

# 1 **Jupiter's atmospheric jet-streams extend thousands of** 2 **kilometers deep**

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18 **The depth to which Jupiter's observed east-west jet-streams extend has been a long-standing**  
19 **question<sup>1,2</sup>. Resolving this puzzle has been a primary goal of NASA's Juno mission to Jupiter<sup>3,4</sup>,**  
20 **which has been in orbit around the gas giant since July 2016. Juno's gravitational measure-**

21 **ments have revealed that Jupiter’s gravitational field is north-south asymmetric<sup>5</sup>, which is**  
22 **a signature of atmospheric and interior flows within the planet<sup>6</sup>. Here we report that the**  
23 **measured gravitational harmonics  $J_3$ ,  $J_5$ ,  $J_7$  and  $J_9$  indicate that the observed jet-streams,**  
24 **as they appear at the cloud-level, extend down to depths of thousands of kilometers beneath**  
25 **the cloud-level, likely to the region of magnetic dissipation at a depth of about 3000 km<sup>7,8</sup>.**  
26 **Inverting the measured gravity values into a wind field<sup>9</sup>, we provide the most likely verti-**  
27 **cal profile of the deep atmospheric and interior flow, and the latitudinal dependence of its**  
28 **depth. Furthermore, the even gravity harmonics  $J_8$  and  $J_{10}$  resulting from this flow profile**  
29 **match the measurement as well, when taking into account the contribution of the interior**  
30 **structure<sup>10</sup>. These results indicate that the mass of the dynamical atmosphere is about one**  
31 **percent of Jupiter’s total mass.**

32       The Juno gravity measurements to date have improved the accuracy of the known gravity  
33 harmonics  $J_2$ ,  $J_4$ ,  $J_6$  and  $J_8$  by more than two orders of magnitude<sup>5,12</sup>. These low-degree even  
34 gravity harmonics are mostly affected by Jupiter’s interior density structure and its shape<sup>13</sup>, and  
35 therefore, although the signal from these harmonics may contain a contribution from the flow  
36 ( $\Delta J_n$ )<sup>14</sup>, it is difficult to use these harmonics to directly infer information about the flows. The  
37 gravity measurements also revealed north-south asymmetries in the gravity field of Jupiter<sup>5</sup>, result-  
38 ing in considerable values of the odd gravity harmonics  $J_3$ ,  $J_5$ ,  $J_7$  and  $J_9$  (see Table 1). Since a  
39 gas planet rotating as a solid-body has no asymmetry between north and south, any non-zero value  
40 of the odd  $J_n$  must come from dynamics<sup>6</sup>. As the observed cloud-level flow is not hemispherically  
41 symmetric (Fig. 1), if enough mass is involved in the asymmetric component of the flow, this will

42 manifest large odd  $J_n$ . At present, the gravity harmonics beyond  $J_{10}$  are still beneath the level of  
 43 the measurement uncertainty<sup>5</sup>, and because the low-degree even  $J_n$  are dominated by solid-body  
 44 rotation, the only current measurements that can be uniquely related to the dynamics are the low-  
 45 degree odd harmonics  $J_3$  to  $J_9$ . Therefore, in the current study, we use only those to infer the depth  
 46 of the cloud-level winds.

47 Since Jupiter is rotating at a short period of 9.92 hours, the flow within the planet to lead-  
 48 ing order is in geostrophic balance, meaning the momentum budget is dominated by the balance  
 49 between the Coriolis force and the horizontal pressure gradients. As a consequence, the flow to  
 50 leading order is in thermal wind balance, namely,

$$2\Omega \cdot \nabla (\rho_s \mathbf{u}) = \nabla \rho' \times \mathbf{g}, \quad (1)$$

51 where  $\Omega$  is the rotation rate of the planet,  $\mathbf{u}$  is the velocity field,  $\rho_s$  and  $\rho'$  are the static and dy-  
 52 namic components of density, respectively, and  $\mathbf{g}$  is the gravity obtained by integrating  $\rho_s$  (see  
 53 Methods)<sup>15</sup>. Non-spherical effects can play a role in this balance (e.g., the deviation of  $\mathbf{g}$  from  
 54 radial symmetry)<sup>16,17</sup>; however, it has been shown that to leading order Eq. (1) captures well the  
 55 dynamical balance<sup>17,18</sup> (Fig. ED1). As the gravity harmonics induced by the flow are directly re-  
 56 lated to  $\rho'$ , this enables to relate the flow field and the gravity spectrum. Thus, given the measured  
 57 gravitational field, inversion of Eq. (1) allows to infer the flow profile that best matches the mea-  
 58 surement. For this inversion we use an optimization based on the adjoint method<sup>9</sup> (see Methods).

59 The relation between the odd gravity harmonics and the flow is shown in Fig. 2 for a simple  
 60 model<sup>6</sup> where the depth of the cloud-level wind is parametrized with a single decay parameter,

61  $H$ . In this scenario, the interior flow is an extension of the cloud-level flow, along the direction  
62 of the spin axis due to angular momentum constraints (see below)<sup>15,19</sup>, but decays exponentially  
63 in radius with  $H$  being the e-folding decay depth<sup>6,20</sup>. The Juno measured values (Fig. 2, dashed),  
64 show that for all four harmonics, independently, the theoretical values capture the correct sign of  
65 the measured harmonics and indicate that the e-folding decay depth of the flow is between 1000  
66 and 3000 km (Fig. 2, gray shading). Inverting the gravity field<sup>9</sup>, taking into consideration the  
67 uncertainties of each of the measured harmonics and their cross-correlated uncertainties (the error  
68 covariance matrix, see Methods), gives an e-folding decay depth of  $\sim 1500$  km. Note however  
69 that the measured value of  $J_5$  deviates by about a factor of two from the corresponding theoretical  
70 value of a single parameter deep wind profile, suggesting that a more elaborate vertical flow profile  
71 than the simple exponential decay is needed in order to match the data.

72         Given that the measurements provide four non-zero odd gravity harmonics, indeed a more  
73 complex optimization of the vertical and meridional flow profile is feasible. Motivated by the  
74 Galileo probe measurement of a relatively constant wind profile between 4 and 22 bars<sup>21</sup>, and  
75 magnetohydrodynamic theory suggesting that Ohmic dissipation will cause a more abrupt decay  
76 of the flow at depth<sup>7,8,22,23</sup> we add in addition to the exponential decay function used in the first  
77 estimation (Fig. 2), a vertical decay profile expressed as a hyperbolic tangent function and a free  
78 parameter,  $\alpha$ , representing the ratio between the two functions. This allows for a much wider range  
79 of vertical decay profiles, with three free parameters defining the vertical profile of the flow: the  
80 depth  $H$  representing the inflection point of the  $\tanh$  function,  $\Delta H$  representing the decay width  
81 of the  $\tanh$  function and the ratio  $\alpha$  between the  $\tanh$  and an exponential decay with the same

82 decay depth  $H$ . Using these three parameters as control parameters in the inverse adjoint model,  
83 the optimization process (Fig. 3) minimizes a cost-function taking into account the uncertain-  
84 ties in the gravity measurements, including the error covariance between the different harmonics  
85 (Methods)<sup>9,24</sup>.

86 Beginning with an assumed vertical decay profile as an initial condition (Fig. 3a, dashed line,  
87 and black squares in Fig. 3b,c), the optimization iteratively minimizes the cost-function reaching  
88 a unique global minimum in the three dimensional parameter space of  $H$ ,  $\Delta H$  and  $\alpha$  (red dot,  
89 Fig. 3b,c). The best optimized solution, defining a particular vertical profile of the zonal flow (red  
90 line, Fig. 3a), is achieved with  $H = 1803 \pm 351$  km,  $\Delta H = 1570 \pm 422$  km and  $\alpha = 0.92 \pm 0.26$ ,  
91 where the error is calculated by the optimization process (see Methods), indicating a very deep  
92 flow profile containing a significant mass. Note that the minimum of the cost-function for  $\Delta H$   
93 is rather flat towards lower  $\Delta H$  (Fig. 3b), indicating that a flow profile with a much more abrupt  
94 decay at depth is compatible with the measured  $J_n$ . Integrating the density profile  $\rho_s$  down to  
95 where the flow decreases significantly ( $\sim 3000$  km) reveals that this region contains about 1%  
96 of Jupiter's mass (the mass dependence on depth is shown in Fig. ED2). This large mass of the  
97 dynamical atmosphere (the region that is differentially rotating) is consistent with the observed  
98 jets' persistence over the past several decades<sup>2</sup>. In a companion paper we show, based on the even  
99 harmonics, that beneath this dynamical atmosphere, in Jupiter's deep interior, there is likely very  
100 little flow<sup>10</sup>. In terms of angular momentum, the angular momentum of this flow is  $2 \times 10^{-5}$  that  
101 of the solid-body planet.

102 The solution shown in Fig. 3a (red line) implies that the meridional profile of the flow at depth  
 103 is strongly correlated to the cloud-level flow. To test the statistical significance of this solution we  
 104 generate a large set of synthetic latitudinal wind profiles (Fig. ED3), by expanding the observed  
 105 flow up to high degree Legendre polynomials and summing them back up while assigning random  
 106 signs to the expansion coefficients. We find that the solution using the observed cloud-level wind  
 107 profile (Fig. ED4, black) is one of the closest solutions to the measurements (Fig. ED4, red) and  
 108 only a small subset of the random flow profiles (less than 1%) give a lower cost-function value  
 109 (Fig. ED4, green). This shows that it is statistically improbable that the meridional profile of  
 110 the flow changes with depth, or that the solution was found by chance (see further discussion in  
 111 Methods).

112 Considering the angular momentum budget is helpful for developing a mechanistic under-  
 113 standing of these deep dynamics. Modeling studies have suggested<sup>19,22</sup>, that the leading order  
 114 angular momentum balance is  $\mathbf{u} \cdot \nabla M = D - S$ , where  $\mathbf{u}$  is the mass averaged velocity,  $D$  is  
 115 the drag due to the Lorentz force at depth and  $S = \frac{1}{\rho} \nabla \cdot (\overline{\rho \mathbf{u}' M'})$  is the eddy angular momen-  
 116 tum flux divergence, with the bar indicating a zonal and time mean. At the observed cloud-level  
 117 the eastward (westward) jets are correlated with regions of eddy momentum flux convergence (di-  
 118 vergence), i.e., where  $S$  is negative (positive)<sup>22,25</sup>. Below that, where the eddy momentum flux  
 119 convergence is expected to become weak<sup>25</sup>, i.e.,  $\mathbf{u} \cdot \nabla M \approx 0$ , the flow is along angular momen-  
 120 tum surfaces, which on Jupiter are almost entirely parallel to the axis of rotation<sup>15,19,26</sup>. Then,  
 121 in the deep region, where the fluid becomes electrically conducting (mainly due to pressure ion-  
 122 ization) and the Lorentz force may become important (depending on the magnetic field structure)

123 the leading order balance is  $\mathbf{u} \cdot \nabla M = D$  and the circulation closes. Kinematic dynamo models,  
124 calculating the magnetic drag at depth based on the radially varying electric conductivity inside  
125 Jupiter, find that the depth where the Lorentz drag ( $D$ ) becomes important is  $\sim 3000 \text{ km}^{7,8}$ . Thus,  
126 the theoretical magnetic field considerations and the gravity measurements, which are completely  
127 independent, give very consistent results.

128 Three-dimensional hydrodynamic models of Jupiter, driven by shallow atmospheric turbulence<sup>22,27</sup>  
129 or deep internal convection<sup>15</sup>, have found that the low latitudes are often more barotropic than high  
130 latitudes. Thus, an additional complexity that can be added to the optimization is allowing the de-  
131 cay depth ( $H$ ) to vary with latitude. In order to limit the number of optimized parameters the decay  
132 depth is expanded in Legendre polynomials to second order, increasing the number of optimized  
133 parameters to four (see Methods). Similar to the case of a latitudinally independent vertical profile  
134 (Fig. 3), in this case the optimized vertical decay profile is rather barotropic at lower depths and ex-  
135 tends very deep (Fig. 4a). The optimization uncertainty is shown graphically by the blue shading,  
136 with the values for the profile at the equator are given in the caption. At higher latitudes, the verti-  
137 cal decay occurs at shallower depths, and the associated uncertainty grows to  $\sim 500 \text{ km}$  (Fig. 4b).  
138 The values of  $J_n$  corresponding to the solutions of Figs. 3 and 4 appear in Table 1. Note that  
139 with more free parameters than used in these optimizations, closer matches to the measurements  
140 can be reached. However, the power of these solutions is that they are based on relatively simple  
141 extensions of the cloud-level flow, giving results remarkably close to all four independent gravity  
142 measurements, and regardless of the exact vertical profile indicate that the observed cloud-level  
143 flows extend to depths of thousands of kilometers.

144 The flow profile determined by the odd harmonics has also a signature in the even harmonics.  
145 Due to the uncertainty in the bulk interior density structure of Jupiter<sup>10,28</sup>, there is a wide range  
146 of solutions for the static gravity harmonics ( $J_n^s$ ) for the lowest harmonics<sup>14,28</sup>, which does not  
147 allow testing uniquely whether the  $\Delta J_n$  from the even harmonics matches the measured values via  
148  $\Delta J_n = J_n - J_n^s$ . However, for  $J_8$  and  $J_{10}$  the interior models are very constraining<sup>10</sup>, giving values  
149 between  $-245.7 \times 10^{-8}$  and  $-246.3 \times 10^{-8}$  for  $J_8^s$ , and between  $20.1 \times 10^{-8}$  and  $20.4 \times 10^{-8}$  for  $J_{10}^s$   
150 (for interior models that match also  $J_4$  and  $J_6$ ). The measured Juno values are  $J_8 = -242.6 \pm 0.8 \times$   
151  $10^{-8}$  and  $J_{10} = 17.2 \pm 2.3 \times 10^{-8}$ , meaning that a positive (negative) correction by the dynamics  
152 is needed in order to match the measurements for  $J_8$  ( $J_{10}$ ). The values corresponding to the flow  
153 profiles presented in Figs. 3 and 4 (Table ED1) are indeed such that for both cases, and for both  
154  $J_8$  and  $J_{10}$ , the dynamical corrections can reconcile the differences between the measurements and  
155 the internal models, further confirming that the inferred flow profile presented here matches the  
156 measurements from Juno. In a companion paper it is shown that using the range of current interior  
157 models gives further constraints on possible deeper interior flow<sup>10</sup>.

158 Juno's gravity measurements are consistent with Juno's microwave radiometer measurements  
159 indicating a north-south asymmetry in the sub cloud-level atmospheric composition, and a di-  
160 rect signature of the main equatorial belt to the maximum depth of the microwave sensitivity at  
161  $\sim 1000$  bars<sup>12,29</sup>. With more Juno orbits the microwave measurements<sup>4,30</sup> will obtain greater and  
162 improved thermal mapping of the deep atmosphere, which will better constrain the water and am-  
163 monia abundances as well as the atmospheric flows at those levels. As the Juno mission completes  
164 its global mapping of Jupiter, the combination of the gravity, magnetic and microwave data may



165 provide further insights into the coupling between Jupiter’s deep interior and atmospheric flows.

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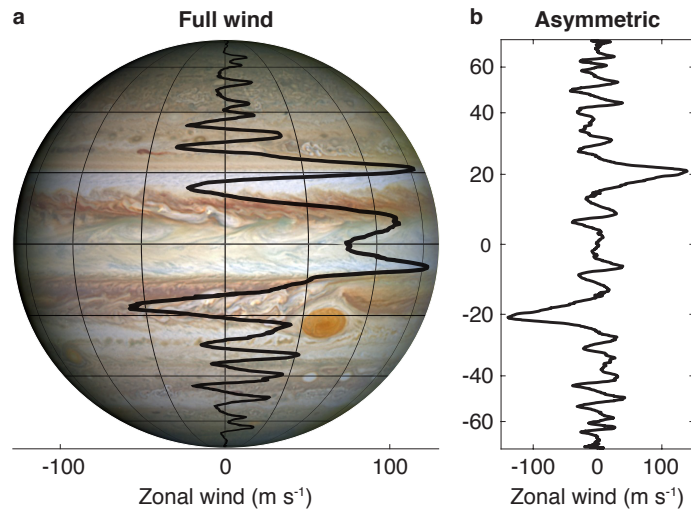


Figure 1: **Jupiter's asymmetric zonal velocity field.** **a.** An image of Jupiter taken by the Hubble wide field camera in 2014, with the cloud-level zonal flows (thick black line) as function of latitude as measured during Juno's 3rd perijove of Jupiter on December 11th 2016<sup>11</sup>. Grid latitudes are as in panel (b) and the longitudinal spread is 45°. Zonal flow scale is the same as the longitudinal grid on the sphere. **b.** The asymmetric component of the flow is taken as the difference between the northern and southern hemisphere cloud-level flows.

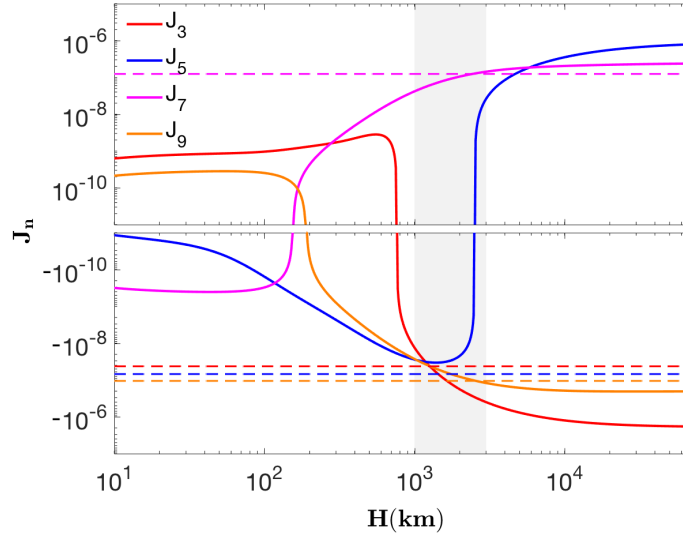


Figure 2: **The odd gravity harmonics as function of a single e-folding decay depth parameter  $H$ .** Theoretical predicted values<sup>6</sup> (solid) and the Juno measured values<sup>5</sup> (dashed, corresponding to the values in Table 1) for  $J_3$  (red),  $J_5$  (blue),  $J_7$  (magenta) and  $J_9$  (orange) are shown as function of  $H$ . All four gravity harmonic measurements, independently, indicate the e-folding depth of the flow is 1000-3000 km (gray shading). All four odd harmonics are small if the flows are shallow, and become large for deeper flows that contain more mass. The change in sign at different decay depths depends on the way the flow pattern projects onto the different Legendre polynomials.

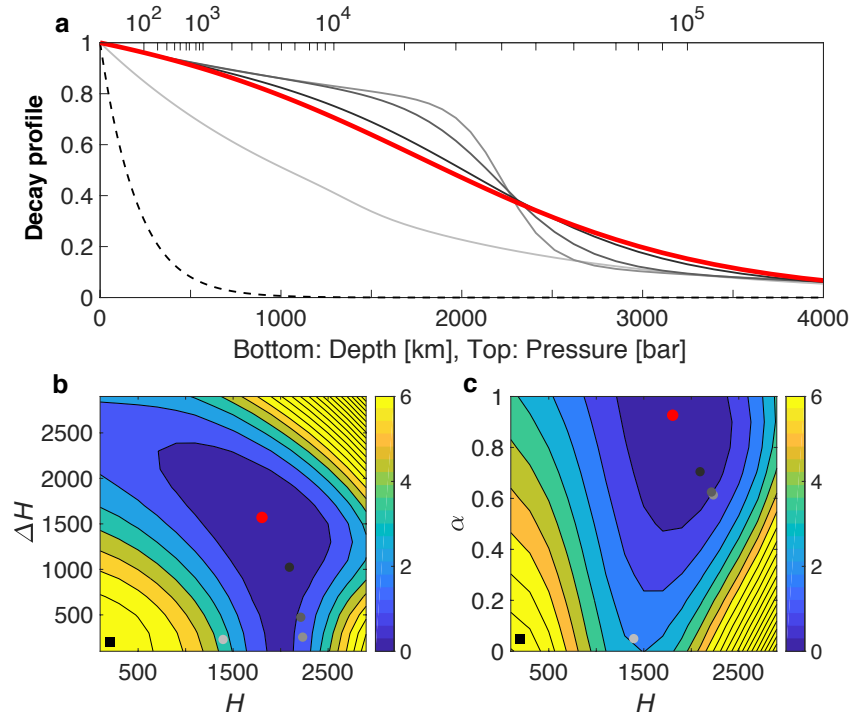


Figure 3: **Jupiter's optimized vertical wind profile.** **a.** The vertical profile of the flow from the optimization process, beginning with an initial profile (dashed), which evolves along the optimization process (from light to dark shades of gray) leading to the best optimized vertical profile (red), with the parameters:  $H = 1803 \pm 351$  km,  $\Delta H = 1570 \pm 422$  km and  $\alpha = 0.92 \pm 0.26$  (Eq. M13 in Methods). Abscissa shows both the depth (bottom) and pressure (top) beneath the 1 bar level. **b.** The cost-function in the plane of  $H$  and  $\Delta H$  showing a robust minimum at  $H = 1803$  km and  $\Delta H = 1570$  km (red dot). **c.** The cost-function in the plane of  $H$  and  $\alpha$  showing a minimum at  $H = 1803$  km and  $\alpha = 0.92$  (red dot). In both panels b and c the gray shaded dots correspond to the gray shaded curves in panel a. Cost-function values in the color-bar are divided by 1000 (see calculation in Methods). A statistical significance test for the latitudinal dependence of the flow profile appears in Figs. ED4 and ED5 (Methods).



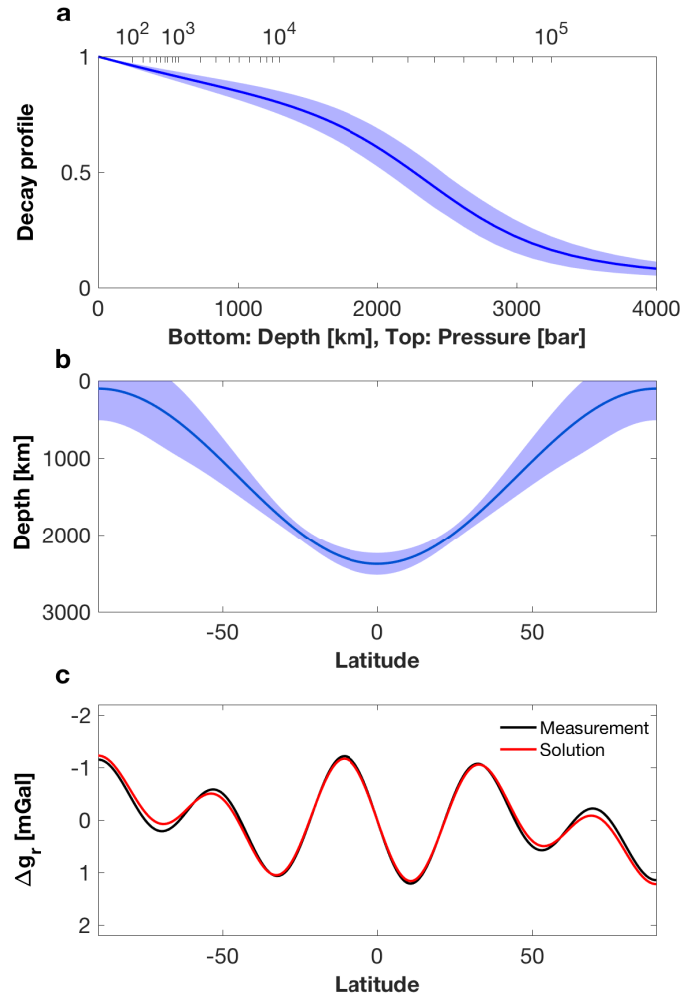


Figure 4: **Jupiter's optimized vertical wind profile when allowing for its latitudinal variation.**

**a.** The vertical profile of the flow at the equator from the optimization process (blue line) and its uncertainty (blue shading). Best optimized values at the equator are  $H = 2379 \pm 142$ ,  $\Delta H = 819 \pm 437$  and  $\alpha = 0.62 \pm 0.09$ . Abscissa shows both the depth (bottom) and pressure (top) beneath the 1 bar level. **b.** The variation of the inflection point (as shown in panel a) with latitude (blue line) and its uncertainty (blue shading). Details of the latitudinal dependence of  $H$  and its functional form are given in Methods (Eq. M13). **c.** The Juno measurement of the asymmetric gravity field (for  $J_3 - J_9$ ) as function of latitude and the corresponding values from the best-fit solution (panels a and b), showing a good match between the measurement and the optimized solution (see calculation in Methods).

$\times 10^{-8}$	Measured	Model without latitudinal variation	Model with latitudinal variation
$J_3$	$-4.24 \pm 0.97$	$-5.71 \pm 1.67$	$-5.96 \pm 2.33$
$J_5$	$-6.89 \pm 0.81$	$-7.73 \pm 0.41$	$-8.00 \pm 0.43$
$J_7$	$12.39 \pm 1.68$	$12.77 \pm 0.54$	$12.04 \pm 0.70$
$J_9$	$-10.58 \pm 4.35$	$-8.84 \pm 0.42$	$-9.71 \pm 0.72$

Table 1: **The Juno measured and model odd gravity harmonics.** Model results are shown for both optimizations with and without variation of flow depth with latitude. The uncertainty is the  $3\sigma$  uncertainty values. The model uncertainty is calculated by the optimization procedure (Methods). For the middle (right) column the  $J_n$  values correspond to the parameter values given in the caption of Fig. 3 (Fig. 4).

# 1 Methods

2 **Calculation of the dynamical gravity harmonics.** The gravity harmonics ( $J_n$ ) are defined as a weighted  
 3 integral over the interior density distribution  $J_n = -(Ma^n)^{-1} \int P_n \rho r^n d^3\mathbf{r}$ , where  $M$  is the planetary mass,  $a$   
 4 is the equatorial radius,  $P_n$  is the  $n$ -th Legendre polynomial,  $\rho$  is the local density and  $r$  is the local radius<sup>31</sup>.  
 5 On planets with internal dynamics, the density is perturbed by the flow so that the total density in  $J_n$  can be  
 6 written as  $\rho = \rho_s + \rho'$ , where the density  $\rho_s$  is the hydrostatic density resulting from the background rotation  
 7 and internal density distribution<sup>32,33,34,28,35</sup>, and  $\rho'$  are the density fluctuations arising from atmospheric and  
 8 internal dynamics<sup>20</sup>. The gravity harmonics can be similarly decomposed into two parts  $J_n = J_n^s + \Delta J_n$ , where  
 9 the static component ( $J_n^s$ ) is due to the planet's internal density distribution and shape<sup>13,36</sup>, and the dynamical  
 10 component ( $\Delta J_n$ ) is due to the density deviations related to the flow<sup>20</sup>.

11 In order to develop the relation between the flow on Jupiter and the gravity field measured by Juno, we  
 12 consider the full momentum balance on a rotating planet

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} + \boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \mathbf{r} = -\frac{1}{\rho} \nabla p + \nabla \Phi, \quad (\text{M1})$$

13 where  $\mathbf{u}$  is the 3D flow vector,  $\boldsymbol{\Omega}$  is the planetary rotation rate ( $1.76 \times 10^{-4} \text{ s}^{-1}$ ),  $\rho$  is density,  $p$  is pressure and  
 14  $\Phi$  is the body force potential set by gravity so that  $\nabla \Phi = -\mathbf{g}$ <sup>37</sup>. The first term on the left hand side is the local  
 15 acceleration of the flow, the second is the Eulerian advection, the third is the Coriolis acceleration, and the  
 16 fourth is the centrifugal acceleration. On the right hand side appear the pressure gradient and the body force.  
 17 Frictional forces are neglected. For Jupiter parameters, and large scale motion, the Rossby number is small  
 18  $Ro \equiv U/\Omega L \approx 0.05$ , where  $U$  is the typical value of the velocity ( $O(100 \text{ m s}^{-1})$ ), and  $L$  is the typical jet scale  
 19 ( $O(10^4 \text{ km})$ ). The small Rossby number implies that the first two terms are negligible compared to the Coriolis  
 20 term, so that

$$2\boldsymbol{\Omega} \times (\rho \mathbf{u}) = -\nabla p - \rho \mathbf{g} - \rho \boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \mathbf{r}. \quad (\text{M2})$$

21 Since for Jupiter parameters the ratio between the two latter terms on the right hand side of Eq. (M2), is  
 22  $\frac{a\Omega^2}{g} \approx 0.1$ , and not two orders of magnitude smaller as it is for Earth parameters, we do not a priori make the  
 23 traditional approximation merging the centrifugal force with the gravity term<sup>38</sup>, but solve for the full system,  
 24 allowing the density, pressure and gravity to be functions of radius ( $r$ ) and latitude ( $\theta$ ). We separate the

25 solution to a static solution in which  $\mathbf{u} = 0$ , and  $\rho_s(r, \theta)$ ,  $p_s(r, \theta)$ , and  $\mathbf{g}_s(r, \theta)$  are solutions to the leading  
 26 order equation

$$0 = -\nabla p_s - \rho_s \mathbf{g}_s - \rho_s \boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \mathbf{r}, \quad (\text{M3})$$

27 and a deviation due to the dynamics  $\rho'(r, \theta)$ ,  $p'(r, \theta)$ , and  $\mathbf{g}'(r, \theta)$ , where  $\rho = \rho_s + \rho'$ ,  $p = p_s + p'$  and  
 28  $\mathbf{g} = \mathbf{g}_s + \mathbf{g}'$ . For the static part of the solution we use solutions from internal models<sup>39,28</sup>. Subtracting Eq. (M3)  
 29 from Eq. (M2) gives the leading order dynamical equation

$$2\boldsymbol{\Omega} \times (\rho_s \mathbf{u}) = -\nabla p' - \rho_s \mathbf{g}' - \rho' \mathbf{g}_s - \rho' \boldsymbol{\Omega} \times \boldsymbol{\Omega} \times \mathbf{r}. \quad (\text{M4})$$

30 Taking the curl of Eq. M4, eliminating the dependence on pressure, yields a single equation in the az-  
 31 imuthal direction

$$-2\Omega r \partial_z (\rho_s u) = -r g_s^{(\theta)} \frac{\partial \rho'}{\partial r} - g_s^{(r)} \frac{\partial \rho'}{\partial \theta} + r \frac{\partial \rho_s}{\partial r} g'^{(\theta)} - g'^{(r)} \frac{\partial \rho_s}{\partial \theta} - \Omega^2 r \left[ \frac{\partial \rho'}{\partial \theta} \cos^2 \theta + \frac{\partial \rho'}{\partial r} r \cos \theta \sin \theta \right] \quad (\text{M5})$$

32 where  $u$  is the velocity component in the azimuthal direction, and the notation  $\partial_z \equiv \cos \theta \frac{1}{r} \frac{\partial}{\partial \theta} + \sin \theta \frac{\partial}{\partial r}$  denotes  
 33 the derivative along the direction of the axis of rotation. Note that this is an integro-differential equation since  
 34 both the gravity  $\mathbf{g}_s$  and  $\mathbf{g}'$ , are calculated by integrating  $\rho_s$  and  $\rho'$ , respectively. Although this equation can  
 35 be solved numerically<sup>18</sup>, it is very difficult to solve at the required resolution and the approximation below is  
 36 sufficient for relating the flow field and the gravity harmonics<sup>18</sup>.

37 A typical solution to Eq. M5, corresponding to the flow field in Fig. 3 in the main text, is given in Fig. ED1.  
 38 It shows that the leading order balance is between the left hand side term and the second term on the right hand  
 39 side of Eq. M5. All other terms are at least an order of magnitude smaller, and have a very small contribution  
 40 to the gravitational harmonics<sup>18</sup>. Thus, taking  $g = g_s(r)$  in Eq. M4 and neglecting the centrifugal term gives  
 41 the leading order solution. Taking the curl of Eq. M4 gives then the leading order equation

$$2\boldsymbol{\Omega} \cdot \nabla (\rho_s \mathbf{u}) = \nabla \rho' \times \mathbf{g}, \quad (\text{M6})$$

42 which is Eq. 1 in the main text, and is a form of the thermal wind equation<sup>15,20</sup>. Note that if a higher correction  
 43 is desired, all terms in Eq. M5 must be maintained since the smaller terms in Eq. M5 partially cancel each  
 44 other (Fig. ED1). Approximations not maintaining all these terms would be invalid<sup>16</sup>.

45 The zonal component of Eq. M6 is then

$$2\Omega r \partial_z (\rho_s u) = g_s^{(r)} \frac{\partial \rho'}{\partial \theta}, \quad (\text{M7})$$

46 which can be integrated to find a solution for the dynamical part of the density given by

$$\rho'(r, \theta) = \frac{2\Omega r}{g_s} \int^{\theta} \partial_z (\rho_s(r) u(r, \theta')) d\theta' + \rho'_0(r), \quad (\text{M8})$$

47 where  $\rho'_0(r)$  is an unknown integration function that depends only on radius. Although the density  $\rho'$  can not  
48 be determined uniquely due to the unknown  $\rho'_0(r)$ , the gravity harmonics due to dynamics

$$\Delta J_n = -\frac{2\pi}{Ma^n} \int_{-\pi/2}^{\pi/2} \cos \theta d\theta \int_0^a r^{n+2} P_n(\sin \theta) \rho'(r, \theta) dr, \quad (\text{M9})$$

49 can be determined uniquely since

$$\int_{-\pi/2}^{\pi/2} \cos \theta d\theta \int_0^a r^{n+2} P_n(\sin \theta) \rho'_0(r) dr = 0. \quad (\text{M10})$$

50 To avoid integrating over discontinuities at the equator the integration is performed from the equator poleward  
51 in both hemispheres separately<sup>40</sup>. Therefore, given any flow profile, the anomalous density gradient can  
52 be determined to leading order (Eq. M8) and the resulting dynamical gravity harmonics can be calculated  
53 (Eq. M9). Note that the sphericity assumption leaves the choice of using the equatorial radius or the mean  
54 radius. For consistency with the standard normalization<sup>41,5</sup> of  $J_n$  we use the equatorial radius, but repeating  
55 the calculation with the mean radius gives results within one percent of those presented here.

56  
57 **Calculation of the gravity anomaly.** Equivalent to the gravity harmonics is the physical gravity anomaly  
58 (Fig. 4c), which emphasizes the nature of the solution as function of latitude<sup>20</sup>. The gravity anomaly in the  
59 radial direction on the surface of a planet that results from the asymmetric flow is given by

$$\Delta g_r(\theta) = -\frac{GM}{a^2} \sum_n (n+1) \Delta J_n P_n(\sin \theta), \quad (\text{M11})$$

60 with  $n = 3, 5, 7, 9$ . In Fig. 4c in the main text we show a comparison between the measured<sup>5</sup> and the calculated

61 gravity anomalies. The better match at low latitudes is a result of the measurements having smaller uncertain-  
 62 ties at low latitudes due to the trajectory of the spacecraft being at periapses near Jupiter’s lower latitudes  
 63 during the initial phase of the Juno mission<sup>12,41</sup>.

64  
 65 **Setup of the flow structure.** Knowledge of the flow field of Jupiter to date comes almost completely  
 66 from cloud tracking<sup>42,11</sup>. We use this flow field as an upper boundary, and extend the flow into the interior by  
 67 optimizing the general functions below. Angular momentum constraints require that the flow into the interior  
 68 follows angular momentum surfaces<sup>26,15,19</sup> (see discussion in the main text), which on Jupiter are nearly  
 69 parallel to the direction of the axis of rotation. Magnetic drag<sup>7</sup> and the compressibility of the fluid<sup>15</sup> require  
 70 that the flow decays at some depth, and therefore we use a flow field with the following general structure

$$u(r, \theta) = u_{\text{cyl}}(s)Q(r), \quad (\text{M12})$$

71 where  $u_{\text{cyl}}(s)$  is the cloud-level azimuthal wind projected downward along the direction of the axis of rotation,  
 72 and  $s = r \cos(\theta)$  is the distance from the axis of rotation.  $Q(r)$  is the radial decay function we optimize, given  
 73 by

$$Q(r) = (1 - \alpha) \exp\left(\frac{r - a}{H(\theta)}\right) + \alpha \left[ \frac{\tanh\left(-\frac{a - H(\theta) - r}{\Delta H}\right) + 1}{\tanh\left(\frac{H(\theta)}{\Delta H}\right) + 1} \right], \quad (\text{M13})$$

74 where  $a$  is the planetary radius,  $\alpha$  is the contribution ratio between an exponential and a normalized hyperbolic  
 75 tangent function and  $\Delta H$  is the width of the hyperbolic tangent. We take a hierarchal approach using this profile  
 76 at several levels of complexity. First, setting  $\alpha = 0$ , the flow is parameterized as a simple exponential decay,  
 77 with  $H$  being independent of latitude, as has been done in many previous studies<sup>20,6,43,44,10</sup>. Then, allowing  
 78  $0 < \alpha < 1$ , the flow is parameterized (Fig. 3 of the main text), with three free parameters,  $\alpha$ ,  $H$  and  $\Delta H$  as  
 79 they appear in Eq. M13, but still keeping  $H$  as a single number. As a final step (Fig. 4 of the main text),  $H$  is  
 80 allowed to vary as a function of latitude and defined as

$$H(\theta) = H_0 + H_2 P_2(\sin \theta), \quad (\text{M14})$$

81 where  $H_0$  is the single latitude independent depth used in the first and second setups, and  $H_2$  is the additional  
 82 parameter used to set the amplitude of the latitude dependent second Legendre polynomial function  $P_2$ . For

83 the optimization shown in Fig. 4 in the main text the values are  $H_0 = 1619 \pm 150$  and  $H_2 = -1519 \pm 459$ . Note  
84 that the hyperbolic function is normalized by its value at the surface of the planet to assure that the surface  
85 flow has the value of the measured cloud-level wind. Expansion of  $H(\theta)$  to higher harmonics is possible, but  
86 additional optimized parameters increase the solution uncertainty (see below), and therefore we restrict this  
87 expansion only to second order.

88  
89 **The Optimization procedure.** The methodology described here is similar to that used in Galanti and  
90 Kaspi (2017)<sup>24</sup>. We find the values of a set of control variables that bring the model solution for the gravity  
91 harmonics to be as close as possible to the measured gravity harmonics. The number of optimized control  
92 variables in the three setups varies between one and four parameters as discussed above. The measure for  
93 the desired proximity of the model solution to the measurements (a cost-function) takes into account our  
94 knowledge regarding the observational errors. The optimization procedure provides an efficient way to reach  
95 the global minimum of the cost-function.

96 Since  $\alpha$  has different units than  $H$  and  $\Delta H$ , the problem is best conditioned when the total control vector  
97 is composed from the different parameters normalized by their typical values. We define the general control  
98 vector as

$$\vec{\mathbf{X}}_{\mathbf{C}} = \{H_0/h_{\text{nor}}, \Delta H/h_{\text{nor}}, \alpha/\alpha_{\text{nor}}, H_2/h_{\text{nor}}\}, \quad (\text{M15})$$

99 where  $h_{\text{nor}} = 10^7$  m and  $\alpha_{\text{nor}} = 1$ . In the optimization procedure, the values of the normalized control variables  
100  $H_0/h_{\text{nor}}$ ,  $\alpha/\alpha_{\text{nor}}$ , and  $\Delta H/h_{\text{nor}}$  are limited to the range of 0 to 1, and the value of  $H_2/h_{\text{nor}}$  between -1 and 1.

101 The cost-function is defined as the weighted difference between the model calculated odd harmonics and  
102 those measured by Juno. Together with an additional penalty term to ensure that initial guess does not affect  
103 the solution, the cost-function is

$$L = (\mathbf{J}^{\text{m}} - \mathbf{J}^{\text{o}})^{\text{T}} \mathbf{W} (\mathbf{J}^{\text{m}} - \mathbf{J}^{\text{o}}) + \varepsilon \mathbf{X}_{\mathbf{C}}^{\text{T}} \mathbf{X}_{\mathbf{C}}, \quad (\text{M16})$$

104 where  $\mathbf{J}^{\text{m}} = \{J_3^{\text{m}}, J_5^{\text{m}}, J_7^{\text{m}}, J_9^{\text{m}}\}$  is the calculated model solution,  $\mathbf{J}^{\text{o}} = \{J_3^{\text{o}}, J_5^{\text{o}}, J_7^{\text{o}}, J_9^{\text{o}}\}$  is the measured one,  
105 and  $\mathbf{W}$  is  $4 \times 4$  weight matrix (Table ED2) calculated as the inverse of the covariance matrix multiplied by  
106 9 (equivalent to 3 times the uncertainties). The diagonal terms give the weight assigned to each harmonic  
107 independently, and the off-diagonal terms give the weights resulting for the cross correlation of the measure-

108 ment errors. The larger the value, the more weight is given in the cost-function. For example, looking at the  
109 diagonal terms, the largest weight is given to  $J_5$  and the smallest one to  $J_9$ . Importantly, the off diagonal terms  
110 have values that are as large as the diagonal terms, i.e., there is a strong correlation between the measurement  
111 errors, and therefore we demand that the discrepancy between the model harmonics and the measured ones  
112 will also be cross correlated in the same manner. The second term in Eq. M16 acts as a penalty term (also  
113 known as 'regularization') whose purpose in this case is to ensure that the optimized solution is not affected  
114 by the initial guess, or any part of the control vector that does not affect the difference between the calculated  
115 and observed gravity harmonics. An extensive discussion of this issue (also known as the null space of the  
116 solution) can be found in previous studies<sup>18,24</sup>. The value of the parameter  $\varepsilon$  is set according to the initial  
117 value of the cost-function, so it affects the solution only when the cost-function is reduced considerably. The  
118 form of the penalty term is set to penalize any non-zero value of the control variable  $\mathbf{X}_C$  since there is no prior  
119 knowledge of the depth of the flow. Given an initial guess for  $\overrightarrow{\mathbf{X}}_C$ , a minimal value of  $L$  is searched for using  
120 the Matlab function 'fmincon' and taking advantage of the cost-function gradient that is calculated with the  
121 adjoint of the dynamical model<sup>9</sup>.

122

123 **Calculating the uncertainties in the solution.** The control variable uncertainties are derived from the  
124 Hessian matrix  $\mathbf{G}$  (second derivative of the cost-function  $L$  with respect to the control vector  $\mathbf{X}_C$ )<sup>9</sup>. For  
125 example, in the third setup of the optimization there are 4 parameters that are optimized, therefore the size of  
126 the Hessian matrix will be  $4 \times 4$ . Inverting the Hessian matrix  $\mathbf{G}$ , we get the solution error covariance matrix  
127  $\mathbf{C}$ . This matrix includes the error covariance associated with combination of each two control variables (off  
128 diagonal terms), and the variance of each one (diagonal terms). Physically, the covariance matrix indicates  
129 to the formal uncertainties in the control variables given the uncertainties of the observations (weights  $\mathbf{W}$  in  
130 the cost-function). The larger the uncertainties in the observations, the smaller are the weights in the cost-  
131 function, and the larger the uncertainties in the control variables. The uncertainties appearing in this study for  
132  $H$ ,  $\Delta H$ , and  $\alpha$ , are the square root of the diagonal terms in the matrix  $\mathbf{C}$ . Note that in all cases analyzed in  
133 this work, the off-diagonal terms in  $\mathbf{C}$  have the same order of magnitude as the diagonal terms, meaning that  
134 uncertainties in the control variable are highly correlated.

135 Using the uncertainties in the control variable, we can calculate the uncertainties in the model solution for  
136  $J_n$ . Since the uncertainties for  $H$ ,  $\Delta H$ , and  $\alpha$  represent the 1<sup>st</sup> standard deviation of the errors, we can statis-  
137 tically estimate the associated error in the  $J_n$  by solving the model with the parameters randomly perturbed



138 around their optimized value (with the perturbations having a normal distribution with the calculated standard  
 139 deviation). In this study we generate 1000 such cases, calculate the  $J_n$  for each case, and then calculate the  
 140 standard deviation for each  $J_n$ . This is the error value given to each gravity harmonic in Table 1 of the main  
 141 text, and Table ED1.

142  
 143 **Statistical significance test for the latitudinal profile.** One of the conclusions of the manuscript is  
 144 that the observed cloud-level meridional wind profile, as observed at the cloud-level, extends deep into the  
 145 interior. This is a strong constraint on the flow, which we investigate its statistical significance here. Since we  
 146 are optimizing a solution with only four measurements, there exists a possibility that the match obtained with  
 147 the gravity measurements is by chance and not because the same meridional profile extends to great depths. In  
 148 order to exclude this possibility we examine whether a match with the gravity measurements could be obtained  
 149 when using a different meridional wind profile than that of the cloud-level flows. To make a sensible test the  
 150 artificial wind profile we examine should have similar characteristics, such as the typical latitudinal width of  
 151 the jets and their amplitude. To accomplish this, the observed cloud-level wind is decomposed into the first  
 152 100 Legendre polynomials

$$U_{\text{surf}}(\theta) = \sum_{i=0}^{99} A_i P_i(\sin \theta), \quad (\text{M17})$$

153 where  $A_i$  are the coefficients of the Legendre polynomials. To create the different artificial wind possibilities,  
 154 the wind is then reconstructed as

$$U_{\text{rand}}^j(\theta) = \sum_{i=0}^{99} S_i^j A_i P_i(\sin \theta), \quad (\text{M18})$$

155 where  $S_i^j$  are a 100 plus or minus signs randomly chosen for each realization  $j$  of the wind. The resulting  
 156 artificial cloud-level wind retains the basic characteristics (width and strength) of the observed zonal jets,  
 157 but their latitudinal locations are now very different. In order to statistically examine our ability to reach  
 158 a solution that gives a good match between the model calculated gravity harmonics and those measured,  
 159 1000 artificial cloud-level wind profiles were generated. Few examples of such randomly generated winds  
 160 are shown in Fig. ED3. Note that while the wind profiles are very different one from the other, the main

161 characteristics of the observed winds are kept. Fig. ED4 shows the resulting  $J_3$ ,  $J_5$ ,  $J_7$  and  $J_9$  for these flow  
162 profiles (blue dots), optimized in the same way that the cloud-level winds are. The results indicate that the  
163 gravity harmonics calculated using the specific cloud-level wind profile (black points with their uncertainty  
164 ellipse), give results closer to the measurements (red points with their uncertainty ellipse) than 99% of the  
165 random profiles, indicating the robustness of this result. Note the tendency of the optimized solutions to be  
166 in the quarter of the phase space where the measurements are (Fig. ED4), particularly for the case of  $J_5$  and  
167  $J_7$ , because for these harmonics the absolute value of the measurement is largest and the relative measurement  
168 error is smallest (see Table 1 in the main text), so their weight in the cost-function is the largest. Taking  
169 the same random set of meridional profiles and calculating their gravity harmonics for a fixed vertical profile  
170 (without the optimization process), gives solutions spread equally over all quarters of the parameter space  
171 (Fig. ED5). This illustrates that also the tendency of the simple exponential decay solution to have the correct  
172 sign and magnitude (Fig. 2 in the main text) is very likely not by chance. As an additional test we calculate  
173 the solution taking the Jupiter observed cloud-level meridional profile, but extended into the interior radially  
174 instead of along the direction of the spin axis. In this case even the sign of the gravity harmonics differs from  
175 the measurements.

176

177 **Non-uniqueness of the gravity inversion.** It is important to note that the gravity inversion problem is  
178 non-unique, and as demonstrated in Figs. 3 and 4 different profiles can give similar gravity signatures. In  
179 addition, the cases presented here do not match the measurements perfectly, and with more free parameters  
180 and/or other meridional profiles<sup>45</sup> one could achieve better matches to the measurements. However, since the  
181 problem is non-unique, achieving a perfect match is not necessarily meaningful. Thus, the rationale of this  
182 study is to show that using a minimal set of assumptions about the vertical and meridional structure, gives  
183 by itself a very good, and statistically significant, match to the measurements, indicating the structure and  
184 extent of the flow. Regardless of the exact vertical profile (which can depend on the parameterization and the  
185 non-uniqueness) the gravity measurements robustly reveal that the east-west jet-streams on Jupiter are very  
186 deep, reaching several thousands of kilometers beneath the cloud-level (several tens of kbar in pressure), and  
187 advect a significant mass that is on the order of 1% the mass of the planet.

188

189 **Code availability:** code for inversion of the gravity data is available at:

190 [http://www.weizmann.ac.il/eserpages/kaspi/juno\\_code/](http://www.weizmann.ac.il/eserpages/kaspi/juno_code/)

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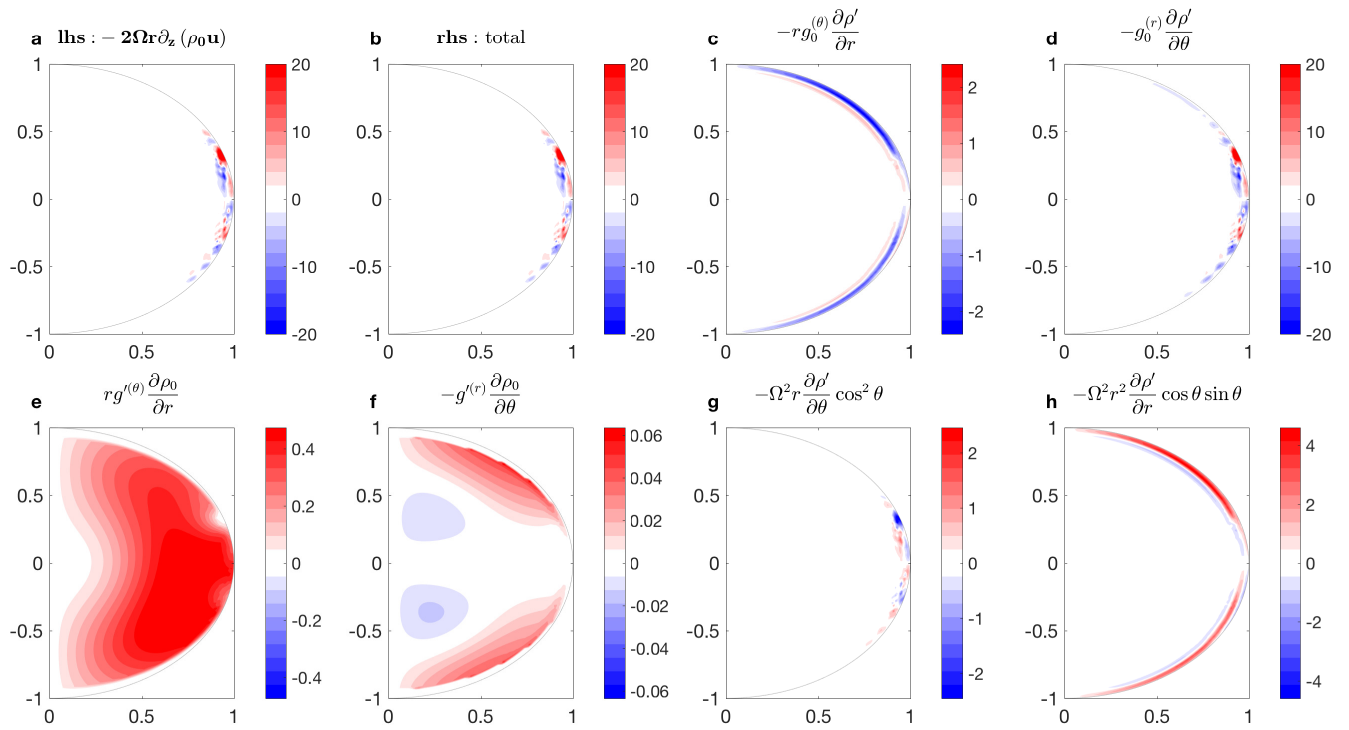


Figure ED1: **The vorticity balance.** Solution to Eq. M5 **a.** left hand side term with the wind profile from Fig. 3 in the main text, **b.** total of the right hand side, **c-h.** the six terms on the right hand side of Eq. M5, showing that the thermal wind balance (panels a and d) is the leading order balance. Note that the different panels have different color scales.

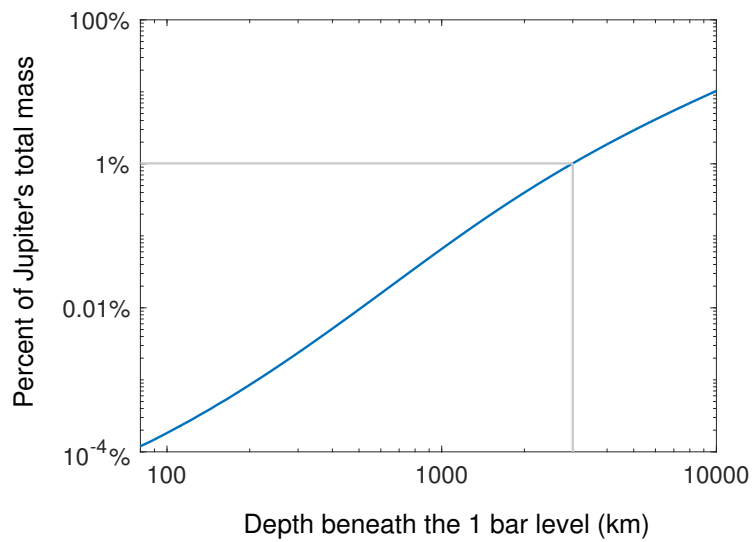


Figure ED2: **Jupiter's mass distribution.** The percent of Jupiter's mass as function of depth beneath the 1-bar level. The gray line shows that roughly 1% of the mass is contained above a depth of 3000 km.

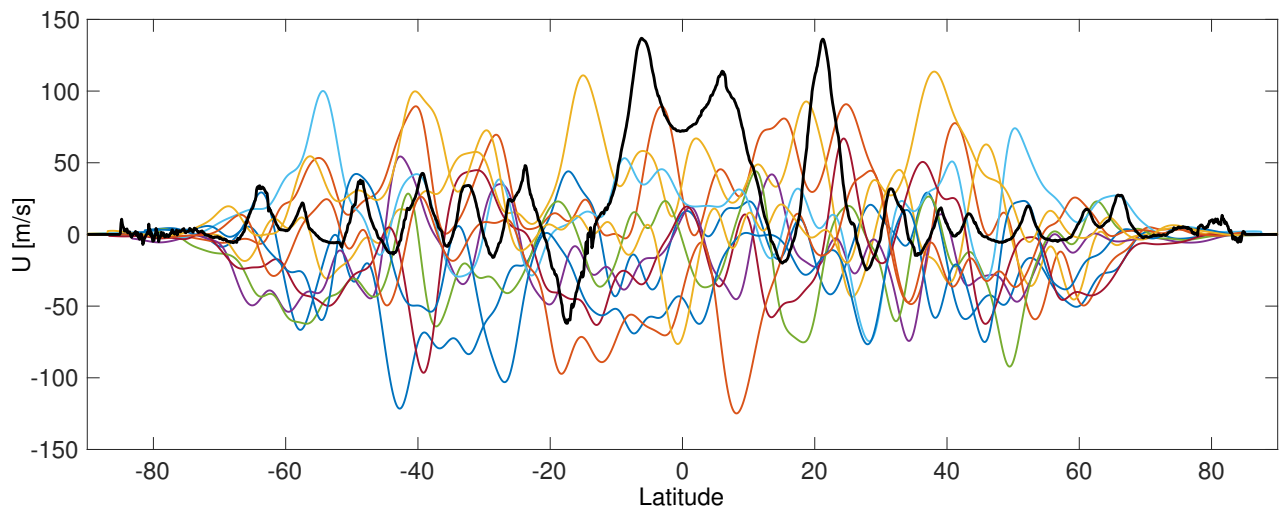


Figure ED3: **Example of wind profiles used for the statistical significance test.** The observed cloud-level wind (black), together with a sample of 10 randomly generated wind profiles.

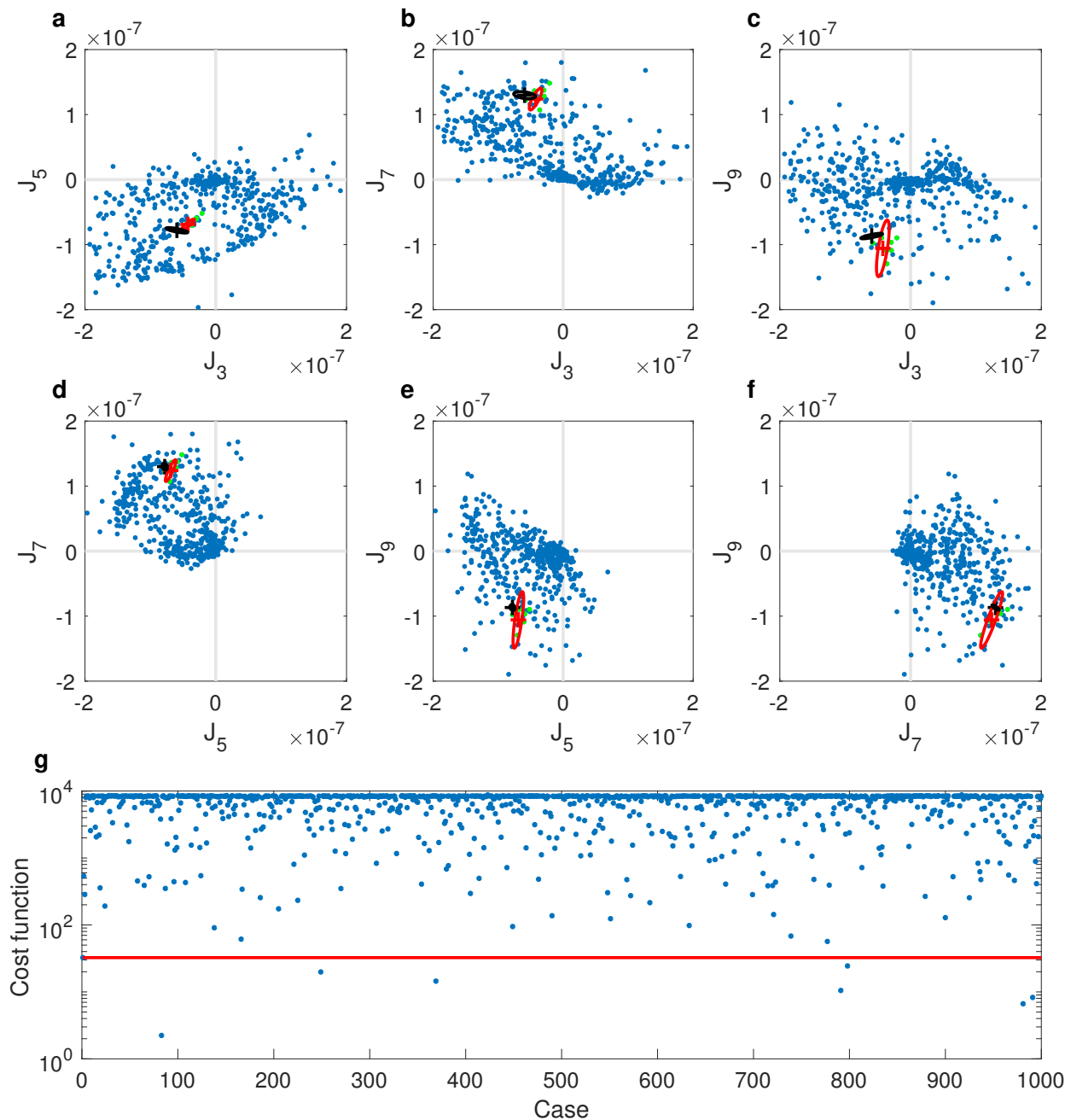


Figure ED4: **Optimized solutions for the odd harmonics using random meridional wind profiles.** **a-f.** Optimized solutions (blue) for  $J_3$ ,  $J_5$ ,  $J_7$  and  $J_9$  for flows with 1000 different artificial meridional profiles (as in Fig. ED3). The Juno measurements are shown in red with their corresponding uncertainty ellipse. The optimized solution corresponding to Jupiter's observed cloud-level meridional wind profile (Fig. 3 in the main text) is shown in black with the corresponding uncertainty ellipse. **g.** The cost-function for all different meridional profiles explored, with the red line corresponding to the solution with the Jupiter meridional wind profile. Less than 1% of the solutions have lower cost functions (green dots in panels a-f).

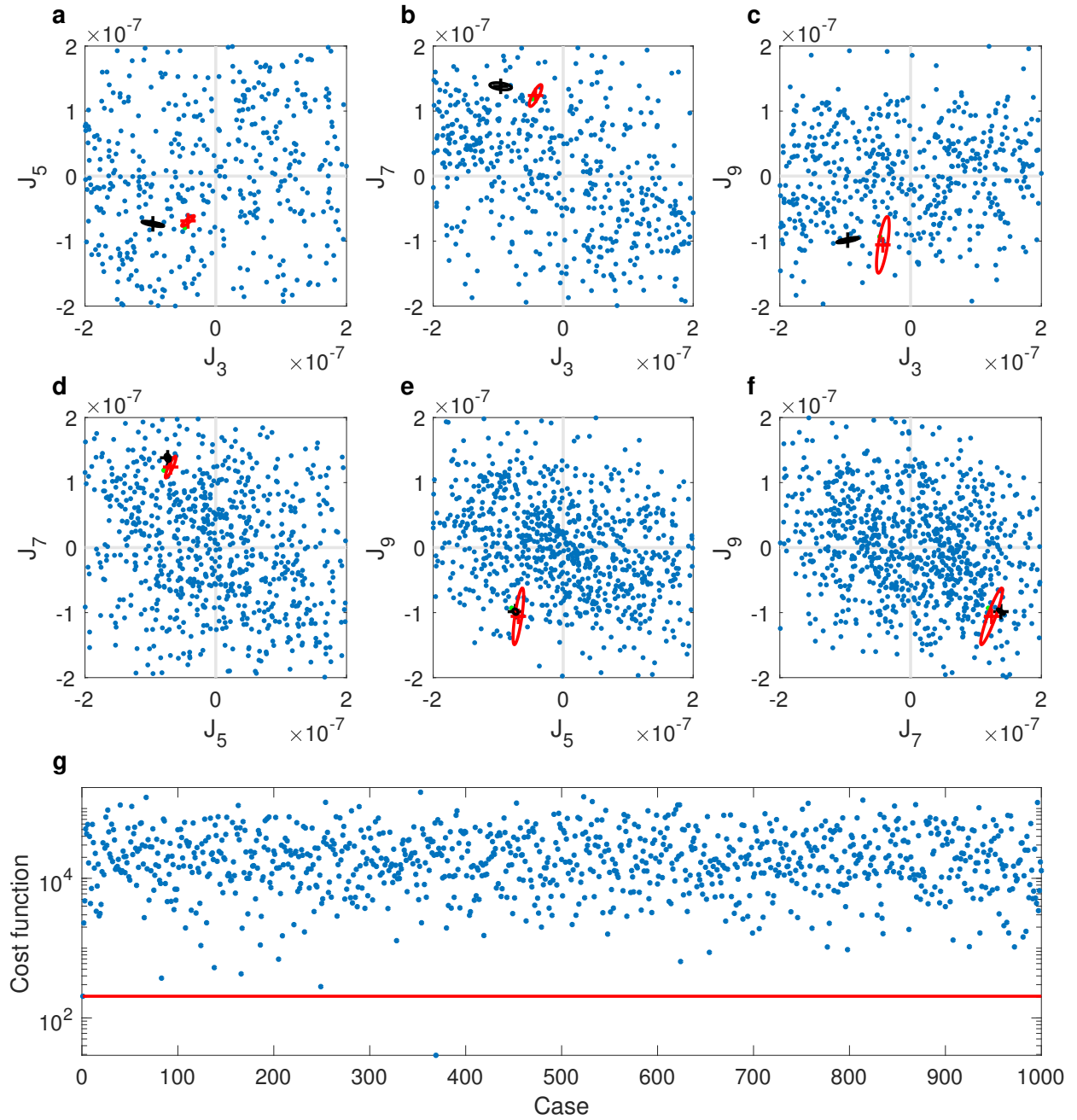


Figure ED5: **Solutions for the odd harmonics using random meridional wind profiles and a fixed vertical profile.** **a-f.** Solutions (blue) for  $J_3$ ,  $J_5$ ,  $J_7$  and  $J_9$  for flows with 1000 different artificial meridional profiles (as in Fig. ED3), and the vertical profile held fixed with  $H = 2000$  km,  $\Delta H = 1500$  km and  $\alpha = 1$ . The Juno measurements are shown in red with their corresponding uncertainty ellipse. The solution with these parameters and using Jupiter's observed cloud-level meridional wind profile is shown in black with the corresponding uncertainty ellipse. **g.** The cost-function for all different meridional profiles explored, with the red line corresponding to the solution with the Jupiter meridional wind profile. This shows that when no optimization is done (which takes into consideration the relative measurement error of the different harmonics), the solutions are spread equally over all four quadrants in these phase spaces (different than Fig. ED4).



$\times 10^{-8}$	Model without latitudinal variation	Model with latitudinal variation
$\Delta J_2$	$54.62 \pm 5.21$	$-48.87 \pm 7.93$
$\Delta J_4$	$-5.18 \pm 0.74$	$-15.01 \pm 7.56$
$\Delta J_6$	$0.33 \pm 0.35$	$0.29 \pm 1.49$
$\Delta J_8$	$5.41 \pm 0.28$	$4.76 \pm 0.61$
$\Delta J_{10}$	$-5.35 \pm 0.25$	$-4.94 \pm 0.71$

Table ED1: **The flow induced even gravity harmonics corresponding to the optimized solutions in Table 1.** The even gravity harmonics solutions for the optimization, with and without variation of flow depth with latitude, that correspond to the solutions presented in Figs. 3 and 5 and Table 1 of the main text. The uncertainties are the  $3\sigma$  uncertainty values.

	$J_3$	$J_5$	$J_7$	$J_9$
$J_3$	8.32	-11.05	1.45	-0.41
$J_5$	-11.05	20.21	-12.26	3.35
$J_7$	1.45	-12.26	14.31	-7.63
$J_9$	-0.41	3.35	-7.63	7.91

Table ED2: **The weights matrix  $\mathbf{W}$  used in the cost function  $\mathbf{L}$  (Eq. M16).** Shown are the weights associated with  $J_3$ ,  $J_5$ ,  $J_7$  and  $J_9$  (diagonal terms) and those associated with the correlation between the harmonics (off-diagonal terms). The values reflect the uncertainties in the measurements, calculated taking the inverse of the measurement error covariance matrix multiplied by 9 (to reflect  $3\sigma$  uncertainties). The larger the value, the larger the weight given to it when minimizing the cost-function. Values shown are multiplied by  $10^{-16}$ .