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Icarus 182 (2006) 224–229

ICARUS

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A large cloud outburst at Titan's south pole

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Received 8 July 2005; revised 6 December 2005

Abstract

Images of Titan acquired over five nights in October 2004 using the adaptive optics system at the Keck Observatory show dramatic increases in tropospheric cloud activity at the south pole compared with all other images of Titan clouds to date. During this time, Titan's south polar clouds brightened to more than 18 times their typical values. The Cassini Ta flyby of Titan occurred as this storm was rapidly dissipating. We find that the brightness of this cloud outburst is consistent with the dramatic transient brightening of Titan observed in atmospheric windows on two nights in 1995 by Griffith et al. [Griffith, C.A., Owen, T., Miller, G.A., Geballe, T., 1998. Nature 395 (6702) 575–578] if we scale the brightness of the cloud by projecting it onto the equator. While apparently infrequent, the fact that large cloud events have been observed in different seasons of Titan's year indicates that these large storms might be a year-round phenomenon on Titan. We propose possible mechanisms to explain these occasional short-term increases in Titan's cloud activity.

Keywords: Titan; Infrared observations; Atmospheres, dynamics; Meteorology

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1. Introduction

Data from the Voyager encounter with Saturn's moon Titan first suggested that Titan might support a methane meteorological cycle including convective methane clouds and rain beneath the smoggy stratospheric haze (Eshleman et al., 1983; Flasar, 1983; Lunine et al., 1983; Toon et al., 1988). Observations with ground-based telescopes in narrow methane windows in the infrared found that Titan's surface was not of uniform albedo but instead had a reproducible infrared lightcurve with maximum brightness occurring near 110° W longitude (Coustenis et al., 1995; Griffith, 1993; Lemmon et al., 1995). HST images (Meier et al., 2000; Smith et al., 1996) and early adaptive optics images (Combes et al., 1997) revealed a continent sized bright feature centered near 110° W longitude now known as Xanadu. None of these observations detected any evidence for transient clouds in Titan's atmosphere.

Transient cloud activity in Titan's troposphere was first detected spectroscopically by Griffith et al. (1998) who reported a dramatic brightening of Titan in atmospheric windows during two nights in September of 1995 compared with observations on twelve other nights from 1993–1997. They found that this brightening corresponded to ~9% cloud cover of Titan's disk and placed the clouds at an altitude of 15 km. Griffith et al. (2000) then reported evidence for smaller scale transient cloud activity occurring on several nights in 1993–1999. These daily clouds were much smaller than the large cloud event witnessed in 1995 and covered less than 1% of Titan's disk.

The first images of Titan's clouds were obtained by Brown et al. (2002) and Roe et al. (2002) using the adaptive optics systems on the Keck and Gemini telescopes. Since then, clouds have regularly been observed near Titan's south pole (Bouchez and Brown, 2005; Gendron et al., 2004; Roe et al., 2005a) and typically contribute about 1% of the total brightness of Titan's disk, consistent with the daily clouds observed spectroscopically by Griffith et al. (2000). The location of the clouds near the south pole lead Brown et al. (2002) to suggest that they may form via insolation driven convection because the south pole was the area of maximum solar insolation on Titan (southern

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0019-1035/$ – see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2005.12.021

summer solstice was in October 2002). The presence of south polar tropospheric clouds at this season is likely controlled in a complex way by both the insolation and the global circulation leading to uplift at the pole. South polar clouds may also form non-convectively by cooling of air parcels as they move poleward (Barth and Toon, 2004).

Between 2001 and mid-2004 clouds had been observed near the south pole of Titan on 66 occasions in Palomar, Keck and Gemini images (Bouchez and Brown, 2005; Bouchez et al., 2004), but at most times the clouds covered no more than 1% of the surface, and at no time did the coverage approach that seen by Griffith et al. (1998). The lack of large cloud features suggested a possible difference in the cloud formation mechanisms between the current south polar summer season and the spring equinox season when the large cloud was observed in 1995.

We report here on a dramatic brightening of Titan's south polar clouds observed on five nights in October 2004 with Keck adaptive optics images and compare the brightness of this cloud outburst to the transient brightening observed in 1995 by Griffith et al. (1998).

2. Observations

Images of Titan presented here were taken with the W.M. Keck 10-m telescope using the adaptive optics system and the NIRC2 near-infrared camera (Wizinowich et al., 2000) through three different filters that probe to different levels in Titan's atmosphere. Images taken through the K' filter (1.95–2.30 μm) probe to Titan's surface, while those taken through the H_2 (1–0) filter (2.11–2.14 μm) probe to ∼10 km altitude (lower troposphere), and the Brγ filter (2.15–2.18 μm) probes to ∼50 km altitude (lower stratosphere). In Titan's atmosphere, photons of the wavelength range seen through the H_2 filter reach an optical depth of unity in the lower troposphere owing to absorption by methane, nitrogen, and hydrogen (Roe et al., 2002). Images in the H_2 filter therefore show only light scattered in Titan's atmosphere above an altitude of about 10 km, thus this filter is ideal for detecting clouds in the middle of Titan's troposphere without the confusion of surface features. We therefore use the H_2 filter for our analysis of cloud locations and magnitudes. Images were flat-fielded, corrected for bad pixels, and oriented so that Titan's north pole is aligned with the vertical axis. At the time of the observations Titan was at a distance of 9.2 AU, so the Keck telescope diffraction limited resolution of 0.05 arcsec corresponds to 330 km on the surface of Titan.

Fig. 1a shows images of Titan from seven nights in 2003 that are typical of the cloud activity seen during this season. Beginning with images on 28 September 2004, however, Titan's south polar cloud system brightened dramatically. This brightening was observed over the course of six nights from 28 September until 28 October (Fig. 1b), when the brightness of Titan's south polar clouds returned to their typical values. At the peak of the cloud outburst on 8 October, the cloud covered at least 8% of the disk of Titan. Also visible in the images from October 2, 3, and 7 are smaller clouds located at mid-latitudes. These clouds are discussed in detail by Roe et al. (2005b) and will not be discussed here.

Titan's clouds are typically not detected or are very faint in Brγ images indicating that they are located in the troposphere at an altitude below that which photons of the wavelength range of the Brγ filter can penetrate (∼50 km) (Roe et al., 2002). In addition, all other measurements of Titan cloud altitudes (Brown et al., 2002; Griffith et al., 1998, 2000, 2005) placed these clouds in the troposphere. Though the large south polar

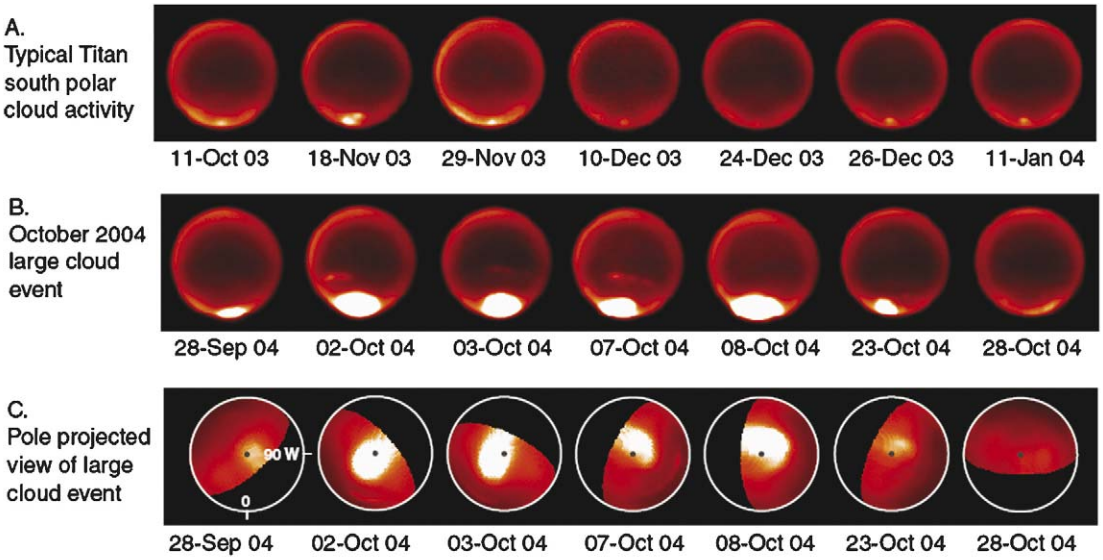

Fig. 1. Keck adaptive optics images of Titan taken through the H_2 (1–0) (2.11–2.14 μm) filter oriented with Titan north up. This filter probes only to Titan's troposphere making it ideal for observing Titan's clouds. (A) Images of Titan from seven nights in 2003 that are typical of the low levels of cloud activity seen from 2001–2004. (B) Cloud activity at the south pole is seen in all seven of these images and dramatic brightening is observed in images from October 2, 3, 7, 8, 2004. (C) Pole projected images of Titan's clouds with the pole location marked with a black dot. All images have Titan 0W longitude pointing up. The Cassini "Ta" flyby occurred on October 26, 2004, by which point cloud activity was rapidly dissipating. By October 28, 2004, cloud activity had dissipated down to typical levels of less than 1% cloud coverage (Bouchez and Brown, 2005). These images also allow us to constrain the duration of the cloud outburst to less than 30 Earth days. Locations of the clouds also indicate that convection on Titan is extremely vigorous and that large clouds can dissipate and reform in several days.

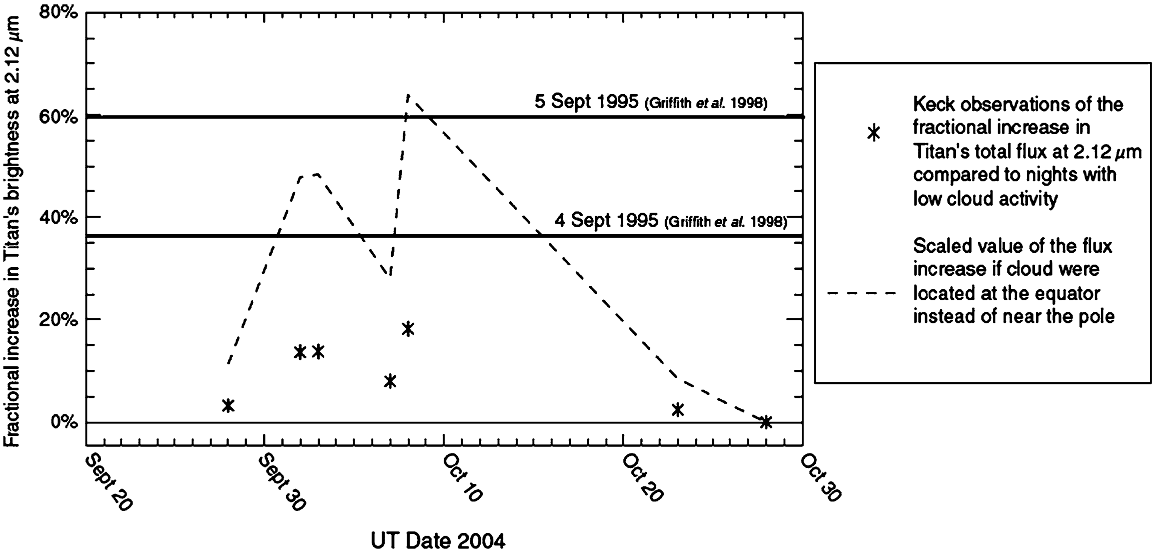

Fig. 2. The fractional increase in Titan's total flux through the cloud filter (2.11–2.14 μm) compared to nights with low cloud activity is shown for each night of the outburst. The total flux of Titan increased by nearly 20% on the brightest night of the outburst (8 October 2004). The solid lines show the flux increase in the same wavelength range for the September 1995 cloud outburst of Griffith et al. (1998). We find that the October 2004 storm at the south pole is not as bright by a factor of 3.3. However, the dashed line shows the flux that the October 2004 outburst would have had if it occurred near the equator rather than the pole, estimated by a simple geometric and methane airmass correction. If the October 2004 clouds were at the equator, they would have appeared to be of similar brightness to the September 1995 clouds observed by Griffith et al. (1998).

cloud can be seen in several of the Brγ images, the contribution of the cloud to the total brightness of Titan in the H_2 (1–0) filter is over five times greater than that in the Brγ filter. A typical cloud with a brightness of ~1% in the H_2 (1–0) filter would not be detected in the Brγ filter were it over five times fainter, consistent with our observations. Therefore, given that all previous measurements of Titan cloud heights place them in the troposphere and the brightness of the large clouds in the Brγ filter is below that which could be detected were these clouds of typical size, we assume that these clouds are also located in the troposphere.

To find the extent of Titan's brightening due to the presence of these clouds, we first photometrically normalized each image by measuring the total brightness of Titan in the H_2 filter and scaling the brightness of the image by the total flux of the relatively unchanging northern half of Titan. We then subtracted the total flux from images of Titan with clouds from the total flux from images of Titan without clouds (28 October 2004, 10 January 2004, 24 December 2003, 25 December 2003). These images with no distinct clouds show only photons scattered from the slowly-changing haze in the stratosphere of Titan. Because of possible long term changes in the haze abundance, we attempt to use closely spaced dates for comparison when possible. However we found only about a 1% difference in cloud brightness regardless of the comparison date used, and we use this value as our estimate of the error in our measurement. The fractional increase in Titan's total flux through the H_2 filter compared with Titan's total flux on nights with low cloud activity is presented in Fig. 2. We find that the total flux of Titan through the H_2 filter increased by 18% on the brightest observed night of the outburst (October 8, 2004).

3. Results

The cloud outburst of October 2004 was significantly larger than any other directly imaged on Titan. To compare the magnitude of this outburst to the Griffith et al. (1998) cloud event detected spectroscopically in 1995, we measure the magnitude of brightening in the H_2 filter wavelength region (2.11–2.14 μm) of the Griffith et al. (1998) spectra from September 4 and 5 1995. We find that the total flux of Titan increased by 36 and 59% in the H_2 filter wavelength region for September 4 and 5, respectively (Fig. 2). Thus the large cloud event of October 2004, though it is the largest south polar cloud seen in several years of monitoring Titan (Schaller et al., 2005), is still 3.3 times fainter than the brightest transient brightening attributed to clouds in 1995.

Griffith et al. (1998), however, suggest that, based on spectral changes from 4 to 5 September, the cloud they observed is consistent with an equatorial location. Such a location would be consistent with the hypothesis that convective clouds form near the latitude of maximum solar insolation (Brown et al., 2002), which was near the equator at the southern spring equinox season of the 1995 observations. The brightness of the 2004 outburst is significantly attenuated relative to a comparably large cloud system near the center of Titan's disk both from geometric foreshortening and from additional methane, nitrogen, and hydrogen opacity through a longer atmospheric path length. If we move the October 2004 clouds from their locations near the pole (see Table 1) to the center of Titan's disk, we find that they would appear brighter by a factor of ~1.7 due to geometric foreshortening. In addition, by following the method of Roe et al. (2002) we find that the decreased gas opacity through a shorter path length would increase the observed brightness of the clouds by an additional factor of 2. Combining these

Table 1
Cloud details

Image date (UT)	Planetocentric latitude, longitude of the cloud centers[a] (deg)	Velocities of the cloud during the storm (m/s)	Cloud brightness at 2.12 μm[b]
2004 Sept 28	$-87^{+3}_{-5},\ 96^{+144}_{-35}$		0.03 ± 0.01
2004 Oct 02	$-73 \pm 3,\ 337^{+10}_{-8}$		0.14 ± 0.02
2004 Oct 03	$-76 \pm 3,\ 321^{+11}_{-14}$	$2.2^{+3.4}_{-2.6}$	0.14 ± 0.02
2004 Oct 07	$-70 \pm 2,\ 163^{+15}_{-13}$		0.08 ± 0.01
2004 Oct 08	$-72 \pm 3,\ 163^{+13}_{-11}$	0 ± 4	0.18 ± 0.02
2004 Oct 23	$-75 \pm 3,\ 160^{+18}_{-17}$		0.02 ± 0.01

[a] Uncertainties are calculated based on ±0.5 pixels in determining the center of Titan and ±1.5 pixels in determining the centers of the cloud positions.
[b] Fractional increase in Titan's total flux at 2.12 μm compared to nights with little to no cloud activity.

two effects, we find that the 2004 clouds would have appeared brighter by at least a factor of ~3.5 if they were near the equator. Therefore if the 2004 cloud event were at the equator, it would have appeared to be of comparable brightness to the 1995 event (Fig. 2, dashed line).

These observations also allow us to constrain the duration and short-term variability of large cloud events. From the seven Keck images we can constrain the duration of the cloud outburst to less than 30 Earth days. In addition, observations on sequential nights indicate that the flux from the storm can stay relatively constant (October 2 and 3) or increase by a factor of two (October 7 and 8) in only 24 h. Rapid variability in cloud flux was also observed by Griffith et al. (1998) during the two nights of the 1995 storm. This variation may have been due to parts of the cloud rotating onto the limb but may have also been due to rapid fluctuation in cloud size or height.

The locations of brightest pixels of the clouds on October 2 and 3 and October 7 and 8 (Fig. 1c and Table 1) allow us to place limits on the troposphere circumpolar wind velocities. From October 2 to October 3 we find that the movement of the cloud is consistent with a velocity of 2 ± 3 m/s. The cloud on October 7 and 8 is consistent with a velocity of 0 ± 4 m/s. However, the October 7 and 8 cloud is 160° in longitude away from the cloud observed on October 2 and 3. In order for the cloud of October 2 and 3 to have blown to the position of October 7 and 8, it would have needed to move 6 ± 1 m/s eastward during the 4 days during which we do not have observations. We find it unlikely that a cloud that was consistent with being relatively stationary in two separate locations in two separate sets of observations would move with such a high velocity between observations, thus the October 2–3 cloud and the 7–8 cloud likely formed separately. The former location of the October 2–3 cloud is visible in images from October 7–8, and no cloud activity is seen at this location, so we know that the October 2–3 cloud has disappeared within 4 days. In addition, the cloud becomes significantly brighter from October 7th to October 8th (the brightest night of the storm) suggesting that it was actively forming at that location. While the overall period of increased south polar cloud activity lasted for ~30 days, individual clouds themselves appear to be rapidly forming and dissipating on timescales as short as one earth day. If the clouds are raining out methane, the fast timescales of their dissipation and possible rapid rainout times are consistent with a large raindrop size predicted by Lorenz (1993) and Lorenz and Renno (2002).

4. Discussion

In order to understand Titan's complex meteorology, it is necessary to understand why cloud activity occasionally increases dramatically and why such increases last for weeks. Clouds can form where a parcel of air is lifted sufficiently to become saturated and condensation occurs which releases latent heat. As the parcel is further lifted, sufficient condensation and latent heating occurs to make the parcel warmer than its surroundings and positively buoyant, initiating free moist-convection and convective clouds. The altitude at which a parcel is positively buoyant is called the Level of Free Convection (LFC). Over most of Titan, the dry convective layer near the ground is much lower than LFC so no clouds are formed. The general circulation models of Tokano (2005) predict superadiabatic lapse rates from ~70°–90° S in the current southern summer season. This location corresponds to where the majority of clouds on Titan have been observed (Roe et al., 2002; Brown et al., 2002; Bouchez and Brown, 2005) suggesting that there may be sufficient surface heating at these locations to lift parcels to the LFC and instigate convective cloud formation. However, an additional mechanism needs to be invoked to explain the large short-term increase in cloud activity observed in October 2004. We suggest three possible mechanisms that could cause such an increase.

4.1. Increased cloud condensation nuclei

Early work suggested that Titan might be lacking in cloud condensation nuclei (CCN) and that the troposphere could therefore be supersaturated in methane (e.g., Courtin et al., 1995; McKay et al., 1997; Samuelson et al., 1997). A large influx of condensation nuclei into an already saturated or supersaturated parcel above the LFC would cause increased cloud activity and rainout of methane. However, Huygens DISR observations suggested abundant haze particles in the troposphere (Doose et al., 2005) and GCMS observations found no evidence for methane supersaturation (Niemann et al., 2005). In addition, cloud activity has been regularly observed near Titan's south pole for the past four years suggesting that condensation nuclei have not been lacking. However, addition of extra CCN by some unknown mechanism could cause increased cloud nucleation rates leading to an increase in cloud activity until these particles are rained out.

4.2. *Localized geologic process leading to surface heating*

Increased surface heating from geothermal or volcanic activity near the pole could increase convection leading to a localized increase in cloud activity at that location. If one hot spot were responsible for the large cloud outburst observed, we would expect to see either a continuous source region or a long-lived cloud that moves. Instead, we find large relatively stationary clouds forming in at least two distinct well-separated areas on different sides of the pole. It is unlikely that two separate hot spots near the pole cloud be responsible for the observed clouds. Therefore, increased surface heating is likely not the cause of the observed cloud outburst.

4.3. *Increased methane humidity at the south pole*

Methane injection into Titan's atmosphere must occur in order to compensate for the constant photochemical loss. The current pole-to-pole global circulation would eventually bring this occasionally injected methane toward the south polar region. Increased cloud activity resulting from lowering the LFC by increasing methane humidity would then occur until the additional methane was depleted. Therefore, large cloud events at the south pole could be tied to methane outgassing somewhere on the surface of Titan. This hypothesis is consistent with large cloud outbursts observed in different seasons of Titan's year. While we cannot rule out some sort of atmospheric wave phenomenon periodically bringing moist air to the pole, the timescales of known terrestrial analog phenomena are at least an order of magnitude longer than the $\sim$30 day timescale of this outburst (Ingersoll et al., 2005) and predictions of cloud lifetimes caused by horizontal poleward transport of air parcels are an order of magnitude shorter (Barth and Toon, 2004). In 1995, we expect that the location of daily clouds and the large cloud outburst observed by Griffith et al. (1998) would have been near the equator because the solar insolation was greatest there and the equator-to-pole cells (Hourdin et al., 1995) would have provided uplift and concentrated occasionally injected methane at the equator.

The Cassini "Ta" flyby occurred on October 26, 2004, when the cloud outburst was in the process of dissipating. Cassini images from Ta still showed a significant degree of cloud activity at the south pole of Titan compared with other flybys indicating that the outburst had not fully dissipated by October 26th. The Keck image from October 28th, however, shows only a small degree of cloud activity at the pole, consistent with cloud cover of less than 1% observed in most ground-based images of Titan to date. Therefore, images from Ta are particularly interesting because of the rapid dissipation of the clouds that occurred within 48 h after they were taken.

Ongoing ground-based monitoring campaigns (Schaller et al., 2005) are important for placing these large storms in the broader context of the full range of cloud activity on Titan. The south pole ceased to be the area of maximum solar insolation in July 2005. Over the next several years, as Titan moves away from southern summer solstice, ground-based monitoring campaigns and the numerous Cassini flybys will help to determine how and if the magnitudes and locations of large cloud events will begin to change with season. While apparently infrequent, the fact that large cloud events have been observed in different seasons of Titan's year (near spring equinox in 1995 and post southern summer solstice in 2004) indicates that these large increases in cloud activity might be a year-round phenomenon on Titan.

Acknowledgments

E.L.S. is supported by an NSF Graduate Research Fellowship. H.G.R. is supported by an NSF Astronomy and Astrophysics Postdoctoral Fellowship under Award AST-0401559. Additional support was provided by NSF Award AST-0307929. We thank Andy Ingersoll and two anonymous referees for helpful comments. The data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The observatory was made possible by the generous financial support of the W.M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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