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SIX YEARS OF CONTINUOUS OBSERVATION OF TITAN CLOUD ACTIVITY WITH CASSINI/VIMS

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Abstract. Since Saturn orbital insertion in July 2004, the Cassini orbiter has been observing Titan throughout most of the northern winter season (October 2002August 2009) and the beginning of spring, allowing a detailed monitoring of Titans cloud coverage at high spatial resolution with close flybys on a monthly basis. This study reports on the analysis of all the near-infrared images of Titans clouds acquired by the Visual and Infrared Mapping Spectrometer (VIMS) during 67 targeted flybys of Titan between July 2004 and April 2010. The VIMS observations show numerous sporadic clouds at southern high and mid-latitudes, rare clouds in the equatorial region, and reveal a long-lived cloud cap above the north pole, ubiquitous poleward of 60^oN. These observations allow us to follow the evolution of the cloud coverage during almost a 6-year period including the equinox, and greatly help to further constrain global circulation models (GCMs). After 4 years of regular outbursts observed by Cassini between 2004 and 2008, southern polar cloud activity started declining, and completely ceased 1 year before spring equinox. The extensive cloud system over the north pole, stable between 2004 and 2008, progressively fractionated and vanished as Titan entered into northern spring. At southern mid-latitudes, clouds were continuously observed throughout the VIMS observing period, even after equinox, in a latitude band between 30^oS and 60^oS. During the whole period of observation, only a dozen clouds were observed closer to the equator, though they were slightly more frequent as equinox approached.Although the latitudinal distribution of clouds is now relatively well reproduced and understood by the GCMs, the non-homogeneous longitudinal distributions and the evolution of the cloud coverage with seasons still need investigation. If the observation of a few single clouds at the tropics and at northern mid-latitudes late in winter and at the start of spring cannot be further interpreted for the moment, the obvious shutdown of the cloud activity at Titans poles provides clear signs of the onset of the general circulation turnover that is expected to accompany the beginning of Titans northern spring. According to our GCM, the persistence of clouds at certain latitudes rather suggests a sudden shift in near future of the meteorology into the more illuminated hemisphere. Finally, the observed seasonal change in cloud activity occurred with a significant time lag that is not predicted by our model. This may be due to an overall methane humidity at Titans surface higher than previously expected.

Keywords: Titan, Atmosphere, Clouds, Meteorology

1 Introduction

Methane on Titan plays a role similar to that of water on Earth. Gaseous methane can condense in the form of liquids or solids at specific latitudes and altitudes and can occasionally precipitate onto the surface, feeding surface and sub-surface reservoirs of liquid methane. Because methane humidity remains low near the surface, liquid methane evaporates, thus maintaining this exotic, active meteorological cycle (Flasar, 1998; Tokano, 2001; Rannou et al., 2006). Ethane and other condensable byproducts are also thought to condense and form clouds, mostly in high latitudes regions during the winter season (Rannou et al., 2006; Griffith et al., 2006). Clouds on Titan were detected as early as 1995 through ground-based telescopic observations (Griffith et al.,

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1998) and have been regularly observed since. The regular flybys of Titan by the Cassini spacecraft provide a unique opportunity to track the cloud activity. The search for Titan clouds location and the monitoring of their long-term activity contribute to the global understanding of Titan climate and atmospheric dynamics, which are key questions to be addressed by the Cassini-Huygens mission.

Investigations from ground-based telescopes using adaptive optics facilities (allowing direct imaging) gathered the first statistical constraints on the location and lifetime of Titan clouds, revealing in particular the variability and periodicity of outbursts of the large South Polar clouds (Brown et al., 2002; Bouchez and Brown, 2005; Schaller et al., 2006a, 2006b; Hirtzig et al., 2006). Ground-based observations also reported in 2004 the first detection of a temperate-latitude cloud system occurring at 40^oS (Roe et al., 2005a, 2005b). Since its insertion into Saturn orbit in July 2004, the Cassini mission has viewed Titan clouds in unprecedented detail with, on average, a monthly close flyby of Titan. The Cassini view widely complements the ground-based observations and provides new constraints on the seasonal evolution of Titan meteorology. Several southern and other discrete clouds were observed during the first flybys by using the Cassini Imaging Science Subsystem (ISS) camera (Porco et al., 2005) and the Visual and Infrared Mapping Spectrometer (VIMS) (Griffith et al., 2005, 2006; Baines et al., 2005; Rodriguez et al., 2009, 2011; Le Mouélic et al., 2012). This latter instrument acquires hyperspectral images in 352 contiguous spectral channels between 0.3 and 5.2 μm (Brown et al., 2003), allowing the detection of clouds not only from their morphologies in simple imagery but also from their spectral behavior. Here, we present the first comprehensive mapping of Titan clouds detected in the full VIMS dataset between the Cassini insertion in July 2004 and April 2010 (i.e., during 67 Titan flybys). .

2 Semi-automatic detection of Titan clouds within VIMS spectro-images

The atmosphere of Titan is opaque at infrared wavelengths, except for seven narrow spectral windows where methane absorption is the weakest (at λ = 0.93, 1.08, 1.27, 1.59, 2.03, 2.75 and 5 μm). Because clouds are efficient reflectors in the near-infrared and substantially reduce the path-length of solar photons in Titan atmosphere, their spectra present a brightening in all spectral windows with particularly bright windows at 2.75 and 5 μm. Wed found that the most robust automated detection criterion to separate pixels that contain cloudy spectral component from any other components is to use the simultaneous brightening of the 2.75 and 5 μm windows (Rodriguez et al., 2009, 2011). Taking a single window or a combination of two other windows leads systematically to false positive detections. We produce, for each VIMS datacube, histogram distributions for the 2.75 and 5 μm windows areas. Two-sigma conservative thresholds on the two areas distributions are automatically calculated in order to only select these cloudy pixels. The reliability of the thresholds is controlled and finely tuned up using the 2.1 μm VIMS channel image as a reference, which is sensitive to tropospheric clouds.

3 Global view of the 2004−2010 cloud coverage of Titan

Figure 1 presents the integrated fractional cloud coverage we observe with VIMS between July 2004 and April 2010. On a global scale, we found that Titans cloud coverage is very low relative to terrestrial standards, with a very patchy cloud coverage. Averaged over the period interval between July 2004 and April 2010, the cloud coverage only represents 10% of Titans entire globe. In comparison, the instantaneous cloud coverage on Earth is seven times greater (75%) on average. Between northern winter and the beginning of spring (the 2004–2010 period), Titan clouds have mostly occurred in three areas which are well delineated in latitude: (1) the north polar region, (2) the temperate southern latitudes, and (3) the south pole. Other regions are almost completely free of clouds, except for very sporadic tropical outbursts and two small clouds at northern mid-latitudes (40^oN).

The northern polar region of Titan is systematically blanketed by an ever-present thin cloud system from the first Cassini observations in mid-2004 until early 2008. As Titans north pole progressively emerges from the night, this large, stratiform cloud system is found to cover the polar region at all longitudes and from 60^oN latitude up to the pole (Griffith et al., 2006; Rodriguez et al., 2009, 2011; Le Mouélic et al., 2012). Poleward of 60^oN the fraction of cloud coverage, averaged over the 2004–2010 period, is greater than 70%. Its total surface coverage however has slightly diminished with time. Very stable between 2004 and 2006, with an overall fractional coverage greater than 80%, this large cloud started slowly recessing since mid-2006. After mid-2008, the north polar cloud began to fractionate and collapse at some places, leaving a cloud ring centered at 60^oN with only small, but more opaque and convective-type cloud patches in its central region. Later on, as Titan passed the spring equinox in August 2009, all that had remained from the large north cloud cap, including the thin 60^{o}N cloud ring, finally disappeared, leaving the north pole free of cloud, apart from small and sporadic clouds, likely to be convective in nature.

Large clouds are also clearly visible at the south pole since the early VIMS observations of Titan in 2004. Cloud events at Titans south pole have been previously reported from Earth-based observation campaigns since December 2001. From telescopic observations, these clouds appeared to be tropospheric large scale stormy outbursts with variability timescales (related to their changes in size and/or height) of a few hours . These storms have sustained their activity almost continuously until November 2004, from which time they were also observed by Cassini. Contrary to what was previously thought from Earth-based imaging, south polar clouds have still retained a substantial activity after this date. They were indeed constantly detected by VIMS after November 2004 up to December 2005, during almost all Cassini flybys of Titan. Nevertheless these events were dimmer and less spatially extended than those seen since 2002, possibly preventing Earth-based telescopes from resolving them. After December 2005, the cloud activity at the south pole began to decline. For the first time since 2001, no clouds near the south pole were observed for 8 months, between January and September 2006. Large outbursts were then regularly detected again for almost a year. Except for some rare and small scale events in 2008, the south pole of Titan ceased all stormy activity starting from the last dissipation in mid-2007, 2 years before the northern spring equinox . This decline is illustrated by the gradual decrease of the mean fractional coverage in clouds poleward of 60^{o}S between 2004–2006 (15%) and 2009–2010 (down to 0%) periods.

Southern mid-latitude clouds were observed by Cassini on a regular basis between July 2004 and April 2010. Indeed, recent VIMS observations show that southern midlatitudes (regions of Titan between 30^{o}S and 60^{o}S) showed a relatively stable fractional coverage in clouds of 10% during the entire 20042010 time interval, reaching a peak mean fractional coverage of 15% between July 2009 and April 2010. These clouds were thus still present, and quite active, at the time of the northern spring equinox (August 2009), and do not seem to display any sign of decline after that date thus far. Southern mid-latitude clouds are generally found to be elongated in the eastwest direction, likely stretched by zonal wind shear at the altitude where they form.

After December 2006, we identify some clouds further north in Titans tropics, equatorward of 30^o latitudes. Most of them are found in the southern hemisphere. However, contrary to what we observed in the high- to mid-latitude regions of the southern hemisphere, these near-equatorial clouds were in general much smaller and significantly more scarce, appearing in less than 5% of the 67 Cassini flybys between July 2004 and April 2010. Equatorial clouds appear with a slightly higher frequency after February 2008, during the approach of equinox.

Finally, we also observe the first, consecutive appearances of two small elongated clouds at northern mid-latitudes (flybys T62 and T63). These unique clouds have an elongated morphology similar to the 40^{o}S clouds, and are not connected to the north polar cloud. They first appeared in late 2009, right after the northern spring equinox, and were observed while 40^{o}S clouds were still active.

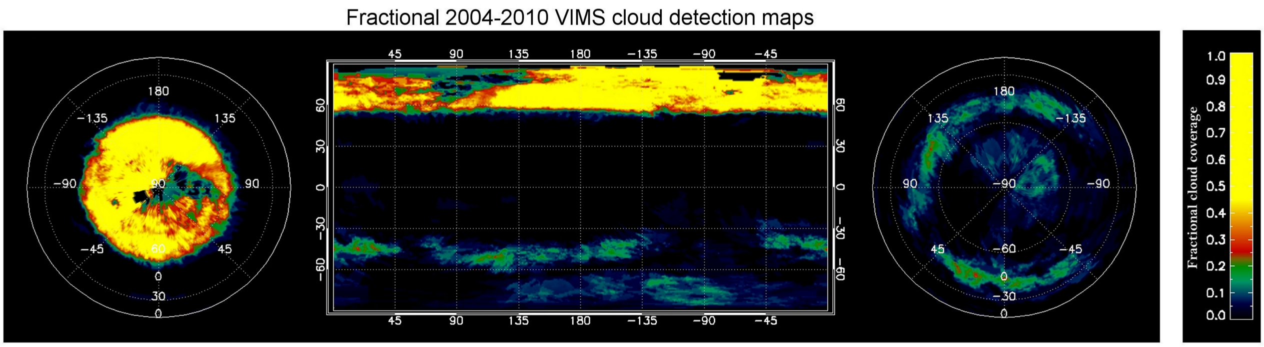

Fig. 1. Fractional cloud coverage in the 2004–2010 period. The mapping projection is rectangular with grid marks every 45^o of longitude and 30^o of latitude (0^o longitude is on the left). Longitude is in degrees east. For the northern (left) and southern (right) polar projections, grid marks are also shown every 45^o of longitude and 30^o of latitude (0^o longitude is down).The resolution of the projection maps are of 0.3^o in longitude and latitude (i.e.14 km per pixel at the equator).The color scale saturates at 0.45 to enhance the southern cloud distribution and equatorial transient events. The fractional coverage in clouds of the north polar region exceeds 0.7 almost everywhere poleward of 60^{o}N. The clouds of Titan mainly cluster at three distinct latitudes during the course of southern summer and at the beginning of southern fall: poleward of 60^{o}N, poleward of 60^{o}S and at 40^{o}S.

4 Discussion and conclusion

The persistence, location, and periodicity of the clouds were compared with the forecast of the global circulation models (GCMs) (Rannou et al., 2006; Mitchell et al., 2006, 2009). These new constraints, along with ground-based observations, can contribute to the refinements of GCMs predictions and to a better understanding of Titans climate. Between 2004 and 2008 (i.e., late northern winter), we show that Titans meteorology was very stable: (1) a widespread and long-lived cloud capped the entire northern polar vortex region, poleward of 60^oN; apart from the polar cloud, the northern hemisphere (winter hemisphere) was entirely cloud-free and (2) sporadic clouds were regularly seen at mid-latitudes and above the pole in the southern hemisphere (summer hemisphere). Our observations support the interpretation that the winter (northern) polar cloud is caused by the sinking and cooling of stratospheric air into the colder troposphere and the preferential condensation of droplets of ethane, and that the summer (southern) stormy clouds are more likely convective in nature and mainly composed of methane droplets. The latitudinal clustering of the clouds and the hemispheric asymmetry of their physical and chemical properties are both satisfactorily predicted by the GCMs.

After mid-2008, we observed the first strong evidence of a global decline of Titans cloud activity. At the end of 2008, the clouds at the south pole disappeared. At the same time, the northern polar cloud began to show clear signs of fragmenting, finally to completely vanish after the equinox as predicted by the IPSL-TGCM (Rannou et al., 2006). We also detected a dozen cloud outbursts at the tropics, which seemed to be more frequent as equinox approaches. All these observations show that we are likely witnessing the onset of the seasonal pole-to-pole circulation turnover on Titan. The meteorology is then expected to completely reverse from one hemisphere to another in the next five or six terrestrial years, as predicted by the models. The persistence of southern mid-latitude clouds at 40^oS through mid-2010, and the occurrence, a few months before and after the equinox, of more frequent equatorial clouds along with first appearance of northern mid-latitude clouds seem to suggest rather an abrupt hemispherical reversal of cloud activity, even if these equatorial and northern mid-latitude events are still too rare to be fully significant. The Cassini Solstice Mission will observe Titan up to the beginning of northern summer, in 2017, and should help to definitively solve the question of the meteorological hemispheric reversal, and the question of the type of atmospheric circulation (symmetric or asymmetric).

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