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TWO-YEAR OBSERVATIONS OF THE JUPITER POLAR REGIONS BY JIRAM ON BOARD JUNO

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Key Points:

- **The Jupiter's polar cyclonic structures, both in the North and in the South Poles, did not change much in two years of observations from February 2017 to February 2019.**
- **This study reports** abundances of atmospheric minor constituents - water, ammonia, phosphine and germane - **measured** in the **hottest spots of the polar regions with higher values registered in the south.**
- **The analysis of the polar structures' dynamics shows similarities to the Earth oceanic cyclones.**

Abstract

We observed the evolution of Jupiter's polar cyclonic structures over two years between February 2017 and February 2019, using polar observations by the Jovian InfraRed Auroral Mapper, JIRAM, on the Juno mission. Images and spectra were collected by the instrument in the 5- μm wavelength range. The images were used to monitor the development of the cyclonic and anticyclonic structures at latitudes higher than 80° both in the northern and the southern hemispheres. **Spectroscopic** measurements **were then used to monitor** the abundances of minor atmospheric constituents water vapor, ammonia, phosphine and germane in the polar regions, where the atmospheric optical depth is less than 1. Finally, **we performed** a comparative analysis with oceanic cyclones on Earth in **an** attempt to explain the spectral characteristics of the cyclonic structures we observe in Jupiter's polar atmosphere.

Plain Language Summary

The Jovian InfraRed Auroral Mapper (JIRAM) is **an instrument** on-board the Juno NASA spacecraft. It **encloses of** an infrared camera, for mapping both **Jupiter's auroras and atmosphere**, and a spectrometer.

49 In February 2017, the complex cyclonic structures that characterize the Jupiter's polar atmospheres
50 were discovered. **Here, we report the evolution of those cyclonic structures during the 2 years**
51 **following the discovery. For the purpose, we use** infrared maps built by the **JIRAM** camera images
52 collected at wavelengths around 5 μm .

53 **The cyclones have thick clouds which** obstruct most of the view of the deeper atmosphere. However,
54 some areas, near the cyclones, are **only** covered by **thin** clouds **allowing** the spectrometer **to** see
55 below **deeper in** the **atmosphere**. In those areas, **the instrument was able to catch** spectral
56 **signatures that permitted to estimate** abundances of water vapor, ammonia, phosphine and
57 germane. **Those gases** are minor but **significant constituents** of the atmosphere.

58 Finally, the dynamics of the Jupiter's polar atmosphere **are** not well understood and **are still** under
59 study. Here, to give indications **about** the possible mechanisms that governs the polar dynamics, we
60 attempted a comparative analysis with some Earth oceanic cyclones that show similarities with the
61 Jupiter ones.

62

63

64 **Keywords:** Jupiter, Planetary Atmosphere, Polar Regions, Composition, Mesospheric Dynamics

65

66 1. Introduction

67

68 The Juno mission entered into Jupiter orbit in July, 2016 (Bolton et al. 2017). The Jovian InfraRed
69 Auroral Mapper, JIRAM, is part of the payload of the spacecraft (Adriani et al. 2017). **Key goals** of
70 this instrument **are** to collect both $\sim 5\text{-}\mu\text{m}$ imaging (M band filter: 4.5 to 5 μm) and spectral
71 observations in the 2-5 μm range with a spectral resolution of about 15 nm to study Jupiter's
72 atmosphere. **The methane transparency window around 5 μm is a region dominated by the**
73 **atmospheric thermal emission. However, the thermal emission is modulated by the presence of**
74 **the clouds and, then, the depth of the infrared sounding depends on the cloud thickness. In**
75 **absence of clouds and for small optical thickness the infrared sounding at wavelengths around**
76 **5 μm can reach depths of 4-5 bar. The imager focal plane is divided in two areas by the presence**
77 **of two optical filters: one in band L dedicated to auroral mapping and the other in band M for**
78 **atmospheric observations. The auroral signal is much less intense than atmospheric thermal**
79 **emission, then the imager has to use different integration times in according to the target to**
80 **observe. This fact means that the two observations are in competition and cannot operated**
81 **simultaneously.** The imager and the spectrometer have a spatial resolution of 250 μrad and are
82 operated simultaneously.

83 The great advantage of Juno's instruments, compared to all the others that have observed Jupiter for
84 years from Earth and from other space missions, is **that Juno is in a polar orbit, allowing an**
85 **unprecedented view of** the planet's poles.

86 On February 2nd 2017, during the fourth fly-by, JIRAM had the opportunity to observe the polar
87 atmosphere of Jupiter for the first time (Adriani et al. 2018). Those observations, together with those
88 of the visible JunoCam imager (**Hansen et al, 2014**), allowed us to survey for the first time the
89 dynamical structure of the polar atmosphere of the planet. The North Pole exhibits a polar cyclone
90 (**or NPC**) surrounded by eight circumpolar cyclones (or CPCs) while the South Pole is characterized
91 by five cyclones surrounding a polar cyclone. The CPCs have approximately the same size as their
92 respective central polar cyclones; the southern cyclones are larger than the northern ones.

93 JIRAM's observation of Jupiter's poles has continued since February 2017 during fly-bys with
94 favorable spacecraft attitudes and when auroral observations by JIRAM were not scheduled. For the
95 sake of simplicity we identify **Juno** orbits with the label PJ (PeriJove) followed by the orbit number.
96 The spacecraft attitude was generally not favorable to the JIRAM observations during orbits when
97 the mission optimized the gravitational mapping of Jupiter (GRAV orbits). Additionally, the

98 instrument can only observe targets that are within $\pm 3^\circ$ of the plane orthogonal to the spacecraft spin
 99 axis. A limited number of orbits have been dedicated to remote sensing instrumentation on board of
 100 Juno. During orbits when the MicroWave Radiometer (MWR) was the prime instrument, JIRAM
 101 could observe the planet during the approach and reasonably cover the North Pole. Orbit 9 (PJ9) was
 102 the last **one in which** JIRAM had a reasonably good coverage of the Pole. On the other hand, the
 103 South Pole could be observed almost during every perijove pass with good coverage and spatial
 104 resolution.

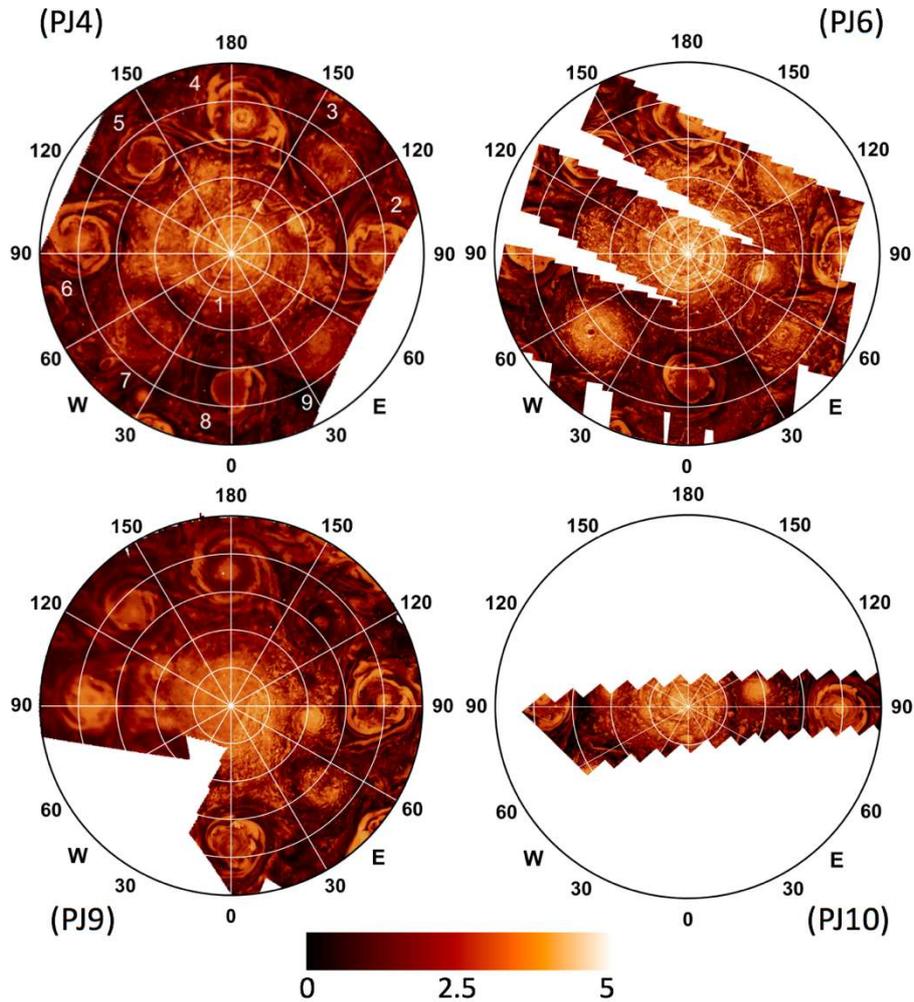
105 Table 1 provides a summary of the observations **for which we were able to obtain good coverage**
 106 **of the polar regions**: four for the North Pole and ten for the South Pole. Observations with more
 107 limited coverage have been excluded from this analysis. Given that Juno maintains a polar orbit of
 108 about 53 days, that is the minimum time interval between two successive observations reported here.
 109 The spatial resolution at the 1-bar pressure level is variable and ranges from about 15 km to about 60
 110 km, depending on the position of the spacecraft in the orbit.
 111

Date	Orbit #	Orbit type	Pole	Average Resolution	Images #
02/02/2017	4	MWR	North	51 km	9
			South	55 km	11
05/19/2017	6	MWR	North	23 km	45
			South	59 km	12
09/01/2017	8	GRAV	South	47 km	18
10/24/2017	9	MWR	North	39 km	40
			South	16 km	40
12/16/2017	10	GRAV	North	15 km	14
02/07/2018	11	GRAV	South	44 km	17
05/24/2018	13	GRAV	South	53 km	12
07/16/2018	14	GRAV	South	57 km	10
09/07/2018	15	GRAV	South	61 km	23
12/21/2018	17	GRAV	South	49 km	16
02/12/2019	18	GRAV	South	46 km	14

112
 113 Table 1. Summary of the polar observations. The average resolution reported here is calculated at 1-
 114 bar level and it is referred to the mosaics shown in Figures 1, 2 and 3. It is the result of the
 115 resampling of the single images at a homogeneous spacing. Last column shows the number of
 116 images used for composing the mosaics of Figures 1,2 and 3.
 117

118 **Moreover, while tropospheric composition in hot spots and in extended regions at Jupiter's low**
 119 **and intermediate latitudes has been investigated by a number of authors on the basis of**
 120 **spacecraft and ground-based telescope data (e.g. Giles et al. 2015 and Giles et al. 2017), no study**
 121 **has yet covered the polar regions. However, starting from the Juno's fourth perijove (PJ4,**
 122 **February 2nd 2017) JIRAM has gradually acquired extensive observations over both poles.**
 123 **Here we calculate the tropospheric content of water, ammonia, phosphine and germane at**
 124 **Jupiter's polar regions from JIRAM spectral data in those areas where the atmospheric optical**
 125 **depth is lower than 1.**

126 Finally, in order to give a contribute to the understanding of the dynamic processes that
 127 regulate the circumpolar structural of the Jupiter we attempt a parallel with oceanic cyclone
 128 observed on Earth.



129
 130 **Figure 1.** North pole during PJ4, PJ6, PJ9 and PJ10 (from top to bottom al left from right). Whitish
 131 colors indicate higher optical depth (τ), i.e. thicker clouds. Cyclone numbering: the polar cyclone is
 132 #1; the cyclone at 90E is #2; the numbering proceeds counterclockwise from #3 to #9. The color bar
 133 on the bottom indicates the value of τ .
 134
 135

136 2. Observations

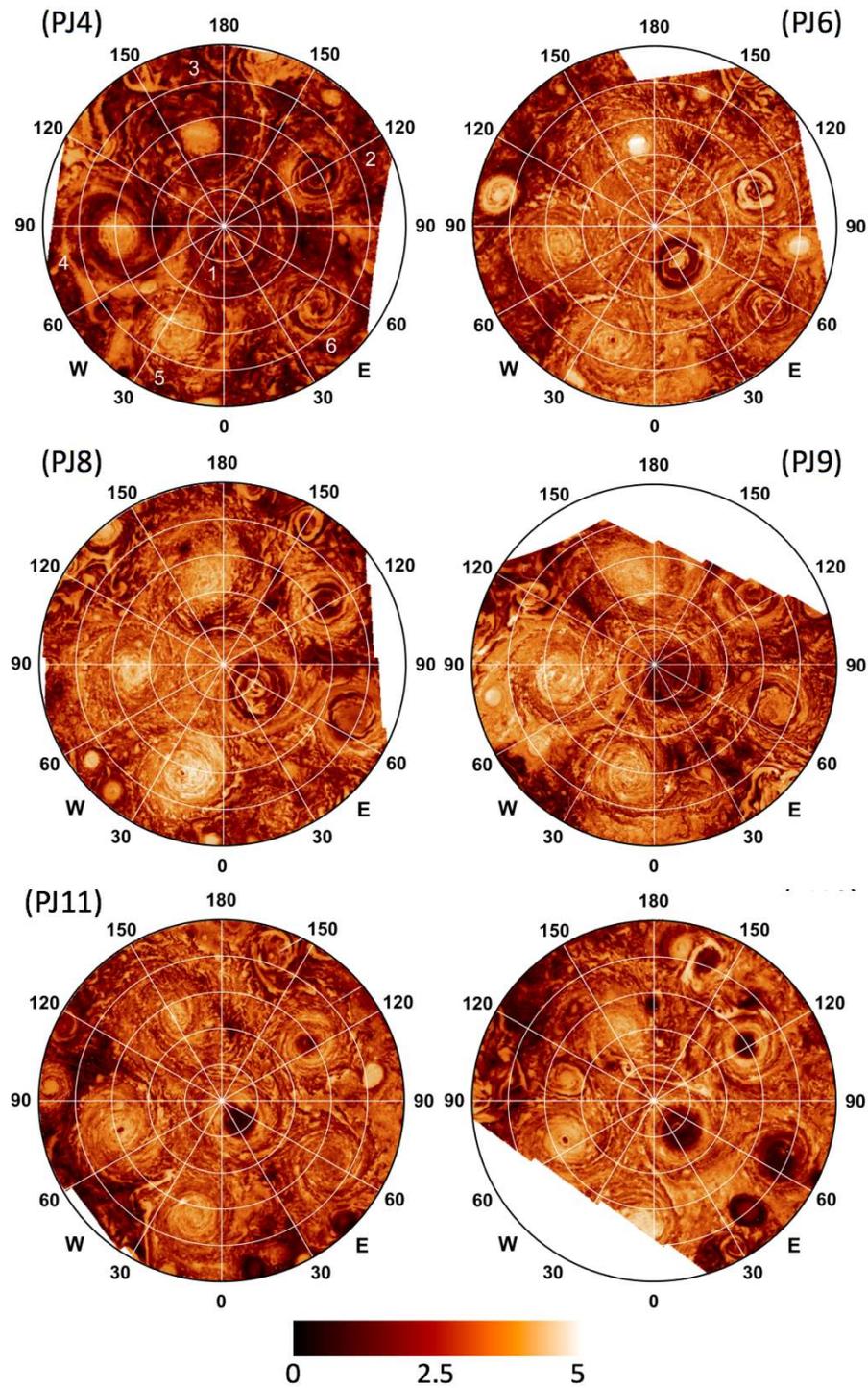
137 Table 1 reports the pixel resolutions of the mosaics built by single stereographic maps based on
 138 System III longitude and planetocentric latitude coordinates and the number of images used for the
 139 relative mosaics. Mosaics are shown in Figures 1, 2 and 3: Figures 1 refers to the North Pole
 140 observations while Figures 2 and 3 refer to those at the South Pole. All the observations and the
 141 analysis reported here are at a latitude higher than 80°N and 80°S. **All the single images used in this
 142 work, as well as the plots in the mosaics of Figures 1, 2 and 3, have been corrected by the Beer's
 143 law, and the data were chosen so that the emission angle (the angle between the normal to the
 144 planet at the pixel location and the direction of the spacecraft) was always lower than 60°
 145 (except for the Northern cyclones #5 and #6 during PJ9). Then, Figures 1, 2 and 3 are plotted
 146 in term of optical depth, $\tau = \log(I_0/I)$, that is normalized to the value $I_0 = 0.65624 \text{ Wm}^{-2}$ which
 147 is the maximum radiance measured at latitudes higher than 80° either in the north or in the**

148 **south. In this scheme, light colors represent thicker clouds. Namely, the figures show the polar**
149 **regions cloudiness making them easier to compare to the visual camera observations of**
150 **JunoCam, the camera on-board Juno. All JunoCam images, since the beginning of the mission**
151 **are available on the Juno Mission website at <https://www.missionjuno.swri.edu/junocam>.**
152 **All the reported data have a geographical reference. We use NAIF-SPICE (Acton, 1996) and**
153 **ENVI tools (by <https://www.harrisgeospatial.com/Software-Technology/>) for each geometric**
154 **calibration and image processing. Ultimately, the pictures in Figures 1, 2 and 3 are compositions**
155 **obtained by assembling different image sequences taken by JIRAM. They are plotted on**
156 **geographic coordinates and show the maps of τ (as defined above) for the two poles. Significant**
157 **differences between North and South are readily apparent from a visual comparison of Figure**
158 **1 versus Figures 2 and 3.**

159 In Figure 1, we present the sequence of four North Pole observations summarized in Table 1. As
160 stated previously by Adriani et al. (2018), the dynamic structure of this pole is shaped in such a way
161 that the cyclones surrounding the polar one are approximately located on the vertices of a ditetragonal
162 pattern. Some of the cyclones kept their cloud patchy structures in the eight months between PJ4 and
163 PJ9, while others showed more clearly ordered cloudy spiral configurations with small cyclones or
164 anticyclones inside the main structure. In general, the CPCs arrangement was quite stable during this
165 entire period, and the internal structure of the single cyclones did not change significantly– including
166 the one visible in PJ10.

167 Beside the small fluctuation of the CPCs around their average position, a big anticyclone was located
168 around 87°N latitude. It has been present since the first JIRAM observation during PJ4 (February
169 2017) **and was still present during PJ10**, a period slightly longer than 10 months. In this time span,
170 it grew slightly in size **from about 1,400 km** up to about 2,000 km in diameter, oscillating between
171 80°E and 120°E longitudes in the “channel” between the polar cyclone and the circumpolar cyclones.
172 Its changes in position can be clearly detected in Figure 1. Unfortunately, its later evolution could not
173 be monitored due to the poor JIRAM coverage of the North Pole that resulted from the spacecraft
174 attitude change during the remaining part of the mission.

175

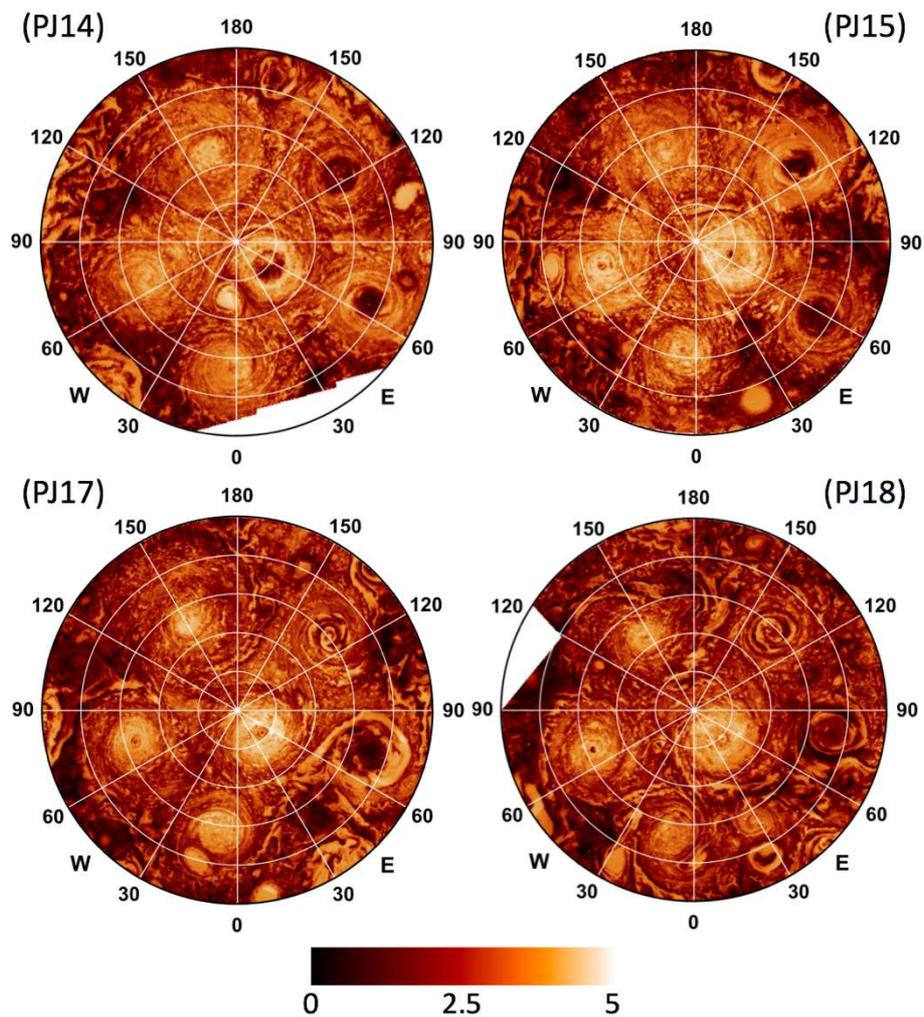


176

177 **Figure 2.** South pole from PJ4 to PJ13 (from top to bottom al left from right). Whitish colors
 178 indicate higher optical depth (τ), i.e. thicker clouds. Cyclone numbering: the polar cyclone is #1;
 179 the cyclone at the longitude of approximately 120E is #2; the numbering proceeds counterclockwise
 180 from #3 to #6. The color bar on the bottom indicates the value of τ .
 181

182 In Figures 2 and 3 we present the sequence of ten South Pole observations summarized in Table 1.
 183 As already stated by Adriani et al. (2018) following the PJ4 observation in February 2017, the South Pole
 184 configuration is quite different from the northern one. The South Pole observations have
 185 continued on regular basis, and here we report about the evolution between PJ4 and PJ18. During a

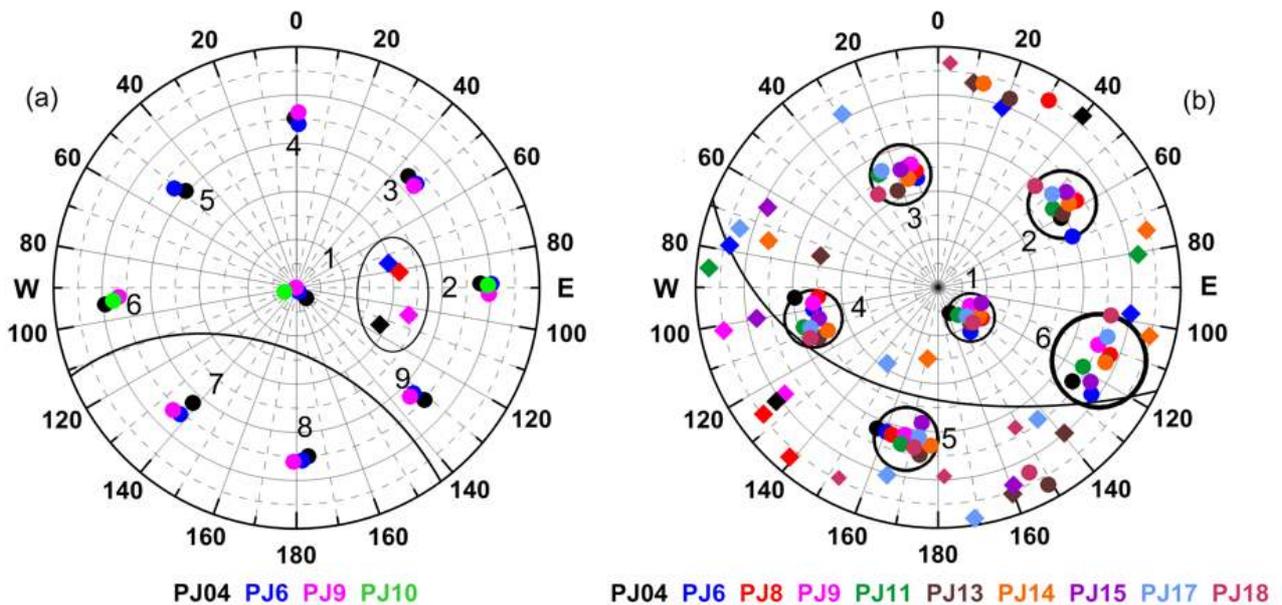
186 time lapse of two years the pentagonal structure remained substantially unchanged, with only
187 occasional perturbations.
188



189
190 **Figure 3.** South pole during PJ14 to PJ18 (from top to bottom al left from right). Whitish colors
191 indicate higher optical depth (τ), i.e. thicker clouds. Cyclone numbering: the polar cyclone is #1;
192 the cyclone at the longitude of approximately 120E is #2; the numbering proceeds counterclockwise
193 from #3 to #6. The color bar on the bottom indicates the value of τ .
194
195

196 As in the north, the six cyclones **slightly changed their internal structure. In particular, as it can**
197 **be seen in Figures 2 and 3, the group formed by cyclones 3, 4 and 5 were more stable over the**
198 **two-years period while the cyclones 1, 2 and 6 were more variable in terms of cloudiness.** Unlike
199 the North Pole, however, no long-lasting anticyclonic structures nested within the pentagonal
200 structure were observed at the South Pole. During the first year, anticyclones appeared episodically
201 within the cyclonic assembly but never lasted to the following perijove. On the other hand, a few
202 relatively large anticyclones were present in the second year of the mission, from PJ13 onward.
203 Moreover, toward the end of the period a new feature appeared between the CPCs #5 and #6 (see
204 Figure 4 for the identification of CPC numbers). This structure is reminiscent of a vortex dipole
205 whose embryo was already recognizable during PJ15. During PJ18 the Southern CPCs appeared to

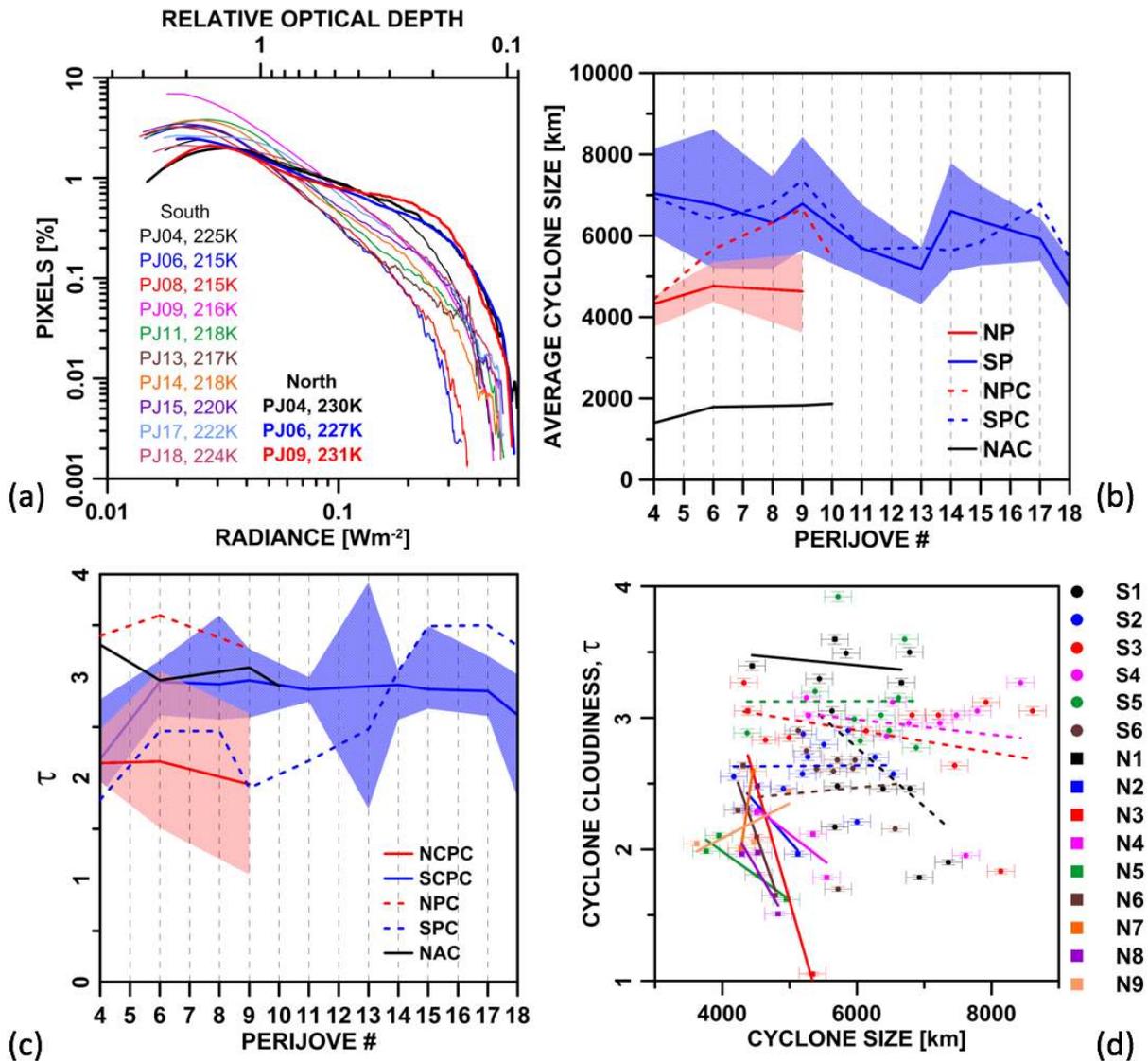
206 move to a hexagonal shape where the new-born vortex is joining the previous ones around the central
 207 cyclone.
 208



209
 210 **Figure 4.** Position of the cyclone centers (dots) during the observation period for North pole [panel
 211 (a)] and South pole [panel (b)]. The colors identify the different perijoves. The black circles indicate
 212 the variation of the position of the southern cyclone centers and are centered at the average position
 213 measured in the all period of observations. The diamonds represent the position of the different
 214 anticyclones with diameters larger than 1000 km. The oval in panel (a) identify the different
 215 positions of the same anticyclone during the different reported perijoves.
 216

217 Figure 4 illustrates the position of the cyclones and the anticyclones with diameters larger than 1000
 218 km observed in the polar region of both hemispheres. In the almost 9 months during which we could
 219 get good coverage of the North Pole no anticyclones of sizes larger than 1000 km were observed at
 220 latitudes higher than 80°N beside the one hovering at 87°N between the NPC and the CPCs. On the
 221 other hand, a large number of anticyclones were observed in the southern regions, particularly at
 222 longitudes between 100°E and 300°E. Most of them appeared to be connected to a cyclone in a dipole
 223 configuration. Sometimes the cyclone was one of the CPCs, as in the case of CPC#5 where the
 224 anticyclone was still present during PJ19 (not shown here). During PJ18, CPC#6 moved significantly
 225 towards lower longitudes leaving space for the intrusion of a cyclone/anticyclone dipole that could
 226 anticipate the formation of a new CPC. Other cyclones with diameters larger than 1000 km
 227 occasionally grew outside the CPCs ring, but they never appeared to last for more than a 53-day
 228 perijove pass.

229 **The average radiances measured in the spectral range 4.5-5.0 μm are systematically higher in**
 230 **the north with an average value of 0.133 Wm⁻², than in the south, where the average is 0.069**
 231 **Wm⁻² [Figure 5 panel (a)]. During PJ4 the southern radiance was at its highest value of 0.1 Wm⁻²**
 232 **followed by an abrupt decay of about 50% during PJ6, after 106 days.**



233
234

235 **Figure 5.** (a): Distribution of pixels radiance, the average brightness temperature at latitudes higher
236 than 80° is given for each perijove. (b): The blue and the red curves gives the average diameter of
237 the circumpolar cyclones for the south and the north respectively; the dashed curve account for the
238 respective polar cyclones; the blue and the red areas show the minimum to maximum variation of
239 the cyclones size; the black curve gives the diameter of the only larger anticyclone observed in the
240 north; (c): optical depth of cyclones, following the color definitions for panel (b). (d): optical depth
241 versus cyclone size; in the legend S stands for south and N for north and the numbering criterion is
242 the same given in figures 1, 2 and 3.

243

244 A slow but progressive increase has been observed after PJ6 [see Figure 4 panel (a) for details]. Panel
245 (a) of Figure 5 shows also the statistics of the pixels' brightness of the two poles in terms of radiance.
246 In the legend, the corresponding average brightness temperature for each PJ and at latitudes higher
247 than 80° N/S is also given. A direct comparison between North and South can be only done for the
248 first year, as no north pole images in the infrared range are available after December 2017.

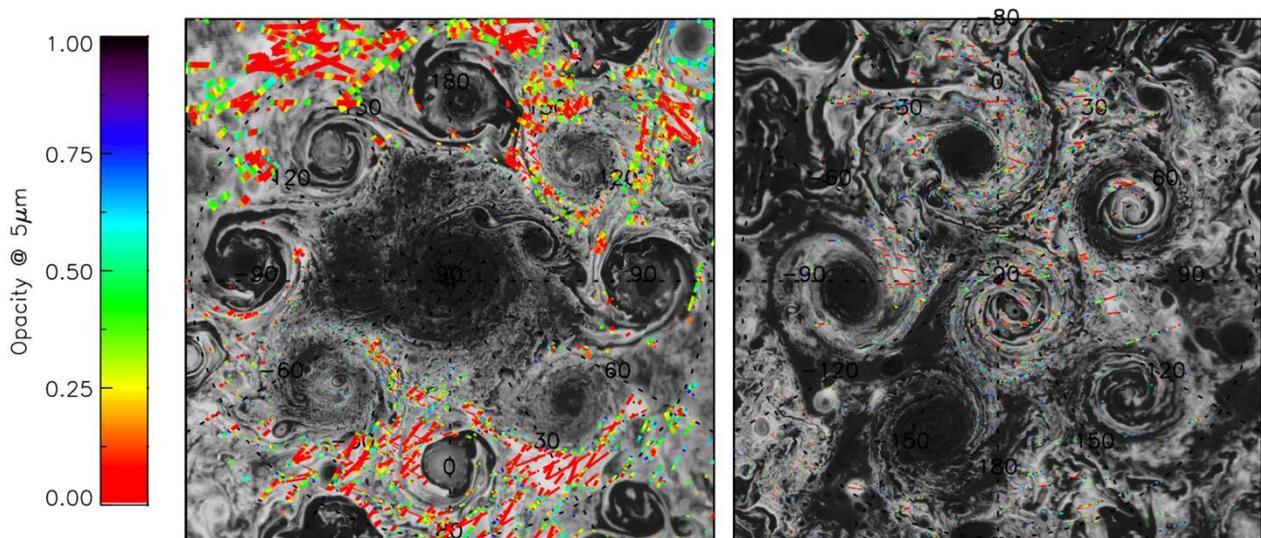
249 Some single cyclone characteristics have been investigated in order to monitor the changes that
250 occurred in the two years of observations, from February 2017 to February 2019. Figure 5 also
251 accounts for changes in the average diameters [panel (b)] and cloudiness [τ , in panel (c)] of the single
252 cyclones versus time from PJ4 to PJ18. The diameters of the northern and southern cyclones are

253 substantially different. The average diameter of the northern cyclones is about 4,600 km. Southern
 254 cyclones, being **fewer but occupying approximately the same latitudinal extension of the**
 255 **northern ones are systematically greater**, their average diameter reaches approximately 6,300 km.
 256 Another difference between south and north is the relative size of the polar cyclone with respect the
 257 surrounding CPCs. While the size of the southern polar cyclone (SPC) is commensurate with the
 258 surrounding CPCs, the northern one (NPC) is significantly larger than its surrounding CPCs [see
 259 panel (b) of Figure 5]. Focusing on the time evolution of southern cyclones' sizes, we note both a
 260 general decrease and a sort of pulsation in the distribution of the dimensions: namely, sometime the
 261 cyclones are quite different from each other, but at other times their sizes are more similar. Also,
 262 from the cloudiness point of view, the NPC differs from the surrounding cyclones showing an average
 263 τ of 3.4 while its CPCs have an average value of 2.1. The opposite happens for the SPC whose
 264 cloudiness ($\tau \approx 2.2$) is systematically lower than the average cloudiness of the surrounding CPCs
 265 ($\tau \approx 2.8$). The SPC cloudiness grows significantly reaching values similar to the NPC during the last
 266 part of the time period analyzed. Finally, **in general**, the cyclones are characterized by the **tendency**
 267 to reduce or maintain more or less their cloudiness when growing in size [see panel (d) of Figure
 268 5]. **In a couple of cases we observed the opposite behavior.**
 269

270 3. Spectral Analysis

271 **The spectral analysis performed here is limited to the wavelength range between 4 and 5 μm**
 272 **considering the only thermal emission of the planet. In fact, even if the polar regions are**
 273 **partially illuminated by the sun, our approximation is justified by our specific focus on the**
 274 **brightest areas where the scattered solar contribution in the 4-5 μm region μm is expected to**
 275 **be between 100 and 800 times smaller than the thermal component, as reported previously by**
 276 **Drossart et al. (1998).**

277 **Most of the polar** regions of Jupiter are affected by thick cloud coverage **but** relatively clear areas
 278 (with cloud total opacities < 1 at 5 μm) exist at some specific locations, **similarly to** the hot spots
 279 frequently observed between the Equatorial Zone and the North Equatorial Belt (Grassi et al. 2017a).
 280 Figure 6 shows the polar areas within 80°N/S latitudes where the optical depth, τ , is lower than 1
 281 at PJ4. Correspondingly, Figure 6 shows the areas where the JIRAM spectra are sensitive to the contents
 282 of ammonia, water vapor, phosphine and – in lesser degree – germane, at the approximate levels
 283 between 2 and 3 bar (Grassi et al. 2017b), well below Jupiter's tropopause level. Water and ammonia



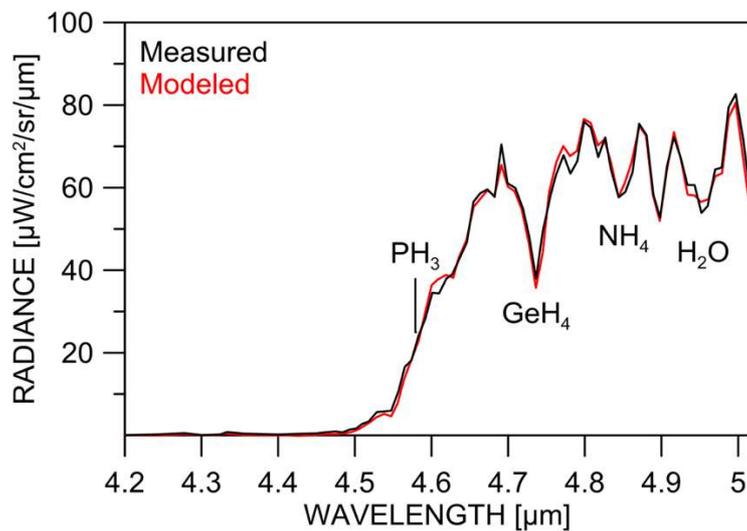
284 **Figure 6.** Areas where the optical depth, in the infrared wavelengths around 5 μm , is lower than 1

285 according to the JIRAM spectrometer data.

286

287 are condensable and involved in the cloud formation while germane and phosphine are disequilibrium
288 species from the deep interior **and they are retrievable from JIRAM spectral data in the range**
289 **4.5-5. μm .**

290 **The set of parameters to be retrieved** has been defined following the scheme already proposed in
291 Irwin et al. (1998) for hot spots. The adopted scheme aims to distinguish, where relevant, the 'deep'
292 content of gaseous species from their mixing ratios in the upper troposphere, where depletion may
293 occur due to condensation or photochemistry. According to that scheme, for the analysis here, we
294 consider different free parameters: H_2O , NH_3 , PH_3 , and GeH_4 "deep" mixing ratios, which are all
295 assumed to be constant with altitude; the H_2O relative humidity above its condensation level and
296 constant with altitude; and the total optical depth at $5\mu\text{m}$ of the main (putative NH_4SH) cloud above
297 the water cloud. The topmost cloud layer (putatively NH_3) is thought to be essentially absent in hot-
298 spot regions, while diffuse haze has been demonstrated to be transparent at $5\mu\text{m}$.
299



300

301 **Figure 7. Comparison between a measured and a reconstructed spectrum between 4.2 and 5**
302 **μm**

303

304

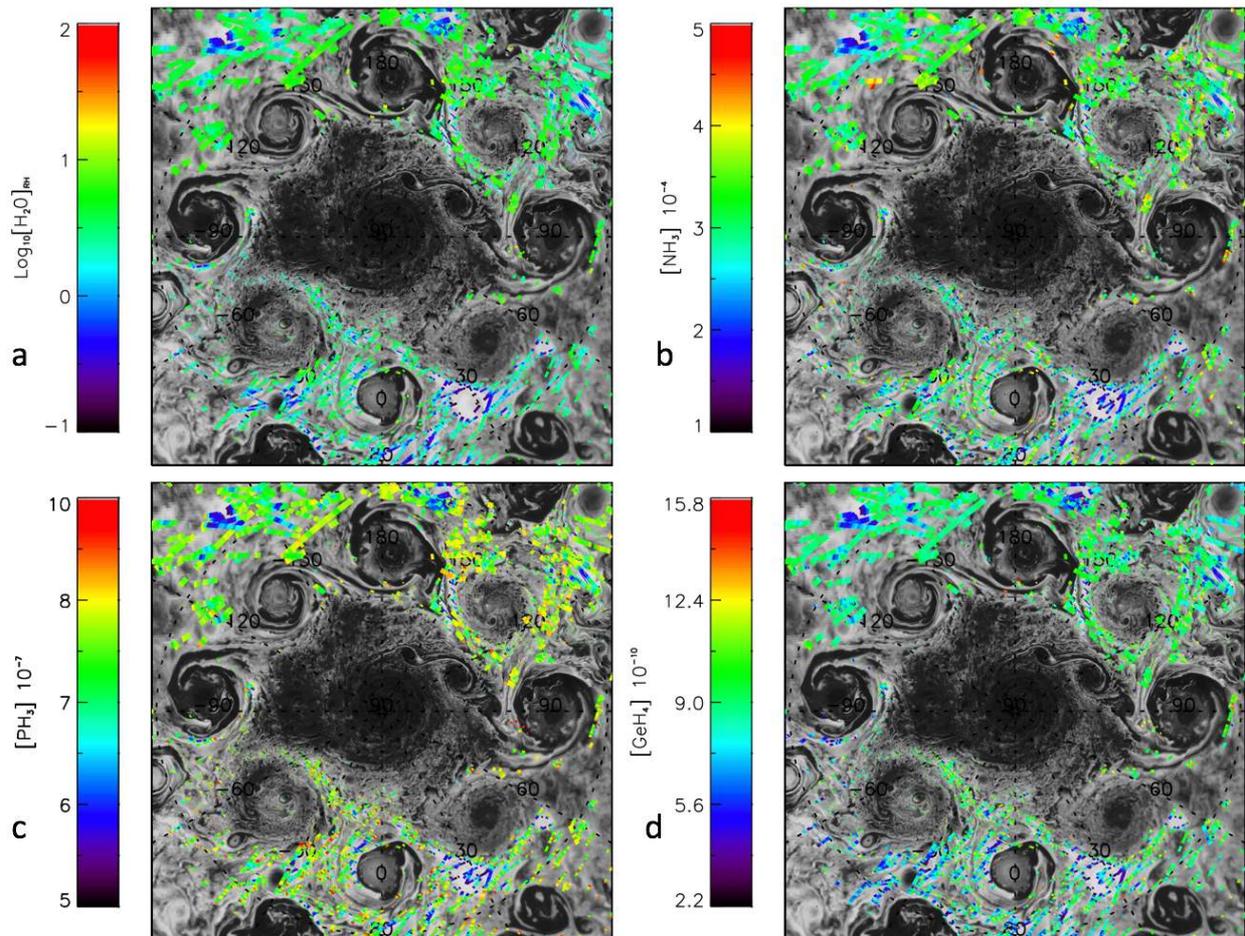
305 **Figure 7 displays the spectral region used for the retrieval. It also shows how the model used in**
306 **the retrieval is able to reproduce the measured spectrum. Performance of the retrieval code has**
307 **been quantified on the basis of test runs on large sets of simulated observations and the retrieval**
308 **errors include the effects of forward-modelling errors in the radiative transfer. Notably, these**
309 **errors exceed by at least a factor of 10 the instrumental Noise Equivalent Radiance, as estimated**
310 **in Adriani et al. [2016]. Considering the typical nominal values of retrieval errors and assuming**
311 **a mean deterioration factor 5 for all gases, we can estimate the approximate uncertainties for**
312 **the retrieved contents of different gases from individual spectra as follows:**
313 **$\text{Log}_{10}([\text{H}_2\text{O}]_{\text{RH}}) \sim 0.08$, $[\text{NH}_3] \sim 3.0 \times 10^{-5}$, $[\text{PH}_3] \sim 6.0 \times 10^{-8}$ and $[\text{GeH}_4] \sim 4.3 \times 10^{-11}$.** As water vapor is
314 **by far the most variable gas in the Jupiter atmosphere, we found therefore correct to keep the**
315 **logarithm of relative humidity (i.e.: the original state vector element in our retrieval code)**
316 **rather than convert it to a mixing ratio.**

317 **Our retrieval model uses the temperature-vs-pressure profile from Seiff et al. [1998] on the**
318 **basis of the Galileo Entry Probe measurements. In order to quantify errors introduced by**
319 **possible variations of the real temperature in respect the assumed value, numerical tests**
320 **demonstrate that systematic increase or decrease of 5K at every fixed pressure level of our**

321 atmospheric model induces a relative variation of about 2% in the retrieved contents of
 322 ammonia and phosphine, of 5% in germane and 15% of the water relative humidity value.
 323 The analysis presented here was performed on PJ4 data (February 2nd, 2017). The method was
 324 already more extensively described by Grassi et al. (2017b) and analysis is restricted to spectra
 325 with low emission angle to limit retrieval uncertainties and attain higher signal.

326

327



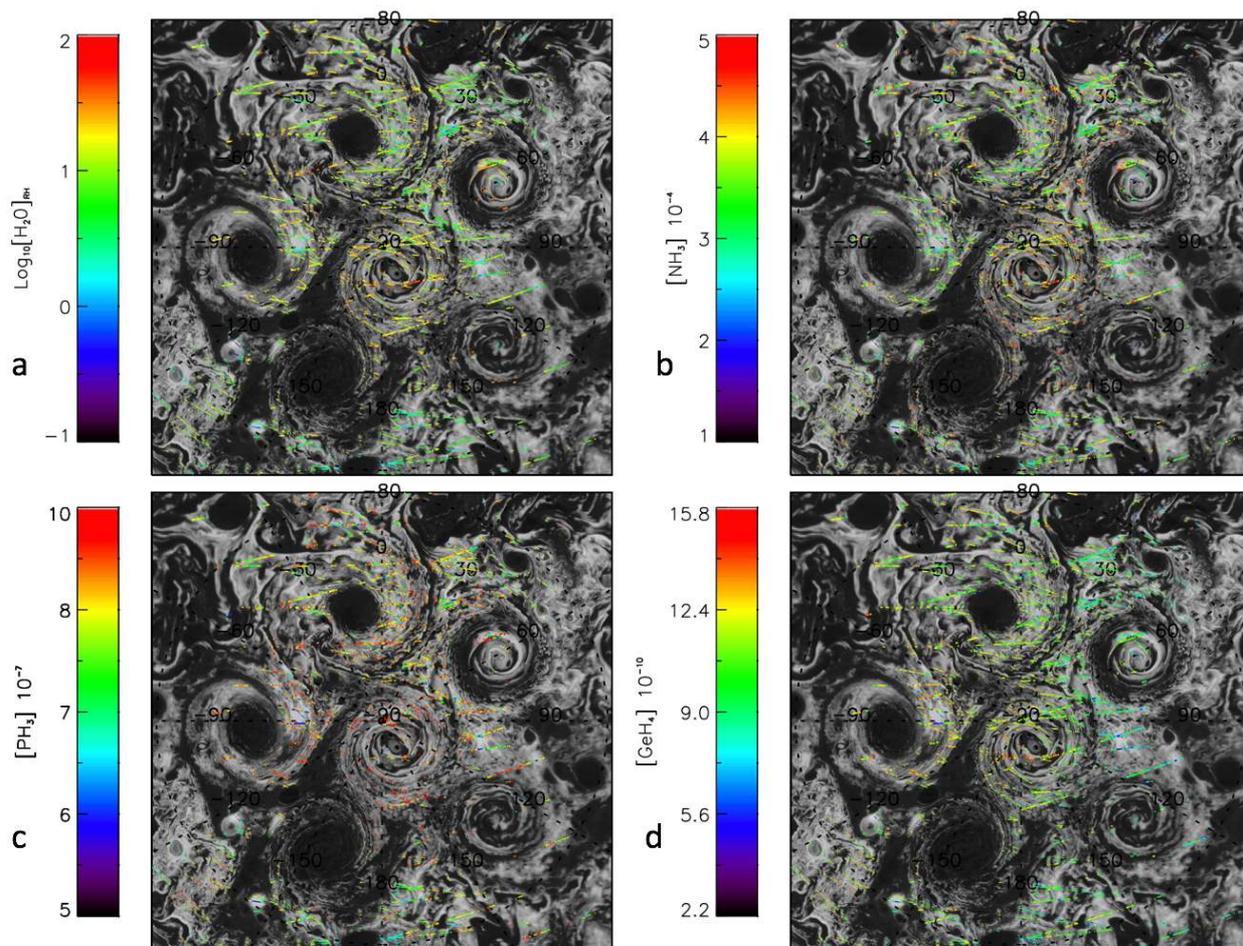
328

329 **Figure 8.** North pole maps of water relative humidity (a), ammonia (b), phosphine (c) and germane
 330 (d) concentrations.

331

332 Results of the analysis are reported in Figures 7 and 8 for the relative humidity of water vapor and
 333 the concentrations of ammonia, phosphine and germane, for the North and South Poles, respectively.
 334 The thickness of the tracks is proportional to the pixel resolution at Jupiter's 1-bar level. It is
 335 noticeable that the abundances of condensable species (H_2O and NH_3) are more depleted over the
 336 lower-opacity regions. However, those gases appear relatively enhanced over the South Pole
 337 compared to northern regions, possibly because of smaller overall opacity of cyclones in the former
 338 areas during Juno PJ4 passage. Values range between 0.3% and 10% for the water vapor relative
 339 humidity and between 100 and 500 ppm for the ammonia mixing ratio in the north (see Figure 8),
 340 and between 0.3% and 20% for both for the water vapor relative humidity and ammonia in the south,
 341 but with an average significantly shifted toward the upper value (see Figure 9).

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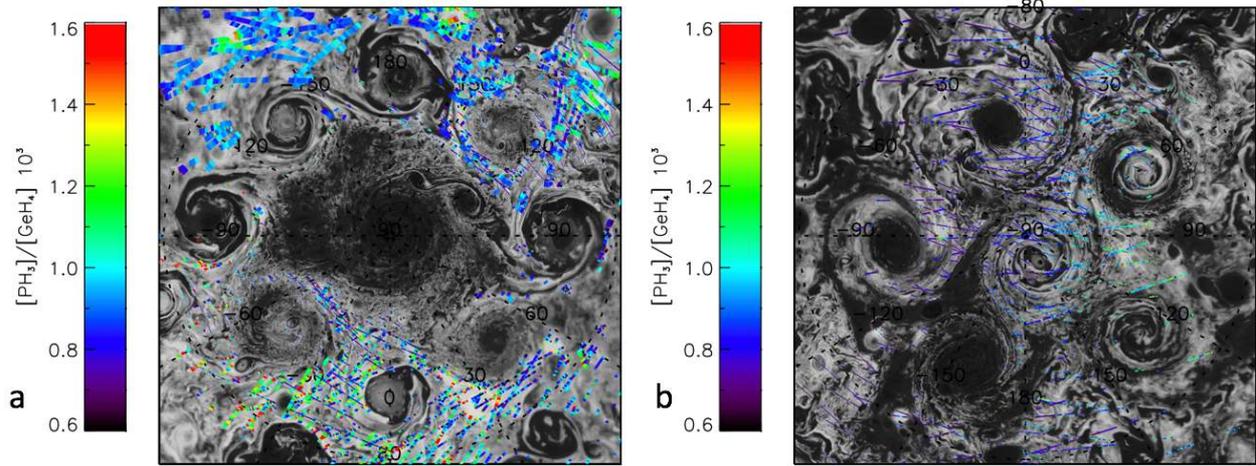
344

345 **Figure 9.** South pole maps of water relative humidity (a), ammonia (b), phosphine (c) and germane
 346 (d) concentrations.

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348 Areas with the lowest cloud cover are found to be considerably depleted in disequilibrium species
 349 (PH_3 and GeH_4) once compared against moderately cloudy ones, suggesting effective suppression of
 350 vertical upwelling (see Figures 7 and 8). **PH_3 has abundances of the order of 0.6-1 ppm in the
 351 north while it reaches up to 2 ppm in the south. Also the GeH_4 shows the same difference
 352 between north and south with values of 6-10 ppb values that reach 15 ppb respectively.**
 353 **However, the comparison of absolute values between the two poles must also consider the
 354 effective better spatial resolution of the southern spectra for most of JIRAM data, capable
 355 therefore of singling out more extreme values.**

356 PH_3 and GeH_4 are not stable at the pressure and temperature conditions of the upper troposphere
 357 where they are detected. They are usually interpreted as tracers of active vertical motions that
 358 replenish the upper levels with fresh material from the much deeper atmosphere, where they are in
 359 equilibrium. The concentration contrasts between bright and dark area appear stronger over the
 360 northern pole and the depletion of germane looks stronger than for phosphine (see Figure 10). **The
 361 ratio $[\text{PH}_3]/[\text{GeH}_4]$ is the order of a thousand.**



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Figure 10. Maps of phosphine to germane ratio for the North (left panel) and for the South (right panel)

366 4. Dynamics

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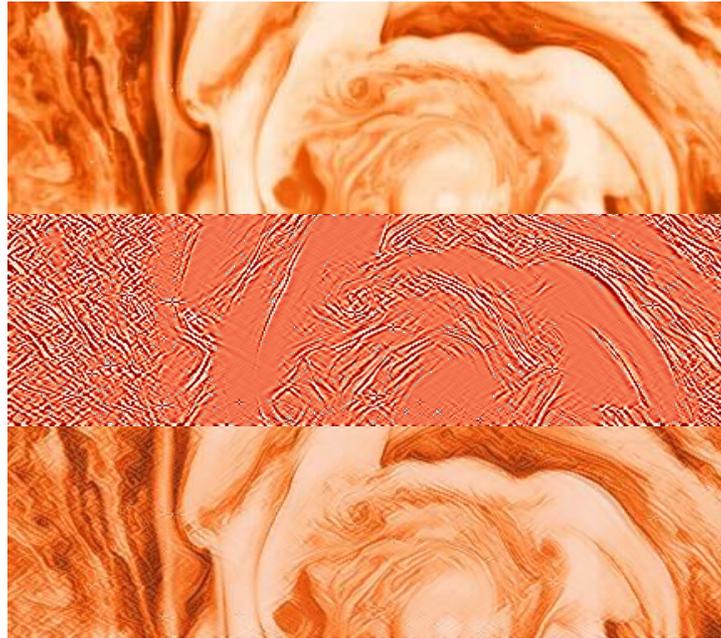
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The process of mosaicking, as seen in Figures 1, 2 and 3, can alter the original images as a re-pixelization process is necessary to create maps. Because of the lowering of the orbit over North Pole, we achieved a resolution better than 16 km for some of the images during PJ9 pass. From a visual analysis of those images, the existence of wavy structures over some parts of the polar cyclones could be conjectured. In fact, a more sophisticated analysis by using 2D Fourier filtering to highlight short-wavelength (high-frequency) perturbation has been applied to some of the single images not affected by image processing. The analysis revealed the presence of many wavy structures hovering near some part of the cyclones. This topic is better described by Moriconi et al. (2019) but an example is given in Figure 11 where the upper panel shows one of the original images taken by JIRAM approaching the northern CPC#2. A 2D Fourier filtering applied to the image provides the result illustrated in the second panel where the full wavy structure has been isolated from the image background. The result indicates a strong dynamical interaction between the lower level, where presumably the top of the cyclones is, with the higher levels of the troposphere. The upper level waves appear to have a typical wavelength of about 20-30km. The wavy perturbations may be induced by the ascending currents in some areas of cyclones that perturb the atmosphere above the cyclones, or they could result from the interaction of the surface wind field with the vortex population, analogously to Langmuir turbulence in the upper turbulent layer of Earth's oceans, the so-called ocean mixed-layer (Hamlington et al., 2014).



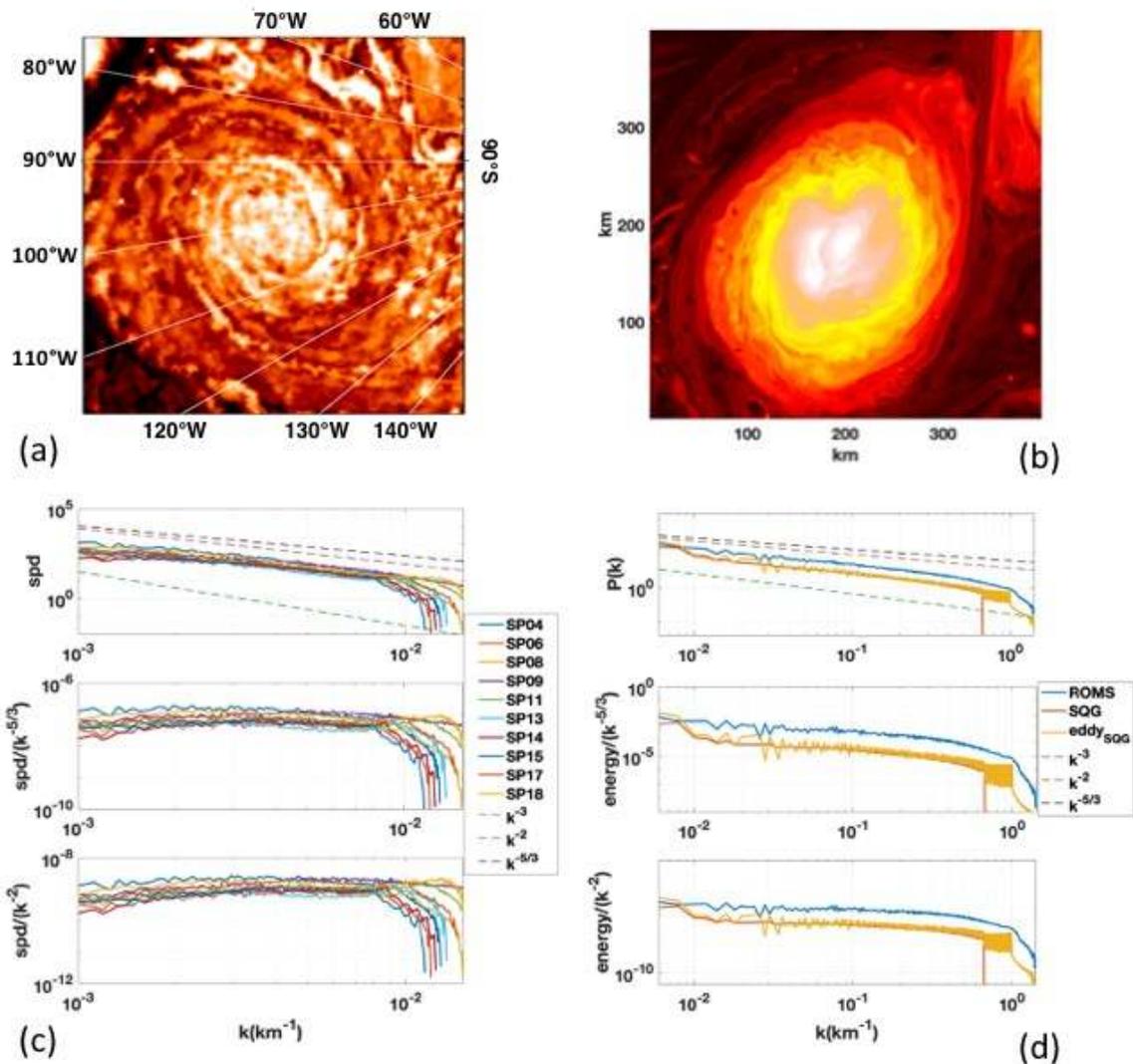
385

386 **Figure 11.** Waves over the cyclone #2 at the North Pole. Upper panel: original JIRAM image;
 387 central panel: result of the 2D Fourier high-pass filtering on the original image; lower panel:
 388 superimposition of the central panel to the upper panel.
 389

390 A more in-depth analysis to understand the structure of the polar cyclones has been performed by
 391 attempting a comparative **power spectrum** investigation of long-living mesoscale (~100 km
 392 diameter) cyclones in Earth's ocean. In fact, the semi-stable, turbulent instabilities observed at
 393 Jupiter's Poles within and around the patterns of cyclones are reminiscent of the dynamics and
 394 instabilities observed in the buoyancy distributions in the Earth's oceanic mixed-layer (McWilliams,
 395 2016) or in the potential temperature anomalies in the upper tropopause (Hakim et al. 2002). In the
 396 ocean, these instabilities develop at scales smaller than the local Rossby deformation radius, between
 397 few hundred meters and 2-3 km, and contribute to the internal structure of mesoscale vortices and to
 398 very large vertical velocities and intense vertical exchanges (e.g Zhong et al., 2017). They are
 399 associated **with** the development of fronts at scales where the planetary rotation is still important but
 400 not dominant, and are characterized by intense vertical velocities (McWilliams, 2016).

401 The emergence of these kilometer-scale fronts cannot **generally** be described by quasigeostrophic
 402 (QG) models, developed by Charney (1971) to describe in a conceptually simple, two-dimensional
 403 framework, the dynamics of atmospheric and oceanographic flows with horizontal length scales
 404 which are very large compared to their vertical extension whenever the strength of inertia is small
 405 compared to the strength of the Coriolis force. On the other hand, the laterally divergent flows
 406 associated with frontogenesis is approximated in two-dimensions **whenever the QG model is**
 407 **applied to a semi-infinite domain with zero potential vorticity (PV) in the interior. In this special**
 408 **case the so-called Surface Quasi-Geostrophy (SQG) approximation, first introduced by Blumen**
 409 **(1978) assumes that the flow evolution is controlled by the advection–diffusion of surface**
 410 **buoyancy at the boundary. It is based on the conservation of this active scalar (surface**
 411 **buoyancy) along the horizontal geostrophic flow, and links velocity and buoyancy.**

412 The SQG model has shown some success in interpreting turbulent dynamics in the troposphere (Held
 413 et al. 1995), the dominance of cyclones over anticyclones at the tropopause (Hakim et al. 2002), and
 414 more recently, observations in the oceanic mixed-layer (Lapere and Klein, 2006).



415
 416 **Figure 12.** (a) Jupiter cyclone #4 from South Pole PJ4 image. (b) Cyclonic eddy in surface
 417 buoyancy in a freely-decaying SQG simulation at a resolution of 1024 x 1024. Several Gaussian
 418 shaped cyclones are seeded as initial conditions in a freely-decaying, unforced run. The figure
 419 shows one of the remaining cyclones after approximately 50 rotation periods. (c) 2D power spectra
 420 for selected data sets from Jupiter South Poles; the power spectra calculated for Jupiter are related
 421 to the latitudes higher than 82°S that are dominated by the presence of the polar cyclones. (d)
 422 2D power spectra for the cyclone in panel (b) in light orange, for the whole SQG field at the time the
 423 cyclone was extracted in dark orange, and for an ocean cyclonic eddy obtained by ROMS run in the
 424 Gulf Stream region at horizontal resolution of 750 m (courtesy of J. Gula). The ocean cyclone is
 425 approximately 200 km in diameter and the non-dimensional SQG eddy has been scaled to match it.
 426

427 One characteristic that sets apart SQG, and flows in the oceanic mixed-layer, from “**traditional**” QG
 428 **and two-dimensional** turbulent flows is the slope of the energy power spectra, which is shallower
 429 than the non-local $E(k) \propto k^{-3}$ predicted for two-dimensional and QG systems in the direct cascade
 430 range (e.g. **Bracco et al., 2004**; Bracco and McWilliams, 2010). An energy spectrum as steep or

431 steeper than k^{-3} is indicative of non-local dynamics, where coherent, large scale vortices dominate.
432 The theoretical SQG slope of buoyancy variance in the direct energy cascade range is indeed $\propto k^{-5/3}$,
433 indicative of local dynamics, where frontal and filamentary structures at scales smaller than the large
434 coherent vortices control mixing. These local dynamics are behind the large vertical velocities and
435 their localization in circulations of scales smaller than the Rossby deformation radius of the flow.
436 Numerical simulations in various configurations using both the SQG approximation, or the primitive
437 equations commonly employed by ocean models, concur in finding spectral slopes slightly steeper
438 than $k^{-5/3}$ and usually approaching k^{-2} (Pierrhumbert et al., 1994; Held et al., 1995; Capet et al., 2008;
439 Zhong and Bracco, 2013). The steepening of the theoretical slope is commonly found in presence of
440 large vortices, **but could also be related to numerical diffusion.**

441 In Figure 12, the power spectra calculated on the full two-dimensional image mosaics return slopes
442 consistent with the SQG model. **The analysis here was done following the empirical**
443 **correspondence between power spectra of atmospheric kinetic energy and those of cloud**
444 **opacities as done by Harrington et al. (1996) for Jupiter on the basis of Travis (1978) previous**
445 **results on Venus and Earth. Travis, in fact, found a close correspondence between power**
446 **spectra of atmospheric kinetic energy and power spectra of visible and infrared cloud**
447 **intensities.** The same figure shows an eddy obtained integrating the SQG equation using a pseudo-
448 spectral code and resolution 1024 x 1024 grid points over a $2\pi \times 2\pi$ non-dimensional domain; the
449 eddy occupies nearly 1/4 of the model domain. The cyclone's energy spectra are shown with the
450 whole domain one **that includes two more cyclones eddies**, and the spectrum of an upper ocean
451 cyclone simulated by the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams,
452 2005) at 750 m horizontal resolution (Gula et al., 2015).

453 **The energy power spectra consistency is supported by a visual similarity, but other turbulent**
454 **systems are characterized by analogous slopes. For example, a recent work (Novi et al. 2019)**
455 **has shown that rapidly rotating convective flows can generate intense vortices close to the Poles**
456 **on a spherical planet in local Cartesian approximations. These convective flows also have slopes**
457 **close to k^{-2} but the structure of convective plumes and their vertical velocities appear to be more**
458 **disorganized within the eddy (see, for a convective cyclonic plume in the high latitude Earth's**
459 **ocean, Fig. 4 in Sun et al., 2017).**

460

461 5. Conclusions

462 Differences between Jupiter's North Pole and South Pole are evident not only by counting the number
463 of persistent cyclonic structures or the anticyclonic activity but also by other properties such as
464 cloudiness, size, and concentration of minor and trace atmospheric species such as water vapor,
465 ammonia, phosphine and germane. The question is whether these differences are only the
466 consequence of an evolution of the two polar zones that proceeds on different time scales or, instead,
467 there is a persistent and more profound connection with the deepest part of the Jovian atmosphere,
468 such as its magnetic field which results to have a very different structures between north and south.
469 In relation to the stability of the vortex configurations found at Jupiter's poles, Reinaud (2019)
470 recently investigated the conditions under which an array of m three-dimensional, unit Burger
471 number, quasi-geostrophic vortices on a ring, with an additional vortex lying on the array center, are
472 in mutual equilibrium. He found that the central vortex, if moderate in strength and having the same
473 rotation sign of the peripheral ones, stabilizes the vortex array for a long time in a QG system. He

474 refers specifically to the cluster of cyclones of Jupiter's polar regions as an example of environmental
475 context where his study can be applied. On the other hand, our comparative analysis shows similar
476 results for cyclones in both the Jupiter and the Earth's case cyclone in the upper ocean mixed-layer,
477 with the size of the cyclones being proportional to the size of the planet to which they belong to. It
478 also suggests the possibility of a well-mixed upper boundary layer on Jupiter's Poles with the
479 cyclones being key mediators of any exchange with deeper layer(s) though large vertical velocities
480 localized in frontal regions that result from local, non-geostrophic dynamics. Indications of the
481 possible presence of fronts come from the strong gradients in optical depth and small scale structure
482 in and around the cyclones. Finally, although our work on JIRAM data has provided insights into the
483 dynamics of Jupiter's polar regions, additional measurements from Juno's other instruments, like the
484 Juno's MicroWave Radiometer (MWR) which is able to sound deeper in the atmosphere, and
485 corresponding analyses are necessary to explain the origin of Jupiter's curious polar cyclones.

486
487

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493 **The data used for this study will be available once the proprietary period ends from the**
494 **NASA's Planetary Data System at <https://pds.jpl.nasa.gov/tools/data-search/>.**

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