Icarus 243 (2014) 129–138

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Subsidence-induced methane clouds in Titan's winter polar stratosphere and upper troposphere

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ARTICLE INFO

Article history:
Received 30 July 2013
Revised 4 September 2014
Accepted 4 September 2014
Available online 16 September 2014

Keywords:
Titan, clouds
Atmosphere
Radiative transfer
Ices, IR spectroscopy

ABSTRACT

Titan's atmospheric methane most likely originates from lakes at the surface and subsurface reservoirs. Accordingly, it has been commonly assumed that Titan's tropopause region, where the vertical temperature profile is a minimum, acts as a cold trap for convecting methane, leading to the expectation that the formation of methane clouds in Titan's stratosphere would be rare. The additional assumption that Titan's tropopause temperatures are independent of latitude is also required. However, Cassini Composite InfraRed Spectrometer (CIRS) and Radio Science Subsystem (RSS) data sets reveal colder temperatures in Titan's tropopause region near the winter pole than those at low latitudes and in the summer hemisphere. This, combined with the presence of a cross-equatorial meridional circulation with winter polar subsidence, as suggested by current general circulation models, implies the inevitable formation of Subsidence-Induced Methane Clouds (SIMCs) over Titan's winter pole. We verified this by retrieving the stratospheric methane mole fraction at 70°N from the strength of the far infrared methane pure rotation lines observed by CIRS and by assuming the RSS-derived thermal profile at 74.1°N. Our retrieved methane mole fraction of $1.50 \pm 0.15\%$ allows for methane to condense and form SIMCs at altitudes between ~48 and ~20 km. Radiative transfer analyses of a color composite image obtained by the Cassini Visible and Infrared Mapping Spectrometer (VIMS) during northern winter appear to corroborate the existence of these clouds.

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1. Introduction

There are two distinct types of cloud systems in Titan's atmosphere. The first and more familiar type consists of convective methane clouds produced in the troposphere. As with water on Earth, methane has a source at Titan's surface, and therefore the methane cycle on Titan has been presumed akin to that of Earth's convective water cycle in which phase changes are confined to the troposphere. During southern summer on Titan, the surface is heated at mid to high southern latitudes, which drives turbulent upwelling (convection). This results in the formation of methane cloud particles that grow large quickly and then fall out of the atmosphere on time scales from hours to days (see for example Griffith et al., 2005). Starting in early southern summer on Titan, ground-based images revealed convective methane clouds located predominantly poleward of 70°S (e.g. Roe et al., 2002). As southern summer progressed, with the arrival of the Cassini Spacecraft in the Saturn system, clouds at mid and low southern latitudes became observable (e.g. Porco et al., 2005). As Titan moved into late northern winter, and then into early northern spring, the high southern latitude clouds essentially vanished (Rodriguez et al., 2011), the mid southern latitude clouds endured, and equatorial, and then mid and high northern latitude convective clouds began to emerge (e.g. Turtle et al., 2011). Thus, Titan's convective methane cloud systems tend to follow the Sun as it migrates with season.

The second type of cloud system is the direct result of Titan's overall atmospheric circulation pattern. Because Titan is a slow rotator, latitudinal heat and momentum transport is accomplished mainly through slow, axially symmetric meridional circulation (Leovy and Pollack, 1973; Flasar et al., 1981). General circulation models (GCMs) that do not include such processes as moist convection, for example, predict only a single cell during northern winter. Circulation is from north to south near the surface, and from south to north in the stratosphere and mesosphere, with upwelling at mid to high southern latitudes and subsidence at mid to high northern latitudes (e.g. Lebonnois et al., 2012, and references therein). This slow, axisymmetric meridional circulation

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http://dx.doi.org/10.1016/j.icarus.2014.09.007
0019-1035/Published by Elsevier Inc.

is responsible for cloud formation in the mid to lower stratosphere. Most organic vapors are produced in Titan's mesosphere and above, and are abundant enough to partially condense as they are transported downward to cooler temperatures, forming Titan's second type of cloud system — subsidence-induced clouds in the winter polar stratosphere. These clouds are relatively stable, long-lived, and tend to have particles with effective radii between 1 and 5 μm. Observed examples include those of condensed dicyanoacetylene (C_4N_2: Khanna et al., 1987; Samuelson et al., 1997a), cyanoacetylene (HC_3N: Anderson et al., 2010), hydrogen cyanide (HCN: Samuelson et al., 2007), blended HCN and HC_3N (Anderson and Samuelson, 2011), and ethane (C_2H_6: Mayo and Samuelson, 2005; Griffith et al., 2006; Anderson and Samuelson, 2011).

Of the various volatile gases, methane vapor provides the major exception. Its source is at the surface, and Titan's meridional circulation pattern by itself will not give rise to methane condensation in the stratosphere as long as tropopause temperatures are roughly constant with latitude. Indeed, both Flasar et al. (1981) and Samuelson et al. (1997b) analyzed Voyager 1 InfraRed Interferometer Spectrometer (IRIS) data and found little tropopause temperature variation between latitudes ±60°. However, Cassini's Composite InfraRed Spectrometer (CIRS) and Radio Science Subsystem (RSS) instruments enable us to determine tropopause temperatures at much higher latitudes (for retrieval procedures see Anderson and Samuelson, 2011; Schinder et al., 2011, 2012). In particular, both instruments indicate tropopause temperatures several kelvins cooler at very high northern latitudes compared with those at lower latitudes, including the 70.43 ± 0.25 K measured value at 10°S by the Huygens Atmospheric Structure Instrument (HASI; Fulchignoni et al., 2005). As we show in the following sections, cooler tropopause temperatures, when coupled with the expected axisymmetric circulation pattern, lead to the formation of Subsidence-Induced Methane Clouds (hereafter SIMCs) in Titan's north polar stratosphere and upper troposphere. We demonstrate that for latitudes poleward of ~65°N, methane ice can, and in fact probably does, comprise much of Titan's northern winter polar cloud discovered by Cassini's Visible and Infrared Mapping Spectrometer (VIMS; Griffith et al., 2006). We discuss the physical processes involved in the formation of SIMCs in Section 2, followed by a determination of the stratospheric CH_4 mole fraction at 70°N in Section 3. We infer temperatures surrounding the tropopause from CIRS data at 85°N in Section 4, and ramifications and results in Section 5. We then provide evidence of SIMCs from VIMS data in Section 6. A synopsis and short discussion are given in Section 7.

2. Physical rationale behind SIMCs

The presence of a long-lived condensation cloud in Titan's stratosphere depends on two requirements: (1) the given volatile must be supersaturated at the ambient temperature, and, (2) as the resulting condensate is removed from a given locale by advection or precipitation, the magnitude of the replacement flux of volatile vapor must be adequate for maintaining the cloud. This flux depends strongly on Titan's atmospheric axially symmetric meridional circulation pattern. The simplified pattern during northern winter solstice that we consider is illustrated in Fig. 1.

In the stratosphere, the downward flux component is the important one, because it transports vapor from warmer regions to colder ones, enabling condensation. The circulation scenario depicted in Fig. 1 implies that very little downward flux of vapor at low latitudes is due to meridional circulation. Any downward flux of vapor there is more likely due to eddy diffusion, which is not very effective in general. The much stronger downward flux due to subsidence is likely to occur only at high northern (winter) latitudes.

Thus vapors originating at high altitudes (this includes all the trace organics) will in all likelihood condense in the mid to lower stratosphere, preferentially at high winter latitudes. Although some condensation may take place in the stratosphere at low latitudes, the associated small downward flux component ensures

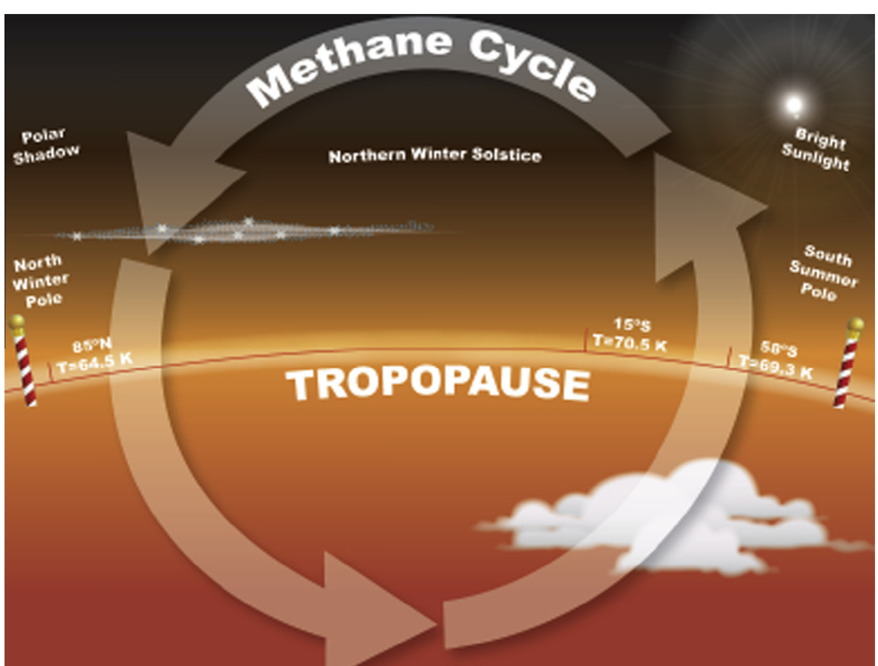

Fig. 1. Schematic illustrating Titan's meridional circulation pattern expected during northern winter. In the south, methane vapor pushes through Titan's cold trap into the stratosphere and then moves along stream lines in the stratosphere and mesosphere to high northern latitudes where subsidence occurs. CIRS and RSS show much colder tropopause temperatures at high northern latitudes, leading to methane condensation there via subsidence in the lower stratosphere and upper troposphere. Image Credit: Jay Friedlander.