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Vorticity and divergence at scales down to 200 km within and around the polar cyclones of Jupiter

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Abstract

Since 2017 the Juno spacecraft has observed a cyclone at the north pole of Jupiter surrounded by eight smaller cyclones arranged in a polygonal pattern. It is not clear why this configuration is so stable or how it is maintained. Here we use a time series of images obtained by the JIRAM mapping spectrometer on Juno to track the winds and measure the vorticity and horizontal divergence within and around the polar cyclone and two of the circumpolar ones. We find an anticyclonic ring between the polar cyclone and the surrounding ones, supporting the theory that such shielding is needed for the stability of the polygonal pattern. However, even at the smallest spatial scale (180 km) we do not find the expected signature of convection – a spatial correlation between divergence and anticyclonic vorticity – in contrast with a previous study using additional assumptions about the dynamics, which shows the correlation at scales from 20 to 200 km. We suggest that a smaller size, relative to atmospheric thickness, of Jupiter’s convective storms compared with Earth’s, can reconcile the two studies.

Plain language summary

The vortices at Jupiter’s poles are interesting because they are arranged in geometric patterns that endure for years. The vortices are cyclones, meaning they spin counterclockwise in the northern hemisphere. We confirm one theory, which says that each cyclone has to be shielded by an anticyclonic ring for the pattern to be stable. We fail to confirm another study, which finds that the vorticity is large where the flow is converging around an axis (the figure skater effect), and vice versa. That would be evidence of convection, but we do not find it. The other study uses assumptions about the dynamics to observe vorticity at scales much smaller than we do. The two studies can be reconciled if convection on Jupiter is smaller relative to the atmospheric thickness than convective storms on Earth.

Introduction

At Jupiter's north pole there are eight cyclones that form an octagon, with one cyclone at each vertex and one additional cyclone in the center^{1,2}. The centers of the cyclones are at latitudes of $83 \pm 1^\circ$, which is about 8700 km from the pole. Jupiter's south pole is the same except there are only five cyclones, which form a pentagon with one at the center. The vertices are at latitudes of $-83 \pm 1^\circ$. The polygons and the individual vortices that comprise them have been stable for the four years since Juno discovered them^{3,4,5}. The polygonal patterns rotate slowly or not at all. The peak azimuthal wind speeds around each vortex range from 70 to 100 m s⁻¹, and the radial distance r from the peak to the vortex center is about 1000 km⁶. In contrast, Saturn has only one vortex, a cyclone, at each pole⁷. The peak winds are 150 m s⁻¹, and the radius at the peak is 1500 km^{8,9}. Saturn has a 6-lobed meandering jet at 75° , but it has no cyclones associated with it. Both laboratory and theoretical models treat the hexagon as a stable wave-like pattern^{10,11,12,13,14}.

There have been a handful of theoretical studies that specifically address the origin of polar cyclones on Jupiter and Saturn^{15,16,17,18}. They are 1-layer and 2-layer models that introduce small-scale motions either as an initial condition or as continuous forcing balanced by dissipation. The small-scale vortices merge and become the large-scale vortices. The cyclones drift poleward, and the anticyclones drift equatorward, as they do on Earth. In some cases the cyclones merge into one big cyclone at the pole. In other cases, with different parameter settings, the cyclones wander about without forming polygons. Only one theoretical study gets stable polygons from random initial conditions, and only if the wavelengths of the initial random disturbances are less than 300 km¹⁹. A Fourier analysis of Juno data reveals that flows with wavelengths larger than 215 km are gaining energy from smaller-scale flows - an example of an upscale energy transfer²⁰. Therefore one goal of the present paper is to measure vorticity and divergence at scales much smaller than the main cyclones and see how the upscale energy transfer takes place.

Another theoretical study²¹, which uses the shallow water equations, introduces cyclones that have the observed gross properties - maximum velocity and radius, and arranges them into different polygonal patterns around the pole to see which ones are stable. The stable ones have shielding - a ring of anticyclonic vorticity surrounding each of the cyclones, and the unstable ones do not. Some models with small-scale forcing develop shielding, but they do not organize into polygons^{15,16,17,18,22}. So another goal of the present paper is to measure the vorticity inside and outside the large cyclones and see whether they are shielded.

The small-scale forcing in the 1-layer and 2-layer models is a crude representation of convection. There are 3D models that treat convection explicitly, in some cases with the Boussinesq (quasi-incompressible) approximation^{23,24,25} and in other cases with density varying vertically by up to 5 scale height^{25,26,27,28}. Some treat fluid in a box with periodic boundary conditions, and others use full spherical geometry. All the 3D models have small-scale convective plumes. The convective plumes produce large-scale vortices by mergers - an upscale transfer of kinetic energy, and some of the vortices arrange themselves into polygonal patterns^{23,28}. Although a relation between divergence and vorticity is not discussed in any of these models, a negative correlation is expected for convection on a rotating planet. Therefore a

third goal of the present paper is to measure divergence and vorticity at scales down to 180 km and look for this signature of convection.

Results

1. Scale analysis

At midlatitudes an important parameter is the length $L_\beta = (U/\beta)^{1/2}$ where U is a characteristic horizontal velocity and $\beta = df/dy = 2\Omega \sin\theta/a$ is the latitudinal gradient of the planetary vorticity $f = 2\Omega \cos\theta$. Here θ is colatitude, y is the northward coordinate, and a and Ω are the planet's radius and angular velocity, respectively. L_β plays a role in the stability of the zonal jets. On both Jupiter and on Saturn, $2\pi/L_\beta$ is approximately equal to the wavenumber of the zonal jet profile with respect to latitude when U is the rms speed^{29,30,31,32,33}. However, L_β is infinite at the poles since β goes linearly to zero there. Therefore, we introduce a different scaling¹⁹, one based on minus the gradient of β at the pole, $\gamma = -d\beta/dy = 2\Omega/a^2$. The associated length scale is $L_\gamma = (U/\gamma)^{1/3}$, and for $U = 80 \text{ m s}^{-1}$ it is about 10,500 km. (We ignore the oblateness and use Jupiter's equatorial radius throughout this paper.) L_γ represents the radius of the circle around the pole inside of which the effect of the vortices - large-scale turbulence - is greater than the effect of β and the zonal jets. Note that L_γ is the distance from a specific point - the pole, and L_β is not. The value of L_γ is close to the 8700 km size of the polygons on Jupiter.

The radius of deformation L_d is c/f , where c is the gravity wave speed of the gravest vertical mode - the one spanning Jupiter's weather layer, which extends from the base of the stratosphere down to the base of the water cloud. The value of c depends on the degree of stratification of the weather layer³⁴, and is assumed to be independent of latitude. Different assumptions about the vertical stratification put the average L_d at the poles in the range 350 - 1300 km^{34,35,36}. This brackets the 1000-km radius of the cyclones.

Originally L_β was defined as the length scale where the flow transitions from turbulence to zonal jets as the scale of the flow increases³⁷. Observations of Jupiter suggest that a similar transition occurs as the latitude of the flow decreases. The critical latitude, below which zonal jets dominate, was shown to be a decreasing function of L_d ^{38,39}. Here we are arguing that a critical latitude, $\pi/2 - L_\gamma/a$, exists even for arbitrarily small values of L_d .

We discuss the observations using parameters of the shallow water (SW) equations, where a single layer of fluid of thickness h floats hydrostatically on a much thicker fluid, which we assume is at rest^{40,41}. The two dependent variables are the horizontal velocity $\mathbf{v}$ and the gravitational potential $\phi = g_r h$, where g_r is the reduced gravity -- the gravitational acceleration times the fractional density difference $\Delta\rho/\rho$ between the two layers⁴¹. ϕ is the column density in the 2D continuity equation, and $\sqrt{\phi}$ is the gravity wave speed c . Also, ϕ enters in the potential vorticity (PV), which is a dynamical scalar that is conserved on fluid elements. For the SW equations PV is $(\zeta + f)/\phi$, where $\zeta = (\nabla \times \mathbf{v}) \cdot \hat{\mathbf{k}}$ is the relative vorticity -- the curl of the horizontal velocity. 3D effects are not completely ignored - they enter through L_d , which is

proportional to the square root of the layer thickness h and the fractional density difference $\Delta\rho/\rho$. Even these quantities are uncertain, so given the paucity of information about vertical structure, it is best to discuss our observations with the SW equations.

2. Vorticity and divergence

Fig. 1 shows the octagon of cyclones surrounding the north pole². Features in the clouds are visible at scales down to ~ 100 km, which is much less than the 1000-km radius where the azimuthal velocity is greatest. The figure was made from infrared images taken by the Jupiter Infrared Auroral Mapper (JIRAM) on February 2, 2017. The JIRAM M filter tracks the clouds at $4.5\text{--}5.0\text{ }\mu\text{m}$ wavelength⁴². The image numbers used in this analysis are listed in Supplementary Table S1 of the Supplementary Information (SI). The geometrically-located images, projected onto the tangent plane at the pole, are Source Data Table SD1. The derived velocity vectors are Source Data Table SD2.

Fig. 2 shows vorticity and divergence maps for two independent determinations of the wind field. The measurement requires tracking clouds in a pair of JIRAM images separated in time to get velocity, and then taking closed line integrals to get vorticity and divergence. The magnitude of the vorticity is larger than that of the divergence. The persistence and movement of vorticity features, even those ~ 180 km in size, shows that the small-scale features are not measurement noise. The motion is visible when one blinks the left and right vorticity maps in Fig. 2 back and forth, as one can do with Supplementary Figures S1-S4.

3. Planetary signal and measurement noise

In Fig. 3, the top two panels show covariances between n0103 and n0204, which are the two independent determinations of the wind fields in Fig. 2. Vorticity is top left, and divergence is top right. If the measurements were perfect, the two measurements would always agree, and the arrays of points would collapse to diagonal straight lines with unit slope. The vorticity measurements come close to this ideal, with a correlation coefficient η of 0.729. Since the measurement noise is uncorrelated with the variation of vorticity on the planet, the noise and planetary variances add (Equation 1a). And since the noise from n0103 is uncorrelated with that from n0204, the covariations do not contain the variance of measurement noise (Equation 1b):

$$\overline{(x - \bar{x})^2} = \overline{(y - \bar{y})^2} = \sigma_p^2 + \sigma_n^2, \quad \overline{(x - \bar{x})(y - \bar{y})} = \sigma_p^2 \quad (1a,b)$$

$$\frac{\overline{(x - \bar{x})(y - \bar{y})}}{\overline{(x - \bar{x})^2}^{1/2} \overline{(y - \bar{y})^2}^{1/2}} = \eta = \frac{\sigma_p^2}{\sigma_p^2 + \sigma_n^2} \quad (2)$$

The quantities involving x and y are measurements and are known, so the measured correlation coefficient η allows one to determine separately the variance σ_p^2 of vorticity on the planet and the variance σ_n^2 of measurement noise. The same reasoning applies to the divergence (Fig. 3, upper right).

Table 1 shows the results for different values of the dimensions of the box used to measure vorticity and divergence. For the upper right panel and the 180x180 box, $\eta = 0.299$,

meaning that there is some divergence on the planet, but its variance is less than the measurement noise. Note that the noise values for vorticity and divergence are about the same for the same box size. The difference is that divergence decreases by a factor of 4.34, and vorticity decreases only by a factor of 1.61 from the 90x90 box to the 360x360 box. This difference is an indication that the divergence is a small-scale phenomenon that averages out for the larger boxes. For the lower two panels of Fig. 3, divergence is plotted on the y-axis with vorticity on the x-axis, and the correlation coefficient is essentially zero. Supplementary Table S2 shows that the noise estimates in the fourth column of Table 1 are best fit by assuming the measurement uncertainty for each component of velocity is 7.8 m/s.

4. Potential vorticity and shielding

Fig. 4 shows the azimuthal mean $\bar{v}$ of the azimuthal velocity around the central cyclone as a function of radius r out to 6000 km. Also shown are the mean relative vorticity $\bar{\zeta}$, the mean gravitational potential $\bar{\phi}$, and the mean potential vorticity $\bar{P}\bar{V}$. In each panel there are three smooth curves. The middle one, colored orange, is derived by a linear least squares fit to the velocity data. The basis functions are given in the Methods section. The profile of $\bar{v}(r)$ agrees with earlier estimates⁶, including the fact that the profile at $r > 2000$ km falls off faster than $1/r$, implying negative vorticity in that region. Note that the fitted curve fits the data even where the velocity becomes negative (clockwise) at 4000-6000 km radial distance. The tabulated data are in Source Data Table SD3.

The gravitational potential ϕ in Fig. 4 is computed from an integral and is therefore uncertain by an additive constant. However, $\phi = g_r h$ is proportional to the thickness, and the thickness cannot be negative. The local maximum of ϕ is at $r = 4075$ km, and the figure is computed with $\phi = 124 \times 10^3 \text{ m}^2\text{s}^{-2}$ there. Having $\phi > 0$ at the origin requires $\phi > 69 \times 10^3 \text{ m}^2\text{s}^{-2}$ at $r = 4075$ km. This gives $L_d > \sqrt{\bar{\phi}/f} = 749$ km at $r = 4075$ km, which is in the middle of estimates obtained from lower latitudes taking the variation of f with latitude into account^{34,35,36}.

Discussion

In a SW model that starts with cyclones of the observed size and velocity arrayed in polygonal patterns around the jovian pole, stability requires an anticyclonic ring - shielding - around each cyclone²¹. With peak azimuthal velocity of 80 m/s and radius at the peak of 1000 km, a single parameter b controls the shape of the velocity profile and the depth of the shielding. The other free parameter is L_d , but it has only a small effect on the results. Mainly the polygons are stable in the range $1 < b < 2$. Below this range, the shielding is too weak and the vortices merge. Above this range, the negative vorticity is too strong, and the anticyclonic rings become two satellites orbiting around the cyclone 180° apart. At $b > 3$, these tripoles are unstable and the polygons fly apart chaotically. The blue curve in Fig. 4 has $b = 1.35$, which is safely in the stable zone according to the SW model. The green curve has $b = 1.10$, which is right on the edge. Moreover, the minimum vorticity in the ring is $-0.27 \times 10^{-4} \text{ s}^{-1}$, which compares favorably with the model value of $-0.21 \times 10^{-4} \text{ s}^{-1}$ for $b = 1.35$. The model results are for isolated cyclones; they do not capture the change in sign of velocity at $r \approx 4000$ km or the upturn of vorticity beyond 5000 km, both of which reflect the presence of circumpolar cyclones circling the pole.

The 200-km scale of vorticity and divergence is at least consistent with convection, Severe thunderstorms on Earth have diameters of 30-40 km, which is about 5 times the pressure scale height^{44,45}. Granules, which are the convective elements in the solar photosphere, are about 1000 km in diameter⁴⁶, which is also about 5 times the scale height of the partially ionized hydrogen gas. The scale height on Jupiter is about 40 km at the water cloud base, so if the ratio of horizontal diameter to scale height were 5, as it is on Earth and the Sun, then convection elements on Jupiter would have diameters of 200 km. This is about the smallest scale we can measure.

The bottom row of Fig. 3 shows no correlation between divergence and vorticity, although both positive and negative values are present. The implications for convection are uncertain. On the one hand, if a parcel conserves PV around a cycle of updrafts and downdrafts, the material derivative of $\zeta + f$ is proportional to the material derivative of ϕ throughout the cycle. But since ϕ is proportional to the thickness h , the material derivative of ϕ is also proportional to minus the divergence $\nabla \cdot \mathbf{v}$. Equivalently, the material derivative of negative (i.e., anticyclonic) vorticity ζ is proportional to the divergence. As a result, negative vorticity lags the divergence by a quarter cycle and there is no measureable correlation. On the other hand, if a parcel has its vorticity reset to zero at the start of each updraft, then negative vorticity develops on rising trajectories, because they diverge at the top. In this case there is a correlation between divergence and negative vorticity, and that would be a sign of convection.

Our feature-tracking approach gives vorticity and divergence at spatial scales of 200 km and larger. An entirely different approach²⁰ is to use infrared brightness itself as a dynamical variable, which extends the spatial scale down to wavelengths of ~ 15 km. The study assumes that negative infrared brightness anomalies, which are related to cloud height, are upward displacements of pressure surfaces and therefore a measure of anticyclonic vorticity. The assumption is verified at scales from 250 to 1600 km, which is smaller than the large cyclones but large enough so that feature tracking is possible. It further assumes that the flow is quasigeostrophic, so the divergence is given by $-1/f$ times the material rate of change of vorticity. This is the surface quasigeostrophic (SQG) model^{47,48}, which is used in meteorology and oceanography^{49,50}. Applied to Jupiter²⁰, one observes the signature of convection - a negative correlation between divergence and vorticity at 100 km scales and an upscale energy transfer from scales less than ~ 200 km to scales greater than ~ 200 km. These scales are just below the reach of our feature tracking method. However, the quasigeostrophic approximation is based on $Ro = \zeta/f \ll 1$, where Ro is the Rossby number. The inequality is not strictly valid for Jupiter's polar cyclones (Fig. 4), and it is even less valid at smaller scales, since Ro is predicted to increase with horizontal wavenumber⁴⁷.

At midlatitudes a *downscale* energy transfer is observed⁵¹, from wavelength scales of 2000 km to the shortest scale measured, which is about 500 km. That study uses Cassini visible light imaging; ours uses Juno infrared imaging; and SQG uses infrared brightness. More work is needed to reconcile these three data sets. A parallel study⁵² of Jupiter's south polar vortices, focusing on vorticity and stability, is a step in the right direction.

Methods

A series of 12 images was started every 8 minutes to cover the same region at the north pole of Jupiter. Ideally the images in a series would fit together like tiles in a mosaic with no overlap and no spaces in between. The spacecraft was approaching Jupiter, and the image resolution changed from 22 km/pixel in the middle of the first series to 14 km/pixel in the middle of the fourth series, 24 minutes later. The two maps on the left of Fig. 2 were made by measuring cloud displacements between the first and third series, which are 16 minutes apart, and the two maps on the right were made from the second and fourth series, which are also 16 minutes apart. Therefore, the left and right maps are separated in time by only 8 minutes, but they use entirely different images.

Supplementary Table S1 in the Supplementary Information (SI) gives the archival filenames and our working names for the 48 images that were used in the analysis. The four series are named n01 to n04, each of which records roughly the same place on the planet 8 minutes after the one before. The first step in the processing is to determine the precise location on the planet of each resolution element in each image. This is done with NAIF/SPICE data from the spacecraft and precise geometric calibration of the JIRAM instrument. The second step is to map the brightness patterns onto a grided reference plane tangent to the planet at the pole. We used 15 km/pixel for this mapping. That data is Source Data Table SD1.

The third step is to measure cloud displacements in the reference plane using the Tracker3 software from JPL. The software automatically searches for the best correlation of brightness patterns between two images. This is done between images in series n01 and n03 and between images in series n02 and n04. Velocity is the displacement in km divided by the time interval, which is always close to 16 minutes but depends on which image in each series was used. Correlation is done within a square box in the reference plane. After experimenting we settled on a 15 x 15 pixel correlation box for the Tracker3 software. Thus, with 15 km/pixel in the reference plane, we are using squares 225 km on a side to define a feature. Therefore, the resolution of the wind measurement is ± 112.5 km. We oversample it by a factor of 2.5 to obtain wind vectors on a 45 x 45 km grid. That data set is Source Data Table SD2. We determine vorticity and divergence at every grid point by integrating around boxes of various sizes using Stokes's theorem and Gauss's law, respectively. Table 1 gives results for boxes 2, 4, 6, and 8 pixels on a side, corresponding to 90, 180, 270 and 360 km on a side, respectively.

The error in the velocity estimate σ_v depends crucially on the granularity of the scene at the scale of the resolution element δ , which on average is about 18 km. Except for no features at all, for which there is no estimate, the worst case is a single cloud feature of size $\leq \delta$, for which the variance $\sigma_v^2 = 2\delta^2/\Delta t^2$, where Δt is the 16-minute time step and the factor of 2 arises because we are subtracting position in two images. Then $\sigma_v = 2^{1/2}\delta/\Delta t$, about 26.5 m/s. However, if the velocity measurement is the average of N statistically independent estimates of velocity, the variance is $2\delta^2/\Delta t^2/N$. The best case is when N is the number of resolution elements in the correlation box, which is L on a side such that $N = (L/\delta)^2$. Then $\sigma_v = 2^{1/2}\delta/\Delta t/N^{1/2} = 2^{1/2}\delta^2/L/\Delta t$, which is 2.1 m/s for $L = 225$ km. Thus σ_v is highly uncertain, but in Supplementary Table S2 we show that $\sigma_v = 7.81$ m/s gives a good fit to the noise column in Table 1.

A quantitative measure of granularity is image entropy H^{43} . We define it for each 15 x 15 correlation box from the histogram of brightness values in the box:

$$H = -\sum p_k \log_2(p_k) \quad (1)$$

The input data are 32-bit numbers, but we only have 225 pixels. We divide the range from the brightest to the darkest pixel into 256 grey levels, and we count the number of times that each grey level appears in the image. That number divided by 225 is p_k , the frequency of occurrence of grey level k normalized so that $\sum p_k = 1$. The sum is over the 256 grey levels. If the brightness corresponding to a particular grey level k_1 does not occur in the image, then $p_{k_1} = 0$. At least 31 of the p_k 's must be zero. If all 225 pixels have brightness corresponding to grey level k_2 , then $p_{k_2} = 1$ and all the other p_k 's = 0, resulting in $H = 0$. If the brightness levels of all the 225 pixels are different, then $H = \log_2(225) = 7.81$. This is the maximum entropy for this problem. Low entropy is bad for feature tracking, and we experimented to find a value that eliminated the most suspicious data, like the large pixel-to-pixel variations in the upper left and lower right corners of the divergence maps. We manually verified that the feature-tracking software was failing in those regions. Supplementary Figure S5 is a histogram of entropy values, and Supplementary Figures S6 and S7 compare the vorticity and divergence maps with the low entropy data present and with them masked out.

The data of Fig. 4 consist of $\sim 26,000$ measured velocity vectors on the 45 x 45 km grid whose radius from the vortex center $r < 6010$ km. Taking the azimuthal component $\bar{v}(r)$ of each vector, and knowing its r , we did two separate least squares fits, one for the a_n and the other for the b_n in Equation (2) to get analytic expressions for $\bar{v}(r)$ and $\partial\bar{\phi}(r)/\partial r$, respectively.

$$\bar{v} = \sum_1^4 a_n r^n + \frac{a_5 r}{(r^2 + r_0^2)}, \quad \frac{\partial\bar{\phi}}{\partial r} = -\frac{\bar{v}^2}{r} - 2\Omega\bar{v} = \sum_1^4 b_n r^n + \frac{b_5 r}{(r^2 + r_0^2)}. \quad (2)$$

This choice of functions has no physical significance. The functions were chosen simply to fit the data and provide analytic expressions for integration and differentiation. For a good fit, the parameter r_0 must be close to the radius of the velocity maximum. Based on visual inspection, it was chosen to be 1060 km for $\partial\bar{\phi}/\partial r$ and 1200 km for $\bar{v}$. We analytically integrated the expression for cyclostrophic balance in Equation (2) to get $\bar{\phi}(r)$ in Fig. 4, and we analytically differentiated the expression $(1/r) \partial(r\bar{v})/\partial r = \bar{\zeta}$ to get vorticity. The table of measured azimuthal velocities is Source Data Table SD3.

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Competing Interest Statement: No competing interests

Box size km x km	Correlation	Signal	Noise
vort 90 x 90	0.501929	0.754479	0.751573
vort 180 x 180	0.728803	0.623902	0.380587
vort 270 x 270	0.861097	0.556075	0.223338
vort 360 x 360	0.816752	0.469033	0.222166
div 90 x 90	0.243513	0.435793	0.768104
div 180 x 180	0.299018	0.264942	0.405655
div 270 x 270	0.277184	0.1736	0.223076
div 360x360	0.289037	0.100508	0.157633

Table 1. Standard deviations of vorticity and divergence for four different sizes of the box used to measure vorticity and divergence. Both signal and noise have units of 10^{-4} s^{-1} . The correlation coefficient η is dimensionless.

Figure Legends

Fig. 1. Infrared image of the northern hemisphere as seen by JIRAM². The circle at 80° latitude is about 12,000 km from the pole. The lines of constant longitude are 15° apart. The radiances have been corrected for nadir viewing, with bright yellow signifying greater radiance and dark red signifying lesser radiance. The average brightness temperature is in the range 215-220 K. The figures shown in Fig. 2 of this paper cover the central cyclone and the two cyclones at 135° and 315° east longitude, respectively. The two dark features at 120-150° east, 86° north, whose filaments spiral toward their centers in a clockwise direction, are anticyclones.

Fig. 2. Vorticity (top row) and divergence (bottom row) derived from two independent determinations of the wind - left and right - termed n0103 and n0204. Each determination is derived from two sets of 12 adjacent images. The sets are ordered in time. n0103 is derived from the first and third sets, which are 16 minutes apart and overlap in time with the second and fourth sets, which are also 16 minutes apart. Thus, the interval between n0103 and n0204 is 8 minutes. The gaps between the 12 images are visible as faint vertical lines, which are especially prominent in n0204. The amorphous white spaces are regions – masks - where the image entropy⁴³ was below a threshold needed for reliable cloud-tracked wind analysis. They cover 1.8% and 2.1% of the pixels in the left and right determinations, respectively. The entropy histogram, with the dividing line below which the masks were applied, and the images with and without masks, are given in Supplementary Figures S5, S6 and S7. The long dimension of the four large rectangles in Fig. 2 is ~20,000 km, and the smallest resolved features are ~100 km in diameter. The central cyclone and the two cyclones at lower left and upper right almost disappear in the divergence maps, but the cyclones at upper left and lower right do not, mainly because the image entropy is low and the velocity error is high. The latter two cyclones are at 90° and 270°E in Fig. 1. The resolution of the original images ranges from 22 to 14 km/pixel. The resolution of the derived velocity field is 45 km. We use Gauss' Law and Stokes' Theorem to calculate divergence and vorticity, integrating around a square box that is 180 km on a side. The color bars are in units of 10⁻⁴ s⁻¹. The step sizes for the colors are 0.25 and 0.15 x 10⁻⁴ s⁻¹ for vorticity and divergence, respectively.

Fig. 3. Covariances of the vorticity and divergence fields of Fig. 2. Each point on the graph comes from a unique point on the planet. Units along the axes are 10^{-4} s^{-1} . In the upper left and upper right panels the points are plotted according to their values from two independent determinations of the wind field, n0204 on the y-axis and n0103 on the x-axis. Vorticity is in the upper left panel and divergence is in the upper right. As explained in the caption to Fig. 2, the time interval between the two determinations is 8 minutes. At 80 m/s, which is about the maximum speed of the clouds, a feature moves 38 km. This is considerably less than the 180 km box size used to measure vorticity and divergence. Thus to a good approximation the two determinations show the same cloud features at the same time. The small motion is still visible, however, when it takes place on a large scale and includes many small-scale, high-contrast features, as with the slight rotation of the features visible in Fig. 2 and Supplementary Figures S1-S4.

Fig. 4. Mean azimuthal velocity and vorticity (top row) and mean gravitational potential and potential vorticity (bottom row). The fitted curve for velocity (orange) is almost covered by the data points (black). The peak relative vorticity ζ at the pole is $2.9 \times 10^{-4} \text{ s}^{-1}$, and is almost equal to the polar planetary vorticity f , which is $3.5 \times 10^{-4} \text{ s}^{-1}$. Potential vorticity is scaled by $2.843 \times 10^{-9} \text{ m}^2 \text{ s}$, which is f at the pole divided by ϕ assuming it is equal to $L_d^2 f^2 = 124 \times 10^3 \text{ m}^2 \text{ s}^2$, corresponding to $L_d = 1000 \text{ km}$. With this assumption, the scaled PV at the pole is 4.18. The variations of PV are mostly due to variations of ζ and ϕ and less due to variations of f , which is the red line sloping gently down to the right. The other two curves (blue and green) were chosen to bracket the data and were used as initial conditions in a model study²¹ that is described in the discussion section. The data points are given in Source Data Table SD3.

Data Availability

JIRAM data are available at the Planetary Data System (PDS) online (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/jiram). The filenames of the images are in Supplementary Table S1. Source data used in this report include calibrated, geometrically controlled, radiance data mapped onto an orthographic projection centered on the north pole and velocity vectors derived from the radiance data. These data products, about 150 MB in volume, are Source Data Tables SD1, SD2, and SD3.

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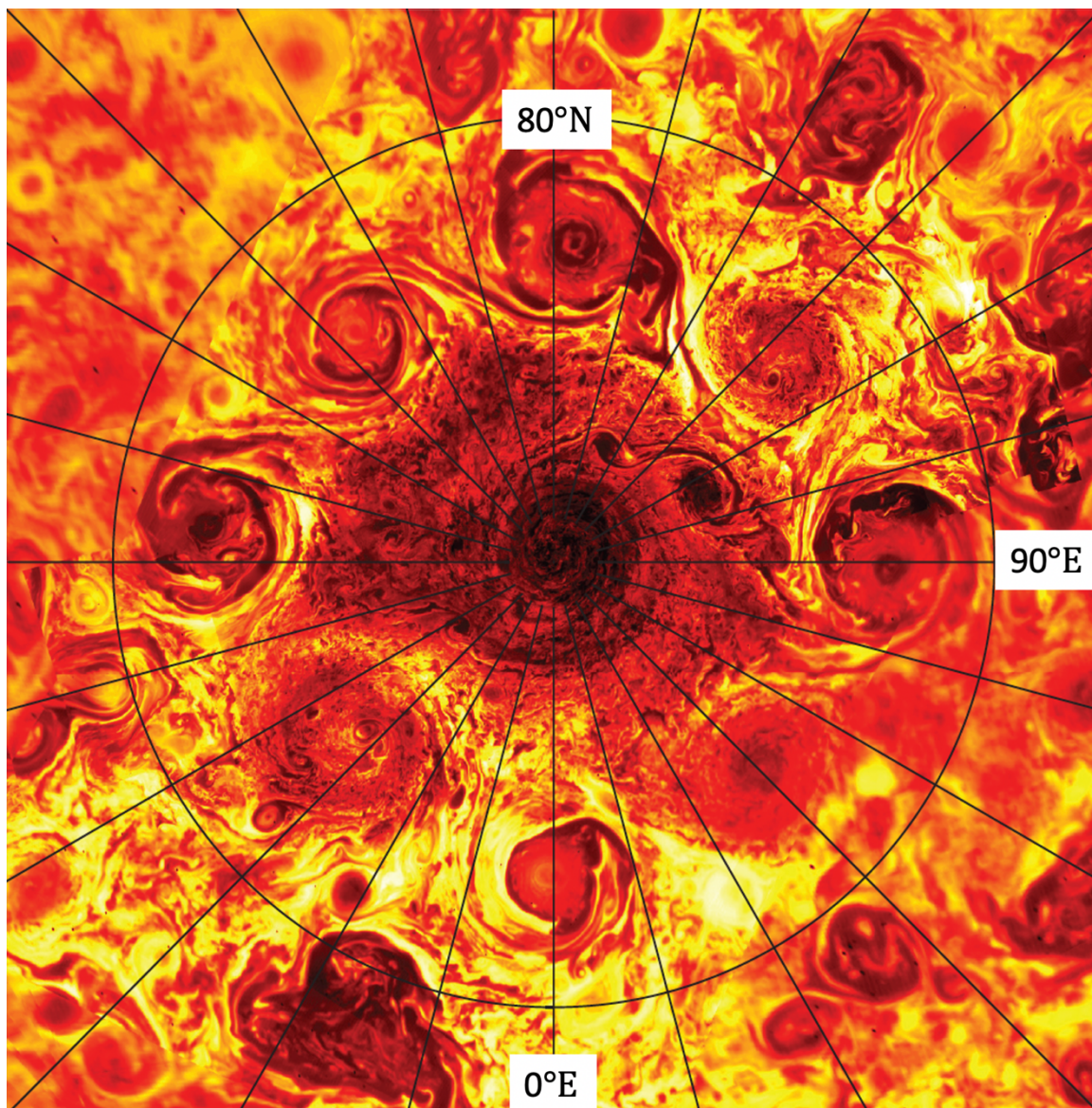


Figure 1

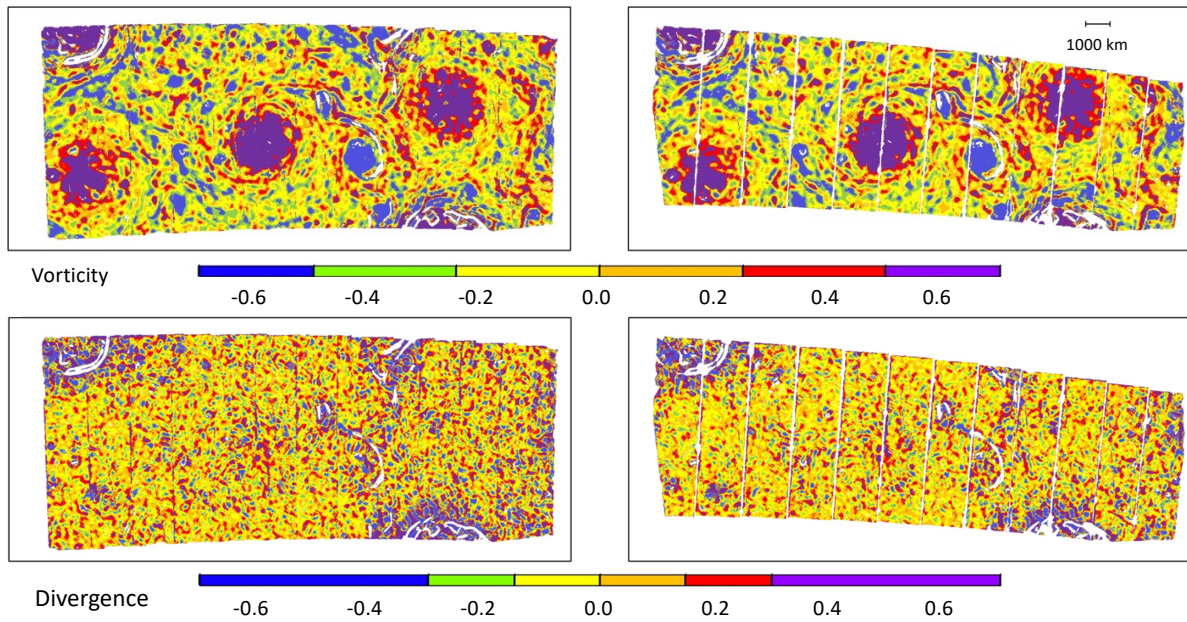


Figure 2

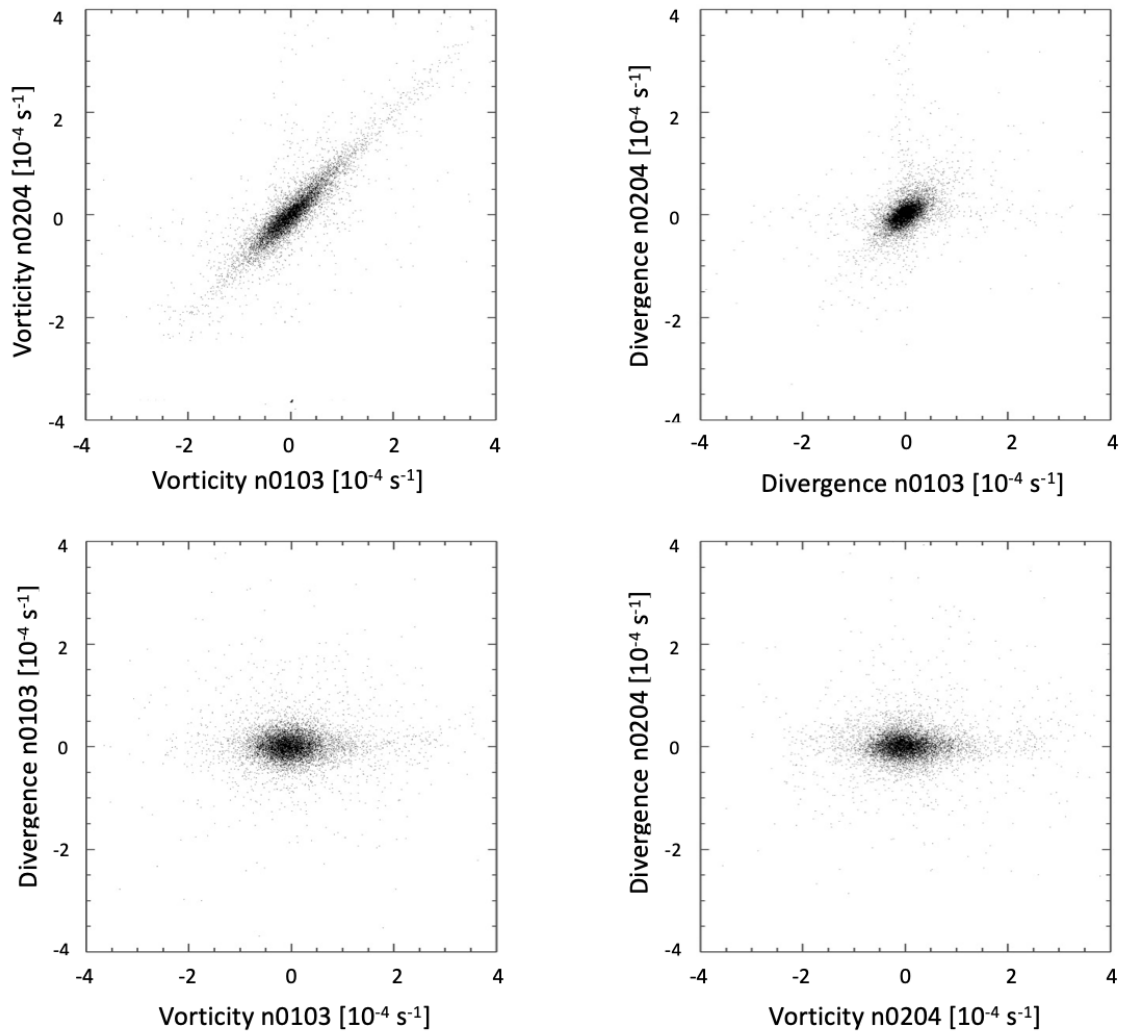


Figure 3

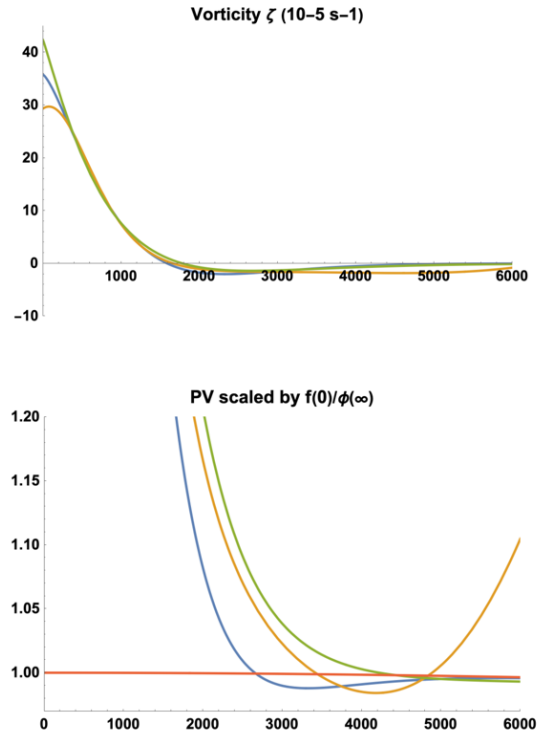
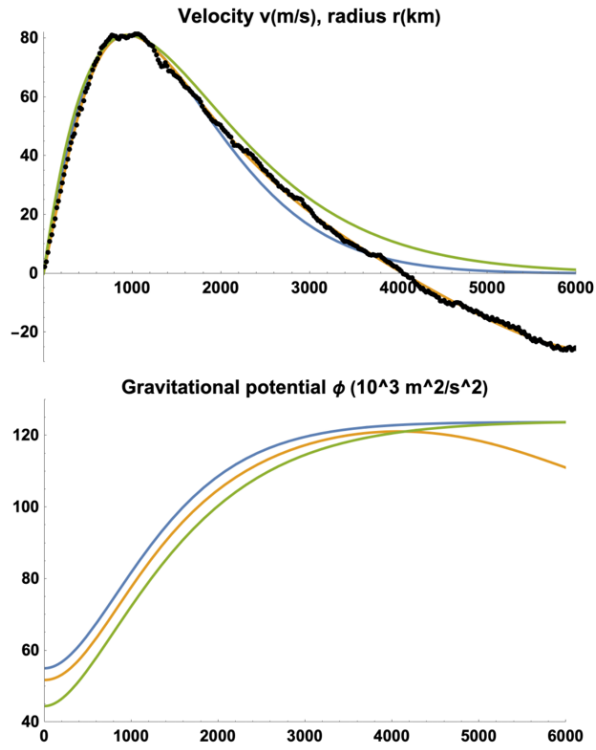


Figure 4