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Seasonal Evolution in the Behavior of Titan's Clouds from *Cassini* ISS, 2004–2017

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Abstract

Cassini's Imaging Science Subsystem (ISS) has documented the changes in cloud distributions, morphologies, and behavior that have accompanied Titan's changing seasons from southern summer at the time of Cassini's arrival in July 2004, through southern-autumnal/northern-vernal equinox in 2009, to early northern summer in 2017 (Fig. 1).

Early on, large convective cloud systems were common over Titan's South Pole (Fig. 1A) [*e.g.*, 1-2], and in the case of a large cloud outburst in October 2004 [1] led to substantial precipitation at Arrakis Planitia [3-4]. Such storms became less common after 2005 [*e.g.*, 5] as southern summer waned. Elongated streaks of clouds (Fig. 1B), sometimes extending over several hundred kilometers and in which convective behavior has been documented [6], were observed consistently at mid-southern latitudes (~40-50° S) from early in the mission until late 2012, well after the southern autumnal equinox. Isolated clouds have also been observed at lower southern latitudes (Fig. 1C).

Starting in 2007 as the sun rose in Titan's north, clouds began to appear at northern latitudes >55◦ N (Fig. 1D). Such clouds were relatively common until the equinox when northern cloud activity dropped off precipitously.

In September 2010, about a year after the equinox, a large outburst was seen, this time at low southern latitudes (Fig. 1E-F). The large arrow-shaped cloud [9] was followed by extensive surface changes due to precipitation across Concordia and Hetpet Regiones, Yalaing Terra, and Adiri [7-8]. After this storm, cloud activity became very rare, with only a few isolated clouds observed at mid-southern and mid-northern latitudes for ~5 years (Fig. 1), suggesting that methane was removed from the atmosphere and the lapse rate stabilized, similar to the drop in activity following the 2004 south-polar storm [5, 10].

As northern summer approaches, the expectation based on atmospheric circulation models [*e.g.*, 11-14] is that storm activity will pick up at Titan's high northern latitudes, as was observed at high southern latitudes upon *Cassini's* arrival. Activity finally began to pick up in 2016, and clouds became common at around 55°N and near Titan's north pole in 2016 (Fig. 1G). However, north-polar storms have yet to appear. Observations of Titan's high northern latitudes by ISS and the Visual and Infrared Mapping Spectrometer (VIMS) during *Cassini's* T120 and T121 flybys in June and July 2016, appeared to show clouds at the longer wavelengths, while surface features were detected at the shorter wavelength (938 nm) of the ISS images. The apparent discrepancy appears to be the result of 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 [15].

We will present observations of Titan's cloud behavior over the course of the *Cassini* mission, documenting changes over the past 13 years, comparisons to other observations [*e.g.*, 16, 17] and models, and implications for Titan's atmospheric circulation. Of particular interest are long-anticipated changes in activity at high northern latitudes and corresponding changes on the surface or in the shorelines of lakes and seas, as the northern solstice approaches.

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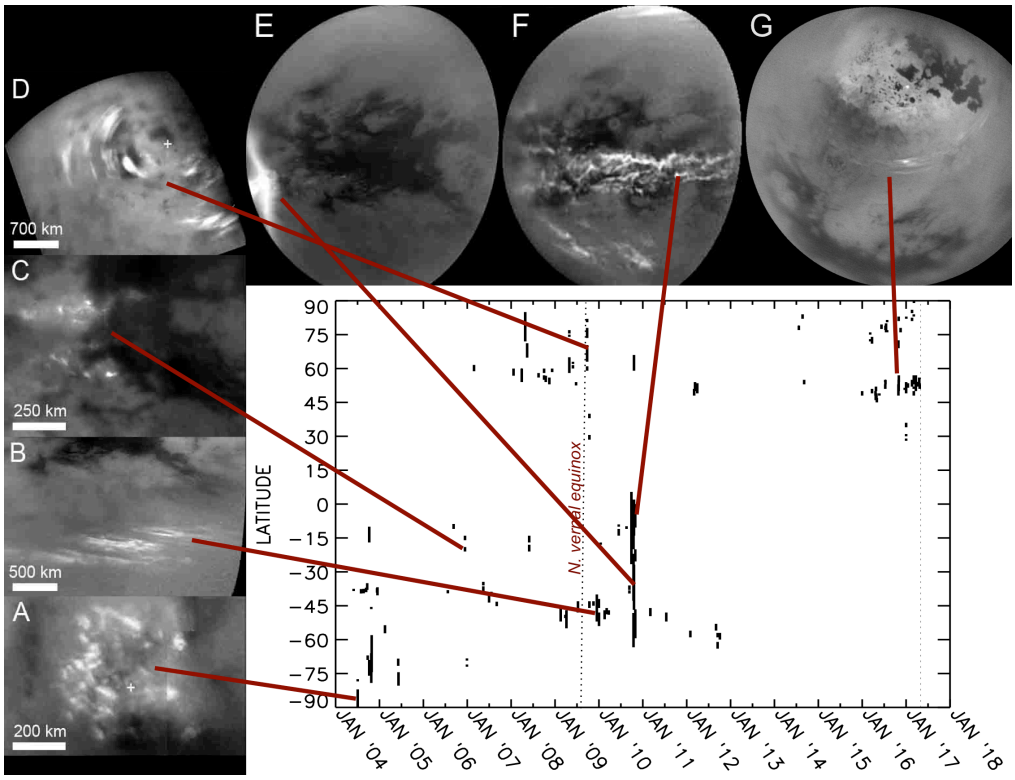

Figure 1: ISS images of different types of clouds (A-G) and graph showing observed cloud latitude over time.