Cassini observations reveal a regime of zonostrophic macroturbulence on Jupiter

Supplementary Material

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1 List of raw image pairs

Tables S1 and S2 list the raw image pairs used in the analysis, from the image list in Vasavada et al. (2008). All use the CB2 filter.

2 Parameters for the PATCH step

The parameters for the PATCH1 step (smoothing and interpolation) in the CIV procedure are listed in the table. This is the final step in the first CIV stage (translation) before the velocity is refined by rotation and deformation of the correlation box. Details about the PATCH1 step and each of these parameters can be found in Sect. 11 of Coriolis Platform / LEGI (2013).

| Parameter     | Value | Description                                                                 |
|---------------|-------|-----------------------------------------------------------------------------|
| rho           | 1     | Thin plate spline smoothing parameter (Coriolis Platform, 2011)             |
| max dev       | 2     | Vectors further than this away from the smoothed field are removed          |
| subdomain size| 600   | Thin plate spline domain size (Coriolis Platform, 2011)                     |
| nx            | 100   | Number of output x grid points                                             |
| ny            | 50    | Number of output y grid points                                             |

3 Fields for days 1, 3, and 4

Figures S1–S4 show equivalent plots to the fields shown in the main document, but for days 1, 3, and 4. The plots for day 2 are shown in Fig. 3 of the main document.

4 Number of filtered velocity vectors

Figure S5 shows the number of filtered velocity vectors used to calculate the velocity in each mosaic grid box, for each of the four days.

5 Velocity errors

Figures S6 and S7 show the estimated random error in the mosaiced u- and v- velocity components.

6 Zonal diagnostics for varying grid spacing

Figures S8 and S9 show the zonal mean diagnostics for the different latitudinal grid spacings.

7 Example vorticity field with pointing uncertainty

Figure S10 shows one of the vorticity fields where 1.0° uncertainty was introduced into the position of each individual image pair before they were combined into the global mosaics.
8 Velocity datasets

The velocity field and error mosaics produced by cloud tracking as described in Sect. 3 of the main text are included as supplementary data file U_V_wERR_050_centric_civ2_master.tgz. This zipped tar archive contains the following files, one for each day:

U_V_wERR_day1_050_centric_civ2_master.dat
U_V_wERR_day2_050_centric_civ2_master.dat
U_V_wERR_day3_050_centric_civ2_master.dat
U_V_wERR_day4_050_centric_civ2_master.dat

The files contain the zonal and meridional velocity fields, along with their 1σ errors. Each data file is a single column of numbers. Apart from the first two lines (which are integers) all numbers are real values with 13 decimal places. The format of each data file is as follows:

1. Number of longitude points $M$ [1 number].
2. Number of latitude points $N$ [1 number].
3. Value used in fields to represent missing data [1 number].
4. List of longitude points ($^\circ$E) [$M$ numbers].
5. List of latitude points ($^\circ$N) [$N$ numbers].
6. Eastward (zonal) velocity (m s$^{-1}$) [$M \times N$ numbers]. The order is
   lat 1 lon 1
   lat 1 lon 2
   lat 1 lon 3
   ...
   lat 1 lon $M$
   lat 2 lon 1
   lat 2 lon 2
   lat 2 lon 3
   ...
   lat 2 lon $M$
   ...
   lat $N$ lon $M$
7. Northward (meridional) velocity (m s$^{-1}$) [$M \times N$ numbers]. Ordered as eastward velocity.
8. Error in eastward velocity (m s$^{-1}$) [$M \times N$ numbers]. Ordered as eastward velocity.
9. Error in northward velocity (m s$^{-1}$) [$M \times N$ numbers]. Ordered as eastward velocity.

Should the reader want to check the values are loaded correctly, they are shown in the following figures:

| Field                   | Day 1 | Day 2 | Day 3 | Day 4 |
|-------------------------|-------|-------|-------|-------|
| Velocity                | S1a   | 3a    | S1b   | S1c   |
| Zonal velocity error    | S6a   | S6b   | S6c   | S6d   |
| Meridional velocity error| S7a  | S7b   | S7c   | S7d   |

References

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Limaye, S. S., 1986. Jupiter: New estimates of the mean zonal flow at the cloud level. Icarus 65, 335–352.

Porco, C. C., West, R. A., McEwen, A., Del Genio, A. D., Ingersoll, A. P., Thomas, P., Squyres, S., Dones, L., Murray, C. D.,
Johnson, T. V., Burns, J. A., Brahe, A., Neukum, G., Veverka, J., Barbara, J. M., Denk, T., Evans, M., Ferrier, J. J.,
Geissler, P., Helfenstein, P., Roatsch, T., Throop, H., Tiscareno, M., Vasavada, A. R., 2003. Cassini imaging of Jupiter’s atmosphere, satellites, and rings. Science 299, 1541–1547.

Vasavada, A. R., Porco, C., the Cassini imaging science team, 2008. NASA Planetary Data System: Cassini Cylindrical-Projection Maps near Jupiter Closest Approach. http://pds-atmospheres.nmsu.edu/Jupiter/CassiniMaps.txt.
Table S1: Raw images used for the northern hemisphere.

| Day | Image 1       | Image 2       | First image 2000-Dec date & time | Second image 2000-Dec date & time | Separation (mm:ss) | Overlap central pixel (System III W longitude) |
|-----|---------------|---------------|-----------------------------------|-----------------------------------|--------------------|-----------------------------------------------|
| 1   | n1355237227   | n1355237227   | 11th 13:32:34                     | 11th 14:35:40                    | 63:06              | 208.75                                        |
|     | n1355237227   | n1355241013   | 11th 14:35:40                     | 11th 15:38:46                    | 63:06              | 246.85                                        |
|     | n1355248585   | n1355252371   | 11th 17:44:58                     | 11th 18:48:04                    | 63:06              | 1.05                                          |
|     | n1355252371   | n1355256157   | 11th 18:48:04                     | 11th 19:51:10                    | 63:06              | 39.15                                         |
|     | n1355256157   | n1355259943   | 11th 19:51:10                     | 11th 20:54:16                    | 63:06              | 77.25                                         |
|     | n1355259943   | n1355263729   | 11th 20:54:16                     | 11th 21:57:22                    | 63:06              | 115.35                                        |
|     | n1355263729   | n1355267515   | 11th 21:57:22                     | 11th 23:00:28                    | 63:06              | 153.45                                        |
|     | n1355267515   | n1355271301   | 11th 23:00:28                     | 12th 00:03:34                    | 63:06              | 191.55                                        |
| 2   | n1355271301   | n1355275087   | 12th 00:03:34                     | 12th 01:06:40                    | 63:06              | 229.60                                        |
|     | n1355275087   | n1355278873   | 12th 01:06:40                     | 12th 02:09:46                    | 63:06              | 267.65                                        |
|     | n1355278873   | n1355282659   | 12th 02:09:46                     | 12th 03:12:52                    | 63:06              | 305.75                                        |
|     | n1355282659   | n1355286445   | 12th 03:12:52                     | 12th 04:15:58                    | 63:06              | 343.85                                        |
|     | n1355286445   | n1355290231   | 12th 04:15:58                     | 12th 05:19:04                    | 63:06              | 21.99                                         |
|     | n1355290231   | n1355294017   | 12th 05:19:04                     | 12th 06:22:10                    | 63:06              | 60.05                                         |
|     | n1355294017   | n1355297803   | 12th 06:22:10                     | 12th 07:25:16                    | 63:06              | 98.10                                         |
|     | n1355297803   | n1355301589   | 12th 07:25:16                     | 12th 08:28:22                    | 63:06              | 136.15                                        |
|     | n1355301589   | n1355305375   | 12th 08:28:22                     | 12th 09:31:28                    | 63:06              | 174.25                                        |
| 3   | n1355305375   | n1355309161   | 12th 09:31:28                     | 12th 10:34:34                    | 63:06              | 212.35                                        |
|     | n1355309161   | n1355312947   | 12th 10:34:34                     | 12th 11:37:40                    | 63:06              | 250.45                                        |
|     | n1355312947   | n1355316733   | 12th 11:37:40                     | 12th 12:40:46                    | 63:06              | 288.55                                        |
|     | n1355316733   | n1355320519   | 12th 12:40:46                     | 12th 13:43:51                    | 63:06              | 326.60                                        |
|     | n1355320519   | n1355324305   | 12th 13:43:51                     | 12th 14:46:57                    | 63:06              | 4.65                                          |
|     | n1355324305   | n1355328091   | 12th 14:46:57                     | 12th 15:50:03                    | 63:06              | 42.75                                         |
|     | n1355328091   | n1355331877   | 12th 15:50:03                     | 12th 16:53:09                    | 63:06              | 80.85                                         |
|     | n1355331877   | n1355335663   | 12th 16:53:09                     | 12th 17:56:15                    | 63:06              | 118.95                                        |
|     | n1355335663   | n1355339449   | 12th 17:56:15                     | 12th 18:59:21                    | 63:06              | 157.05                                        |
|     | n1355339449   | n1355343235   | 12th 18:59:21                     | 12th 20:02:27                    | 63:06              | 195.10                                        |
| 4   | n1355343235   | n1355347105   | 12th 20:02:27                     | 12th 21:06:57                    | 64:30              | 233.60                                        |
|     | n1355347105   | n1355350891   | 12th 21:06:57                     | 12th 22:10:03                    | 63:06              | 272.10                                        |
|     | n1355350891   | n1355354677   | 12th 22:10:03                     | 12th 23:13:09                    | 63:06              | 310.15                                        |
|     | n1355354677   | n1355358463   | 12th 23:13:09                     | 13th 00:16:15                    | 63:06              | 348.25                                        |
|     | n1355358463   | n1355362211   | 13th 00:16:15                     | 13th 01:18:43                    | 62:28              | 26.15                                         |
|     | n1355362211   | n1355365978   | 13th 01:18:43                     | 13th 02:21:30                    | 62:47              | 63.95                                         |
|     | n1355365978   | n1355369821   | 13th 02:21:30                     | 13th 03:25:33                    | 64:03              | 102.20                                        |
|     | n1355369821   | n1355373067   | 13th 03:25:33                     | 13th 04:28:39                    | 63:06              | 140.55                                        |
Table S2: Raw images used for the southern hemisphere.

| Day | Image 1   | Image 2   | First image 2000-Dec date & time | Second image 2000-Dec date & time | Separation (mm:ss) | Overlap central pixel (System III W longitude) |
|-----|-----------|-----------|----------------------------------|----------------------------------|-------------------|-----------------------------------------------|
| 1   | n1355233845 | n1355237631 | 11th 13:39:18                    | 11th 14:42:24                   | 63:06             | 212.75                                         |
|     | n1355307631 | n1355241117 | 11th 14:42:24                    | 11th 15:45:30                   | 63:06             | 250.85                                         |
|     | n1355245203 | n1355248989 | 11th 16:48:36                    | 11th 17:51:42                   | 63:06             | 327.05                                         |
|     | n1355248989 | n1355252775 | 11th 17:51:42                    | 11th 18:54:48                   | 63:06             | 5.15                                           |
|     | n1355252775 | n1355256561 | 11th 18:54:48                    | 11th 19:57:54                   | 63:06             | 43.25                                          |
|     | n1355256561 | n1355260347 | 11th 19:57:54                    | 11th 21:01:00                   | 63:06             | 81.35                                          |
|     | n1355260347 | n1355264133 | 11th 21:01:00                    | 11th 22:04:06                   | 63:06             | 119.40                                         |
|     | n1355264133 | n1355267919 | 11th 22:04:06                    | 11th 23:07:12                   | 63:06             | 157.45                                         |
|     | n1355267919 | n1355271705 | 11th 23:07:12                    | 12th 00:10:18                   | 63:06             | 195.55                                         |
| 2   | n1355271705 | n1355275491 | 12th 00:10:18                    | 12th 01:13:24                   | 63:06             | 233.65                                         |
|     | n1355275491 | n1355279277 | 12th 01:13:24                    | 12th 02:16:30                   | 63:06             | 271.75                                         |
|     | n1355279277 | n1355283063 | 12th 02:16:30                    | 12th 03:19:36                   | 63:06             | 309.85                                         |
|     | n1355283063 | n1355286849 | 12th 03:19:36                    | 12th 04:22:42                   | 63:06             | 347.95                                         |
|     | n1355286849 | n1355290635 | 12th 04:22:42                    | 12th 05:25:48                   | 63:06             | 26.00                                          |
|     | n1355290635 | n1355294421 | 12th 05:25:48                    | 12th 06:28:54                   | 63:06             | 64.05                                          |
|     | n1355294421 | n1355298207 | 12th 06:28:54                    | 12th 07:32:00                   | 63:06             | 102.15                                         |
|     | n1355298207 | n1355301993 | 12th 07:32:00                    | 12th 08:35:06                   | 63:06             | 140.25                                         |
|     | n1355301993 | n1355305779 | 12th 08:35:06                    | 12th 09:38:12                   | 63:06             | 178.35                                         |
| 3   | n1355305779 | n1355309565 | 12th 09:38:12                    | 12th 10:41:18                   | 63:06             | 216.45                                         |
|     | n1355309565 | n1355313351 | 12th 10:41:18                    | 12th 11:44:24                   | 63:06             | 254.50                                         |
|     | n1355313351 | n1355317137 | 12th 11:44:24                    | 12th 12:47:29                   | 63:06             | 292.55                                         |
|     | n1355317137 | n1355320923 | 12th 12:47:29                    | 12th 13:50:35                   | 63:06             | 330.65                                         |
|     | n1355320923 | n1355324709 | 12th 13:50:35                    | 12th 14:53:41                   | 63:06             | 8.75                                           |
|     | n1355324709 | n1355328495 | 12th 14:53:41                    | 12th 15:56:47                   | 63:06             | 46.85                                          |
|     | n1355328495 | n1355332281 | 12th 15:56:47                    | 12th 16:59:53                   | 63:06             | 84.95                                          |
|     | n1355332281 | n1355336067 | 12th 16:59:53                    | 12th 18:02:59                   | 63:06             | 123.00                                         |
|     | n1355336067 | n1355339853 | 12th 18:02:59                    | 12th 19:06:05                   | 63:06             | 161.05                                         |
|     | n1355339853 | n1355343639 | 12th 19:06:05                    | 12th 20:09:11                   | 65:59             | 199.15                                         |
| 4   | n1355343639 | n1355347598 | 12th 20:09:11                    | 12th 21:15:10                   | 65:59             | 238.10                                         |
|     | n1355347598 | n135535143 | 12th 21:15:10                    | 12th 23:20:55                   | 63:06             | 352.95                                         |
|     | n135535143 | n1355358929 | 12th 23:20:55                    | 13th 00:24:01                   | 63:06             | 30.30                                          |
|     | n1355358929 | n1355362570 | 13th 00:24:01                    | 13th 01:24:42                   | 60:41             | 30.30                                          |
|     | n1355362570 | n1355366357 | 13th 01:24:42                    | 13th 02:27:49                   | 63:07             | 67.65                                          |
|     | n1355366357 | n1355370295 | 13th 02:27:49                    | 13th 03:33:27                   | 65:38             | 106.50                                         |
|     | n1355370295 | n1355374081 | 13th 03:33:27                    | 13th 04:36:33                   | 63:06             | 145.35                                         |
Figure S1: Velocity fields $\mathbf{u} = (u, v)$. The vectors are subsampled by a factor of 3 in both directions (i.e. are $1.5^\circ$ apart). The colour scale is the same for each day. Figure 3a in the main document contains the plot for day 2.
Figure S2: Relative vorticity $\nabla \times (u, v)$. The colour scale is the same for each day. Figure 3b in the main document contains the plot for day 2.

(a) Day 1

(b) Day 3

(c) Day 4

Relative vorticity ($s^{-1}$)

-1.3e-04 -9.4e-05 -5.1e-05 -2.8e-05 4.6e-06 3.8e-05 7.1e-05 1.0e-04 1.4e-04
Figure S3: Total kinetic energy $|\mathbf{u} \cdot \mathbf{u}|/2$. The colour scale is the same for each day. Figure 3c in the main document contains the plot for day 2.
Figure S4: Eddy kinetic energy $|u - \bar{u}|^2/2$. To improve colour contrast we manually removed a few regions with errors above the 99th $u$-velocity percentile (regions are indicated in the subcaptions), and restricted the maximum value to $10^4$ m$^2$ s$^{-2}$. The colour scale is the same for each day. Figure 3d in the main document contains the plot for day 2.

(a) Day 1. Points removed near 20°S 280°W, 5°S 220°W, and 5°N 105°W.

(b) Day 3. Points removed near 25°S 40°W.

(c) Day 4. Points removed near 0°N 335°W, 5°N 300°W, 15°N 110°W, and 40°N 40°W.
Figure S5: Number of filtered velocity vectors in each mosaic gridbox spanning $(\lambda_i, \phi_j)$ to $(\lambda_i + \delta\lambda, \phi_j + \delta\phi)$. Note the colour scale is different for each subfigure.
Figure S5: continued.

(c) Day 3

(d) Day 4
Figure S6: Estimated random error in $u$ (zonal) velocity component. The maximum in the colour scale is the 99th percentile of the error distribution; points with error in the top 1% are coloured white to preserve the contrast at the low end of the scale. The maximum $u$ error over the four days is 129 m s$^{-1}$. The colour scale is the same for each day.

(a) Day 1

(b) Day 2
Figure S6: continued.

(c) Day 3

(d) Day 4

Velocity error (m s⁻¹)
Figure S7: Estimated random error in $v$ (meridional) velocity component. The maximum in the colour scale is the 99th percentile of the error distribution; points with error in the top 1% are coloured white to preserve the contrast at the low end of the scale. The maximum $v$ error over the four days is 66 m s$^{-1}$. The colour scale is the same for each day.
Figure S7: continued.

(c) Day 3

(d) Day 4
Figure S8: Zonal mean zonal velocity $\bar{u}$ for different latitudinal grid spacings, calculated by binning the filtered velocities (not the mosaiced fields). The dotted line is from Porco et al. (2003), and the dashed line is from Limaye (1986).

(a) $0.30^\circ$
(b) $0.50^\circ$
(c) $0.75^\circ$
(d) $1.00^\circ$
Figure S9: Zonal mean meridional velocity $\tau$ for different latitudinal grid spacings, calculated by binning the filtered velocities (not the mosaiced fields). Dashed lines show ± one standard error from the mean.
Figure S10: Relative vorticity field for day 2, with an uncertainty of 1.0° introduced into the position of individual image pairs before they were combined into the mosaic.