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The Evolution of Titan's Mid-Latitude Clouds

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Spectra from Cassini's Visual and Infrared Mapping Spectrometer reveal that the horizontal structure, height, and optical depth of Titan's clouds are highly dynamic. Vigorous cloud centers are seen to rise from the middle to the upper troposphere within 30 minutes and dissipate within the next hour. Their development indicates that Titan's clouds evolve convectively; dissipate through rain; and, over the next several hours, waft downwind to achieve their great longitude extents. These and other characteristics suggest that temperate clouds originate from circulation-induced convergence, in addition to a forcing at the surface associated with Saturn's tides, geology, and/or surface composition.

The atmosphere of Saturn's largest moon, Titan, contains methane, which, like water on Earth, can exist as a gas, ice, and liquid. This moon is hypothesized to resemble Earth, with a methane cycle similar to the terrestrial hydrological cycle, involving methane clouds, rain, and surface liquids. Yet, unlike Earth, only two kinds of clouds have been detected recently on Titan: large storms near the south pole and long clouds predominantly at -40° latitude (*1-8*). The south polar clouds reside at the altitude of neutral buoyancy (*2, 3*), which is indicative of convection (*5*). Their morphologies and Titan's recent south summer solstice (during October 2002) suggest a seasonal explanation for their formation,

through a polar updraft resulting from Titan's pole-to-pole circulation and dynamical lifting from surface heating (*3, 9, 10*). The narrow mid-latitude clouds, observed between -37° and -44° latitude, extend several hundred to several thousand kilometers in longitude, residing primarily at $0^\circ \pm 40^\circ$ and secondarily at $90^\circ \pm 40^\circ$ west longitude (*4*). The clouds' propensity for particular spots on Titan's disk suggests a tie to the surface (*4*). Yet Cassini images do not display the morphologies expected of orographic clouds nor the dark and uniform appearance expected of seas (*11, 12*) that would suggest marine clouds. Cloud formation through methane volcanic outgassing could explain the large amounts of methane in Titan's atmosphere (despite its photochemical loss rate of $\sim 6 \times 10^7$ kg/day), in addition to the temperate clouds' locations. However, the volcanoes would have to coincidentally reside at -40° latitude or outgas sufficient methane to instigate widespread deep convection. The longitude most preferred by the mid-latitude clouds coincides with the sub-Saturn point, which experiences large variations in pressure as Titan orbits Saturn (*13*). However, there has been no observed correlation with cloud activity and Titan's orbital position. Alternatively, Titan's general circulation may give rise to latitudinally confined clouds. Yet this answer does not explain the clouds' preferences for certain longitudes. Here we present measurements from the Cassini Visual and

Infrared Mapping Spectrometer (VIMS) (*14*) of the structure and evolution of Titan's clouds, which are diagnostic of the physical processes that govern their formations.

Six spectral images of Titan's clouds were recorded by VIMS on 13 December 2004 as Cassini approached Titan on the third (TB) flyby, from a distance of 236,000 to 179,000 km (Fig. 1). The pixel resolution of the clouds ranged from 90 to 130 km and 50 to 70 km in the roughly east-west and north-south directions, respectively, with the highest resolutions achieved in the last image recorded during the 3-hour sequence. Each pixel within the images consists of a spectrum from 0.8 to 5.0 μm , with a resolving power of 143 at 2 μm . Our analysis focuses on the 2- to 2.5- μm section of the spectra that, as a result of variable methane absorption, samples Titan's atmosphere from 100 km to the surface. Within the center of the methane bands (at 2.25 μm), Titan's atmosphere is opaque and sunlight is reflected from the stratosphere, at roughly 100 km altitude. Between the methane bands (at 2.0 μm), Titan's atmosphere is fairly transparent and sunlight reaches the surface. At intermediate wavelengths (2.12 to 2.16 μm), sunlight probes Titan's troposphere at 10 to 40 km, where methane condenses (*1*). Hourly variations in Titan's 2.12- to 2.16- μm albedos occur solely as a result of changes in the opacity of clouds in the middle to upper troposphere (*1, 5*). Four mid-latitude clouds are readily identified in the six VIMS images. They reside at the latitude and longitude coordinates of $[-61:134]$, $[-47:157]$, $[-43,176]$, and $[-41,115]$ and are referenced as cloud 1 through cloud 4, respectively (Fig. 1).

We approximate the radiative transfer equation with the discrete ordinates algorithm to simulate the absorption and scattering of Titan's atmosphere and surface (*15*). Comparing the calculated spectra to the data, we estimate the optical depths of the stratospheric haze and methane clouds, the cloud altitudes, and surface reflectivity. Methane, the primary absorber, is calculated from line-by-line techniques, using parameters from the HITRAN database (*16*) and assuming a Voigt line profile and the Voyager temperature profile (*17*). We also include pressure-induced absorption (*18*) due to H_2 and N_2 . We assume a methane relative humidity of 50% (0.088 mixing ratio) at the surface and a constant mixing ratio (0.017) in the stratosphere (*19, 20*). A constant methane mixing

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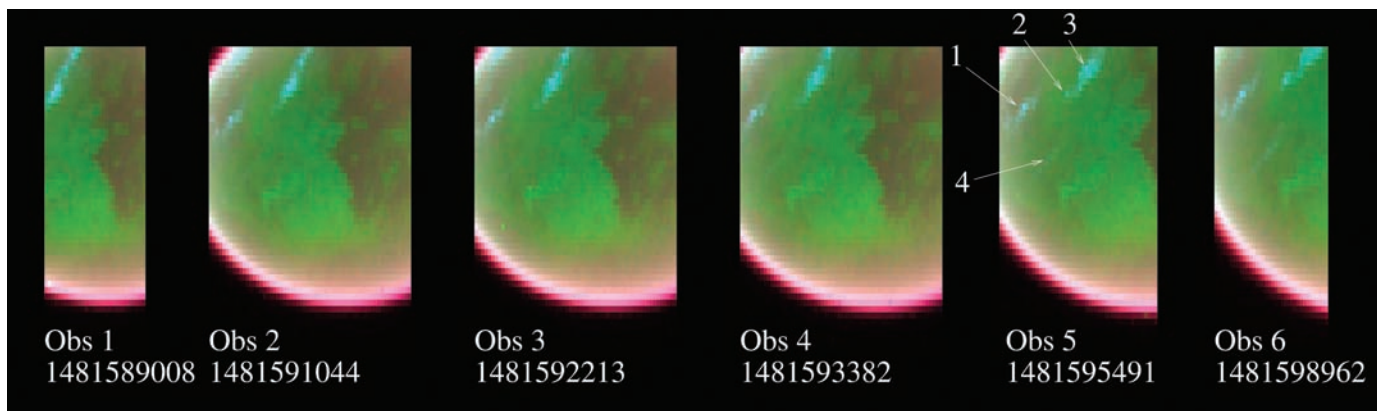


Fig. 1. Six observations (Obs) of Titan's mid-latitude clouds constructed by mapping the 2.13- μm channel to blue, the 2.00- μm channel to green, and the 2.3- μm channel to red. These wavelengths are most sensitive to Titan's clouds, surface, and stratospheric haze, respectively. Obs 1 to 6

(shown with VIMS identification numbers) were recorded at intervals of 34, 20, 20, 35, and 58 min from each other. Clouds 2 to 4 lie near Titan's -40° latitude, whereas cloud 1 resides at -61° . Note the evolution of the clouds with time.

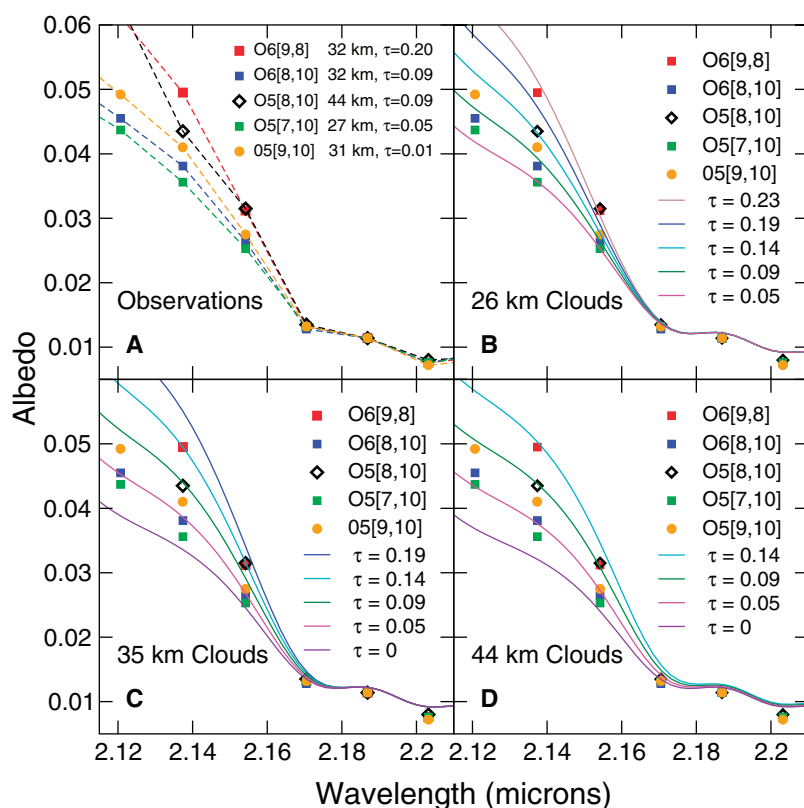


Fig. 2. Observed spectra of cloud 1 are compared to calculated spectra. (A) Examples of VIMS spectra resulting from clouds of varying optical depths and altitudes. Indicated are the data observation numbers (Fig. 1), the pixel number (in brackets), and the derived cloud heights and optical depths (τ). Higher clouds affect Titan's spectrum at spectral regions of greater methane opacity (longer wavelengths) for a given optical depth. The dependence of the 2.13- to 2.16- μm slope on the cloud altitudes can be seen by comparing O6[9,8] to O5[8,10]. (B) Observations (points) are compared to models (solid lines) calculated with a uniform cloud layer at 26 km altitude for several optical depths. The model spectra between 2.13 and 2.16 μm indicate that pixel O5[7,10] has a cloud near 26 km, of optical depth 0.05. (C) Observations O6[9,8], O6[8,10], and O5[9,10] have 2.13- to 2.16- μm slopes similar to models calculated assuming clouds at 35 km, indicating the presence of clouds near this level. (D) Observation O5[8,10] matches the model spectrum of a cloud at 44 km, of optical depth 0.09.

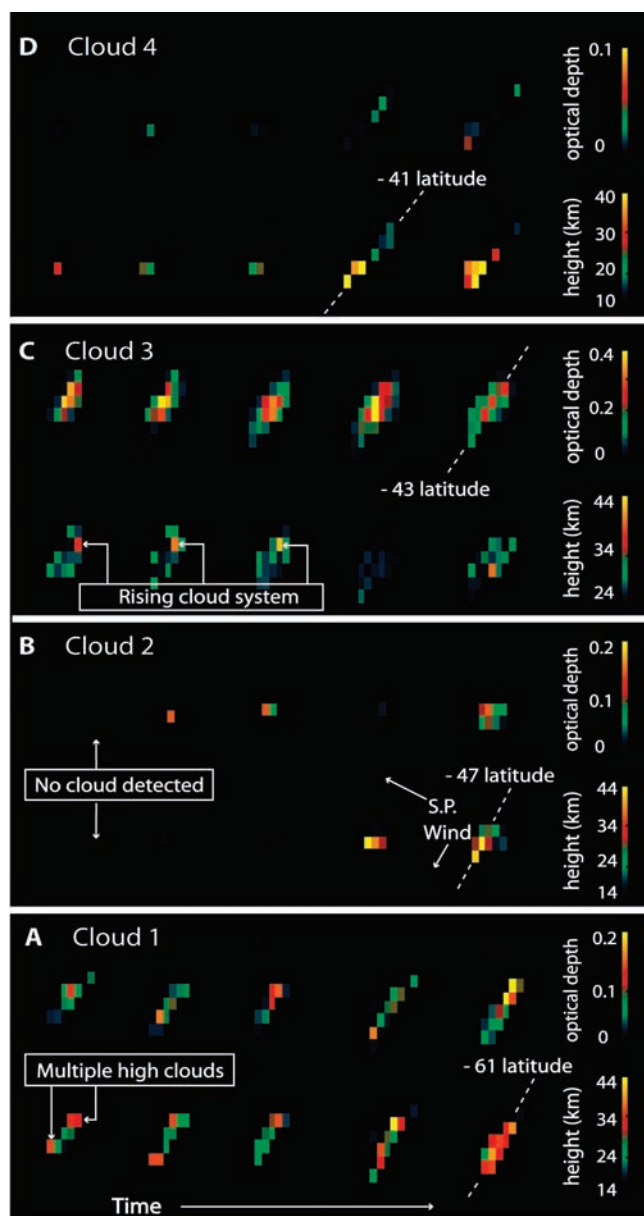
ratio is adopted from the surface to the level where saturation is reached, above which methane is saturated up to the tropopause.

Uncertainties of a factor of 2 in the methane abundance (greater than expected) cause uncertainties of 5 km in the derived cloud

altitudes and 20% in the derived optical depths. We assume spherical haze particles having radii of 0.2 μm from 180 to 90 km altitude. Below 90 km, radii increase with atmospheric pressure to 0.8 μm at 40 km altitude (21). We adopt a simple haze profile with a constant density scale height of 120 km above 100 km and a particle density of 1.7 cm^{-3} at 140 km, a constant density of 5 cm^{-3} from 100 to 70 km, and a constant density of 2 cm^{-3} at 70 to 40 km altitude, which fits Titan's cloudless 2.13- to 2.2- μm spectra, although not uniquely. Nonetheless, because the haze optical depth (~ 0.2) significantly exceeds the gas optical depth (~ 0.05) above 30 km altitude at 2.13 μm , we estimate fairly accurately the haze optical depth above the clouds. Cloud heights are then derived from the slope of Titan's 2.12- to 2.18- μm spectra, and the 2.13- μm albedo manifests the cloud coverage or optical depth (Fig. 2). Our data do not independently determine the cloud coverage and optical depth. For each pixel, we present the optical depth of a uniform cloud across the pixel, which for a value of $\tau = 0.3$ is equivalent to an optically thick cloud covering 3% of the pixel area.

The four clouds we observed had similar morphologies. Cloud 2 was the simplest; it appeared for the first time in the second observation, O3, as a compact unresolved cloud in one pixel that grew and rose from 20 to 42 km in 35 min (Fig. 3B). Cloud 3 constituted a large area of high (20 to 30 km) clouds within which a small system of clouds rose, penetrated the tropopause at 42 km, and then dissipated within the following 20 min (Fig. 3C). The last image of cloud 3 suggests the beginnings of another rising plume. Multiple centers of activity also appeared in cloud 1 (Fig. 3A) and in the final observations of cloud 4 (Fig. 3D). Cloud 4 displayed the vertical evolution of cumuli from 26 to 42 km in 35 min, followed

Fig. 3. Images of derived cloud heights (bottom rows) and optical depths (top rows) of Titan's four clouds in a time sequence from left to right indicate the temporal evolution of the clouds (refer to the color bars at right). The orientation of each observation mimics that of Fig. 1, with the south pole in the top left corner of each image, as indicated by S.P. in (B). The clouds extend lengthwise in longitude. (A) The optical depths and heights of each pixel comprising the O2 to O6 observations (as referenced in Fig. 1) of cloud 1 (latitude -61° , central longitude 134°). The first observation, O2, is shown in the lefthand column; subsequent observations proceed in order from left to right, recorded at time intervals of 20, 20, 35, and 58 min from the preceding observation (Fig. 1). (B) The optical depths and heights of observations O2 to O6 of cloud 2 (latitude -47° , longitude 157°) at intervals of 20, 20, 35, and 58 min. The cloud in O3 and O4 is at ~ 13 km altitude and thus is not apparent in the bottom row. (C) The optical depths and heights of observations O1 to O5 of cloud 3 (latitude -43° , longitude 176°) at intervals of 34, 20, 20, and 35 min. (D) The optical depths and heights of observations O2 to O6 of cloud 4 (latitude -41° , longitude 115°) at intervals of 20, 20, 35, and 58 min.



by a growth in size, as seen in the last observation. In both small, perhaps young, clouds (Fig. 3, B and D), horizontal growth followed updrafts, with clouds detected in adjacent eastward pixels (~ 50 km distance) within 1 hour. If the eastward displaced optical depth results from cloud transport, the implied prograde winds were on the order of 14 m/s, which is consistent with measurements by Cassini's Imaging Science Subsystem (ISS) (11). In summary, we detected small centers of vigorous updraft that rose at rates of 2 to 4 m/s in the larger clouds 1 and 3 and 8 to 10 m/s in the more discrete clouds 2 and 4. The slower measured ascent in clouds 1 and 3 may be an artefact of averaging the altitudes of rising plumes with more quiescent ambient clouds within a pixel.

High cloud centers were seen to dissipate or fall 10 km to the ambient cloud level within half an hour (Fig. 3, A and C) and to evolve in the eastward direction (Fig. 3, B to D).

The cloud updraft rates agree well with those predicted for convective plumes on Titan (22), and incidentally with rates of terrestrial thermals (Fig. 3). The 1/2-hour fall time of the cloud tops from ~ 40 to 30 km is consistent with the fall velocity of millimeter-sized raindrops (23, 24). The clouds' rapid evolution, discrete high centers, and accompanying increase in optical depth and extent after updrafts indicate that clouds originate as compact convective cells that dissipate through rain and evolve further through zonal wind transport to new longitudes. If fueled by latent heat alone, the convective evolu-

tion of a plume requires a parcel to be nearly saturated at the surface; otherwise, thermals would not reach their observed heights at the tropopause (5). Alternatively, strong dynamical forcing is required in the form of updrafts, low-level convergence, and/or high-altitude divergence.

The confinement of the clouds primarily to the $0^\circ \pm 40^\circ$ and $90^\circ \pm 40^\circ$ longitudes at -40° latitude suggests a connection to Titan's surface (4). However, consistent with Cassini ISS observations (11), we detect deviations from this trend. Of the four clouds described here, only one of them (cloud 4) lay near 0° or 90° longitude. Thus, the clouds' association with the surface was either a weak one or would appear to require many surface "events" (such as volcanoes, high winds over mountains, or near-surface methane saturation). Considering ground-based and Cassini observations, event longitudes would include $0^\circ, 39^\circ, 67^\circ, 90^\circ, 115^\circ, 157^\circ, 176^\circ,$ and 200° , lined up near -40° latitude [(4, 11) and this work]. Additionally we would have to account for the singular presence of similar clouds at $-14^\circ, -33^\circ,$ and -61° latitude [(11) and this work] and no cloud detections in the northern hemisphere.

Yet, volcanically outgassed methane would remain confined for a while to a narrow latitude band, because Titan's meridional winds are weak, estimated to be 1 mm/s on average (25), in comparison to its zonal winds of tens of meters per second (11). One can imagine the humidification of a latitude band, as a result of single volcano, which (if saturation incurred throughout the surface mixing layer) would aid subsequent convective events at the same latitude. We explore this possibility by comparing the mass of a large -40° latitude cloud to the mass of methane required to render the atmosphere unstable to deep convection. We assume the highest optical depth determined in this study, $\tau = 0.4$, and a cloud area of $A = 50,000$ km², corresponding to a latitude width of 50 km and a downwind longitude extent of 1000 km (4). The length of the clouds indicates the airlifted mass transported to new longitudes by one cloud event. The mass of the cloud is given approximately by

$$M = \frac{\tau}{2\pi r^2} \frac{4}{3} \pi r^3 \rho A = 2.3 \times 10^8 \text{ kg} \quad (1)$$

where $\rho = 0.06$ g/cm³ is the mass density of methane ice. The radius of the cloud particles r is taken to be 30 μm : that which survives aloft for the observed cloud lifetimes of 48 hours without falling 10 km out of view. The alternative approach of assuming discrete optically thick clouds covering an effective area of 1000 km², a vertical extent of 10 km, and a mass density of 1 g/m³ (typical of terrestrial clouds) indicates a greater mass of 10^{10} kg.

Assuming an initial humidity of 50%, the mass of methane required to saturate a 0.5-km-thick mixing layer over the entire -37° to -44° latitude band from 0° to 200° longitude, where clouds are observed, is 1.6×10^{14} kg, which is four orders of magnitude greater than the estimated production of one event. However, the cloud mass estimate is uncertain to an order of magnitude, and it is not clear what fraction of the latitude band needs to be saturated to provide the observed activity. In addition, the frequency of potential volcanic events is unknown because of the paucity of observations, leaving open the volcanic possibility. Nonetheless, the volcanic solution is not bolstered by Titan's average -37° to -44° surface albedo at $5 \mu\text{m}$, which mimics that between -44° and -50° latitude to within 10% (at 100 km resolution). In addition, the 0° longitude point where clouds are most prevalent (thus the best site for cryovolcanic activity) lies downwind, if prograde as indicated by the ISS observations (11), of the less frequent secondary cloud events.

The correlation of Titan's clouds with surface location is only loose, as evidenced by the multiple active centers within the clouds (separated by 200 to 400 km in longitude) and their detections at numerous longitudes. The stronger tie of the clouds to latitude indicates that global circulation plays a role in their formations. To date, clouds have been detected only at southern latitudes, where solar insolation is greatest and the upward branch of the pole-to-pole circulation is expected. In addition, the latitude of -40° , where most clouds are observed, coincides closely with an abrupt decrease in the vast layer of diffuse particles that surrounds the south pole (26, 27). The cutoff of this veil suggests a change in circulation at -40° latitude, which is not predicted in most circulation models of Titan. Yet a recent general circulation model of Titan includes haze caps at Titan's pole (28, 29) and indicates the presence of a converging circulation branch at -40° latitude (30). In this model, the thick haze inhibits surface heating at the poles, thereby causing the hottest summer surfaces (which trigger updrafts and convergence) to occur at more temperate latitudes.

The clouds' propensity for 0° and 90° longitude nonetheless suggests a secondary forcing mechanism from the surface. Solar surface heating, Saturn's tidal forcing, and maritime clouds would imply that clouds correlate with surface reflectivity, orbital position, or surface liquids, respectively, which is not observed. Volcanically produced clouds would persist at 0° and 90° longitude and -40° latitude as the seasons change, in contrast to the seasonal latitudinal change expected of circulation-driven clouds. These causes are testable with future observations. Although

observations suggest that Titan's circulation dictates the latitude of Titan's clouds, the processes that establish the clouds' longitude remain unclear and involve unknown characteristics of Titan's still largely unexplored surface.

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Geographic Control of Titan's Mid-Latitude Clouds

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Observations of Titan's mid-latitude clouds from the W. M. Keck and Gemini Observatories show that they cluster near 350°W longitude, 40°S latitude. These clouds cannot be explained by a seasonal shift in global circulation and thus presumably reflect a mechanism on Titan such as geysering or cryovolcanism in this region. The rate of volatile release necessary to trigger cloud formation could easily supply enough methane to balance the loss to photolysis in the upper atmosphere.

Saturn's largest moon, Titan, is surrounded by a thick atmosphere of nitrogen and methane. Observations of tropospheric clouds (1–6) and the recent Huygens images of channels show that Titan has an active methane hydrological cycle. The recent discovery (6) and continued observations (7) of cloud activity at 40°S latitude have led to the suggestion that these mid-latitude clouds are likely the result of seasonally evolving global circulation (6). Because photolytic chemistry should deplete methane within 10^7 to 10^8 years (8–10), the presence of methane in

Titan's atmosphere implies that there is a source on Titan's surface, although no sites of active methane release have yet been discovered.

Tropospheric clouds are best observed in a narrow spectral region around a wavelength of $2.12 \mu\text{m}$ (11). Using adaptive optics systems at the W. M. Keck Observatory's 10-m telescope (12) and the Gemini Observatory's 8-m telescope (13), we imaged Titan's clouds and surface with a resolution of ~ 300 km in just a few minutes of observing time. During the 2003–2004 and 2004–2005 apparitions of Titan, we acquired usable data on 41 nights with the Keck telescope (14) and 47 nights with the Gemini telescope (15) (82 separate nights). Although most nights showed cloud activity at latitudes south of 70°S , on 15 nights we observed separate clouds near 40°S

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