Icarus 241 (2014) 269–279

Contents lists available at ScienceDirect

Icarus

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

Titan's past and future: 3D modeling of a pure nitrogen atmosphere and geological implications

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ARTICLE INFO

Article history:
Received 27 September 2013
Revised 29 May 2014
Accepted 4 July 2014
Available online 23 July 2014

Keyword:
Titan, atmosphere
Titan, hydrology
Atmospheres, evolution

ABSTRACT

Several clues indicate that Titan's atmosphere has been depleted in methane during some period of its history, possibly as recently as 0.5–1 billion years ago. It could also happen in the future. Under these conditions, the atmosphere becomes only composed of nitrogen with a range of temperature and pressure allowing liquid or solid nitrogen to condense. Here, we explore these exotic climates throughout Titan's history with a 3D Global Climate Model (GCM) including the nitrogen cycle and the radiative effect of nitrogen clouds. We show that for the last billion years, only small polar nitrogen lakes should have formed. Yet, before 1 Ga, a significant part of the atmosphere could have condensed, forming deep nitrogen polar seas, which could have flowed and flooded the equatorial regions. Alternatively, nitrogen could be frozen on the surface like on Triton, but this would require an initial surface albedo higher than 0.65 at 4 Ga. Such a state could be stable even today if nitrogen ice albedo is higher than this value. According to our model, nitrogen flows and rain may have been efficient to erode the surface. Thus, we can speculate that a paleo-nitrogen cycle may explain the erosion and the age of Titan's surface, and may have produced some of the present valley networks and shorelines. Moreover, by diffusion of liquid nitrogen in the crust, a paleo-nitrogen cycle could be responsible of the flattening of the polar regions and be at the origin of the methane outgassing on Titan.

1. Introduction

Titan's atmosphere is thick (~1.47 bar), essentially composed of N_2 (more than 95%) and methane (~5% close to the surface and ~1.5% above the tropopause) (Niemann et al., 2010). Methane photodissociation generates a complex chemistry, leading to the formation of H_2, organic molecules and haze. Currently, Titan's surface temperature is around 93 K (Jennings et al., 2011). It is controlled by a greenhouse effect dominated by collision-induced absorption (CIA) of N_2–N_2, CH_4–N_2 and H_2–N_2, and by the absorption of sunlight by CH_4 and haze in the upper atmosphere, generating an anti-greenhouse effect (McKay et al., 1991).

The inventory of total carbon (atmospheric methane, lakes, sand dunes,...) present on the surface of Titan seems far smaller (2–3 orders of magnitude) than the amount estimated to have been produced throughout Titan's history, as estimated from the present rate of methane photolysis (Lorenz et al., 2008; Sotin et al., 2012). Hence, this carbon might have a recent origin. Tobie et al. (2006) suggested that Titan's atmospheric methane originated from episodic outgassing, which released methane from clathrates, starting approximately 0.5–1 billion years ago. This is consistent with the dating derived from isotopic analysis of C^{12}/C^{13}, which provides an upper limit of no more than 470 Ma for methane outgassing (Mandt et al., 2012), as well as with the time required for the formation of the dunes, estimated to range between 50 and 630 Ma (Sotin et al., 2012). Before this outgassing, Titan's atmosphere might therefore have been depleted in methane and its photochemical products. In such conditions, the greenhouse effect was limited to the CIA of N_2–N_2, and the atmosphere was colder and could have condensed (Lorenz et al., 1997), forming liquid nitrogen on the surface.

This state could also occur in the future. Indeed, atmospheric CH_4 has a lifetime of about 20 million years (Krasnopolsky, 2009). Thus, if it is not resupplied, it disappears, together with all

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http://dx.doi.org/10.1016/j.icarus.2014.07.009
0019-1035/

its photoproducts. In such a case, haze particles are no more produced and H_2 molecules escape from the atmosphere. The atmosphere is therefore exclusively composed of nitrogen after approximately 20 million years. Currently, no source of methane, able to maintain the present-day level in Titan's atmosphere has been identified. There might be a subsurface source of methane explaining the detection of possible tropical lakes (Griffith et al., 2012). Half of the methane could be resupplied by ethane diffusion in polar clathrates (Choukroun and Sotin, 2012), but it would not be sufficient. Titan could therefore end up in the liquid nitrogen state within a few million years.

Lorenz et al. (1997) studied the surface temperature and pressure under such conditions with a 1D model. They found that, with a faint Sun and a high albedo (higher than 0.5), the atmosphere might have undergone a collapse leading to a Triton-like frozen state, with a thin atmosphere. Their model did not include clouds, assuming that they would quickly fall to the ground. In this paper, we study the climates and atmospheric collapse of a pure nitrogen atmosphere with a 3D Global Climate Model (GCM) during Titan's history. The model incorporates cloud formation and their radiative effect. In Section 2, we describe the model and the assumptions on the nitrogen cycle. We then analyze the radiative impact of clouds, theoretically and with the GCM. We study the nitrogen cycle and atmospheric collapse for past and future climates. Finally, we discuss the implications of a paleo-nitrogen cycle on the surface erosion and shape, and methane outgassing on Titan.

2. Method

Simulations were performed using a new type of GCM, the Generic LMDZ, specifically developed for exoplanet and paleoclimate studies (Wordsworth et al., 2011, 2013; Forget et al., 2013; Leconte et al., 2013; Charnay et al., 2013). The radiative scheme was based on the correlated-k model, with the absorption data calculated directly from high resolution spectra computed by a line-by-line model from the HITRAN 2008 database (Rothman et al., 2009). Rayleigh scattering by N_2 is included, using the method described in Hansen and Travis (1974), and using the Toon et al. (1989) scheme to compute the radiative transfer. The N_2–N_2 continuum from the HITRAN database, fundamental for this study, was included. We used 16 spectral bands in the thermal infrared and 18 at solar wavelengths.

The nitrogen cycle and cloud modeling is based on physical principles. We used the same method as CO_2 clouds on early Mars in Forget et al. (2013). The nitrogen condensation is assumed to occur when atmospheric temperature drops below the saturation temperature from Armstrong (1954). Local mean N_2 cloud particle sizes are determined from the amount of condensed nitrogen and the number density of cloud condensation nuclei (CCN) by:

$$r = \left(\frac{4q}{3N_c\pi\rho_{N2}}\right)^{1/3} \quad (1)$$

with r the mean cloud particle radius, q the mass mixing ratio of condensed nitrogen, N_c the number density of CCN per mass unit of air, and ρ_{N2} the volumic mass of condensed nitrogen.

The values used for the number density of CCN are discussed in the next section. We did not make any distinction between liquid and icy particles for the radiative transfer. Single scattering properties were calculated considering spherical particle Mie theory with the optical properties of nitrogen ice of Quirico et al. (1996). As for Rayleigh scattering, the radiative transfer for nitrogen cloud in the GCM uses the Toon et al. (1989) scheme. Liquid and icy particles were assumed to sediment according to Stokes law (Forget et al., 1999) and evaporate during their fall. No coalescence of liquid droplets is taken into account because the number density of CCN in our simulations is too small to allow this process (see next section).

No ground infiltration for liquid nitrogen is taken into account. Therefore, liquid nitrogen from precipitation or surface condensation is conserved on the surface. Surface condensation (evaporation) of N_2 occurs when the surface temperature goes below (above) the saturation temperature. It is calculated from energy conservation principles, using a latent heat for N_2 of 198 kJ/kg. When condensation or evaporation occurs on the ground or in the atmosphere, the atmospheric pressure is adjusted in consequence. In this study, all simulations were initiated with a surface pressure of 1.47 bar, similar to present-day pressure on Titan. The lack of methane should slightly reduce the pressure, but the change is too small to affect our results. We used a surface emissivity of 1 and a thermal inertia for the ground of 400 $J\,s^{-1/2}\,m^{-2}\,K^{-1}$, a value estimated by Tokano (2005). We have run the model with a higher inertia of 2000 $J\,s^{-1/2}\,m^{-2}\,K^{-1}$, and did not notice any change on the mean surface temperature at any latitude. We also implemented a diffusion scheme for the liquid nitrogen at the surface, representing slow surface flows. We used a diffusivity of 100 $m^2\,s^{-1}$, equal to the one used by Schneider et al. (2012) for liquid methane. Most of our simulations have been run without such a diffusivity, but we discuss its impact.

One of the main parameters in this study is the surface albedo. For simplicity, we assumed a constant value over all Titan. We neglected a change of the surface albedo by liquid nitrogen. Indeed, liquid nitrogen is not radiatively active at visible wavelengths and so its impact on the albedo should be limited. The present surface albedo should be around 0.2–0.3 (Schröder and Keller, 2008), pretty small compared to other saturnian moons (i.e. ∼0.4–0.6 (Howett et al., 2010)). Enceladus has a very high albedo around 0.95, but it is a particular case with a permanent resurfacing produced by a geological activity. The Galilean moons have a similar or higher albedo (around 0.2 for Callisto, 0.3 for Ganymede, and 0.5 for Io and Europa). Triton, which is covered by ices of water, nitrogen and methane, has a high albedo around 0.7. Before the methane outgassing the surface albedo on Titan was certainly higher than today because of the lower amount of dark organic material on the surface. Thus, it was likely between 0.3 and 0.5, closer to Bond albedo values of the other saturnian and Galilean moons. In this study, most of the simulations were run with different values of albedo, varying from 0.2 to 0.5. Yet, we took an albedo of 0.3 as reference, in particular to estimate the impact of nitrogen clouds (next section).

The simulations were run with a mean solar insolation at top of Titan's atmosphere of 3.77 W/m^2 for the present-day Sun. For paleo-climates we use the Gough (1981) law to calculate past insolation. We used the present-day values for astronomical parameters (i.e. Saturn's distance to the Sun, Saturn's eccentricity and obliquity). We neglect the fact that Saturn's distance to the Sun could have been different at 4 Ga, before the Late Heavy Bombardment (Tsiganis et al., 2005).

In the early Solar System, Saturn was warmer. According to the thermal evolution model from Leconte and Chabrier (2013), Saturn's effective temperature was between 130 and 200 K at 4 Ga (compared to ∼96 K today), corresponding to an additional infrared warming of Titan between 0.01 and 0.06 W/m^2. Yet, this remains small compared to the solar flux on Titan (3.8 W/m^2 for the present Sun and 2.8 W/m^2 at 4 Ga) and we therefore neglected it.

3. Effects of nitrogen clouds

We first ran the GCM for a pure nitrogen atmosphere with non-radiative cloud to analyse the possibility for nitrogen cloud formation. Two cases were considered, when the atmosphere can con-