# JUMP – Data collection.

## Part II: Zonal jets and potential vorticity in three different approaches, laboratory - Global Climate Models - observations.

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## Contents

We present data sets used in the paper Cabanes et al. (2020a). Using the present data one can recompute the full statistical analysis with our open source numerical codes published on GitHub at: `https://github.com/scabanes`

## Part I

# Jets in the lab

**We designed an experimental device to reproduce the appropriate conditions for generating planetary like zonal jets. The experimental set-up Fig 1 is a rotating**

**30 cm square tank, filled with 4 cm of salt-water and is spun at 29 revolutions per minute. We run 9 independent experiments of electromagnetically driven zonal jets forced by a range of circular magnets placed at the bottom of the tank and centered on the rotating spin axis along an arc of either 90° or 180°. Experiments differ by the strength and the direction of the forcing, i.e. eastern and western jets are explored. Experimental measurements of the surface velocities are acquired by recording the tracks of small floating particles from a top lid camera onboard the rotating frame and analysing their paths using a Lagrangian tracking method (Galperin et al., 2016). Acquisition of 2D surficial velocity maps covers 58 rotation periods at a frequency of 20 Hz.**

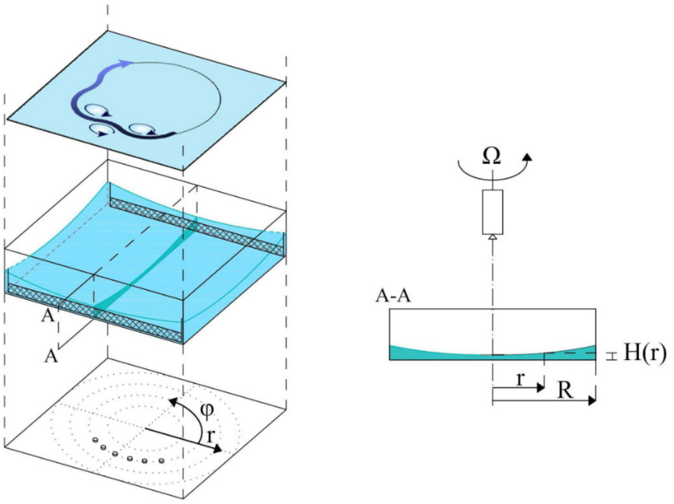

*figure 1:* **Schematic representation of the experimental device. The magnets are placed in a 90° arc of the radius a = 17 cm (sector I).**

Our device is based on several previous set-ups detailed in Espa et al. (2014); Galperin et al. (2014a, 2016). It consists of a $L_x = 0.68$ by $L_y = 0.69$ m rectangular tank of 0.20 m height that is attached to the rotating table by a rigid aluminium super-structure. The tank is filled with an electrolytic saline solution (mean depth of 4 cm) rotating counterclockwise with the angular velocity $\Omega = 3$ rad s$^{-1}$. A transparent lid insulated the working fluid from the ambient air (The experimental facility is shown Fig. 1). The radius of the working section is $R = 0.297$ m and the topographic $\beta$-effect $\beta = 2\Omega H^{-1} dH/dr$ is related to the column fluid height,

$$H = H_o + \frac{\Omega^2}{2g}\left(r^2 - \frac{L_x^2 + L_y^2}{12}\right) \tag{1}$$

where $r$ is the cylindrical radius and $g$ is the gravitational constant. In our spectral analysis, $\beta$ corresponds to the averaged value $\beta = 0.53$ cm$^{-1}$ s$^{-1}$. The forcing is produced by passing a constant electric current through the working fluid over an array of permanent magnets (12 mm in diameter and spaced by 1-2 cm from each other) mounted under the bottom of the tank in a 90° or 180° arc of a 17 cm radius. Using magnets' polarity, we can induce a westward and an eastward momentum that facilitated formation of westward and eastward zonal jets. In Fig. 1, we show the two electrodes positionned on the side of the tank, represented by two black grids. Consequently the electrical current is along cartesian coordinates. Experiments are run in both configurations for an electrical current intensity that goes from $I = 2, 4$ to 6 A. Files containing the experimental data set is attached with this document and uses the nomenclature summarize in Table 1.

Velocities were measured at flow surface by analyzing images of passively advected styrene particles with mean size of about $5 \cdot 10^{-5}$ m monitored by a video camera with a spatial resolution

| Experiment N° | Jets (arc in ∘) | I (A) | $\epsilon \times 10^4$ (W kg$^{-1}$) |
|---|---|---|---|
| Esp_2A_west_90 | 1: Western-jet (90°) | 2 | $2.1 \cdot 10^{-8}$ |
| Esp_4A_west_90 | 2: Western-jet (90°) | 4 | $11 \cdot 10^{-8}$ |
| Esp_6A_west_90 | 3: Western-jet (90°) | 6 | $29 \cdot 10^{-8}$ |
| Esp_2A_east_90 | 1: Eastern-jet (90°) | 2 | $2.1 \cdot 10^{-8}$ |
| Esp_4A_east_90 | 2: Eastern-jet (90°) | 4 | $11 \cdot 10^{-8}$ |
| Esp_6A_east_90 | 3: Eastern-jet (90°) | 6 | $21 \cdot 10^{-8}$ |
| Esp_2A_west_180 | 1: Western-jet (180°) | 2 | $2 \cdot 10^{-8}$ |
| Esp_4A_west_180 | 2: Western-jet (180°) | 4 | $8 \cdot 10^{-8}$ |
| Esp_6A_west_180 | 3: Western-jet (180°) | 6 | $20 \cdot 10^{-8}$ |

*Table 1:* **Laboratory runs with an electromagnetic forcing inducing a western and eastern momentum with an electrical current intensity I in ampere (A). Eastern jets are produced with a 90° arc of magnets while wetern jets are produced in 90° and 180° arc of magnets. We report an estimate of the energy transfer rate $\epsilon$ in W kg$^{-1}$.**

of 1023 × 1240 pixels at a frequency of 20 Hz. The acquired images were analyzed by a feature tracking algorithm that reconstructs instantaneous Lagrangian velocities (Lacorata and Espa, 2012). The time history of the Eulerian velocity field was then obtained by interpolating the sparse data over a regular polar and cartesian grid.

## Files for each experiment:

We deliver the folder named **JUMP-JetsInTheLab.zip**, containing velocity fields in polar and Cartesian coordinates. For each file, velocities are in cm.s$^{-1}$ and the relative vorticity is in s$^{-1}$.

**InfosFile.m :** contains informations on the experiment in which it is nested. This file is required to run numerical codes from `https://github.com/scabanes`. This file contains the number of points on which the velocity field have been interpolated, Nri, Nti, the number of available frames, nFrames, as well as file names of the velocity fields NameVt, NameVr, NameU, NameV, NameVort and detailed below.

**Vz_X_XX (NameVt):** is a mtx file containing the interpolated velocity field of the zonal/azimuthal components in polar coordinate centered on the center of the tank. For each experiment X = Nri the number of point in radius, XX = Nti the number of point in azimuth. The mtx file contains a 2D matrix Vz_X_XX = (Nti×*Nri, nFrames).

**Vr_X_XX (NameVr):** is the radial velocity component interpolated on the same grid than the zonal velocity. Then, Vr_X_XX = (Nti×*Nri , nFrames).

**U2_cart (NameU):** is a mtx file containing the interpolated velocity field of the y component in cartesian coordinate. The mtx file contains a 2D matrix U = (Ny×*Nx , nFrames), with Ny=Nx the number of points on the y and x coordinates respectively. Nx=Ny=128 points.

**V2_cart (NameV):** is a mtx file containing the interpolated velocity field of the x component in cartesian coordinate. The mtx file contains a 2D matrix V = (Ny×*Nx , nFrames), with Ny=Nx the number of points on the y and x coordinates respectively. Nx=Ny=128 points.

**Vort2_cart (NameVort):** is a mtx file containing the relative vorticity in cartesian coordinate, $\omega = \nabla \times (U + V)$. The mtx file contains a 2D matrix Vort = (Ny×*Nx , nFrames), with Ny=Nx the number of points on the y and x coordinates respectively. Nx=Ny=128 points.

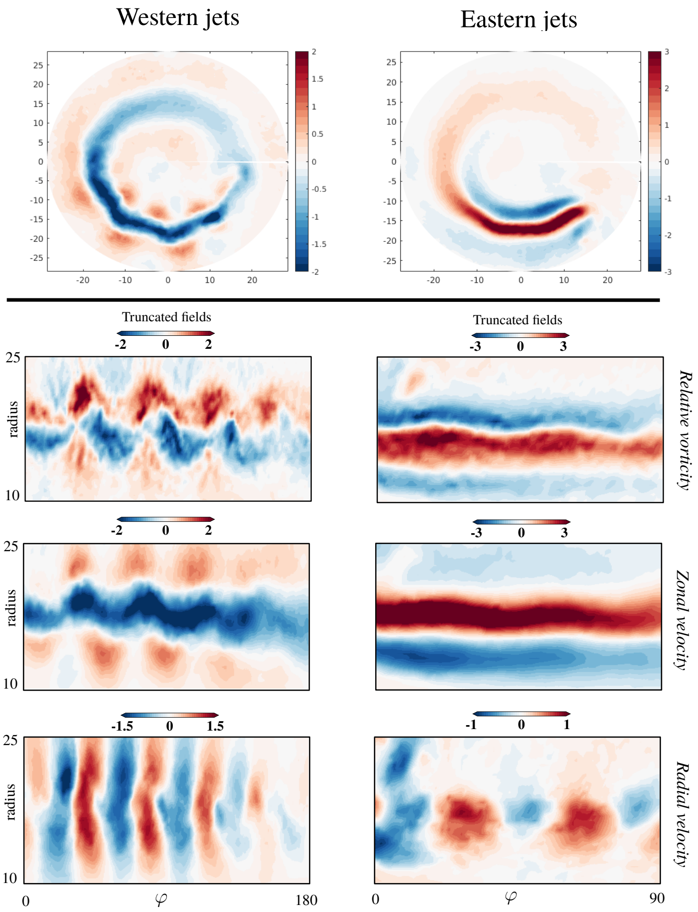

*figure 2:* **Laboratory fields and spectral analysis. From top to bottom, vorticity ($s^{-1}$), zonal velocity ($m\ s^{-1}$) and radial velocity ($m\ s^{-1}$) fields as well as spectral distribution of kinetic energy ($m^2\ s^{-2}$). All quantities are reported for an eastern/western jet forced on a 180°/90° arc of magnets with a forcing that corresponds to an electrical current of $I = 6A$. Upper field are full field of the azimuthal velocity component when loaded from VzX_XX_XXX. Bottom fields are truncated in the region of interest for all three components.**

**fes2_.FES:** contains informations on the data acquisition/calibration and interpolation of the velocity measurements. Informations are automatically loaded to compute the grid related to the velocity fields.

# Part II

# Jets from a Global Climate numerical model – DYNAMICO

**We use a high performance Global Climate Models (GCMs) to model the atmospheric circulation of gas giants with appropriate physical parametrizations for Saturn's atmosphere. The high-resolution model is named DYNAMICO and solves for 3D primitive equations of motion. We ran a Saturn simulation covering 15 Saturn years using the Saturn DYNAMICO GCM. Wind fields are output every 20 Saturn days at 32 pressure levels onto 1/2° latitude-longitude grid maps. Details on this Saturn reference simulation are given in Spiga et al. (2020) and Cabanes et al. (2020b). We now detail data that have been used for our publication Cabanes et al. (2020a).**

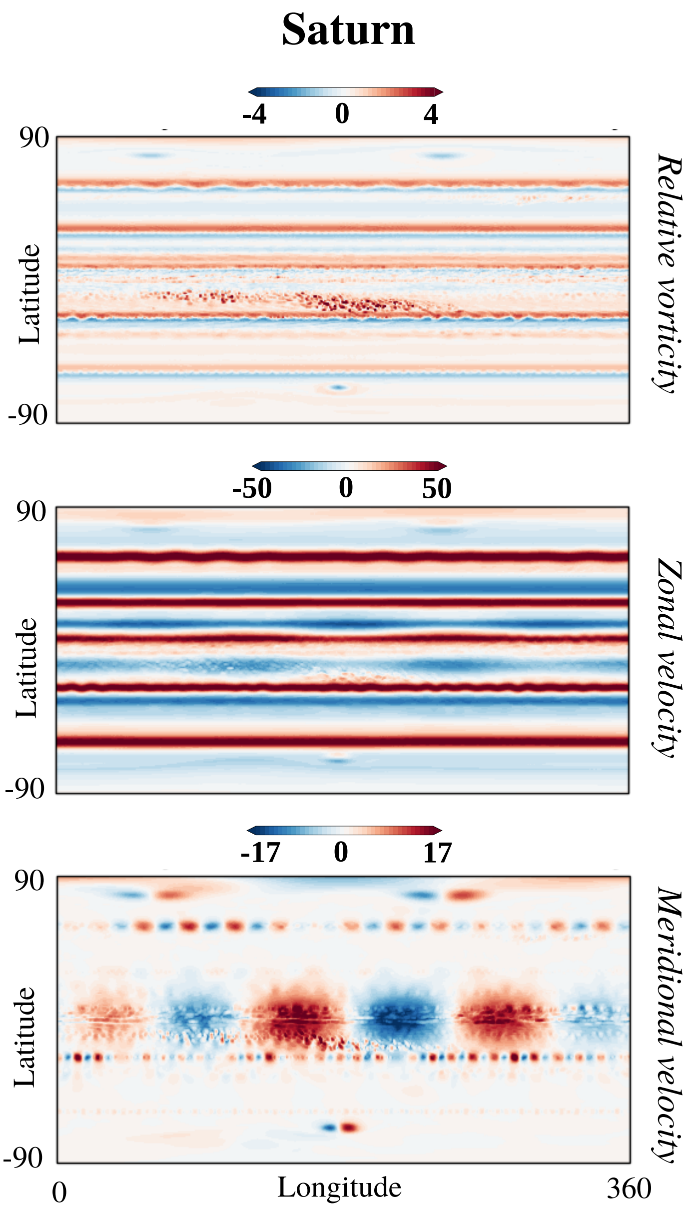

*figure 3:* **Saturn GCM fields. Top to bottom, relative vorticity is $\times 10^{-5}$ s$^{-1}$, zonal velocity and meridional velocities are in m s$^{-1}$.**

## Files from Saturn reference Simulation:

We deliver files to compute the full statistical analysis of our Saturn reference simulation. An example of latitude-longitude maps from our Saturn reference simulation is shown in Fig. 3 and the data file is available at the link `https://doi.org/10.5281/zenodo.3638105` and under the name,

**uvData-SRS-istep-312000-nstep-50-niz-12.nc:** is a netcdf file containing velocity fields for 12 pressure levels corresponding to the altitudes 34.9, 58.3, 82.3, 94.3, 106.3, 130.3, 154.3, 166.3, 178.3, 202.3, 226.3, 250.3 km, (with 0 km at the 3-bar level, which is the bottom of the model) and for 50 time steps between the simulated 12.7 and 12.84 Saturn years.

The file contain the following variables in m.s$^{-1}$:

- We note **u** and **v** the zonal and meridional velocity components respectively. The horizontal velocity fields are projected on a latitudinal-longitudinal grid. Grid space is of 0.5° and range in latitude from -89.75° to 89.75° and in longitude from 0.25° to 359.75°.

- We note **u_SMerid** and **v_SMerid** the zonal and meriodional velocity components sampled in a meridional cross section. The meridional cross section is at longitude 0.25° on known on 32 pressure levels from altitudes 0 to 375 km (with 0 km the bottom of the model).
- the vector "dsteps" contains all time steps, with dsteps/24430 gives time in Saturn's year.

=> From file uvData-SRS-istep-312000-nstep-50-niz-12.nc on can compute the full statistical analysis using the Fortran 90 code statistical_analysis_JupObs_xyzt.f90 available on GitHub at `https://github.com/scabanes/POST`. It results an output file StatisticalData.nc (an example of this file is given at `https://doi.org/10.5281/zenodo.3638105` and can easily be recomputed) which contains the full statistical analysis described in Cabanes et al. (2020b) and vorticity maps. This statisitcal analysis can be shown using the plots library that requires the following files.

**filePTS.zono.temp:** contains information of the Saturn reference simulation and is required to use the plots library. The following variables need to be appropriately set for our Saturn reference simulation:

- omega_sat = 0.000165121 The planetary rotation rate in $s^{-1}$.
- R_sat = 58232000 planetary radius in m
- SatDay_s = 38052 Planetary day length in second
- Ck = 6 Kolmogorov constant of $ER(n) = C_k$ epsilon$^{2/3}n^{-5/3}$ ; $[Ck]$ = non-dim
- epsilon = 0.0000013 Energy transfer rate [epsilon] = m$^2$/s$^3$
- Cz = 0.2 Zonal constant of $EZ(n) = C_z\beta^2 n^{-5}$ ; [Cz] = non-dim
- H-atm = 59000 Planetary atmospheric height. $[H] = m$
- N = 0.01 Mean Brunt-Väisälä frequency. $[N] = s^{-1}$
- epsilon_f = 0.0000013 Energy transfer rate $<< f.u >_s>_T$ en m$^2$.s−3
- n_f = 0. unused
- tau_f = 0. Numerical time for physical package iteration. Don't have to be changed
- epsilon_i = 0.0000013 Energy transfer rate $<< f.u >_s>_T$ en m$^2$.s$^{-3}$

Note that all Energy transfer rate have to be at the same value.

**filePTS.plots.infos:** Contains information for the time evolution plots using the code General-Tevo-PltStat.py. One has to choose the suitable variables for time and vertical averaging:

- omega_ref = 0.000165121 Planetary rotation rate in $s^{-1}$
- time = 1 2 3 Are time step to plot in the time evolution plots
- Vertical average is performed from level iz1 to iz2
- iz1 = 2 lower altitude levels on which the vertical average is computed
- iz2 = −1 upper altitude levels on which the vertical average is computed
- itime = −170 Time step we average on.

## Part III

# Jets from Cassini observations

For Jupiter, we use 2D horizontal velocity maps projected onto a latitude-longitude grid that have been derived by Galperin et al. (2014b) using cloud tracking analyses in Cassini high resolution images. We focused on the data set G14g that covers three rotation periods of the planet over 360° in longitude and ±50° in latitude (see example of field maps Fig. 4). In order to perform the same analysis than the one computed for "Jets from a Global Climate numerical model – DYNAMICO" we deliver a netcdf file that gather velocity fields from Galperin et al. (2014b) and can easily be used to run our numerical codes from GitHub.

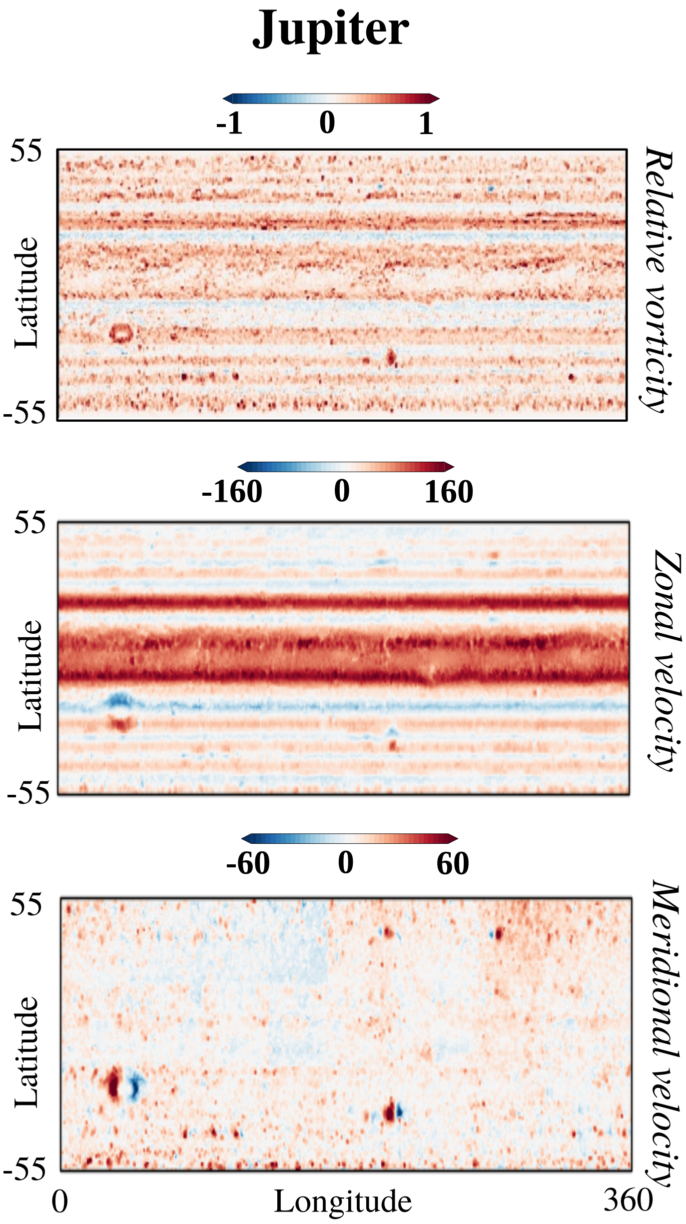

*figure 4:* Saturn GCM fields. Top to bottom, relative vorticity is $\times 10^{-5}$ $s^{-1}$, zonal velocity and meridional velocities are in m $s^{-1}$.

# Files for Jupiter direct observations:

All data can be found in the "Supplementary material" from the paper Galperin et al. (2014b). Here, we deliver a netcdf file of the G14g data set named **uvData-JupObs-istep-0-nstep-4-niz-1.nc**. In this file, velocity fields are projected on the same latitudinal-longitudinal grid that the one used for Saturn reference simulation, i.e. it ranges in latitude from -89.75° to 89.75° and in longitude from 0.25° to 359.75°, zonal and meridional velocity components are **u** and **v** respectively. Following the same procedure one can obtain the statistical analysis for Jupiter flow setting the appropriate planetary constant in the Fortran 90 code statistical_analysis_JupObs_xyzt.f90 and then make compilation. By running the file on the Jupiter velocity fields one obtains the output file StatisticalData.nc that contains the associated statistical analysis and vorticity maps (StatisticalData-JupObs.nc is given as an example of this file). The plots library is then used with the following files:

**filePTS.zono.temp:** contains information of the Saturn reference simulation and is required to use the plots library. The following variables need to be appropriately set for Jupiter observations:

- omega_sat = 0.0001750 The planetary rotation rate in $s^{-1}$.
- R_sat = 69911000 planetary radius in m
- SatDay_s = 1 Planetary day length in second
- Ck = 6 Kolmogorov constant of $ER(n) = C_k$ epsilon$^{2/3}n^{-5/3}$ ; $[Ck]$ = non-dim
- epsilon = 0.00009 Energy transfer rate [epsilon] = m$^2$/s$^3$
- Cz = 0.2 Zonal constant of $EZ(n) = C_z\beta^2 n^{-5}$ ; [Cz] = non-dim
- H-atm = 1000000 Planetary atmospheric height. $[H] = m$
- N = 0.01 Mean Brunt-Väisälä frequency. $[N] = s^{-1}$
- epsilon_f = 0.00009 Energy transfer rate $<< f.u >_s>_T$ en m$^2$.s−3
- n_f = 0. unused
- tau_f = 0. Numerical time for physical package iteration. Don't have to be changed
- epsilon_i = 0.00009 Energy transfer rate $<< f.u >_s>_T$ en m$^2$.s$^{-3}$

Note that all Energy transfer rate have to be at the same value.

**filePTS.plots.infos:** Contains information for the time evolution plots using the code General-Tevo-PltStat.py. One has to choose the suitable variables for time and vertical averaging:

- omega_ref = 0.0001750 Planetary rotation rate in $s^{-1}$
- time = 1 2 Are time step to plot in the time evolution plots
- Vertical average is performed from level iz1 to iz2. Note that for Jupiter observations only one pressure level is available.
- iz1 = 0 lower altitude levels on which the vertical average is computed
- iz2 = 1 upper altitude levels on which the vertical average is computed
- itime = −4 Time step we average on.

## Part IV

# Potential vorticity profiles from Jupiter and Saturn observations

**Profiles of Ertel potential vorticity (PV) on isentropic surfaces (IPV) and/or quasi-geostrophic potential vorticity (QGPV) are well established in dynamical meteorology as powerful sources of insight into dynamical processes involving "balanced" flow. The previous study of Read et al. (2006) and Read et al. (2009) derive profiles of zonal-mean IPV and QGPV in Jupiter's and Saturn's upper troposphere and lower stratosphere by making use of a combination of measurements, derived from the images of Voyager 1 and 2 and Cassini missions. This potential vorticity profiles have been used for PV monotonization in our publication Cabanes et al. (2020a).**

## Files for Jupiter and Saturn PV profiles:

The most fundamental form is the Ertel potential vorticity formulation on isentropic surfaces, usually called IPV (Ertel and Rossby, 1949). Under the quasi-geostrophic (QG) approximation, an alternative form of PV defined on isobaric surfaces is QGPV (Gierasch et al., 2004). Both IPV and QGPV involve thermodynamical terms and their exact formulations are detailed in the Methods of our article Cabanes et al. (2020a). All the data can be found in the file named **IPV-QGPV-Jupiter-Saturn.zip** and are organized as follow,

**For Jupiter:**

- *qq_ CIRSjupiter.dat* and *qq_ V1jupiter.dat* are QGPV profiles using CIRS and IRIS instruments respectively as detailed in the caption of Figure 5.
- *qt_ CIRSJupiter.dat* and *qt_ V1Jupiter.dat* are IPV profiles using CIRS and IRIS instruments respectively as detailed in the caption of Figure 6.
- *utn_ CIRSjupiter.dat* and *utn_ V1jupiter.dat* are zonal velocity profiles from the Cassini and Voyager instruments, see Figure 5 and 6 .

**For Saturn:**

- *CIRS-Sat_ qq.dat* are QGPV profiles using CIRS instrument as detailed in the caption of Figure 7.
- *CIRS-Sat_ qt.dat* are IPV profiles using CIRS instrument as detailed in the caption of Figure 7.
- *utn_ CIRSsaturn.dat* are zonal velocity profiles profiles using Cassini instrument as detailed in the caption of Figure 7.

In all files, the first column is the vector of latitudes, and the other columns are the IPV and QGPV data with a first line heading that corresponds to the temperature level in Kelvin (for IPV) and the pressure level in hPa (for QGPV).

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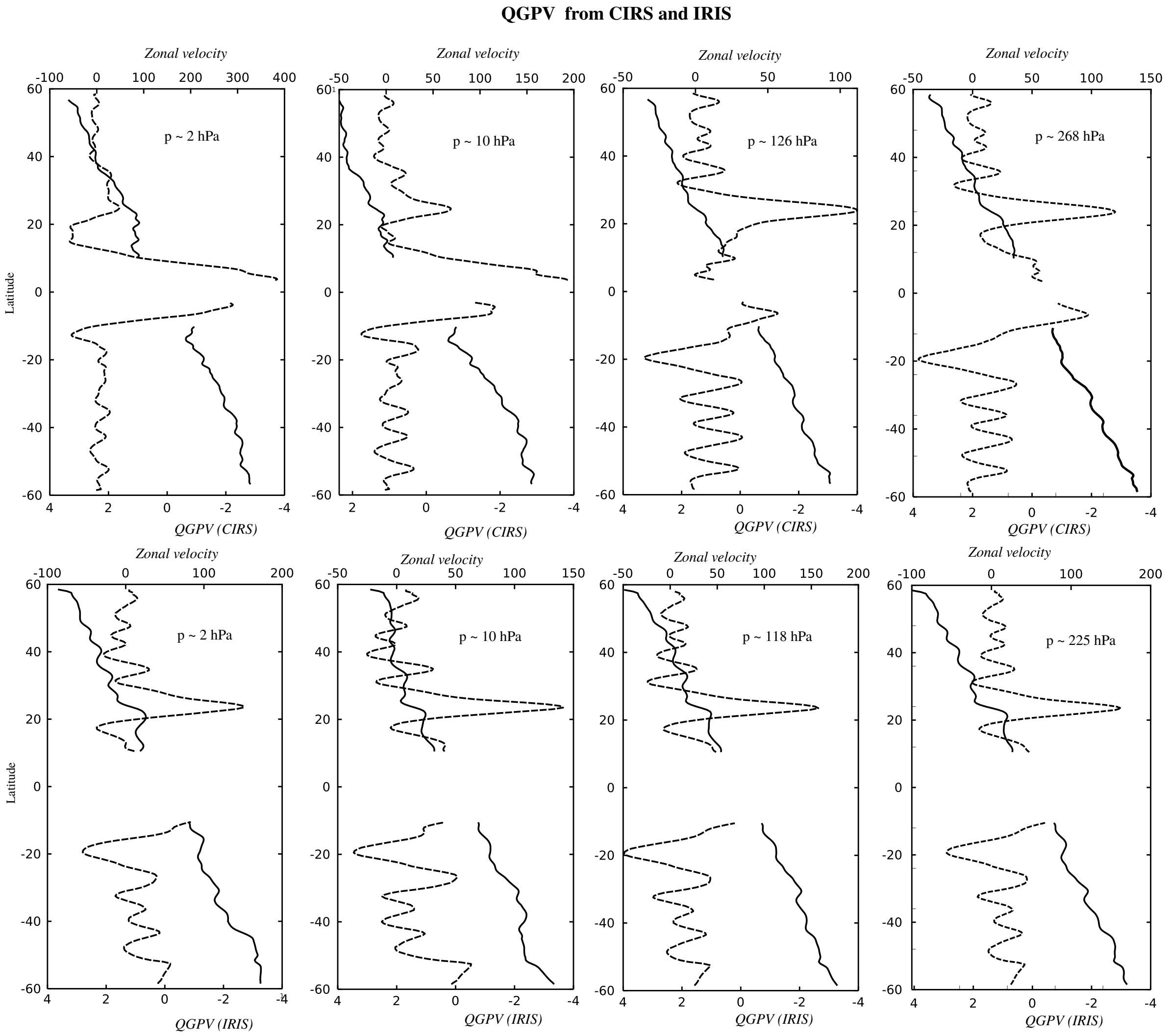

*figure 5:* **Jupiter QGPV and averaged zonal velocity profiles. To compute QGPV latitudinal profiles for Jupiter (limited to ±58° in latitude), Read et al. (2006) combined velocity measurements, derived by tracking cloud features in Voyager 1 and 2 and Cassini images, and thermal measurements from the Voyager 1 InfraRed Interferometric Spectrometer (IRIS) (Conrath et al., 1998) and Cassini Composite InfraRed Spectrometer (CIRS) (Porco et al., 2004) instruments. QQPV from CIRS and IRIS instruments are shown as black thick lines in units of $\times 10^{-4}$ s$^{-1}$, and zonal velocity is shown as dashed lines in units of m s$^{-1}$. The pressure level $p$ where profiles are measured are labeled in each panel. For more details on QGPV profiles see Read et al. (2006).**

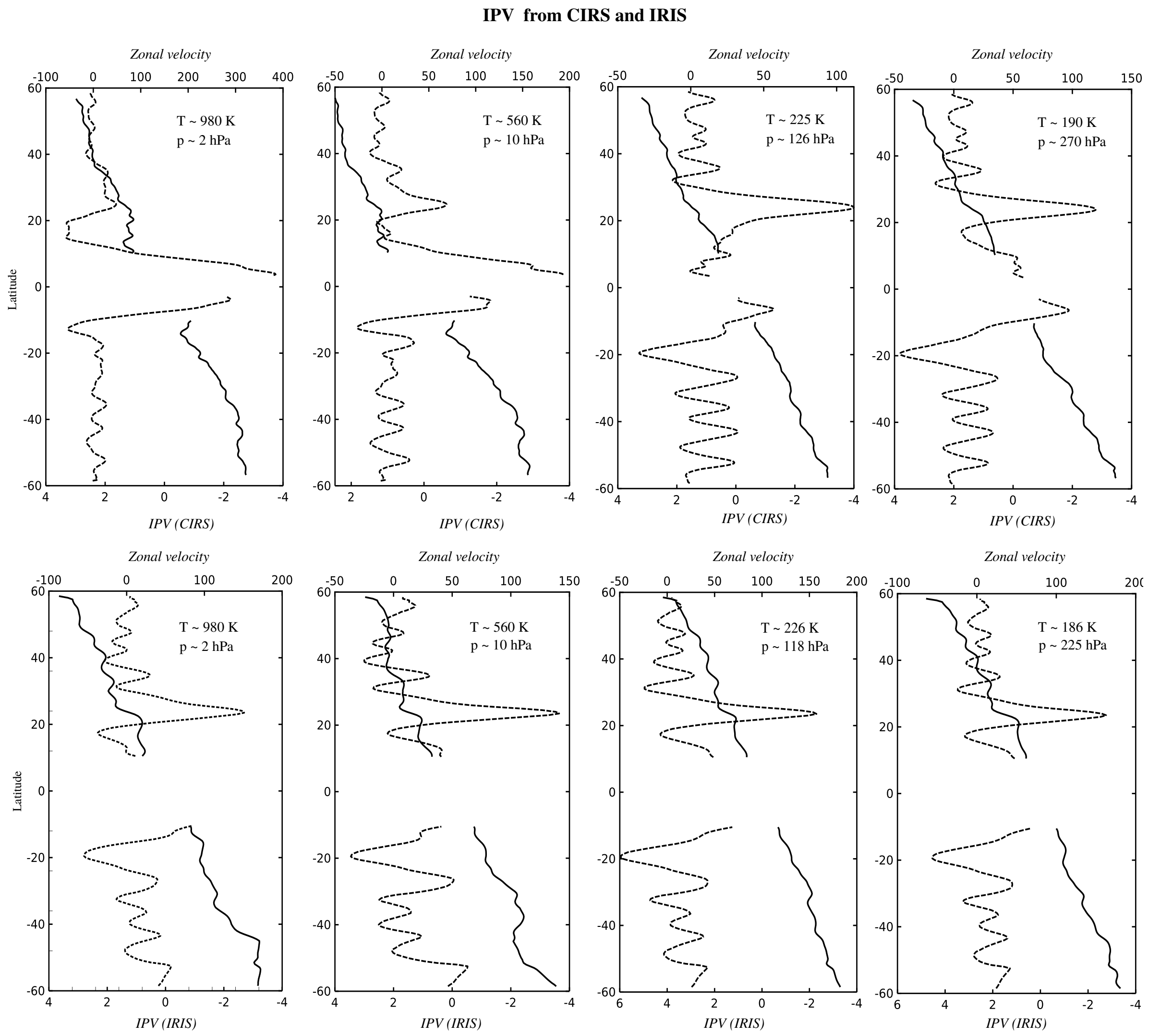

***figure 6:*** **Jupiter IPV and averaged zonal velocity profiles. To compute IPV latitudinal profiles for Jupiter (limited to ±58° in latitude), Read et al. (2006) combined velocity measurements, derived by tracking cloud features in Voyager 1 and 2 and Cassini images, and thermal measurements from the Voyager 1 InfraRed Interferometric Spectrometer (IRIS) Conrath et al. (1998) and Cassini Composite InfraRed Spectrometer (CIRS) (Porco et al., 2004) instruments. IPV from CIRS and IRIS instruments are shown as black thick lines in units of $\times 10^{-4}$ $s^{-1}$, and zonal velocity is shown as dashed lines in units of m $s^{-1}$. The pressure level $p$ and the temperature $T$ of the isentropic level at which profiles are measured in the atmosphere, are labeled in each panel. For more details on IPV profiles see Read et al. (2006).**

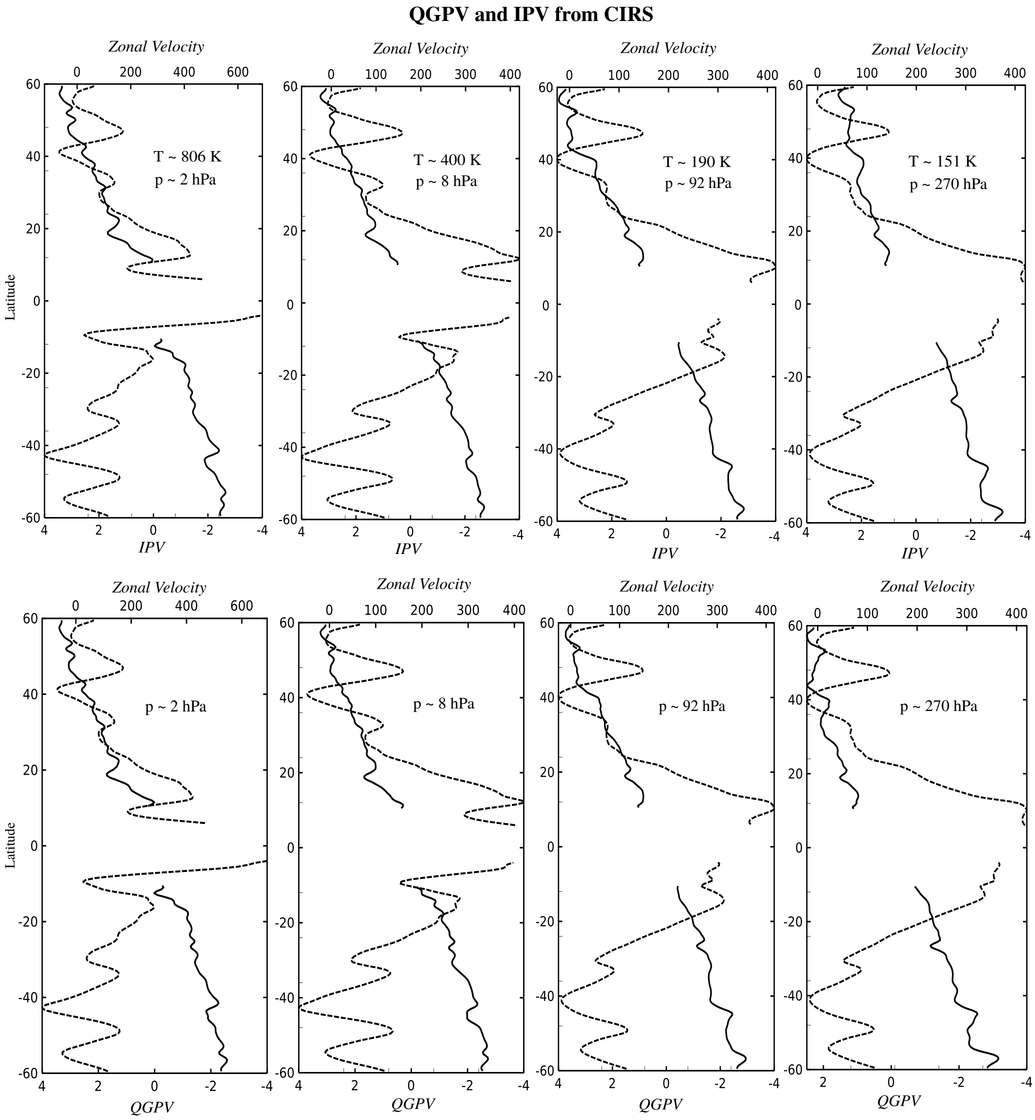

***figure 7:*** **Saturn potential vorticity and averaged zonal velocity profiles. We show IPV and QGPV measured from CIRS-instrument and represented in thick black lines in units of $\times 10^{-4}$ $s^{-1}$. Zonal velocity are dashed lines in units of m $s^{-1}$. The temperature of the isentropic level and/or the pressure level $p$ at which profiles are measured in the atmosphere, are labeled in each panel. For more details on the IPV and QGPV profiles see Read et al. (2009).**