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Modeling cloud microphysics using a two-moments hybrid bulk/bin scheme for use in Titan's climate models: Application to the annual and diurnal cycles

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A B S T R A C T

Microphysical models describe the way aerosols and clouds behave in the atmosphere. Two approaches are generally used to model these processes. While the first approach discretizes processes and aerosols size distributions on a radius grid (bin scheme), the second uses bulk parameters of the size distribution law (its mathematical moments) to represent the evolution of the particle population (moment scheme). However, with the latter approach, one needs to have an *a priori* knowledge of the size distributions.

Moments scheme for Cloud microphysics modeling have been used and enhanced since decades for climate studies of the Earth. Most of the tools are based on Log-Normal law which are suitable for Earth, Mars or Venus. On Titan, due to the fractal structure of the aerosols, the size distributions do not follow a log-normal law. Then using a moment scheme in that case implies to define the description of the size distribution and to review the equations that are widely published in the literature.

Our objective is to enable the use of a fully described microphysical model using a moment scheme within a Titan's Global Climate Model. As a first step in this direction, we present here a moment scheme dedicated to clouds microphysics adapted for Titan's atmosphere conditions. We perform comparisons between the two kinds of schemes (bin and moments) using an annual and a diurnal cycle, to check the validity of our moment description.

The various forcing produce a time-variable cloud layer in relation with the temperature cycle. We compare the column opacities and the temperature for the two schemes, for each cycles. We also compare more detailed quantities as the opacity distribution of the cloud events at different periods of these cycles. Results show that differences between the two approaches have a small impact on the temperature (less than 1 K) and range between 1% and 10% for haze and clouds opacities. Both models behave in similar way when forced by an annual and by a diurnal cycles. We note that in our model, the diurnal cycle produces a remarkable asymmetry between the morning and the evening, that can be associated to morning/evening limb asymmetry observed with ground-based telescopes.

1. Introduction

On Titan, the haze layer is a dominant component of the atmosphere and clouds where long suspected before their first detection (Griffith et al., 1998) and first imaging (Roe et al., 2002). As a part of the effort to understand Titan's climate, the study of the haze and the putative cloud layer led to the development of microphysical models (Toon et al., 1980, 1988a,b; McKay et al., 1989; Cabane et al., 1992, 1993). The recent advance in the knowledge of Titan led many teams to produce models simulating the haze and cloud microphysics in details, with multiple condensing species, to explain specific observations (Barth and Toon, 2003, 2004, 2006; Lavvas et al., 2008a,b, 2011). Beyond one dimensional models, cloud and haze microphysical models were also included in Global Climate Models (GCMs) (Rannou et al., 2002, 2004, 2006) and in regional models (Hueso and Sánchez-Lavega, 2006; Barth and Rafkin, 2007; Barth, 2010; Barth and Rafkin, 2010) to investigate the geographical variation of the cloud cover and the link with the atmosphere dynamics.

The most complete microphysical models used for Titan are based on bin schemes where particles size distribution is divided in sections (bins), defined by their boundaries and characteristic radii. The law describing the physical processes (coagulation, coalescance, condensation, etc.) manages the particles growth in

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terms of transfer of population from one bin to the others (Toon et al., 1988b; Cabane et al., 1992, 1993; Barth and Toon, 2006; Lavvas et al., 2011). The advantage of this description is that no *a priori* distribution is needed, and the size distribution can evolve following the laws of physics. The main drawback is the number of calculations associated to this technique, due to the large number of bins required to get a good accuracy.

An alternative solution is to use a moment scheme for microphysics description: Particles size distributions are no longer divided in bins (typically 45 bins for a 1D model, and 10 for the 2D IPSL-GCM) and are rather defined by some of the moments of the distribution law. Most of the time only one or two moments are used for convenience. The major constraint is the fact that the size-distribution law should be prescribed a priori. Then, a good knowledge of the expected distribution is needed.

Titan's aerosols have been shown to be aggregates of particles with fractal structure since the early 1990s (West, 1991; West and Smith, 1991; Cabane et al., 1992, 1993) and since then several studies have clearly shown that fractal particles was the best candidates to match observations data (Rannou et al., 1995, 1997; Tomasko et al., 2008, 2009). The fractal structure of Titan's aerosols implies significant modifications in the microphysics law. For such aerosols, the relation between the apparent surface and the proper volume is radically different than for compact aerosols. They coagulate faster and have a reduced sedimentation velocity compared to spherical particles of same mass (Cabane et al., 1993). As a result, the shape of Titan's aerosol size distribution is not comparable to that expected for spherical aerosols and therefore cannot be represented by a log-normal function (Cabane et al., 1993). This fact prevent us from using schemes already developed and necessitates to review in depth the way the equations are written for the moment scheme.

A motivation for developing a microphysical model with a moment scheme is to enable the use of a sophisticated microphysical model in the frame of the 3D IPSL-GCM (Lebonnois et al., 2012). In the current 2D IPSL-GCM, aerosols and cloud condensation nucleii (CCN) distributions are described with 10 bins as well as the volume of each condensate species. Two different species (CH_4, C_2H_6) were allowed to condense in the model of Rannou et al. (2006) and the current version now includes acetylene. Then, this model now deals with 50 quantities. The equivalent model with moments, as it is presented here, includes 7 moments (two for aerosols and CCN distributions and one for each condensate specie). This lower number of quantities to deal with in the microphysics, and also in the transport processes, will speed up the model.

In this paper we work on the description of the cloud microphysical laws in moments and the prescription of size distributions for Titan's aerosols and CCN. We left the description of the haze microphysical laws with moments for a further publication. One should note however that the cloud model is much more sensitive because clouds are in coupled interactions with their environment in multiple ways, while aerosols essentially impact the thermal structure with only a weak feedback. We expect the cloud model to be the most challenging part of the project. This article is structured as follows:

The first section is dedicated to a reminder of the clouds microphysics and to the adaptation microphysics law for the moments scheme. This part is quite general and depends on the aerosols structure quite marginally. In a second part, we discuss the size distribution specific to Titan aerosols and we show its analytical description. This is the core of the method since that here lay the difference with the schemes already published elsewhere. Then, in the third section, we perform two simulations to test the model described with moments that we compare to the reference model with a bin description. Sensitivity test over relevant microphysical parameters have also been performed and are presented in the fourth section. Finally, we give a conclusion.

2. Microphysical equations with a description of particle distributions in moments

2.1. Principle of the moment scheme

The microphysics equations that we use for Titan come from the classical theory of the microphysics (Pruppacher and Klett, 1978). For our work, we use the haze microphysical model developed by Cabane et al. (1992, 1993) and for clouds, the model initially developed by Montmessin et al. (2002) and used for Titan by Rannou et al. (2006). All these models find indeed their roots in the model of Toon et al. (1988b). The scope of our work is to adapt the equations of cloud microphysics to a two-moments scheme in the specific frame of Titan's aerosols.

Cloud formation involves several components in the model: the photochemical aerosols (which serve as CCN), the CCN and the condensible species that are found as gas and as condensate material (ice or liquid). In the model of Rannou et al. (2006), the size distribution of photochemical aerosols and CCN are described under the form of a concentration per bins of radius. The grid of radius bins is described in such a way that the particle radius increases geometrically. For instance, Cabane et al. (1992) defined a system of 45 radius bins with the smaller radius $r_1 = 1.3$ nm. Then, the relation $r_{i+1} = r_i \times s$ with $s = 2^{1/3}$ defines all the other radius bins. The value of s defines the roughness of the grid and allows to adapt the number of bins on a given interval. To run the Titan IPSL-GCM, which was much more demanding in term of computational resources, Rannou et al. (2002) chose a value of $s = 16^{1/3}$ in order to run the microphysics with 10 size bins. In the present work, we define a radius grid with a geometrical step of $s = 2.347^{1/3}$ which is close to the one used by Cabane et al. (1993) and with 40 bins. This will constitute our reference case. In the following, we note $n_{aer}(r)$ and $n_{nuc}(r)$ the size distribution for aerosols and for CCN, respectively.

To describe a distribution in term of moments, we first need to define a law that well represents the size distribution of Titan aerosols. For our work, the discrete distribution coming out from the "bin scheme model" will yield the idealized distribution for Titan. But, noteworthy, the writing up of the general equations for the description in moment do not depends on the definition of the size distribution itself. Then, we postpone the discussion about the size distribution to the next section and focus on the modification of the microphysical laws.

The n^{th} moment of a distribution $f(x)$ is defined as follows (Eq. (1)):

$$M_n(f) = \int_I x^n \, f(x) \, \mathrm{d}x \tag{1}$$

A distribution can also be parametrized with parameters that are meaningful, as the total number of particles N_0, the mean radius r_0 of the particles, the variance of the distribution v_0. Each of these three parameters can be related to moments, and we need as much as moment than free parameters. For our study, we find with the 2D-IPSL GCM that the shape of Titan aerosol distribution in troposphere is stable all over the planet and only the mean radius and the total number of aerosols vary. Thus, we can set the shape of the distribution once for all and modify only N_0 and r_0. For practical reason, we decided to use moments of order 0 and 3 of the size distribution which are respectively equal to the density number and proportional to the volume mixing ratio of particles. Aside from the physical meaning behind these two moments, they also lead to simplification of the equations as soon as a process is known to conserve the total number of particles or the total volume.