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 μm, 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 cryvolcanic 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 μm (*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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latitude. (Figs. 1 and 2; table S1) Most of the clouds were clustered tightly near 350°W longitude, with a lesser population apparent between ~45°W and ~160°W (Fig. 3).

In contrast to the south polar clouds, which have been observed to have lifetimes of several weeks (*5*), the mid-latitude clouds had lifetimes of only ~1 Earth day, although remnant wisps below our resolution and contrast limits may have existed for a longer period of time. We possibly observed the same clouds on two consecutive nights on only three occasions (8 and 9 April 2004, 4 and 5 May 2004, and 2 and 3 October 2004). In each case, the cloud appeared to be less prominent on the second night. On 3 November 2004 and 21 February 2005, we observed mid-latitude clouds that were not present in images taken the previous night and the following night. During a full night of observing on 19 December 2004, we observed the development of a mid-latitude cloud system from nothing to full prominence in ~6 hours. By the following night (20 December 2004) this cloud system had disappeared, although we observed new clouds at approximately the same geographic location on 21 December 2004. The short lifetimes of these clouds suggest that methane humidity is substantially less than saturation in the atmosphere on average. A formation mechanism that can cycle on and off in much less than a Titan day is required.

We first observed a mid-latitude cloud on 18 December 2003, and we observed clouds frequently throughout 2004. The sudden appearance after 16 nights of not seeing mid-latitude clouds led us to propose that these clouds were a new phenomenon caused by a seasonal change in the global circulation on Titan (*6*). Coincidently, our observations before December 2003 were significantly biased to the hemisphere nearly opposite the concentrated region of cloud formation, as shown in Fig. 3. A major reason for not seeing mid-latitude clouds before December 2003 could be simply that we had very few observations covering the longitude region in which they are concentrated. To test the statistical significance of the lack of observed clouds before December 2003, we modeled the clouds as two populations, one between 310°W and 30°W longitude with a ~15% probability of a cloud existing at any given moment, and the second population lying between 40°W and 150°W with a ~4% probability. The expected number of observed clouds in the data collected before December 2003 is less than one in both cases, with the probability of observing zero clouds being 0.58 for the first population and 0.66 for the second. Our data set is consistent with these clouds being an ongoing phenomenon on Titan, and we cannot rule out their existence before December 2003 with any statistical significance. Our hypothesis that these clouds only started forming in December 2003 is no longer supported, and thus a seasonal change in global circulation no longer need be invoked to explain the lack of mid-latitude cloud observations before December 2003.

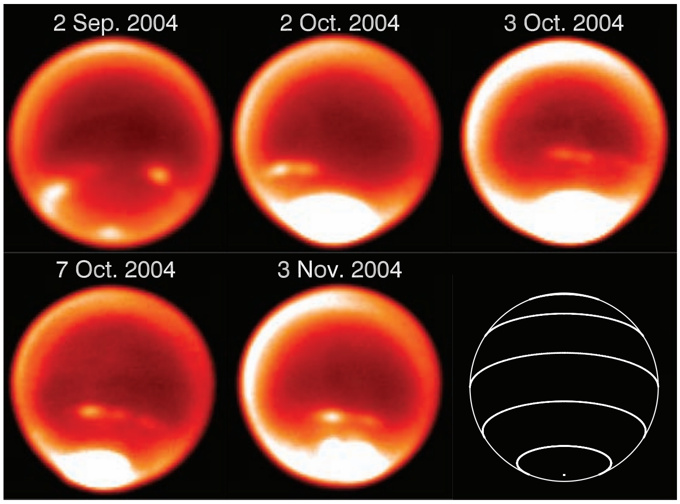

Fig. 1. Images of Titan in a narrowband 2.12-μm-wavelength filter from 5 nights of prominent mid-latitude cloud activity. At lower right, lines of constant latitude for every 30° from equator to pole are plotted at the same scale as the Titan images. Titan's current season is early southern summer, and thus the south pole is visible at the bottom of the image. In October and November 2004, a giant storm was in progress near the south pole. The 2.12-μm-wavelength filter is chosen as it best separates tropospheric cloud features from surface features.

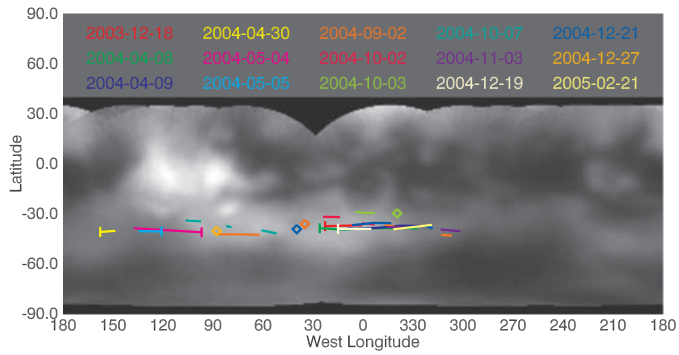

Fig. 2. Locations of all mid-latitude clouds observed to date, shown over a surface map of Titan created from the Keck imagery. Clouds smaller than the spatial resolution of the data (~300 km) are shown as diamonds (◊).

Titan's mid-latitude clouds are nearly always extended in longitude and often appear in groupings of several clouds along a line nearly parallel to longitude. A cloud strung out along a line, parallel to the expected dominant wind flow, is suggestive of a single source forming a cloud that is then sheared out by wind. This morphology and the clustering of the clouds over one small surface region are suggestive of a geographically controlled formation mechanism. If mid-latitude clouds are formed over only a single geographic feature and the tropospheric winds do not shift direction, then the short cloud lifetimes should allow us to pinpoint that source feature. However, a recent study (*16*) of tidal forces shows that Titan's lower tropospheric winds may shift substantially over the course of a Titan day. In one case (2 to 3 October 2004) we saw a cloud that appeared to have moved eastward at 8 m/s and northward at 3 m/s, which is consistent with the expected direction and magnitude of the tidal winds at the time. The extreme clustering of clouds near longitude ~350°W and latitude ~40°S shows that the primary source of the mid-latitude clouds must be nearby. A second, lesser population of clouds at longitudes 40°W to 150°W suggests that additional source regions may exist.

The thermal structure of most of Titan's troposphere is controlled by radiative, rather than convective, processes (*17*). At the troposphere's base, a region of active dry convection maintains a temperature difference of a few degrees between atmosphere and surface. The top of this convective boundary layer (TCBL) is only a few hundreds of meters to a few kilometers above the surface. The level of free convection (LFC) is the altitude at which a parcel of moist air is buoyant as a result of the release of latent heat from condensation. Over most of Titan, the LFC is several kilometers above the TCBL. Convective clouds are formed on Titan when either the TCBL is raised up to the LFC or the LFC is lowered

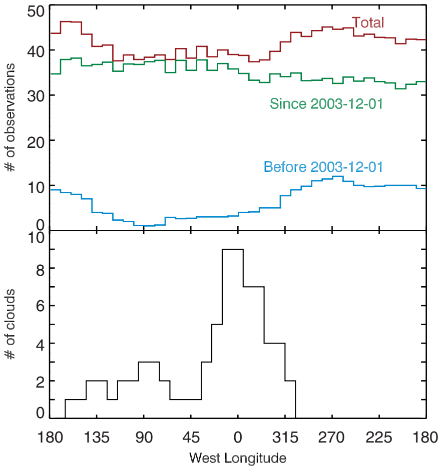

Fig. 3. The number of clouds observed in each 10° bin of planetocentric longitude is shown on the bottom. The total number of nights our observations covered each 10° bin of longitude is shown on the top, as well as divided into the periods of before and after 1 December 2003. In the 2-year data set, the mean number of observations of each 10° bin of longitude was 41 and the minimum number was 37. Through coincidence, the observations taken before 1 December 2003 are heavily biased away from the region where we see the most mid-latitude cloud activity.

down to the TCBL. The TCBL can be lifted by heating of the surface or lower atmosphere, thus requiring more energy to be convectively transported upward. The LFC for a parcel of air can be lowered by injection of methane. The conditional instability of Titan's atmosphere to saturation below ~15 km means that simply raising the humidity to 100% by injecting methane at Titan's surface will lead to a convective cloud (*2*).

Titan's surface can be heated by solar radiation or internal sources, such as cryovolcanism and the subsurface motions of water-ammonia cryo-lava. Solar radiation cannot explain the observed localization of clouds at this season. The time scale for surface temperature changes due to geologic activity is almost certainly much longer than the rate at which mid-latitude cloud formation starts and stops, and geothermal activity seems unlikely to be the sole driver of mid-latitude cloud formation.

Injection of methane into the atmosphere, either by geysers or during cryovolcanic activity, appears to be the most plausible triggering mechanism for the mid-latitude clouds, as any such process would be sporadic and localized geographically. Recent speculation exists that an unusually shaped 30-km feature imaged by Cassini on Titan's surface might be the remnant dome of a cryovolcano (*18*). We have seen no cloud activity in this region (8.5°N latitude, 143.5°W longitude) and no evidence for release of volatiles from this site.

Injection from a geologic source could also solve the conundrum of the long-term existence of Titan's methane atmosphere. Methane is lost from Titan's atmosphere at a rate of ~200 kg/s resulting from photolytic chemistry in the upper atmosphere (*9*, *19*). Assuming a background humidity of 60%, a geyser need only saturate a region of the boundary layer 2 km in diameter and 300 m high once every 7 days to resupply the lost methane. Notably, the rate of mid-latitude cloud formation we observe could easily account for the entire methane resupply needed to explain the current atmospheric methane abundance. A strong sporadic source of methane would not only create clouds in the surrounding region but also raise the background methane abundance in its latitude band. A weaker source of methane, which at other latitudes would not generate substantial clouds, would then more easily generate clouds because of the enhanced background methane abundance. Thus, the lesser population of clouds observed at longitudes ~45°W to 160°W may be the result of one or more weaker sources of methane boosted by the latitudinal band of methane enhancement from the strong methane source near ~350°W longitude.

A possible driver of geologic activity is the tides caused on Titan by the eccentricity of its orbit about Saturn. Titan's sub-saturnian point lies at 0° latitude and 0°W longitude, not far from the region in which we see the most significant mid-latitude cloud activity. On Jupiter's moon Io, the largest effect of tidal heating is seen near the sub-jovian point (*20*). From our observations of mid-latitude clouds, the region around ~350°W longitude, ~40°S latitude appears to be the most likely place on Titan to find present-day release of volatiles and geologic activity, including possibly cryovolcanism.

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11. At 2.12 μm, the combined opacity of methane, nitrogen, and hydrogen is strong enough to obscure the surface but weak enough to allow probing of the tropospheric region of interest (*1*). On most nights we observed in three filters, chosen to probe varying altitude levels in Titan's atmosphere. Images in the K′ filter [2.03 to 2.36 μm (*21*)] are dominated by surface features, although tropospheric clouds are also visible. Images in the $H_2$1-0 filter (2.111 to 2.137 μm) show primarily tropospheric cloud activity. As a result of high methane, opacity images in the Brγ filter [2.154 to 2.183 μm (*21*)] show only the high haze layers approximately above the tropopause. The clouds do not appear in the Brγ filter images, thus allowing us to restrict their altitude range to the troposphere. At these wavelengths the scattering due to haze particles is much weaker than at shorter visible wavelengths, giving the clearest possible view of atmospheric and surface features on Titan.
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15. We acquired images with high enough contrast and resolution to detect the mid-latitude clouds on the Gemini telescope on UTC dates: 13 November 2003, 15 November 2003, 17 to 18 November 2003, 4 to 9 April 2004, 30 April 2004, 4 to 7 May 2004, 23 to 24 October 2004, 1 to 2 November 2004, 4 to 5 November 2004, 21 December 2004, 24 to 25 December 2004, 27 December 2004, 16 January 2005, 23 to 25 January 2005, 28 January 2005, 8 to 10 February 2005, 12 February 2005, 14 to 16 February 2005, 19 to 22 February 2005, 1 to 2 March 2005, 4 to 5 March 2005, 9 March 2005, and 24 March 2005.
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Supporting Online Material
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Table S1

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