
Microphysics of Titan’s methane storms

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Summary. Titan, Saturn’s largest satellite, is the only moon in the Solar System owning a significant atmosphere. The arrival of the Voyagers spacecrafts to the Saturnian system on the early 80s suggested that Titan might support a methane meteorological cycle including convective methane clouds and rain beneath the dense stratospheric haze [1]. Here we report on numerical simulations of methane cumulus clouds on Titan. We make special emphasis on the microphysics of methane droplets growing to precipitation size particles.

1 Introduction

Observations of Titan in spectral windows able to penetrate the upper dense cloud haze show the appearance of discrete cloud features on the South Polar Region over the years 1998-2005 [2]. These clouds have been interpreted as outbursts of convective activity with the formation of abundant methane cloud material [3] (see fig. 1). At the cold conditions of Titan’s atmosphere (surface temperature ~ 90 K) methane plays a role similar to water on the Earth hydrological cycle but its overall role on the dynamics of Titan’s atmosphere is far from being understood [4].

Knowledge of Titan’s atmosphere significantly grew with the first results obtained by the Cassini spacecraft [6] and the Huygens in situ exploration of the atmosphere and the surface [7].

In a previous paper [8] we presented dynamical simulations of methane cloud storms forming in the atmosphere of Titan. The model was based on a convective model originally developed to study the convective storms on Jupiter and Saturn [9], [10] while the microphysics scheme was only briefly outlined on [8]. The simulations showed that intense methane storms are possible given favorable environment conditions with large relative humidities on the order of 80-90 % and abundance of suitable condensation nuclei of $N > 1 \text{ cm}^{-3}$. In this paper we discuss relevant physical aspects to the development of methane storms as well as the microphysics scheme used in the fully 3D simulation of cumulus clouds.

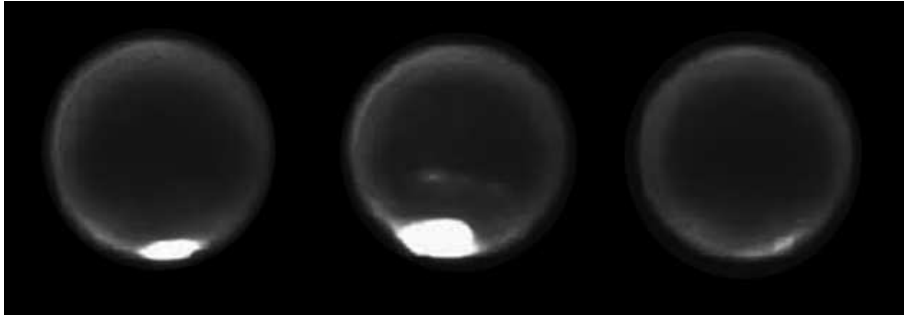


Fig. 1. Development of a large convective cloud on Titan’s south pole and its fading stage as observed using the Keck telescope [5]. The images span from September 28 2004 to 28 October 2004 and represent the largest convective system observed on Titan.

2 Microphysical model

The subject of cloud microphysics is one of the most complex in the study of atmospheric sciences. The growth of cloud particles from submicrometer size to fully developed rain with particles on the order of the cm involves several longitude scales and a variety of processes that include: Nucleation of particles, vapor diffusion, collection by differential sedimentation, fallout and breakup of drops. In the case of cold clouds where ice can be present the problem is complicated by the different type of ices and their mutual interaction along with the warm cloud particles. The success in reproducing the characteristics of rain processes on local atmospheric models requires parameterizations finely tuned after observations of cloud particle size distribution and precipitation rates.

In order to study the development of methane precipitation on Titan we will use a simple model of cloud particles growth where only gas and liquid phases are allowed and we represent the spectrum of particle sizes through a discrete and continuous bin size distribution. A competing continuous microphysical scheme relevant to the steady-state atmosphere is available in the literature [11] but it is not usable in a convective atmosphere where fast changes are taking place across the full simulation.

2.1 Condensation-evaporation

The growth or evaporation of a liquid methane particle of a given size r_i is calculated using a formulation adapted from vapor diffusion into water clouds on Earth [12]

$$\frac{dm_i}{dt} = r_i f_v \frac{4\pi}{F_K + F_D} \left(\tilde{S} - \frac{\hat{a}}{r_i} \right). \quad (1)$$

Here m_i is the mass of particles in bin i , r_i is their radius and f_v is a ventilation factor that takes into account the ventilation of the drop by airflow around it and is computed as an empirical law function of the Reynolds and Schmidt number [13]. The other terms can be calculated [12]:

$$\tilde{S} = P_v/P_{sat} - 1, \quad (2)$$

$$F_K = \frac{L^2}{k_a R_v T^2}, \quad (3)$$

$$F_D = \frac{R_v T}{D_\nu P_{sat}}, \quad (4)$$

$$\hat{a} = \frac{2\sigma}{\rho_l R_v T} \quad (5)$$

$$(6)$$

F_K is a term that incorporated the effects of latent heat release in vapour diffusion, F_D introduces the diffusivity, \tilde{S} is the supersaturation, and \hat{a} is a factor accounting for the surface tension in the liquid droplet. For sufficiently small particles a given supersaturation \tilde{S} can not produce condensation over a liquid methane droplet. This introduces the problem of nucleation, i.e., the process of creating a small cloud particle. On the Earth, cloud particles are generally nucleated around existing dust or salt particles of small size. On Titan nucleation sites are available through the particles falling from the smoggy hydrocarbon haze.

2.2 Sedimentation

A full description of sedimentation of methane droplets in Titan is available in the literature [13]. Here we give a short description of the sedimentation process. Particles precipitate under the action of gravity and atmospheric drag. The drag is computed using a drag coefficient that depends on the Reynolds number. Turbulence is not considered since the particles always fall at speeds low enough to make the flow laminar. Particles falling at large velocities are deformed by the air drag and break at a limiting diameter of 6-7 mm on Earth and 9-10 mm on Titan. Fig. 2 shows the terminal speed of particles of a variety of sizes as a function of height.

2.3 Differential-sedimentation

The number of particles of size i sedimenting at terminal speed V_i colliding with smaller size j particles in a given time interval Δt is calculated as:

$$N_C = N_i N_j \pi (r_i^2 + r_j^2) (V_i - V_j) \Delta t, \quad (7)$$

The number of particles i and j decreases by N_C and N_C particles of a larger size k of mass $m_k = m_i + m_j$.

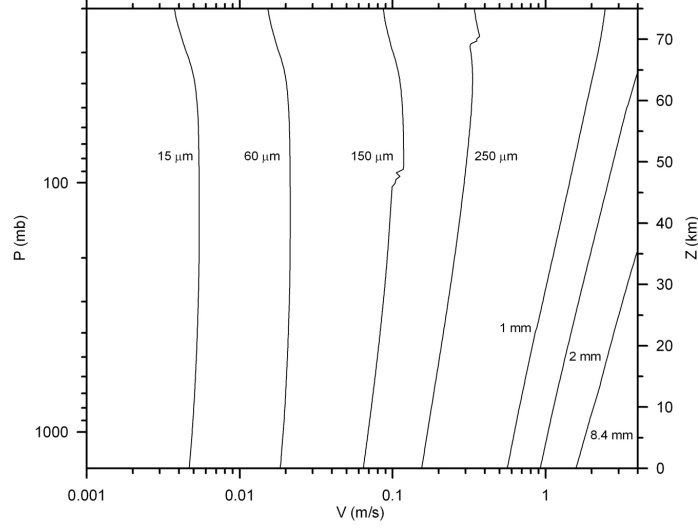


Fig. 2. Sedimentation velocity as a function of particle size for liquid droplets of methane.

2.4 Redistribution to the discrete mass distribution

Both growth mechanisms produce particles of different size to the discrete bins used in the model. We redistribute them between the nearest sizes in the discrete bin distribution imposing mass continuity and conservation of the total number of particles. Let's suppose $m_l < m_k < m_{l+1}$. These conditions translates into

$$N_{l+1} = N_C \frac{m_{l+1} - m_k}{m_{l+1} - m_l} \quad (8)$$

$$N_l = N_C \frac{m_k - m_l}{m_{l+1} - m_l} \quad (9)$$

This procedure produces a certain amount of numerical dispersion and requires a rather large resolution in particle size in the bin distribution. We found that stable results in the full storm-microphysics simulations were reached for $N_{sizes} \sim 25$ and chose $N_{sizes} = 34$ for safety. The drawback of including this large number of particle size bins is the computational cost of computing their advection by the flow and their mutual interaction by coagulation.

3 Storm models and results

The results of the simulations presented in [8] are fully comparable to the dynamics of real cumulus clouds on Earth. One of the simulated storms appear

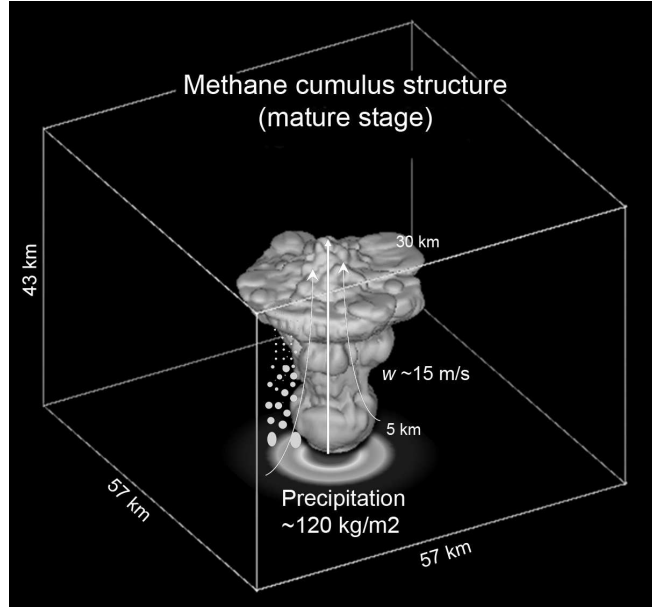


Fig. 3. Mature stage of a methane convective cumulus cloud developing in a highly humid environment (relative humidity 90 %)

on Fig. 3. In both worlds, Titan and Earth, the release of latent heat in the condensation drives the cloud convective activity. There are some differences worth mentioning:

- Methane's latent heat is $\sim 1/4$ that of water.
- Titan's gravity is $\sim 1/5$ that of Earth and vertical motions are expected to happen more slowly than on Earth.
- Methane is a hundredth of times more abundant on Titan's atmosphere than water on Earth.
- The vertical scales where convection can take place is larger on Titan than on Earth since its tropopause is less firmly located at 40 km whereas it is only 10 km on Earth.

When comparing methane convective activity with Earth water cumulus the first two points weaken Titan's methane cumulus clouds while the next two points tend to increase the power of Titan's storms. According to our own numerical simulations [8] the expected activity of a single cumulus cloud on Titan could be very similar to the typical activity of Earth's cumulus storms with rains lifetimes of a few hours, updrafts vertical velocities on the order of 20 m/s and large precipitation rates on the order of 100-200 l/m².

The large amount of precipitation predicted in some cases is in excellent accordance with Cassini Radar observations of Titan's surface where lakes and intricate systems of channels are common [14] (see fig. 4). Although the

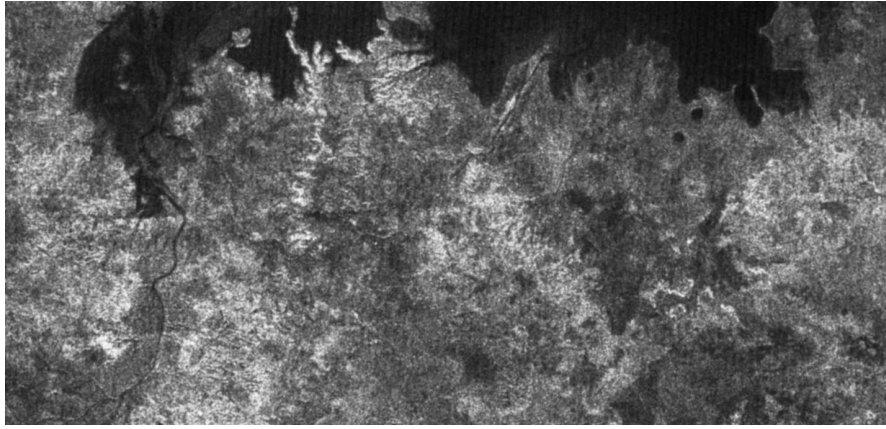


Fig. 4. A lake shoreline with drainage channels and a long (100 km) river-like feature captured by the Cassini radar instrument. The image (PIA01942) is centered near 73 degrees north latitude, 343 degrees west longitude, and measures about 300 kilometers by 140 kilometers).

conditions required for the development of a cumulus cloud on Titan are rather strong the precipitation is comparable to flash-floods events on Earth and should strongly modify the local orography [15].

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