Rapid and Extensive Surface Changes Near Titan's Equator: Evidence of April Showers

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Rapid and Extensive Surface Changes Near Titan's Equator: Evidence of April Showers

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Although there is evidence that liquids have flowed on the surface at Titan's equator in the past, to date, liquids have only been confirmed on the surface at polar latitudes, and the vast expanses of dunes that dominate Titan's equatorial regions require a predominantly arid climate. We report the detection by Cassini's Imaging Science Subsystem of a large low-latitude cloud system early in Titan's northern spring and extensive surface changes (spanning more than 500,000 square kilometers) in the wake of this storm. The changes are most consistent with widespread methane rainfall reaching the surface, which suggests that the dry channels observed at Titan's low latitudes are carved by seasonal precipitation.

Titan's landforms include high-latitude lakes of liquid hydrocarbons [e.g., (*1*, *2*)] and vast equatorial areas of long-lived longitudinal dunes (*3*), indicating that low latitudes are primarily arid (*4*). However, fluvial channels are observed at all latitudes (*5*), and the Huygens Probe detected moisture (methane) in the shallow subsurface (*6*–*8*) of the cobble-strewn flood plain at ~10°S where it landed (*9*, *10*). To date, Cassini observations span only about one-fourth of a Titan year (2004–2011): late southern summer to early northern spring. Thus, the extent to which the distribution of surface liquids changes over a titanian year (or over longer time scales) is unknown. Does methane rain flood Titan's low-latitude channels during rare seasonal storms, between which the surface dries out (*11*), or are the channels remnants of an earlier, wetter equatorial climate (*12*)?

Changes in weather patterns have accompanied Titan's seasons: Storm activity over Titan's south (summer) pole during 2004–2005 (*13*, *14*), including one observation of possible surface flooding (*13*), appears to have given way to cloud outbursts at lower latitudes (*15*, *16*). Models predict low-latitude storms around equinox, although insufficient precipitation to accumulate there over the course of a year (*11*), consistent with the presence of dune fields. Two major low-latitude cloud events have been observed, at ~247°W in April 2008 (*15*) and at ~320°W on 27 September 2010 (Fig. 1), by Cassini's Imaging Science Subsystem (ISS). In both cases, cloud activity was observed at low latitudes over several weeks (*15*, *16*).

ISS observations in October 2010 (Figs. 1 and 2) of a region east of the cloud outburst [Titan's clouds usually move eastward (*16*)] revealed differences in surface brightness along the southern boundary of Belet, an extensive dune field. Some of the bright terrain bordering Belet darkened by >10% while adjacent areas remained unchanged (Fig. 2). Although clouds obscured some areas on 14 October, changes had occurred by that time (Fig. 2F). However, in many areas the change has been short-lived: Only some of the darkened area persisted through 29 October (Fig. 2G), and even more territory had reverted by 15 January 2011 (Fig. 2H). A few isolated areas may have brightened relative to their original appearance (Fig. 1E, Fig. 2H, and fig. S1).

The darkening extends ~2000 km east-west and >130 km across. Although changes are more difficult to distinguish in terrain that was originally dark, we have detected differences in some of these areas too. The measured extent of changes that persisted until 29 October is 510,000 ± 20,000 km^2.

Titan's dark regions consist of hydrocarbons (*2*, *4*, *17*, *18*), and brighter material is thought to be bright aerosol deposits (*18*). Cassini synthetic aperture radar (SAR) and Visual and Infrared

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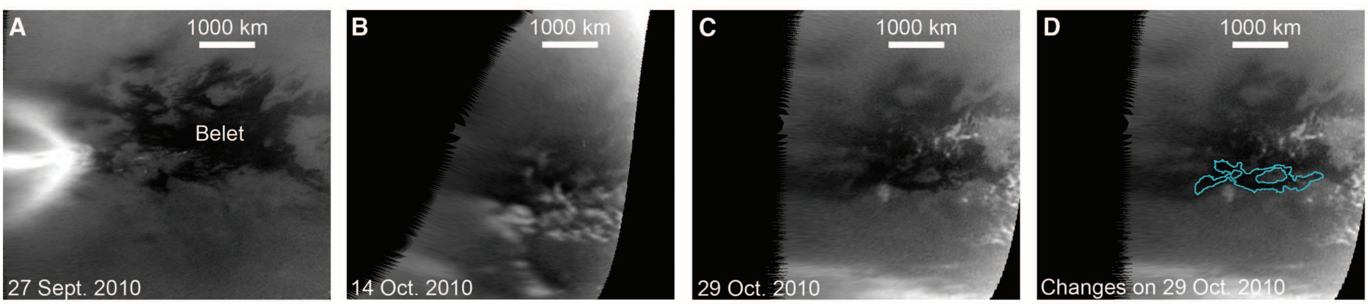

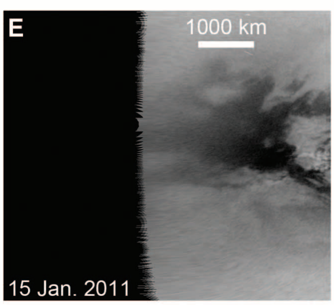

Fig. 1. (**A** to **E**) ISS observations of clouds and surface changes on Titan's trailing hemisphere: 27 September 2010 (A), 14 October 2010 (B), 29 October 2010 [(C) and (D)], and 15 January 2011 (E); shown in (D) is an outline of surface change based on a ratio of the 29 October image to an earlier image (Fig. 2). Brightest features are methane clouds in Titan's troposphere (fig. S1). Light and dark shades of gray are surface features. Decreasing contrast toward the tops of the images in (B) to (E) is due to increasing emission angles. (Image details in table S1.)

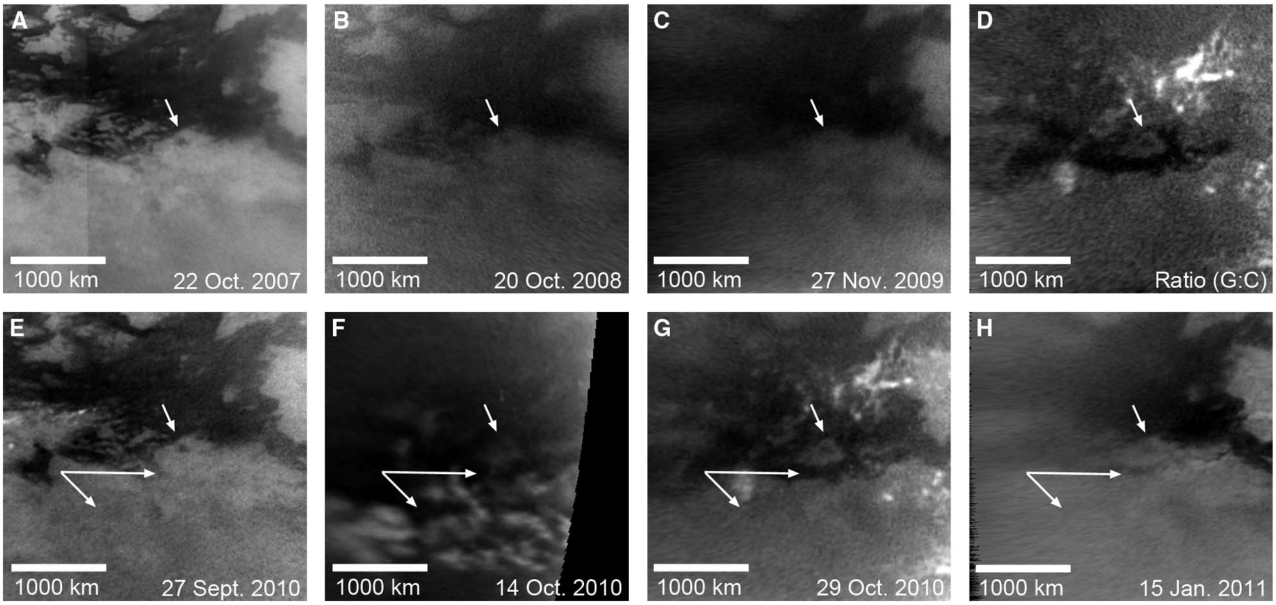

Fig. 2. (**A** to **C** and **E** to **H**) Sequence of ISS observations. Single arrow indicates isolated unchanged area between Belet and the darkened swath. Double arrow indicates locations of changes that reverted between 14 and 29 October 2010 (lower arrow) and that persisted through October and began to revert by January 2011 (upper arrow). (**D**) Ratio of observations acquired at similar phase angles on 29 October 2010 (G) and 27 November 2009 (C). (Image details in table S1.)

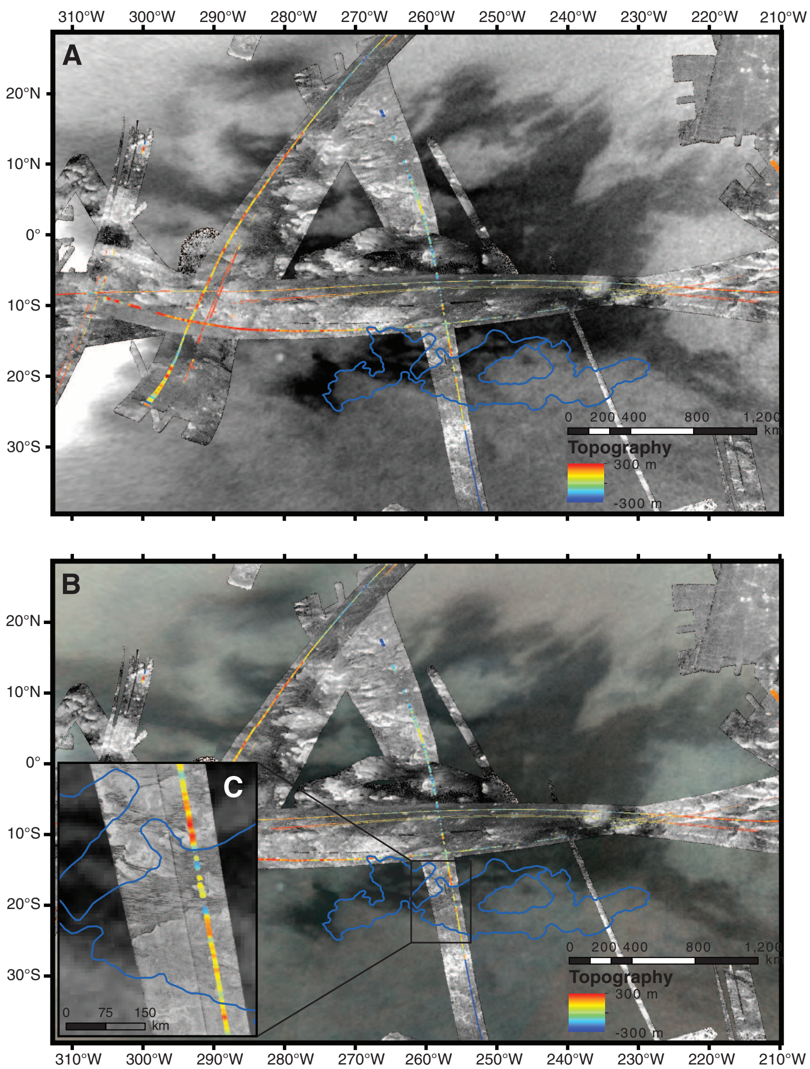

Fig. 3. (**A** and **B**) SAR over September 2010 ISS (A) and August and December 2009 VIMS (B) with red, 5.0 μm; green, 2.0 μm; blue, 1.3 μm. SAR from Cassini Titan flybys designated T8, 28 October 2005; T19, 9 October 2006; T21, 12 December 2006; T39, 20 December 2007; T41, 22 February 2008; T49, 21 December 2008; T50, 7 February 2009; T57, 22 June 2009; T61, 25 August 2009; T64, 28 December 2009. (**C**) Zoom of T49 SAR over ISS. Blue outline indicates area of change as observed on 29 October 2010.

Table 1. ISS observations of Titan's surface and clouds south of Belet. (Image details in table S1.)

Date	Phase angle	Pixel scale (km)	Appearance
13 May 2007	29°	1.9	Normal
*22 Oct 2007	23°	2.7	Normal
Apr–May 2008 (Earth-based)	4.9°	130	Large cloud, 29°S, 247°W (*15*)
*20 Oct 2008	89°	5.3	Normal; similar (high) phase angle to 29 Oct 2010
*27 Nov 2009	89°	7.2	Normal; similar (high) phase angle to 29 Oct 2010
13 Sep 2010	70°	15	Normal
*27 Sep 2010	44°	7.7	Large arrow-shaped cloud to west (~12°S, 300°–340°W); surface appeared normal coincident with cloud
*14 Oct 2010	113°	12	New dark territory south of Belet
*29 Oct 2010	88°	11	Decrease in darkened area
15 Jan 2011 (03:15 UTC)	78°	5.0	Continued decrease in darkened area
*15 Jan 2011 (18:00 UTC)	66°	6.0	Continued decrease in darkened area

*Image in Fig. 2.

Mapping Spectrometer (VIMS) observations of this region (Fig. 3) confirm the presence of dunes in areas originally seen by ISS to be dark. The boundaries of the changed region do not correlate with preexisting albedo boundaries in ISS and VIMS observations or with obvious morphologic or topographic boundaries in the SAR data (Figs. 2 and 3).

We can rule out observational effects and clouds, thereby establishing that the differences represent changes on Titan's surface. ISS has observed this region several times since May 2007 (Table 1): Its appearance was consistent before October 2010, regardless of phase angle. Images acquired in October 2008 and November 2009 at phase angles and resolutions similar to those in October 2010 show nothing unusual when compared to images acquired at lower phase angles from October 2007 and September 2010 (Fig. 2). Areas with consistent borders from 14 to 29 October exhibit a level of constancy not observed in Titan's clouds (*16*), and even low-lying clouds (*17*) and features identified as fog (*19*) are bright at the ISS wavelength used for Titan (938 nm). Cloud shadows are also unlikely: Titan's substantial atmospheric scattering (*10*) diffuses shadows, whereas the changed areas are distinct at pixel scales of ≤12 km.

Methane precipitation could affect a huge area over a short period of time, explaining the rapid appearance (and disappearance) of the changes and their extensive and nonuniform nature. The cloud observed on 27 September was more than 1000 km in extent. Surface brightness could change by flooding or wetting, which renders materials darker by changing their optical properties (*20*, *21*). The degree of darkening is comparable to surface liquids seen elsewhere by ISS (*13*). In the case of flooding, areas of change should correlate with low-lying areas. However, the narrow strip of SAR topography that crosses the darkened area (Fig. 3) does not demonstrate such a relationship, nor are there any obvious correlations between the new boundaries and morphologic features in the SAR data. Furthermore, the observations would require standing liquid over an area larger than Kraken Mare, Titan's largest sea. Both of these issues are resolved if, at least in some areas, the darkening is caused merely by surface wetting: Much less precipitation is necessary, and the observed pattern results from variations in precipitation and potentially the nature of the surface. Wetting of fine aerosol particles (*22*) could be part of the unknown process by which such material is cemented together to form particles large enough to undergo saltation, required for dune formation. Precipitation can also explain the rebrightening observed later in some places as different areas drain (by overland flow or infiltration) or dry at different rates. In an unsaturated permeable medium, vertical infiltration rates will be high [>20 mm/week (*23*)]. Evaporation rates of 20 mm/week have been documented at Titan's poles (*24*), and equatorial rates of >1 mm/week are predicted (*11*). Small areas that might have brightened relative to their original appearance are stationary compared to typical clouds (fig. S2), so they could be bright surfaces [potentially water ice (*17*)] cleaned by runoff or persistent low-altitude clouds or fog.

Another hypothesis is aeolian modification, perhaps a result of high surface winds accompanying the storm, redistributing dark material or removing bright mantling material (*18*) to reveal a dark substrate. SAR and VIMS data (Fig. 3) demonstrate the existence of dark dune material in the vicinity of the observed changes. However, assuming sufficient source material, the question is whether winds could transport it hundreds of kilometers over such a short time. A conservative estimate requires a mass flux of 0.12 kg/ms, corresponding to a free-stream wind speed of 2.2 m/s (*25*). According to large-scale general circulation models (*26*), sustained winds of such speeds are highly unlikely. Storm-generated downdrafts and gravity currents could enhance surface winds, but at issue is whether they could persist consistently for several days. A critical complication for an aeolian hypothesis is the need for multiple events to explain areas reverting to their previous appearance over time.

Volcanism is another mechanism for rapid large-scale surface changes. Flows would require control by preexisting structures and prohibitively fast deposition of extreme amounts of dark material; terrestrial flood volcanism takes thousands of years to cover comparable areas (*27*). Explosive cryovolcanism, perhaps more consistent with the time scale and extent of the changes, is not expected on Titan (*28*).

The most likely explanation for the formation of the low-latitude clouds is a seasonal change in weather patterns encouraging development of convective cloud complexes, perhaps associated with the equatorial crossing of a titanian intertropical convergence zone (*11*, *16*, *26*). Other possibilities include topographic features generating orographic uplift or cryovolcanic outgassing of methane triggering cloud formation (*29*). The equatorial lower atmosphere is too dry to support free (unforced) moist convection (*12*, *30*, *31*), but a source of methane gas at the surface would increase the relative humidity and thus the potential for convective outbursts. Intriguingly, the only other low-latitude cloud outburst of this scale occurred at similar longitudes (*15*). However, no cryovolcanic features have been identified in this area, and clouds do not appear to occur here preferentially (*16*).

Precipitation from a large methane storm over Titan's arid low latitudes, as predicted near equinox by atmospheric models (*11*), best explains the observed surface changes. Infrequent events would not prevent long-term development and preservation of the dune fields. A few meters of dune erosion, which could be repaired between equinoxes, would not be visible at scales smaller than the SAR resolution of a few hundred meters. Occasional storms are sufficient to form the observed channels (*32*, *33*), and, although the dune fields demonstrate that these latitudes are predominantly dry, they do not preclude occasional precipitation; many terrestrial drylands are geomorphologically dominated by fluvial activity.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/331/6023/1414/DC1
Figs. S1 and S2
Table S1
References

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Isotopic Evidence of Cr Partitioning into Earth's Core

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The distribution of chemical elements in primitive meteorites (chondrites), as building blocks of terrestrial planets, provides insight into the formation and early differentiation of Earth. The processes that resulted in the depletion of some elements [such as chromium (Cr)] in the bulk silicate Earth relative to chondrites, however, remain debated between leading candidate causes: volatility versus core partitioning. We show through high-precision measurements of Cr stable isotopes in a range of meteorites, which deviate by up to ~0.4 per mil from those of the bulk silicate Earth, that Cr depletion resulted from its partitioning into Earth's core, with a preferential enrichment in light isotopes. Ab initio calculations suggest that the isotopic signature was established at mid-mantle magma ocean depth as Earth accreted planetary embryos and progressively became more oxidized.

Determining the chemical composition of Earth's core provides key constraints on the physicochemical conditions at the time of the planet's formation. Because primitive meteorites are believed to be similar in composition to the material from which Earth accreted (*1–4*), they provide a good proxy for the undifferentiated bulk Earth composition that eventually differentiated to form the metallic core and silicate mantle. These estimations are most accurate for refractory elements (such as Ca and Al) that did not fractionate by volatilization before or during Earth's accretion. The abundances of the moderately volatile elements in Earth's core are therefore poorly constrained because of difficulties in choosing meteorite samples that represent the bulk Earth (*1–4*).

Experiments suggest that Cr could fractionate into the core under conditions prevailing in Earth's lower mantle or at the base of a magma ocean (*2*, *5–8*). It has been shown that the partitioning behavior of Cr is more sensitive to temperature (*6*, *7*) and oxygen fugacity (fO_2) (*2*, *5*, *8*) than to pressure (*6*, *7*). Its depletion in the silicate Earth in comparison to chondrites suggests that the Cr could have been partitioned into Earth's core (*1–8*). However, Cr is also a moderately volatile element (*1*, *4*, *9*), and its depletion in the silicate Earth in comparison to bulk chondrites may reflect its volatility (*10*, *11*).

Here we report high-precision stable isotopic compositions of Cr in meteorites to understand the origin of the depletion of Cr in the silicate Earth. It is now possible to measure variations in the stable isotope composition of Cr with high precision and accuracy (*12–14*). We analyzed the bulk Cr isotopic composition of seven carbonaceous chondrites from the different major groups: Orgueil (CI1), Dar al Gani 749 (CO3.1), Ningqiang (CK3), Vigarano (CV3), Lance (CO3.4), Cold Bokkeveld (CM2), and Murchison (CM2); five ordinary chondrites: Nadiabondi (H4), Forest City (H5), Ausson (L5), Tuxtuac (LL5), and Dimmit (H3.7); one enstatite chondrite: Sahara 97103 (EH3); and six single chondrules from Chainpur (LL3.4) (*15*) (table S3). The full range of Cr isotope fractionation per atomic mass unit (δCr/amu) (*16*) in the chondrites (bulk rock and individual chondrules) is ~0.40 per mil (‰)/amu (Fig. 1).

The condensation/evaporation processes operating in the early solar system may have induced isotopic fractionations of Cr with a loss of light isotopes. The Chainpur chondrules with heavy Cr isotope enrichment appear to show such an effect (Fig. 1). If true, such processes should also affect other elements; in particular, those elements more volatile than Cr. Both Zn and Cu are more volatile than Cr [the condensation temperature (T_c) of Zn = 726 K and T_c(Cu) = 1037 K, versus T_c(Cr) = 1296 K (*9*)]. In addition, Zn isotopes have been shown to be fractionated during evaporation processes (*17–19*). However, both Cu (*20*) and Zn (*21*) show reverse volatility trends, opposite to Cr (*13*). The systematics are most pronounced in carbonaceous chondrites. Figure 2, A and B, show that δCr is anticorrelated with δCu, and δZn, respectively. Moreover, δCu and δZn are negatively correlated with refractory/volatile elemental ratios [Mg/Cu, Mg/Zn, T_c(Mg) = 1336 K (*9*)] (Fig. 2, D and E), whereas δCr is positively correlated with Mg/Cr (Fig. 2F). Most important, the fact that δCr, δZn, and δCu all correlate with Δ^{17}O (Fig. 2C) (*13*, *20–21*), a mass-independent fractionation tracer (*22*), suggests large-scale two-reservoir mixing in the early solar nebula, with one component enriched in light isotopes of Cr and heavy isotopes of Zn and Cu and high Δ^{17}O, and a second component enriched in heavy isotopes of Cr and light isotopes of Zn and Cu and low Δ^{17}O. This contrasting behavior of Cr on one hand, and of Cu and Zn on the other hand, and their correlations with Δ^{17}O, collectively argue against isotopic fractionation by volatilization and are instead consistent with the conclusions of Luck *et al.* (*22*)

Recently, Schoenberg *et al.* (*14*) showed that terrestrial igneous silicates, including mantle xenoliths, ultramafic cumulates, and oceanic as well as continental basalts, are isotopically homogenous in Cr and give an average δCr/amu = –0.12 ± 0.10‰ (2 SD) (±0.02‰, 2 SE) for the bulk silicate Earth relative to the SRM 979 Cr standard. Therefore, the silicate Earth is enriched in heavy isotopes of Cr relative to chondrites (Fig. 1). Based on a mass balance between the silicate Earth and the chondrites, the core may control the

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