Vol 460 | 13 August 2009 | doi:10.1038/nature08193

LETTERS

Storms in the tropics of Titan

E. L. Schaller[1], H. G. Roe[2], T. Schneider[3,4] & M. E. Brown[3]

Methane clouds, lakes and most fluvial features on Saturn's moon Titan have been observed in the moist high latitudes[1–6], while the tropics have been nearly devoid of convective clouds and have shown an abundance of wind-carved surface features like dunes[7,8]. The presence of small-scale channels and dry riverbeds near the equator observed by the Huygens probe[9] at latitudes thought incapable of supporting convection[10–12] (and thus strong rain) has been suggested to be due to geological seepage or other mechanisms not related to precipitation[13]. Here we report the presence of bright, transient, tropospheric clouds in tropical latitudes. We find that the initial pulse of cloud activity generated planetary waves that instigated cloud activity at other latitudes across Titan that had been cloud-free for at least several years. These observations show that convective pulses at one latitude can trigger short-term convection at other latitudes, even those not generally considered capable of supporting convection, and may also explain the presence of methane-carved rivers and channels near the Huygens landing site.

Insolation on Titan varies seasonally during Saturn's 29.5-year orbit because of its 27° obliquity. The frequent presence of tropospheric clouds near the south pole at the southern summer solstice[1,2] led to the hypothesis that seasonally varying insolation controlled Titan's cloud locations[1]. Recent observations have shown that Titan's clouds display more complicated behaviour, including clouds at southern mid-latitudes[14,15] and clouds associated with lakes near the north pole[6]. Titan general circulation models have predicted that the majority of convective cloud activity should occur near the summer poles, with some cloud activity occurring at mid-latitudes, and very little in the tropics[10–12,16]. Although there are differences in the precise locations and frequencies of clouds in these models, they all predict that the equatorial regions should generally be the driest locations on the moon throughout most of Titan's year. In contrast with these predictions, images taken during the descent of the Huygens probe through Titan's atmosphere in January 2005 revealed small-scale channels and streams that appeared to have been carved by fluids (presumably methane) at equatorial (10° S) latitudes[17]. The morphologies of these channels also suggested that a high precipitation rate was needed to form them[18].

Unlike the Earth, which is approximately 65% cloud covered throughout the year[19], observations of Titan since 1990 have generally revealed a small amount of tropospheric cloud activity, covering only a small fraction (less than 1%) of Titan's disk[7,20,21]. However, on two occasions (September 1995 and October 2004; refs 22 and 23) clouds were observed to brighten dramatically, covering 5–7% of the surface, and, in the case of the October 2004 event, were found to last for at least a month. To determine the frequencies and causes of these short-lived cloud brightenings, which are thought to be associated with significant amounts of methane precipitation[24], we developed a long-term observing programme with the National Aeronautics and Space Administration (NASA) Infrared Telescope Facility (IRTF) to determine the percentage of tropospheric cloud coverage of Titan's disk on a frequent (nearly nightly) basis[25].

Although 138 nights of observations spread over 2.2 years revealed extremely low levels of cloud activity (0.3% coverage)[25], on 13 April 2008 we observed an increase in flux at surface- or troposphere-probing wavelengths of brightness comparable to that of the events from 1995 and 2004 (Fig. 1). The following night we triggered adaptive optics observations with the Near Infrared Imager (NIRI) on the Gemini North telescope. These infrared images revealed a large cloud system in Titan's troposphere centred at 29° S, 247° W and with a latitudinal extent of ±15°. In observations over the next three nights, the brightness centroid of this cloud system moved with an apparent eastward velocity of $3 \pm 1\ \mathrm{m\,s^{-1}}$. The system also spread out in a southeastward direction, and finally rotated completely off the limb on 17 April. On 16–17 and 20–23 April, clouds also appeared near the south pole (81–60° S), with brightnesses not seen in the previous three years[7] (Figs 2 and 3).

The south pole was not predicted to be capable of supporting convective clouds during the season these clouds were observed (one year before vernal equinox)[10,12,26], and clouds of this brightness had not been observed since November 2004 despite frequent imaging[7] and IRTF spectral monitoring[25]. Thus the appearance of relatively bright south polar clouds 3–7 days after the largest increase in Titan cloud activity observed in over three years points to a causal relationship. The south polar clouds were probably instigated by an atmospheric teleconnection mediated by planetary Rossby waves, formed from the initial pulse of cloud activity that occurred between 9 and 13 April. Rossby waves are large-scale atmospheric waves familiar from the

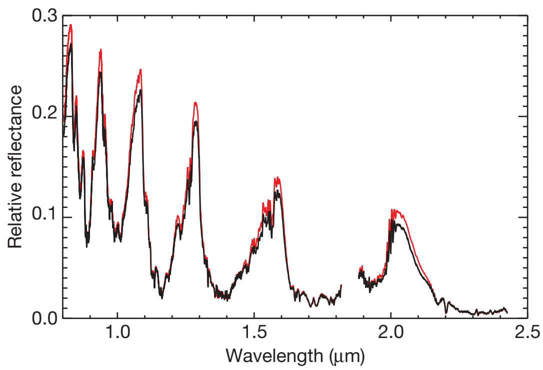

Figure 1 | Titan IRTF spectra. Near-infrared spectra of Titan from 28 March and 13 April 2008. Both spectra have approximately the same central longitude (227° W), but the spectrum from 13 April (red) shows increased flux in the transparent regions of Titan's atmosphere (0.8, 0.95, 1.2, 1.6 and 2.0 μm) while staying the same brightness in the high-opacity regions. Gemini images from the following night show the presence of a large extended cloud centred at 29° S, 247° W. Large cloud outbursts such as these (where Titan's clouds are seen to increase by over a factor of ten over typical levels) have been observed on only two other occasions[22,23]. The methane rainout from these large storms is thought to be responsible for carving Titan's streams and valley networks[18,24].

[1]Institute for Astronomy, University of Hawaii, Honolulu, Hawaii 96822, USA. [2]Lowell Observatory, Flagstaff, Arizona 86001, USA. [3]Geological and Planetary Sciences, [4]Environmental Science and Engineering, California Institute of Technology, Pasadena, California 91125, USA.

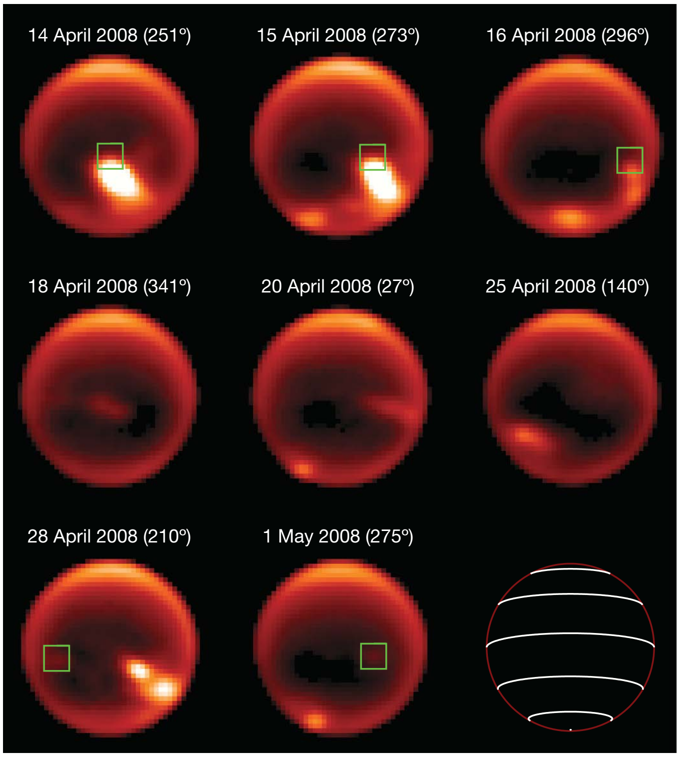

Figure 2 | Gemini adaptive optics images of Titan. Titan sub-Earth longitude and Universal Time date are noted for each observation. Images were taken through the H2(1-0) (2.1 μm) filter that probes to Titan's troposphere. Clouds were first detected on 13 April 2008 by our whole-disk spectroscopic monitoring programme with IRTF (Fig. 1). Clouds were subsequently detected in tropical, polar, and temperate latitudes using the Gemini adaptive optics system. Images from 28 April 2008 and 1 June 2008 show a faint cloud persisting over the same location as the northwesternmost extent of the initial large cloud from 14 April 2008 (15° S, 250° W; green box), perhaps indicating that the initial cloud outburst may have been localized here (see also Fig. 3).

Earth's atmosphere, which can propagate in the zonal and meridional directions. They can instigate cloud activity by modifying the temperature structure of the atmosphere and by inducing convergent flow near the surface. For a wave generated in the tropics to reach 72° S latitude in 3–7 days, it needs to travel with a meridional velocity of 3–8 $m s^{-1}$. Deep (barotropic) Rossby waves with wavenumbers of ~2 have zonal and meridional group velocities consistent with the observed propagation velocities (see Supplementary Information). Such long waves are probably the only ones able to propagate out of low-latitude generation regions (see Supplementary Information).

In addition to cloud activity near the south pole, on 18–20 April we also observed cloud activity from 20–12° S latitude, which are the closest latitudes to the equator we have ever observed cloud activity from the ground. Given the near lack of cloud activity at these low latitudes in all other observations (even from Cassini[27,28]), it is likely that these clouds were also triggered by the initial outburst. The near-equatorial clouds persisted for several days and had extended streak-like morphologies, similar to the mid-latitude clouds observed from 2003 to 2006 (refs 14, 15).

On 24 and 25 April 2008, the initial cloud rotated back onto the observable limb, decreased in brightness from that of the initial outburst but still moving with the same velocity of ~3 $m s^{-1}$ as in the initial three days of observations (Figs 2 and 3). South polar cloud activity was nearly non-existent. However, the image from 28 April shows that the same cloud system had grown significantly brighter, perhaps caused by the initial wave re-instigating cloud activity downstream. This new pulse of cloud activity, comparable in brightness to the original pulse from 14 April, displayed a similar morphology to the clouds seen on 15 and 16 April. Similarly, days later, clouds were also observed near the south pole and at near-equatorial latitudes. These observations demonstrate that a convective pulse at one latitude can trigger cloud activity at other latitudes thought to be incapable of supporting convective cloud activity. The cloud activity observed near the south pole indicates that for this short time period, convection was remarkably vigorous. Clouds appeared and re-appeared over different longitudes only days apart, indicating the likely formation and reformation of these cloud systems (similar to what was observed in October 2004). The precise locations where clouds formed were probably related to local surface conditions and methane abundances. An extremely dry location on Titan might not form clouds even if wave activity favoured it—whereas a methane lake might need only a small trigger to generate cloud activity above it (note that all of the south polar clouds that formed during this event were centred near 72° S, the latitude of Ontario Lacus).

Subsequent frequent observations from both Gemini and IRTF (30 distinct nights) revealed little to no cloud activity from 15 May to the end of the observable Titan season from the ground (7 July), indicating that the total duration of the increased cloud activity was less than one month. The duration of this period of increased cloud activity matched that of the last such outburst, which occurred in

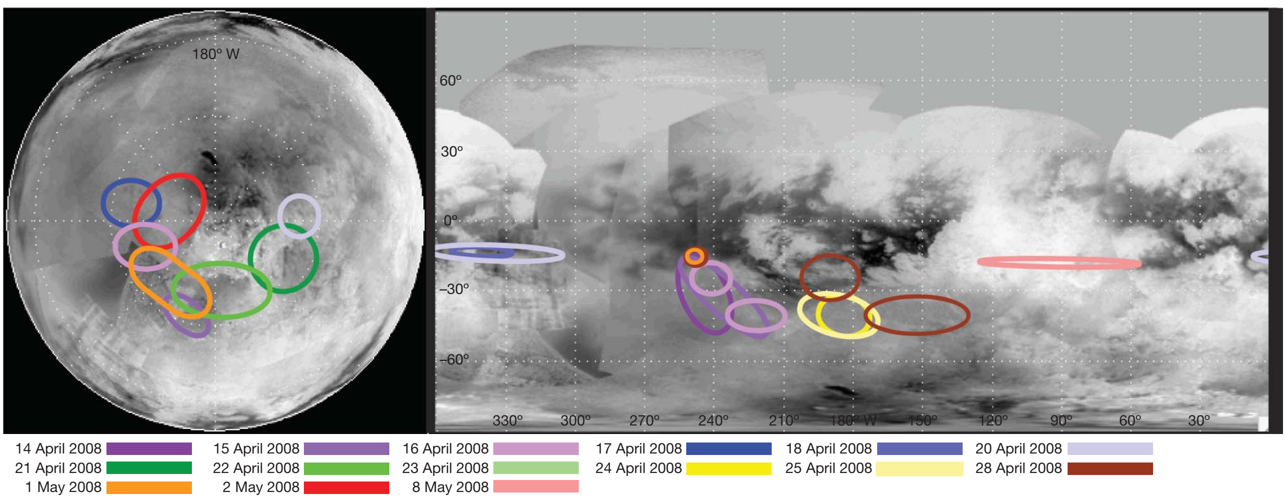

Figure 3 | Titan cloud locations. Cassini ISS surface maps (from http://ciclops.org) with locations of clouds from 14 April to 8 May 2008. No clouds were observed on 23 April 2008. Clouds that are located poleward of 55° S latitude are shown on the pole-projected surface map. Both maps show latitude lines in 30° increments. The northwesternmost latitudes encompassed by the initial pulse of cloud activity on 14 April show the continued presence of a small cloud for at least 19 days after the initial event, indicating a potential tie to the surface.

October 2004 and lasted for approximately 30 days. Large cloud outbursts such as these are thought to be associated with significant amounts of precipitation[24] and probably play a major part in shaping the geological features on the surface of Titan.

One of the most intriguing questions is the cause and precise location of the initial pulse of cloud activity. Observations from 28 April and 1 May show that the northwesternmost regions encompassed by the initial pulse of cloud activity (15° S, 250° W) still remain bright in the 2.1-μm images, indicating the continued presence of a small cloud (Figs 2 and 3). This region could have been the location of the initial pulse of cloud activity given the subsequent southeastward velocity of the bright cloud features. The Cassini ISS surface map in this region is unremarkable. Although several locations on Titan have been suggested to show evidence for cryovolcanic activity[14,29] (specifically regions that are bright at 5 μm), this region is not one of them. The difficulty of forming large convective clouds at tropical latitudes, combined with the continued brightness of this region for at least 19 days, may point to a potential connection to the surface. If the surface were locally heated from below only slightly, parcels of air could be more easily lifted up to the level of free convection, leading to deep convective clouds. Additionally or alternatively, an injection of methane from the subsurface at this location could have a similar effect by lowering the level of free convection. The brightness and rapid formation of the initial cloud system indicates that the region centred on 15° S, 250° W is a good candidate location for observing surface changes due to methane rainout and, if the initial pulse were indeed tied to the surface, perhaps also recent cryovolcanism.

Received 5 March; accepted 2 June 2009.

1. Brown, M. E., Bouchez, A. H. & Griffith, C. A. Direct detection of variable tropospheric clouds near Titan's south pole. *Nature* **420,** 795–797 (2002).
2. Roe, H. G., de Pater, I., Macintosh, B. A. & McKay, C. P. Titan's clouds from Gemini and Keck adaptive optics imaging. *Astrophys. J.* **581,** 1399–1406 (2002).
3. Stofan, E. R. *et al.* The lakes of Titan. *Nature* **445,** 61–64 (2007).
4. Lorenz, R. D. *et al.* Fluvial channels on Titan: Initial Cassini RADAR observations. *Planet. Space Sci.* **56,** 1132–1144 (2008).
5. Brown, R. H. *et al.* The identification of liquid ethane in Titan's Ontario Lacus. *Nature* **454,** 607–610 (2008).
6. Brown, M. E. *et al.* Discovery of lake-effect clouds on Titan. *Geophys. Res. Lett.* **36,** LO1103 (2009).
7. Schaller, E. L., Brown, M. E., Roe, H. G., Bouchez, A. H. & Trujillo, C. A. Dissipation of Titan's south polar clouds. *Icarus* **184,** 517–523 (2006).
8. Barnes, J. W. *et al.* Spectroscopy, morphometry, and photoclinometry of Titan's dunefields from Cassini/VIMS. *Icarus* **195,** 400–414 (2008).
9. Soderblom, L. A. *et al.* Topography and geomorphology of the Huygens landing site on Titan. *Planet. Space Sci.* **55,** 2015–2024 (2007).
10. Mitchell, J. T., Pierrehumbert, R. T., Frierson, D. M. & Caballero, R. The dynamics behind Titan's methane clouds. *Icarus* **103,** 18421–18426 (2006).
11. Mitchell, J. L. The drying of Titan's dunes: Titan's methane hydrology and its impact on atmospheric circulation. *J. Geophys. Res. Planets* **113,** EO8015 (2008).
12. Rannou, P., Montmessin, F., Hourdin, F. & Lebonnois, S. The latitudinal distribution of clouds on Titan. *Science* **311,** 201–205 (2006).
13. Griffith, C. A., McKay, C. P. & Ferri, F. Titan's tropical storms in an evolving atmosphere. *Astrophys. J.* **687,** L41–L44 (2008).
14. Roe, H. G., Brown, M. E., Schaller, E. L., Bouchez, A. H. & Trujillo, C. A. Geographic control of Titan's mid-latitude clouds. *Science* **310,** 477–479 (2005).
15. Griffith, C. A. *et al.* The evolution of Titan's mid-latitude clouds. *Science* **310,** 474–477 (2005).
16. Tokano, T. *et al.* Methane drizzle on Titan. *Nature* **442,** 432–435 (2006).
17. Lebreton, J.-P. *et al.* An overview of the descent and landing of the Huygens probe on Titan. *Nature* **438,** 758–764 (2005).
18. Perron, J. T. *et al.* Valley formation and methane precipitation rates on Titan. *J. Geophys. Res. Planets* **111,** E11001 (2006).
19. Rossow, W. B. & Schiffer, R. A. Advances in understanding clouds from ISCCP. *Bull. Am. Meteorol. Soc.* **80,** 2261–2287 (1999).
20. Griffith, C. A., Hall, J. L. & Geballe, T. R. Detection of daily clouds on Titan. *Science* **290,** 509–513 (2000).
21. Bouchez, A. H. & Brown, M. E. Statistics of Titan's south polar tropospheric clouds. *Astrophys. J.* **618,** L53–L56 (2005).
22. Griffith, C. A., Owen, T., Miller, G. A. & Geballe, T. Transient clouds in Titan's lower atmosphere. *Nature* **395,** 575–578 (1998).
23. Schaller, E. L., Brown, M. E., Roe, H. G. & Bouchez, A. H. A large cloud outburst at Titan's south pole. *Icarus* **182,** 224–229 (2006).
24. Hueso, R. & Sánchez-Lavega, A. Methane storms on Saturn's moon Titan. *Nature* **442,** 428–431 (2006).
25. Schaller, E. L., Brown, M. E. & Roe, H. G. Seasonal change in Titan's cloud activity observed with IRTF/SpeX. *Astron. J.* (submitted).
26. Tokano, T. Meteorological assessment of the surface temperatures on Titan: constraints on the surface type. *Icarus* **173,** 222–242 (2005).
27. Turtle, E. P. *et al.* Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes. *Geophys. Res. Lett.* **36,** L02204 (2009).
28. Brown, M. E., Roberts, J. & Schaller, E. L. Clouds on Titan during the Cassini prime mission: a complete analysis of the VIMS data. *Icarus* (submitted).
29. Barnes, J. W. *et al.* A 5-micron-bright spot on Titan: evidence for surface diversity. *Science* **310,** 92–95 (2005).

Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements E.L.S. is supported by a Hubble Postdoctoral Fellowship. H.G.R is supported by the NASA Planetary Astronomy Program. M.E.B. is supported by an NSF Planetary Astronomy grant. We thank IRTF telescope operators, D. Griep, W. Golisch, P. Sears and E. Volquardsen. The IRTF is operated by the University of Hawaii under a cooperative agreement with the Planetary Astronomy Program of the NASA Science Mission Directorate. Gemini Observatory is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the International Gemini partnership.

Author Contributions E.L.S. analysed and interpreted the IRTF and Gemini observations and wrote the paper. H.G.R. was responsible for the Gemini observations, data reduction, and analysis. T.S. helped interpret the observations. T.S. and E.L.S. wrote the Supplementary Information. M.E.B. supervised the project. All authors discussed the results and implications and commented on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. Correspondence and requests for materials should be addressed to E.L.S. (schaller@ifa.hawaii.edu).