarus.2010.](https://doi.org/10.1016/j.icarus.2010.01.022)
973 [01.022](https://doi.org/10.1016/j.icarus.2010.01.022).
- 974 Fletcher, L.N., Guerlet, S., Orton, G.S., Cosentino, R.G., Fouchet, T., Irwin,
975 P.G.J., Li, L., Flasar, F.M., Gorius, N., Morales-Juberías, R., 2017. Disrup-
976 tion of Saturn’s quasi-periodic equatorial oscillation by the great northern
977 storm. *Nature Astronomy* 1, 765–770. doi:[10.1038/s41550-017-0271-5](https://doi.org/10.1038/s41550-017-0271-5),
978 [arXiv:1803.07875](https://arxiv.org/abs/1803.07875).
- 979 Fletcher, L.N., Hesman, B.E., Achterberg, R.K., Irwin, P.G.J., Bjoraker, G.,
980 Gorius, N., Hurley, J., Sinclair, J., Orton, G.S., Legarreta, J., García-
981 Melendo, E., Sánchez-Lavega, A., Read, P.L., Simon-Miller, A.A., Flasar,
982 F.M., 2012. The origin and evolution of Saturn’s 2011-2012 stratospheric
983 vortex. *Icarus* 221, 560–586. doi:[10.1016/j.icarus.2012.08.024](https://doi.org/10.1016/j.icarus.2012.08.024).

- 984 Fletcher, L.N., Hesman, B.E., Irwin, P.G.J., Baines, K.H., Momary, T.W.,
985 Sanchez-Lavega, A., Flasar, F.M., Read, P.L., Orton, G.S., Simon-Miller,
986 A., Hueso, R., Bjoraker, G.L., Mamoutkine, A., del Rio-Gaztelurrutia, T.,
987 Gomez, J.M., Buratti, B., Clark, R.N., Nicholson, P.D., Sotin, C., 2011. Ther-
988 mal Structure and Dynamics of Saturn's Northern Springtime Disturbance.
989 *Science* 332, 1413. doi:[10.1126/science.1204774](https://doi.org/10.1126/science.1204774).
- 990 Fletcher, L.N., Irwin, P.G.J., Sinclair, J.A., Orton, G.S., Giles, R.S., Hurley, J.,
991 Gorius, N., Achterberg, R.K., Hesman, B.E., Bjoraker, G.L., 2015. Seasonal
992 evolution of Saturn's polar temperatures and composition. *Icarus* 250, 131–
993 153. doi:[10.1016/j.icarus.2014.11.022](https://doi.org/10.1016/j.icarus.2014.11.022).
- 994 Fletcher, L.N., Kaspi, Y., Guillot, T., Showman, A.P., 2019. How well do we
995 understand the belt/zone circulation of Giant Planet atmospheres? *arXiv*
996 e-prints , arXiv:1907.01822[arXiv:1907.01822](https://arxiv.org/abs/1907.01822).
- 997 Fouchet, T., Greathouse, T.K., Spiga, A., Fletcher, L.N., Guerlet, S., Leconte,
998 J., Orton, G.S., 2016. Stratospheric aftermath of the 2010 Storm on Saturn
999 as observed by the TEXES instrument. I. Temperature structure. *Icarus* 277,
1000 196–214. doi:[10.1016/j.icarus.2016.04.030](https://doi.org/10.1016/j.icarus.2016.04.030), [arXiv:1604.06479](https://arxiv.org/abs/1604.06479).
- 1001 Fouchet, T., Guerlet, S., Strobel, D.F., Simon-Miller, A.A., Bézard, B., Flasar,
1002 F.M., 2008. An equatorial oscillation in Saturn's middle atmosphere. *Nature*
1003 453, 200–202. doi:[10.1038/nature06912](https://doi.org/10.1038/nature06912).
- 1004 Friedson, A.J., 1999. New Observations and Modelling of a QBO-Like Oscilla-
1005 tion in Jupiter's Stratosphere. *Icarus* 137, 34–55. doi:[10.1006/icar.1998.](https://doi.org/10.1006/icar.1998.6038)
1006 [6038](https://doi.org/10.1006/icar.1998.6038).
- 1007 Friedson, A.J., Moses, J.I., 2012. General circulation and transport in Saturn's
1008 upper troposphere and stratosphere. *Icarus* 218, 861–875. doi:[10.1016/j.](https://doi.org/10.1016/j.icarus.2012.02.004)
1009 [icarus.2012.02.004](https://doi.org/10.1016/j.icarus.2012.02.004).
- 1010 Galperin, B., Young, R.M.B., Sukoriansky, S., Dikovskaya, N., Read, P.L., Lan-
1011 caster, A.J., Armstrong, D., 2014. Cassini observations reveal a regime of

- 1012 zonostrophic macroturbulence on Jupiter. *Icarus* 229, 295–320. doi:[10.1016/](https://doi.org/10.1016/j.icarus.2013.08.030)
1013 [j.icarus.2013.08.030](https://doi.org/10.1016/j.icarus.2013.08.030).
- 1014 Giorgetta, M.A., Manzini, E., Roeckner, E., 2002. Forcing of the quasi-biennial
1015 oscillation from a broad spectrum of atmospheric waves. *Geophysical Research*
1016 *Letters* 29, 86–1–86–4. doi:[10.1029/2002GL014756](https://doi.org/10.1029/2002GL014756).
- 1017 Guerlet, S., Fouchet, T., Bézard, B., Flasar, F.M., Simon-Miller, A.A., 2011.
1018 Evolution of the equatorial oscillation in Saturn’s stratosphere between 2005
1019 and 2010 from Cassini/CIRS limb data analysis. *Geophysical Research Letters*
1020 38, L09201. doi:[10.1029/2011GL047192](https://doi.org/10.1029/2011GL047192).
- 1021 Guerlet, S., Fouchet, T., Bézard, B., Moses, J.I., Fletcher, L.N., Simon-Miller,
1022 A.A., Michael Flasar, F., 2010. Meridional distribution of CH₃C₂H and
1023 C₄H₂ in Saturn’s stratosphere from CIRS/Cassini limb and nadir observa-
1024 tions. *Icarus* 209, 682–695. doi:[10.1016/j.icarus.2010.03.033](https://doi.org/10.1016/j.icarus.2010.03.033).
- 1025 Guerlet, S., Fouchet, T., Bézard, B., Simon-Miller, A.A., Michael Flasar, F.,
1026 2009. Vertical and meridional distribution of ethane, acetylene and propane
1027 in Saturn’s stratosphere from CIRS/Cassini limb observations. *Icarus* 203,
1028 214–232. doi:[10.1016/j.icarus.2009.04.002](https://doi.org/10.1016/j.icarus.2009.04.002).
- 1029 Guerlet, S., Fouchet, T., Spiga, A., Flasar, F., Fletcher, L.N., Hesman, B.E.,
1030 Gorius, N., 2018. Equatorial Oscillation and Planetary Wave Activity in
1031 Saturn’s Stratosphere through the Cassini Epoch. *Journal of Geophysical*
1032 *Research: Planets* .
- 1033 Guerlet, S., Spiga, A., Sylvestre, M., Indurain, M., Fouchet, T., Leconte, J.,
1034 Millour, E., Wordsworth, R., Capderou, M., Bézard, B., Forget, F., 2014.
1035 Global climate modeling of Saturn’s atmosphere. Part I: Evaluation of the
1036 radiative transfer model. *Icarus* 238, 110–124. doi:[10.1016/j.icarus.2014.](https://doi.org/10.1016/j.icarus.2014.05.010)
1037 [05.010](https://doi.org/10.1016/j.icarus.2014.05.010).
- 1038 Hamilton, K., Wilson, R.J., Hemler, R.S., 2001. Spontaneous Stratospheric
1039 QBO-like Oscillations Simulated by the GFDL SKYHI General Circula-

- 1040 tion Model. *Journal of Atmospheric Sciences* 58, 3271–3292. doi:[10.1175/
1041 1520-0469\(2001\)058<3271:SSQLOS>2.0.CO;2](https://doi.org/10.1175/1520-0469(2001)058<3271:SSQLOS>2.0.CO;2).
- 1042 Holton, J.R., Lindzen, R.S., 1972. An Updated Theory for the Quasi-Biennial
1043 Cycle of the Tropical Stratosphere. *Journal of Atmospheric Sciences* 29, 1076–
1044 1080. doi:[10.1175/1520-0469\(1972\)029<1076:AUTFTQ>2.0.CO;2](https://doi.org/10.1175/1520-0469(1972)029<1076:AUTFTQ>2.0.CO;2).
- 1045 Kraichnan, R.H., 1967a. Inertial Ranges in Two Dimensional Turbulence.
1046 *Physics of Fluids* 10, 1417–1423.
- 1047 Kraichnan, R.H., 1967b. Inertial ranges in two-dimensional turbulence. *The*
1048 *Physics of Fluids* 10, 1417–1423. doi:[10.1063/1.1762301](https://doi.org/10.1063/1.1762301).
- 1049 Kuroda, T., Medvedev, A.S., Hartogh, P., Takahashi, M., 2008. Correction to
1050 “Semiannual oscillations in the atmosphere of Mars”. *Geophysical Research*
1051 *Letters* 35, L23202. doi:[10.1029/2008GL036061](https://doi.org/10.1029/2008GL036061).
- 1052 Leovy, C.B., Friedson, A.J., Orton, G.S., 1991. The quasiquadrennial oscilla-
1053 tion of Jupiter’s equatorial stratosphere. *Nature* 354, 380–382. doi:[10.1038/
1054 354380a0](https://doi.org/10.1038/354380a0).
- 1055 Li, L., Jiang, X., Ingersoll, A.P., Del Genio, A.D., Porco, C.C., West, R.A.,
1056 Vasavada, A.R., Ewald, S.P., Conrath, B.J., Gierasch, P.J., Simon-Miller,
1057 A.A., Nixon, C.A., Achterberg, R.K., Orton, G.S., Fletcher, L.N., Baines,
1058 K.H., 2011. Equatorial winds on Saturn and the stratospheric oscillation.
1059 *Nature Geoscience* 4, 750–752. doi:[10.1038/ngeo1292](https://doi.org/10.1038/ngeo1292).
- 1060 Li, X., Read, P.L., 2000. A mechanistic model of the quasi-quadrennial oscilla-
1061 tion in Jupiter’s stratosphere. *Planetary and Space Science* .
- 1062 Lian, Y., Showman, A.P., 2008. Deep jets on gas-giant planets. *Icarus* 194,
1063 597–615. doi:[10.1016/j.
1064 icarus.2007.10.014](https://doi.org/10.1016/j.icarus.2007.10.014).
- 1065 Lian, Y., Showman, A.P., 2010. Generation of equatorial jets by large-scale
1066 latent heating on the giant planets. *Icarus* 207, 373–393. doi:[10.1016/j.
1066 icarus.2009.10.006](https://doi.org/10.1016/j.icarus.2009.10.006).

- 1067 Lindzen, R.S., Holton, J.R., 1968. A Theory of the Quasi-Biennial Os-
1068 cillation. *Journal of Atmospheric Sciences* 25, 1095–1107. doi:[10.1175/
1069 1520-0469\(1968\)025<1095:ATOTQB>2.0.CO;2](https://doi.org/10.1175/1520-0469(1968)025<1095:ATOTQB>2.0.CO;2).
- 1070 Liu, J., Schneider, T., 2010. Mechanisms of Jet Formation on the Giant Planets.
1071 *Journal of Atmospheric Sciences* 67, 3652–3672. doi:[10.1175/2010JAS3492.
1072 1](https://doi.org/10.1175/2010JAS3492.1), [arXiv:0910.3682](https://arxiv.org/abs/0910.3682).
- 1073 Lott, F., Guez, L., Maury, P., 2012. A stochastic parameterization of
1074 non-orographic gravity waves: Formalism and impact on the equatorial
1075 stratosphere. *Geophysical Research Letters* 39, L06807. doi:[10.1029/
1076 2012GL051001](https://doi.org/10.1029/2012GL051001).
- 1077 Lu, H., Baldwin, M.P., Gray, L.J., Jarvis, M.J., 2008. Decadal-scale changes in
1078 the effect of the qbo on the northern stratospheric polar vortex. *Journal of
1079 Geophysical Research: Atmospheres* 113. doi:[10.1029/2007JD009647](https://doi.org/10.1029/2007JD009647).
- 1080 Mayr, H.G., Lee, J.N., 2016. Downward propagating Equatorial Annual Os-
1081 cillation and QBO generated multi-year oscillations in stratospheric NCEP
1082 reanalysis data. *Journal of Atmospheric and Solar-Terrestrial Physics* 138,
1083 1–8. doi:[10.1016/j.jastp.2015.11.016](https://doi.org/10.1016/j.jastp.2015.11.016).
- 1084 Murgatroyd, R.J., Singleton, F., 1961. Possible meridional circulation in the
1085 Stratosphere and Mesosphere. *Quarterly Journal of the Royal Meteorological
1086 Society* .
- 1087 Orton, G.S., Friedson, A.J., Caldwell, J., Hammel, H.B., Baines, K.H.,
1088 Bergstralh, J.T., Martin, T.Z., Malcom, M.E., West, R.A., Golisch, W.F.,
1089 Griep, D.M., Kaminski, C.D., Tokunaga, A.T., Baron, R., Shure, M.,
1090 1991. Thermal maps of Jupiter - Spatial organization and time depen-
1091 dence of stratospheric temperatures, 1980 to 1990. *Science* 252, 537–542.
1092 doi:[10.1126/science.252.5005.537](https://doi.org/10.1126/science.252.5005.537).
- 1093 Orton, G.S., Yanamandra-Fisher, P.A., Fisher, B.M., Friedson, A.J., Parrish,
1094 P.D., Nelson, J.F., Bauermeister, A.S., Fletcher, L., Gezari, D.Y., Varosi, F.,

- 1095 Tokunaga, A.T., Caldwell, J., Baines, K.H., Hora, J.L., Ressler, M.E., Fu-
1096 jiyoshi, T., Fuse, T., Hagopian, H., Martin, T.Z., Bergstralh, J.T., Howett, C.,
1097 Hoffmann, W.F., Deutsch, L.K., van Cleve, J.E., Noe, E., Adams, J.D., Kas-
1098 sis, M., Tollestrup, E., 2008. Semi-annual oscillations in Saturn's low-latitude
1099 stratospheric temperatures. *Nature* 453, 196–199. doi:[10.1038/nature06897](https://doi.org/10.1038/nature06897).
- 1100 Plumb, A.R., Bell, R.C., 1982. A model of the quasi-biennial oscillation on an
1101 equatorial beta-plane. *Quarterly Journal of the Royal Meteorological Society*
1102 108, 335–352. doi:[10.1002/qj.49710845604](https://doi.org/10.1002/qj.49710845604).
- 1103 Pouquet, A., Marino, R., 2013. Geophysical turbulence and the duality of the
1104 energy flow across scales. *Physical Review Letters* 111, 234501. doi:[10.1103/
1105 PhysRevLett.111.234501](https://doi.org/10.1103/PhysRevLett.111.234501).
- 1106 Rajendran, K., Moroz, I.M., Read, P.L., Osprey, S.M., 2016. Synchronisation
1107 of the equatorial QBO by the annual cycle in tropical upwelling in a warming
1108 climate. *Quarterly Journal of the Royal Meteorological Society* 142, 1111–
1109 1120. doi:[10.1002/qj.2714](https://doi.org/10.1002/qj.2714).
- 1110 Reed, R.J., Campbell, W.J., Rasmussen, L.A., Rogers, D.G., 1961. Ev-
1111 idence of downward propagating annual wind reversal in the equatorial
1112 stratosphere. *Journal of Geophysical Research* 66, 813–818. doi:[10.1029/
1113 JZ066i003p00813](https://doi.org/10.1029/JZ066i003p00813).
- 1114 Rhines, P.B., 1977. The dynamics of unsteady currents. *The sea* 6, 189–318.
- 1115 Richter, J.H., Solomon, A., Bacmeister, J.T., 2014. On the simulation of
1116 the Quasi-Biennial Oscillation in the Community Atmosphere Model, ver-
1117 sion 5. *Journal of Geophysical Research (Atmospheres)* 119, 3045–3062.
1118 doi:[10.1002/2013JD021122](https://doi.org/10.1002/2013JD021122).
- 1119 Ruan, T., Lewis, N.T., Lewis, S.R., Montabone, L., Read, P.L., 2019. Inves-
1120 tigating the semiannual oscillation on mars using data assimilation. *Icarus*
1121 333, 404 – 414. URL: <http://www.sciencedirect.com/science/article/>

- 1122 [pii/S0019103518306055](https://doi.org/10.1016/j.icarus.2019.06.012), doi:[https://doi.org/10.1016/j.icarus.2019.](https://doi.org/10.1016/j.icarus.2019.06.012)
1123 [06.012](https://doi.org/10.1016/j.icarus.2019.06.012).
- 1124 Schinder, P.J., Flasar, F.M., Marouf, E.A., French, R.G., McGhee, C.A., Kliore,
1125 A.J., Rappaport, N.J., Barbini, E., Fleischman, D., Anabtawi, A., 2011.
1126 Saturn's equatorial oscillation: Evidence of descending thermal structure from
1127 Cassini radio occultations. *Geophysical Research Letters* 38, L08205. doi:[10.](https://doi.org/10.1029/2011GL047191)
1128 [1029/2011GL047191](https://doi.org/10.1029/2011GL047191).
- 1129 Schneider, T., Liu, J., 2009. Formation of Jets and Equatorial Superrotation on
1130 Jupiter. *Journal of Atmospheric Sciences* 66, 579. doi:[10.1175/2008JAS2798.](https://doi.org/10.1175/2008JAS2798.1)
1131 [1](https://doi.org/10.1175/2008JAS2798.1), [arXiv:0809.4302](https://arxiv.org/abs/0809.4302).
- 1132 Shaw, T.A., Shepherd, T.G., 2007. Angular Momentum Conservation and Grav-
1133 ity Wave Drag Parameterization: Implications for Climate Models. *Journal*
1134 *of Atmospheric Sciences* 64, 190. doi:[10.1175/JAS3823.1](https://doi.org/10.1175/JAS3823.1).
- 1135 Showman, A.P., Tan, X., Zhang, X., 2019. Atmospheric Circulation of Brown
1136 Dwarfs and Jupiter and Saturn-like Planets: Zonal Jets, Long-term Vari-
1137 ability, and QBO-type Oscillations. *The Astrophysical Journal* 883, 4.
1138 doi:[10.3847/1538-4357/ab384a](https://doi.org/10.3847/1538-4357/ab384a), [arXiv:1807.08433](https://arxiv.org/abs/1807.08433).
- 1139 Simon-Miller, A.A., Poston, B.W., Orton, G.S., Fisher, B., 2007. Wind varia-
1140 tions in Jupiter's equatorial atmosphere: A QJO counterpart? *Icarus* 186,
1141 192–203. doi:[10.1016/j.icarus.2006.08.009](https://doi.org/10.1016/j.icarus.2006.08.009).
- 1142 Sinclair, J.A., Irwin, P.G.J., Fletcher, L.N., Moses, J.I., Greathouse, T.K.,
1143 Friedson, A.J., Hesman, B., Hurley, J., Merlet, C., 2013. Seasonal varia-
1144 tions of temperature, acetylene and ethane in Saturn's atmosphere from 2005
1145 to 2010, as observed by Cassini-CIRS. *Icarus* 225, 257–271. doi:[10.1016/j.](https://doi.org/10.1016/j.icarus.2013.03.011)
1146 [icarus.2013.03.011](https://doi.org/10.1016/j.icarus.2013.03.011).
- 1147 Solomon, S., Kiehl, J.T., Garcia, R.R., Grose, W., 1986. Tracer Transport by
1148 the Diabatic Circulation Deduced from Satellite Observations. *Journal of the*
1149 *Atmospheric Sciences* .

- 1150 Spiga, A., Guerlet, S., Millour, E., Indurain, M., Meurdesoif, Y., Cabanes, S.,
1151 Dubos, T., Leconte, J., Boissinot, A., Lebonnois, S., Sylvestre, M., Fouchet,
1152 T., 2020. Global climate modeling of Saturn’s atmosphere. Part II: Multi-
1153 annual high-resolution dynamical simulations. *Icarus* 335, 113377. doi:[10.](https://doi.org/10.1016/j.icarus.2019.07.011)
1154 [1016/j.icarus.2019.07.011](https://doi.org/10.1016/j.icarus.2019.07.011).
- 1155 Sukoriansky, S., Galperin, B., Dikovskaya, N., 2002. Universal spectrum of
1156 two-dimensional turbulence on a rotating sphere and some basic features of
1157 atmospheric circulation on giant planets. *Physical review letters* 89, 124501.
- 1158 Sylvestre, M., Guerlet, S., Fouchet, T., Spiga, A., Flasar, F.M., Hesman, B.,
1159 Bjoraker, G.L., 2015. Seasonal changes in Saturn’s stratosphere inferred
1160 from Cassini/CIRS limb observations. *Icarus* 258, 224–238. doi:[10.1016/](https://doi.org/10.1016/j.icarus.2015.05.025)
1161 [j.icarus.2015.05.025](https://doi.org/10.1016/j.icarus.2015.05.025).
- 1162 Wheeler, M., Kiladis, G.N., 1999. Convectively Coupled Equatorial Waves:
1163 Analysis of Clouds and Temperature in the Wavenumber-Frequency Domain.
1164 *Journal of Atmospheric Sciences* 56, 374–399. doi:[10.1175/1520-0469\(1999\)](https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2)
1165 [056<0374:CCEWAO>2.0.CO;2](https://doi.org/10.1175/1520-0469(1999)056<0374:CCEWAO>2.0.CO;2).
- 1166 Young, R.M., Read, P.L., 2017. Forward and inverse kinetic energy cascades in
1167 jupiter’s turbulent weather layer. *Nature Physics* 13, 1135.

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compared to observation

- Saturn's ring shadowing impacts the stratospheric equatorial dynamics, the equatorial scillation periodicity and equatorial winds intensity