SIMULATED METHANE CLOUDS IN THE TITAN TROPOSPHERE WITH THE TITAN PLANETARY CLIMATE MODEL

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Abstract. On Titan, methane plays a central role in the climatic characteristics and prebiotic chemical processes taking place on this moon. In addition, methane and minor gases from photochemical reactions generate clouds and precipitation that shape the satellite's landscape. We have coupled the Titan PCM with a new microphysical model of haze and clouds, enabling us to include phenomena hitherto omitted from 3D simulations, such as the nucleation and condensation of methane clouds, which contribute significantly to the observable cloud cover on Titan. The results of the current model more accurately reflect the different distributions present on Titan, notably that of gas, haze and clouds. This substantial improvement translates into more accurate atmospheric wind and temperature profiles, as well as a better description of the satellite's cycles and related processes.

Keywords: Planetary Science, Titan, Atmosphere, Model, Climate, Clouds

1 Introduction

Observations of Titan by the Cassini probe have mapped the thermal structure and composition of Saturn's moon's stratosphere over almost a year of Titan (Mathé et al. 2020; Vinatier et al. 2020). Analysis of these observations has revealed numerous seasonal variations in the thermal structure and atmospheric composition of the stratosphere, as well as the planet's global circulation and its inversion over the course of the year showing the presence of seasonal cycles on Titan. Despite radio-occultations of the lower stratosphere probed by Cassini (Schinder et al. 2012) and CIRS observations of its composition (Sylvestre et al. 2020), most of the phenomena that occur in the troposphere remain unexplained. In particular, the impact of clouds on thermal profiles and the distribution of haze in the satellite's lower atmosphere.

The last few years have seen major improvements to the IPSL Titan GCM from Lebonnois et al. (2012), now called Titan Planetary Climate Model (Titan PCM). A new microphysical model for haze (Burgalat & Rannou 2017) and clouds (Burgalat et al. 2014) has been implemented in moment, in contrast to conventional bin-distribution models, to overcome the problem of excessive computational resources of bin models. We therefore have a description of aerosol distributions in terms of moments of distribution. We are now able to model the methane clouds and the mist of minor species present in Titan's trposphere, in order to then study the methane cycle, its sources, sinks and related processes including clouds and rains.

2 Methode : The Titan PCM

2.1 Overview of the model

The Titan PCM is based on the IPSL Titan GCM presented in Lebonnois et al. (2012). This new model features numerous improvements and modifications. Its dynamics have been upgraded, we now use the LMDZ5 dynamical core from Hourdin et al. (2013) (previously the LDMZ4). We continue to use an horizontal resolution of 32 longitudes by 48 latitudes, with each grid covering 11.25°×3.75°. This resolution is destined to be increased for more accurate simulations. The vertical extension is also unchanged, with 55 levels extending up to ∼500 km, a surface pressure of ∼1.467 bar, but now with a topography.

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The physical parameterization of the model has also been improved. A new correlated-k radiative transfer scheme has been implemented in the model. It enables us to better describe the thermal structure of the upper stratosphere, in particular by modeling the stratopause, never before simulated in the Titan PCM. We have increased the number of radiative transfer calls per Titan day to 50 in order to better take these new phenomena into account. The photochemistry has also been improved thanks to the efforts of (Vuitton et al. 2019), enabling a better description of the gas cycles. We won't dwell on these last two points, as an article in prep. is dedicated to them. Above all, we have now coupled the radiative transfer to a new microphysical model of haze and clouds in moment. A more detailed description of this microphysical model is given in sections 2.2 and 2.3.

2.2 Microphysical model of haze

The equation governing the evolution of aerosols in the atmosphere is written as follows :

$$\frac{d}{dt}C(r,z) = Q(r,z) + \frac{d}{dt}C(r,z)|_{sedimentation} + \frac{d}{dt}C(r,z)|_{coagulation} \tag{2.1}$$

Where $C(r,z)$ is the concentration of particles of radius r at altitude z. $Q(r,z)$ corresponds to the particle production function, while the other two terms correspond respectively to the evolution of concentration under the effect of sedimentation and coagulation.

The model of Burgalat & Rannou (2017) describes these phenomena in terms of distribution moments. Here we present the main elements of this model, described for two aerosol populations, "small" spherical aerosols (denoted S) and "large" fractal aerosols (denoted F), interacting by Brownian coagulation.

The k^{th} moment of the distribution law of aerosols in radius $n(r)$, is defined by :

$$M_k(n) = \int_0^{\infty} x^k n(r) dr \tag{2.2}$$

In this model, we only deal with two selected moments (particle number density M_0 and particle volume concentration M_3), which are used in the most part of the microphysical processes discussed here.

The main phenomenon involved in aerosol microphysics is intra-modal or inter-modal coagulation. The equation describing the temporal evolution of the moments through coagulation depends on the flow regime in which we are working. On Titan, we're in a transition regime, with the flow regime shifting continuously from the molecular regime in the upper stratosphere to the continuous regime in the troposphere. The details of the calculations are given in Burgalat & Rannou (2017), we will recall here only the final form of the equations :

$$\frac{dM_0^S}{dt} \propto \beta_1 \times M_0^{S^2} - \beta_2 \times M_0^S M_0^F \quad ; \quad \frac{dM_3^S}{dt} \propto \delta_1 \times M_3^{S^2} - \delta_2 \times M_3^S M_3^F \tag{2.3}$$

$$\frac{dM_0^F}{dt} \propto \gamma_1 \times M_0^{S^2} - \gamma_2 \times M_0^{F^2} \quad ; \quad \frac{dM_3^F}{dt} \propto -\delta_1 \times M_3^{S^2} + \delta_2 \times M_3^S M_3^F \tag{2.4}$$

Where the prefactors β_i, γ_i and δ_i depend on the atmospheric properties of the environment, and shape properties of aerosols.

Sedimentation process is implemented in the model using a flux method as presented by Toon et al. (1988). Its equation depends on the fractal dimension of the particle, and uses the first order approximation of the slip-flow correction. It is expressed in moment as :

$$\frac{d}{dt}M_k(z) = -\vec{\nabla}.\vec{\Phi}_{sed} = -\frac{d}{dz}\frac{2\rho_p g}{9\eta E}\left(M_{\frac{D_f(k+3)-3}{D_f}} + \frac{A\lambda_g}{E}M_{\frac{D_f(k+3)-6}{D_f}}\right) \tag{2.5}$$

Where $E = r_m^{\frac{D_f-3}{D_f}}$, with D_f the fractal dimension of the aerosol and r_m the monomer radius. ρ_p is the aerosols bulk density, η the air viscosity, A the coefficient used in the first order slip-flow correction, and λ_g the atmospheric mean free path.

2.3 Microphysical model of clouds

Like aerosols, clouds are subject to microphysical laws. In this section, we present the phenomena of nucleation and condensation, the two "first steps" in cloud formation and the evolution of the droplets that characterize them. As far as sedimentation is concerned, this process follows the same principle whether we're dealing with aerosols or drops, with the difference that drops here are considered to be perfect spheres ($D_f = 3.0$).

We have adapted the microphysical cloud model in moment of Burgalat et al. (2014). This model gives us the nucleation equation expressed in moment :

$$\frac{d}{dt} M_k^{core} = 4\pi J_{het} r_m^{-1} \times M_{k+3}^{aer} \quad (2.6)$$

Where M_k^{aer} and M_k^{core} are the k-order moments of aerosols and nucleation core respectively. J_{het} is the heterogeneous nucleation rate given by Keesee (1989). On Titan, nucleation is effective mainly in the troposphere, where only fractal particles remain. We therefore consider here that all the moments associated with aerosols are those of the fractal mode, and the k-order moment evolution of aerosols is the opposite of that for core.

Condensation only controls the evolution of drop size. It affects the volume of condensate making up the drop, while the number of core remains constant. In the current model, each of the condensable species χ is considered independent and there is no mixing between species. The evolution of the total volume of condensate M_3^χ associated with the drops corresponds to the product of the evolution of the volume of an effective drop and the total number of available core M_0^{core} :

$$\frac{dM_3^\chi}{dt} = 4\pi r_g \times \frac{S - S^*}{R_c + R_d} M_0^{core} \quad (2.7)$$

Where r_g is the droplet radius, S corresponds to the environment saturation (far from the drop), and S^* the saturation at the surface of the drop. R_c and R_d are resistance terms that will slow down condensation.

3 Results : Model Cycles

3.1 *The seasonal haze cycle*

In the stratosphere, there is a predominant meridional circulation pattern characterized by a vast cell extending from one pole to the other. During the summer hemisphere, this cell features ascending winds, while during the winter pole's season, it experiences descending winds. This pole-to-pole circulation pattern undergoes a change in direction approximately every twelve Earth years (a Titan year ∼ 30 Earth years). In figure 1, the meridional

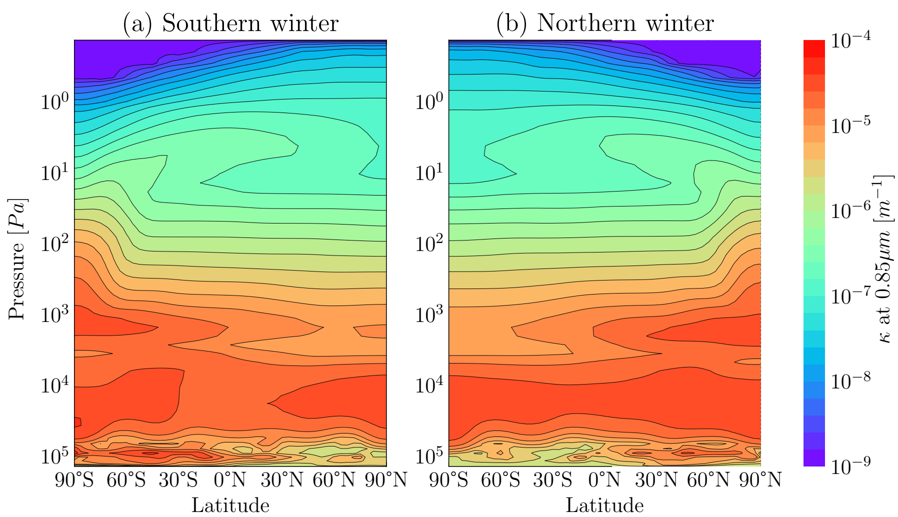

Fig. 1. Modeled latitude-pressure distribution of the extinction coefficient at 0.85μm, for (a) southern winter (L_S = 155°) and (b) northern winter (L_S = 335°).

distribution of haze and clouds is shown during the northern and southern winters. It mainly highlights the seasonal variation of the main haze layer and its detached layer. More precisely, the haze follows the pole-to-pole stratospheric circulation, enriching the winter poles with aerosols. We also note the reversal of circulation that occurs at the northern spring equinox. This transition period leads to a haze cycle, which has a direct impact on temperature profiles (not shown here), accentuating temperature differences between northern and southern regions. This influences atmospheric circulation and contributes to reinforcing atmospheric superrotation. A final point to note is the presence of an almost aerosol-free layer near the surface. This layer has been depleted of aerosols by precipitation from clouds higher up in the troposphere.

3.2 *Tropospheric clouds*

Consistently, our model produces clouds where clouds are actually observed (Fig. 2), but it also predicts clouds that have not (or not yet) been observed. Only clouds present in southern mid-latitudes between 2008 and 2010 (at the time of the circulation inversion) are not predicted by our model. In general, clouds form where methane is transported upwards by the circulation and condenses in the coldest regions. Methane clouds frequently appear in the rising branch of the tropospheric Hadley cell in the summer hemisphere (south in 2004). The mixing process produces a large region where the methane ratio is almost uniform and close to

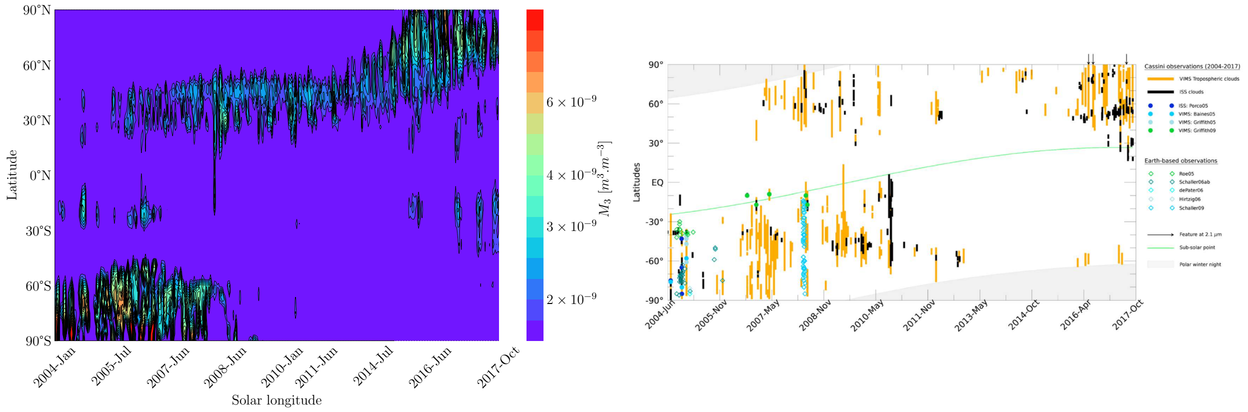

Fig. 2. Left: Modeled timescale-latitude distribution of the total volume of methane clouds. **Right:** Latitudes of tropospheric clouds observed from June 2004 through the end of the Cassini mission in September 2017 : Imaging Science Subsystem (ISS; black), Visual and Infrared Mapping Spectrometer (VIMS; orange), and Earth-based telescopes. From Turtle et al. 2018.

5%. In winter, temperature falls sharply with latitude, producing a zone of oversaturation. This pocket of supersaturation is fed by mixing, and the clouds that form at the lower edge of the region do not effectively remove the excess methane. These conditions are conducive to frequent cloud formation at mid-latitudes in winter. With radii of few tens of μm, methane droplets quickly sediment to the surface or evaporate a few kilometers lower down, in undersaturated layers. The time scale of sedimentation is much smaller than the time scale to restore, by upward mixing or advection, the methane saturation ratio to the critical saturation ratio (the ratio at which nucleation is triggered). As a result, methane clouds appear essentially as sporadic clouds rather than as a set of permanent clouds. Their lifespan is limited by their sedimentation timescale (several Earth days).

4 Conclusions

Based on the work of IPSL's Titan GCM, we have implemented a new microphysical model, which includes phenomena related to haze but now also includes clouds. Compared to the previous version of the model, we now have a better description of haze distribution, reinforcing temperature contrasts and thus super-rotation. We are also able to model clouds realistically, with a full description of their properties such as volume, drop size, or optical properties. The model can still be improved, taking into account deep convective clouds in the model. This type of phenomenon plays an important role in the global methane cycle. These developments will allow to go further in the understanding of the major cycles of Titan (methane, minor species, haze, etc.).

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