

RESEARCH ARTICLE

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Key Points:

- Main vortices on the Jupiter polar regions are cyclones, with peak wind speeds up to 110 m/s
- Maximum speeds are observed about 1,000 km from the centers of the vortices
- Smaller and weaker anticyclonic areas are also identified

Supporting Information:

- Supporting Information S1
- Supporting Information S2

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








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First Estimate of Wind Fields in the Jupiter Polar Regions From JIRAM-Juno Images

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Abstract We present wind speeds at the ~ 1 bar level at both Jovian polar regions inferred from the 5- μ m infrared images acquired by the Jupiter InfraRed Auroral Mapper (JIRAM) instrument on the National Aeronautics and Space Administration Juno spacecraft during its fourth periapsis (2 February 2017). We adopted the criterion of minimum mean absolute distortion (Gonzalez & Woods, 2008) to quantify the motion of cloud features between pairs of images. The associated random error on speed estimates is 12 m/s in the northern polar region and 9.8 m/s at the south. Assuming that polar cyclones described by Adriani et al. (2018, <https://doi.org/10.1038/nature25491>) are in rigid motion with respect to System III, tangential speeds in the interior of the vortices increase linearly with distance from the center. The annulus of maximum speed for the main circumpolar cyclones is located at approximately 1,000 km from their centers, with peak cyclonic speeds typically between 80 and 110 m/s and ~50 m/s in at least two cases. Beyond the annulus of maximum speed, tangential speed decreases inversely with the distance from the center within the Southern Polar Cyclone and somewhat faster within the Northern Polar Cyclone. A few small areas of anticyclonic motions are also identified within both polar regions.

1. Introduction

The estimate of wind fields from the tracking of cloud features represents a key tool in constraining the dynamical behavior of planetary atmospheres. The case of Jupiter is, by no means, an exception. Global-scale zonal wind profiles have been derived from a variety of data sets: Voyager Imaging Science System (Ingersoll et al., 1981; Limaye, 1986), Hubble Space Telescope (García-Melendo & Sánchez-Lavega, 2001), Cassini Imaging Science Subsystem, during the Jupiter flyby of December 2000 (Porco et al., 2003), and ground-based telescopic observations (Hueso et al., 2017). These studies suggest a long-term stability of the inferred latitudinal profiles of mean zonal winds. On a local scale, wind fields have been derived, among others, for the Great Red Spot (Asay-Davis et al., 2009; Choi et al., 2007; Read et al., 2006) and hot spots and plume areas (Hueso & Sánchez-Lavega, 1998) on the basis of Voyager, Galileo, and Hubble Space Telescope data.

Moving to higher latitudes, a system of circumpolar waves in Jupiter's stratosphere was first identified by Sánchez-Lavega et al. (1998), while Vincent et al. (2000) described extensively the motions in Jupiter's stratosphere with description of specific features up to approximately 75°. More recently, Barrado-Izagirre et al. (2008) focused their attention on circumpolar regions at latitudes below 80°, where longitudinal variations appear to be caused by Rossby waves.

However, very limited information on polar regions beyond the 80° latitude was available prior to 2016. Ground-based observations are adversely affected by high viewing angles, a factor difficult to mitigate due to the very small axial tilt of the planet. Furthermore, the trajectories of Voyager, Cassini, Galileo, and New

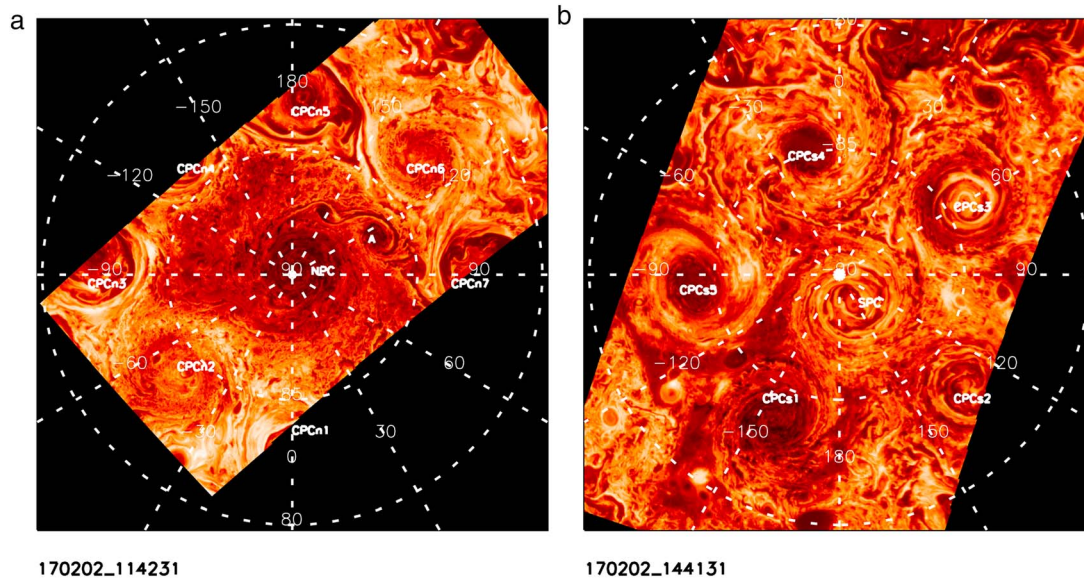


Figure 1. (a, b) Examples of mosaics composed from spatially interpolated images. Each mosaic contains only images from the JIRAM sequence given in the label. Further details on geometric properties of the observations are provided in Table 1. Labels identify individual features mentioned in the text according to the nomenclature adopted in Adriani et al. (2018).

Horizons spacecraft through or in the Jupiter system remained rather close to Jupiter's equatorial plane, resulting in similar viewing limitations. Pioneer 11 passed over the north pole of Jupiter but could not measure winds due to limitations in the imaging system and to the very large distance of the observations (Baker et al., 1975; Orton et al., 1981). On 4 July 2016 the Juno spacecraft entered into a polar orbit around Jupiter, providing the opportunity to acquire the best view of its polar regions achieved so far (Bolton et al., 2017). Among the Juno instruments, the Jupiter InfraRed Auroral Mapper (JIRAM; Adriani et al., 2014) is proving particularly useful in studying the upper troposphere (between 5 and 1 bars) at high latitudes. The instrument includes an infrared-imager channel equipped with a broadband filter centered at 4.8 μm . This wavelength region allows one to cover simultaneously the dayside and nightside of the polar regions, enabling synoptic coverage of large areas not achievable by observations acquired at shorter wavelengths dominated by reflected sunlight. The 4.8- μm region hosts an important transparency window of the gaseous absorption spectrum. In absence of clouds, the ultimate source of opacity is represented by the H_2 collision-induced absorption and observed thermal radiation emerges from a pressure level calculated to be about 5.5 bars (see discussion in Grassi, Adriani, et al., 2017; Grassi, Ignatiev, et al., 2017). The absence of clouds above the 5-bar level is, however, a condition very rarely seen: globally, averaged equilibrium thermodynamics models predict several different cloud layers of ammonia, ammonium hydrosulfide, and water, extending over several tens of kilometers in altitude (Atreya et al., 1999). The analysis of Galileo Near-Infrared Mapping Spectrometer spectra by Irwin et al. (2001) found that changes in brightness at 5 μm —at least at the low and intermediate latitudes considered in their study—are correlated not with variability of the higher ammonia cloud but rather with opacity variations associated with cloud layers between 1 and 2 bars of pressure. In the subsequent discussion, we will assume that features observed in JIRAM images reside in this particular pressure range.

The overall morphologies of north and south poles of Jupiter as seen by JIRAM and by the JunoCam instruments were described by Adriani et al. (2018). In the current work we adopt the feature nomenclature presented in that paper; a suffix “n” or “s” is added where needed to distinguish northern and southern features. The north pole hosts a central vortex that rotates counterclockwise: this structure is named NPC (as for “North Polar Cyclone”) in Adriani et al. (2018) and as such is labeled in Figure 1a. Given its location in the northern hemisphere it will be considered a cyclone, with a local minimum of pressure at its center. This cyclone shows a low infrared brightness (suggestive of relatively thick cloud coverage), with sizes of turbulent eddies developed down to the smallest scales resolved in the images (about 12 km). NPC is surrounded by

four additional, equally spaced, cyclones, all of which have centers at latitude 83.3° . Three of these cyclones present internal features (approximately within 1,000 km from respective centers) with turbulent eddies with sizes down to few tens of kilometers (among them, CPCn6 and CPCn2, where CPC stands for “Circum-Polar Cyclone”), while the fourth (CPCn8 of Adriani et al., 2018, located at 135°W , not shown in Figure 1a) has a central part with a more “laminar” aspect, with eddy scales appearing to be limited to at least 100 km. Four other equally spaced cyclones with centers at 82.5° and spaced 45° from the first set of four complete the north pole dynamical organization (among them, CPCn3 and CPCn7). The external four cyclones again present a laminar aspect, with an apparent lack of small-scale eddies in their centers. The south pole presents a slightly more complex morphology. A central laminar vortex (SPC in Figure 1b, as for “South Polar Cyclone”) exists there, but its apparent center is more clearly displaced from geographical pole than its northern counterpart. SPC is surrounded by five vortices irregularly spaced and of different appearance. All six main vortices of the south pole rotate in cyclonic motions (clockwise in the southern hemisphere), suggesting low-pressure centers. While all cyclones show turbulent external parts, with eddies developed at a variety of scale lengths, only three vortices (CPCs2, 5, and 1) have low-brightness, turbulent centers with eddies of the size of few tens of kilometers, while the remaining two (CPCs 6 and 3, the former not shown in Figure 1b) present laminar central parts.

The methods described in Grassi, Ignatiev, et al. (2017), albeit developed for the specific conditions of Hot Spots, can be tentatively applied to the JIRAM spectra acquired over the two poles, to obtain a quantitative estimate of aerosol optical thickness at $5\ \mu\text{m}$ ($\tau_{5\mu\text{m}}$), in the assumption of a single cloud deck located at about 1 bar. Results indicate that clouds over extended areas in the NPC present $\tau_{5\mu\text{m}}$ exceeding 6, while they remain considerably optical thinner ($\tau_{5\mu\text{m}}$ 2–3) in CPCn2 and CPCn6. In the south pole, $\tau_{5\mu\text{m}}$ above 6 are found in the central parts of CPCs4, 5, and 1, as well as in the area between CPCs4, 1, and SPC. Most of the SPC, as well as the central part of CPCs3, appears to have $\tau_{5\mu\text{m}}$ 2–3.

Adriani et al. (2018) presented preliminary estimates of tangential speeds of the polar vortices observed by JIRAM. In the current paper, we substantially extend those findings, presenting the wind fields derived over large continuous areas of both polar regions by a fully automated algorithm. We use JIRAM images acquired during the fourth Juno close passage (“perijove”; J4) on 2 February 2017, the most recent flyby for which sufficient numbers of image pairs are available for wind speed computations.

2. Materials

The JIRAM instrument includes a spectrometer and two image channels operating in different spectral regions. In this paper, we will focus our attention solely on one of these channels (the so-called M-filter), where images are acquired by integrating the incoming radiance over the 4.54- to 5.03- μm range. Images have a size of 432×128 pixels. All image pixels are acquired simultaneously, that is, the bidimensional image is formed directly on the focal plane and not by the stacking of consecutive lines in a push broom scan. The field of view of individual pixels is about $240\ \mu\text{rad}$. A complete description of the JIRAM instrument can be found in Adriani et al. (2014).

Juno is a spin-stabilized spacecraft and JIRAM acquires one image at each Juno spacecraft rotation (2 rpm). JIRAM pointing has only 1 degree of freedom, and the pointing can be set only along the maximum circle orthogonal to the spin axis. The Juno spin axis is kept pointed toward the Earth and, therefore, roughly toward the Sun. Moreover, the Juno orbital plane is approximately orthogonal to the spacecraft’s spin axis. As a consequence of these constraints, JIRAM images acquired near the close approach are often placed very close to the planet terminator. In most circumstances, JIRAM is operated to acquire a set of consecutive images (a “sequence”), spaced as to create an almost spatially continuous mosaic over a given region.

Figure 1 provides two examples of mosaics created with images from individual sequences.

During the fourth periaxis passage (PJ4), JIRAM acquired 21 sequences of 13 images each over the north pole and 6 sequences of 19 images each over the south pole. The time interval between two consecutive sequences was 16 min over the north pole and 20 min over the south pole. The best pixel spatial resolution at the reference 1-bar level varies from 100 to 9.6 km because of the high eccentricity of Juno’s orbit. Similarly, the mean emission angle within a given sequence varies from 75° to 3° . In the analysis presented here we considered only sequences with a spatial resolution better than 40 km. An exception was made for

Table 1
Summary of JIRAM M-Filter Image Sequences Considered for This Study

Name	Pole	Pixel resolution range (km)	Emission angle range (deg)	Number of images	Latitude range (deg)	Time coverage (hhmmss UTC)
170202_114231	N	28.1–27.7	17.13–37.14	12	83.15 N–79.89 N	114006–114541
170202_115039	N	24.6–23.7	12.10–31.38	12	83.49 N–80.46 N	114813–115348
170202_115846	N	21.2–19.7	5.36–24.50	12	83.51 N–80.54 N	115620–120155
170202_120653	N	17.9–15.8	3.22–15.67	12	82.85 N–79.99 N	120426–121002
170202_121429	N	15.6–12.4	2.83–25.93	12	80.26 N–78.91 N	121202–121738
170202_122236	N	17.7–9.6	20.80–68.95 ^a	12	64.11 N–78.52 N	122007–122544
170202_140125	S	21.6–25.8	3.57–19.10	19	80.54S–76.56S	135859–140808
170202_142113	S	30.5–33.2	4.47–24.08	19	79.37S–79.89S	141846–142755
170202_144131	S	39.8–41.22	10.46–35.15	19	76.86S–80.07S	143904–144813

Note. For each sequence, we list the range of mean pixel resolution and mean emission angle (as computed within individual images) found in the sequence. The sequence file name encodes the mean acquisition time of images according the scheme: yymmdd_hhmmss. Latitude range provides the latitude centers of images at the extremes of each sequence. Sequences of images pass always over the corresponding pole. Time coverage provides the acquisition times of images at the extremes of each sequence. JIRAM = Jupiter InfraRed Auroral Mapper.

^aSome images exceeding the 40° mean-emission angle limit were excluded from analysis.

sequence 170202_144131, to get at least three sequences over the south pole. The emission angle also needs to be limited, to cope with uncertainties on the radiance emission angle correction in these unexplored cloud conditions. The limit was arbitrarily set to 40°.

Table 1 lists the sequences selected for this study.

Geometric parameters of each image (geographic locations of pixel corners and centers, solar zenith, emission and phase angles, slant distance, etc.) were computed by means of the SPICE Toolkit (Acton, 1996; Acton et al., 2017) on the basis of the reconstructed kernel files available at <https://naif.jpl.nasa.gov/pub/naif/JUNO/kernels/>. The nominal pointing uncertainty of JIRAM images is about 1 pixel, translating into minimum pointing uncertainties of about 12 km for the data considered in this study.

3. Methods

The winds were estimated by tracking the motions of different atmospheric features (clouds) over frames acquire at different times. This method relies on the assumption that changes in feature positions are caused solely by the motion of air parcels instead of other phenomena such as condensation/sublimation (notably, due to the propagation of waves).

The wind motions were tracked by minimizing the mean absolute distortion (MAD), as defined in equation (8.2)–(37) of Gonzalez and Woods (2008). The method compares two images taken at different times. First, the images are reinterpolated over a common bidimensional sampling grid (in our case, with a uniform sampling step of 11.6 km in both spatial directions, corresponding to 0.01° in latitude). Then, for a neighborhood of each point of the first image, the our algorithm finds the bidimensional displacement vector that better matches what is observed in the second image (in our case, the neighborhood of a given point is defined as the square 21 × 21 pixels image section centered over the point). This allows one, on the basis of the time elapsed between acquisitions, to compute a bidimensional speed vector for each point of the first image, creating therefore a “speed field.” Notably, the retrieved speed fields have an *effective* spatial resolution comparable to the adopted size of search neighborhood; therefore, values reported in this paper shall be interpreted as mean air speeds averaged over an area of about 240 × 240 km around the point of interest. From here on we will use the term “amplitude” to indicate the length of a speed vector. Further details are provided in text in supporting information S1.

The estimate of displacements between images is performed in terms of integer numbers of sampling steps along both axes. This implies a minimum detectable motion of one sampling step (11.6 km). For images acquired 16 min apart—such as the north pole pairs presented in section 4—this corresponds to a minimum detectable speed of 12 m/s; this value reduces to 9.6 m/s for the south pole pairs acquired 20 min apart. These values represent the expected amplitude of random error on our wind estimates that affects independently each point of the retrieved speed fields.

Table 2
Details of Velocity Fields Presented in This Study

Field name	First component	Second component	Correction on x component of speed (m/s)	Correction on y component of speed (m/s)
N1	170202_114231	170202_115846	−14	0
N2	170202_115039	170202_120653	−33	−1
N3	170202_115846	170202_121429	−28	4
N4	170202_120653	170202_122236	−30	1
S1	170202_140125	170202_142113	18	4
S2	170202_142113	170202_144131	18	15

Note. The source JIRAM sequences are listed for the first and second components used for motion tracking. The last two columns provide the systematic corrections on x and y components of speed deemed necessary to make the central vortex axially symmetric (see section 4 for details). JIRAM = Jupiter InfraRed Auroral Mapper.

Conversely, systematic speed errors are those affecting by the same amount the entire velocity field computed from a given pair of images, adding a uniform (over space) unknown vector in the retrieved velocity field. They are mostly caused by the limited precision achievable in pointing reconstruction. Eventually, pointing uncertainties on reinterpolated images can produce apparent shifts of atmospheric features over the assumed geographical grid—and therefore additional spurious components in speed fields—even in the absence of any intrinsic air parcel motion. Exploiting the large degree of spatial overlap between individual images inside each of the sequences listed in Table 1, we were able to develop a method to compare the speeds retrieved from different pairs of images and to remove at least the *relative* differences in the systematic errors between different parts of the mosaics of speed maps. Details are provided in text in supporting information S1.

The six north pole sequences were arranged in pairs, in order to achieve a time gap around 16 min between the selected components of a pair. Pairs with a shorter time gap would have a correspondingly greater minimum detectable wind speed (24 m/s for the 8-min case). Pairs with a longer time gap would require computational times for the algorithm exceeding our currently available capabilities. Moreover, longer time intervals also increase the possibility of occurrence for phenomena that cannot be accounted for by the MAD criterion, such as small-scale rotations and changes of the cloud patterns due to wave activity. For the three south pole sequences, the only options were pairs with a time gap around 20 min between the selected components.

Table 2 details the sequence pairs used for speed fields determination.

4. Results

4.1. Preliminary Analysis

The retrieved velocity field for the N1 case—in reference to the System III coordinate system—is shown in Figure 2.

A first notable feature is the azimuthal variation of the velocity amplitude around the NPC center (approximately located at [89.5°N, 130°E]) that tends to diminish considerably along the 0° longitude meridian and to increase along the 180° longitude meridian. In each point within 2° latitude from NPC center, the direction of wind remains essentially orthogonal to the line joining the considered point with V1 centers, with no significant radial components, making it unlikely that local decreases/increases of wind speeds are related to a Rossby wave. On the other hand, visual inspection of NPC cloud features as imaged by JIRAM (Figure 3) demonstrates a remarkable degree of axial symmetry (in terms of typical signal amplitudes and frequency of variations at fixed distance from the center) up to about 1,700 km from NPC center. Moreover, the wind direction in regions of low velocity amplitude around NPC (namely, those about the 87° latitude circle) as seen in Figure 2b appears to be systematically oriented toward the approximately 90°W meridian (negative x direction).

4.2. Introduction of a Symmetrization Procedure

These facts possibly can be explained assuming the existence of a systematic component in the retrieved speed field presented in Figure 2. This component would be a single bidimensional vector, uniform over

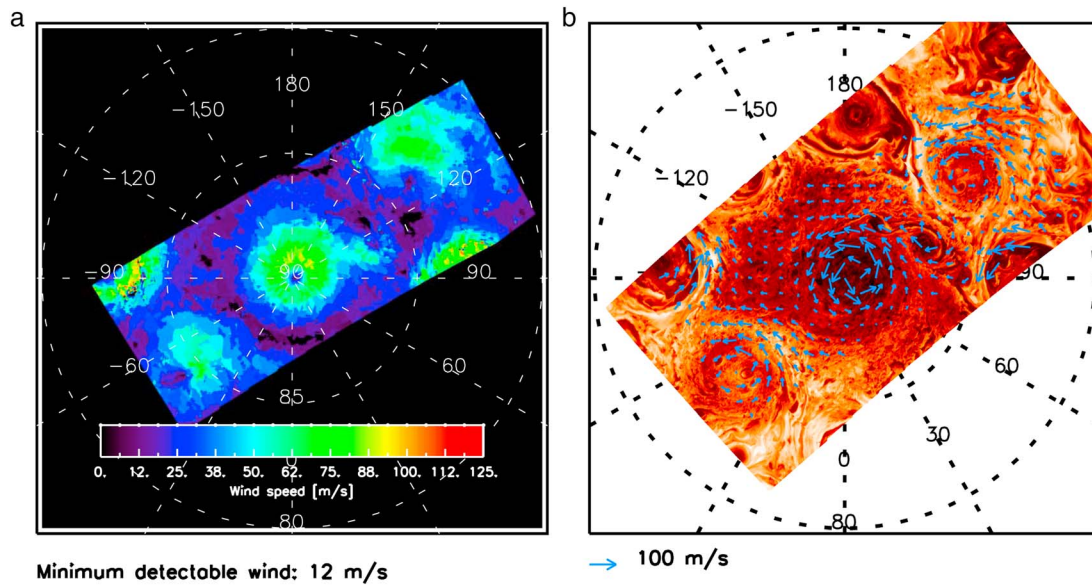


Figure 2. Wind velocity amplitudes (a) and directions (b) with respect to System-III coordinates, as derived in the N1 case. Background image for the left panel is a mosaic of the original images from the 170202_114231 sequence. Directions are presented only in the areas where overlap with images of sequence 170202_115846 exists.

the speed field or at least in large areas around NPC and approximately oriented along the x axis. It should be stressed that this systematic component can be caused by a pointing error or by an actual motion of NPC with respect to the System III coordinate or by a combination of the two. Ideally, its removal from the retrieved field should be able to compensate at the same time systematic directions observed in weak wind areas as well as the azimuthal speed asymmetry around NPC center. This latter feature is particularly desirable, since azimuthal symmetric speed fields can more easily justify the long-time persistence of NPC that was again observed with similar size, position, and appearance in JIRAM images from PJ5 and PJ6.

In practical terms, the removal of the systematic component consists in the subtraction of a uniform velocity vector (a pair of uniform components along x and y axes) from the entire velocity field returned by the procedure described in text in supporting information S1, without the introduction of any additional rotation or further transformation.

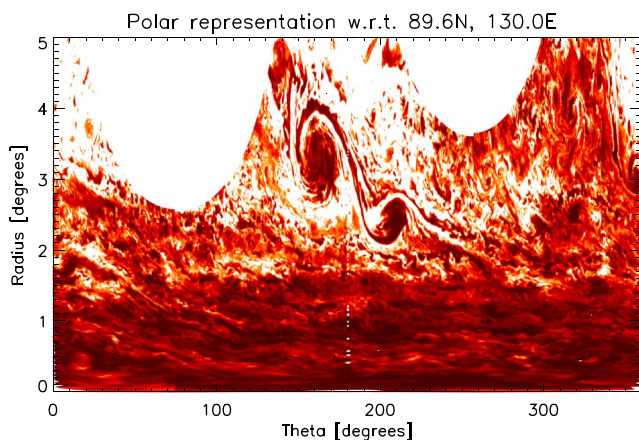


Figure 3. Detailed view of the NPC region from sequence 170202_120653. Data were reprojected as follows: The distance of pixel along the y axis (radius) corresponds to its radial distance from the estimated vortex center at [89.6°N, 130°E]; the distance of pixel along the x axis (theta) corresponds to the angle between the directions pixel-vortex center and pole-vortex center. This representation allows one to appreciate the degree of axial symmetry of vortex cloud structure up to at least 1.5° from vortex center (1,750 km). NPC = North Polar Cyclone.

The criterion that we chose to adopt to compute the systematic component was the maximization of axial symmetry of velocity amplitudes around NPC, upon removal of the searched component from the original speed field. This was achieved by minimizing the total standard deviation of the speed amplitude, as computed over several annuli around the apparent NPC center up to a distance of about 1,500 km. This method is formally equivalent to searching, in each annulus, for the systematic component that, upon subtraction, brings the velocity amplitudes as close as possible to their mean value. This symmetrization procedure—that introduces a (uniform over the field) correction of the speed field—has been exploited extensively in our subsequent analysis to determine the mean vortices' motions with respect to System III. Notably, the symmetrization procedure relies on a large number of independent wind speed estimates around the vortex center and therefore exploits correlations among independent measurements. Numerical tests have demonstrated that variations in the order of 2.5 m/s on the systematic component to be removed are enough to introduce detectable variations in the derived total standard deviation of the speed amplitudes used to estimate the degree of azimuthal symmetry.

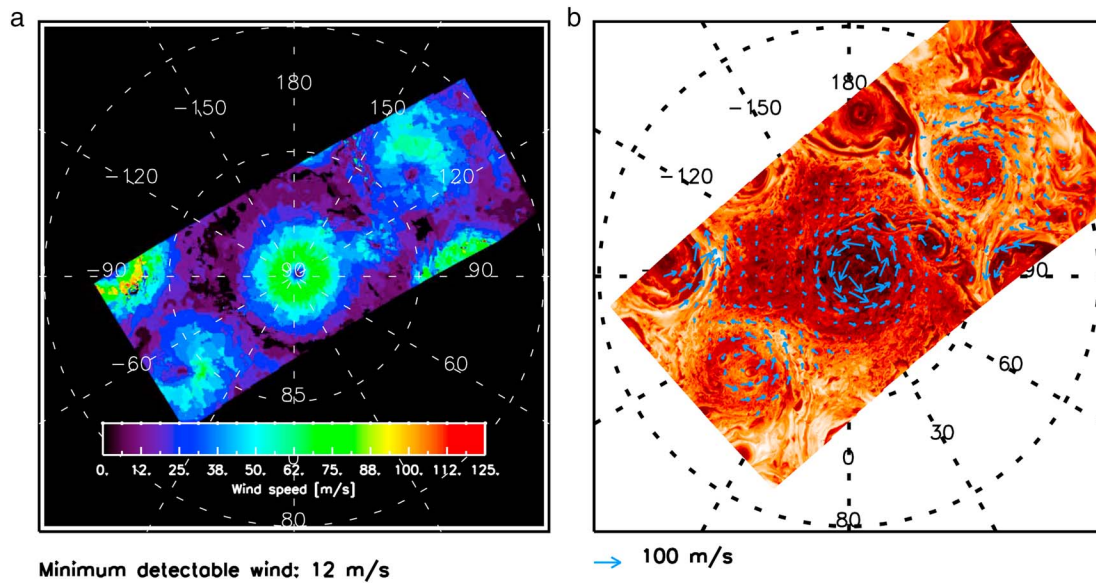


Figure 4. Wind velocity amplitudes (a) and directions (b) over the north pole, derived for the N1 case of Table 2, as corrected to achieve maximum azimuthal symmetry of wind speed around the center of NPC. Figure A2 in supporting information S1 provides analogous information for cases N2, N3, and N4. NPC = North Polar Cyclone.

The removal of the component of systematic motion due to the actual motion of NPC with respect to System III is conceptually equivalent to putting oneself in a reference frame, in motion with respect to System III, where the vortex center remains stationary and the speed field becomes axially symmetric around that center.

In the case of field N1, corrections of $v_x = -14$ m/s and $v_y = 0$ m/s were deemed adequately to make NPC axially symmetric (Figures 4a and A2 in supporting information S1). This correction is indeed capable of effectively nullifying velocity amplitudes around the 87° latitude. For the other north pole cases N2–N4, the same symmetrization procedure adopted for NPC provided corrections on the x component of the winds between -33 and -28 m/s and on the y component of the winds between -1 and 5 m/s. These values are listed in the last two columns of Table 2. We reiterate that these corrections for the N1–N4 cases may include the compensations for a systematic genuine motion of NPC with respect to the System III coordinate system (that must be constant for the different cases, given the short time elapsed between different sequences) as well as for the pointing errors (variable from case to case). Albeit these two effects cannot in principle be disentangled and despite the extremely limited statistics (just four cases), we notice that along the x axis we have inferred consistently correction components above the uncertainty level toward the negative direction, suggesting therefore the occurrence of an actual motion of the NPC with respect to the System III coordinates along the 90° W direction. Figures 4 and A2 in supporting information S1 present the wind speeds measured over the north pole region in the four available fields, once the removal of systematic components to obtain symmetry for the central pole NPC has been applied to the entire corresponding field. Figures 5 and A3 in supporting information S1 present the same quantities for the south pole, after symmetrization for SPC.

4.3. Revised Analysis of NPC After Symmetrization Procedure

At the north pole, NPC shows the highest wind speed amplitude of 75 m/s at about $1,000$ km from the vortex center (Figure 6a). The mean relative vorticity—twice the azimuthal velocity divided by the radius—is therefore $1.5 \times 10^{-4} \text{ s}^{-1}$, which is about half the planetary vorticity at the pole of $3.5 \times 10^{-4} \text{ s}^{-1}$ and of the same sign. The NPC center has an offset from the nominal Jupiter rotation pole (albeit not as evident as observed for the SPC), with offset estimates varying between 0.4 (from photometric estimate of signal symmetry of mosaic 170202_120653) and 0.15 (from location of wind speed minima in N3) latitude degrees. Despite the adopted symmetrization procedure, the wind field retains some asymmetry around speed minima. Namely, the speed peak appears consistently larger in width and slightly lower in peak value along the

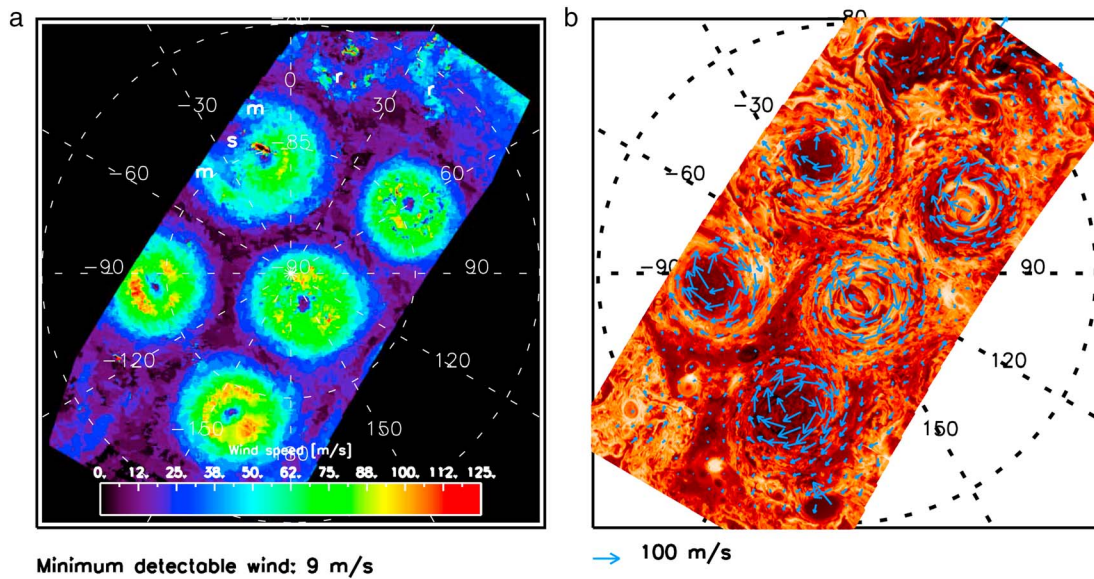


Figure 5. Wind velocity amplitudes (a) and directions (b) over the south pole, derived for the S2 case of Table 2, as corrected to achieve maximum azimuthal symmetry of wind speed around the center of SPC. Labels m, s, and r indicate specific features discussed in the text. Figure A3 in supporting information S1 provides analogous information for case S1. SPC = South Polar Cyclone.

positive x and y directions (i.e., along the 135°E meridian). This asymmetry is possibly related to the presence of the small “A” vortex along the 120°E meridian. Wind speed sections from different fields are essentially consistent once the nominal error of 12 m/s is kept in mind.

4.4. Possible Evidence of Relative Motions Between Cyclones in the North Polar Region

Among the four internal vortices around NPC, only two (CPCn6 and CPCn2) are covered by our maps. We should note that *symmetrization* of the wind field for NPC did not lead to axial symmetric velocity fields for these two features, which appear weaker on the east sides for both vortices. Moreover, the velocity patterns in Figures 4 and A2 in supporting information S1 around CPCn6 and CPCn2 are quite constant from N1 to N4, suggesting that axial asymmetry of CPCn6 and CPCn2 is not an observational artifact. The axially symmetric appearance of both features in JIRAM images as well as their stability over several Juno orbits points again toward the occurrence of relative motions of the two vortices with respect to NPC center, such that the velocity fields appear indeed axially symmetric in the reference frames moving along their own centers. Moving from this assumption, we repeated the symmetrization procedure described above separately for both CPCn6 and CPCn2 vortices, retrieving the corresponding corrections. Once this correction is subtracted from the correction provided by the symmetrization of NPC, we can infer the net relative velocity of each feature

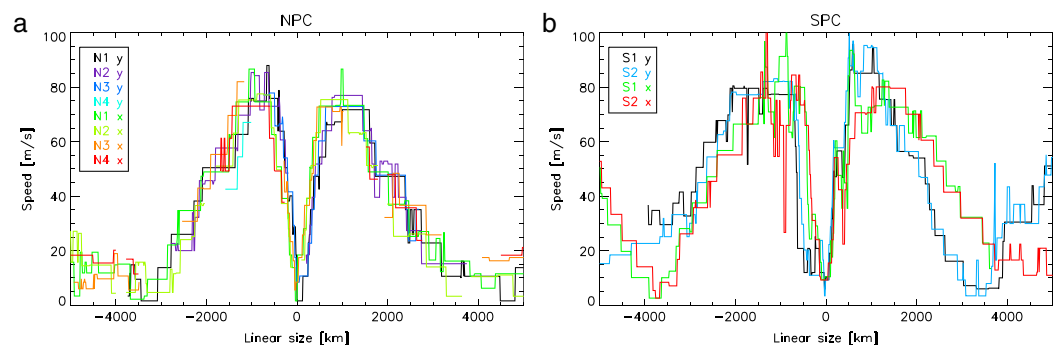


Figure 6. Cross sections of wind velocity amplitudes fields along the x and y directions of Figure 1 for the central vortices over the north (a) and south (b) poles. Different colors are for different cases listed in Table 2 and different directions.

Table 3
Motion of CPCn6 and CPCn2 Centers With Respect to NPC, as Derived Imposing Corrective Speed Components on Wind Fields to Achieve Approximate Axial Symmetry of Wind Fields (Separately) Around Each Vortex Center

Field name	CPCn6		CPCn2	
	Net v_x (m/s)	Net v_y (m/s)	Net v_x (m/s)	Net v_y (m/s)
Field N1	16.	-3.	2	-7.5

Note. CPC = Circum-Polar Cyclone; NPC = North Polar Cyclone.

with respect to NPC. This study is best performed in the N1 case, because of the continuous spatial coverage offered by this speed field. Results are reported in Table 3. Since speeds for both CPCn6 and CPCn2 refer to NPC, difference between these components provides also the relative motion of the two circumpolar cyclones.

Unfortunately, it is not possible to verify independently the relative motions of cyclones by tracking their centers over JIRAM images acquired at different times. The large uncertainties on the definition of vortex “centers,” regardless of the adopted method (radiometric barycenters or minima of speed field), imply errors on derived feature speeds

much larger than those achieved by speed axial symmetrization. For example, in the NPC case the position of center can be defined with an uncertainty of 0.15° in longitude: this implies an uncertainty on speeds of 180 m/s for the northern cases listed in Table 3, about an order of magnitude greater than the values reported in Table 3.

The magnitude of speed of CPCn6 presented in Table 3 around NPC would imply a rotation period of about 3×10^6 s, that is, about 85 Jupiter rotation periods or 35 Earth days. However, net speeds of CPCn6 and CPCn2 with respect to NPC are neither oriented along the parallels (i.e., both have a meridional component) nor consistent with a rigid rotation of the entire pattern of nine northern vortices around the pole, since both cyclones appear to move approximately toward the 150 W meridian. JIRAM images of the north polar region acquired during subsequent JIRAM pericenter passages (from PJ5 to PJ10, in December 2017) clearly show the same pattern of cyclones presented in Figure 1a, with circumpolar cyclones with distinctive morphologies (notably CPCn4) at approximately the same positions. This fact strongly supports the long-time stability (in the time scale of tents of months) of these structures as well as the fact that relative motions presented in Table 3 are either irregular in time or subject to periodic reversals. Unfortunately, during later pericenter passages overlap of JIRAM image sequences over the north pole was not adequate to retrieve independent speed fields such as those presented in Figure 4.

4.5. CPCs and Other Features in the North Polar Region

The sizes of CPCn6 and CPCn2, as inferred from wind speed fields, are comparable to that of NPC, but absolute peak speeds (even after symmetrization) are considerably lower, reaching about 55 m/s again at about 1,000 km from their apparent centers.

The small A feature is an anticyclonic feature and presents maximum speeds around 42 m/s. At least four further smaller anticyclonic structures exist around NPC (three are seen Figure 7a and a further one in Figure 7b marked as “a”).

Results on CPCn3 and CPCn7 are more problematic. First, their marginal positions on N1 did not allow a symmetrization to be performed to compensate the joint effects of the motion of the feature with respect to System-III coordinates and of pointing errors. Second, significant portions of external rims (beyond 2° from their respective apparent centers, regions hosting both very dark and very bright areas in Figure 1a) are essentially featureless, strongly limiting the validity of motion tracking by mean of MAD estimate. Despite these limitations, some results are robust: their central parts (at intermediate brightness in Figure 1a) are rich in features that allow effective tracking of wind speeds. The fastest annulus on CPCn3 at about 1,000 km from cyclone center shows speeds in the range 100–110 m/s. The mean relative vorticity is therefore around $2 \times 10^{-4} \text{ s}^{-1}$, to be compared against a planetary vorticity at 82.5° of $3.47 \times 10^{-4} \text{ s}^{-1}$ and of the same sign. Coverage of CPCn7 is less complete, and the area corresponding to the high-speed annulus in CPCn3 is not included in N1. Nevertheless, the region where estimates are available is already suggestive of much higher speeds than the ones observed in NPC, CPCn6, and CPCn2. An interesting feature associated with CPCn3 is located at $[85^\circ\text{N}, 90^\circ\text{E}]$ where velocity maps, supported by visual inspection, demonstrate how the flow is strongly accelerated (Figure 7b, marked as “f”), moving from the stagnant regions at $[83^\circ\text{N}, 105^\circ\text{E}]$.

4.6. Cyclones in the South Polar Region

Over the south pole, symmetrization of velocity fields around SPC provided—for both the S1 and S2 cases—correction values that once extended to the entire corresponding speed field provided rather symmetric values also around the centers of CPCs3, CPCs5, and CPCs1. The symmetrization procedure for the two

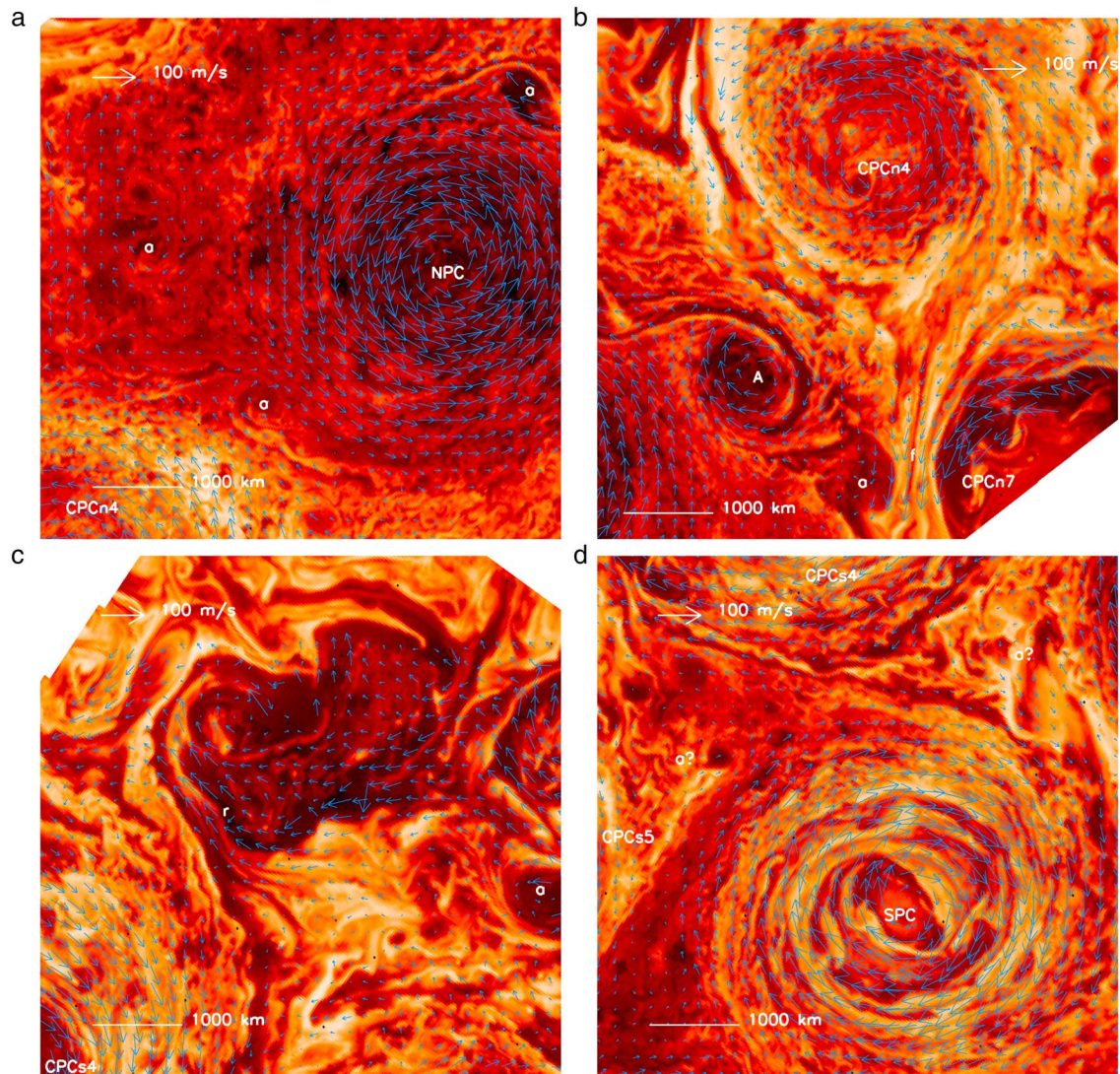


Figure 7. Details from speed fields N1 (a and b) and S2 (c and d). A and a letters indicate anticyclonic areas. “a?” indicates possible locations of further anticyclonic areas. f and r indicate other features discussed in the text.

cases S1 and S2 returned similar corrections, possibly suggestive of an overall motion of most of the south pole six vortices pattern toward the approximate direction of 60°E. The amplitudes of the corrections are, however, rather small once compared to the expected systematic uncertainties on speed determination due to the pointing, and consequently, the values reported in Table 2 should actually be interpreted as upper limits for the overall motions of south pole vortices. Notably, the computation of total standard deviation of the velocity amplitudes—implied by the symmetrization procedure—was limited to distances from nominal SPC center entirely covered by available velocity maps, to avoid biases related to vicinity of image borders.

It should be noted that even a simple visual inspection of Figure 1b demonstrates the asymmetric nature of SPC: its central part appears clearly elongated along the 150°E meridian, and its center shows an offset of about 1.5° from the nominal south pole. It is therefore not surprising to observe a residual asymmetry of speed amplitudes even after the symmetrization of speed amplitudes had been performed at the best degree allowed by the removal of a uniform vector in the entire SPC region. With comparison to NPC, the speed sections (Figure 6b) present higher peak values (up to 90 m/s at 1,000 km from the center) and a slightly higher relative vorticity of $1.8 \times 10^{-4} \text{ s}^{-1}$.

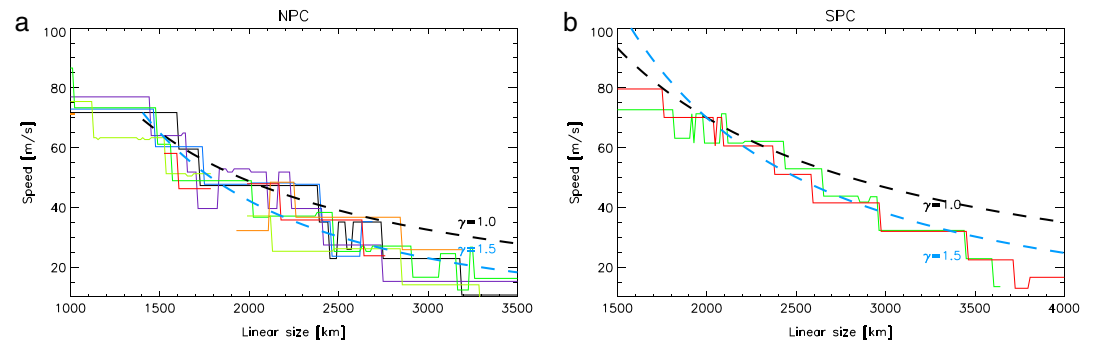


Figure 8. Velocity amplitude profiles versus radius presented in Figure 6 for vortices NPC and SPC are compared against power law profiles $v = c \times r^{-\gamma}$. (a) NPC. C_1 is such to provide a speed of 65 m/s at 1,500 km from estimated vortex center. (b) SPC. C_1 is such to provide a speed of 70 m/s at 2,000 km from estimated vortex center. NPC = North Polar Cyclone; SPC = South Polar Cyclone.

CPCs4, even after an attempt to symmetrize separately speed amplitudes around its apparent center, shows a very peculiar structure, with two arms at moderate speed (approximately 55 m/s, indicated by “m” in Figure 5a) apparently embracing a relatively stagnant area at [84°S, 25°W] (s in Figure 5a). Larger images of the same area strongly suggest that the upper arm is associated with an apparent acceleration of the flow from an area located at [80°S, 45°W] (just west of area “J” in Figure 4 of Adriani et al. (2018)).

CPCs5 presents the highest wind speeds observed in Jupiter polar vortices, exceeding 115 m/s. No evident high speed arms were detected for this vortex, as well as for CPCs1, despite their morphological resemblance (very opaque center) with CPCs4. CPCs3 presents some small scattered areas of apparent low speed along its high-speed annulus (seen as blue specks within CPCs5 in Figure 5a), but these turned out to be associated with featureless regions in Figure 1b and are therefore likely related to algorithm failures.

4.7. Other Features in the South Polar Region

The south polar region presents a number of other interesting features. An irregular ribbon of moderate wind (55 m/s) exists around [83°S, 15°E] (rightmost “r” label in Figure 5a), surrounding a very opaque area centered at [81°S, 15°E]. In the entire region, winds appear to rotate clockwise, as observed for the main southern vortices (CPCs) described above. Figure 7c provides further details of the area (a part of the ribbon is marked there as r). A second similar ribbon exists between 30°E and 45°E (leftmost r label in Figure 5a). Both ribbons represent likely the southern parts of highly distorted cyclonic structures, only partially covered in our velocity maps, possibly smaller versions of the folded filamentary regions reported in Orton et al. (2017) at lower latitudes in JunoCam data.

A number of small anticyclones, with very opaque centers, are observed at [85°S, 130°W], [82°S, 40°W] (also visible in Figure 7c and marked there as a) and [81°S, 175°W]. The small bright feature with a more opaque center at [82.5°S, 125°W] also appears to be an anticyclone. Extremely weak anticyclonic circulation is tentatively identified in two regions with low wind speeds (<20 m/s) between SPC, CPCs5, and CPCs4 (Figure 7d, marked as a?) but with patterns much less defined in comparison to what is observed around NPC.

4.8. Velocity Versus Radius Beyond the Vortex Center

The NPC has a constant angular speed at least out to 500 km from vortex center. Beyond 1,400 km, the decay of the tangential speed may be modeled as

$$v = C_1 \cdot r^{-\gamma} \quad (1)$$

Here v is the tangential velocity, r is distance from the vortex center, and C_1 is a constant. We observe (Figure 8a) that speeds decay more quickly than expected for the case of an irrotational vortex, for which $\gamma = 1$. A fit of speed data between 1,500 and 3,200 km returns a value of $\gamma = 1.40 \pm 0.04$. The SPC from 2,000 to 2,600 km displays a trend of speed with $\gamma = 1.06 \pm 0.18$. Beyond a radius of 2,600 km, the tangential speed drops more quickly with increasing distance, with γ approaching the value of 1.5 (Figure 8b). These

profiles differ from a Rankine-type vortex because the latter has $\gamma = 1$ (vorticity = 0) outside a circular region of constant vorticity.

5. Discussion

With the NPC center as a reference, symmetrization of the wind field in the region within 3,000 km yields a vortex that is essentially circular, that is, the detected radial motions are comparable to the estimated speed error. For a circular vortex that is small compared to the planet's radius, cyclostrophic balance applies and the radial force balance in pressure coordinates is

$$-\frac{v^2}{r} - fv = -g \left(\frac{\partial z}{\partial r} \right)_p \quad (2)$$

Here f is $2\Omega \sin \phi$, ϕ is latitude, Ω is the planet's angular velocity, and $z(r, p)$ is the height of a constant pressure surface. For the NPC the ratio of the first and second terms is 0.21, meaning that the Coriolis acceleration dominates and the force balance is nearly geostrophic.

Assuming that v is a linear function of r from 0 at the center to 75 m s^{-1} at $r = 1,000 \text{ km}$, the height z at $r = 1,000 \text{ km}$ compared to that at the center is 640 m. This is about 0.025 times the pressure scale height at the 1-bar level, where the temperature is 165 K. The mean relative vorticity ζ , which is the line integral of velocity around the circumference divided by the area, is $2v/r$, and the vortex Rossby number ζ/f (Legarreta & Sánchez-Lavega, 2005) is $Ro = 2v/(rf)$. Thus, $Ro = 0.43$ for the NPC.

Other vortices on Jupiter (Choi et al., 2007; Hueso et al., 2009; Simon-Miller et al., 2002; Sussman et al., 2010; Vasavada et al., 1998) have wind speeds that are comparable to the $\sim 100 \text{ m s}^{-1}$ speeds of the polar vortices. Legarreta and Sánchez-Lavega (2005) performed an extensive study to measure the vorticity of Jupiter cyclones and anticyclones. They report absolute values of Ro in the range from ~ 0.2 to 0.5. For the Great Red Spot and White Ovals the values are 0.30 and 0.33, respectively. The NPC value is consistent with the other vortices, although it is on the high side of the distribution. The vorticity itself, which is $15 \times 10^{-5} \text{ s}^{-1}$, is higher than all but one of the values reported by Legarreta and Sanchez-Lavega, but it is still well below the planetary vorticity of $35 \times 10^{-5} \text{ s}^{-1}$.

Tropical cyclones on Earth have wind speeds similar to those of the NPC and SPC, but the radius of maximum wind is much smaller. A category 5 hurricane is defined as $v \geq 70 \text{ m/s}$. A typical radius for the "eye," where the winds are strongest, is 25 km. At $\phi = 30^\circ$, corresponding to the south coast of the United States, the Rossby number is 39, meaning that the Coriolis acceleration in equation (2) is almost negligible. Despite this huge difference between cyclones on Earth and Jupiter, the height variation of a constant pressure surface relative to the scale height is about the same, 0.030 and 0.025 respectively.

The polar cyclones on Saturn have about the same size and speed as those on Jupiter (Dyudina et al., 2009), but there is only one cyclone at each pole. This is a significant difference between the two planets that has yet to be explained. The radius of the eye is $\sim 1,000 \text{ km}$, the atmosphere within the eye is warmer than that outside, and the eyewall clouds are 1–2 scale heights above the clouds in the center.

Adriani et al. (2018) observe that the constellation of CPCs is reminiscent of vortex crystals, which occurs in strictly two-dimensional (2-D) flows. Starting with Lord Kelvin (Thomson, 1878), many authors have studied laboratory-scale mechanical systems that exactly simulate the 2-D motion of columnar vortices (Campbell & Ziff, 1979; Fine et al., 1995; Mayer, 1878). The laboratory results have been verified by numerical integration of the 2-D Euler equations, with a variety of forcings, boundary conditions, and vorticity distributions (Jimenez & Guegan, 2007; Schechter et al., 1999). The common feature is the 2-D nature of the flow, where the velocity around an isolated vortex falls off as $1/r$, the stream function grows as $\log(r)$, and the circulation is a constant out to infinity.

These are long-range interactions. Planetary atmospheres are more complicated. Moderate vertical stratification or simply a free surface that moves up and down produces a finite radius of deformation, which limits the range of interaction. Rotation and spherical geometry produce a background vorticity gradient, a beta effect, which allows planetary wave propagation (Vallis, 2017). These effects are small close to the pole if the stratification is strong enough, and that could help explain the existence of Jupiter's polar vortices.

The $1/r^\gamma$ falloff with distance shown in Figure 8, where γ is 1.4–1.5, is not inconsistent with a strictly 2-D flow. It simply means that the NPC and SPC are surrounded by fluid with anticyclonic vorticity. The vorticity associated with a $1/r^\gamma$ falloff is proportional to $(1 - \gamma)/r^{\gamma+1}$, which is negative when $\gamma > 1$. If one uses a straight line fit near the outer region, one would conclude that the velocity is 0 at $r = 4,000$ km for the NPC and is 0 at 4,500 for the SPC. Then the circulation would be 0 at those distances, and one would have a “shielded” vortex in which the spatially integrated vorticity is 0. Such behavior is inconsistent with a laboratory model (Fine et al., 1995; Schechter et al., 1999) that has only one sign of vorticity, but it is consistent with a 2-D simulation (Jimenez & Guegan, 2007) that has both signs of vorticity and a spatial average of 0.

6. Conclusions

Results presented here are a first attempt to extract wind fields over large portions of Jupiter polar areas, with random errors in the order of 12 m/s. Data were acquired during a single Juno pericenter passage on 2 February 2017.

The two cyclones placed over both poles (NPC and SPC) reach their maximum speeds at about 1,000 km from their respective centers; the southern vortex appears to rotate slightly faster than the northern counterpart (90 and 75 m/s, respectively). In the surrounding circumpolar cyclones, speed exceeds 100 m/s in at least three cases (CPCn3, CPCs1, and CPCs5). Considering the other circumpolar cyclones included in our maps, the two southern structures (CPCs4 and CPCs3) show slightly lower maximum speeds (80–90 m/s), while the two northern vortices (CPCn2 and CPCn6) appear considerably slower (about 55 m/s). In all cases, the peak speeds are reached at about 1,000 km from their respective centers, but in general, peaks are rather broad, and therefore, the definition of the size of maximum speed ring is prone to an uncertainty of about 500 km.

Central polar vortices in both hemispheres are in moderate cyclostrophic balance and with velocities increasing linearly along radius within 500 km from their centers. In the outer parts of the southern vortex, flow is irrotational in a large annulus ($\gamma = 1.06 \pm 0.18$); in the northern vortex, rotational speed decays along radius faster than expected for irrotational flow ($\gamma = 1.40 \pm 0.04$).

While the main vortices are confirmed to be cyclones, several smaller anticyclonic features are also detected.

We made azimuthal averages around vortex centers, to account both for pointing errors as well as systematic motions of vortices with respect to the System-III coordinates. Despite the ambiguity related to the absolute pointing, both polar cyclones appear to be subject to overall motions with respect to System III, with translation speeds of the vortex centers in the order of 25 m/s for the northern cyclone and slightly less (18 m/s) for the southern cyclone. The stability of vortex patterns over several Juno perijove passages implies, however, that these motions are not constant and may reverse between Juno perijoves.

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