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Seasonal changes in Titan's meteorology

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[1] The Cassini Imaging Science Subsystem has observed Titan for ~1/4 Titan year, and we report here the first evidence of seasonal shifts in preferred locations of tropospheric methane clouds. South-polar convective cloud activity, common in late southern summer, has become rare. North-polar and northern mid-latitude clouds appeared during the approach to the northern spring equinox in August 2009. Recent observations have shown extensive cloud systems at low latitudes. In contrast, southern mid-latitude and subtropical clouds have appeared sporadically throughout the mission, exhibiting little seasonality to date. These differences in behavior suggest that Titan's clouds, and thus its general circulation, are influenced by both the rapid temperature response of a low-thermal-inertia surface and the much longer radiative timescale of Titan's cold thick troposphere. North-polar clouds are often seen near lakes and seas, suggesting that local increases in methane concentration and/or lifting generated by surface roughness gradients may promote cloud formation. **Citation:** Turtle, E. P., A. D. Del Genio, J. M. Barbara, J. E. Perry, E. L. Schaller, A. S. McEwen, R. A. West, and T. L. Ray (2011), Seasonal changes in Titan's meteorology, *Geophys. Res. Lett.*, *38*, L03203, doi:10.1029/2010GL046266.

1. Background

[2] Cassini's Imaging Science Subsystem (ISS) began imaging Titan in April 2004, as the spacecraft approached the Saturnian system. Since then, Titan's seasons have progressed from southern summer to early southern autumn, and changes in the distribution and activity of tropospheric methane clouds have been observed (Figure 1). Through 2004, large convective cloud systems were common over Titan's South Pole [e.g., *Porco et al.*, 2005; *Schaller et al.*, 2006a]; however, since 2005 such storms have been infrequent. Elongated cloud streaks have been common at mid-southern latitudes throughout the mission and appeared at high northern latitudes (>50°N) starting in 2007. Only twice have we detected clouds at mid-northern latitudes. Recently, extensive cloud systems have been observed at equatorial latitudes. We present observations of Titan's clouds, and thus atmospheric behavior, over timescales of hours to years, documenting changes that have resulted from shorter-term weather and potentially longer-term seasonal effects and their implications for Titan's active methane cycle and atmospheric circulation.

2. Observations and Interpretation

[3] In 2004, extensive cloud systems were common in Titan's south-polar region, experiencing late summer at the time. These clouds (Figure 2a) exhibited morphologies and behavior consistent with convection, not unexpected if enhanced solar heating were driving upwelling motion in the atmosphere. An especially large outburst was observed in October 2004 [*Schaller et al.*, 2006a; E. P. Turtle et al., Shoreline retreat at Titan's Ontario Lacus and Arrakis Planitia from Cassini Imaging Science Subsystem observations, submitted to *Icarus*, 2011], in the wake of which south-polar cloud activity decreased significantly (Figure 1a). This change may have been an immediate effect of the depletion of atmospheric methane due to precipitation during the storm [*Schaller et al.*, 2006b], given observations of apparent flooding [*Turtle et al.*, 2009] and of subsequent retreat of shorelines [*Hayes et al.*, 2011; E. P. Turtle et al., submitted manuscript, 2011]. However, the dearth of south-polar clouds in the years after this event suggests a connection to the seasonal cycle as well. Near solstice, surface heating induces forced large-scale low-level ascent and methane convergence, which resupply moisture depleted by colocated convective drying and allow convection to continue. At some later time, however, when peak insolation has moved away from the pole, drying and stabilizing of the atmosphere by major precipitation events may arrest further convection for a sufficiently long time to allow radiative destabilization of the column and low-level moisture convergence to slowly be established at lower latitudes, finally triggering a seasonal shift in the general circulation.

[4] Clouds have also been observed at mid- and low southern latitudes (Figure 1a and Table S1 of the auxiliary material).[1] Mid-southern-latitude single or multiple elongated streaks, often extending several hundred kilometers (Figure 2b), have appeared throughout the mission, occurring at ~40° ± 5°S during the first several years of the mission and shifting several degrees poleward (to ~45° ± 5°S) more recently (Figure 1). These clouds, too, exhibit convective behavior at small spatial scales [*Griffith et al.*, 2005]. Small (~10 km) isolated clouds, presumably individual cells, have also been observed, alone or in dispersed groups, throughout the mission (Figure 2c). These typically occur near 15°S, occasionally as low as ~10°S.

[5] Titan's north pole was in darkness at the start of the Cassini mission, and ISS views poleward of ~30°N were

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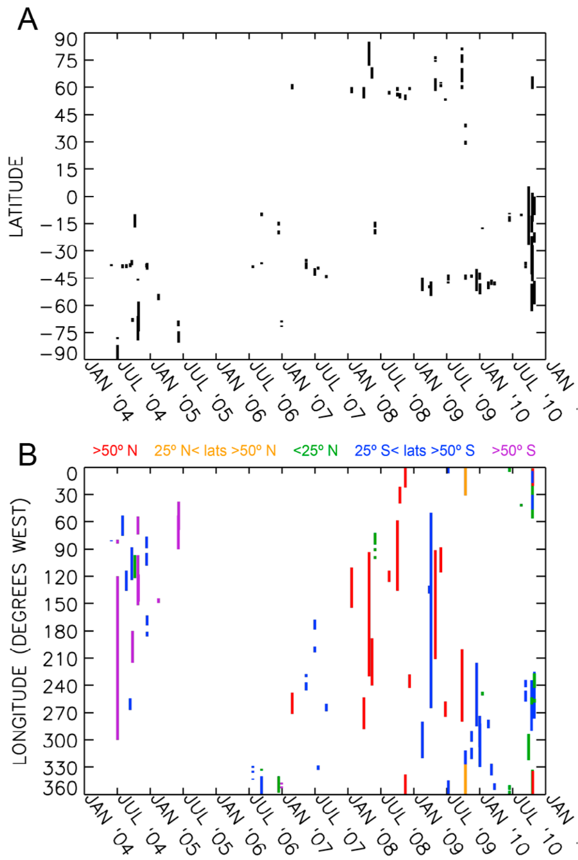

Figure 1. (a) Latitudes and (b) longitudes (color indicates latitude range) of clouds observed by ISS as a function of time through October 2010 (Table S1).

generally at larger emission angles (Figure S1), obscured by Titan's haze. The first ISS observation of a methane cloud in the northern hemisphere occurred in early 2007. No others were observed until January 2008, after which they became quite common (Figures 1a, 2d, and 3). (*Griffith et al.* [2006] inferred the clouds detected at high northern latitudes by the Visual and Infrared Mapping Spectrometer (VIMS) to be extensive small-particle ethane cloud decks, as opposed to the discrete tropospheric methane clouds to which ISS is sensitive.) So far only elongated clouds have been observed at high northern latitudes; none of the northern clouds have exhibited the morphology of clusters of individual convective clouds observed at high southern latitudes in late southern summer. This difference may be related to lower north-polar surface temperatures, 1.0–1.5 C° cooler than the south pole [*Jennings et al.*, 2009], possibly sufficient to suppress convection, although Titan's general circulation may be the dominant factor. We anticipate convective cloud systems at high northern latitudes by late northern summer or sooner; northern summer solstice is in May 2017. With few exceptions, all of the northern clouds observed to date have been at latitudes poleward of 50°. In summer 2009, ISS detected two clouds at mid-northern latitudes; it is anticipated that these clouds, too, will become more common as northern spring and summer progress.

[6] In September and October 2010, large cloud systems were observed at low to equatorial latitudes, including an arrow-shaped cloud which extended for >1000 km (Figure 2e) and a broad equatorial band of clouds (Figure 2f). Whether the later clouds are the result of the dissipation of the September 2010 outburst is unknown, as no observations were acquired in between (during solar conjunction of Saturn).

[7] When possible, we have observed Titan continually over extended periods of time to follow cloud evolution (e.g., Figures 3 and S2). Individual cells can form and dissipate over several hours, although systems of clouds can persist for days. Wind speeds measured by tracking discrete clouds demonstrate primarily eastward motion, generally ranging from 0.5 to ~10 m/s (Figure S3). The wide range of speeds is a sign of eddy variability, a result of tracking clouds at different altitudes, or both. An intriguing ~34-m/s measurement (Figure S3) [also *Porco et al.*, 2005] was made from a distant observation during Cassini's approach to Saturn. The lower-resolution images increase the uncertainty in this measurement. However, it could be the result of a relatively large outbreak in which the clouds reached higher altitudes where higher wind speeds might be expected [*Bird et al.*, 2005]. In this case the lack of detection of comparable speeds since then could be an unfortunate

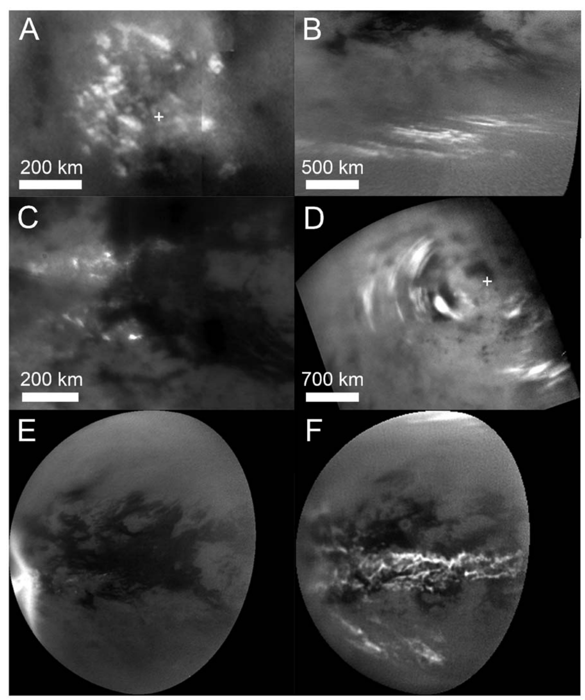

Figure 2. (a) South-polar field of clouds, 3 July 2004; + indicates South Pole. (b) Elongated streaks at mid-southern latitudes, 13 December 2009 (24-hour sequence in Figure S2). (c) Discrete cells near ~15°S, 12 December 2006. (d) Clouds at high northern latitudes, 22 September 2009 (24-hour sequence in Figure 3); + indicates North Pole, scale bar at 60° latitude. (e) Equatorial arrow-shaped cloud, 27 September 2010. (f) Equatorial, mid-southern-latitude and high-northern-latitude clouds, 18 October 2010. Bright features are tropospheric methane clouds; grey and darker shades are surface features. North is up with the exceptions of Figures 2a and 2d.

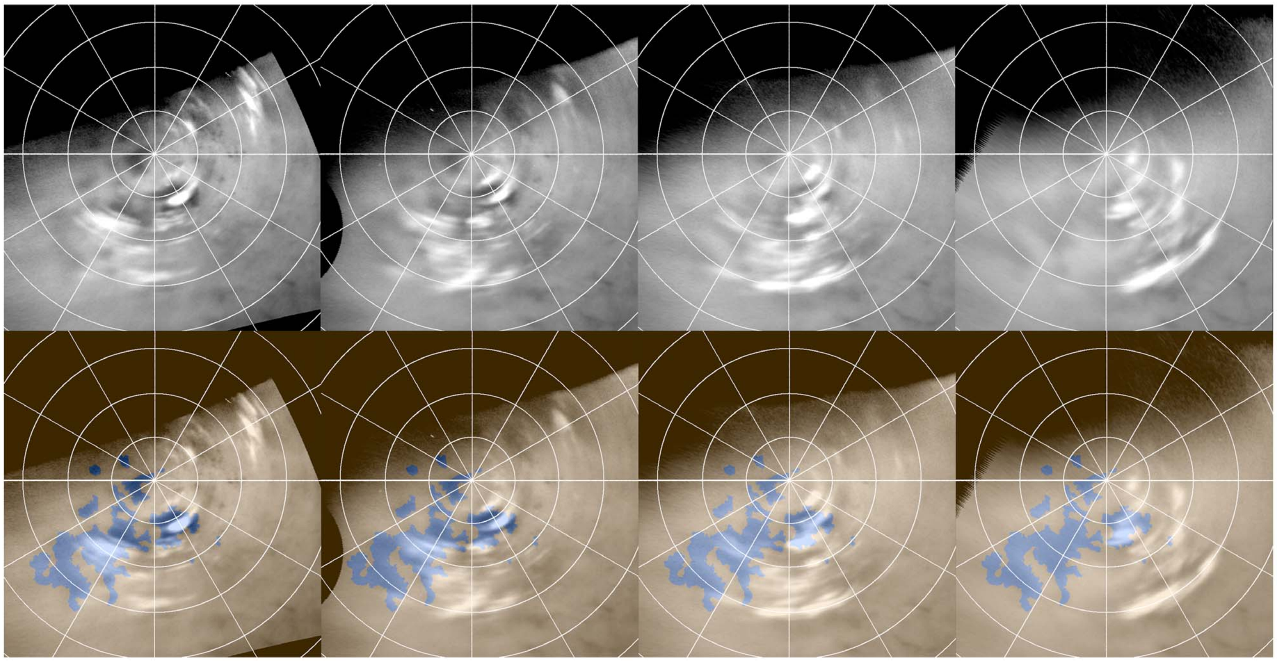

Figure 3. 24-hour series of observations of clouds at high northern latitudes: 60–82°N, 220–260°W. ISS images (top) with overlay highlighting locations of northern lakes and seas in blue (bottom). Titan's north pole is at center, the 90° meridian is to the top, and latitude grid spacing is 10°. From left to right, the observations were acquired at: 23:06 on 22 September 2009 and 05:03, 11:06, and 23:02 on 23 September 2009. Tracking of individual features yields eastward winds 0.5–9.7 m/s.

consequence of not having had opportunities to track clouds associated with such large outbursts.

3. Behavior Patterns and Implications for Global Circulation Models

[8] The observed locations of Titan's clouds in ISS images are generally consistent with those reported by VIMS over the same time period [*Brown et al.*, 2010; *Rodriguez et al.*, 2009], but our results extend the record for an additional two years, through and beyond the northern spring equinox, and document the first occurrence of clouds in northern mid-latitudes. The results have implications for global circulation patterns, although the extent to which seasonal variations can be assessed is somewhat limited by the sporadic nature of Titan's cloud activity and the fact that Cassini has observed only a quarter of a Titanian year to date (ISS' strategies for observing clouds are provided in the auxiliary material and Table S1). The observations provide important constraints on models of atmospheric circulation, especially during the transition around equinox. Dry circulation models [*Hourdin et al.*, 1995; *Mitchell et al.*, 2006; *Tokano*, 2007; *Richardson et al.*, 2007] consistently predict pole-to-pole circulation with rising motion throughout the summer hemisphere. Since clouds can generally be considered tracers of upward motion, the observation of preferred latitudes in their distribution implies that moist processes influence Titan's general circulation.

[9] Therefore, we compare two Titan circulation models that incorporate moist processes and document the seasonality of clouds and/or precipitation [*Rannou et al.*, 2006; *Mitchell*, 2008; *Mitchell et al.*, 2009]. Both are two-dimensional, limiting their ability to portray atmospheric variability, but the models incorporate different physics, leading to very different predictions of the seasonal variation of clouds and precipitation. Among the most important differences are: (1) *Rannou et al.* [2006] incorporate cloud microphysics but do not account for moist convection, while *Mitchell* [2008] and *Mitchell et al.* [2009] parameterize convection but do not explicitly represent clouds; and (2) *Mitchell* [2008] and *Mitchell et al.* [2009] use a purely symmetric circulation model, whereas *Rannou et al.* [2006] include a horizontal diffusion term representing eddy angular momentum transport due to barotropic instabilities derived from the *Hourdin et al.* [1995] 3-dimensional model, a process thought to promote super-rotation on Titan [*Del Genio and Zhou*, 1996].

[10] Both models produce clouds at the poles and in mid-latitudes, as observed by ISS, but for different reasons. In the models of *Mitchell* [2008] and *Mitchell et al.* [2009], as low-level air flows poleward in the summer hemisphere, convection is triggered at mid-latitudes and the latent heat release causes rising motion there and arrests the poleward progression of the Hadley cell. Deep convection on Titan requires high near-surface methane relative humidity [*Barth and Rafkin*, 2010] and thus responds to surface heating and the resulting low-level methane convergence. So the rising branch of the Hadley cell oscillates between the mid-latitudes of the two hemispheres over the annual cycle, including convection at the equator in the equinox seasons, but with a phase lag due to the long radiative time scale of the troposphere [*Mitchell et al.*, 2006]. Convection also exists at the summer pole near and after summer solstice. The relative contributions of these two sources of cloud/precipitation formation vary as the size of the subsurface methane reservoir is varied, with smaller and larger reservoirs

favoring, respectively, polar or mid-latitude convection and surface methane "soil moisture" buildup. *Rannou et al.* [2006] instead predict a 3-cell meridional circulation in each hemisphere, but with slanted cells such that the large-scale rising motion in the tropical Hadley cell saturates in mid-latitudes while that in the polar cell saturates close to the pole. Rather than being driven by cumulus convection, these cells are driven by an equator-pole temperature gradient about twice that observed [*Jennings et al.*, 2009] and by the parameterized eddy momentum flux. They appear to release symmetric instability, leading to a slantwise neutral state. This model predicts more cloudiness at the winter pole than the summer pole, more mid-latitude cloudiness in summer than winter, disappearance of mid-latitude clouds at the equinoxes, and a more latitudinally fixed cloud distribution, with few clouds between 50–70° in either hemisphere and between 15°N-15°S.

[11] Both models have some features in common with the observations and some discrepancies, which may indirectly reveal the physics driving Titan's general circulation. *Mitchell* [2008] appears to more faithfully reproduce the seasonality of polar methane cloudiness, which is the result of moist convection and consistent with the morphology of the south-polar clouds seen by ISS (Figure 2a). *Rannou et al.* [2006], on the other hand, better predict the appearance of clouds preferentially at certain latitudes rather than continuous migration from one hemisphere to the other. The apparent preference for clouds to appear sporadically at 15° ± 5°S over the ≥6 years documented by ISS images (Figure 1a) implies mean ascent at these latitudes, which is not predicted by either model. The tendency for clouds to appear at fixed latitudes suggests that the dynamics of the troposphere, whose radiative time scale greatly exceeds a Titan year, may include a component that responds sluggishly to its internal dynamics in addition to a component that responds more quickly to surface forcing. For example, methane convection may determine which hemisphere is cloudier in the solstice seasons, while large-scale eddy momentum transports mechanically drive a multiple-cell meridional circulation that prevents a smooth latitudinal migration of the rising branch of the Hadley cell. It is worth noting that the Intertropical Convergence Zone (ITCZ) on Earth shifts abruptly from the winter to the summer hemisphere; in the *Xian and Miller* [2008] model this is due partly to the large thermal inertia of the ocean and partly to non-linear meridional advection of angular momentum by the mean circulation. Perhaps momentum advection in a super-rotating atmosphere, combined with a large atmospheric thermal inertia, plays a similar role on Titan. If so, then we might predict: (1) that the observed southern mid-latitude clouds, which have lasted longer than predicted by either Titan circulation model, will disappear in the next few years; while (2) our first observation of northern mid-latitude clouds in late 2009 is a harbinger of a "sudden" (by Titan time-scale standards of a few years) shift of its ITCZ into the more illuminated hemisphere.

[12] The recent appearance of extensive near-equatorial clouds (Figures 2e and 2f) is reminiscent of an Earthlike ITCZ on Titan and suggests higher methane humidity [*Barth and Rafkin*, 2010] than at the time of the Huygens probe entry. However, there are, as yet, too few observations over too little time to distinguish whether these clouds represent part of a seasonal migration or an isolated short-lived event. The nature and timescale of an equinoctial transition phase on Titan will put significant constraints on atmospheric models. That of *Rannou et al.* [2006] has a distinct equinox season with double Hadley-cell circulation, lasting a short period of time before returning to pole-to-pole circulation. It is not clear whether this occurs in the models of *Mitchell* [2008] and *Mitchell et al.* [2009], although precipitation in these models shows a short, but continuous, migration from one hemisphere to the other after equinox. Whether the transition of activity from Titan's southern to northern hemisphere is discontinuous (cf., the transition over Earth's oceans [*Xian and Miller*, 2008]) or gradual and how long it takes are important questions that will reveal the relative roles of elements of Titan's atmospheric circulation, e.g. the rapid response of the surface to gradual changes in external forcing by solar illumination in contrast to the high inertia of Titan's thick atmosphere.

[13] ISS observations do not indicate preferred longitudes for cloud occurrences (Figure 1b), nor do clouds seem to be related to specific surface features in general, although the existence of such relationships cannot be ruled out at the temporal resolution of the dataset. Lake-effect clouds have been suggested at high northern latitudes [*Brown et al.*, 2009], and an ISS image sequence in September 2009 (Figure 3) revealed numerous clouds correlated in latitude with the northern lakes and seas. These clouds are first observed over and eastward of Kraken Mare and move toward the east at speeds of up to 9.7 m/s. However, without earlier observations to demonstrate that the clouds did not originate westward of Kraken Mare, whether they are generated at lakes and seas cannot be determined conclusively. Even if not directly connected to the lakes and seas, it seems likely that the frequent detections of clouds at high northern latitudes since 2007 are related to the availability of methane at the surface in this region.

4. Conclusions

[14] ISS observations of Titan's clouds from late southern summer in 2004 to early northern spring in 2010 have revealed strong latitudinal preferences and the first evidence of seasonal changes in Titan's general circulation. Moist processes are essential to reproducing the observed atmospheric behavior, and the tropospheric dynamics may reflect a combination of a long-term response by the high-thermal-inertia atmosphere and more rapid forcing by temperature variations of the surface. Although longitudinal preferences are not evident, at high northern latitudes clouds are often seen near lakes and seas, consistent with availability of methane at the surface facilitating cloud formation. Observations over the next few years will be essential to documenting the length and nature of the equinox transition, e.g., revealing whether the recent dramatic appearance of equatorial clouds, more than a year after the equinox, represents a stage in the migration of the ITCZ to the northern hemisphere.

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