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MAPPING THE CLOUDS OF TITAN OVER 3.5 YEARS WITH VIMS/CASSINI: IMPLICATIONS FOR TITAN CLIMATOLOGY

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Abstract. The N_2-rich atmosphere of Saturns largest moon Titan contains a few percent of methane (CH_4) (Kuiper 1944) which dissociates to produce a plethora of organic compounds, the most abundant of which is ethane (C_2H_6) (Yung et al. 1984; Toublanc et al. 1995). Methane and ethane are involved in a cycle similar to the terrestrial hydrological cycle, including clouds, rain, surface or sub-surface liquids and evaporation (Flasar 1998; Tokano 2001; Rannou et al. 2006). Clouds are visible consequences of meteorological activity on Titan. The Cassini spacecraft, in orbit in the Saturnian system since July 2004, has provided an unprecedented view of Titans clouds. We present here the first comprehensive map of cloud events, detected from the Visual and Infrared Mapping Spectrometer onboard the Cassini spacecraft. We detect more than one hundred and fifty cloud events between July 2004 and December 2007. Three categories of clouds have been identified: 1) bursts of clouds at the south pole, 2) a long lived widespread cloud system at the north pole, and 3) transient temperate clouds centered around 40°S which may display longitudinal variations. These observations are consistent with control of the cloud spatial distribution dominated by the global atmospheric circulation, possibly combined with some geographic forcing (gravity waves imposed by Saturns tides and local surface sources of methane), mostly observable at temperate latitudes. Global circulation models (GCM) predict dramatic changes in the cloud activity as Titans equinox approaches (2009). Such long-term variations should be observed during the extension of the Cassini mission.

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. 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 Titans clouds location and the monitoring of their

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long-term activity contribute to the global understanding of Titans climate and meteorological cycle, 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 Titans clouds, revealing in particular the variability and periodicity of outbursts of the large South Polar clouds (Brown et al. 2002; Bouchez & 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 Saturns orbit in July 2004, the Cassini mission has viewed Titans 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 Titans meteorology. Several southern and other discrete clouds were observed during the first flybys by using the Cassinis Imaging Science Subsystem (ISS) camera (Porco et al. 2005) and the Visual and Infrared Mapping Spectrometer (VIMS) (Griffith et al. 2005, 2006; Baines 2005). 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 Titans clouds detected in the full VIMS dataset between the Cassini insertion in July 2004 and December 2007 (i.e. during 39 Titans flybys).

2 Titan's clouds detection with VIMS: Methods and results

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 Titans atmosphere, their spectra present a broadening of all spectral windows with particularly broad and bright windows at 2.75 and 5 μm. We 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 widening of the 2.75 and 5 μm windows. 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 with the help of reference images. Note that, if the deliberate choice of a conservative threshold allow us to avoid false positive and assure us that each detection is real, it can lead to the non-detection of optically thin or very low clouds, of clouds that are much smaller than a VIMS pixel, or clouds that are too close to the limb. This can also lead to the warping of the shape of some clouds, as the clouds edges are the most delicate part to detect.

Between July 2004 (flyby T0) and December 2007 (T38), VIMS acquired more than 10,000 images of Titan. By eliminating redundant, night side, limb viewing, very low time exposure and also very small images, we reduced the dataset down to 1,600 images useful for the purpose of cloud detection. This still represents several millions of spectra, which prohibits the effective use of a manual detection technique. We therefore developed a semi-automated algorithm to detect clouds in VIMS images, using mainly the simultaneous broadening of the 2.75-μm and 5-μm windows. Clouds show up at three distinct latitudes: the south polar region (poleward of 60^oS), the north polar region (poleward of 50^oN), and a narrow belt centered at 40^oS.

Our observations show that the southern pole wide cloud system faded at the beginning of 2005. Ten months later (October 2005), a cloud event appeared. This second outburst, (also reported by Schaller et al. (2006a)), lasts less than two months, significantly shorter than previous south pole events. A large cloud reappears again at the south pole nine months later in September 2006, and some clouds sporadically burst equatorward of 60^oS in continually smaller and more transient patches in October 2006, January 2007, and April 2007. June 2007 marks the reappearance of another huge, but very brief (less than one month), south pole cloud burst, almost exactly nine months after the last occurrence in September 2006. Thus, over three and a half years of VIMS observations, the south polar cloud appears quasi-periodically with a period of 8 to 9 months. However, these periodic bursts appear more erratic and less intense as Titan equinox approaches and the maximum solar illumination progressively shifts towards northern latitudes.

This study clearly shows the predicted stability of the north polar cloud (Griffith et al. 2006; Le Mouélic et al. 2008) as we have systematically detected it over the 2004-2007 period. We generally observe this extensive meteorological event poleward of 50-60^{o}N. All of these clouds are spectrally different from the southern clouds (presumably made of liquid/solid methane), because they show up in our detection algorithm with significantly less signal at 5 μm than any other cloudy features. This indicates lower backscattering at 5 μm and is consistent with clouds composed of micron sized particles made of solid ethane intimately mixed with aerosols, within the north polar haze cap (Rannou et al. 2006; Griffith et al. 2006).

We also detect numerous isolated and transient tropical clouds between 55^{o}S and 30^{o}S (more than one hundred). A few small clouds, whose areas never exceed 4000 km2 and therefore are undetectable in ground-based observations, are also observed closer to the equator (up to 15^{o}S). The density distribution in latitudes of all temperate clouds peaks at 40^{o}S latitude, within a narrow 25^o wide latitude band. Most of these clouds are elongated in the east-west direction, as it was previously observed (Roe et al. 2005a, 2005b; Griffith et al. 2005; Baines et al. 2005), due to strong zonal winds of tens of meter per second (Porco et al. 2005). They do not appear uniformly distributed around Titan, confirming with a better statistic previous ground-based observations (Roe et al. 2005b). Our longitudinal distribution peaks every 90^o at 30^{o}E, 120^{o}E, -150^{o}E and -60^{o}E, shifted 30^o towards the east from the sub-Saturn, trailing, anti-Saturn and leading points respectively. The peak in the direction of Saturn is two times larger than the others. The 90^o periodicity strongly suggests that the longitudinal distribution of tropical clouds may be connected to tidal forcing caused by the strong tides Titan experiences during its elliptic orbit around Saturn. The non-uniformity of the distribution may also partly be due to localized geological processes as suggested by Roe et al. (2005b). The temperate clouds appeared during two time periods, in 2004 and between August 2006 and August 2007. Except in October 2005 (Schaller et al. 2006b) and January 2006 (this work), we did not observe any temperate clouds for a long period between December 2004 and August 2006, perhaps due to the combination of less frequent Titans flybys by Cassini (one flyby every two months on average during this period against two per month on average after) and a momentary decline in cloud activity. The 40^{o}S clouds reappeared after this quiet phase until mid-2007 but their activity tended to progressively decrease during late 2007.

3 Comparison with the Global Circulation Model (GCM) from Rannou et al. (2006)

The cloud layer as monitored by VIMS shows that significant atmospheric changes occurred during the observing time period. Since clouds trace the atmospheric circulation, these changes give new insight into Titan's global wind pattern and its seasonal evolution, just before equinox. Most of the clouds reported here can be understood in the framework of the global atmospheric circulation triggered by seasonal solar insolation variations. Titan's global circulation in the troposphere and lower stratosphere is characterized by a Hadley-type cell with an ascending branch at mid-latitude (30-40^o) in the summer hemisphere, and two descending branches near $\pm 60^o$ (Tokano 2001; Rannou et al. 2006). Models also predict small slant cells near the poles, and especially the summer pole, triggered by the temperature contrast in the polar region (Rannou et al. 2006). In the upper stratosphere and the mesosphere, the circulation is dominated by a large thermally direct cell similar to the Brewer-Dobson circulation on Earth. Before the forthcoming northern spring equinox in 2009, this circulation has an ascending branch in the southern hemisphere and a descending branch in the north polar region. According to Titan's Global Circulation Model (GCM)(Rannou et al. 2006; Mitchell et al. 2006), ascending motions of methane-rich air in the troposphere result in the formation of methane clouds, owing to adiabatic cooling. Clouds are then predicted in the convergence zone of the troposphere circulation, at 40^o in the summer hemisphere, and near 12 km altitude, which represents an analog of the cloud belt in the inter-tropical convergence zone on Earth and on Mars. Clouds are also predicted very near the summer pole, in the troposphere, where methane, driven from warmer region, condenses and can generate convective structures (Rannou et al. 2006; Hueso & Sanchez-Lavega, 2006; Barth & Rafkin, 2007). The downwelling stratospheric circulation, in the northern (winter) region, drives an ethane and aerosol enriched stratospheric air into the cold tropopause of the polar night (above 40 km) which lead to the formation of clouds identified as ethane clouds (Griffith et al. 2006). The three classes of clouds reported in this work are observed at the latitudes predicted by the GCM. The observed stability of the north polar clouds is interpreted, with GCM, as the result of a constant incoming flux of ethane and aerosols from the stratosphere, producing a mist of ethane (and probably other products) droplets of few micrometers which slowly settles down. On the other hand, the summer hemisphere clouds timing predicted by GCM weakly reproduces our observations. The GCM (Rannou et al. 2006) and mesoscale models (Hueso & Sanchez-Lavega, 2006; Barth & Rafkin, 2007) show that summer hemisphere clouds produced by wet methane convection should be sporadic by nature (with lifetimes of several hours to few days due to sedimentation, rainfall and dissipation). This variability is readily observed in our data. Yet, predictions show that the southern cloud activity should progressively decrease as the equinox approaches, which is a consequence of a change in the south polar circulation pattern. Although the GCM prediction only gives a statistically averaged view of the cloud activity, this southern declining meteorological activity is not observable in our data. According to the GCM, the south polar clouds should have disappeared in mid-2005 and the mid-latitudes clouds should have progressively fade out since 2005. The global trend of the evolution of the southern clouds activity that we observe with VIMS is qualitatively different: the southern clouds are still observable even late in 2007 and are particularly active at 40^oS since mid-2007. This may indicate that methane is resupplied and clouds can form in Titans low atmosphere in a more efficient way than GCM can predict, especially at temperate latitudes, probably because GCM do not take into account of gravity waves and/or cryovolcanism. In late 2007, polar clouds occurrences seem to be less frequent in our data and the mid-latitude clouds are scarcer and tend to disappear. These slight declining trends in southern cloud activity may indicate that we are probably witnessing the forthcoming seasonal circulation turnover as we approach the equinox, but with a different timing pattern than forecasted by the GCM. The timing of cloudy events monitored by VIMS just before the circulation turnover strongly depends on the underlying atmospheric processes. This makes a new constraint for climate models to understand the details of cloud formation on Titan.

4 Perspectives

In the coming decade, we expect that the complete reversal in the general circulation of Titans atmosphere will be probed through the long-term joint monitoring by Cassini and ground-based facilities with observations of positions, altitudes and morphologies of Titans clouds. Furthermore, the cloud locations may give useful hints about the distribution of possible surface methane reservoirs. For instance, an asymmetry in the climatology of the cloud layer may explain the observed north/south asymmetry in the distribution of clouds, lakes and seas. In the near future, it will be of prime importance to carry on comparing close flyby observations, as those presented in this report, with ground-based data to avoid a misinterpretation about Titans cloud distribution. Relating space-based and Earth-based views, using the longest time interval possible, is compulsory to prepare for the development and interpretation of Titan post-Cassini nominal mission observations.

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