Timescale for oceans in the past of Titan

Richard Larsson a,*, Christopher P. McKay b

a Department of Computer Science, Electrical and Space Engineering, Linköping University of Technology, Space Campus 1, SE-58180 Linköping, Sweden
b NASA Ames Research Center, Division of Space Sciences and Astrobiology, Mail Stop 245-3, Moffett Field, CA 94035, USA

Article info

Article history:
Accepted 7 December 2012
Available online 22 December 2012

Keywords:
Titan
Surface
Methane ocean
Planetary evolution

1. Introduction

Methane is the second most abundant constituent in Titan’s atmosphere with a concentration of 1.5% in the upper atmosphere to 4.5% at the surface near the equator (Niemann et al., 2005, 2010). There are also lakes of methane on the surface, but more is in the atmosphere than on the surface. The lakes have 200–2000 kg/m² of column mass of organics and the atmosphere contains 4000 kg/m² column mass of methane relative to the surface (Lorenz et al., 2008).

Methane is destroyed by photochemistry, and due to the loss of H to space there is an irreversible conversion of methane to organic molecules with a higher C/H ratio, such as ethane and organic tholin. The rate is best estimated from the loss of H₂ to space (with a loss flux rate of about 10¹⁰ cm⁻² s⁻¹, Cui et al., 2008), giving a timescale for the loss of the entire estimated atmospheric and surface reservoir on Titan of 100 million years. To date there is no clear evidence of a source of methane, such as cryovolcanism. Without a source, Titan will lose its atmospheric methane in a time short compared to a geologic timescale. In addition, in the geological past Titan would have had many times more methane than the present inventory. Presumably this additional methane would have accumulated in surface reservoirs.

Today, lakes are present in the polar regions (Stofan et al., 2007; Hayes et al., 2011) and there might be lakes in the equatorial region (Griffith et al., 2012), although these are not confirmed. A curious feature of Titan is the evidence of shorelines and fluvial features in the equatorial region (e.g., Moore and Howard, 2010). Presently, storms seem unable to bring enough liquid from the polar lakes to the equator to explain this, as models of storm formation (Barth and Rafkin, 2007) requires a relative humidity of methane of ~ 65% whereas the measured RH is 45% (Niemann et al., 2005). The extensive cloud events seen at the equator such as those reported by Schaller et al. (2009) are not necessarily associated with rain at the surface. Turtle et al. (2011) reported on direct observations of surface darkening over large areas of the equatorial region after the passage of clouds. They concluded that “the darkening is caused merely by surface wetting”. This is perhaps consistent with the drizzle postulated for the Huygens landing site (Tokano et al., 2006). If so, these events seem to only be able to create occasional moist surfaces (Niemann et al., 2005; Lorenz et al., 2006; Williams et al., 2012). If present equatorial rain events are not adequate to form channels, this suggests that there was once sufficiently standing liquid on the equator to raise the RH to at least 65%, allowing stormy weather.

Recently, Schneider et al. (2012) have developed a global circulation model that predicts strong precipitation at the equator even with present climate. This is in contrast with previous work but does not disprove the existence of such events. For example, the treatment of solar radiation is monochromatic. This is particularly problematic for predicting precipitation because, as the authors note, precipitation depends on the moist static energy which “only net radiation at the top of the atmosphere drives the vertically integrated MSE balance”. We feel that while the Schneider et al. (2012) results open up an important alternative it is premature to dismiss previous work which indicates that heavy rain storms at the equator are not possible.
Sotin et al., (2012) recently suggested that a model for Titan’s history involving an outburst of methane a few hundred million years ago followed by the loss methane. They pointed out that this would be consistent with both the present observations of lakes and haze accumulations on the surface and recent measurements of isotopic ratios in atmospheric methane.

Several authors have considered hypothetical hydrocarbon oceans before this work (e.g., Sagan and Dermott, 1982; Lunine et al., 1983; Dubouloz et al., 1989; Sears, 1995), partly to stabilize the atmosphere against loss of methane by photolysis. This work does not consider the methane reservoir on Titan as long term stable. Instead in this paper we will calculate how long ago, given the current loss fluxes and no sources, there was enough methane such that substantial parts of the equator of Titan could be connected to a polar ocean and global ocean. We assume that at least one of the polar regions must be connected to the equator since an isolated equatorial sea would have a rate of evaporation that is larger than its rate of condensation. Essentially, the polar region condensation and the subsequent flow back of liquid to the equator is necessary to maintain an equatorial sea.

2. Method

There is a continuous destruction of CH4 in the atmosphere of Titan due to UV radiation (see, e.g., Yung et al., 1984; Wilson and Atreya, 2009). The rate at which the total atmosphere and surface inventory of liquid is depleted depends on the loss rate of H2 and the relative production of other liquids, principally C2H6. Assuming pure CH4 lakes then the timescale to deplete the present inventory (or double it going backward in time) is between 100 and 143 million years covering the range of estimate for the total inventory mentioned above. In the other extreme, with CH4 converted to C2H6, the doubling time is about 95 million years.

The rate of loss relative to a 2575 km sphere is

\[ \nu_{\text{CH}_4} = \frac{F_{\text{H}_2}}{2} \times \frac{C_m+4H_m}{\rho_{\text{CH}_4}}, \]

where \( F_{\text{H}_2} \) is the loss flux of H2 (Cui et al., 2008), \( C_m+4H_m \) represents the average weight of a single methane molecule (as derived from Niemann et al., 2005 \(^{13}\text{C}/^{13}\text{C} \) and D/H ratios) and \( \rho_{\text{CH}_4} \) is the density of methane (see Tokano, 2005). Given this we see that \( \nu_{\text{CH}_4} \approx 0.1 \text{ m}^3/\text{m}^2/\text{yr} \) per million year (i.e., 10 cm of column volume loss per million year related to the surface).

2.1. Ocean coverage

Using the hypsometry found by Lorenz et al. (2011) and the seventh order spherical harmonics fit by Zebker et al. (2009) combined with the geoid of Fig. 1 of Iess et al. (2012), it is possible to calculate the global column volume necessary to cover a given percentage of the surface by

\[ V_i = \frac{H_i \sum_{i=1}^{l}(A_i) - \sum_{i=1}^{l}(H_i A_i)}{\sum_{i=1}^{l} A_i}, \]

where the height vector \( H \) contains the height elements, the vector \( A \) contains the area represented by each element of the height vector and the produced column volume vector \( V \) is in units of \( \text{m}^3/\text{m}^2 \). Note that the surface coverage in this case is \( \sum_{i=1}^{l}(A_i)/\sum_{i=1}^{l} A_i \).

Taking the present reservoir of methane and the speed of loss into account it is possible to convert column volume into past time as

\[ t = \frac{V \rho_{\text{CH}_4} - \sigma_{\text{lake}}}{\nu_{\text{CH}_4} \rho_{\text{CH}_4}}, \]

where the results will be presented for column mass \( \sigma_{\text{lake}} = 200 \) and 2000 kg/m². The atmospheric partial pressure of methane is assumed constant over time. This may introduce a slight error as when the atmospheric humidity increases the amount of methane in the atmosphere will also increase. If the equatorial humidity increases from 45% to 65% the atmosphere would be able to hold 1.4 times its present level or roughly 50 Myrs of production.

By using spherical harmonics it is also possible to estimate what global coverage means for good equatorial coverage. The model used to estimate the coverage at the equator assumes that the polar oceans must be connected to the equator. As such, two cases are of interest. The first is when the lowest amount of liquid at one polar ocean exceeds a level such that one of the basins of the equator is flooded. The second case is when there is such an extent of methane that the liquid can flow freely between the poles.

In all cases, we have neglected any loss of methane to subsurface reservoirs. The nature of the subsurface on Titan is unknown and may be impermeable or it may be that the present lakes are indicative of subsurface reservoirs that are already full. If the subsurface can absorb liquid methane then the timescales computed here are lower limits.

3. Results and discussion

The fraction of the surface of Titan that is covered by liquid is shown in Fig. 1 as a function of time assuming that the only change is a constant rate of increase in the surface inventory of methane going backwards in time. Clearly for extrapolations beyond approaching a billion years this restrictive assumption will not apply due to changes in the solar constant, changes in the rate of methane destruction, and changes in the landscape on Titan. Hence, the fraction covered by liquid should be considered just a rough estimate for these longer times.

At the present epoch the model matches the observed areal coverage of lakes on Titan at about 3%. The fraction of the surface covered by liquid increases rapidly with times past and at about 1 Gyrs ago 50% of the surface is covered. With increasing time (total methane content) the fraction of the surface covered continues to increase but the rate of increase slows.

We find that about 25% global coverage is necessary for the southern polar ocean to flood the equator, as can be seen in Fig. 2a. This coverage corresponds to a time period of 300 million years.
We also find that a global coverage of about 35% results in the polar oceans being fully connected to a global ocean, as can be seen in Fig. 2b. This coverage, in turn, corresponds to a time period of 600 million years ago. These timescales are upper limits in the sense that channels and other small scale features are not included in the spherical harmonics nor detailed in the topographical data of Titan, due to limited detailed measurements. It might also be of interest to note that approximately 20% of the equatorial regions of Titan would be flooded on timescales of a few hundred million years. These results are not inconsistent with models for past climate on Titan (e.g., Lunine and Rizk, 1989; McKay et al., 1993).

4. Conclusions

Given no sources of methane and assuming the present loss rate of methane from the atmosphere, we conclude that the equator of Titan may have been flooded by liquid in the past on a timescale of a few hundred million years. We find that substantial parts of the equator would have been flooded by a polar ocean on a timescale of 300 million years and that the equator would have been connected to a global ocean on a timescale of 600 million years.

The increased relative humidity of methane at the equator would allow storms to shape the surface more readily. Thus, an equatorial sea provides one possible explanation for the fluvial features and shoreline seen near the equator on Titan. Even further back in time, even larger parts of the equatorial region would have been covered by methane. By accepting this model, we speculate that the features observed by Moore and Howard (2010) as fluvial features was formed some 200–300 million years ago when the low latitude RH was higher.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version of http://dx.doi.org/10.1016/j.pss.2012.12.001.