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Special Section:
Cassini's Final Year: Science Highlights and Discoveries

Titan's Meteorology Over the Cassini Mission: Evidence for Extensive Subsurface Methane Reservoirs

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Key Points:
- Cassini's Imaging Science Subsystem and Visual and Infrared Mapping Spectrometer documented tropospheric clouds on Titan for over 13 years
- Meteorological activity generally followed Titan's seasons but showed key differences from model predictions in timing and cloud locations
- Comparison to models suggests broad polar subsurface methane reservoirs are accessible to the atmosphere in addition to the lakes and seas

Supporting Information:
- Supporting Information S1
- Table S1
- Table S2

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Abstract Cassini observations of Titan's weather patterns over >13 years, almost half a Saturnian year, provide insight into seasonal circulation patterns and the methane cycle. The Imaging Science Subsystem and the Visual and Infrared Mapping Spectrometer documented cloud locations, characteristics, morphologies, and behavior. Clouds were generally more prevalent in the summer hemisphere, but there were surprises in locations and timing of activity: Southern clouds were common at midlatitudes, northern clouds initially appeared much sooner than model predictions, and north polar summer convective systems did not appear before the mission ended. Differences from expectations constrain atmospheric circulation models, revealing factors that best match observations, including the roles of surface and subsurface reservoirs. The preference for clouds at mid-northern latitudes rather than near the pole is consistent with models that include widespread polar near-surface methane reservoirs in addition to the lakes and seas, suggesting a broader subsurface methane table is accessible to the atmosphere.

Plain Language Summary We monitored methane clouds in the atmosphere of Saturn's moon Titan for over 13 years, using images from the Cassini spacecraft. The observations cover almost half of Titan's year, showing how weather patterns changed from late southern summer to northern summer (approximately mid-January through late June on Earth). During southern summer, extensive clouds and, on one occasion, rainfall were observed near Titan's south pole. But surprisingly, this weather pattern did not repeat at the north pole in northern summer. By comparing weather observations to atmospheric models, we can determine sources for the moisture in the atmosphere. Our analysis shows that, in addition to Titan's lakes and seas, there may also be liquid beneath the surface near both poles. This result is consistent with other evidence that suggests there may be underground connections between some of the lakes and seas. Knowing there may be more liquid below Titan's surface helps explain how methane is supplied to the atmosphere and how Titan's methane cycle works (similar to Earth's water cycle: evaporation, cloud formation, rain, and surface collection into rivers, lakes, and oceans). With the end of the Cassini mission, Earth-based telescopes will continue to watch for large clouds on Titan.

1. Introduction

Understanding Titan's meteorology and the role methane plays in its atmospheric and surface processes was a high Titan science priority for Cassini-Huygens. Over the course of the mission, remote sensing observations of Titan with the Imaging Science Subsystem (ISS; Porco et al., 2004) and Visual and Infrared Mapping Spectrometer (VIMS; Brown et al., 2004) tracked cloud distributions, morphologies, altitudes, behavior, and precipitation, as well as temporal variations therein (e.g., Corlies et al., 2017; Kelland et al., 2017; Rodriguez et al., 2009, 2011; Turtle, Del Genio, et al., 2011; Turtle, Perry, Hayes, Lorenz, et al., 2011). In Titan's year, this time frame spanned late northern winter through the northern summer solstice, almost half the annual cycle; with the 26.7° obliquity of the Saturnian system, seasonal variation in illumination is similar to that on Earth, albeit over the much longer timescale of 29.5 years.

Observations revealed how cloud patterns changed over time (Rodriguez et al., 2009, 2011; Turtle, Del Genio, et al., 2011), including two precipitation events (Turtle et al., 2009; Turtle, Perry, Hayes, Lorenz, et al., 2011, as well as the nature and global distribution of surface features. Surface liquids are concentrated in high-latitude lakes and seas (Birch et al., 2017; Hayes et al., 2008, 2017; Stofan et al., 2007), while low latitudes have been sufficiently arid for vast equatorial expanses of longitudinal dunes to have formed (Lorenz et al., 2006; Radebaugh et al., 2008; Rodriguez et al., 2014), although Huygens detected methane moisture in the subsurface where it landed at 10°S (Karkoschka & Tomasko, 2009; Niemann et al., 2005). Together with the temporal variations in the distribution of clouds, these observations provide information about Titan's methane hydrology and seasonal exchange, putting constraints on the connectivity to and size of methane reservoirs (surface and subsurface) and the overall methane budget (e.g., Lorenz et al., 2008; Mitchell, 2008; Sotin et al., 2012), which are key to understanding Titan as a system and the longevity of its atmosphere (Hörst, 2017, and references therein; Lunine & Lorenz, 2009; Mitchell & Lora, 2016; Nixon et al., 2018; Tobie et al., 2006). Here we present the complete record of Cassini detections of tropospheric methane clouds on Titan. We have compared these observations to atmospheric models in order to constrain aspects of Titan that drive its seasonal weather patterns.

Although photochemical models predict ethane to be the primary product of methane photolysis, production rates in the upper atmosphere limit its abundance relative to methane and it saturates in the troposphere at much lower vapor pressures than does methane. It is therefore a minor species. Its abundance in Ontario Lacus, the largest lake in the southern hemisphere, may be comparable to that of methane (Brown et al., 2008; Mastrogiuseppe et al., 2018), while in the northern seas ethane is a smaller but significant component (Mastrogiuseppe et al., 2018). Clouds detected by VIMS at high altitudes and latitudes have been interpreted as ethane clouds (Griffith et al., 2006; Le Mouelic et al., 2012; Rodriguez et al., 2011) and are discussed by Le Mouélic et al. (2017, 2018). Hydrogen cyanide spectral signatures were also detected in stratospheric clouds in the north and the south (de Kok et al., 2014; Le Mouélic et al., 2017, 2018).

2. Cassini Observations 2004–2017

2.1. Detecting Titan's Clouds With ISS

ISS began observing Titan in April 2004 during Cassini's approach to Saturn and continued through the end of the mission on 15 September 2017 (Figure 1; supporting information Table S1). To detect clouds, ISS primarily used the narrow-band "CB3" filter at 938 nm (Porco et al., 2004), which is within a methane atmospheric "window" (i.e., not in an absorption band) and in the near-infrared since scattering by the haze is reduced at longer wavelengths, thus best revealing Titan's lower atmosphere and surface (Porco et al., 2005; Turtle et al., 2009; supporting information). At this wavelength, clouds appear bright against the darker gray of Titan's surface features (Figure 2). In a few cases, clouds were detected in images through the ISS clear filters as well. Most of the cloud features detected by ISS were in Titan's troposphere, but as southern winter started a south polar vortex was observed at higher altitude (West et al., 2016).

Over the course of the mission, ~20,000 images were acquired of Titan through the CB3 filter. During the nominal mission (2004–2008), observations were generally limited to close ("targeted") Titan flybys, which occurred every few weeks. In Cassini's extended missions, more frequent distant snapshots of Titan were included between flybys to increase the number of opportunities to detect cloud activity, which had at times been missed between Titan encounters (e.g., Schaller et al., 2009).

2.2. Detecting Titan's Clouds With VIMS

VIMS observed Titan starting in July 2004 (Figure 1; Table S2), acquiring more than 65,000 hyperspectral image cubes in the 0.3- to 5.1-μm spectral range (Figure 3; Brown et al., 2004). Eliminating images of the nightside, limb, redundant or very small areas, or very short exposures leaves ~3,400 cubes useful for identifying clouds, representing several million spectra. Rodriguez et al. (2009, 2011) developed a method that combines automatic detection with visual inspection. The algorithm takes into account the general spectral characteristics of clouds (e.g., Figure 3), separating VIMS pixels with a cloudy spectral component from other components based on simultaneous increased flux in both the 2.75- and 5-μm methane atmospheric windows (Rodriguez et al., 2009). This technique was augmented with the capability to select regions of interest, mask Titan's bright limb, and check detections with a 2.1-μm reference image that is particularly sensitive to tropospheric clouds (Rodriguez et al., 2011).

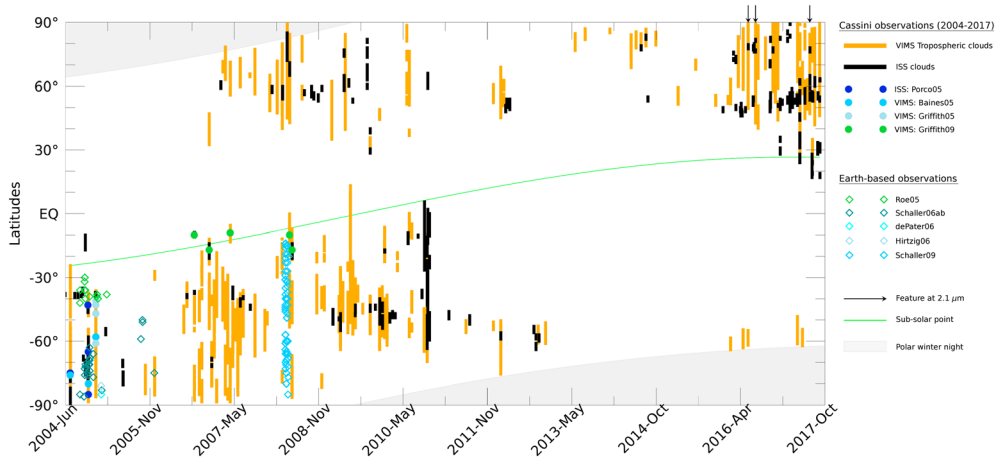

Figure 1. Latitudes of tropospheric clouds observed from June 2004 through the end of the Cassini mission in September 2017: Imaging Science Subsystem (ISS; black), Visual and Infrared Mapping Spectrometer (VIMS; orange), and Earth-based telescopes. (Clouds detected at higher altitudes [Le Mouélic et al., 2012; West et al., 2016] are not included here.) Cloud extent is not indicated but can vary from small isolated cells to broad cloud systems (e.g., Figures 2 and 3). The green line tracks the subsolar point, and gray shading indicates unilluminated polar regions during winter. VIMS can detect clouds even where the surface is not illuminated.

Conservative detection thresholds avoid false detections; however, they can also lead to nondetection of clouds that are optically thin or at very low altitude, much smaller than a VIMS pixel, or too close to the bright limb. So automated detections are complemented by systematic and thorough visual inspection (Kelland et al., 2018) to confirm their relevance and accuracy and to ensure detection of the faintest clouds, adding

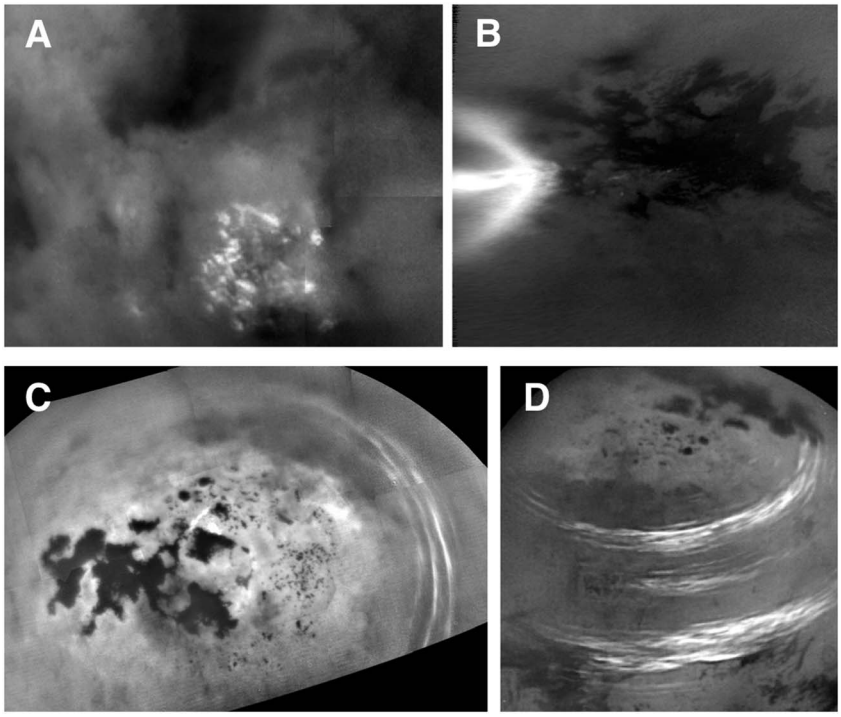

Figure 2. Examples of clouds observed by Cassini's Imaging Science Subsystem: (a) south polar convective cells (>77°S), 2 July 2004, Titan's late southern summer (Turtle et al., 2009); (b) large low-latitude cloud (27°S–6°N) thought to result from an equatorially trapped kelvin wave (Mitchell et al., 2011), 27 September 2010, ~1 year after northern vernal equinox in August 2009 (Turtle, Del Genio, et al., 2011; Turtle, Perry, Hayes, Lorenz, et al., 2011); (c) narrow, midlatitude streaks (52°N–55°N) and small, isolated north polar cells (>80°N), 17 February 2017; (d) complex, midlatitude cloud streaks (30°N–65°N), 7 May 2017, just before northern summer solstice on 24 May 2017.

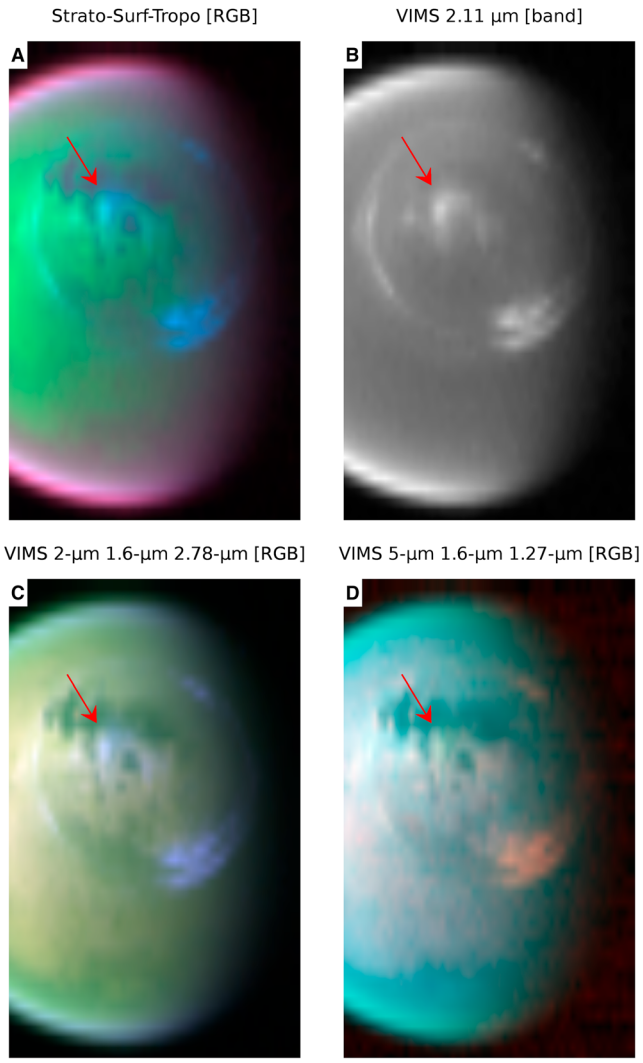

Figure 3. Visual and Infrared Mapping Spectrometer (VIMS) north polar image from 10 July 2017, shortly after northern summer solstice, illustrating spectral characteristics of cloud features: (a) color composite with red = "stratospheric" filter, green = "surface" filter, and blue = "tropospheric" filter (Brown et al., 2010; Kelland et al., 2018); (b) 2.11-μm band; (c) representative color view with red = 2 μm, green = 1.6 μm, and blue = 2.78 μm; (d) representative color view with red = 5 μm, green = 1.6 μm, and blue = 1.27 μm. Elongated clouds around 60°N were seen by both Imaging Science Subsystem and VIMS at all wavelengths. The higher-latitude feature visible (red arrow) was not detected by Imaging Science Subsystem and hardly seen in VIMS channels shorter than 2 μm and longer than 2.75 μm.

an estimated 2–3% to the clouds found with the automated search. For the visual cloud detection, multiple images are generated for each VIMS cube: an RGB image using spectral channels based on observational sensitivity (Brown et al., 2010) to features on the surface (Figure 3a), in the troposphere (Figures 1 and 3), or in the stratosphere (Le Mouélic et al., 2012, 2017, 2018); its gray scale counterpart; a stratospherically corrected tropospheric image produced by subtracting the tropospheric image from the stratospheric image; and a 5-μm view. This strategy provides greater confidence throughout the cloud selection process and makes it possible to distinguish between clouds and artifacts due to bright surface features or albedo variations near the terminator or limb. Clouds are reprojected on Titan's globe for each of the cubes spanning 2004–2017 to produce maps and time evolution plots (Figure 1).

2.3. Observed Seasonal Cloud Patterns and Comparison to Model Predictions

Given the obliquity of the Saturnian system (26.7°), there is a substantial seasonal shift in insolation, and Titan's weather patterns are expected to evolve seasonally. Early Titan general circulation models (GCMs) with dry physics had predicted pole-to-pole circulation with rising motion at the summer pole (Hourdin et al., 1995; Richardson et al., 2007; Tokano, 2007). Convective tropospheric systems were indeed observed over the south pole, initially via Earth-based imaging (Roe et al., 2002) and continuing late into Titan's southern summer when Cassini arrived in 2004 (e.g., Figure 2a; Porco et al., 2005; Rodriguez et al., 2009; Schaller, Brown, Roe, & Bouchez, 2006) and in the case of a large cloud outburst in October 2004 led to precipitation at Arrakis Planitia (Turtle et al., 2009; Turtle, Perry, Hayes, & McEwen, 2011). Such activity became less common after 2005 (e.g., Rodriguez et al., 2009, 2011; Schaller, Brown, Roe, Bouchez, & Trujillo, 2006; Turtle et al., 2009; Turtle, Del Genio, et al., 2011) as southern summer waned.

Unexpectedly, elongated streaks of clouds exhibiting convective behavior and often extending over several hundred kilometers were observed consistently at mid-southern latitudes (~40°S–50°S) from early in the mission until late 2012 (Figure 1; Griffith, 2009; Rodriguez et al., 2011; Turtle, Del Genio, et al., 2011), well after the southern autumnal equinox. Isolated clouds have also been observed at lower southern latitudes. Summer midlatitude cloud activity was simulated in GCMs once moist physics was incorporated (Mitchell et al., 2006; 2009; Rannou et al., 2006).

Starting in 2007, as the Sun rose at high northern latitudes, ISS and VIMS began to detect large clouds >55°N (Figure 1), which remained relatively common through the equinox. In September 2010, about a year after the equinox, an outburst was seen at low southern latitudes (Figure 2, upper right): The large arrow-shaped cloud (Mitchell et al., 2011) was followed by extensive surface changes due to precipitation across Concordia and Hetpet Regiones, Yalaing Terra, and Adiri (Barnes et al., 2013; Turtle, Perry, Hayes, Lorenz, et al., 2011). These equatorial clouds, more than a year after the equinox, may have represented a stage in the migration of the Intertropical Convergence Zone to the northern hemisphere. However, subsequently cloud activity dropped off precipitously and remained rare, with only a few isolated clouds observed at mid-southern and mid-northern latitudes for ~5 years (Figure 1). This pattern suggested the possibility that the removal of methane by strong precipitation dried and stabilized the atmosphere, similar to the shorter drop in activity following

the 2004 south polar cloud outburst (Rodriguez et al., 2009, 2011; Schaller, Brown, Roe, Bouchez, & Trujillo, 2006; Turtle, Del Genio, et al., 2011).

As northern summer approached, the expectation based on moist atmospheric circulation models (e.g., Lora et al., 2015; Mitchell, 2008; Mitchell & Lora, 2016; Mitchell et al., 2011, 2006; Newman et al., 2016; Rannou et al., 2006; Schneider et al., 2012) was that cloud activity would pick up at Titan's high northern latitudes, perhaps as early as ~2010. Clouds did finally begin to appear consistently in 2016 (Figure 1), becoming common around ~55°N and increasingly widespread through 2017 (e.g., Figures 2c, 2d, and 3). In the last year of the mission, some small clouds also appeared at ~15°N–40°N (Figure 1), consistent with, but a few years later than model predictions. However, in contrast to predictions of extensive north polar cloud activity and precipitation, ISS and VIMS only observed small isolated cells near Titan's north pole (e.g., Figure 2c); no substantial systems of north polar convective clouds, similar to those detected by Earth-based observers or Cassini at high southern latitudes in southern summer, were observed before the end of the mission in September 2017. On the other hand, the south polar convective cloud systems were observed almost ~1.6 year after the southern summer solstice, whereas Cassini's last observations of Titan came less than 0.3 year after the northern summer solstice. Another potential complication is that due to Saturn's obliquity, orbital eccentricity, and current longitude of perihelion, Titan's seasons are asymmetric with southern summers being shorter and receiving ~24% stronger insolation (e.g., Aharonson et al., 2009) than those in the northern hemisphere.

Complicating interpretation of the northern summer cloud patterns, VIMS observations of Titan's high northern latitudes in June and July 2016 and again in 2017 appeared to show cloud features at 2.1 and 2.75 μm that were not apparent to either VIMS or ISS in other spectral atmospheric windows (Turtle et al., 2016, 2018). Instead, surface features were clearly detected at 0.94, 2.0, and 5.0 μm. Possible explanations include clouds made up of very small droplets or high-altitude cirrus that is optically thick compared to Titan's atmospheric haze at longer wavelengths but optically thin compared to the haze at shorter wavelengths. However, these hypotheses cannot account for all aspects of the observations (Turtle et al., 2016, 2018), so the unusual spectral dependence of these features remains unexplained pending radiative transfer modeling to provide a better understanding of the apparent discrepancy.

There have been some suggestions of longitude preferences (Brown et al., 2009; Rodriguez et al., 2009, 2011; Roe et al., 2005; Turtle, Del Genio, et al., 2011), but no strong trends indicating longitudinal control of cloud formation have been detected (Figure S1). Although some clouds appear to be associated with the maria (seas; e.g., Figure 2d in Turtle, Del Genio, et al., 2011), the data cannot easily distinguish whether they are preferentially generated over the seas.

3. Interpretations and Implications for Atmospheric Circulation and Titan's Methane Cycle

Cloud distributions and behavior over time are valuable tracers of atmospheric circulation, with the caveat that Titan's cloud activity can be sporadic and Cassini imaging opportunities were not continuous. Furthermore, the observations span just under half of an annual cycle, which may or may not have exhibited typical weather patterns. Nonetheless, observed differences from predictions put important constraints on GCMs, which differ in their handling of factors like moist convection, methane transport, availability of methane reservoirs, and atmospheric superrotation, and can reveal cloud-forming processes that provide the best match to observations, especially during the equinox and solstice transitions.

Observations of convective methane clouds through October of 2010 were consistent with distributions of precipitation predicted by models incorporating moist convection (Mitchell, 2008; Mitchell et al., 2006, 2009) and suggested that tropospheric dynamics, particularly the extended persistence of clouds at mid-southern latitudes (Figure 1), resulted from a long-term response due to the atmosphere's high thermal inertia combined with seasonal forcing by surface temperature variations (Turtle, Del Genio, et al., 2011) and possibly higher than expected surface moisture (Rodriguez et al., 2011). Such model-data comparisons rely on the fact that clouds are a prerequisite for precipitation, although it is recognized based on terrestrial and Titanian observations that clouds do not necessarily result in precipitation; indeed, only two events that apparently produced precipitation have been detected in Cassini observations (Turtle et al., 2009; Turtle, Perry, Hayes, Lorenz, et al., 2011). More detailed analysis is currently underway that could lead to

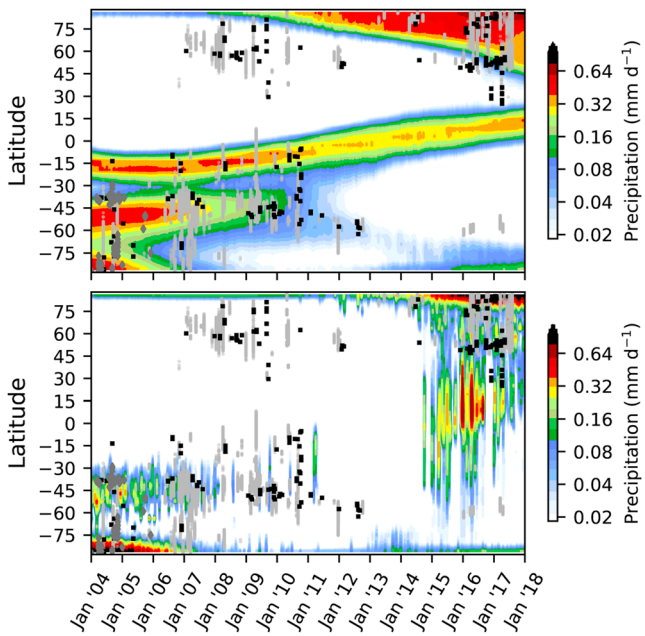

Figure 4. Comparison of cloud observations (Figure 1) to general circulation model precipitation predictions for two scenarios of surface methane: (a) global surface methane reservoir and (b) "wetlands" scenario with inexhaustible methane reservoirs poleward of 60° latitude (Faulk et al., 2017).

identification of smaller or subtler surface changes (Karkoschka et al., 2017). North polar clouds had been common leading up to and around the equinox, consistent with increased insolation and availability of methane at the surface but earlier than precipitation or cloud frequency predictions by a number of models (e.g., Mitchell, 2008; Schneider et al., 2012). Some models were consistent with the scarcity of low-latitude clouds after equinox and the observed cloud activity at high northern latitudes (Lora et al., 2015; Newman et al., 2016), but models did not satisfactorily predict the lack of clouds over a period of several years between the equinoctial north polar clouds and the activity at middle and high northern latitudes that finally picked up as the summer solstice approached. This decrease followed not only the early north polar clouds but also the 2010 equatorial outburst and precipitation so could be similar to the dearth of clouds over a shorter period of time in the wake of the 2004 south polar cloud outburst and precipitation, which was hypothesized to be due to the substantial amount of methane removed from the atmosphere by the event and consequent stabilization of the atmosphere (Schaller, Brown, Roe, Bouchez, & Trujillo, 2006; Turtle, Del Genio, et al., 2011).

A number of modeling studies of Titan's climate system have demonstrated the sensitivity of the hydrologic cycle to the total methane reservoir available to the atmosphere (Faulk et al., 2017; Lora et al., 2015; Mitchell, 2008; Mitchell et al., 2006; Mitchell & Lora, 2016; Newman et al., 2016). Midlatitude activity is particularly sensitive, with models simulating precipitation in those regions only when methane thermodynamics are included (Mitchell et al., 2006), and when there is sufficient surface evaporation to supply the atmosphere (Lora et al., 2015; Mitchell & Lora, 2016). The transition between idealized "moist" and "dry" climates occurs when methane reservoirs have approximately the mass that exists in the surface-atmosphere system (Mitchell, 2008), which makes it difficult to determine whether Titan is in either of these regimes.

GCM simulations with global or nearly global, effectively unrestricted surface reservoirs of methane result in zonal mean precipitation patterns that move continuously from pole to pole, overestimating low-latitude activity particularly around equinox (Figure 4a; Lora et al., 2015; Mitchell, 2008; Mitchell et al., 2006, 2011; Newman et al., 2016; Schneider et al., 2012). In recent three-dimensional models, the timing of increased north polar precipitation also matches the onset of observed equinoctial cloud activity (Lora et al., 2015; Newman et al., 2016). In contrast, a smaller methane supply generally results in simulations in which precipitation is restricted to polar regions (Lora et al., 2015; Mitchell, 2008; Newman et al., 2016) and which therefore do not match observed cloud activity at midlatitudes during solstice or low latitudes during equinox.

Simulations with global and limited methane reservoirs each have characteristics that match some aspect of observed cloud distributions over time, but neither idealized scenario is satisfactory. Moreover, an unrestricted methane supply is not consistent with other data that indicate generally arid conditions at low latitudes (e.g., dune fields; Lorenz et al., 2006; Radebaugh et al., 2008; Rodriguez et al., 2014). Based on a scarcity of craters at high latitudes, Neish and Lorenz (2014) suggested that Titan's low-elevation polar regions could be wetlands, with ample high-latitude methane available beyond the locations of the maria and lakes. Used as a boundary condition in GCMs, this "wetlands" scenario—with moist polar surfaces and dry lower latitudes—proves to be the most consistent with observations, as it predicts significant precipitation events at midlatitudes, the primary mechanism for which is baroclinic instability; frequent activity at the poles; and infrequent (but not absent) equinoctial low-latitude storms (Figure 4b; Faulk et al., 2017; Lora & Mitchell, 2015; Mitchell & Lora, 2016). In these simulations, sporadic polar activity is predicted between equinox and solstice, although generally at higher latitudes than observed. These results suggest that Titan's climate in fact lies in an intermediate regime in terms of methane availability to the atmosphere and one where soil moisture may play an important role. More work to explore the impact of subsurface methane storage, subsurface transport, and surface runoff on the global hydrologic cycle are necessary to move our understanding beyond idealized surface methane distributions.

4. Conclusions

Cassini ISS and VIMS have documented the distribution and behavior of Titan's clouds over more than 13 years, providing key data regarding this dynamic moon's atmospheric circulation and methane cycle. Clouds as atmospheric tracers, combined with information about Titan's geography, provide constraints on driving processes and properties, including the presence of unseen but accessible methane reservoirs. Although cloud activity and two precipitation events generally followed Titan's seasonal evolution, there were key differences in the timing and locations of observed clouds compared to most GCM predictions, with north polar clouds becoming common earlier than expected and then disappearing for several years before reappearing with a strong preference for ~60°N latitude rather than the summer pole. Matching these patterns over almost half a Titan year with GCM results suggests that although liquids are only observed to cover parts of the surface at high latitudes, primarily in the north, there may be a substantial subsurface methane table at each pole above 60° latitude that is available for exchange with the atmosphere. This interpretation is consistent with other results based on a variety of data and techniques (e.g., RADAR imaging and topography, ISS and VIMS surface imaging and spectra, subsurface transport models, surface temperatures, and tropospheric methane mole fractions) that suggest connected subsurface hydrology at Titan's north pole (e.g., Birch et al., 2017; Hayes et al., 2008, 2017; Horvath et al., 2016; Jennings et al., 2016; Lora & Ádámkovics, 2017).

Earth-based telescopic observations of Titan have also played a critical role in understanding the distribution and frequency of clouds before, during, and now after the Cassini mission (Brown et al., 2002; Griffith et al., 1998; Roe et al., 2002): Higher observing cadences caught cloud activity that would otherwise have been missed by Cassini (Schaller, Brown, Roe, & Bouchez, 2006; Schaller et al., 2009), and dedicated integral field units made it possible to constrain evolution and dynamics in combination with VIMS observations (Ádámkovics et al., 2010). Observations of the nonsaturated absorption bands in the 1.6-μm atmospheric window by Keck NIRSPEC (Near Infrared Spectrometer) can monitor cloud features at Titan's northern latitudes (Sotin et al., 2017). Through the northern summer solstice, ISS and VIMS detected only small convective tropospheric clouds near Titan's north pole (Figures 1–3), and none had sufficient size or intensity to have been detected from Earth-based telescopes. This lack of large polar clouds is in marked contrast with Earth-based observations that documented significant south polar cloud activity over several years leading up to the southern summer solstice (Brown et al., 2002; Roe et al., 2002). With the end of Cassini, such telescopic observations are the only means with which to monitor Titan's weather patterns for the foreseeable future. Although they lack spatial resolution (typically several hundred kilometers), they can offer high temporal cadence, and the next generation of 30-m class telescopes, for example, the Giant Magellan Telescope, the Thirty Meter Telescope, and the Extremely Large Telescope will help improve this spatial resolution. The James Webb Space Telescope, with higher near-infrared spectral resolution than Cassini and higher near-infrared spatial resolution than the Hubble Space Telescope, also has significant potential for Titan observations, including monitoring cloud activity and searching for large-scale surface changes (Nixon et al., 2016).

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