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Dissipation of Titan's south polar clouds

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Abstract

Nearly all adaptive optics images of Titan taken between December 2001 and November 2004 showed tropospheric clouds located within 30° of the south pole. We report here on a dissipation of Titan's south polar clouds observed in twenty-nine Keck and Gemini images taken between December 2004 and April 2005. The near complete lack of south polar cloud activity during this time, and subsequent resurgence months later at generally higher latitudes, may be the beginning of seasonal change in Titan's weather. The ∼5 month decrease in cloud activity may also have been caused by methane rainout from a large cloud event in October 2004. Understanding the seasonal evolution of Titan's clouds, and of any precipitation associated with them, is essential for interpreting the geological observations of fluid flow features observed over a wide range of Titan latitudes with the Cassini/Huygens spacecraft.

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

1. Introduction

Data obtained from the Voyager encounters with Saturn's moon Titan first suggested that Titan might support a methane meteorological cycle analogous to Earth's hydrological cycle including methane clouds, rain and oceans (Flasar, 1983; Lunine et al., 1983; Yung et al., 1984). Titan's thick stratospheric haze prevented Voyager cameras from imaging the lower atmosphere and surface to confirm or deny the existence of oceans or clouds. The first images of Titan's surface were taken in the near infrared with the Hubble Space Telescope (Smith et al., 1996). These images revealed large bright and dark regions on Titan's surface that were hypothesized to correspond to continent-like land masses and hydrocarbon oceans, respectively.

Arecibo radar observations seemed to confirm the idea that Titan's surface possessed bodies of liquid methane or other hydrocarbons (Campbell et al., 2003). In 12 out of 16 observed locations on Titan's surface, Campbell et al. (2003) saw a specular reflection indicating that Titan was extremely smooth on the scale of centimeters in these locations. It was expected that data from the Cassini spacecraft would reveal lakes or seas of liquid methane or other hydrocarbons. The Huygens lander was even designed to function if it landed on a liquid surface (Lebreton and Matson, 2002). However, the Huygens landing spot was solid even though it landed in one of the dark areas originally thought to be composed of liquid hydrocarbons (Zarnecki et al., 2005).

Recent Keck observations in the infrared have also found no evidence for specular reflection indicating that Titan is not smooth on the scale of microns (West et al., 2005). The radar and IR observations are consistent if the surface is smooth on centimeter scales but not on micron scales. Such a surface could be formed by evaporite deposits, frozen cryolavas, or deposits of organic haze (West et al., 2005). In addition, the VIMS instrument has found no evidence for specular reflection anywhere it has looked (Brown et al., 2005).

Though Cassini has not found any evidence for liquids currently on the surface, images taken during the Huygens descent

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provide strong morphological evidence that liquids have flowed across the surface in the past (Lebreton et al., 2005). Huygens descent images revealed incised, river-like channels appearing to empty into a dark flat area. These images force questions about how long ago liquid methane last flowed through these channels. Are Titan's channels similar to ancient valley networks on Mars where water dried up billions of years ago, or does methane still rain down and flow across the surface of Titan today?

The scarcity of impact craters observed by Cassini point to a young surface age. Though Titan's atmosphere screens out impactors that form craters of less than ∼20 km, the dearth of midsized craters is consistent with a relatively young surface age (Lunine et al., 2005). Though the cratering record can provide constraints on Titan's surface age, in order to begin to answer questions about when and where liquid methane last flowed across the surface of Titan, the most important pieces of available data are observations of Titan's clouds. Understanding Titan's complex meteorological cycle can provide clues about when it last rained at the Huygens landing site and when it might rain again.

Clouds on Titan were first detected in 1995 by Griffith et al. (1998) via whole disk spectroscopy. On two nights out of 12 that they observed, Griffith et al. (1998) witnessed Titan brightening by up to 200% in regions of Titan's spectrum in which photons penetrated to the troposphere. They found that this dramatic, transient brightening corresponded to cloud cover of ∼7–9% of Titan's disk with a cloud altitude of ∼16 km. While there is some evidence that this cloud was near the equator based on spectral changes from one night to the next, the latitude of the cloud is unknown. Griffith et al. (2000) continued their spectroscopic monitoring of Titan in methane windows and found daily clouds that appeared to vary on the timescales of hours and corresponded to total cloud coverage of <1% of Titan's disk.

The first direct detection of clouds on Titan was achieved with the adaptive optics systems on the Keck and Gemini telescopes by Brown et al. (2002) and Roe et al. (2002). These observations also revealed cloud cover of ∼1% of Titan's disk consistent with the magnitudes of the daily clouds observed spectroscopically by Griffith et al. (2000). Images of Titan's clouds revealed that they were all located within about 30° of the south pole. The location near the pole and the fact that Titan summer solstice occurred in October 2002, led Brown et al. (2002) to propose a convective cloud formation mechanism driven by surface heating due to the increased solar insolation at the south pole. Small (∼1°) increases in surface temperature increase the lapse rate sufficiently to instigate moist convection in Titan's usually convectively stable atmosphere (Brown et al., 2002). Brown et al. (2002) predicted that the locations of the clouds should move north with the changing season.

Recent GCM modeling of Titan by Tokano (2005) has predicted that the temperature at the south pole could vary by ∼4° during the course of a Titan year assuming a surface composed of porous icy regolith. Tokano (2005) also mapped locations of convective zones (locations where the lapse rate exceeds the dry adiabat) near the surface for different seasons. He found

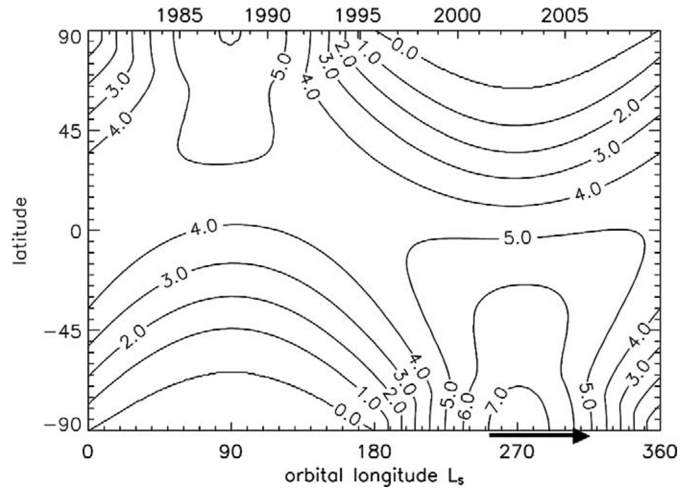

Fig. 1. Mean daily insolation at the top of Titan's atmosphere vs latitude and season in units of W/m^2. During most of the four years of adaptive optics observations of Titan's clouds (indicated by the black arrow), the south pole received the maximum daily insolation of anywhere on Titan. In July 2005 the south pole ceased to be the area of maximum solar insolation. The dissipation of Titan's south polar clouds and recent resurgence at higher latitudes may be the first indications of seasonal change in Titan's cloud activity.

superadiabatic lapse rates between 50°–90° S latitude at L_s 270 (southern summer solstice) with the highest values of the lapse rate at the south pole. The locations of Tokano's convective zones are consistent with the observed locations of Titan's clouds which have regularly been observed from ∼60°–90° S latitude by ground based observers since 2001 and by Cassini (e.g., Bouchez and Brown, 2005; Gendron et al., 2004; Brown et al., 2002; Roe et al., 2002; Porco et al., 2005).

In October 2004 Schaller et al. (2006) witnessed a brightening of Titan's south polar clouds of comparable magnitude to the large cloud event observed in 1995 by Griffith et al. (1998). This observation indicated that large cloud events occasionally occur during different seasons of Titan's year (southern spring equinox and southern summer solstice). Schaller et al. (2006) suggested that these large cloud events might be caused by methane injection somewhere on the surface of the planet that is then concentrated near the pole via Titan's global circulation.

The four years of adaptive optics observations of Titan comprise less than 1/7 of a full Titan year and have essentially bracketed the period surrounding southern summer solstice (Fig. 1). However, as of July 2005, the south pole ceased to be the area of maximum solar insolation on Titan. The discovery of streaky, extended clouds at temperate latitudes (∼40° S) in December 2003 was initially thought to be evidence for seasonal change in Titan's cloud activity (Roe et al., 2005a). However, subsequent observations by Roe et al. (2005b) showed that these clouds were clustered in longitude (near 350° W) and that due to an odd coincidence of when Titan was observed prior to 2003, there was very little coverage of the side of Titan on which the midlatitude clouds occasionally appear. Roe et al. (2005b) suggested that the strong tie to a particular location on Titan's surface indicated that these clouds form by the release of volatiles or other geologic activity occurring near 40° S, 350° W. Other authors (Griffith at al., 2005;

Rannou et al., 2006) have suggested that the midlatitude clouds form as a result of Titan's global circulation.

In contrast to the simple picture of cloud locations generally following the area of maximum solar insolation, modeling by Rannou et al. (2006) predicts that Titan's tropospheric methane clouds should be present near the south and north poles at nearly all seasons. Their model also predicts sporadic tropical methane clouds occurring at ∼40° S corresponding to the ascending branch of the troposphere Hadley cell. These clouds should appear at ∼40° N around the time of northern solstice. They predict that south polar clouds should decrease in frequency in the years following the summer solstice and then reappear after equinox in about 2010. The differences between the Tokano (2005) and Rannou et al. (2006) models may be due to the high value of thermal inertia (2000 $\mathrm{J\,m^{-2}\,s^{-0.5}\,K^{-1}}$) used by Rannou et al. (2006) compared to case 1 of the Tokano (2005) model with a thermal inertia of 335 $\mathrm{J\,m^{-2}\,s^{-0.5}\,K^{-1}}$. The high value of thermal inertia does not allow the surface temperature to vary significantly with season which could influence the predicted locations of cloud activity. Another difference between the models is in their treatment of the spectral properties and spatial extent of Titan's stratospheric haze. The aggregate particles and high haze optical depth at the poles used in the Rannou et al. (2006) model may be more realistic. The properties of Titan's stratospheric haze may significantly influence the locations of its tropospheric clouds.

One potential inconsistency with the simple picture of cloud systems following insolation and circulation and support for the Rannou et al. (2006) model comes from early observations of Gibbard et al. (2004) in 1998 near the time of the equinox. At a time when clouds would be expected near the equator in the insolation driven model, they obtained tentative evidence of a cloud near the south pole. Unfortunately, the data were obtained before the days of routine high-resolution adaptive optics imaging and instead had to use the much more difficult technique of speckle interferometry. This technique can introduce artifacts, particularly near sharp edges such as the south pole. The data look tentatively convincing, but it is difficult to assess their reliability. The best resolution of this data point will come over the next few years as we observe Titan's cloud systems again move through the equinox. If Titan's clouds continue to occur near the south pole even sporadically during equinox, then the simple picture of convective clouds driven by surface heating should be discarded.

Thus far, there is no confirmed evidence for seasonal variation of Titan's clouds. Small, daily clouds have been regularly observed near the south pole since 2001 when adaptive optics observations began. Large cloud events, while infrequent, have been observed to occur in two different seasons, (spring equinox and 2 years post summer solstice). Midlatitude clouds may be caused by surface outgassing and/or may be related to the global circulation (Griffith at al., 2005; Roe et al., 2005b). However, there is no evidence that they are a recent phenomenon (Roe et al., 2005b). We report here on a near-complete disappearance of Titan's south polar clouds observed in twenty-nine Keck and Gemini images taken between December 2004 and April 2005 and comment on the possibility that this decrease and subsequent resurgence of cloud activity at generally higher latitudes could be the start of seasonal change in Titan's cloud activity. These observations will provide the best tests for discriminating between competing models of cloud formation.

2. Observations and results

Titan images presented here come from two long-term Titan monitoring programs carried out on the W.M. Keck 10-m and the Gemini North 8-m telescopes (Table 1). Keck images were taken the facility adaptive optics system and the either the NIRC2 near-infrared camera (Wizinowich et al., 2000) or the imager on the OH Suppressing Infrared Imaging Spectrograph (OSIRIS) (Quirrenbach et al., 2006). Gemini images were acquired with the Altair adaptive optics system and the facility near infrared camera (Herriot et al., 2000; Hodapp et al., 2003).

Keck NIRC2 and Gemini images were taken through three different filters that probe to different levels in Titan's atmosphere. Because the strength of the collision induced absorption from methane and H_2–N_2/N_2–N_2 depends greatly on wavelength in the near infrared, we are able to probe to different levels in Titan's atmosphere with the use of different filters. Keck NIRC2 images were taken through the K' filter (1.948–2.299 um) that probes to Titan's surface, the H_2 (1–0) filter (2.1112–2.1452 um) that probes to ∼10 km altitude (lower troposphere), and the Brg filter (2.1426–2.1780 um) that probes to ∼50 km altitude (tropopause). Keck OSIRIS images were taken through the Kn2 (2.0381–2.1429 um) and Kn3 (2.1216–2.2297) filters. The Kn2 filter probes to Titan's surface while the Kn3 probes to the troposphere. Gemini images were taken through the K' surface probing filter, the H_2 (1–0) troposphere probing filter and the Brg tropopause probing filter. Titan's clouds are visible in the surface probing filters (though they are often difficult to distinguish from surface features), visible in the troposphere-probing filter, and then generally not visible in the tropopause/stratosphere probing filters indicating that they are located in the troposphere. We use the troposphere probing filters in our analysis of cloud locations.

The Keck and Gemini Titan monitoring programs have yielded 83 individual nights of Titan images from September 2003 to December 2005 (Table 1). We combine our dataset with Titan adaptive optics images from the Palomar 200-inch (previously published in Bouchez and Brown, 2005), and Keck images previously published in Brown et al. (2002) and Roe et al. (2002). The combined dataset yields 100 separate nights spanning the time period from December 2001 through December 2005. Images were flat-fielded, corrected for bad pixels and oriented so that Titan's north pole was aligned with the vertical axis. Cloud locations were measured from a latitude/longitude grid projected onto Titan's disk. Errors in cloud locations are derived from the uncertainty in locating the center of Titan's disk (estimated to be $\frac{1}{2}$ pixel) and the uncertainty in locating the centers of the clouds (estimated to be 1 pixel).

Fig. 2 shows the latitudes of Titan's clouds observed in all images from 2001 to 2005. Also plotted are dates of observa-

Table 1
Cloud details

UT date	Telescope/ instrument	Cloud latitudes (S latitude)
2003 Sep 17	Keck NIRC2	84 ± 2
2003 Oct 10	Keck NIRC2	85 ± 3
2003 Oct 11	Keck NIRC2	84 ± 5
2003 Oct 12	Keck NIRC2	85 ± 4
2003 Nov 09	Keck NIRC2	81 ± 2
2003 Nov 11	Keck NIRC2	83 ± 2
2003 Nov 12	Keck NIRC2	84 ± 2
2003 Nov 13	Keck NIRC2	85 ± 3
2003 Nov 14	Keck NIRC2	82 ± 3
2003 Nov 15	Gemini	85 ± 5
2003 Nov 17	Gemini	88 ± 3
2003 Nov 18	Keck NIRC2	79 ±2
		78 ±2
2003 Dec 10	Keck NIRC2	90 ± 4
2003 Dec 15	Keck NIRC2	87 ± 4
2003 Dec 17	Keck NIRC2	83 ± 4
2003 Dec 18	Keck NIRC2	82 ± 3
2003 Dec 24	Keck NIRC2	83 ± 4
2003 Dec 25	Keck NIRC2	None
2003 Dec 26	Keck NIRC2	85 ± 3
2003 Dec 27	Keck NIRC2	86 ± 3
2004 Jan 10	Keck NIRC2	87 ± 4
2004 Apr 04	Gemini	81 ± 6
2004 Apr 05	Gemini	90 ± 7
2004 Apr 06	Gemini	87 ± 6
2004 Apr 07	Gemini	77 ± 7
2004 Apr 08	Gemini	83 ± 5
2004 Apr 09	Gemini	84 ± 6
2004 Apr 30	Gemini	84 ± 3
2004 May 04	Gemini	None
2004 May 05	Gemini	83 ± 5
2004 May 06	Gemini	82 ± 4
2004 May 07	Gemini	86 ± 5
2004 Sep 02	Keck NIRC2	85 ± 3
2004 Sep 28	Keck NIRC2	86 ± 3
2004 Oct 02	Keck NIRC2	73 ± 3
2004 Oct 03	Keck NIRC2	76 ± 3
2004 Oct 07	Keck NIRC2	71 ± 2
2004 Oct 08	Keck NIRC2	72 ± 3
2004 Oct 23	Keck NIRC2	75 ± 2
2004 Oct 24	Gemini	76 ± 6
2004 Oct 28	Keck NIRC2	71 ± 2
2004 Nov 01	Gemini	69 ± 5
2004 Nov 02	Gemini	71 ± 2
2004 Nov 03	Keck NIRC2	69 ± 2
		63 ± 3
2004 Nov 04	Gemini	74 ± 4
2004 Nov 05	Gemini	68 ± 3
2004 Nov 27	Keck NIRC2	77 ± 3
		66 ± 3
2004 Dec 21	Gemini	None
2004 Dec 24	Gemini	None
2004 Dec 25	Gemini	None
2004 Dec 27	Gemini	None
2005 Jan 14	Keck NIRC2	None
2005 Jan 16	Gemini	None
2005 Jan 20	Keck NIRC2	83 ± 2
2005 Jan 23	Gemini	None
2005 Jan 24	Gemini	None
2005 Jan 25	Gemini	None
2005 Jan 28	Gemini	None
2005 Feb 08	Gemini	None
2005 Feb 09	Gemini	None
2005 Feb 10	Gemini	None
2005 Feb 12	Gemini	None
2005 Feb 14	Keck NIRC2	None
2005 Feb 15	Keck NIRC2	None
2005 Feb 16	Gemini	None
2005 Feb 19	Gemini	None
2005 Feb 20	Gemini	None
2005 Feb 21	Gemini	None
2005 Feb 22	Gemini	None
2005 Feb 25	Gemini	None
2005 Mar 01	Gemini	None
2005 Mar 02	Gemini	None
2005 Mar 04	Gemini	None
2005 Mar 05	Gemini	None
2005 Mar 09	Gemini	None
2005 Mar 24	Gemini	None
2005 Sep 29	Keck NIRC2	59 ± 2
2005 Oct 09	Keck OSIRIS	50 ± 3
2005 Oct 10	Keck OSIRIS	51 ± 3
2005 Nov 21	Keck OSIRIS	None
2005 Nov 22	Keck OSIRIS	None
2005 Nov 24	Keck OSIRIS	None
2005 Dec 24	Keck NIRC2	75 ± 2

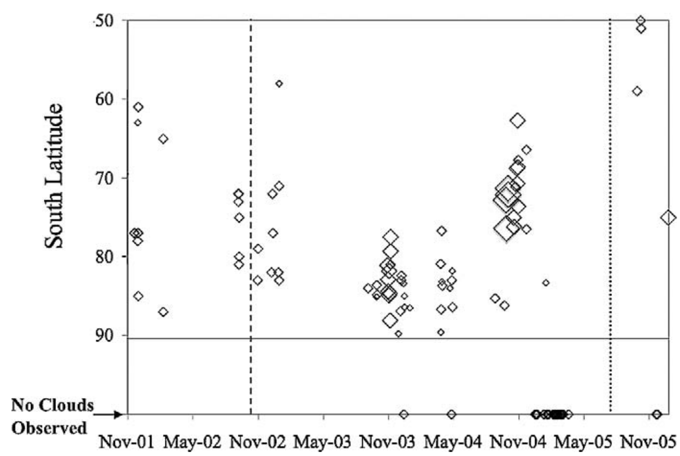

Fig. 2. Titan cloud locations vs time. This figure excludes all midlatitude clouds from Roe et al. (2005a) which are all located near 40° S and are clustered in longitude near 350° W. Diamond sizes indicate the relative size of the cloud observed. Dashed line marks Titan southern summer solstice which occurred in October 2002. Dotted line marks July 2005, the time at which the south pole ceased to be the area of maximum solar insolation on Titan. Before December 2004, clouds were observed within 30° of the south pole in nearly every adaptive optics image of Titan. During the five month period between December 2004 and April 2005 only one image shows even a small amount of cloud activity at the pole. Images taken in the current (2005–2006) Titan apparition show a resurgence of Titan's clouds at the highest latitudes yet seen.

tions where no clouds were observed. We ignore midlatitude clouds (Roe et al., 2005a, 2005b; Griffith at al., 2005) in this analysis as their formation mechanism may be tied to the surface geography. We find that a cloud or clouds were present between 58°–90° S latitude in 62 out of 64 images from December 2001 to November 2004 and most were clustered between 75°–90° S. We find no statistically significant trend of cloud latitude with time in images before 2004. We also mea-

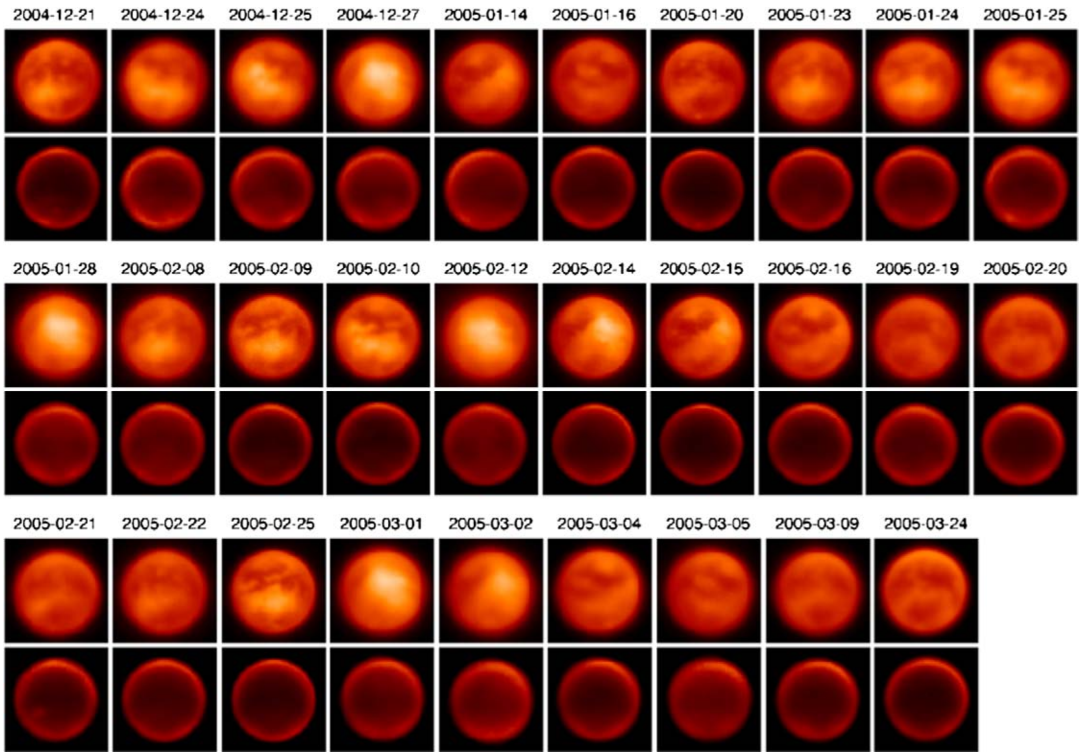

Fig. 3. Twenty-nine nights of Titan images taken with the Keck and Gemini adaptive optics systems. The top set of images are taken through the K′ (surface probing) filter, while the second set of images are taken through the H_2 (1–0) (troposphere probing) filter. All images show extremely low to nonexistent cloud activity near the south pole compared with all previous images (see Bouchez and Brown, 2005; Brown et al., 2002; Roe et al., 2002; Schaller et al., 2006). In Keck and Gemini images we could have detected point source clouds with brightnesses of 0.03 and 0.04% of Titan's total flux. In order to confirm a cloud detection, we required it to be observable in both the K′ and H_2 filters.

sured the longitudes of Titan's clouds and found no correlation between longitude with time or with Titan time of day.

In contrast to images taken before December 2004, we found no south polar clouds at all in 28 out of 29 images from December 2004 to April 2005. Point source clouds with brightnesses of 0.03 and 0.04% of Titan's could have been detected in Keck and Gemini images, respectively. The lack of clouds in these images is a striking change in the behavior of Titan's south polar clouds compared with all other previous observations. Fig. 3 shows the 29 nights of Titan images taken between December 2004 and April 2005 showing the decreased to nonexistent cloud activity at the south pole (only one image has even a small cloud discernable near the pole). Recent images taken in the 2005–2006 Titan apparition show a resurgence of Titan's south polar cloud activity at generally lower latitudes. OSIRIS images from October 9 and October 10 show clouds at 50° and 51° S which is the furthest north these clouds have ever been observed.

3. Discussion and conclusions

The timing of the observed breakup of Titan's south polar cloud system along with the resurgence of clouds at generally lower southern latitudes (∼55° S) is consistent with the timing of the seasonal shift of the location of maximum solar insolation away from the south pole. The timing is also consistent with an expected decrease in south polar cloud activity predicted in the Rannou et al. (2006) model. As of July 2005, the latitude of maximum insolation on the disk moved to 35° S and will continue moving north until it reaches the equator in 2008 and then moves to the north pole. Subsequent observations of Titan over the next several years may continue to show decreased to nonexistent cloud activity near the south pole. However, if convective cloud activity continues near the south pole and is observed near the north pole significantly before northern summer solstice, then the simple picture of cloud activity following the insolation will need to be discarded. Frequent equatorial clouds after 2008 and a lack of south polar clouds would provide support for the insolation driven cloud model. The latitudes of Titan's clouds with season are likely controlled by complex interplay between insolation and uplift from global circulation, and may behave in complicated ways as the season changes. In addition to possible seasonal change, periods of low cloud activity on Titan might also be explained by the fact that they generally occur following periods of increased cloud activity. The ∼5 month near disappearance of Titan's clouds observed from November 2004 to at least April 2005 occurred immediately following the largest cloud outburst ever observed. The brightness of Titan's south polar clouds increased by over 15 times their typical values for approximately 30 days in October 2004 (Schaller et al., 2006). In addition, one of only two times before December 2004 when there were no clouds observed, occurred following brighter clouds observed in November 2003 (Fig. 2). The lack of cloud activity following large cloud events might indicate that these large events are associated with methane rainout, the evaporation of which could cool the atmosphere or surface and inhibit subsequent convection for periods of weeks to months. In addition, rainout could have washed out cloud condensation nuclei thereby inhibiting cloud formation. It is likely that the low level of cloud activity observed from December 2004 to April 2005 was caused by both the large cloud outburst of October 2004 and by the beginnings of seasonal change caused by the changing insolation and circulation.

While Cassini has found no specular evidence for liquids on Titan's surface, the geometry of the flybys have prevented looking for specular points in the far southern latitudes—exactly location where liquids, if they do currently exist on the surface, are most likely to be found in the present season. The recent discovery of the dark lake-like feature in ISS images (Turtle et al., 2005), and the detection of a shoreline-like feature in RADAR images (Lopes et al., 2005) near the south pole suggests that liquid methane might currently exist on the surface of Titan. The locations of liquids on the surface may shift from pole to pole as a result of rain out from the clouds that may move according to the changing seasons or may remain near the south pole according to the Rannou et al. (2006) model. Titan observations over the next few years will reveal how cloud activity changes with season and will help to clarify and interpret when and how the fluvial surface features seen in Huygens descent images were formed.

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