nature geoscience

LETTERS

PUBLISHED ONLINE: 16 OCTOBER 2011 | DOI: 10.1038/NGEO1292

Equatorial winds on Saturn and the stratospheric oscillation

Liming Li[1★], Xun Jiang[1], Andrew P. Ingersoll[2], Anthony D. Del Genio[3], Carolyn C. Porco[4], Robert A. West[5], Ashwin R. Vasavada[5], Shawn P. Ewald[2], Barney J. Conrath[6], Peter J. Gierasch[6], Amy A. Simon-Miller[7], Conor A. Nixon[8], Richard K. Achterberg[8], Glenn S. Orton[5], Leigh N. Fletcher[9] and Kevin H. Baines[5]

The zonal jets on the giant planets have been thought to be stable in time[1–3]. A decline in the velocity of Saturn's equatorial jet has been identified, on the basis of a comparison of cloud-tracking data across two decades[4], but the differences in cloud speeds have since been suggested to stem from changes in cloud altitude in combination with vertical wind shear, rather than from temporal changes in wind strength at a given height[5]. Here, we combine observations of cloud tracks and of atmospheric temperatures taken by two instruments on the Cassini spacecraft to reveal a significant temporal variation in the strength of the high-altitude equatorial jet on Saturn. Specifically, we find that wind speeds at atmospheric pressure levels of 60 mbar, corresponding to Saturn's tropopause, increased by about 20 m s^{-1} between 2004 and 2008, whereas the wind speed has been essentially constant over time in the southern equatorial troposphere. The observations further reveal that the equatorial jet intensified by about 60 m s^{-1} between 2005 and 2008 in the stratosphere, that is, at pressure levels of 1–5 mbar. Because the wind acceleration is weaker near the tropopause than higher up, in the stratosphere, we conclude that the semi-annual equatorial oscillation of Saturn's middle atmosphere[6,7] is also damped as it propagates downwards.

Does the equatorial jet vary with time on the giant planets? A comparison[4] of zonal winds between Voyager (1981–1982) and Hubble Space Telescope (1995–2002) observations suggested that the velocity of Saturn's equatorial jet has decreased with time. Conversely, an analysis[5] of observations by the Imaging Science Subsystem (ISS) on Cassini argued that the decrease of the equatorial jet discussed in the previous study[3] could instead be explained by changes in altitude of the tracked clouds within a zonal wind structure with vertical shear. Studies[8,9] based on data from the Composite Infrared Spectrometer (CIRS) on Cassini determine that vertical shear is present in the equatorial zonal winds. However, other studies[10,11] indicate that the vertical shear is not strong enough to explain the wind decrease. The above debates reveal the need to further characterize the equatorial jet on Saturn with altitude and time. Such results are also critical for discriminating between different theories of large-scale circulation on the giant planets because they provide some important constraints on stability that must be fulfilled.

The equatorial thermal and dynamical structure of planetary atmospheres is also perturbed by quasi-periodic oscillations. A temperature oscillation with a period of 4–5 Earth years, known as the Quasi-Quadrennial Oscillation, has been discovered in the equatorial stratosphere of Jupiter[12]. A recent study[13] indicates that there may be a wind oscillation on Jupiter that is related to the temperature oscillation, similar to the Quasi-Biennial Oscillation on Earth. Cassini observations[4,5] recently showed a Semi-Annual Oscillation of stratospheric temperature in the equatorial region of Saturn. However, we have little information about the temporal variation of equatorial stratospheric winds. Such observations would not only enrich our knowledge of giant-planet dynamics but also help us explore the full phenomenology of Saturn's Semi-Annual Oscillation.

Here we use long-term (2004–2009) observations from ISS and CIRS on board Cassini to examine the temporal variations of the equatorial jet in both the troposphere and stratosphere of Saturn. To obtain accurate measurements of zonal winds in the equatorial region, we select only the ISS image pairs with relatively long time separations and high spatial resolutions to decrease the uncertainty of wind measurements. In addition, the selected ISS images contain long segments of the planetary limb so that they can be navigated well. The selected images on two dates (10 May 2004 and 30 December 2008) and the image processing steps are described in Supplementary Information. Figure 1 shows examples of the processed maps at the strong methane filter (MT3) and the corresponding continuum filter (CB3). The MT3 observations are restricted to the hydrocarbon hazes or other photolysis products in the upper atmosphere[11,14], which are ∼60 mbar in the equatorial region of Saturn[15]. The CB3 observations are generally thought to represent ammonia clouds around 500 mbar. The map scale of Fig. 1 is 0.1° per pixel in latitude and longitude, which corresponds to a spatial resolution of ∼105 km per pixel at the equator. The region very close to the equator (0°–5° S) has low contrast due to the sunlight scattered from Saturn's rings. We identified few cloud features in this region, and exclude it from this study.

After selecting the ISS images, we searched for simultaneous thermal observations in the CIRS data. We found CIRS observations

[1]Department of Earth and Atmospheric Sciences, University of Houston, Houston, Texas 77204, USA, [2]Division of Geological and Planetary Sciences, Caltech, Pasadena, California 91125, USA, [3]NASA Goddard Institute for Space Studies, New York, New York 10025, USA, [4]CICLOPS/Space Science Institute, Boulder, Colorado 80301, USA, [5]Jet Propulsion Laboratory, Caltech, Pasadena, California 91109, USA, [6]Department of Astronomy, Cornell University, Ithaca, New York 14853, USA, [7]NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA, [8]Department of Astronomy, University of Maryland, College Park, Maryland 20742, USA, [9]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford OX1 3PU, UK. *e-mail: lli7@mail.uh.edu.

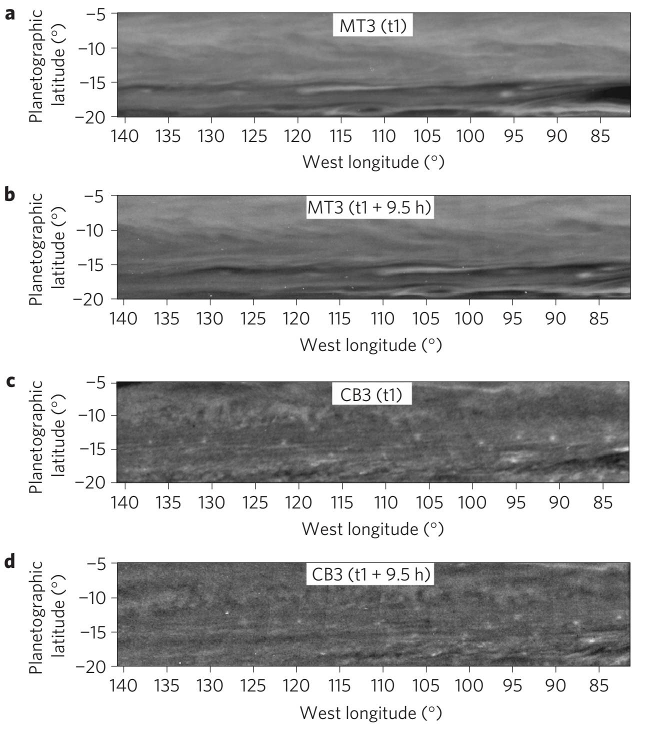

Figure 1 | Southern equatorial maps based on ISS multifilter images taken on 10 May 2004. The spatial resolution of the cylindrical maps is ~105 km per pixel (please refer to Supplementary Table S1). **a**, MT3 map at time 1 (t1). **b**, MT3 map at time 2 (t2), which is taken by ISS 9.5 h later than t1. **c**,**d**, The same as **a**,**b** except that the ISS images are taken at filter CB3.

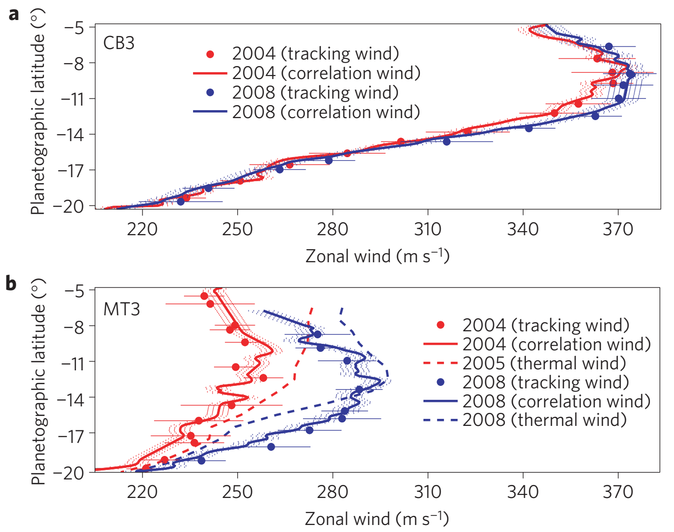

Figure 2 | Saturn wind measurements on different dates. a, Low-altitude winds from the ISS CB3 images. The CB3 winds are located at or deeper than the 500 mbar pressure level, and used as the boundary condition of thermal winds. **b**, High-altitude winds from the ISS MT3 images and the CIRS thermal observations. The CIRS thermal winds at 60 mbar are taken from the tropospheric thermal winds in Supplementary Information. The horizontal solid lines and dashed lines are the uncertainties for the cloud-tracking winds and the correlation winds, respectively.

on 29 December 2008, nearly simultaneous to the ISS observations on 30 December 2008. Unfortunately, we did not find CIRS observations corresponding to the ISS observations on 10 May 2004. The closest CIRS observations of the equatorial region were taken on 8 April 2005. Details of the selected CIRS observations and the procedure of temperature retrieval are also discussed in Supplementary Information.

Based on the ISS and CIRS observations, we apply three methods to measure the zonal winds in the equatorial region of Saturn. The first method is a manual feature tracking. By tracking cloud features that do not substantially alter their shape over time, we can convert their movements into the zonal winds. The derived winds are averaged in 1° latitude bins. The second method is similar to that of ref. 16, in which east–west strips of pixels are extracted from image pairs and shifted to find the maximal cross-correlation coefficient. The third method applies the thermal wind equation to the CIRS temperature maps, as described in our previous study[9]. We use winds measured from the ISS CB3 images to define the boundary level of the thermal wind integration, to maintain approximate consistency in time between the boundary condition and the CIRS temperature.

Wind measurements in Saturn's upper troposphere (that is, ~50–500 mbar) are shown in Fig. 2. The uncertainty of wind measurements based on the ISS images comes from three sources: the standard deviation of multiple wind measurements, the optical characteristics of ISS cameras, and the accuracy of locating cloud/haze features in the ISS images. Uncertainty is discussed in the Supplementary Information. Figure 2 shows that the two image-based methods give a consistent result from the ISS CB3 images. The CB3 zonal wind near 500 mbar increased by a few m s^{-1} from 2004 to 2008, which is within the uncertainty of the measurement. Measurements on the ISS MT3 images (Fig. 2b), which probe the relatively high hazes around 60 mbar, reveal an increase of ~20 m s^{-1} from 2004 to 2008 around 12° S, significantly larger than the uncertainty. We conclude that the wind speed at the level of the high-altitude hazes (~60 mbar) increased, whereas the wind speed at the level of ammonia clouds (~500 mbar) remained constant (within uncertainty) from 2004 to 2008.

To examine the temporal variation of zonal winds revealed by the ISS images, we further analyse the thermal winds in the equatorial region of Saturn. Figure 2 shows the profile of thermally derived zonal winds at 60 mbar, which is based on Supplementary Fig. S1. The 60 mbar thermal winds also show an increase of ~20 m s^{-1} around 12° S between 2005 and 2008. The increase is mainly due to the warming of the equatorial region and the corresponding changes of the temperature gradient in the troposphere of Saturn (Supplementary Fig. S1). The uncertainty of thermal winds is closely related to the uncertainty of the retrieved temperature and the corresponding meridional gradient, which is difficult to estimate quantitatively. The uncertainty of the CIRS retrieved temperature is ~1 K in the upper troposphere[17], smaller than the magnitude of temperature variation of ~2 K in the equatorial region shown in Supplementary Fig. S1. The retrieval process leaves some uncertainty in the magnitude of warming around the equator, but the warming trend from 2005 to 2008 is robust[17]. The warming trend of atmospheric temperature intensifies the zonal winds through the thermal wind relationship, which explains the qualitative consistency of the high-altitude winds between the ISS measurements and the CIRS observations. On the other hand, the temperature of the relatively deep atmosphere around 500 mbar does not change significantly (Supplementary Fig. S1), which is probably due to the long timescale of radiative adjustment of the deep atmosphere.

We also apply the thermal wind equation to the stratospheric temperature retrieved from the CIRS nadir observations (Supplementary Fig. S2). Supplementary Fig. S2 shows that the thermal winds in the stratosphere increased by ~60 m s^{-1} from 2005 to 2008, which confirms the previous results from the CIRS limb observations[18]. The temporal variation of the equatorial jet in the stratosphere is related to the varying temperature, which has been observed previously[17–19]. In these previous studies[18,19], the varying temperature and the related thermal winds are further linked to the vertical propagation of Saturn's equatorial oscillation.

In this study, we report the temporal variation of equatorial jet speed at different altitudes in the troposphere and stratosphere of Saturn. We find that the wind speed of the equatorial jet around the tropopause (∼60 mbar) increased by ∼20 m s^{-1} from 2004 to 2008. This is the first change of the equatorial jet around the tropopause to be observed at the timescale of a few Earth years. At the timescale of one Saturn year (∼29.4 Earth years), inter-annual variations of cloud morphology[20] and heat budget[21] have been discovered on the giant planets. The season of Saturn will be the same in 2010–2011 as it was during the Voyager epoch (1980–1981). A detailed comparison of the wind field between the Cassini extended mission and the Voyager mission will shed light on the inter-annual variation of equatorial jet structure on Saturn.

As well as enriching our knowledge of the equatorial jet and oscillation, the temporal variation of zonal winds has important implications for atmospheric dynamics on Saturn. The high-altitude equatorial jet is at 60 mbar, which is near the tropopause[17]. The direct measurement of zonal winds near the tropopause will benefit the exploration of thermal winds in the stratosphere. In refs 6 and 18 the thermal wind equation is integrated in Saturn's low-latitude stratosphere by assuming a null wind as the boundary condition around 20 mbar. Obviously, measured winds near the tropopause will be a better boundary condition for deriving the thermal winds in the stratosphere, even though the different boundary conditions do not change the vertical structure of zonal winds discussed in the previous studies[6,18]. The weaker time variation of the equatorial jet at 60 mbar (∼20 m s^{-1}) than at 1 mbar (∼60 m s^{-1}) further implies a commonality in the vertical propagation of the equatorial oscillation between Saturn and Earth[22]. Finally, the difference in behaviour in the time variation of zonal winds between the troposphere (for example, 500 mbar) and the stratosphere (for example, 1 mbar) suggests that the driving mechanisms of zonal winds are probably different between the stratosphere, where the radiative effects are important, and the troposphere, where the convection and turbulence are important.

Received 16 February 2011; accepted 14 September 2011; published online 16 October 2011

References

1. Irwin, P. G. J. *Giant Planets of Our Solar System* 141–142 (Praxis Publishing, 2003).
2. Cho, J. Y. & Polvani, L. M. The morphogenesis of bands and zonal winds in the atmospheres on the giant outer planets. *Science* **19,** 335–337 (1996).
3. Galperin, B., Sukoriansky, S. & Huang, H. Universal n^{-5} spectrum of zonal flows on giant planets. *Phys. Fluids* **13,** 1545–1549 (2001).
4. Sanchez-Lavega, A., Perez-Hoyos, S., Rojas, J. F. & French, R. G. A strong decrease in Saturn's equatorial jet at cloud level. *Nature* **423,** 623–625 (2003).
5. Porco, C. C. *et al.* Cassini imaging science: Initial results on Saturn's atmosphere. *Science* **307,** 1243–1247 (2005).
6. Fouchet, T. *et al.* An equatorial oscillation in Saturn's middle atmosphere. *Nature* **453,** 200–202 (2008).
7. Orton, G. S. *et al.* Semi-annual oscillations in Saturn's low-latitude stratospheric temperatures. *Nature* **453,** 196–199 (2008).
8. Flasar, F. M. *et al.* Temperatures, winds, and composition in the Saturnian system. *Science* **307,** 1247–1251 (2005).
9. Li, L. *et al.* Strong jet and a new thermal wave in Saturn's equatorial stratosphere. *Geophys. Res. Lett.* **35,** L23208 (2008).
10. Perez-Hoyos, S. & Sanchez-Lavega, A. On the vertical wind shear of Saturn's equatorial jet at cloud level. *Icarus* **180,** 161–175 (2006).
11. Sanchez-Lavega, A., Hueso, R. & Perez-Hoyos, S. The three-dimensional structure of Saturn's equatorial jet at cloud level. *Icarus* **187,** 510–519 (2007).
12. Leovy, C. B., Friedson, A. J. & Orton, G. S. The quasi-quadrennial oscillation of Jupiter's equatorial atmosphere. *Nature* **354,** 380–382 (1991).
13. Simon-Miller, A. A. & Gierasch, P. J. On the long-term variability of Jupiter's winds and brightness as observed from Hubble. *Icarus* **210,** 258–269 (2010).
14. García-Melendo, E., Sánchez-Lavega, A., Rojas, J. F., Pérez-Hoyos, S. & Hueso, R. Vertical shears in Saturn's eastward jets at cloud level. *Icarus* **201,** 818–820 (2009).
15. Garcia-Melendo, E., Sanchez-Lavega, A., Legarreta, J., Perez-Hoyos, S. & Hueso, R. A strong high altitude narrow jet detected at Saturn's equator. *Geophys. Res. Lett.* **37,** L22204 (2010).
16. Limaye, S. S. Jupiter: New estimates of the mean zonal flow at the cloud level. *Icarus* **65,** 335–352 (1986).
17. Fletcher, L. N. *et al.* Seasonal change on Saturn from Cassini/CIRS observations, 2004–2009. *Icarus* **208,** 337–352 (2010).
18. Guerlet, S., Fouchet, T., Bezard, B., Flasar, F. M. & Simon-Miller, A. A. Evolution of the equatorial oscillation in Saturn's atmosphere between 2005 and 2010 from Cassini/CIRS limb data analysis. *Geophys. Res. Lett.* **38,** L09201 (2011).
19. Schinder, P. J. *et al.* Saturn's equatorial oscillation: Evidence of descending thermal structure from Cassini radio occultations. *Geophys. Res. Lett.* **38,** L08205 (2011).
20. Baines, K. H. *et al.* Polar lightning and decadal-scale cloud variability on Jupiter. *Science* **318,** 226–229 (2007).
21. Li, L. *et al.* Emitted power of Jupiter. *J. Geophys. Res.* **115,** E11002 (2010).
22. Baldwin, M. P. *et al.* The quasi-biennial oscillation. *Rev. Geophys.* **39,** 179–229 (2001).

Acknowledgements

NASA Cassini Data Analysis Program funded this work. We acknowledge E. Garcia-Melendo, R. Hueso, A. Sanchez-Lavega, and S. Perez-Hoyos for providing comments and discussions. We are also grateful for comments and suggestions on this work from two anonymous reviewers.

Author contributions

L.L. measured the ISS winds (correlated), computed the thermal winds and conceived the overall research. X.J. carried out the ISS wind measurements (cloud tracking). X.J., A.P.I., A.D.D.G., C.C.P., R.A.W., A.R.V., S.P.E., B.J.C., P.J.G., A.A.S-M., C.A.N., R.K.A., G.S.O., L.N.F. and K.H.B. provided assistance in interpreting the observational results.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to L.L.