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Clouds on Titan during the Cassini prime mission: A complete analysis of the VIMS data

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ABSTRACT

We use data from the VIMS instrument on board the Cassini spacecraft to construct high sensitivity and high spatial-resolution maps of the locations of tropospheric clouds on Titan in the late northern winter season during which the Cassini prime mission took place. These observations show that, in this season, clouds on Titan are strongly hemispherically asymmetric. Mid-latitude clouds, in particular, occur only in the southern hemisphere and have not ever been observed in the north. Such an asymmetry is in general agreement with circulation models where sub-solar surface heating controls the locations of clouds and appears in conflict with models where perennial polar hazes prevent significant summertime polar heating from affecting the circulation. The southern mid-latitude clouds appear to be distributed uniformly in longitude, in contrast to some previous observations. Southern high-latitude clouds exhibit a significant concentration, however, between about 180° and 270°E longitude. A spatially and temporally uniform cloud always appears northward of ~50°N latitude. This cloud appears unchanged over the course of the observations, consistent with the interpretation that it is caused by continuous ethane condensation as air subsides and radiatively cools through the tropopause. The location of this cloud likely provides a direct tracer of elements of north polar atmospheric circulation, potentially allowing continuous monitoring of circulation changes as Titan passes through equinox into north polar spring and summer. We show that a similar analysis of this dataset by Rodriguez et al. (2009) contains substantial errors and should not be used.

1. Introduction

The dramatic images of stream networks, shorelines, and rounded pebbles on Titan taken from the Huygens probe convincingly show that Titan, like the Earth, has a surface carved by flowing fluids. Cassini imaging and radar have shown abundant lakes near the north pole, dry dunes near the equator, and a smaller number of lakes near the south pole. The central phenomenon connecting and likely explaining these disparate observations is the seasonal methane meteorological cycle on Titan.

While for many years it was thought that Titan was incapable of supporting clouds or precipitation (i.e. Hunten et al., 1984), observations of variable cloud systems – first from ground-based observations and later from Cassini – have demonstrated that convection, condensation, and – presumably – precipitation are indeed sporadically prevalent across Titan. Understanding this methane meteorological cycle holds the key to understanding much of the diversity of features on the surface of Titan.

The first evidence for clouds on Titan came in 1995, just before Titan autumnal equinox, when Griffith et al. (1998) saw Titan brighten dramatically in surface-penetrating windows in near-infrared whole disk spectra. Radiative transfer analysis showed that this brightening was not tied to the surface but rather came from the middle of the troposphere, at the level expected for clouds caused by moist convection. The clouds that caused the brightening were estimated to have covered ~5–7% of the disk of Titan. Griffith et al. (2000) later found that a small amount of variable tropospheric cloud change was detected in 9 out of 11 nights of observations spanning from September 1993 until September 1999 (bracketing the 1995 equinox). These changes covered ~0.5% of the disk of Titan during this period and, for the small number of observations available, at times varied on time scales of hours or days suggesting vigorous convection.

The first successful imaging of clouds on Titan came in December 2001, just before southern summer solistice, when Brown et al. (2002) and Roe et al. (2002) found variable clouds clustered near the south pole. This polar phenomenon had not been predicted, but it was suggested by Brown et al. to be due to the heating of the surface during the years-long perpetual daylight of the polar summer and the subsequent initiation of convective instabilities.

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This hypothesis immediately suggested that Titan's meteorological cycle would be strongly seasonally dependent, and that understanding of this cycle will require observations over a large fraction of Titan's 30 year season.

Long term monitoring from large ground-based telescopes revealed the first hints of seasonal change occurring on Titan. Roe et al. (2005a) detected the first clouds seen at a location other than the south polar regions. These clouds were concentrated in a band near 40° southern latitude. Continued long term monitoring, however, suggested that these clouds were preferentially forming over a single longitude on the surface of Titan, indicative of some sort control by surface geography, rather than a seasonal effect (Roe et al. 2005b). Observations by Cassini, in contrast, missed the large mid-latitude cloud outbursts seen by Roe et al., but suggested that smaller mid-latitude clouds were a more persistent presence apparently uncorrelated with geography (Griffith et al., 2005).

In perhaps the strongest clue to date for understanding the seasonality of the hydrological cycle, Schaller et al. (2006b) found that the south polar cloud system, which was visible in almost every single image from 2001 until late 2004 suddenly disappeared. The disappearance came within several month of the time period in which the south pole had abruptly become no longer the latitude of maximum insolation.

As the north pole of Titan began to come into sunlight and into view (from the Cassini perspective) starting in 2004, a large ubiquitous scattering layer poleward of about 50° and at an altitude around 40 km began to reveal itself. Griffith et al. (2006) used indirect evidence to suggest that this northern hood was caused by ethane condensation that had been earlier predicted by Rannou et al. (2006). Closer examination allowed Brown et al. (2009) to infer that underneath this high generally unvarying cloud sporadic convective clouds were also rapidly changing, possibly through a mechanism similar to that which forms lake-effect clouds on the Earth.

Motivated by these and subsequent observations, several models of Titan's circulations, clouds, and precipitation have been developed over the past few years (Mitchell et al., 2006; Rannou et al., 2006; Tokano, 2005). While most of these models broadly predict the general features that have already been observed (south polar clouds at the time of southern summer solstice, for example), they give quite different predictions for the future, including details as critical as when or if rain should occur in the equatorial regions near the Huygens landing site, whether a north–south asymmetry in precipitation should be expected, and whether the dune regions on Titan should be dry. Understanding the locations and style of cloud activity, particularly as Titan goes through equinox, is the key to understanding which of these predictions is most robust and how Titan's seasonal methane cycle interacts with the geology, hydrology, and atmosphere of the satellite.

The four-year-long Cassini prime mission provides a sampling of Titan for an equivalent of approximately mid-January until the end of February for terrestrial seasons. While full-season shifts are unlikely on these moderately short time spans, careful observation may well begin to detect the effects of the movement from southern summer solstice (in October 2002) to the approach of vernal equinox (in August 2009). The Visual and Infrared Mapping Spectrograph (VIMS) on Cassini is particularly well suited to the detection and study of clouds. VIMS creates hyperspectral images which allow the extraction of a spectrum at each point within the field. These spectral images can then be used to measure cloud positions and heights (Griffith et al., 2005).

VIMS has some distinct advantages over ground-based telescopes. First, the resolution and sensitivity of VIMS can be significantly higher owing to the advantage of being on a spacecraft making a close encounter. Second, a full spectrum from 1 to 5 μm can be obtained without gaps due to terrestrial atmospheric absorptions. Third, VIMS is not constrained to limited observing seasons as are the ground-based observations. Finally, Cassini can view Titan from multiple viewpoints, allowing, for example, better observations of the poles than can be obtained from the Earth.

These advantages are not without cost. One main disadvantage of VIMS observations is the lack of information on time scales of several days. Usually data are collected in a single flyby and then no further observations are obtained for weeks or sometimes even months. Ground-based observations have shown that cloud behavior on Titan can develop over time scales of a week or longer which can be inaccessible to VIMS. Similarly VIMS can miss sporadic short-lived events that can be seen from the ground. A further disadvantage is the lack of randomly phased observations. Cassini will often encounter Titan many times in a row at the same illumination geometry, leading to possible biases in observed clouds.

Taking into account the advantages and disadvantages of VIMS observations of Titan clouds, we concentrate on three major questions that can best be answered with the VIMS data:

1. Does the latitudinal distribution of clouds on Titan point to a specific circulation style that is captured by any of the circulation models available?
2. Do the longitudinal concentrations seen by Roe et al. (2005b) in rare bright mid-latitude cloud outbursts occur in the more frequent smaller clouds?
3. Is the north polar cloud attributed to the presence of ethane persistent and stable?

2. Observations and analysis

All VIMS observations from the Cassini prime mission are publically available. The VIMS observations were obtained from the Planetary Data Systems (PDS) Imaging Node maintained at the Jet Propulsion Laboratory. All images in the archive were downloaded, and those with a target name of "TITAN" were retained for analysis. The calibration routines provided in the PDS archive were used to turn the raw data into flux calibrated and flat-fielded images with appropriate wavelengths for each channel. ISIS3 software was used to extract geometric information from each of the images which were then converted into standard FITS files for ease of manipulation.

Clouds on Titan are best identified by their unique spectral behavior. Titan is spectrally dominated in the infrared by a series of absorptions from methane where the atmosphere is optically thick to the surface (Fig. 1). Between these absorptions the atmosphere is largely transparent and the surface can be seen. On the wings of the absorptions the atmosphere can be optically thick to the surface, but optically thin to higher altitudes within the atmosphere. Ground-based studies take advantage of this behavior by obtaining images at wavelengths of ~2.0 μm to see to the surface, ~2.1 μm to isolate altitudes within the troposphere (where clouds occur) and higher, and ~2.2 μm to isolate altitudes in the stratosphere (above the clouds) and higher. Clouds can be identified by the appearance in the surface and troposphere filters but their absence in the stratospheric filters.

For the VIMS data we perform a similar analysis by synthetically creating images out of wavelengths sensitive to particular altitudes. While we could determine optimal wavelengths theoretically through a radiative transfer model of the atmosphere, we have found, instead, that empirically determined wavelengths are more effective. We found these by first taking wavelengths similar to the ground-based filter wavelengths, isolating obvious cloud and surface features, and examining the best wavelengths for distinguishing among these. The channel numbers that we use to construct our final synthetic images are shown in Table 1 and shown in Fig. 1.

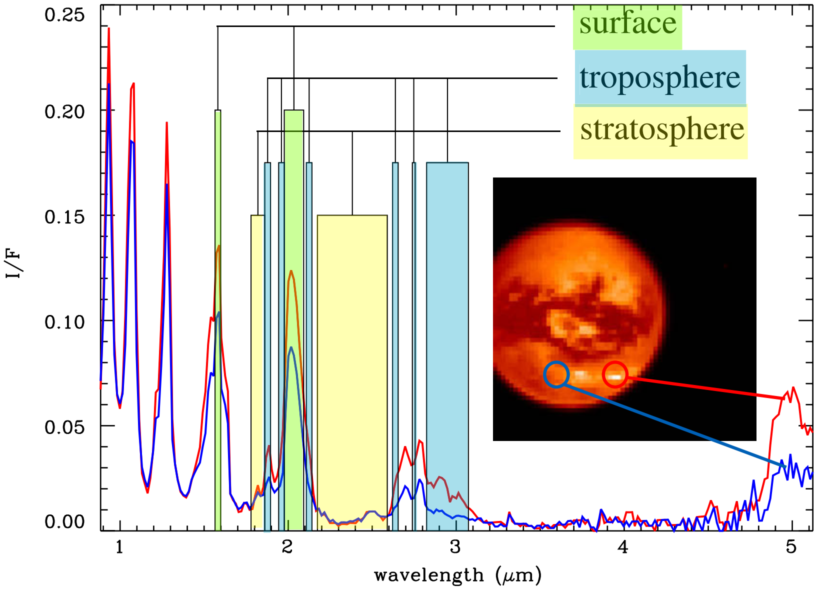


Fig. 1. Spectrum of a location on Titan with a tropospheric cloud (red) compared to the spectrum of a nearby location without a tropospheric cloud (blue). The wavelength regions that we use to construct our synthetic surface, troposphere, and stratosphere images are shown. The surface images are constructed from wavelengths with little methane absorption, the troposphere images is constructed from wavelengths with moderate methane absorption, and the stratosphere images are constructed from wavelengths with strong methane absorption. In the 2.0–2.4 µm region, the wavelengths closely reproduce those used from the ground. With VIMS, however, we can add in many additional wavelengths to increase sensitivity and signal-to-noise. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

To construct the final images for cloud identification and remove occasional bad pixels within the hyperspectral image, we median each of the three sets of channels after normalizing each of the surface channels by a typical surface spectrum, each of the troposphere channels by a typical cloud spectrum, and each of the stratosphere channels by a typical stratosphere spectrum. Examples of the images are shown in Figs. 1 and 2.

Table 1
Synthetic image channels and center wavelengths.

Surface		Troposphere		Stratosphere	
42	1.57361	60	1.86933	55	1.78771
43	1.59018	61	1.88679	56	1.80401
67	1.98531	65	1.95191	57	1.82004
68	2.00167	66	1.96871	58	1.83616
69	2.01781	75	2.11667	59	1.85288
70	2.03424	76	2.13337	79	2.18288
71	2.05091	106	2.63000	80	2.19920
72	2.06757	107	2.64650	81	2.21591
73	2.08400	113	2.74770	82	2.23282
		118	2.83247	83	2.24952
		119	2.84954	84	2.26622
		120	2.86609	85	2.28238
		121	2.88242	86	2.29921
		122	2.89878	87	2.31612
		123	2.91540	88	2.33325
		124	2.93143	89	2.35043
		125	2.94726	90	2.36765
		126	2.96327	91	2.38472
		127	2.97720	92	2.40156
		128	3.00072	93	2.41820
		129	3.01382	94	2.43471
		130	3.02970	95	2.45097
		131	3.04806	96	2.46723
		132	3.06446	97	2.48360
				98	2.50002
				99	2.51659
				100	2.53292
				101	2.54916
				102	2.56437
				103	2.58176

Each of the approximately 9000 triplets of images is visually inspected to search for clouds. Many of the brightest clouds are sufficiently obvious in the images that no extra care need be taken in the identification. For the faintest clouds, we confirm their presence on multiple images – obtained either immediately before or after – before identifying as clouds. For each of the images identified as having clouds, we hand-select all image pixels that contain a cloud, making a binary map of observed clouds on Titan for each image. For each image we also construct a second map showing where clouds could have been observed had they been present. We have found empirically that pixels that are viewed at a solar phase angle of under 90° and a surface emission angle of under 90° are excellent for cloud detection. Clouds can occasionally be seen at higher angles, but these can often disappear into or be confused by the stratospheric hazes. At this point we have an image showing surface coverage and cloud locations for each VIMS image of Titan. As a final product, we take each of the cloud and coverage images and reproject them to common map projections. We chose a rectangular projection, with a resolution of 0.5° in latitude and longitude (corresponding to 22 km per pixel at the equator), and north and south polar satellite-like projections with resolutions of 16 km per pixel. We refer to these final reprojected products as cloud and coverage maps.

The cloud maps contain no information on the brightness of a cloud. Optically thin clouds which are just barely detectable are treated identically to the largest optically thick clouds. While additional information could be gleaned from cloud brightness, the variations in viewing geometries make such an analysis prohibitive. We will, instead, continue to consider the simple question of whether or not a cloud of any brightness or thickness was present during an observation.

3. Results

To examine the cloud locations on Titan, we first group each of the observations into temporal clusters all obtained within a ~3 day period. In general these clusters are targeted flybys of Titan,

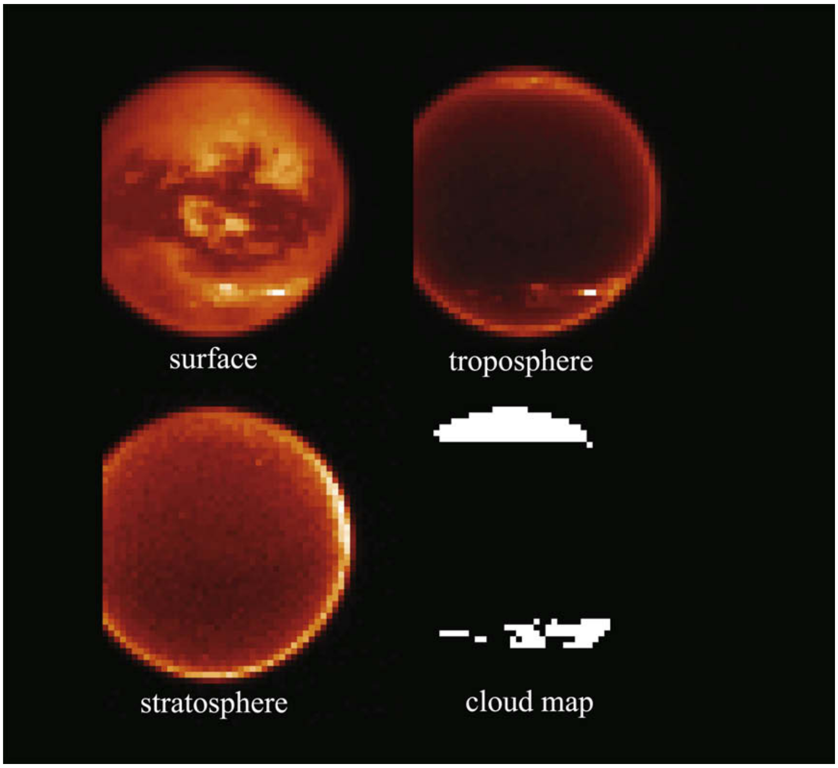


Fig. 2. Examples of constructed surface, troposphere, and stratosphere images, along with the binary map showing where clouds have been identified. The images are constructed from VIMS file v1561870175_1 obtained on 30 June 2007. The clouds seen in this image include typical southern mid-latitude clouds and the ubiquitous high altitude north polar cloud. Small lake-effect clouds can be seen within the north polar cloud.

but there are occasional non-flyby clusters that we also examine. We then take each set of image and coverage maps for each temporal image cluster and construct full map projections showing where there was coverage or cloud at any point in the temporal cluster. While we know Titan clouds to be variable on time scales as fast as hours, we consider these maps to be a reasonably accurate representation of the instantaneous distribution of clouds during each of the Titan flybys and non-targeted clusters (Fig. 3). We refer to these as flyby cloud and coverage maps.

We first examine the overall distribution of clouds. Using each of the 48 flyby coverage maps we create a surface coverage map, showing the number of flybys that each spot on the surface has been observed with solar phase and emission angles lower than 90° (Fig. 4a). Other than the far north, which remains in the dark during this late northern winter dataset, all locations on Titan have been covered a minimum of four times, with a median number of times of coverage of 20 and with the maximum coverage being 34. We next create a fractional cloud coverage map by summing the flyby cloud maps and dividing by the total coverage map. From this map, shown in Fig. 4b, we can then see the fraction of the VIMS observations in which a cloud was present at each location on the surface.

Several features stand out in the fractional cloud coverage map. First, significant latitudinal structure exists in the fractional cloud coverage. Fig. 5 shows the mean fractional cloud coverage as a function of latitude over the 4 year duration of the prime mission. Most significantly, clouds are nearly always present north of 50N latitude. Indeed, an examination of the individual flyby cloud maps shows that the observations are consistent with the coverage of the cloud being essentially 100% above these latitudes at all times. The only locations at these northern latitudes that do not show cloud cover are on the limbs of images where all of the non-limb locations show cloud cover. It appears likely that the northern cloud cover is indeed complete and we are simply insensitive at the extreme limbs. Based on the determination of Griffith et al. (2006) that this cloud is at higher altitudes than the other clouds, we will refer to it as the high altitude north polar cloud.

The southern clouds appear to consist of a group between 30 and 60S latitude, which we will call the southern mid-latitude clouds, and the group south of 60S latitude. Though there appears to be no distinction in coverage, we will label the group from 60 to 80S latitude the high-latitude clouds and those within 10° of the south pole the south polar clouds. Equatorial clouds (within 30° of the equator) have been extremely rare, and no northern equivalents to the southern mid-latitude clouds have ever been seen. Indeed, an examination of the individual flyby maps shows that all clouds in the north are connected to the high altitude north polar cloud and that the apparent excursions to lower latitude in the north are simply regions where the southernmost extent of the northern polar cloud is slightly ambiguous in the images.

A key indicator to the style of circulation on Titan is not just the latitudinal distribution of clouds, but the seasonal evolution of this distribution. Fig. 6 shows cloud latitudes with time for each of the 48 flyby maps. Several interesting features appear in the temporal distribution with latitude. First, after the large cloud outbursts of late 2004, initially documented by Schaller et al. (2006a), cloud activity does indeed seem to diminish for a period of time. Schaller et al. (2006b) found that cloud activity detectable from the ground all but ceased in 2005. From VIMS clouds are still visible during this time owing to the higher sensitivity of VIMS to clouds, but these clouds are at a reduced level compared to earlier and later times. Schaller et al. (2009) found continued diminished cloud activity approximately from October 2006 until June 2007. Interestingly, this period appears as a resurgence of cloud activity in the VIMS data. A direct comparison of the times of the Schaller et al. (submitted for publication) observations with the VIMS observations shows, again, that small-scale cloud activity can be

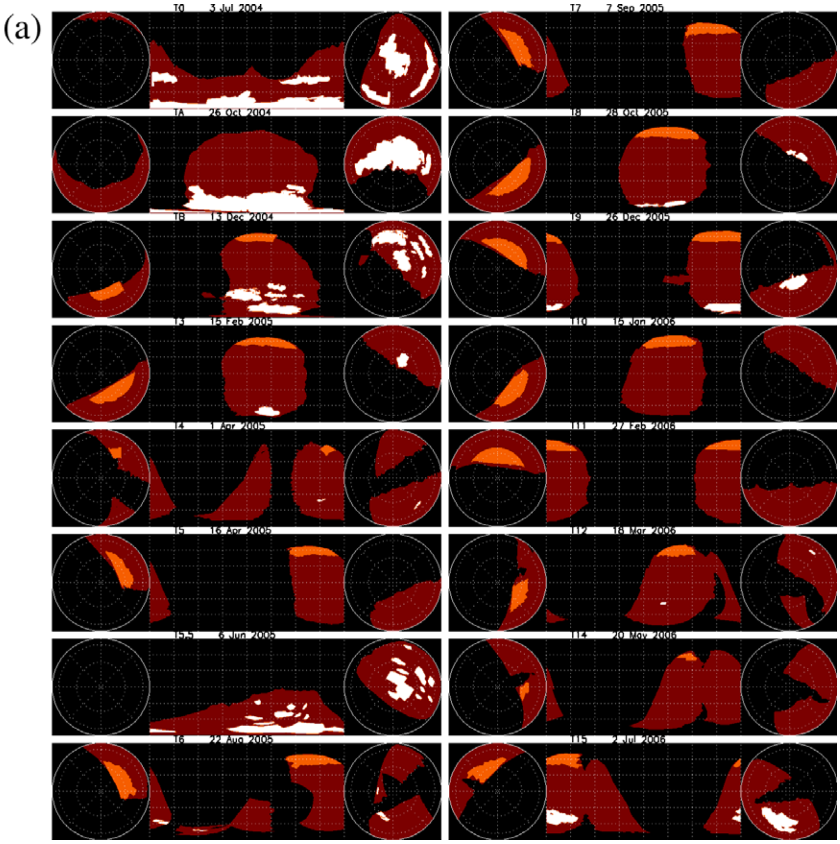


Fig. 3. Tropospheric clouds observed by Cassini/VIMS. For each flyby we show a north polar, rectangular, and south polar projection. For the polar projections the latitude grids are shown at 60° and 30° north or south and 0° longitude is down. The rectangular projections have grid marks every 45° of longitude and 30° of latitude. Zero degrees longitude is on the left. Dark red marks the regions that were observed by VIMS during each flyby with coverage sufficient to have detected clouds. White marks regions of tropospheric clouds detected. Orange shows detections of the north polar ethane cloud near the tropopause. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

seen from VIMS that is missed by the ground-based imaging or spectroscopic data.

As of June 2008 – approximately one terrestrial year before Titan equinox – little latitudinal evolution of cloud position appears, though the beginning of 2008 did see clouds the furthest north they had ever been detected (excluding the north polar clouds). The 12 May 2008 T43 flyby, in which clouds cover latitudes essentially from the south pole to the equator, occurs in the aftermath of the large scale cloud outburst detected from the ground by Schaller et al. (2009) beginning on 14 April 2008. In this event a single localized atmospheric disturbance appears to have propagated waves which initiated cloud activity throughout the southern hemisphere of Titan.

Circulation models of cloud activity on Titan all assume a longitudinally homogeneous surface and produce no large-scale longitudinal variations in cloud activity. While the distribution of southern mid-latitude clouds appears essentially uniform, the distribution of southern high-latitude clouds observed by VIMS appears decidedly non-uniform. In Fig. 7 we show the fractional coverage of mid- and high-latitude southern clouds as a function of longitude. The frequency of occurrence of high-latitude clouds with a peak between 180 and 270°E longitude.

We examine several factors that could conspire to show longitudinal structure when none is present. First, the distribution of observing geometries is far from random. An examination of Fig. 3 shows that, for example, for nine flybys between 22 July 2006 and 29 January 2007 the viewing geometry was nearly identical and only side of Titan was observed. Such biases in observing, combined with seasonal variation in global cloudiness, could lead to detection of longitudinal variation when none is actually present. To investigate this possibility, we examine subsets of the flybys, excluding blocks of times when the overall cloud activity seems high or seems low. In all cases we have investigated, the longitudinal structures of the southern clouds remain. We conclude that they are not due to biased sampling and are a persistent feature in overall cloudy and non-cloudy conditions.

Precisely estimating the statistical significance of the observed longitudinal structure of the high-latitude clouds is difficult. Clouds are correlated on unknown spatial and temporal scales and different flybys had different sensitivities and coverages. One imperfect way to estimate the statistical significance is make simulated observations of known distributions and determine the frequency with which extreme longitudinal variation is seen. As a simple method of implementing this technique, we take each flyby and add a randomly chosen systematic offset to all longitudes. We then reconstruct coverage and fractional cloud maps and examine longitudinal distributions. This method has the advantage of precisely retaining the actual longitudinal and latitudinal correlations of the observed clouds, with a disadvantage that the longitudinal observing biases cannot be taken into account. Creating such simulated datasets 1000 times, we have found that longitudinal maximum as high as those seen in the real data (27%) are seen only 4.4% of the time. By this imperfect test the longitudinal variations seen in the VIMS data are significant at the 95% confidence level. Adding in the unknown factor of longitudinal observing biases allows the possibility that the longitudinal structure could be due to random chance, but we will instead tentatively conclude that the longitudinal high-latitude cloud structure is real.

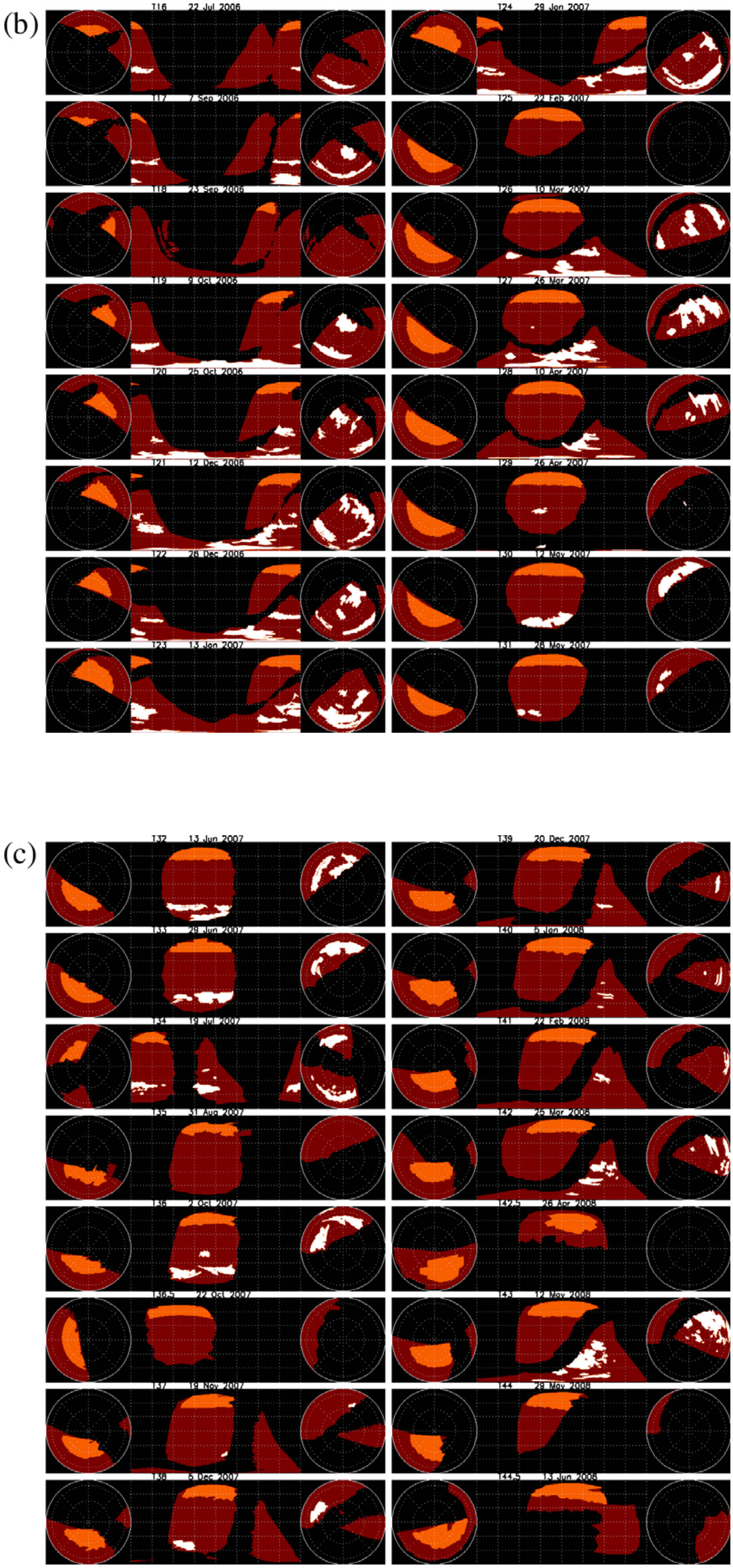
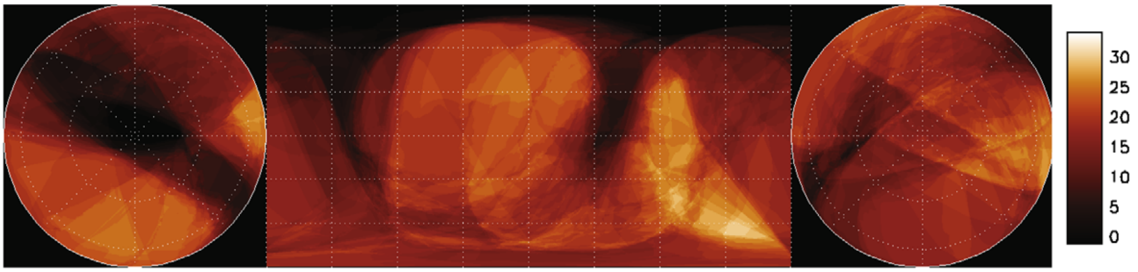
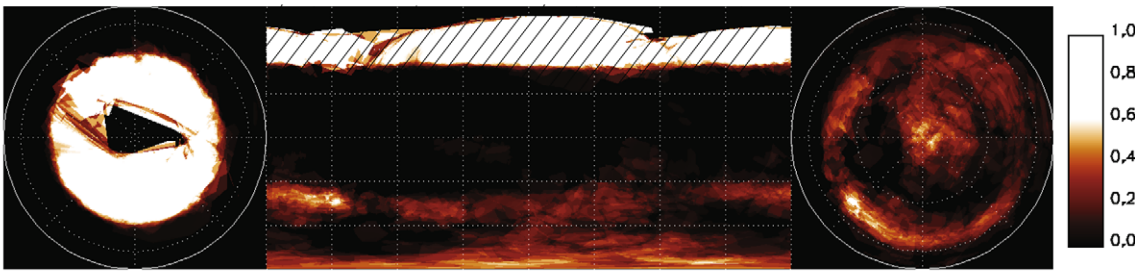


Fig. 3 (*continued*)

(a) VIMS coverage map



(b) Fractional cloud coverage map



(c) ISS basemap

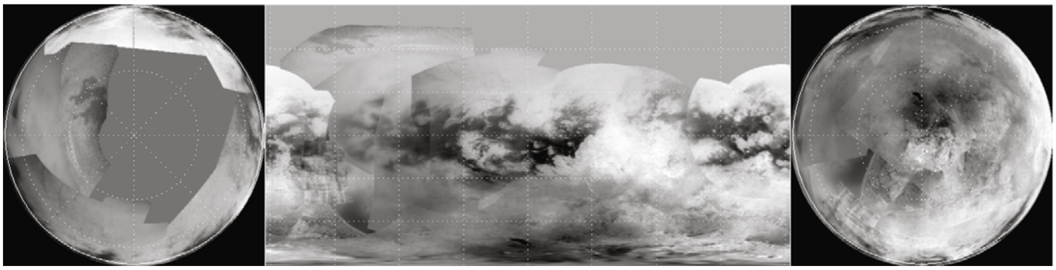


Fig. 4. (a) A map of the coverage of the surface of Titan by VIMS. The color scale shows the number of flybys during which each region of the surface was imaged at appropriate solar and spacecraft geometry for the detection of clouds. The projection geometry is identical to that in Fig. 3. (b) A map of the fractional cloud coverage on Titan. The grey scale shows the number of times that a cloud was observed at each region divided by the number of times that each region was observed (a). The scale bar saturates at 0.6, which is the maximum fractional coverage in the southern mid-latitude clouds. The fractional cloud cover of the north polar ethane cloud approaches 100%. The hatched regions show the extent of the northern near-tropopause ethane cloud. (c) An ISS base map for comparison to the cloud locations. The southern high-latitude clouds are suggestively located near the darkest regions of the south pole. (For interpretation of color mentioned in this figure legend the reader is referred to the web version of the article.)

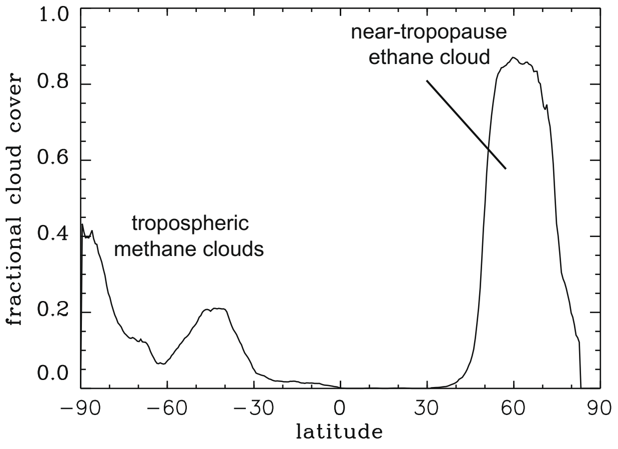


Fig. 5. The fractional cloud coverage on Titan as a function of latitude.

We conclude that the longitudinal variation seen in the high-latitude southern clouds is not caused by temporal variability of overall cloud cover coupled with observing bias, nor is it likely that

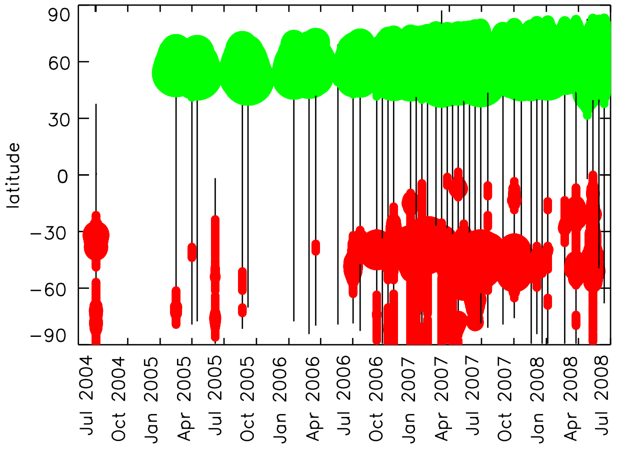


Fig. 6. The time evolution of cloud latitude through the Cassini prime mission. The solid lines show the time of each flyby as well as the range of latitudes covered. The circles show latitudes at which clouds were observed. Red circles show tropospheric clouds while the green circles show the near-tropopause ethane cloud. The size of the circle is proportional to areal coverage of clouds at that latitude. (For interpretation of color mentioned in this figure legend the reader is referred to the web version of the article.)

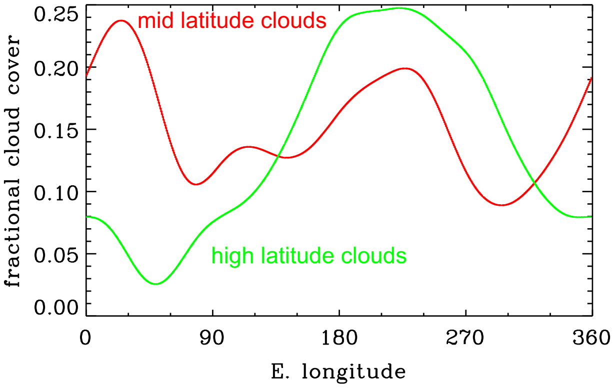


Fig. 7. Fractional cloud coverage as a function of longitude for the southern mid-latitude (red) and high-latitude (green) clouds. The raw curves have been smoothed by a 20° wide boxcar smoothing. The mid-latitude clouds show no statistically significant structure, while the high-latitude clouds show substantial longitudinal structure that is modestly statistically significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

it is a simple sampling fluctuation. The variation is most likely real and, if so, indicative of complexities in cloud formation on Titan beyond the simple featureless planet models.

4. Discussion

We use the observed spatial and temporal distribution of clouds to examine circulation, longitudinal structure, and stability of the high-altitude northern cloud, and we compare these results to other analyses of the same dataset.

4.1. Circulation

Models of tropospheric cloud formation for Titan's atmosphere can generally be classified by the large-scale latitudinal structure of their tropospheric circulation. The models of Rannou et al. (2006) predict a moderately hemispherically symmetric tropospheric circulation with northern and southern mid-latitude clouds being formed from air which ascends from near the equator. In this circulation the overall mid-latitude cloud frequency on Titan changes with time, but little latitudinal evolution appears in the locations of clouds. Clouds, when they appear, are nearly always at the poles or at northern and southern mid-latitudes.

Other circulation models are more strongly seasonally varying and hemispherically asymmetric (Mitchell, 2008; Mitchell et al., 2006; Tokano, 2005). In these models the location of the mid-latitude clouds comes closer to tracking, with some time lag, the seasonal latitude of maximum insolation. The location of the mid-latitude clouds marks the equivalent of the terrestrial intertropical convergence zone.

From the sensitivity studies performed by Tokano (2005), it appears that one critical difference between these two very different styles of model – the presence of perennial polar haze in the Rannou et al. (2006) model – can have dramatic effects on circulation. This haze prevents significant solar heating from occurring at the summer pole, causing the surface temperature maximum to be confined to within ∼30° of the equator at all seasons. The muting of summer surface temperatures appears to prevent a significant seasonal circulation asymmetry from developing.

Quantitative comparison between models and observations is difficult, but we attempt to examine some of the major differences between the models for clues as to which, if any, more correctly describe Titan's circulation. All models correctly predict the southern mid-latitude clouds and the general occurrence of polar clouds. The biggest discrepancies between the observations and any of the models are the lack of the northern mid-latitude clouds that are predicted by Rannou et al. (2006) and the presence of substantial high-latitude southern clouds that are not predicted by Rannou et al.

The lack of appearance of northern mid-latitude clouds in ground-based data has long been known (Roe et al., 2005b; Schaller et al., 2006b), but, because of viewing angle and sensitivity limits, no definitive answer to the question of the existence of these clouds could be made. The VIMS data, however, with their substantially improved sensitivity and frequently excellent viewing condition conclusively show that Titan mid-latitude clouds are only present in the southern hemisphere during late northern winter. The continued presence of high-latitude southern clouds has not been seen from ground-based observations because of the poor viewing geometry, but with excellent VIMS coverage it is seen that these clouds are frequently present. The discrepancy with the Rannou et al. model appears substantial.

Comparison of the observations to models of Mitchell et al. shows that these models match the lack of northern mid-latitude clouds and predict the substantial high-latitude southern clouds. In general, the Mitchell et al. models provide a substantially better match to the observations.

A possible cause of the discrepancies between the Rannou et al. (2006) model and the observations could be the inclusion of significantly larger amounts of summer haze than actually occur on Titan. Examination of detailed haze distributions produced by the original models of Rannou et al. (2004) shows that they predict summer polar haze to be within a factor of two of the winter polar haze optical depth. While no studies have specifically focused on quantitatively examining the most recent summertime polar haze opacity, the long series of high-quality ground-based adaptive optics that were obtained starting near summer solstice (i.e. Brown et al., 2002; Roe et al., 2005a,b; Schaller et al., 2006a,b) showed significant winter haze at the north pole while showing essentially no haze over the summer southern pole. Observations at shorter wavelength could better constrain the polar haze opacities. Copious late-southern-summer observations are now available from Cassini which could quantitatively and definitively answer this question. Such an analysis should be considered a high priority. The Mitchell et al. models include no haze. While significant winter haze is indeed known to accumulate, there is no substantial sunlight to block, so the overall effect of the circulation is small.

While the comparison to the data strongly favors the more asymmetric Mitchell et al. type of tropospheric circulation over the more symmetric Rannou et al. type of tropospheric circulation, the definitive test of these types of models will come, however, as Titan moves through equinox in August 2009. The Mitchell et al. models predict a band of clouds that moves continuously from southern latitudes until it reaches northern mid-latitudes. The Rannou et al. model predicts the disappearance of all non-polar clouds for about five years until both northern and southern mid-latitude clouds reappear. The cloud systems should, at this point, move through the equatorial regions (or perhaps disappear entirely) before reappearing at northern mid-latitudes and polar latitudes. While only a hint of such movement can be seen in the data to March 2008 the rapid shifting should begin quite soon in these models.

4.2. Longitudinal structure

Roe et al. (2005b) found that the occurrence of southern mid-latitude clouds was strongly peaked at a longitude of 10°E. A broad secondary peak was also present between about 180° and 270°E longitude. No such significant mid-latitude structure appears in the present data. There is a small amount of temporal overlap of the VIMS data, which begins on 3 July 2004, and the Roe et al. data, which ends on 21 February 2005. During this time period the ground-based observations frequently showed mid-latitude clouds centered near 10°. The VIMS data, however, covered that longitude only once, and a cloud near 0° was indeed seen.

The difference between the geographic control of mid-latitude cloud location as observed by Roe et al. (2005b) and the consistent-with uniform coverage seen in the current observations is striking. No simple explanation is particularly satisfactory.

The high-latitude clouds, in contrast to those at mid-latitude, do indeed appear to exhibit non-random longitudinal structure. Interestingly, the region of cloud concentration is in the generally darker region of the south pole and covers an area observed to darken sometime between July 2004 and June 2005 (Turtle et al., 2009). Clouds could be more prevalent over regions of surface moisture, such as seen at the north pole (Brown et al., 2009), or, alternatively, the presence of clouds could contribute to precipitation and the darkening of the polar region. Without additional knowledge of the geological properties of the south polar region it will be difficult to understand this observed longitudinal structure.

4.3. North polar cloud

Early VIMS observations were used to suggest that the high altitude north polar cloud was a distinct type of cloud from the rapidly varying convective methane clouds observed earlier (Griffith et al., 2006). The north polar cloud was found to be higher in elevation and spatially and temporally unvarying on the scales observed. In addition, spectral information was used to show that the north polar cloud particles were significantly smaller than the particles in the convective clouds in the southern hemisphere. All of these properties were used to suggest that these clouds were the features predicted by Rannou et al. (2006) to be caused by ethane as subsiding air at the north pole radiatively cools and condenses near the tropopause. While we have argued above that Rannou et al. get the general characteristics of the circulation wrong, it is clear that this prediction of an ethane condensation cloud in regions of subsidence is independent of the details of the circulation. Indeed, a close examination of the Rannou et al. (2006) model shows that between 2004 and 2008, substantial opacity is predicted on above $\sim$70° latitude. The significantly further southern extent of this cloud is reminder that while the prediction of the ethane cloud is likely correct, the overall circulation predicted by this model – including the regions where subsidence should be occurring – is likely different.

The existence of this high altitude north polar cloud formed at the location where stratospheric air subsides through the cold tropopause provides a potentially interesting tracer of atmospheric circulation and cooling on Titan. While tropospheric clouds have been used to attempt to trace regions of uplift and convection, their generally rare and stochastic nature makes them difficult to interpret as a tracer. The north polar cloud, in contrast, appears uniform and omnipresent over the region. While no clear change in the location of the north polar cloud can be seen in the present data, tracking the extent of this cloud, particularly through and beyond equinox could provide key insights into winter circulation and cooling on Titan.

4.4. Comparison with other results

A similar analysis of a smaller subset of VIMS clouds has recently appeared from Rodriguez et al. (2009), who use an automated routine – rather than human inspection – to detect the existence of clouds. A direct comparison between our human-generated results and their automated results shows significant differences. While some common clouds are detected by both methods, both analyses frequently show clouds were the other does not.

We have reexamined the full VIMS dataset and found that in each case of discrepancy the fault lies with the automated results of Rodriguez et al. (2009). The automated routine appears to do a poor job of detecting clouds: it lacks sensitivity, so faint clouds are almost always missed. In other cases, however, such as the T17 flyby, the automated routine misses the brightest cloud feature on the satellite, at the south pole, but picks up much fainter mid-latitude clouds. Oddly, one of the brightest clouds seen during the Cassini mission, during the T0 flyby, is missed entirely, while at the same time the automated routine reports clouds in other places during T0 where we verify that no clouds exist. Other flybys have cloud detections reported where we have verified that no clouds exists, including high southern latitude clouds during T4, T17, T29, T30 and T38 and northern mid-latitude clouds during T5.

It appears that the task of automatically identifying clouds in a dataset with variable resolution, phase angles, and emission angles through a still poorly modeled atmosphere is a prohibitively difficult task. Human identification, while tedious, appears to date the only reliable method. Given the poor behavior of their cloud detection routine, we conclude that the products of the Rodriguez et al. (2009) analysis should not be used.

5. Conclusions

High sensitivity and high resolution observations from the VIMS instrument on board the Cassini spacecraft show the overall behavior of clouds on Titan in the late winter season. These observations show that clouds on Titan are strongly hemispherically asymmetric. Mid-latitude clouds, in particular, occur only in the southern hemisphere and have not ever been observed in the north. Such an asymmetry is at odds with circulation models in which strong summer polar haze prevents significant summer polar heating, leading to lessened seasonal variation in cloud activity (i.e. Rannou et al., 2006). The hemispheric asymmetry of the clouds instead points to a surface where seasonal temperature variations control the latitudinal appearance of clouds on Titan (i.e. Mitchell, 2008).

No longitudinal variations are seen in the mid-latitude clouds, including no peak at the location, where Roe et al. (2005b) previously observed a concentration of much brighter mid-latitude clouds. High-latitude clouds do, however, appear preferentially over latitudes seen by ISS to be generally darker, including one region seen to undergo albedo changes (Turtle et al., 2009). While surface differences might be responsible for the longitudinal variations, interpretation is currently hindered by our almost complete lack of geological knowledge of the south polar regions.

The high altitude north polar cloud appears unchanged over the course of the observations, consistent with the interpretation that it is caused by ethane condensation as air subsides and radiatively cools. The location of this cloud could provide a tracer of north polar atmospheric circulation, potentially allowing continuous monitoring of circulation and cooling changes as Titan passes through equinox into north polar spring and summer.

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