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# Discovery of lake-effect clouds on Titan

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[1] Images from instruments on Cassini as well as from telescopes on the ground reveal the presence of sporadic small-scale cloud activity in the cold late-winter north polar region of Saturn's large moon Titan. These clouds lie underneath the previously discovered uniform polar cloud attributed to a quiescent ethane cloud at ~40 km and appear confined to the same latitudes as those of the largest known hydrocarbon lakes at the north pole of Titan. The physical properties of these clouds suggest that they are due to methane convection and condensation. Such convection could be caused by a process in some ways analogous to terrestrial lake-effect clouds. The lakes on Titan could be a key connection between the surface and the meteorological cycle. **Citation:** Brown, M. E., E. L. Schaller, H. G. Roe, C. Chen, J. Roberts, R. H. Brown, K. H. Baines, and R. N. Clark (2009), Discovery of lake-effect clouds on Titan, *Geophys. Res. Lett.*, *36*, L01103, doi:10.1029/2008GL035964.

## 1. Introduction

[2] Tropospheric cloud cover on Titan is significantly more sparse and more variable than on the Earth, with typical surface coverage being less than 1%, but with large storms occasionally covering up to 10% of the surface [*Griffith et al.*, 1998, 2000; *Schaller et al.*, 2006a]. The locations of the clouds appear to be controlled by solar insolation. During southern summer solstice, when the point of maximum insolation was the pole itself, clouds were a persistent presence at high southern latitudes [*Bouchez and Brown*, 2005; *Brown et al.*, 2002]. As southern summer has waned to southern fall, the south polar clouds have mostly dissipated [*Schaller et al.*, 2006b] and clouds at southern mid-latitudes have become more frequent [*Roe et al.*, 2005]. While the time scale for radiative heating or cooling of Titan's atmosphere is so long that seasonal effects were initially thought to be irrelevant [*Hunten et al.*, 1984], it is now seen that the general seasonal behavior of Titan's clouds is moderately well reproduced with general circulation models (GCMs) where Titan's surface has a low enough thermal inertia that the seasonally changing surface temperature controls the large scale seasonal circulation changes [*Mitchell et al.*, 2006; *Mitchell*, 2008; *Tokano*, 2005]. Clouds appear in regions of uplift where air parcels become saturated with methane which then condenses out as they ascend through the troposphere.

[3] In this simple picture of clouds and circulation, no clouds would be expected near the winter pole where the air is primarily descending from the stratosphere. On Titan, however, other condensable species–the most abundant being ethane–are produced in the stratosphere by photolysis of methane. If air containing these species subsides across the cold tropopause a separate type of cloud system can form [*Rannou et al.*, 2006]. Such clouds were recently observed in the late winter near the pole [*Griffith et al.*, 2006]. These clouds are distinctly different from the previously observed clouds. They are near the ~40 km height of the tropopause, rather than at ~20 km in the middle of the troposphere; they appear to be composed of small particles which do not scatter efficiently at wavelengths of 5 microns and longer, in contrast to the much larger particles found in the other clouds; and they are spatially and temporally homogenous [*Griffith et al.*, 2006]. These characteristics are precisely those expected for a cloud formed from condensation of higher order hydrocarbons as they subside across the tropopause [*Griffith et al.*, 2006].

[4] While this north polar cloud has appeared continuously since it was first discovered, a careful examination of images from the Cassini spacecraft reveals that a separate type of cloud can also be seen sporadically at the north pole. In this study we examine images and spectra of this new cloud system and discuss their origin and implications.

## 2. Observations

[5] We examined the north polar clouds of Titan using data from VIMS and ISS instruments on board the Cassini spacecraft and from adaptive optics observations from the Gemini observatory and full-disk spectroscopy of Titan from the NASA Infrared Telescope Facility (IRTF). The Cassini data were obtained from the Planetary Data Systems (PDS) imaging archive (www.pds-imaging.jpl.nasa.gov) and covered 36 Titan flybys from July 2004 until August 2007. The VIMS data were calibrated using routines provided by the PDS. No calibration routines appear for ISS data, so the data are used in raw form.

[6] North polar knots and streaks are identified in the VIMS data by constructing a tropospheric image out of each hyperspectral image by summing the data from the channels at wavelengths between 2.83 and 2.90 microns, all of which are wavelengths of moderate methane opacity where photons reach the troposphere but not the surface. We examine each image and look for spatial inhomogeneities in the north polar cloud. A feature is not labeled as a north polar knot or streak unless it appears in multiple images and multiple pixels.

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[7] Clouds are identified in the ISS images by morphological appearance alone, as no information is available on their heights. Locations of clouds are determined by comparison of the surface image to a surface base map released by the ISS team at www.ciclops.org

[8] The Gemini data were obtained in a continuation of a long term monitoring program of *Roe et al.* [2005] and calibrated identically to the earlier program. With the much lower spatial resolution of these ground-based images no individual north polar features are resolved, but, on occasion, the north polar region temporarily brightens dramatically in the 2.11–2.137 micron filter which is sensitive to scattering in troposphere and above. While the ground-based data are significantly less sensitive to these cloud features, the much more frequent imaging from the ground allows a better temporal understanding of the largest of these cloud outbursts.

[9] Spectral monitoring of Titan was performed by the IRTF telescope and the SpeX instrument in the program described by *Schaller* [2008]. Synoptic variations in the full disk spectra were used to monitor changes in total cloud coverage and to measure the heights of clouds detected. On several occasions, simultaneous imaging from Gemini and spectra from IRTF allow us to both pinpoint the location of a cloud and measure its altitude.

## 3. North Polar Knots and Streaks

[10] The large ethane-like north polar cloud appears essentially unchanged in every image of the north pole of Titan obtained since its discovery, but a close look shows small bright knots or steaks within the otherwise homogeneous north polar cloud. With the small amount of time that any spot on Titan is imaged during any one flyby, little short term temporal information is available, but on one occasion images taken 5.5 hours apart show that new bright knots are capable of appearing on time scales of hours (Figure 1). The earliest that such a knot was observed was 14 February 2005; they have since been observed in almost every Titan flyby since February 2007. The presence of these brightenings within the otherwise homogeneous north polar cloud has also been seen from ground based adaptive optics images with the Gemini telescope. While the ground-based images have lower resolution and poorer viewing geometry, the brightest north polar events can nonetheless be detected, and these have been seen on 14 occasions since 13 April 2007. On 4 of those occasions we have simultaneous full-disk spectra of Titan from the IRTF which show that the brightenings seen in the Gemini images are confined to wavelengths shortward of 2.16 microns, as has typically been seen for Titan's south polar and mid-latitude clouds [*Schaller*, 2008].

[11] Detections of the clouds are confined to regions north of 55 N latitude, precisely the same latitudes as the largest known lakes [*Hayes et al.*, 2008]. Cassini has seen such clouds almost exclusively between longitudes of about 60 and 240 E, but 10 of the 11 flybys from February 2007 until August 2007–when most of the north polar streaks and knots have been observed–have covered the same longitude range. The ground-based images are unbiased in longitude, however, and show no statistically significant longitudinal preference (Figure 2).

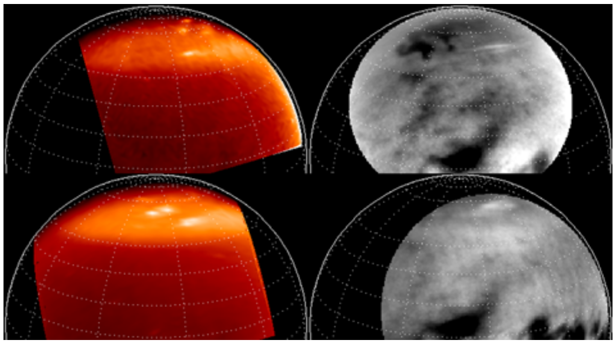

**Figure 1.** Map projected images of time-variable clouds at the winter north pole of Titan from the (left) VIMS (both from 27 April 2007) and (right) ISS (from (top) 24 Feb 2007 and (bottom) 13 April 2007) imagers on board the Cassini spacecraft. A latitude-longitude grid is imposed on all images. Lines of latitude are shown every 10 degrees, with the north pole barely visible at the top. Lines of longitude are shown every 30 degreed; the VIMS images are projected with a central meridian longitude of 140 E, while the ISS images are projected with a central meridian longitude of 80 E. The VIMS images are a sum of 5 images between 2.83 and 2.90 microns, which are wavelengths that exclusively probe regions of Titan at the troposphere and higher. These images show the general north polar cloud previously observed [*Griffith et al.*, 2006] as a general brightening northward of 50 degrees latitude. The newly discovered clouds are visible as spatially and temporally variable brightening within this region. The two VIMS images were obtained within 5.5 hours of each other. Clouds are more difficult to discern in the ISS data because of the lack of appropriate filters to exclusively probe higher levels in the atmosphere; nonetheless these clouds can be detected through their morphology, brightness, and variability.

## 4. Spectral Analysis

[12] On 29 June 2007 the VIMS instrument [*Brown et al.*, 2004] on board Cassini, fortuitously obtained a high spatial resolution hyperspectral image of a north polar cloud streak, allowing us to carefully assess its spectral properties. We find that the spectrum of the streak differs significantly from the background north polar cloud. The streak is bright at 5 microns, while the north polar cloud is undetectable at these wavelengths, implying that, while the north polar cloud must be composed of particles that are smaller than 5 microns, particles that make the streak must be larger (Figure 3).

[13] In addition to being composed of larger particles, the streak appears to be significantly lower in the atmosphere than the north polar cloud. With the hyperspectral images from VIMS, the location where a cloud first appears is easily determined. We examine, in particular, the well-studied 2.0–2.23 micron region where most of the ground-based work has been done. Little methane opacity exists at 2.02 microns, so images at the wavelength see all the way to the surface. By 2.23 microns, in contrast, the methane opacity is so high that Titan is dark except for any scattering high in the stratosphere. Between 2.02 and 2.23 microns the methane opacity

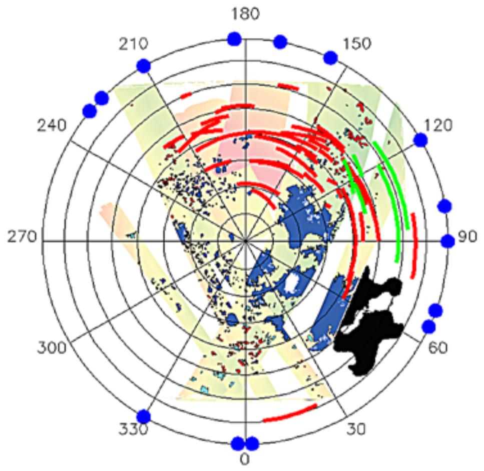

**Figure 2.** Locations of detected clouds plotted on a polar projection of radar detections of lake and lake-like features at the north pole of Titan [*Hayes et al.*, 2008] Lines of latitude are shown every 5 degrees. The southern extent of the large lake visible in the ISS image in Figure 1 is projected in black onto the radar map to examine the southern extent of the large lakes. Detections from VIMS are shown as red lines, while detections from ISS are shown as green lines. The blue dots at 50 degrees latitude show the approximate longitude of the detections of north polar brightening from ground-based Gemini adaptive-optics images. With the low resolution and poor viewing geometry of the ground-based images, no accurate latitude can be measured.

increases. At 2.02 microns the surface, north polar streaks, and north polar clouds are all visible. By 2.10 microns the surface is no longer visible, but the north polar streak and north polar cloud can still be seen. The north polar steak is visible until wavelengths of 2.15 microns; by 2.17 microns only the north polar cloud can be seen. The north polar cloud remains visible until 2.20 microns, when it, too, disappears due to high methane opacity. This spectral structure demonstrates conclusively that the north polar streaks are above the surface but below the north polar cloud. Indeed, the wavelengths at which the north polar streaks are visible are identical to those at which Titan's mid-latitude convective clouds are also visible [*Griffith et al.*, 2005], demonstrating that they are at similar altitudes of 20–30 km. A similar conclusion is reached by examining the simultaneous ground-based images and spectra, which show that the northern brightening are confined to the heights as has previously been seen for south polar and mid-latitude clouds [*Schaller*, 2008].

## 5. Source of the Clouds

[14] The properties of these north polar streaks show that they are a distinct phenomenon from the north polar cloud. In fact, these properties suggest a specific general cause for this new phenomenon. The arguments put forth to suggest that the north polar cloud is caused primarily by ethane subsidence can be reversed to suggest that the north polar streaks are caused by the lifting of methane. The larger particle size for the streaks is expected for the dominant

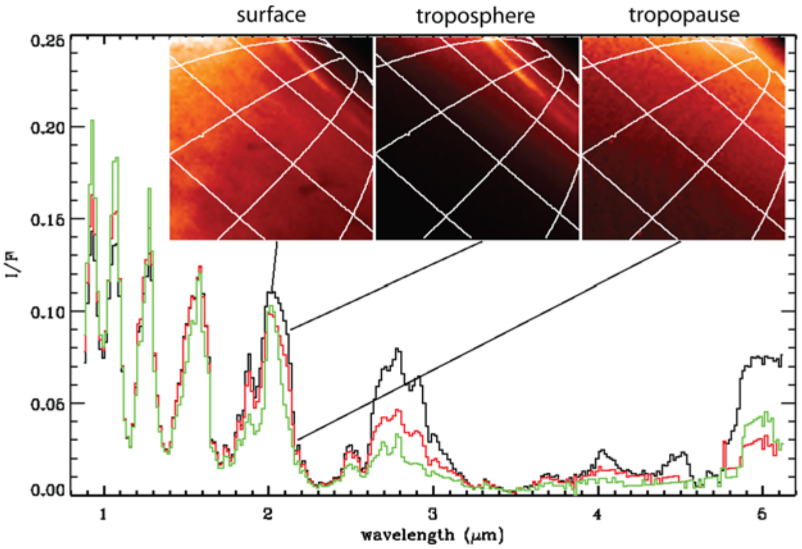

**Figure 3.** VIMS images and spectra of a fortuitous high spatial resolution observation of a north polar streak. The images show three wavelengths of the hyperspectral images which are sensitive to three different locations in the atmosphere. Latitude lines between 40 and 80 N degrees are shown at 10 degree intervals, and longitude lines between 130 and 150 E are shown at 10 degree intervals. At 2.02 microns little methane opacity exists so the image shows features all the way to the surface. At 2.13 microns, in a region of moderate methane opacity, the surface is no longer visible but the streaks and north polar cloud are clearly seen. At a wavelength of 2.17 microns, where methane opacity is high, the streaks can no longer be seen, but the north polar cloud is visible. At 2.3 microns (not shown) the methane opacity is so high that no features can be seen. The spectra show isolated regions of the image. The black line shows the spectrum of a bright streak, the green line shows the spectrum of the north polar cloud outside of the streak, while the red line shows the spectrum of the region below 50 degrees N latitude where no cloud is present. The streaks are significantly more reflective at 3 and 5 microns than the surface or north polar cloud, while the north polar cloud is brighter at wavelengths shorter than 2 microns.

condensable species in the atmosphere; the high spatial and temporal variability is expected for convective clouds; and the ~20–30 km altitude of the clouds is the expected height for convective clouds in Titan's troposphere [*Griffith et al.*, 2000]. Methane lifting and condensation can readily explain all of the observed properties. With the low insolation at the north pole in the late winter (Titan will not reach equinox until August 2009), however, the air should be stably stratified and no convection should be occurring.

[15] We consider three general mechanisms that could cause winter convection in what should otherwise be stably stratified air. First, near-surface air from low latitudes could be slant-wise advected to the pole until it reaches the middle troposphere where it then becomes convectively unstable. Second, otherwise stable air could be made unstable by the external addition of humidity, effectively lowering the level of free convection to near the surface, and, third, otherwise stable air could be made unstable by the addition of external heat, causing the air to rise to the level of free convection where subsequent instability will be unleashed.

[16] The first mechanism–polar convection instigated by slant-wise advection from lower latitudes–has been suggested by the circulation modeling of *Rannou et al.* [2006]. The Rannou et al. circulation model also predicts the existence of more easily observed winter mid-latitude clouds from this same general mechanism. Such clouds have never been observed on Titan. Other circulation models which provide a better match to observed (and unobserved) clouds [*Mitchell et al.*, 2006; *Tokano*, 2005] do not predict this slant-wise advection or the unobserved winter mid-latitude clouds. We thus suspect that slant-wise advection is unlikely to be occurring in Titan's winter hemisphere, and thus we seek alternative explanations for the winter polar convective clouds.

[17] The second and third convection-causing mechanisms–injection of humidity and injection of heat into the air–have a common terrestrial analog. On the Earth, winter convection is frequently seen over and downwind of lakes such as the Great Lakes in what are called lake-effect clouds. Terrestrial lake-effect clouds typically occur when cold stably stratified air passes over warmer lake water, causing an increase in air humidity and temperature, leading to condensation in an expanded convecting boundary layer. Such clouds typically have streak-like morphology resulting from secondary flows within the planetary boundary layer [*Brown*, 1980]. Morphologically and spatially, the winter polar clouds on Titan have intriguing similarities to terrestrial lake-effect clouds. All of the Titan clouds imaged at sufficient resolution are seen to have streak-like morphologies, and many–but definitely not all–of these streaks appear to originate on the eastern edges of the largest north polar lakes (Figure 2). We thus investigate whether lakes on Titan can provide the required humidity or heat to cause analog lake-effect clouds.

[18] The interaction of the lakes and the atmosphere on Titan depends critically on the lake composition. If the lakes are almost exclusively methane, air traveling over the lake surface can become saturated with evaporated methane, leading to convection. Due to the small seasonal temperature differences and strong cooling effect from methane evaporation [*Mitri et al.*, 2007], however, it is unlikely that such methane-rich lakes will ever have temperatures which will exceed air temperatures, so they cannot provide heat as terrestrial lakes would. Indeed, evaporative cooling in a dominantly-methane lake is so strong that it can inhibit its own evaporation. A methane lake will cool from evaporation until saturated air at the temperature of the lake is no longer buoyant compared to near-surface air, at which point turbulent exchange of heat and humidity will essentially shut-off [*Mitchell*, 2008]. When insolation causes the lake temperature to reach the threshold at which lake-temperature air is again buoyant, significant evaporation will recommence, lowering the lake temperature back below the threshold value. This unstable system would lead to sporadic evaporation as individual lakes go through cycles of radiative heating, evaporative cooling, and turbulent shut off, as the lake surface temperature stays close to the threshold value. The evaporation would peak at summer solstice when the maximum insolation keeps the lake temperature above the turbulent threshold temperature for the maximum amount of time.

[19] A dominantly ethane lake, in contrast, cannot provide methane humidity to the atmosphere, but it will likewise not be subject to evaporative cooling. Such a lake could–like large terrestrial lakes–potentially stay warm throughout the winter and thus provide a source for sensible heat flux to the atmosphere. In simulation of temperatures of a global ocean, the liquid surface was found to cool more than a solid surface would [*Tokano*, 2005], but these simulations considered only ~20 m deep lakes. The largest lakes at the north pole of Titan, with sizes of 500 km or more, are likely significantly deeper and so could store much more summer heat. A deep lake with a sinusoidally varying energy input at the surface which remains thermally stratified, for example, will never cool significantly below the seasonal average temperature. Such a lake could provide substantial sensible heat flux. In the summer, the sensible heat flux from the solid surface is thought to be ~1% of the total insolation, or ~0.04 W $m^{-2}$ near the summer pole. A similar sensible heat flux during the ~10 years of winter from a warm ethane lake 1 km deep will drain ~20 MJ $m^{-2}$ from the lake, leading to a winter ethane temperature drop of only ~0.015 K (1 km $d^{-1}$), where $d$ is the lake depth.

[20] An obvious objection to the lake-effect cloud hypothesis is that, unlike on the Earth, these clouds are not precisely correlated with the locations of the largest lakes. While many of the clouds appear to originate at or near the eastern boundary of the largest lakes, many more appear further east still and have no obvious connection to a lake. On Titan, however, these clouds are not trapped with the boundary layer, as they are on Earth. Instead, their heights indicate deep convection. Unlike Earth, then, these clouds can be blown far downwind of their source region. We note that the only cloud that we have seen actively form (Figure 1), forms almost precisely on the eastern edge of one of the large lakes.

[21] While the lake-effect cloud hypothesis appears plausible, additional evidence is still required to consider the hypothesis secure. Future Cassini and ground-based observations will be critical to test the following predictions. First, any observed newly forming clouds should always be found at the locations of large lakes. Second, as long as the lifetime of the clouds is short compared to the wind speed circulation time, a (spatially-lagged) correlation should appear between

the locations of the clouds and that of the lakes. For both of these predictions, more extensive observations over a wider range of longitudes are needed.

[22] The future behavior of these clouds also points to which mechanism is most likely. In the slant-wise advection scenario of *Rannou et al.* [2006] the advection and thus north polar clouds remain essentially constant. Evaporation from dominantly methane lakes will increase dramatically as the polar insolation increases through and following equinox, so, in this case, these clouds would similarly increase. Warm ethane lakes, in contrast, will become much less significant of a heat source as the solid surface warms up through spring, so these clouds would be predicted to decrease.

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