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Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes

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[1] Cassini's Imaging Science Subsystem (ISS) has been observing Titan since April 2004, compiling a nearly global surface map and monitoring the surface and atmosphere for activity. Early images of the south-polar region revealed numerous dark surface features and contemporaneous convective cloud systems, suggesting the presence of hydrocarbon lakes similar to those later detected at Titan's North Pole. Intriguingly, repeated south-polar imaging by ISS revealed differences consistent with ponding of hydrocarbon liquids on the surface due to precipitation from a large storm. More recent ISS images of high northern latitudes illustrate the full extents (>500,000 km^2) of hydrocarbon seas, sections of which have been observed by Cassini's RADAR. These observations demonstrate dynamic processes at work on Titan and that the poles harbor liquid-hydrocarbon reservoirs, the extents of which differ from pole to pole and which may be coupled to seasonally varying circulation. **Citation:** Turtle, E. P., J. E. Perry, A. S. McEwen, A. D. DelGenio, J. Barbara, R. A. West, D. D. Dawson, and C. C. Porco (2009), Cassini imaging of Titan's high-latitude lakes, clouds, and south-polar surface changes, *Geophys. Res. Lett.*, *36*, L02204, doi:10.1029/2008GL036186.

1. Background

[2] Titan's substantial atmosphere is composed primarily of nitrogen (>90%), a few percent methane, and lesser amounts of other species [*Yung et al.*, 1984; *Niemann et al.*, 2005]. Methane and ethane can exist as liquids under Titan's lower atmospheric and surface conditions [*Tyler et al.*, 1981], consistent with frequent detection of clouds inferred to be composed of methane and ethane [*Porco et al.*, 2005; *Schaller et al.*, 2006a, 2006b; *Griffith et al.*, 2006]. Photochemical processes acting in the atmosphere convert methane into more complex hydrocarbons, substantial quantities of which may have precipitated from the atmosphere over Titan's history [*Yung et al.*, 1984; *Lorenz and Lunine*, 2005]. These processes create Titan's atmospheric hazes and destroy methane over relatively short timescales, $\sim 10^7 - 10^8$ yr [*Yung et al.*, 1984]. Therefore, Titan is hypothesized to have reservoirs of liquid methane to resupply the atmosphere [e.g., *Lunine*, 1993]. Knowledge of the distribution of liquids on Titan's surface and clouds in its atmosphere, as well as any changes in either, provides constraints that are essential to furthering our understanding of Titan's methane cycle, its atmospheric dynamics, its total methane inventory and, thus, the sustainability of its current atmosphere.

[3] Early Earth-based observations of Titan's surface revealed albedo patterns interpreted as dark hydrocarbon liquids occupying lows between higher-standing exposures of bright water-ice bedrock [*Lorenz and Lunine*, 2005; *Smith et al.*, 1996]. Cassini-Huygens has revealed Titan's surface in much greater detail, including almost complete global coverage (Figure 1) by the Imaging Science Subsystem (ISS) at 938 nm at resolutions ranging from several kilometers to the limit (~1 km) imposed by scattering by atmospheric haze particles [*Porco et al.*, 2004]. The compositions of the materials responsible for Titan's albedo variations are complex and still not fully known [*Soderblom et al.*, 2007b]. Nonetheless, observations by Cassini-Huygens have provided evidence that large-scale dark regions often consist of accumulations of liquid or solid hydrocarbons [*Stofan et al.*, 2007; *Lopes et al.*, 2007; *Lorenz et al.*, 2006; *Soderblom et al.*, 2007b; *Brown et al.*, 2008]. However, although Huygens' observations of channels and rounded cobbles [*Tomasko et al.*, 2005; *Soderblom et al.*, 2007a] and its detection of moisture (methane) in the shallow subsurface [*Niemann et al.*, 2005] were made at low latitudes, it is not the long-observed equatorial dark areas that currently hold liquid seas. Instead, extensive dunes composed of particulate hydrocarbon material [*Lorenz et al.*, 2006; *Soderblom et al.*, 2007b] cover these regions; currently, lakes and seas appear to occur only at high latitudes [*McEwen et al.*, 2005; *Stofan et al.*, 2007; *Lopes et al.*, 2007; *Brown et al.*, 2008].

2. Surface Observations and Interpretations

[4] ISS imaged Titan's south-polar region in July 2004 and June 2005. Both observations revealed numerous dark surface features as well as bright tropospheric clouds (Figure 2). One of the most distinctive features is 235-km-long Ontario Lacus, with a smooth, relatively bright margin and a dark featureless interior suggestive of a lake [*McEwen et al.*, 2005]. Spectra obtained during a recent observation by Cassini's Visual and Infrared Mapping Spectrometer (VIMS) suggest that Ontario Lacus contains liquid ethane [*Brown et al.*, 2008]. We have documented 55 dark surface features poleward of

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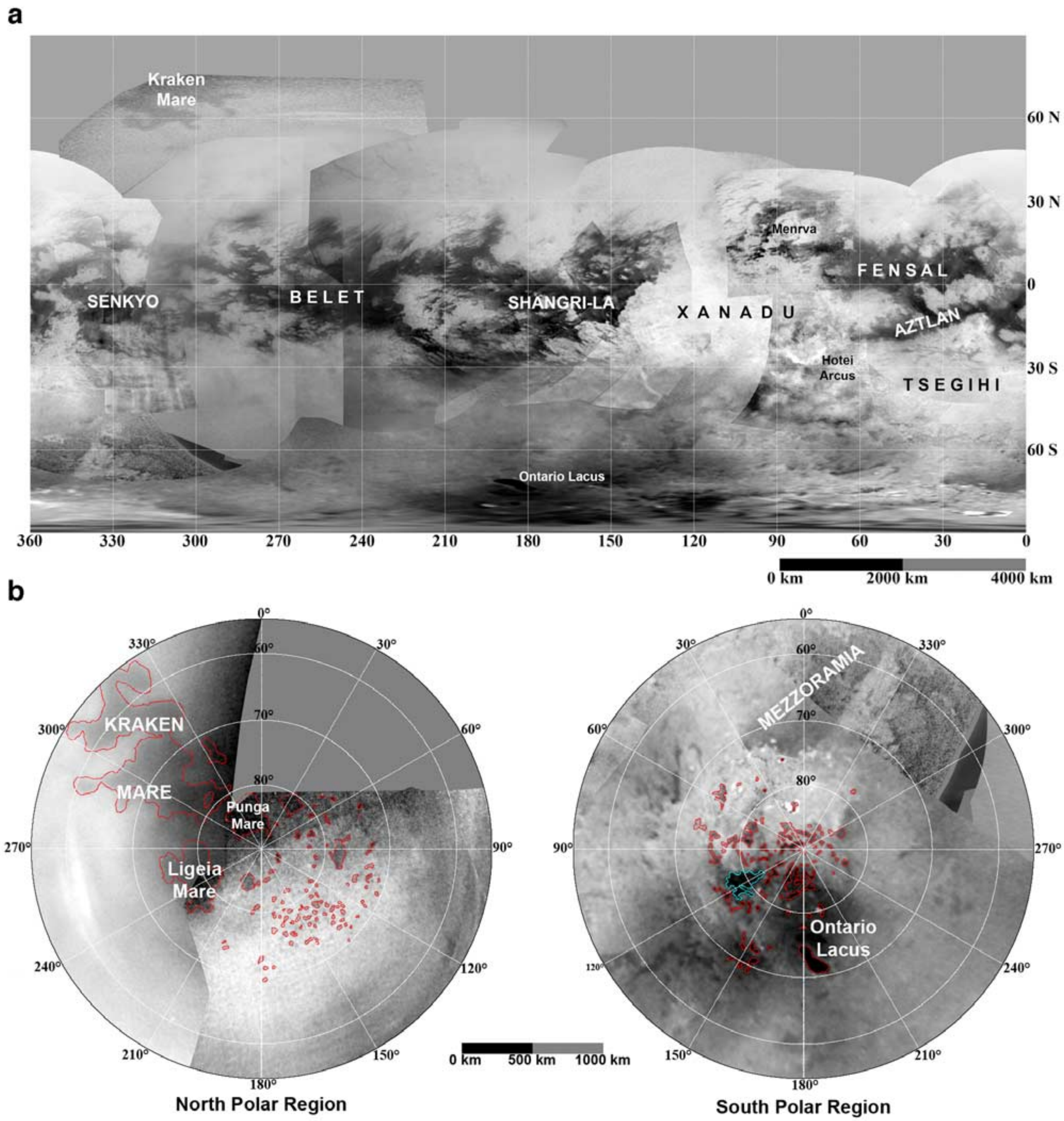

Figure 1. Maps of Titan from ISS 938-nm observations: April 2004 through August 2008. Resolution varies from a few to a few tens of kilometers. Brightness variations are due to differences in surface albedo rather than topographic shading. (a) Simple cylindrical projection. (Atmospheric effects complicate incorporation of data from high northern latitudes.) (b) (left) North and (right) south polar projections, 55°–90° latitude. Colored lines illustrate albedo boundaries interpreted as potential shorelines: blue indicates features that changed between ISS observations (Figure 2).

69°S (Figure 1b), ranging from 15,300-km^2 Ontario Lacus to some less than 100 km^2, covering a total of ~120,000 km^2, or ~5% of the surface in this area.

[5] More recent ISS observations of northern latitudes as winter's darkness recedes have revealed numerous small dark features and several much more extensive features, including Kraken Mare, which is more than 1100 km long with a convoluted boundary (Figure 1). These features coincide with areas interpreted as liquid-filled lakes and seas in overlapping Cassini RADAR data [*Stofan et al.*, 2007; *Lopes et al.*, 2007]. If the entirety of Kraken Mare as revealed by ISS were currently filled with liquid, it would represent a sea with an area over 400,000 km^2. Together, the north-polar dark features observed by ISS cover >510,000 km^2.

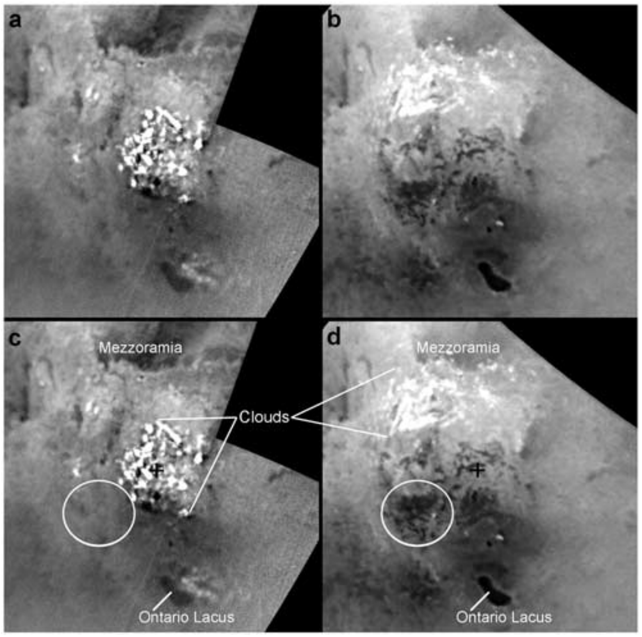

Figure 2. ISS mosaics of Titan's South Pole acquired on (left) 3 July 2004 and (right) 6 June 2005 oriented with the pole in the center and the 0° meridian up. Image resolutions are several kilometers. (Details of images and processing thereof provided in the auxiliary material and Table S1.) Dark features may be, or have been, liquid-filled lakes. Very bright features are tropospheric clouds. The region that exhibits the most prominent differences between the two observations is circled and black plus signs indicate the location of the pole.

[6] Observation of specular reflections, which indicate smoothness at a scale comparable to the wavelength used, could confirm the presence of liquids. Geometric constraints restrict ISS and Earth-based observations of the specular point to low latitudes, where no enhancement has been detected at visible or infrared wavelengths [*West et al.*, 2005; *Fussner*, 2006]. Nonetheless, substantial evidence supports the interpretation that the dark features observed by ISS at high latitudes are lakes or lakebeds: the existence of channels clearly demonstrates modification of Titan's surface by flowing liquid [*Tomasko et al.*, 2005; *Soderblom et al.*, 2007a]; south-polar clouds exhibiting convective behavior [*Porco et al.*, 2005; *Griffith et al.*, 2005] associated with precipitation were common through 2004 [*Schaller et al.*, 2006a, 2006b]; and characteristics consistent with liquids have been identified in RADAR and VIMS observations of polar features [*Stofan et al.*, 2007; *Lopes et al.*, 2007; *Brown et al.*, 2008].

[7] Comparison of the two ISS south-polar observations provides the first evidence of temporal changes in polar surface features (Figure 2), suggesting that at least some of these features may be ephemeral. Although clouds obscure portions of the surface in each observation, differences in the dark features can, nonetheless, be seen. Atmospheric scattering complicates determination of absolute albedos, a problem that is compounded by the potential for localized hazes or clouds to go unrecognized if very optically thin. The lack of absolute albedo measurements means that variations in lighting geometry (Figure S1 of the auxiliary material)[1] could account for features that differ in contrast but not morphology: for example, the diminished contrast of Lacus Ontario in the earlier observation. However, other features that are obvious in the later observation do not appear at all in the earlier one, particularly the ~34,000 km^2 region around 80°S, 120°W (circled in Figure 2). Such differences are difficult to attribute solely to atmospheric scattering. Figure 3 illustrates profiles of pixel values across this region. Ontario Lacus and an unnamed dark feature near the beginning of the profile are easily identified in both profiles, despite the variations in viewing geometry (Figure S1). The dark region in question (circled in Figure 2) stands out dramatically in relative brightness in the later observation, while in the earlier observation there is little deviation from the overall trend.

[8] Although clouds complicate surface observations, they may also provide evidence for the origin of differences observed. In October 2004, between the two ISS observations, Earth-based observers detected a large outburst of clouds at Titan's South Pole [*Schaller et al.*, 2006a]. Atmospheric models suggest that a large storm could produce tens of centimeters of precipitation [*Tokano et al.*, 2001; *Hueso and Sanchez-Lavega*, 2006; *Barth and Rafkin*, 2007]. Therefore, these ISS observations may well document ponding of hydrocarbon rain. The subsequent dearth of south-polar clouds is consistent with seasonal changes or the atmosphere being locally depleted in methane after the outburst [*Schaller et al.*, 2006b].

[9] The one south-polar Cassini RADAR observation acquired to date (December 2007) revealed substantially fewer candidate lakes [*Lunine et al.*, 2008] than would have been predicted based on the distribution of dark features observed by ISS. This comparison could indicate that the material properties in these areas impart different near-infrared and radar albedos, as we have observed in some other locations. Indeed, RADAR could penetrate a thin (~meters) surface layer, detecting deeper material [*Lorenz et al.*, 2008]. However, the ~2.5 years that elapsed between the later ISS observation (July 2005) and that of RADAR suggests another explanation. Given modeled annual evaporation rates of 0.3–10 m [*Mitri et al.*, 2007] and possible local depletion in atmospheric methane as a result of the cloud outburst [*Schaller et al.*, 2006b], as well as the potential for drainage into pore spaces in the underlying material [*Hayes et al.*, 2008], enough liquid could have evaporated or percolated into the subsurface during the intervening years to explain the lack of lakes observed by RADAR in December 2007.

[10] The low-albedo features observed by ISS at both poles cover over 600,000 km^2, almost 1% of Titan's total surface area; however, even if all of these features are currently liquid-filled, they do not appear to provide enough methane to keep Titan's atmosphere resupplied for a substantial amount of time [*Lorenz et al.*, 2008]. Thus, although *Mitri et al.* [2007] have demonstrated that evaporation from lakes covering 0.002–0.02 of the surface could maintain the current methane relative humidity over short timescales,

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036186.

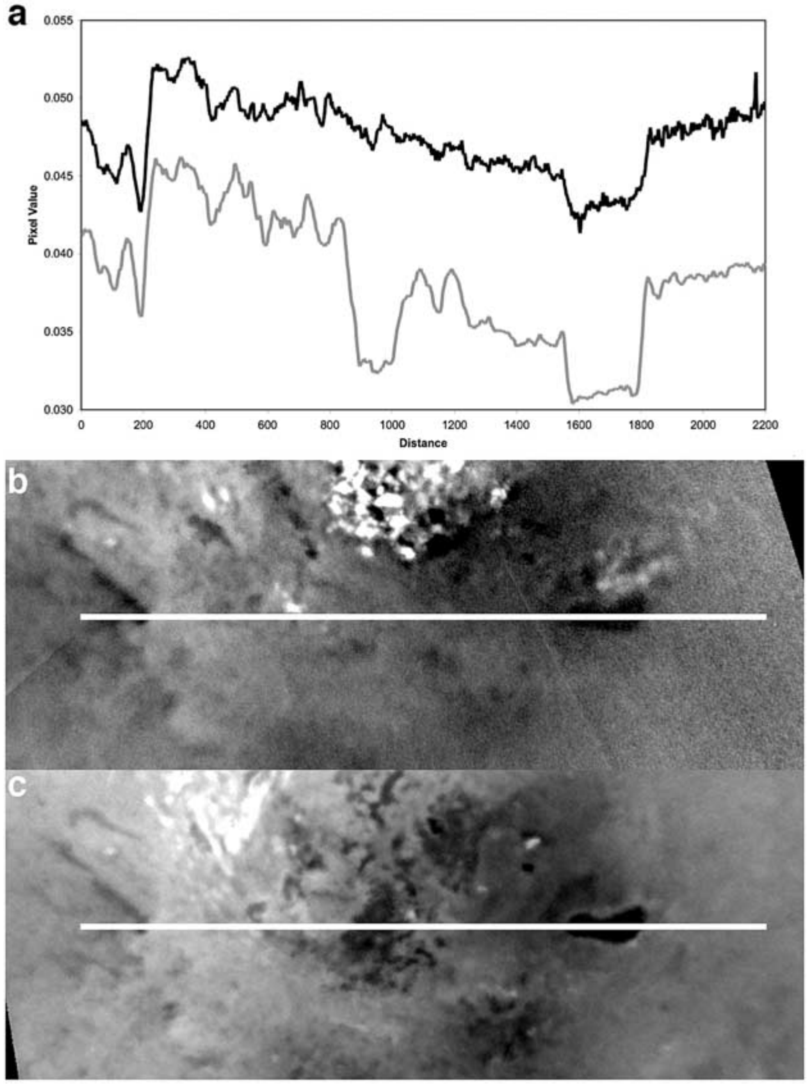

Figure 3. (a) Pixel values as a function of distance across the south-polar region, illustrating changes on the surface between the (b) 2004 (black curve) and (c) 2005 (grey curve) observations. Although the absolute values differ, the general trends and relative offsets over the first 200 km and over Ontario Lacus (between 1600 and 1800 km) match reasonably well, with the exception of the region between ~800 and 1050 km, where the surface is significantly darker in the later observation (cf. Figure 2).

only a relatively small fraction of the liquid reservoirs required to replenish atmospheric methane over geologic timescales currently appears to exist on the surface.

3. Atmospheric Observations and Implications

[11] Monitoring by ISS also provides information on Titan's meteorology and changes therein as the seasons progress from southern summer to fall. Figure 4 shows the geographic and temporal distribution of clouds observed by ISS to date (details provided in Table S2). During 2004, substantial systems of apparently convective clouds were common near Titan's South Pole (>85°S) [*Porco et al.*, 2005; *Schaller et al.*, 2006a, 2006b]. In general, clouds evolve rapidly over a few hours and dissipate over time-scales of hours to days [*Porco et al.*, 2005; *Griffith et al.*, 2005]. Since 2005, ISS has not detected south-polar clouds,

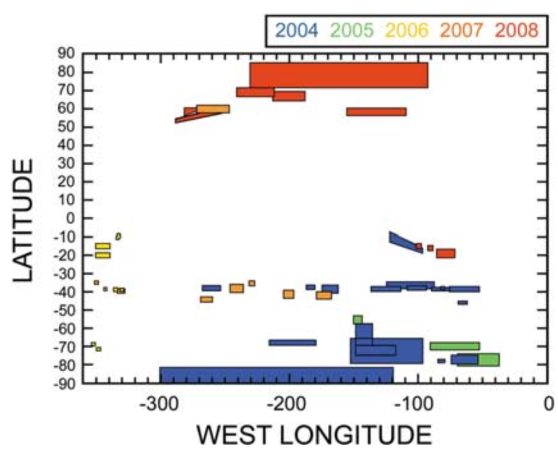

Figure 4. Locations of all clouds observed by ISS from April 2004 through June 2008 (Table S2).

possibly related to the need to recharge atmospheric methane after storms or to seasonal changes [*Schaller et al.*, 2006b]. In 2006–2007, ISS observed clouds as far north as 9°S. Clouds have been especially common at ~35–40°S, although distributed widely enough in longitude to suggest that their formation is not tied to specific surface features. In contrast to the south-polar cloud systems, at lower latitudes elongate streaks or small (~10 km) isolated clouds are observed. Streaks have recently become common in the northern hemisphere, where pairs of parallel clouds up to ~1000 km long have been observed several times at ~60°N and single streaks have been seen up to 80°N.

[12] The latitudinal distributions of lakes and clouds have implications for Titan's meteorology. General circulation models of Titan's atmosphere differ in dimensionality, dynamics, and the incorporation of interactive physics of aerosols, clouds, and moist convection. These variations lead to different surface energy budgets, latitudinal surface-temperature profiles, and tropospheric circulation patterns, some producing a single overturning cell with rising motion at the summer pole and others a more terrestrial three-cell circulation. Preferred cloudiness at 35–40°S and 70–90°S suggests low-level convergence and rising at, or equatorward, of these latitudes and, thus, multiple-cell circulation. This behavior only occurs in models with moist physics [*Mitchell et al.*, 2006; *Rannou et al.*, 2006], suggesting that phase changes have a first-order effect on the atmospheric dynamics. Although low relative humidity (50%) was measured at the Huygens landing site [*Niemann et al.*, 2005], we might expect higher humidity in the higher-latitude summer convergence zones and lower humidity in the descending branches of the circulation, especially at the winter pole. A model [*Mitri et al.*, 2007] using the Huygens methane value considers a low-latitude surface energy balance in which upward latent heat flux balances downward sensible heat flux, with net radiation playing a minor role. If methane convergence occurs near the summer pole, higher polar relative humidity might reduce evaporation and surface cooling, creating a surface energy balance in which the net radiation is balanced primarily by evaporative flux over lakes and upward sensible heat flux elsewhere. Greater evaporation would occur into the drier subsiding atmosphere at the winter pole, in which case the more extensive north-polar lakes and seas would not be a consequence of seasonal circulation but of differing geologic properties at the two poles. Given the apparent central role of methane condensation, different methane supplies at the two poles might lead to different circulation strengths at each solstice and a significant annual cycle in global atmospheric methane concentration.

[13] The evidence for past precipitation at the Huygens landing site [*Tomasko et al.*, 2005; *Soderblom et al.*, 2007a] suggests that upwelling and convection occur there at least occasionally. It will, therefore, be of interest to observe whether convective clouds proliferate at lower latitudes as Titan enters northern spring and the upward branch of the tropical Hadley circulation shifts northward across the equator [*Mitchell et al.*, 2006], or whether clouds are suppressed by the absence of sedimenting nucleating aerosol particles there [*Rannou et al.*, 2006]. Furthermore, the changes we report at the South Pole during its summer season imply that as the insolation peak shifts to high northern latitudes (ca. 2015–2018), large-scale convective cloud systems should become more common in the north-polar region and the area covered by dark surface deposits of liquid methane and ethane could increase.

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