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LETTERS

Global circulation as the main source of cloud activity on Titan

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Clouds on Titan result from the condensation of methane and ethane and, as on other planets, are primarily structured by circulation of the atmosphere[1–4]. At present, cloud activity mainly occurs in the southern (summer) hemisphere, arising near the pole[5–12] and at mid-latitudes[7,8,13–15] from cumulus updrafts triggered by surface heating and/or local methane sources, and at the north (winter) pole[16,17], resulting from the subsidence and condensation of ethane-rich air into the colder troposphere. General circulation models[1–3] predict that this distribution should change with the seasons on a 15-year timescale, and that clouds should develop under certain circumstances at temperate latitudes (~40°) in the winter hemisphere[2]. The models, however, have hitherto been poorly constrained and their long-term predictions have not yet been observationally verified. Here we report that the global spatial cloud coverage on Titan is in general agreement with the models, confirming that cloud activity is mainly controlled by the global circulation. The non-detection of clouds at latitude ~40° N and the persistence of the southern clouds while the southern summer is ending are, however, both contrary to predictions. This suggests that Titan's equator-to-pole thermal contrast is overestimated in the models and that its atmosphere responds to the seasonal forcing with a greater inertia than expected.

The Visual and Infrared Mapping Spectrometer[18] (VIMS) on board NASA's Cassini spacecraft provides a unique opportunity to regularly and accurately chart cloud activity from a close vantage point—hence with high spatial resolution and good spectral coverage. We developed a semi-automated algorithm to isolate clouds from other contributions in VIMS images (Fig. 1) and applied it to 10,000 images of Titan. These images encompass several million spectra, acquired during 39 monthly fly-bys of Titan between July 2004 and December 2007.

The total distribution of cloud events derived from our detections (Fig. 2) and the time variation of their latitudinal distribution (Fig. 3a) indicates that cloud activity is clustered at three distinct latitudes during the 2004–2007 period: the south polar region (poleward of 60° S), the north polar region (poleward of 50° N) and a narrow belt centred at ~40° S. Individual detection maps are provided for each fly-by in Supplementary Figs 1–4.

Our study clearly shows the stability of the north polar cloud, which is systematically detected over the 2004–2007 period. We observe this extensive meteorological system poleward of 50–60° N. All of these clouds spectrally differ from the southern clouds, which are presumably formed by wet convection and are made of large (tens of micrometres in size), liquid/solid methane droplets[2,16]. They produce much less signal at 5 μm than any other cloudy features we detect elsewhere on Titan, indicating less backscattering at that wavelength. Given that complex indices of refraction of methane and ethane are not that different at 5 μm, the difference in backscattering comes essentially from the particle size. Relatively less backscattering at 5 μm is consistent with north polar clouds composed of smaller (micrometre-sized) particles more probably made of solid ethane[2,16,17]. We also detect small, elongated clouds at ~60–70° N in March and April 2007. Surrounded by the large north polar ethane cloud, these clouds are thought to be convective methane clouds connected to the underlying lakes[19]. Their higher brightness at 5 μm confirms that they are similar to the methane clouds found in the southern hemisphere.

A few tropical clouds, thought to be rare during Titan's summer, are detected close to the equator (~15° S) on 12 December 2006. Their areas never exceed 10,000 km^2. These clouds therefore could not have been detected from ground-based observations. More details about tropical clouds are given in ref. 20. We also observe more than 100 isolated and transient temperate clouds near 40° S (Figs 2 and 3a). Most of them are elongated in the east–west direction, as was previously reported[7,8,13–15], possibly owing to orographic waves over zonally oriented topography and/or shearing and stretching by strong zonal winds of tens of metres per second[7]. This type of cloud appeared during two periods, in 2004 and then regularly (in two-thirds of the fly-bys) between July 2006 and October 2007. Between December 2004 and August 2006, temperate clouds are observed very rarely (only in October 2005 (ref. 10) and January 2006 (this study)). This could be attributed to less frequent fly-bys of Titan by Cassini and/or a momentary decline in cloud activity.

We compared our latitudinal and time distribution of clouds (Fig. 3a) with predictions of the IPSL-TGCM[2], which so far is the only general circulation model for Titan to include a microphysical cloud scheme and, thus, predict the cloud cover (Fig. 3b). Except for the lack of winter mid-latitude clouds (40° N), we find that the main spatial characteristics of our cloud distribution are well reproduced by the IPSL-TGCM. Clouds appear in the model near altitude 12 km at latitude ~40° in the summer hemisphere (the southern hemisphere until 2009), and are associated with the ascent of the convergence zone of a Hadley-type cell[1–3]. Clouds are also predicted very near the summer pole, where methane, driven from the warmer region below, condenses, generating convective structures[2,21–23]. In the winter polar region, the cloud formation is related to the downwelling stratospheric circulation, which drives ethane- and aerosol-enriched stratospheric air into the cold tropopause of the polar night (above 40 km). The

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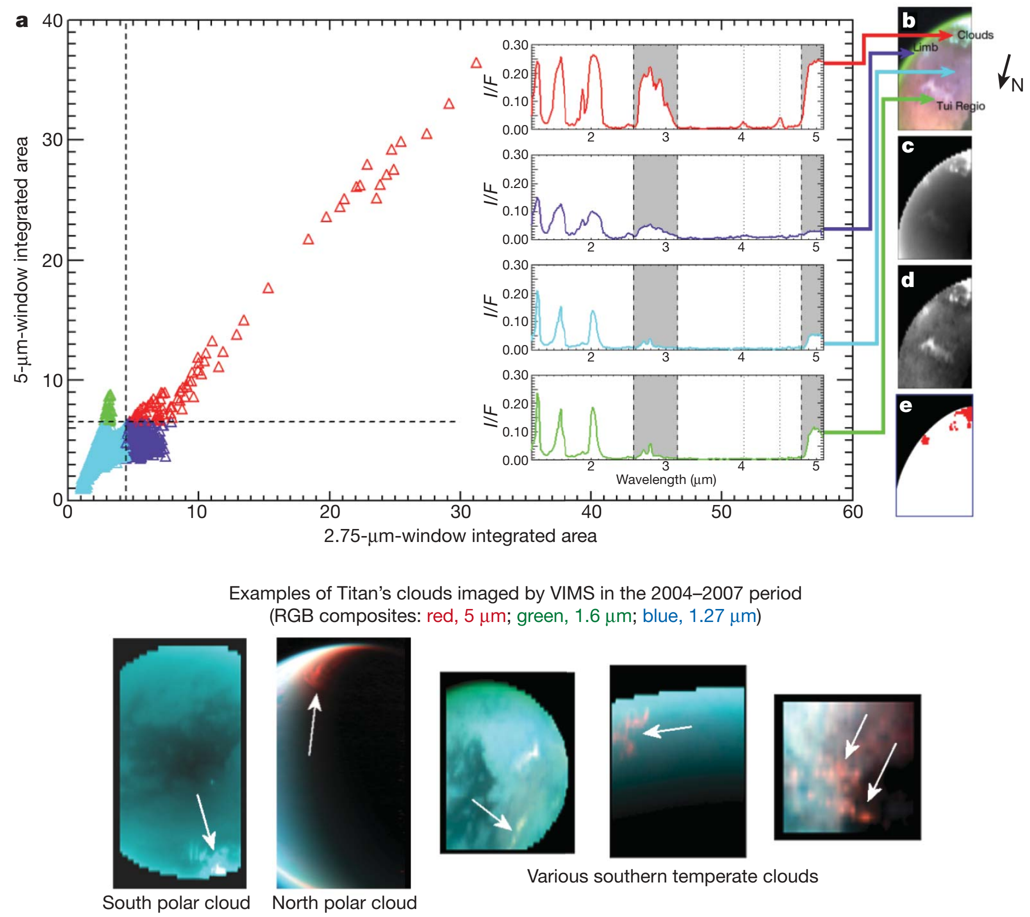

Figure 1 | Method of spectral detection of Titan's clouds illustrated on a representative VIMS data cube. The VIMS on board Cassini acquires a 352-channel spectrum from 0.3 to 5.1 μm for each pixel of an image[18]. **a**, Scatter plot of the 2.75-μm-window integrated area versus the 5-μm-window integrated area of the VIMS colour image shown in **b**, with red indicating a wavelength of 2.03 μm; green, 2.78 μm; and blue, 5 μm. The window integrated areas correspond to the integral of I/F within the spectral range shown in grey in the spectra (I is the observed specific intensity and πF is the incident solar intensity). **c**, **d**, Images of the 2.75-μm-window (**c**) and 5-μm-window (**d**) integrated areas, coded in greyscale (high values appear bright). Characteristic spectra are inset in **a**, showing clouds (red), limb (violet), typical surface (cyan) and a high 5-μm signal surface feature (Tui Regio[27], green). 'Surface' windows correspond to peaks at 1.27, 1.59, 2.03, 2.75 and 5 μm. Because clouds are efficient reflectors and reduce the path lengths of solar photons, their spectra present a brightening of all surface windows relative to other spectra. We found that the most robust spectral criterion to separate cloud pixels from other contributions (surface and limb) is the simultaneous increased integrated areas of the 2.75- and 5-μm windows. Conservative, 2σ thresholds for the integrated areas of these two windows are automatically calculated to isolate pixels corresponding to clouds (red triangles in **a**). We deliberately choose a conservative threshold to avoid false positives. This can lead to the rare non-detection of optically thin or low-altitude clouds, of clouds much smaller than a VIMS pixel or of clouds that are too close to the limb. **e**, The resulting cloud-pixel detection (in red), which we reproject on a global map (Fig. 2).

observed stability of the north polar clouds is interpreted, using the IPSL-TGCM, as the result of a constant incoming flux of ethane and aerosols from the stratosphere[24], producing a mist of micrometre-sized droplets of ethane and other products that slowly settles.

However, present observations do not confirm the clouds at ~40° N predicted by the IPSL-TGCM. In the model, these clouds should result from horizontal diffusive transport by inertial instabilities of air, partially humid (relative humidity, 50%) in tropical regions, towards the colder north pole. At an altitude of 12 km, where these clouds are formed, the model predicts an equator-to-pole temperature contrast of $T_{80^\circ\mathrm{N}} - T_{0^\circ} = -4$ K. Such a contrast causes the air to become saturated and to produce clouds around 40° N. The lack of such clouds in observations could be explained by an actual equator-to-pole temperature contrast of about −1.5 K instead of the −4 K predicted by the IPSL-TGCM. Such a small thermal contrast would allow air parcels with relative humidities of 50% in tropical regions to move towards the pole without condensing. Conversely, it could also enable the north polar region, where lakes are observed and which is saturated in methane, to wet the tropical regions up to 50% humidity. If we consider the conditions at the surface, computations, including phase equilibrium with a N_2–CH_4 mixture, show that with an equator-to-pole temperature contrast near the ground of −4.2 K (instead of −6.5 K in the IPSL-TGCM), an air parcel at methane saturation near the pole (fed by lakes) would be at 50% humidity if transported at the tropics. Only 80% humidity would be needed at the north pole if the temperature contrast at the surface were to drop to −3 K, which is actually observed[25].

In addition, the timing of the summer-hemisphere clouds as constrained by our observations is poorly reproduced by the IPSL-TGCM. Figure 3b shows that the southern cloud activity should gradually decrease as the equinox approaches, as a consequence of a progressive change in the south polar circulation pattern. This forecasted decline of southern meteorological activity is not supported by our data. According to the IPSL-TGCM, the south polar clouds should have disappeared in mid-2005 and the mid-latitude clouds should have gradually disappeared since 2005, whereas in our observations the southern clouds are still present even late in 2007 and are particularly active at 40° S until mid-2007. The significant latency in the

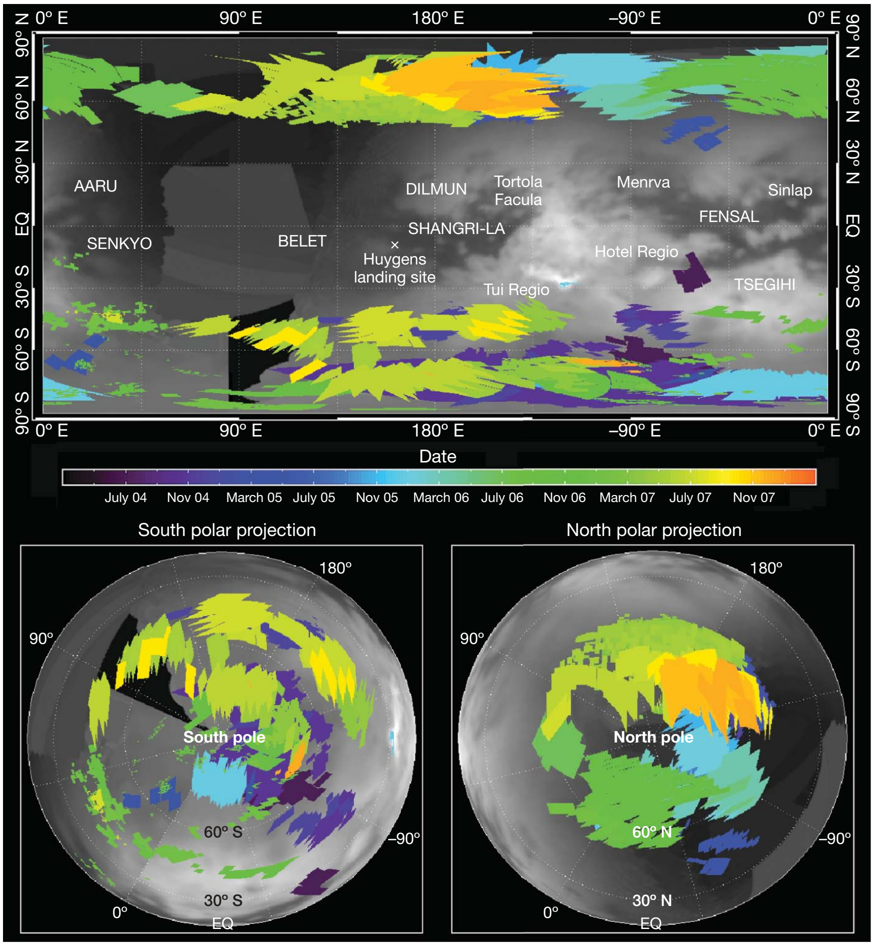

Figure 2 | Maps of Titan's clouds derived from VIMS observations from July 2004 to December 2007. Our detections are presented in cylindrical (top) and polar orthographic (bottom) projections. The colours of the clouds correspond to the date of each cloud observation. A VIMS greyscale mosaic of Titan's surface (adapted from RGB colour-composite global mosaics in ref. 28) is used as background. Clouds are found to be distributed in three clustered regions: the two poles and the southern temperate latitudes. Only very few occurrences of clouds are found in equatorial regions. One cloud event is found on December 2005 just above particularly interesting terrain thought to be of cryovolcanic origin (Tui Regio[27]), and may indicate recent cryovolcanic activity. EQ, equator.

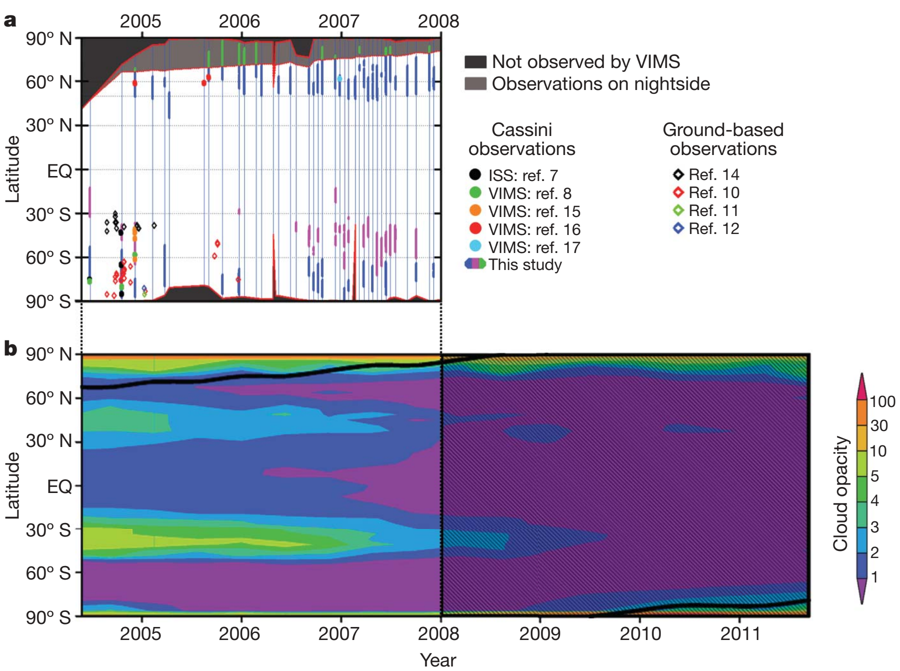

Figure 3 | Titan's latitudinal cloud coverage over time compared with global circulation model[3] predictions. a, Latitudinal distribution of clouds detected using VIMS, plotted as a function of time between July 2004 and December 2007. The thin blue vertical lines mark the time of the VIMS observations. The latitude extent of the clouds we detect is enhanced with thicker vertical lines, in blue when on dayside and in green when in polar night. Isolated temperate clouds are coloured purple. The previous Cassini and ground-based observations reported in the literature are superimposed over our latitudinal distribution using coloured dots and diamonds, respectively. Our detections are in very good agreement with the previous observations. ISS, Imaging Science Subsystem (on board Cassini). **b,** Titan's integrated cloud opacity above 10 km, summed each year, predicted by the atmospheric global circulation model of ref. 2 (IPSL-TGCM) between 2004 and 2011. The thick black lines show the edge of the polar night. The spatial distribution of clouds forecasted by the IPSL-TGCM, confining clouds at the two poles and around 40° S, is in very good agreement with our observations (see **a** and Fig. 2). By contrast, the observed cloud timing is poorly reproduced by the IPSL-TGCM. In the time interval monitored using VIMS for this work, the IPSL-TGCM predict that the south polar cloud should vanish before the equinox for more than one year, and that the cloud belt at 40° S should reach a maximum of intensity between 2004 and 2007 and then should gradually vanish with the incoming circulation turnover. This seems to be observed by VIMS with a significant delay (see text).

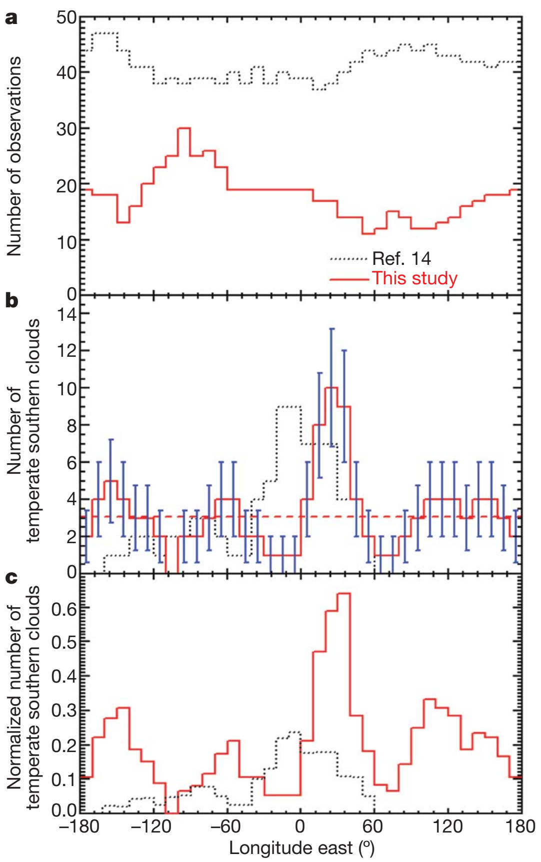

Figure 4 | The southern temperate cloud distribution as a function of longitude. **a**, The total number of observations in each 10° longitude bin is shown by the solid red line for our study and by the black dotted line for ref. 14. **b**, The number of clouds observed by VIMS between July 2004 and December 2007 (our study, solid red line) and during ground-based observations between December 2003 and February 2005 (ref. 14, black dotted line) in each 10° bin of planetocentric longitude summed between 60° S and 0°. Blue bars indicate the Poisson standard deviation for each VIMS cloud count. The statistics indicate that the overall shape of the longitudinal distribution is significant. **c**, Comparison of normalized number of clouds (number of clouds divided by the number of observations) from ref. 14 and from this study. Our distribution shows two minima, at the sub-Saturn point (0° E)—where ref. 14 saw a maximum—and at the anti-Saturn point (180° E). Two other minima are also present, in the neighbourhoods of 70° E and −110° E. Owing to the limitation of Cassini's Saturn tour, the detection of clouds was heavily precluded here by particularly low spatial resolution (Supplementary Fig. 5a) and very unfavourable observation conditions (resulting from high air mass; Supplementary Fig. 5b), so these two minima cannot be interpreted with confidence.

predicted disappearance of summer clouds suggests that Titan's atmosphere responds to seasonal forcing with a greater inertia than expected. Since August 2007, however, the occurrence of south polar clouds seems to be less frequent in our data and the mid-latitude clouds seem to be scarcer. These very subtle declining trends may indicate that we are witnessing the approaching seasonal circulation turnover as we approach the equinox, but with a timing pattern different from that forecasted by the IPSL-TGCM.

Besides, Fig. 4 shows that, between July 2004 and December 2007, the mid-latitude clouds are not uniformly distributed in longitude, as already noticed during previous ground-based observations[14] (December 2003–February 2005). The propensity of the clouds to form around longitude 0° found in 2003–2005 was attributed to localized geological forcings from the surface that are possibly related to an active cryovolcanic province[14]. However, three years later, the distribution we measure differs markedly, showing more structure (Fig. 4c). In contradiction to ref. 14, we observe mid-latitude clouds at almost all longitudes, with an excess at longitudes (from 60° E to 180° E, which corresponds to the leading hemisphere of Titan) where ref. 14 detected none. The strong and secondary peaks in the number of clouds reported by ref. 14 have drifted eastward by 30° at an estimated rate of ~10° per terrestrial year. In addition, we found two troughs at longitudes facing towards (0°) and away from (180°) Saturn. Although the strong link between cloud number and latitude indicates that global circulation has a major role in cloud formation[1–3], the wavy pattern of our cloud distribution suggests a secondary forcing mechanism. The longitudinal shift in cloud distribution by 30° between 2003–2004 (ref. 14) and 2005–2007 (this study), as well as the loose correlation of clouds with surface location, excludes surface geological activity as the primary triggering mechanism.

Both the drift in longitude and the discovery of two diametrically opposite minima favour processes taking place in Titan's atmosphere, which we attribute to external forcing by Saturn's tides. Saturn's tides are predicted to generate tidal winds in Titan's dense atmosphere that are particularly significant in the troposphere[26] at altitudes where temperate clouds are found to develop[2,3,13–15]. These winds manifest themselves as east-moving planetary-scale waves of degree two and change west–east direction periodically during each tidally locked orbit of Titan[26]. Consequently, tidally induced winds periodically modify the convergence of air masses, mostly at two preferential longitudes 180° apart, potentially resulting in perturbations to cloud formations[26].

The extension of the Cassini mission possibly up to the summer solstice in 2017, and the continuation of ground-based observations, will provide further observational constraints on the general circulation models. The refined models should provide more accurate information about the global atmospheric circulation, which is crucial for understanding the carbon cycle on Titan.

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

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