

## Evidence for multiple Ferrel-like cells on Jupiter

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### Key Points:

- Measurements from multiple instruments of the Juno mission are interpreted to reveal the meridional circulation beneath Jupiter's clouds
- 16 Jet-paired deep cells, extending to at least 240 bar, are revealed between latitudes 60°S and 60°N, driven by turbulence similar to Earth's Ferrel cells
- The findings are supported by modeling the advection of tracers due to the cells, showing agreement with NH<sub>3</sub> data

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## Abstract

Jupiter's atmosphere is dominated by multiple jet streams which are strongly tied to its 3D atmospheric circulation. Lacking a rigid bottom boundary, several models exist for how the meridional circulation extends into the planetary interior. Here we show, collecting evidence from multiple instruments of the Juno mission, the existence of mid-latitude meridional circulation cells which are driven by turbulence, similar to the Ferrel cells on Earth. Different than Earth, which contains only one such cell in each hemisphere, the larger, faster rotating Jupiter can incorporate multiple cells. The cells form regions of upwelling and downwelling, which we show are clearly evident in Juno's microwave data between latitudes 60°S and 60°N. The existence of these cells is confirmed by reproducing the ammonia observations using a simplistic model. This study solves a long-standing puzzle regarding the nature of Jupiter's sub-cloud dynamics and provides evidence for 8 cells in each Jovian hemisphere.

## Plain Language Summary

The cloud layer of Jupiter is divided into dark and bright bands that are shaped by strong east-west winds. Such winds in planetary atmospheres are thought to be tied with a meridional circulation. The Juno mission collected measurements of Jupiter's atmosphere at various wavelengths, which penetrate the cloud cover. Here we provide evidence, using the Juno data, of 8 deep Jovian circulation cells in each hemisphere encompassing the east-west winds, gaining energy from atmospheric waves, and extending at least to a depth of hundreds of kilometers. Different than Earth, which has only 1 analogous cell in each hemisphere, known as a Ferrel cell, Jupiter can contain more cells due to its larger size and faster spin. To support the presented evidence, we modeled how ammonia gas would spread under the influence of such cells and compared it to the Juno measurements. The presented results shed light on the unseen flow structure beneath Jupiter's clouds.

## 1 Introduction

Over the last few decades, spacecraft and ground-based observations have gathered data about Jupiter's atmosphere, including measurements of cloud reflectance (García-Melendo & Sánchez-Lavega, 2001), winds (Porco et al., 2003; Salyk et al., 2006; Tollefson et al., 2017), composition (Taylor et al., 2004) and lightning flashes (Little et al., 1999). Since 2016, the Juno spacecraft has provided unprecedented measurements that revealed new information on the deep dynamics of Jupiter (Bolton et al., 2017). Gravity science enabled an accurate mapping of Jupiter's gravitational field (Iess et al., 2018), resulting in the inference that the zonal jets penetrate  $\sim 3000$  km deep (Kaspi et al., 2018; Guillot et al., 2018), where they possibly decay due to magnetic drag (Liu et al., 2008; Dietrich & Jones, 2018; Kaspi et al., 2020) and may also require the presence of a stable layer (Christensen et al., 2020). The Jovian Infrared Auroral Mapper (JIRAM) provided measurements of tropospheric species distribution below the cloud level (Grassi et al., 2020). The Microwave Radiometer (MWR) measurements, inferred as brightness temperature ( $T_b$ ), revealed the deep ammonia abundance (Li et al., 2017; Oyafuso et al., 2020), as well as lightning at a frequency of 600 MHz (Brown et al., 2018). The combination of these observations allows the essential nature of Jupiter's deep overturning circulation to be revealed, as the flows associated with such circulation are directly related to cloud formation, temperature variations, lightning occurrences, tracer distributions and turbulence.

Earth's atmosphere is commonly referred to as possessing a three-cell meridional structure in each hemisphere (Vallis, 2017), which can be recognized in the zonal-averaged velocities. Circulation cells of such nature are thought to prevail in the atmospheres of terrestrial planets (Read et al., 2018) and were observed, for example, on Mars (Lewis

78 et al., 2007) and Venus (Limaye, 2007). On the terrestrial planets, the solid surface drag  
 79 plays a part in maintaining the circulation in the cells. However, as the giant planets hold  
 80 no such surface, the mere possibility of them possessing meridional circulation cells re-  
 81 mained uncertain. Earth’s midlatitudes are governed by the Ferrel cells, which are driven  
 82 by atmospheric turbulence, creating regions of eddy momentum flux convergence at mid-  
 83 latitudes (Vallis, 2017). These cells accompany the midlatitude jets and are connected  
 84 to the cloud structure in Earth’s atmosphere.

85 The prominent banded structure at the cloud tops of Jupiter’s atmosphere (Fig.  
 86 1a) has been observed for centuries (Vasavada & Showman, 2005). These reflectivity con-  
 87 trasts are partially aligned (mainly at low latitudes, Ingersoll et al. (2000)) with the belts  
 88 and zones (Fig. 1a), defined by the sign of the zonal-wind vorticity ( $\bar{\zeta} = -\partial\bar{u}/\partial y$  in Fig.  
 89 1c, where  $u$  is zonal velocity,  $y$  is in the meridional direction and an over-line represents  
 90 a zonal mean). Voyager measurements suggested that the zones are associated with as-  
 91 cending motion, but this was limited to low latitudes due to its equatorial trajectory and  
 92 to altitudes above 0.5 bar (Gierasch et al., 1986). The latitudinal profile of the zonal wind,  
 93 calculated using cloud-tracking (Garcia-Melendo & Sánchez-Lavega, 2001; Porco et al.,  
 94 2003; Tollefson et al., 2017), reveals that the equatorial region is characterized by a strong  
 95 eastward flow, while the midlatitudes exhibit alternating jets, spaced  $2-8^\circ$  apart in lat-  
 96 itude (Fig. 1b). The midlatitude jets are correlated with the eddy momentum flux con-  
 97 vergence (Salyk et al., 2006) ( $-\partial(\overline{u'v'})/\partial y$  in Fig. 1d, where  $v$  is meridional velocity and  
 98 an apostrophe represents deviations from the zonal mean, i.e. “eddy” terms), implying  
 99 that the midlatitude jets are eddy-driven (Ingersoll et al., 2000; Young & Read, 2017),  
 100 similar to the jets within Earth’s Ferrel cells (Schneider, 2006; Vallis, 2017). To illustrate  
 101 the relation between the jets and the eddies, regions of positive (negative) vorticity gra-  
 102 dient,  $\partial\zeta/\partial y = -\partial^2\bar{u}/\partial y^2$ , at midlatitudes, are marked by light red (blue) bands (Fig. 1),  
 103 where counter-clockwise (clockwise) Ferrel-like circulation cells are expected in the north-  
 104 ern hemisphere (NH). Similar circulations, but in opposite directions, apply for the south-  
 105 ern hemisphere (SH). Evidence for vertical motion comes also from observations of light-  
 106 ning flashes (Little et al., 1999; Porco et al., 2003; Brown et al., 2018), suggesting up-  
 107 drafts in cyclonic belt regions (e.g., Fig. 1e).

108 Additional information regarding Jupiter’s deep atmosphere can be obtained by  
 109 probing Jupiter’s interior at microwave frequencies. Juno’s MWR has 6 microwave chan-  
 110 nels (Janssen et al., 2017), each measuring the atmospheric  $T_b$  at a different depth (Janssen  
 111 et al., 2017; Bolton et al., 2017; Oyafuso et al., 2020; Fletcher et al., 2021), and collec-  
 112 tively covering the range between  $\sim 0.7$  and  $\sim 240$  bar (Fig. 1g,h, see also supporting  
 113 information - SI).  $T_b$  measurements are affected by both ammonia abundance and tem-  
 114 perature [and water in the case of the longest wavelengths, Li et al. (2017, 2020); Fletcher  
 115 et al. (2021)]. If the latitudinal gradients of  $T_b$  were primarily driven by temperature changes,  
 116 then thermal wind balance implies that the midlatitude jets strengthen from the cloud-  
 117 deck to about  $\sim 8$  bar, and then decay slowly towards the interior (Fletcher et al., 2021).  
 118 However, interpreting  $T_b$  as temperature would also imply that the equatorial wind dou-  
 119 ble its magnitude below the cloud level (Bolton et al., 2017), which is inconsistent with  
 120 gravity constraints (Duer et al., 2020). Thus, the latitudinal variation of  $T_b$  is probably  
 121 governed by ammonia opacity, resulting in a map of ammonia abundance (Li et al., 2017),  
 122 and implying that the zonal winds are nearly barotropic (Fletcher et al., 2021). The over-  
 123 all ammonia structure, supported also by earlier observations (de Pater et al., 2001), re-  
 124 veals stratification of ammonia with depth, although the mean ammonia profile changes  
 125 the sign of its vertical gradient at the  $\sim 2-8$  bar region (Giles et al., 2017; Li et al.,  
 126 2017; de Pater et al., 2019). The atmospheric depletion and stratification of ammonia  
 127 is likely linked to small-scale storm activity (Guillot, Li, et al., 2020; Guillot, Stevenson,  
 128 et al., 2020), where water-ammonia hail, forming around the 1-bar level, falls below the  
 129 water-cloud base and releases ammonia and water at altitudes below 10 bar (Guillot, Steven-  
 130 son, et al., 2020). Additional measurements of ammonia come from Juno’s JIRAM, which  
 131 evaluated the ammonia distribution at a depth of  $\sim 5-6$  bar (Grassi et al., 2010, 2020)

(Fig. 1f), indicating, as the MWR measurements, that ammonia varies with latitude. These variations are the key observation for this study, as ammonia anomalies (deviations from the isobaric mean) can reveal details about Jupiter’s overturning circulation (Ingersoll et al., 2017; Fletcher et al., 2021; Lee & Kaspi, 2021).

## 2 Ammonia anomalies due to vertical advection

In the presence of a stable vertical ammonia concentration gradient, advection by the vertical branches of a meridional circulation can affect the concentration distribution, potentially leading to steady anomalies. Therefore, the wavy structure of Jupiter’s ammonia distribution (Fig. 1f-h) can be explained by the presence of meridional circulation cells. On Jupiter, as condensation of ammonia is expected only at the upper levels of the atmosphere (0.5 – 1 bar), the ammonia concentration at those levels should be lower than at depth (Fletcher et al., 2020). In addition, precipitation, small-scale turbulence, thermochemical and chemical reactions, and diffusion are also expected to determine the vertical ammonia distribution ( $M_a$ ) (Guillot, Stevenson, et al., 2020). The  $M_a$  profile estimated from the MWR (Li et al., 2017) reveals a local minimum at  $\sim 6$  bar (Fig. 2a). This profile is used in this study as the background state, to explain the ammonia anomalies.

Here, we focus on two regions with distinctly different deep dynamics: the equatorial region (planetocentric latitudes  $20^\circ\text{S}$  to  $20^\circ\text{N}$ ), where superrotation is assumed to be fueled by eddy momentum fluxes perpendicular to the spin axis (e.g., Busse, 2002), and midlatitudes ( $60^\circ\text{S}$  to  $20^\circ\text{S}$  and  $20^\circ\text{N}$  to  $60^\circ\text{N}$ ), where alternating jets are postulated to be driven by horizontal eddies associated with mass-transporting meridional cells (e.g., Salyk et al., 2006; Schneider & Liu, 2009; Young et al., 2019).

We begin with the midlatitudes, where the meridional cells are mechanically driven (see below) by turbulence, similar to Earth’s Ferrel cells, which form as a consequence of atmospheric waves breaking in midlatitudes (Vallis, 2017). Unlike the largely baroclinic midlatitudes of Earth, which result in mostly non-mass-transporting Ferrel cells (Jukes, 2001; Vallis, 2017), the predominantly barotropic flows on Jupiter (at the depth range associated with the MWR measurements) (Kaspi et al., 2018; Kaspi et al., 2020; Galanti & Kaspi, 2021) may allow mass-transporting meridional cells (see SI). Consistently, deep convection models of Jupiter also show barotropic flows (e.g., Busse, 1976; Aurnou & Olson, 2001). The upper branch of Earth’s Ferrel cells consists of a balance between the Coriolis force and the eddy momentum flux convergence,

$$-f\bar{v} = -\frac{\partial(\overline{u'v'})}{\partial y}, \quad (1)$$

where  $f$  is the Coriolis parameter. This upper branch balance, which is the leading order balance of the steady state zonal mean zonal momentum equation, is expected to hold within the equivalent cells on Jupiter (see SI). This balance can hold down to a depth of only a few bars, as inferred from energy considerations (Liu & Schneider, 2010), implying flows from belts to zones within the cloud layer of the Jovian atmosphere. In the lower branch of the terrestrial Ferrel cells, the balance is between the Coriolis force and a surface drag (Vallis, 2017). Since the Jovian atmosphere lacks a bottom solid boundary, surface drag cannot act to oppose the Coriolis force, although it has been suggested that if the cells extend as deep as the jets (Kaspi et al., 2020), the Lorentz force can act as a magnetic drag (Liu et al., 2008; Liu & Schneider, 2010; Wicht et al., 2019). Another possible mechanism that allows the jets to be barotropic in the upper atmosphere and decay in the interior is the presence of a stable layer, as was shown lately in several studies (Debras & Chabrier, 2019; Christensen et al., 2020; Wicht & Gastine, 2020).

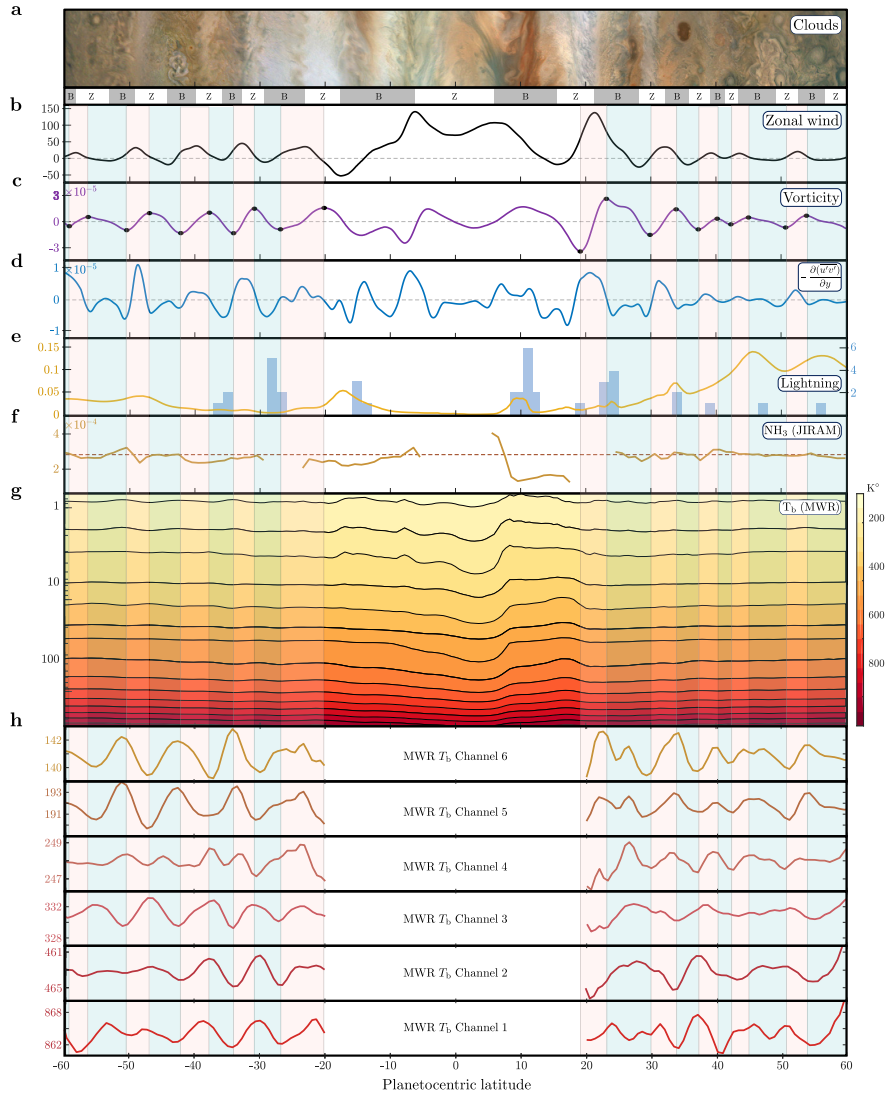


Figure 1: Observations of Jupiter’s atmosphere. (a) Image of Jupiter’s clouds (longitudes  $69 - 87^\circ$ ) taken by JunoCam on Dec. 26th 2019 during perijove 24 (image credit: NASA/JPL/SwRI/MSSS/Gerald Eichstaedt/John Rogers), with the traditional “dark” belts (“bright” zones) defined as regions of cyclonic (anticyclonic) vorticity, identified below as ‘B’ (‘Z’). (b) Jupiter’s zonally averaged zonal wind [ $\pm 15 \text{ m s}^{-1}$ ] measured by the Hubble space telescope on December 11, 2016, during Juno’s third perijove (Tollefson et al., 2017). (c) The zonally averaged vorticity [ $\text{s}^{-1}$ ], calculated from the zonal wind profile (panel b). Black dots represent local extrema in the midlatitudes. (d) Eddy momentum flux convergence [ $\pm 2 \times 10^{-6} \text{ m s}^{-2}$ ] calculated from 58 image pairs taken by Cassini during its Jupiter flyby in December, 2000 (Salyk et al., 2006). (e) Lightning detections [ $\text{s}^{-1}$ ] by Juno’s MWR during perijoves 1-8 (yellow, left axis, Brown et al., 2018) and number of lightning storms detected by the Cassini during its flyby (blue, right axis, Porco et al., 2003). (f) Distribution of ammonia [volume mixing ratio] and its mean (dashed) at a depth of  $\sim 6$  bar, measured by Juno’s JIRAM during perijoves 1-15 (Grassi et al., 2020). (g) Nadir  $T_b$  [ $^\circ\text{K}$ ] (color) interpolated between pressure levels of 0.7 and 240 bar (vertical axis), measured by Juno’s MWR during perijoves 1-12 (Oyafuso et al., 2020). (h) Reconstructed MWR Brightness temperature at midlatitudes. A frequency filter is applied according to Eq. S7. The standard deviation of each channel and latitude is available in Fig. S3 and Fig. S4. It can be seen that  $T_b$  changes its trend at the borders between cells, consistent with the Ferrel-like cells hypothesis. (b-h) Light red (blue) bands in the midlatitudes indicate regions of positive (negative) vorticity gradients.

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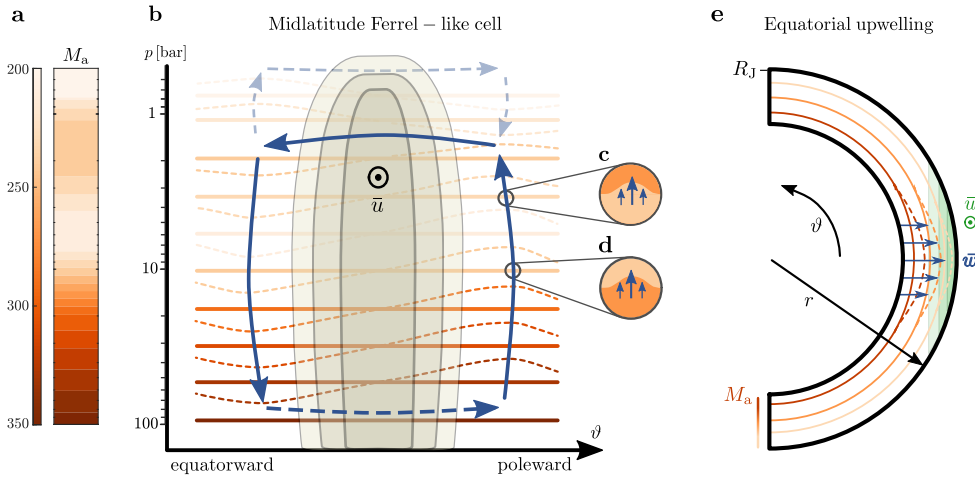


Figure 2: Schematics of Jupiter’s meridional circulation as inferred from the ammonia distribution. (a) The vertical structure of the meridionally averaged ammonia concentration ( $M_a$ ) [ppm], as interpreted from the  $T_b$  data (Li et al., 2017). (b) Illustration of a midlatitude Ferrel-like circulation cell (blue arrows) in the NH, looking from east towards the west. The cells are accompanied by an eddy-driven barotropic jet ( $\bar{u}$ ), which peaks at the center of the cell (beige contours). Ammonia constant-concentration lines are illustrated with orange shades (according to the ammonia vertical profile from panel a). Dashed orange lines are deviations from  $M_a$ , driven by vertical advection. The return flow of the cell, illustrated by a dashed blue arrow, lies at an unknown depth. An oppositely directed upper cell, as suggested by pre-Juno measurements (Ingersoll et al., 2000; Showman & de Pater, 2005; Fletcher et al., 2020), is demonstrated by dashed transparent arrows.  $p$  is pressure, taken as a vertical coordinate. (c) A closer look at the region where the rising air advects ammonia-poor fluid to an ammonia-rich layer, associated with pressure levels between 1.5 and 6 bar. (d) Here, rising gas drags higher ammonia concentration to a lower ammonia concentration region, associated with pressure levels deeper than 6 bar. (e) A cross section of Jupiter’s equatorial upwelling ( $\bar{w}$ ), associated with a superrotating jet ( $\bar{u}$ , green contours), leading to ammonia concentration maximum. The equatorial  $M_a$  (orange contours) is assumed to decrease with radius (Fig. S8).  $R_J$  is Jupiter’s radius and  $\vartheta$  and  $r$  are the latitudinal and radial directions, respectively.

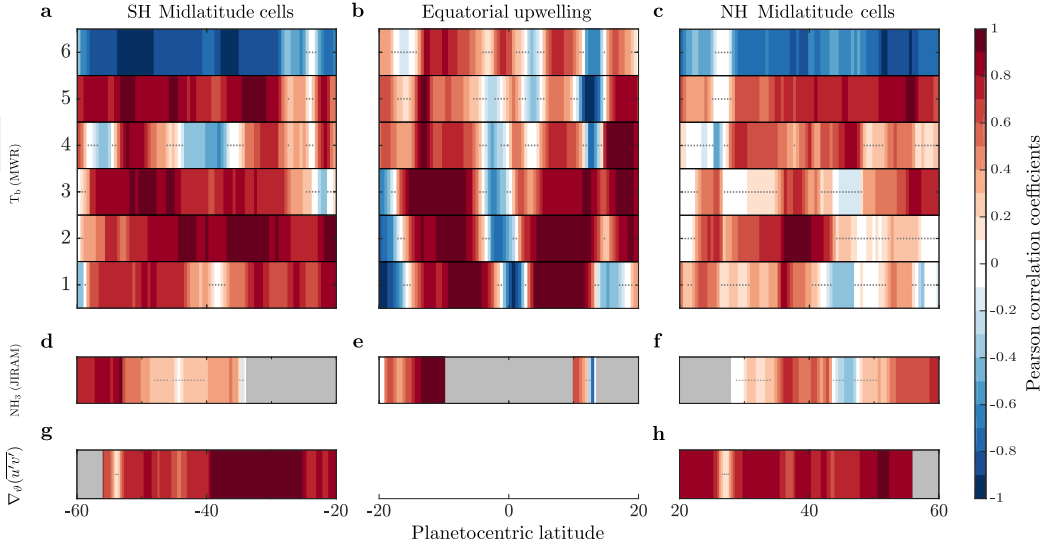


Figure 3: Pearson correlation coefficients as a function of latitude. The correlations exemplify the relations presented in Fig. 2. (a) and (c), correlations calculated between the zonal jets ( $\bar{u}$ ) and the  $T_b$  meridional gradients ( $\partial_y T_b$ ), adjusted by the sign of the vertical gradient of  $M_a$ , in the six MWR channels, for the SH and NH, respectively. (b) Correlations computed between the zonal jet velocity and  $T_b$  ( $\bar{u} \propto -T_b$ ). (d) and (f), Correlations between the zonal velocity and the ammonia abundance gradients ( $\partial_y \text{NH}_3$ ), measured by JIRAM, in the SH and NH, respectively. (e) Correlations between the zonal velocity and the ammonia abundance from JIRAM ( $\bar{u} \propto \text{NH}_3$ ). (g) and (h) Correlations between the zonal velocity and the eddy momentum flux convergence ( $\bar{u} \propto -\partial_y (\overline{u'v'})$ ), in the SH and NH, respectively. Gray dots represent correlations that are not statistically significant (confidence level 95%) and gray regions show where measurements were not available. No data is available for the eddy fluxes in the equatorial region, as evaluating them requires measurements of the vertical winds (see SI), which are yet to be achieved.

178 The direction of each Ferrel-like cell corresponds to the direction of the respective  
 179 midlatitude jet. Eastward (westward) jets are located in cells of eastward momentum  
 180 flux convergence (divergence) implying (Eq. 1) a counterclockwise (clockwise) circula-  
 181 tion in the NH, and a clockwise (counterclockwise) circulation in the SH (Fig. 1b,d). The  
 182 upper branch of the Ferrel-like cells may coincide with the lower branch of stacked up-  
 183 per cells with an opposite circulation (Ingersoll et al., 2000; Showman & de Pater, 2005)  
 184 (dashed transparent lines in Fig. 2b), and therefore may share the same balance (Eq. 1).  
 185 Indications for the upper cells come from temperature and shallow tracer distributions  
 186 (Gierasch et al., 1986; Fletcher et al., 2016; de Pater et al., 2019). Similar to the balance  
 187 describing the deeper branch of the lower cells, the upper branch of the upper cells re-  
 188 quires a drag force, which may result from breaking of atmospheric waves (Gierasch et  
 189 al., 1986; Ingersoll et al., 2021).

190 The background ammonia profile is skewed by the vertical branches of the cells (dashed  
 191 orange lines in Fig. 2b), maximizing the ammonia meridional gradient where the jet ve-  
 192 locity peaks (i.e., in the middle of the cell). This means that a correlation (along isobars)  
 193 is expected between the zonal jets and the meridional gradient of the ammonia concen-  
 194 tration at midlatitudes (Duer et al., 2020; Fletcher et al., 2021). However, since the ver-  
 195 tical gradient of  $M_a$  changes with depth (Li et al., 2017) (Fig. 2a), the nature of the cor-  
 196 relation should change as well, as illustrated in Fig. 2c,d. These simple considerations

197 motivate the examination of the correlation between  $\bar{u}$  and  $\partial_y m_a$  ( $-\partial_y T_b$ ) in midlati-  
 198 tudes (Fig. 3a,c, also see SI). Note that  $T_b$  corresponds inversely to ammonia abundance  
 199 at a certain pressure level (Li et al., 2017). For a deep-wind estimate, we use the mea-  
 200 sured cloud-level winds (Tollefson et al., 2017) projected inward in a direction parallel  
 201 to the axis of rotation, without any change in magnitude (in the upper 240 bar), as im-  
 202 plied by gravity measurement constraints (Galanti & Kaspi, 2021; Galanti et al., 2021).  
 203 The correlations are performed using a  $4^\circ$  latitudinal bin (see SI). By this, the suggested  
 204 correlations in Fig. 2 can be tested locally, rather than over an entire hemisphere (Duer  
 205 et al., 2020; Fletcher et al., 2021).

206 At midlatitudes the overall positive correlations for MWR channels 1-5 indicate the  
 207 existence of Ferrel-like cells at depths between 1.5 and 240 bar (Fig. 3a,c). The positive  
 208 correlation with ammonia estimates by JIRAM (Fig. 3d,f) further strengthens the promi-  
 209 nence of the proposed cells. Channel 6 ( $\sim 0.7$  bar) exhibits negative correlations in mid-  
 210 latitudes (Fig. 3a,c), implying that the deep cells do not extend higher than  $\sim 1$  bar,  
 211 and support the existence of counter-rotating cells above that level (Ingersoll et al., 2000;  
 212 Showman & de Pater, 2005; Fletcher et al., 2020). To verify that the relation shown in  
 213 Eq. 1 holds in the cells as illustrated in Fig. 2b, regional correlations between  $\bar{u}$  and  $-\partial_y (\overline{u'v'})$   
 214 are shown for midlatitudes (Fig. 3g,h). This positive correlation further strengthens the  
 215 existence of the Ferrel-like cells, where converging eddy momentum fluxes are the source  
 216 of momentum. Overall, the correlation analysis reveals multiple deep Ferrel-like cells,  
 217 extending from  $\sim 1$  bar to at least 240 bar.

218 The equatorial region of Jupiter, characterized by a wide eastward jet, needs to be  
 219 treated differently. Gravity analysis reveals that Jupiter's interior (deeper than  $\sim 3000$  km)  
 220 is rotating as a rigid body (Guillot et al., 2018). Extending the zonal wind along the di-  
 221 rection of the spin axis thus separates the equatorial region ( $17^\circ$  S to  $17^\circ$  N) from the trun-  
 222 cated cells at midlatitudes (see SI). The superrotating wind at low latitudes requires a  
 223 source of momentum (Imamura et al., 2020). Theories for such sources include merid-  
 224 ional (Potter et al., 2014; Laraia & Schneider, 2015) and vertical (Aurnou & Olson, 2001;  
 225 Busse, 2002; Christensen, 2002; Heimpel et al., 2005; Kaspi et al., 2009; Dietrich & Jones,  
 226 2018), propagation of waves. For the vertical case, several studies have shown that an  
 227 equatorial superrotation in giant planets can be driven by eddy momentum fluxes per-  
 228 pendicular to the axis of rotation (Heimpel et al., 2005; Kaspi et al., 2009; Gastine et  
 229 al., 2014). These fluxes transfer momentum outwards and lead to a mean upwelling at  
 230 the equatorial region (see SI). Such an upwelling should lead to a maximum concentra-  
 231 tion anomaly of any stably stratified matter (Fig. 2e). In the equatorial region, the min-  
 232 imum in  $M_a$  around  $\sim 6$  bar nearly vanishes (Fig. S8), suggesting that the positive am-  
 233 monia anomalies at the equatorial region (Fig. S2a) are due to the upwelling from deep.  
 234 To examine this, at the equator, the correlation is calculated between the zonal veloc-  
 235 ity ( $\bar{u}$ ) and the ammonia concentration itself ( $-T_b$  for the MWR or  $\text{NH}_3$  for the JIRAM  
 236 measurements). Using a regional correlation analysis (see SI), it is apparent that the cor-  
 237 relations are largely positive at all depths (Fig. 3b,e), implying that an equatorial up-  
 238 welling is dominant from the cloud deck and down to at least 240 bar. Very close to the  
 239 equator, the correlation is negative due to the local minimum in the zonal velocity (Fig. 1b).

### 240 3 Model reconstruction of Jupiter's ammonia distribution

241 To further validate that the positive correlations shown in Fig. 3a,c are indeed due  
 242 to the existence of meridional circulation cells, we reconstruct the measured variations  
 243 using a simplified advection-relaxation model. Beginning with a steady-state zonal-mean  
 244 conservation of species equation for ammonia, assuming that diffusion terms are small,  
 245 the leading-order balance is



$$\bar{w}(\vartheta, r) \frac{\partial m_a(\vartheta, r)}{\partial r} + \bar{v}(\vartheta, r) \frac{\partial m_a(\vartheta, r)}{r \partial \vartheta} = -G(r) (m_a(\vartheta, r) - M_a(r)), \quad (2)$$

where  $\bar{w}$  is the zonally averaged radial velocity, and  $m_a$ , the variable solved for by the model, is the (zonal-mean) molar fraction of ammonia.  $M_a$  is the ammonia concentration averaged over isobaric surfaces (Fig. 2a), and  $G$  is the inverse of a Newtonian relaxation timescale. The two terms on the left-hand side represent advection by the mean circulation, and the right-hand side term is a source term parameterized as a simple Newtonian relaxation of ammonia. This relaxation term is assumed to include all the processes resulting in the observed  $M_a$  as it acts against local anomalies toward this mean vertical structure. To qualitatively illustrate how the Ferrel-like cells' footprint might appear in the ammonia distribution map ( $m_a$ ), we solve the advection-relaxation balance shown in Eq. 2, for the midlatitudes between 1.5 and 240 bar (see SI). As the balance in Eq. 2 indicates, it is assumed that the relaxation time scale ( $G^{-1}$ ) is such that the advection and relaxation terms balance each other.

The zonally averaged velocity components ( $\bar{v}, \bar{w}$ ) of the circulation cells, necessary for setting the advection terms of Eq. 2, can be projected from the available wind data according to the outline illustrated in Fig. 2b. Specifically, we relate between the circulation cells and the wind data corresponding to the following assumptions (see also SI). The borders between the cells are set at local extrema of the observed cloud-level vorticity, the directions of the circulation cells are set according to the directions of the jets in the middle of each cell, and the strength of the circulation in each cell is set by the measured eddy momentum flux convergence along the cell (Fig. S5). As the three terms in Eq. 2 should be proportional, but cannot be uniquely determined, the values of  $\bar{w}$ ,  $\bar{v}$  and  $G$  are normalized (Fig. 4a). This normalization means that while the model cannot produce absolute values of winds due to unmeasured quantities, it can predict qualitatively how these velocities would be structured spatially and what should be their relative magnitudes, which are sufficient for assessing the existence of the cells. Using scaling arguments, the value of Jupiter's static stability has recently been estimated to be in the order of  $10^{-2} \text{ s}^{-1}$  (Lee & Kaspi, 2021), which can provide a further step towards estimating the magnitude of the velocities in the cells.

The described wind scheme results in upwellings (downwellings) on the poleward (equatorward) sides of eastward jets (Fig. 4a). The cells are reversed for westward jets. Finally, as a benchmark for the model results, derivation of the ammonia abundance ( $m_a^{(\text{data})}$ ) from the measured  $T_b$  between the latitudes  $60^\circ\text{S}$  and  $60^\circ\text{N}$  is implemented (see SI, Fig. S2). As the depth of the cells, the width of their branches and the parameter  $G$  are unknown, an optimization procedure is performed for determining these parameters to best match the data (see SI). To ensure that this procedure does not influence the qualitative nature of the results, Eq. 2 is also solved with a predefined physically-oriented set of parameters (Figs. S6 and S7).

Using the above assumptions, we solve Eq. 2 to predict the ammonia map ( $m_a^{(\text{model})}$ ), and compare it to  $m_a^{(\text{data})}$  (Fig. 4). We stress that the latitudinal variations appearing in the results (Fig. 4c), stem only from the cloud-level wind observations without any assumption on the meridional ammonia variation. For a clear comparison between the  $m_a^{(\text{data})}$  and  $m_a^{(\text{model})}$ ,  $M_a$  is subtracted from both, such that only anomalies are visible (Fig. 4b,c). Around 10 bar (Fig. 4b), where  $M_a$  greatly increases with depth, enriched (depleted) ammonia anomalies appear where upwellings (downwellings) are expected (Fig. 4a). These features flip sign around the 6-bar level, where  $M_a$  decreases with depth. These elements are captured well by the advection-relaxation model (Fig. 4c). In the SH, all 18 anomalies apparent in the observations have a counterpart of similar sign, shape and position in the model results, suggesting the existence of 8 meridional circulation cells. This agreement validates that advection by the vertical branches of the cells is the main contributor in the creation of the observed ammonia anomalies. In the NH, similar results are achieved, although the cells are slightly less coherent, perhaps due to unexplained

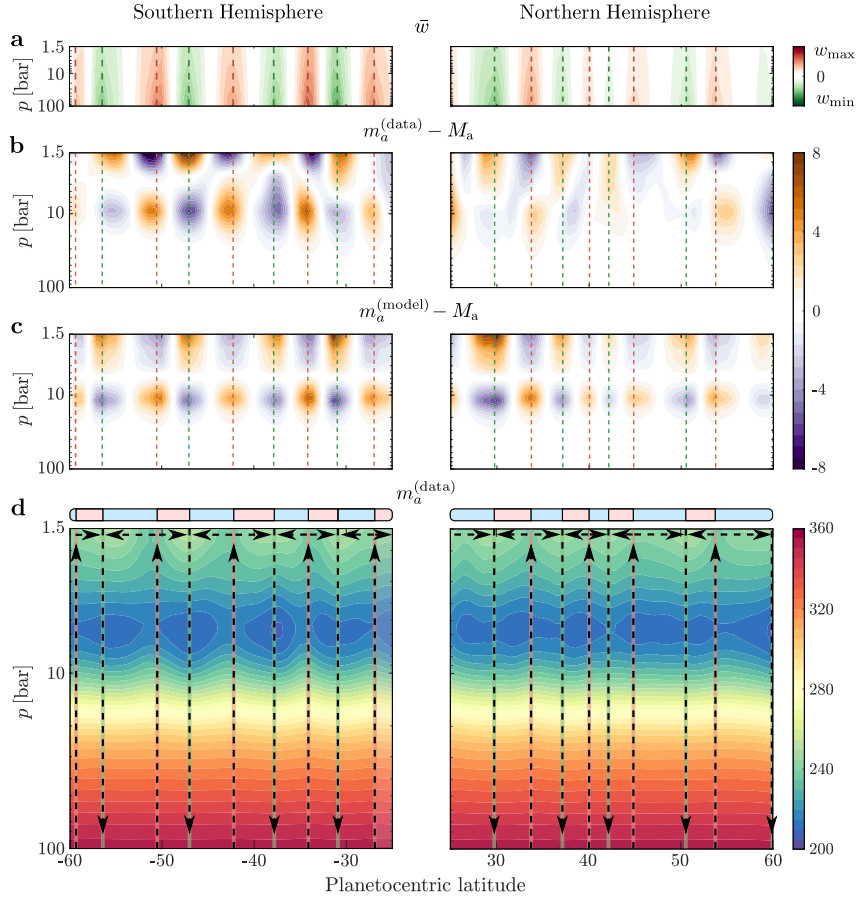


Figure 4: Jupiter’s Ammonia distribution driven by an array of circulation cells. (a) The normalized vertical zonal-mean wind ( $\bar{w}$ ), as a function of latitude and pressure, used in the model. Red and green contours are upward and downward winds, respectively. (b) The ammonia anomalies reconstructed from the data [ppm]. Here the vertical mean profile  $M_a$  is removed from the ammonia map  $m_a$ . (c) The ammonia anomalies [ppm] produced by the advection-relaxation model. (d) The full reconstructed ammonia map  $m_a^{(\text{data})}$  [ppm]. Arrows represent the direction of the cells’ vertical and meridional winds. (a-d) Red and green vertical lines are the locations of the upward and downward branches of the cells, respectively. For reference, light red (blue) bands indicate regions of positive (negative) vorticity gradient as in Fig. 1. The vertical axis is truncated at 100 bar as  $M_a$  becomes largely uniform beyond this depth, thereby suppressing footprints of advection.

297 differences between the perijoves in the NH midlatitudes [Fig. S3, Oyafuso et al. (2020);  
 298 Fletcher et al. (2021)], which might mask the cells' footprints in the MWR data. Nev-  
 299 ertheless, the lightning data reinforces the existence of the NH cells, as lightning peaks  
 300 are aligned with the rising branch of the cells at the poleward side of the eastward jets  
 301 (Fig. 1e, Fig. S1), which combined with the MWR data (Fig. 4b-d) provide indication  
 302 for 8 northern cells. Additional NH centered perijoves during the Juno extended mis-  
 303 sion may provide data to better constrain the NH cells. For more intuition, one can look  
 304 at the full ammonia map (Fig. 4d), where iso-concentration lines are pulled up and down  
 305 by the vertical winds (as schematically illustrated in Fig. 2b), emphasizing the locations  
 306 of the 16 eddy-driven cells evident in the MWR data.

## 307 4 Discussion

308 The identified array of alternating cells in midlatitudes, along with the equatorial  
 309 upwelling, are key features in the meridional overturning circulation of the Jovian at-  
 310 mosphere (Fig. 5). The cell's depth that can be inferred from the MWR measurements  
 311 is limited to the sensing range ( $\sim 240$  bar), and while the midlatitudinal cells are me-  
 312 chanically driven, as the Ferrel cells in Earth's troposphere, they are likely to extend deeper  
 313 into the planet, as suggested by multiple theoretical studies (e.g., Liu & Schneider, 2010;  
 314 Christensen et al., 2020). Similarly, deep meridional cells, which are mechanically driven,  
 315 have been suggested to exist on the Sun (Miesch & Hindman, 2011).

316 This study provides an explanation for the observed meridional ammonia anom-  
 317 alies, given the meridionally averaged vertical ammonia profile. The consistency of these  
 318 results suggest that the  $T_b$  latitudinal variations are dominated by the opacity of a pas-  
 319 sive tracer, rather than the kinetic temperature. Note that evidence for the part of the  
 320 deep cells extending from 1.5 to 6 bar depends on the flip of the background ammonia  
 321 gradient (Fig. 2a), and without it these depths might be part of upper inverse cells (Fletcher  
 322 et al., 2021). The shape of this vertical profile might be set by precipitation, diffusion,  
 323 and small-scale mixing, all of which might change with latitude and depth (Guillot, Li,  
 324 et al., 2020). Nonetheless, the remarkable agreement between the model and the data,  
 325 together with the robust correlation analysis, provide strong evidence that the observed  
 326 distribution of ammonia is governed by the existence, number, position and relative strength  
 327 of the Ferrel-like circulation cells in Jupiter.

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329 All the data used in this study is publicly available, see Tollefson et al. (2017) for the  
 330 winds data, Salyk et al. (2006) for the eddies data, Li et al. (2017) for the ammonia data,  
 331 Brown et al. (2018) for the lightning data and Oyafuso et al. (2020) for the brightness  
 332 temperature data.

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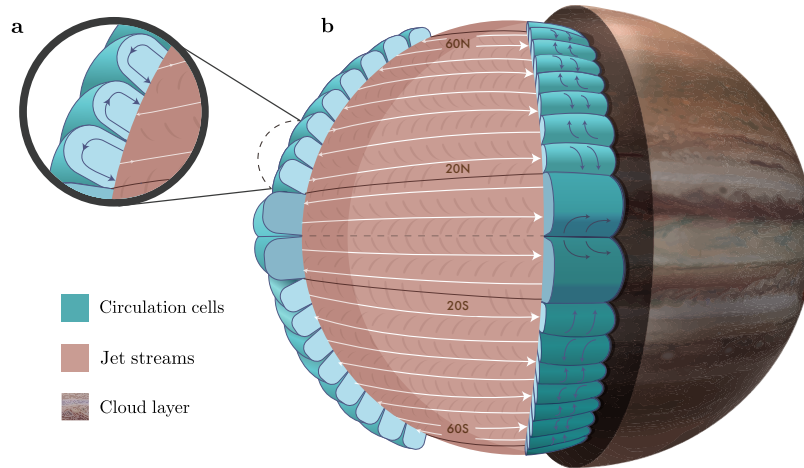


Figure 5: A figurative cross section of Jupiter’s meridional circulation and a magnification of the midlatitude circulation cells. The circulation cells (blue) are axisymmetric in the zonal direction. The pink shell represents a deep layer characteristic for all depths within the circulation cells. The white arrows represent alternating jet streams and are symmetric around the equator for the purpose of clarity. Each jet between latitudes  $20^{\circ} - 60^{\circ}$  N/S is accompanied by a turbulence-driven circulation cell (blue arrows) in the meridional plane as illustrated in Fig. 2b. The equatorial upwelling associated with the superrotating jet is drawn at the equator, as illustrated in Fig. 2e, as part of a larger possible equatorial cell (dark blue).

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