Icarus 243 (2014) 264–273

Contents lists available at ScienceDirect

Icarus

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

# Simulations of Titan's paleoclimate

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ARTICLE INFO

*Article history:*
Received 17 February 2014
Revised 25 August 2014
Accepted 26 August 2014
Available online 4 September 2014

*Keywords:*
Titan
Atmospheres, dynamics
Atmospheres, evolution

ABSTRACT

We investigate the effects of varying Saturn's orbit on the atmospheric circulation and surface methane distribution of Titan. Using a new general circulation model of Titan's atmosphere, we simulate its climate under four characteristic configurations of orbital parameters that correspond to snapshots over the past 42 kyr, capturing the amplitude range of long-period cyclic variations in eccentricity and longitude of perihelion. The model, which covers pressures from the surface to 0.5 mbar, reproduces the present-day temperature profile and tropospheric superrotation. In all four simulations, the atmosphere efficiently transports methane poleward, drying out the low- and mid-latitudes, indicating that these regions have been desert-like for at least tens of thousands of years. Though circulation patterns are not significantly different, the amount of surface methane that builds up over either pole strongly depends on the insolation distribution; in the present-day, methane builds up preferentially in the north, in agreement with observations, where summer is milder but longer. The same is true, to a lesser extent, for the configuration 14 kyr ago, while the south pole gains more methane in the case for 28 kyr ago, and the system is almost symmetric 42 kyr ago. This confirms the hypothesis that orbital forcing influences the distribution of surface liquids, and that the current observed asymmetry could have been partially or fully reversed in the past. The evolution of the orbital forcing implies that the surface reservoir is transported on timescales of ~30 kyr, in which case the asymmetry reverses with a period of ~125 kyr. Otherwise, the orbital forcing does not produce a net asymmetry over longer timescales, and is not a likely mechanism for generating the observed dichotomy.

## 1. Introduction

The drastic hemispheric asymmetry observed in the distribution of Titan's lakes has been suggested to be the consequence of asymmetric seasonal forcing. Aharonson et al. (2009) hypothesized that net drying of the pole subject to shorter but more intense summers would lead to this asymmetry on a timescale comparable to the period of Saturn's orbital variations, $10^4$ years. This would imply that $\sim$30 kyr in the past, when the orbital parameters produced a longitude of perihelion passage near the northern summer solstice, the asymmetry would have been reversed.

General circulation models (GCMs) of present-day Titan have shown that the atmosphere effectively transports methane poleward, drying the equatorial regions (Rannou et al., 2006; Mitchell, 2008) where dune fields are located (Radebaugh et al., 2008). Schneider et al. (2012) used a GCM that included diffusion of surface liquids to further show that increased precipitation at the north pole, which undergoes milder but longer summers in the current epoch, results in buildup of its surface reservoir, creating such an asymmetry.

Recent clouds (Schaller et al., 2009) and rainstorms (Turtle et al., 2011) have been observed at Titan's low latitudes, strengthening the possibility that equatorial fluvial surface morphologies, like the channels observed by Huygens (Tomasko et al., 2005) and washes seen by Cassini RADAR (Lorenz et al., 2008), are the result of seasonal rainfall as observed in the present, despite the prevalence of desert-like conditions near the equator.

In this paper, we investigate the effects that changes in Saturn's orbit have had on Titan's climate in its recent geologic history. With a general circulation model, we simulate Titan's climate during four characteristic orbital configurations that occurred in the past 42 kyr. In addition to the present day, the times chosen correspond to the maximum (14 kyr ago) and minimum (42 kyr ago) values in the recent variation of Saturn's orbital eccentricity, and a midpoint between them (28 kyr ago). The timespan of these snapshots also corresponds to a large variation of longitude of perihelion (see Table 1). All of these orbital elements are representative of those over the past Myr, as can be seen in Fig. 1; a description of their computation is provided in Appendix.

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http://dx.doi.org/10.1016/j.icarus.2014.08.042
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Of particular interest is the distribution of surface methane over the past 40 millennia: Where have liquids accumulated over this time? Are there marked differences in the distribution of surface temperatures? Has the circulation of the atmosphere changed significantly?

## 2. Model description

### 2.1. Dynamical core

The model integrates the hydrostatic primitive equations, in vorticity-divergence form, using the Geophysical Fluid Dynamics Laboratory's (GFDL's) spectral transform dynamical core (Gordon and Stern, 1982). The core is run with triangular truncation, leapfrog time integration and Robert filter, and eighth-order hyperdiffusion. In this study, the resolution is T21 (approximately equivalent to 5.6° horizontal resolution) to minimize computational time.

The vertical coordinate, here using 25 levels, is a hybrid that smoothly transitions from unequally-spaced sigma coordinates near the planetary surface to pressure coordinates near the model top, at approximately 0.5 mbar. This choice allows for the inclusion of topography, though this is not presently used. It also provides higher resolution in the boundary layer than would an evenly-spaced sigma coordinate.

Energy and moisture are corrected by a multiplicative factor to guarantee conservation by the dynamics. An additional multiplicative factor correction is made to the surface liquid reservoir to ensure that total methane is conserved in the model after exchange between surface and atmosphere, during which small numerical errors otherwise produce a systematic sink for methane. The details of the exchange processes and the reservoir are described further below.

### 2.2. Radiation

Because atmospheric dynamics are in essence driven by radiative heating, and in particular because Titan's seasonal weather is controlled by fluxes from the surface, which in turn respond to insolation, the accuracy of radiative transfer is of primary importance. Therefore, we developed a nongray, multiple scattering radiative transfer module that takes advantage of relevant data from the Cassini-Huygens mission. Titan's diurnal and seasonal cycles are fully accounted for in the computation of the top-of-atmosphere insolation.

The radiative transfer uses delta-Eddington and hemispheric-mean two stream approximations (Toon et al., 1989) for computation of solar (visible and near-infrared) and thermal infrared fluxes, respectively. Radiative fluxes between atmospheric layers are computed using layer scaled optical properties—extinction optical depth, single scattering albedo, and asymmetry parameter—combined from individual sources of opacity. These sources (including multiple scattering in the solar spectrum) are methane, haze, and Rayleigh scattering for solar radiation, and collision-induced absorption (CIA) from combinations of $N_2$, $CH_4$ and $H_2$ pairs, as well as molecular absorption by $CH_4$, $C_2H_2$, $C_2H_4$, $C_2H_6$, HCN, and absorption by haze, in the infrared. The profiles of the stratospheric molecular species are fixed to observed values (Vinatier et al., 2007).

A combination of exponential-sum fits and correlated $k$ coefficients (Lacis and Oinas, 1991; Fu and Liou, 1992) is used to define gas broadband transmittances for each layer. In the solar portion of the spectrum, opacities for methane at wavelengths short of 1.6 μm are calculated with fits to transmittance from DISR absorption coefficients (Tomasko et al., 2008a), while methane opacities between 1.6 and 4.5 μm are accounted for using correlated $k$ coefficients calculated from HITRAN line intensities (Rothman et al., 2009). In the thermal infrared, CIA opacities are calculated with fits to transmittance from HITRAN binary absorption cross-sections (Richard et al., 2011), while molecular absorption is treated with correlated $k$ coefficients from temperature- and pressure-corrected (Rothman et al., 1996) HITRAN line intensities. Both the fit parameters and coefficients (with associated weights) are computed off-line for the range of temperatures and pressures relevant to Titan.

The effects of haze are incorporated using the optical parameters from DISR at solar wavelengths, and extinction coefficients determined from Cassini/CIRS data between 20–560 $\mathrm{cm}^{-1}$ (Anderson and Samuelson, 2011) and 610–1500 $\mathrm{cm}^{-1}$ (Vinatier et al., 2012) at infrared wavelengths. Multiple scattering is accounted for using the haze single scattering albedo and asymmetry factors, computed from phase functions, at solar wavelengths (Tomasko et al., 2008b). The haze is assumed to be a pure absorber in the thermal infrared (Tomasko et al., 2008c). The haze is also not dynamically coupled, and is thus assumed to be horizontally homogeneous. Haze coupling has been shown to amplify wind speeds and temperature contrasts in the stratosphere (Rannou et al., 2004), but this effect should be of little consequence for the lower troposphere, as the most significant haze accumulation occurs over winter high latitudes in polar night, and as such the insolation distribution is not affected.

### 2.3. Moist processes

Parameterization of large-scale condensation (LSC), which occurs when the relative humidity in a grid box reaches or exceeds 100%, is included. Resulting methane condensate is allowed to re-evaporate as it falls through the atmosphere below, such that rain only reaches the surface when the atmosphere below the condensing grid box becomes saturated.

The saturation vapor pressure is calculated either over methane–nitrogen liquid (Thompson et al., 1992) or methane ice (Moses et al., 1992). In the former case, we assume a fixed latent heat of vaporization (with a reference saturation vapor pressure of 106.0 mbar at 90.7 K) and a constant nitrogen mole fraction of 0.20. The transition between liquid and ice is chosen to occur where the vapor pressure curves intersect, at approximately 87 K. This represents a mild suppression of the freezing point below the triple point of pure methane due to the binary liquid. Where condensation occurs, only the latent heat of vaporization is used, ignoring the ∼10% difference with that of sublimation; this is equivalent to assuming that only rain is produced, which avoids the need to also include the liquid-ice transition for energy balance. Given the uncertainties in the composition of the condensate and the expectation that surface precipitation is liquid (Tokano et al., 2006), this assumption does not add to the uncertainty in the simulations.

The effects of ethane are not modeled. Because of its much lower vapor pressure, ethane would have only an indirect effect in reducing the methane evaporation rate by its fractional abundance in the liquid. Unless ethane dominates strongly over methane, this is not a big effect, and would also impact all simulations equally. Furthermore, though ethane may be incorporated in condensates in the troposphere, its effect should be small and previous studies of the humidity profile have also neglected it (i.e. Tokano et al., 2006).

In addition to LSC, a quasi-equilibrium convection scheme is included, as in previous studies of Titan's methane cycle (Mitchell et al., 2006; Schneider et al., 2012). Moist convection is parameterized with a simplified Betts–Miller scheme (Frierson, 2007; O'Gorman and Schneider, 2008), where a convectively unstable column of atmosphere is relaxed toward a moist pseudoadiabat, wringing out excess liquid. This approach assumes that