

## Hydrocarbon lakes on Titan

Giuseppe Mitri<sup>a,\*</sup>, Adam P. Showman<sup>a</sup>, Jonathan I. Lunine<sup>a,b</sup>, Ralph D. Lorenz<sup>a,c</sup>

<sup>a</sup> Department of Planetary Sciences and Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721-0092, USA

<sup>b</sup> Istituto di Fisica dello Spazio Interplanetario INAF-IFSI, Via del Fosso del Cavaliere, 00133 Rome, Italy

<sup>c</sup> Now at Space Department, Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA

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### Abstract

The Huygens Probe detected dendritic drainage-like features, methane clouds and a high surface relative humidity (~50%) on Titan in the vicinity of its landing site [Tomasko, M.G., and 39 colleagues, 2005. *Nature* 438, 765–778; Niemann, H.B., and 17 colleagues, 2005. *Nature* 438, 779–784], suggesting sources of methane that replenish this gas against photo- and charged-particle chemical loss on short (10–100) million year timescales [Atreya, S.K., Adams, E.Y., Niemann, H.B., Demick-Montelara, J.E., Owen, T.C., Fulchignoni, M., Ferri, F., Wilson, E.H., 2006. *Planet. Space Sci.* In press]. On the other hand, Cassini Orbiter remote sensing shows dry and even desert-like landscapes with dunes [Lorenz, R.D., and 39 colleagues, 2006a. *Science* 312, 724–727], some areas worked by fluvial erosion, but no large-scale bodies of liquid [Elachi, C., and 34 colleagues, 2005. *Science* 308, 970–974]. Either the atmospheric methane relative humidity is declining in a steady fashion over time, or the sources that maintain the relative humidity are geographically restricted, small, or hidden within the crust itself. In this paper we explore the hypothesis that the present-day methane relative humidity is maintained entirely by lakes that cover a small part of the surface area of Titan. We calculate the required minimum surface area coverage of such lakes, assess the stabilizing influence of ethane, and the implications for moist convection in the atmosphere. We show that, under Titan's surface conditions, methane evaporates rapidly enough that shorelines of any existing lakes could potentially migrate by several hundred m to tens of km per year, rates that could be detected by the Cassini orbiter. We furthermore show that the high relative humidity of methane in Titan's lower atmosphere could be maintained by evaporation from lakes covering only 0.002–0.02 of the whole surface.

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### 1. Introduction

Titan has a massive nitrogen atmosphere with a pressure at surface level of ~1.5 bars, in which molecular nitrogen N<sub>2</sub> is the dominant constituent and methane CH<sub>4</sub> is the second most abundant component, having a mixing ratio of 4.9% near-surface (Niemann et al., 2005). The atmosphere of Titan is photochemically active, producing ethane, ethylene, acetylene and propane as minor components. At the present photolysis rate, the total amount of methane in the atmosphere would be photodissociated in tens of millions of years (Atreya et al., 2006). During the Voyager mission, the hypothesis was ad-

vanced that large areas of Titan's surface would be covered by liquid hydrocarbons (Lunine et al., 1983; Flasar, 1983). Since Cassini–Huygens indicates that such oceans are not present, the atmospheric methane abundance might be the result of a geologically recent outgassing episode from the interior (Tobie et al., 2006). If methane outgassing activity was insufficient to saturate the atmosphere and put liquid on the surface, it must have occurred less than 100 million years ago (or been ongoing over the last 100 million years), and the methane relative humidity has been declining in a steady fashion over time. Alternatively, a larger outgassing episode might have occurred earlier (~500 million years ago in the model of Tobie et al., 2006), saturating the atmosphere and producing reservoirs of liquid methane on (Lorenz and Lunine, 2005) or within the surface (Stevenson, 1992; Kossacki and Lorenz, 1996). Such

\* Corresponding author.

E-mail address: [mitri@lpl.arizona.edu](mailto:mitri@lpl.arizona.edu) (G. Mitri).

reservoirs would release methane into the atmosphere and allow the presently observed photochemical cycle to last for a much longer period of time. In this case the methane relative humidity observed today might be a long-term value fixed by the surface/near-surface reservoirs.

Evidence for surface/subsurface reservoirs of methane is subtle but not absent. The Descent Imager Spectral Radiometer (DISR) Experiment on the Huygens Probe does not show evidence of liquid lying on the surface at the landing site (Tomasko et al., 2005), but liquids are present just below the surface (Niemann et al., 2005). The surface science package accelerometry data admits either wet or dry surface materials (Zarnecki et al., 2005), although preliminary analysis of the probe thermal response hints that the soil had liquid in it (Lorenz et al., 2006b). Otherwise during the descent, DISR has shown dendritic drainage pattern-like features that strongly suggest fluvial erosion caused by, most likely, methane and perhaps ethane (Tomasko et al., 2005). Cassini remote sensing data indicated that dendritic features are common features on the surface (McEwen et al., 2005; Porco et al., 2005; Lopes et al., 2005). More notably, the Cassini narrow-angle camera detected a dark area in the south polar region with smooth boundaries ( $\sim 230$  km by 70 km) during the flyby on June 6, 2005 that could be a lake of liquid hydrocarbons, or remnant lakebed (McEwen et al., 2005). Most intriguing is that the feature sports a shoreline-like ring around the darker area (McEwen et al., 2005).

Clouds with two distinct morphologies have been detected on Titan. Near the south pole, large agglomerations of convective clouds were observed. Clouds as persistent spots are detected between  $-37^\circ$  and  $-44^\circ$  north latitude and between  $0^\circ \pm 90^\circ$  and  $90^\circ \pm 40^\circ$  west longitude, suggesting a correlation with the surface (Griffith et al., 2005).

The overall impression of Titan, then, is of a world bereft of large bodies of methane liquid but with transient streams of such liquid and possibly lakes of small to moderate size. In this paper we consider the hypothesis that such small lakes exist and are maintaining the equatorial near-surface methane mole fraction at 5% against the gradual photochemical loss of methane, under the assumption that globally rainfall and evaporation rates balance. We calculate the areal fraction of lakes required, and address two key questions: (i) Are the observations of atmospheric methane relative humidity and convective frequency consistent with a “desert planet” containing only tiny fractional lake coverage? (ii) Are hydrocarbon (methane–ethane) lakes stable on the surface of Titan? The evaporation rates we calculate are of interest for a number of questions beyond those that motivated this study, such as the longevity of transient (seasonal or rainfall-induced) hydrocarbon lakes or rivers.

In Section 2 we present the model and the results. In Section 2.1 we determine the evaporation rate of liquid hydrocarbons on the surface of Titan and the resulting elevation change of the lake surface. In Section 2.2 we use these evaporation rates to show that the observations of the atmospheric methane relative humidity and convective cloud frequency are consistent with a “desert planet.” In Section 2.3 we discuss the implica-

tions of the data available at the landing site. In Section 2.4 we show that if any surface source for methane convective clouds exists, then it is much more likely to result from an evaporating lake than from presently active volcanism. In Section 3 we summarize tests of this model from observations.

## 2. Model and results

### 2.1. Stability of hydrocarbon lakes

In this section we determine the evaporation rate of methane and of a mixture of methane, ethane and nitrogen, using direct measurements of pressure, ground wind velocity, temperature, and humidity profiles by Huygens instrumentation, and in consequence the elevation change of the lake surface. Tokano et al. (2001) has determined the evaporation rate of pure methane using the surface exchange coefficients for momentum and heat assuming terrestrial conditions; our results reported here represent an improvement by considering actual Titan conditions and liquid mixtures of ethane and methane.

In Section 2.1.1 we review the present knowledge of physical parameters of Titan. In Section 2.1.2 we determine the melting temperature of hydrocarbon lakes. In Section 2.1.3 we present the bulk aerodynamic method, which is a standard method for calculating the evaporation rate from bodies of liquid, and adapt it to Titan. In Section 2.1.4 we determine the transport coefficient for the conditions of a hydrocarbon lake on Titan. Based on the results of the previous sections, in Section 2.1.5 we compute the evaporation rate of a hydrocarbon lake. The symbols and parameters used in the model are summarized in Table 1.

#### 2.1.1. Pressure, ground wind velocity, temperature, air density, humidity and molar fraction of a lake

The GCMS on the Huygens Probe measured a mole fraction of methane  $\text{CH}_4$  almost constant ( $4.92 \times 10^{-2}$ ) between  $\sim 5$  km altitude and the landing site (Niemann et al., 2005). The mole fraction of ethane  $\text{C}_2\text{H}_6$  near the surface was too small to be measured (Niemann et al., 2005). Indirect determination of methane mole fraction from the Voyager data indicates that the mole fraction of methane near the surface is  $\sim 6 \times 10^{-2}$  in equatorial regions and decreases to  $\sim 2 \times 10^{-2}$  in the polar regions (Samuelson and Mayo, 1997). The Huygens Probe measured a ground temperature of 93.7 K (Fulchignoni et al., 2005). Voyager 1 data indicate a temperature difference between the surface at the equator and mid-high latitudes of  $\sim 3$  K or less; we will not know until later in the Cassini mission whether in fact the poles are colder than the equator. The ground temperature probably changes diurnally and seasonally (one Titan year is 29.5 Earth years) by a few Kelvin (Tokano and Neubauer, 2002). General circulation model (GCM) results (Tokano and Neubauer, 2002) suggest seasonal variation of air temperatures near the surface of less than 1 K at low latitudes and up to 4 K at the poles with a maximum temperature of  $\sim 94$  K during the southern summer solstice, and a minimum temperature of  $\sim 90$  K during the polar winter (Tokano and Neubauer, 2002). Huygens measured a surface pressure of 1.47 bars (Fulchignoni

Table 1  
Symbols and parameters

| Symbol               | Unit                              | Value       | Parameter   |
|----------------------|-----------------------------------|-------------|---|
| $a$                  |                                   | 1           | Scalar correction                                 |
| $A$                  | $\text{m}^2$                      |             | Fractional area covered by lakes                  |
| $c_{p,\text{air}}$   | $\text{J mol}^{-1} \text{K}^{-1}$ | 1004        | Air specific heat                                 |
| $C_D$                |                                   | 0.0012      | Drag coefficient                                  |
| $E$                  | $\text{kg m}^{-2} \text{s}^{-1}$  | Computed    | Evaporation rate                                  |
| $F$                  | $\text{W m}^{-2}$                 |             | Heat flux   |
| $F_h$                | $\text{W m}^{-2}$                 |             | Sensible heat flux                                |
| $g$                  | $\text{m s}^{-2}$                 | 1.35        | Gravity   |
| $K$                  |                                   | 0.0013      | Transfer coefficient                              |
| $K_h$                |                                   | 0.0013      | Transfer coefficient of sensible heat             |
| $m$                  |                                   | 28.01       | Mean molecular weight of air                      |
| $m_{\text{CH}_4}$    |                                   | 16.04       | Molecular weight of methane                       |
| $\dot{M}$            | $\text{kg m}^{-2} \text{s}^{-1}$  |             | Globally averaged tropospheric vertical mass flux |
| $P$                  | Pa                                |             | Pressure  |
| $q$                  |                                   |             | Specific humidity                                 |
| $q^*$                |                                   |             | Saturation specific humidity                      |
| $Q$                  | $\text{J mol}^{-1}$               | 8182        | Latent heat of vaporization                       |
| $R$                  | $\text{J mol}^{-1} \text{K}^{-1}$ | 8.314       | Gas constant                                      |
| $RH_{\text{CH}_4}^*$ |                                   |             | Relative humidity of the methane                  |
| $S$                  | $\text{J K}^{-1}$                 |             | Entropy   |
| $T$                  | K                                 |             | Temperature                                       |
| $T_{\text{lake}}$    | K                                 | Computed    | Surface temperature of a lake                     |
| $u_r$                | $\text{m s}^{-1}$                 | 0.1–1.0     | Component of wind speed                           |
| $u_*$                | $\text{m s}^{-1}$                 |             | Frictional velocity                               |
| $z_r$                | m                                 | 1           | Reference height                                  |
| $z_0$                | m                                 |             | Thermal roughness length                          |
| $\alpha$             |                                   | 0.010–0.035 | Charnock constant                                 |
| $\mu$                | J                                 |             | Chemical potential                                |
| $\xi$                |                                   |             | Molar concentration                               |
| $\rho_{\text{air}}$  | $\text{kg m}^{-3}$                |             | Air density                                       |
| $\tau_{\text{over}}$ | s                                 |             | Tropospheric overturn timescale                   |
| $\tau_s$             | Pa                                |             | Surface stress                                    |

et al., 2005). An air density of  $\sim 5 \text{ kg m}^{-3}$  was inferred from the measurement of pressure, temperature and air composition (Fulchignoni et al., 2005). According to GCM results, tides and thermal gradients generate winds with a typical velocity  $0.3\text{--}1 \text{ m s}^{-1}$  near the surface (Tokano and Neubauer, 2002).

For a liquid hydrocarbon body the mole fraction of methane, ethane, and nitrogen are estimated in Lunine (1993) as a function of the mole fraction in the atmosphere for a surface pressure of 1.5 bars. The relative fraction of methane, ethane and nitrogen in the liquid is sensitive to the temperature. For a temperature of 92.5 K and for a  $\text{CH}_4$  mole fraction of  $\sim 4.9 \times 10^{-2}$  in the atmosphere near the surface (see Fig. 2 in Lunine, 1993), the model predicts a mole fraction of  $\text{CH}_4 \sim 0.35$ , of  $\text{C}_2\text{H}_6 \sim 0.60$ , of  $\text{N}_2 \sim 0.05$  in a liquid hydrocarbon body. For the same temperature and for a  $\text{CH}_4$  mole fraction of  $\sim 2.0 \times 10^{-2}$  in the atmosphere near the surface, the model of Lunine (1993) predicts a mole fraction in liquid deposits at Titan's surface of  $\sim 0.08$  for  $\text{CH}_4$ , of  $\sim 0.90$  for  $\text{C}_2\text{H}_6$ , of  $\sim 0.02$  for  $\text{N}_2$ . Because the GCMS measured a mole fraction of  $4.9 \times 10^{-2}$ , however, we adopt this as the nominal value to determine the evaporation rate of a hydrocarbon lake.

### 2.1.2. Melting temperature of a hydrocarbon mixture

The air temperature near the surface of Titan is close to the melting temperature of pure methane and ethane—90.7 K and 90.4 K, respectively (Younglove and Ely, 1987). Nitrogen or ethane dissolved in methane depresses the triple point of the mixture significantly. Although the planetological literature has extensively considered the possible presence of hydrocarbon liquids on Titan's surface (e.g., Lunine et al., 1983; Lunine, 1993), there has not been a careful determination of the actual freezing point of a hydrocarbon mixture and, hence, a definitive determination of whether ethane–methane bodies would be liquid or solid. In this section, we determine first the variation of the triple point. We use the estimate in Lunine (1993) of the mole fraction of methane, ethane and nitrogen for a liquid hydrocarbon body and the Huygens measurement of the methane mole fraction in the atmosphere near the surface to compute the triple point of the hydrocarbon mixture. Successively we determine the melting point of a hydrocarbon mixture. The computation of the hydrocarbon mixture freezing temperature will be used in the subsequent sections.

The chemical potential is defined as  $\mu = (\partial \varepsilon / \partial n)_{S,V}$ , where  $\varepsilon$  is the energy of the system,  $n$  is the number of particles,  $V$  is the volume and  $S$  is the entropy. A system is in thermodynamic equilibrium if its temperature  $T$  and chemical potential  $\mu$  are constant. Mixtures of different components in liquid phase are in equilibrium with the vapor if the temperature of the liquid is equal to the temperature of the vapor, and if the chemical potential of each component in liquid phase is equal to the chemical potential of the vapor phase (see Landau and Lifshitz, 1958). Therefore, the equilibrium of methane in liquid and vapor phases is given by

$$\mu^l(P, T) - \xi_l RT = \mu^v(P, T) - \xi_v RT, \quad (1)$$

where  $\mu^l(P, T)$  and  $\mu^v(P, T)$  are the chemical potential of methane in liquid and vapor phases (indices  $l$  and  $v$  are for liquid and vapor) that are functions of the pressure  $P$  and the temperature  $T$ ,  $\xi_l$  and  $\xi_v$  are the molar concentration of methane in the liquid and vapor, and  $R$  is the gas constant ( $8.314 \text{ J mol}^{-1} \text{ K}^{-1}$ ). We expand the function of Eq. (1) around the point  $(P_0, T_0)$  on the equilibrium curve of the two phases (liquid and vapor) as (Landau and Lifshitz, 1958, pp. 278–281)

$$\begin{aligned} \mu^l(P_0, T_0) \frac{\partial \mu^l(P_0, T_0)}{\partial T} \Delta T + \frac{\partial \mu^l(P_0, T_0)}{\partial P} \Delta P - \xi_l RT \\ = \mu^v(P_0, T_0) + \frac{\partial \mu^v(P_0, T_0)}{\partial T} \Delta T + \frac{\partial \mu^v(P_0, T_0)}{\partial P} \Delta P \\ - \xi_v RT \end{aligned} \quad (2)$$

with  $\Delta P = P - P_0$  and  $\Delta T = T - T_0$ . At equilibrium of pure methane, the chemical potentials of the methane in liquid and vapor phase are  $\mu^l(P_0, T_0) = \mu^v(P_0, T_0)$ . A methane, ethane and nitrogen mixture in liquid and vapor phases is a thermodynamic system with three components, two phases and, therefore, the system has three degrees of freedom. The differential of the chemical potential is written as  $d\mu = -SdT + VdP$  where  $S$  is the entropy,  $T$  is the temperature,  $V$  is the volume, and  $P$  is the pressure. If the pressure  $P$  is a constant, then the

entropy of the liquid and vapor phases is given by

$$S^{l,v} = -\frac{\partial \mu^{l,v}(P, T)}{\partial T}. \quad (3)$$

The phase transition between the liquid and vapor is reversible, and the temperature  $T$  is constant during the phase transition. Therefore, we can write the heat of transition as (Landau and Lifshitz, 1958)

$$Q = -\int_{S^l}^{S^v} T dS = -T(S^v - S^l). \quad (4)$$

Combining Eqs. (2)–(4) for a phase transition with  $\Delta P = 0$ , we can write the variation of the triple point for a mixture of methane, ethane and nitrogen considering the molar concentration of methane in the liquid and in vapor phase as

$$\Delta T = -\frac{RT_{\text{tp}}^2(\xi_l - \xi_v)}{Q}, \quad (5)$$

where  $T_{\text{tp}}$  is the triple point (the methane triple point is 90.68 K). The latent heat of vaporization of methane  $Q$  at a pressure of 1.013 bar and temperature of 111.4 K is  $5.1 \times 10^5 \text{ J kg}^{-1}$  corresponding to  $8182 \text{ J mol}^{-1}$  (Younglove and Ely, 1987). For a system with a molar concentration of  $\text{CH}_4$  of 0.35 in liquid phase and  $4.9 \times 10^{-2}$  in vapor phase, the variation in triple point is  $\Delta T = -2.52 \text{ K}$  and, therefore, the melting temperature (last occurrence of solid phases) of the hydrocarbon mixture is 88.16 K.

### 2.1.3. Bulk aerodynamic method

We determine the evaporation rate  $E$  [ $\text{kg m}^{-2} \text{ s}^{-1}$ ] of liquid methane and of a mixture of methane, ethane and nitrogen on the surface of Titan with the bulk aerodynamic method (see Fairall et al., 1996; Edson et al., 2004). This method provides a parameterized means for estimating the evaporation rate under the assumption that the evaporation rate is proportional to the difference between the saturation humidity and the actual humidity, which is approximately true in laboratory and field experiments on Earth. The evaporation rate is given by (Fairall et al., 1996)

$$E = \rho_{\text{air}} K (q^* - q) u_r, \quad (6)$$

where  $\rho_{\text{air}}$  is the density of the air,  $K$  is the transport coefficient evaluated at a reference height  $z_r$ ,  $q^*$  and  $q$  are the saturation specific humidity and the specific humidity respectively, and  $u_r$  is the horizontal component of the averaged wind speed relative to the surface at height  $z_r$ . A periodic fluctuation in time does not change the average value of  $E$  or the results of our model. The relationships used in the bulk aerodynamic method (for example, the evaporation rate given by Eq. (6), the transport coefficient by Eq. (13) in Section 2.1.4, and the sensible heat flux Eq. (20) in Section 2.1.5) are derived from field experiments where vapor and temperature profiles and atmospheric fluxes were collected (e.g., Edson et al., 2004).

Physically, we expect that evaporated molecules first diffuse through a thin laminar boundary layer, above which they are

transported away from the lake surface by turbulent air motions. The transport coefficient, which is dimensionless, parameterizes the efficiency of these processes and hence depends in general on both wind speed and surface properties (high wind speeds and rough surfaces promote turbulence, leading to larger turbulent fluxes). We return to these issues in Section 2.1.4.

The methane specific humidity is given by

$$q_{\text{CH}_4} = \frac{m_{\text{CH}_4} p_{\text{CH}_4}}{m p} = 0.573 \xi_{\text{CH}_4}, \quad (7)$$

where  $m_{\text{CH}_4}$  is the molecular weight of methane (16.04),  $m$  is the mean molecular weight of air that we take equal to the molecular weight of the nitrogen  $\text{N}_2$  (28.01) that is the dominant constituent of the atmosphere,  $p_{\text{CH}_4}$  is the vapor pressure of methane,  $p$  is the atmospheric pressure, and  $\xi_{\text{CH}_4}$  is the methane mole fraction in the air. The methane saturation specific humidity is given by

$$q_{\text{CH}_4}^* = 0.573 \frac{p_{\text{CH}_4}^*}{p}, \quad (8)$$

where  $p_{\text{CH}_4}^*$  is the methane saturation vapor pressure. Fig. 1 shows the saturation vapor pressure of methane and ethane as a function of temperature. The ethane saturation specific humidity is given by

$$q_{\text{C}_2\text{H}_6}^* = 1.096 \frac{p_{\text{C}_2\text{H}_6}^*}{p}, \quad (9)$$

where  $p_{\text{C}_2\text{H}_6}^*$  is the ethane saturation vapor pressure (molecular

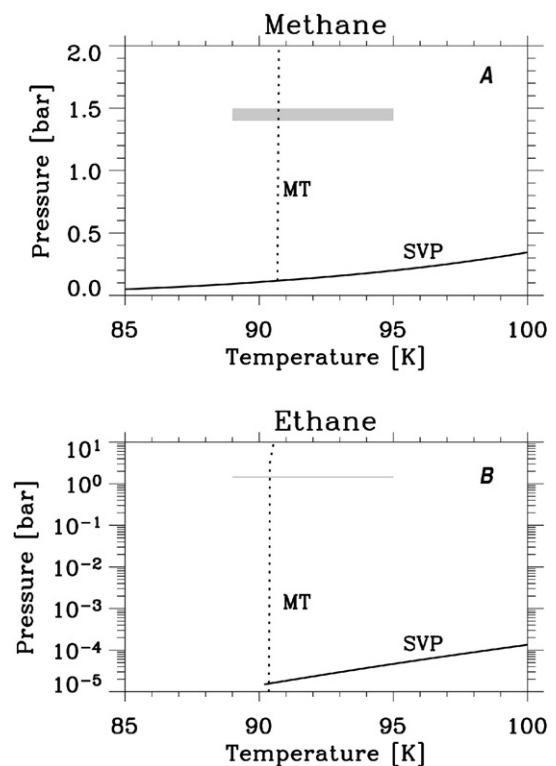


Fig. 1. Saturation vapor pressure SVP (solid line) and melting temperature MT (dotted line) of methane and ethane (Younglove and Ely, 1987). Grey area shows the pressure  $P$ –temperature  $T$  range for conditions of the surface of Titan ( $1.4 \leq P \leq 1.5 \text{ bar}$ ;  $89 \leq T \leq 95 \text{ K}$ ).



weight of ethane  $m_{\text{C}_2\text{H}_6} = 30.71$ ). The relative humidity, expressed in percent, is

$$RH_{\text{CH}_4}^* = 100 \frac{p_{\text{CH}_4}}{p_{\text{CH}_4}^*}. \quad (10)$$

The nitrogen is abundant in the atmosphere, so its high evaporation rate will be almost canceled by an equal rate of dissolution from the air to the liquid, while the saturation vapor pressure of ethane is small and therefore not a significant contributor to the evaporation of a lake. Therefore, only the methane is relevant for Titan lake evaporation. We consider that the hydrocarbon liquid is an ideal solution and, then, the vapor pressure and the saturation vapor pressure of each component is equal to the vapor pressure and the saturation vapor pressure of the pure substance times the mole fraction in the solution (Raoult's law). Therefore, the saturation specific humidity of the methane in a mixture of methane, ethane and nitrogen is given by

$$q_{\text{CH}_4}^* = 0.573 \frac{\xi_{\text{CH}_4} p_{\text{CH}_4}^*}{p} \quad (11)$$

and the methane specific humidity is given by

$$q_{\text{CH}_4} = 0.573 \frac{\xi_{\text{CH}_4} p_{\text{CH}_4}}{p}. \quad (12)$$

#### 2.1.4. Transport coefficient

We determine the transport coefficient of Eq. (6) for plausible physical conditions of hydrocarbon lakes on Titan. The transport coefficient is related to the roughness length and is given by (Fairall et al., 1996; Edson et al., 2004)

$$K = \left[ \frac{\kappa a}{\ln(z_r/z_0)} \right]^2, \quad (13)$$

where  $\kappa$  is the von Kármán constant ( $\kappa = 0.40$ ),  $a$  is a scalar correction ( $a = 1$ ) (Fairall et al., 1996),  $z_r$  is a reference height and  $z_0$  is the thermal roughness length. The thermal roughness length is given by (Fairall et al., 1996)

$$z_0 = \frac{\alpha u_*^2}{g} + 0.11 \frac{\eta_{\text{air}}(T)}{\rho_{\text{air}} u_*}, \quad (14)$$

where  $\alpha$  is the Charnock constant and  $g$  is the gravity constant ( $1.35 \text{ m s}^{-2}$  for Titan).  $\alpha$  is an empirical constant introduced for the first time by Charnock (1955) to describe the relationship between the sea surface roughness  $z_0$  and the friction velocity  $u_*$  as  $z_0 = \alpha u_*^2/g$ . In the literature the Charnock constant value ranges between 0.010 and 0.035 (Fairall et al., 1996). We will consider values spanning this range, although we emphasize that, because of the logarithm in Eq. (13), the transport coefficient has only a modest dependence on the Charnock constant.  $\eta_{\text{air}}(T)$  is the temperature dependent  $T$  air viscosity given by the viscosity of the nitrogen as (Lorenz, 1993)

$$\eta_{\text{air}}(T) = 1.718 \times 10^{-5} + 5.1 \times 10^{-8} (T - 273) \text{ [Pa s]}. \quad (15)$$

For the ground temperature of the Huygens landing site the air viscosity is  $\eta_{\text{air}}(93.7\text{K}) = 8 \times 10^{-6} \text{ Pa s}$ . The friction velocity

$u_*$  is related to the surface stress  $\tau_s$  as

$$u_* = \left( \frac{\tau_s}{\rho_{\text{air}}} \right)^{1/2}. \quad (16)$$

The surface stress is given by

$$\tau_s = \rho_{\text{air}} C_D u_r^2, \quad (17)$$

where  $C_D$  is the drag coefficient at some reference height and  $u_r$  is the wind speed relative to the lake surface at that same height. We can write the friction velocity as

$$u_* = C_D^{1/2} u_r. \quad (18)$$

The square root of the drag coefficient at the elevation  $D$  is  $C_D^{1/2} = \kappa (\ln D/z_0)^{-1}$ , where  $\kappa$  is the von Kármán constant. For a thermal roughness length  $z_0$  of  $10^{-5} \text{ m}$  and  $D = 1 \text{ m}$ ,  $C_D^{1/2} \sim 0.035$  (the square root of the drag coefficient for the Earth's marine layer is  $C_D^{1/2} \approx 0.035$ ; Edson et al., 2004). In this model, we consider as reference value of the square root of the drag coefficient of a hydrocarbon lake on Titan  $C_D^{1/2} \sim 0.035$ . For a ground wind speed on Titan of  $1 \text{ m s}^{-1}$ , the friction velocity is then  $\sim 0.035 \text{ m s}^{-1}$ . For Earth, the friction velocity is typically  $u_* \sim 0.3 \text{ m s}^{-1}$ . For Titan, a lower wind velocity could decrease up to an order of magnitude the frictional velocity compared to typical values over the Earth oceans.

For  $\alpha = 0.010$  and  $u_* \sim 0.035 \text{ m s}^{-1}$ , the thermal roughness length for Titan is of order  $z_0 = 1.4 \times 10^{-5} \text{ m}$ . The flow regime is characterized by the roughness Reynolds number  $Re_r$ , given by

$$Re_r = \frac{u_* z_0 \rho_{\text{air}}(T)}{\eta_{\text{air}}(T)}. \quad (19)$$

When  $Re_r < 0.13$  the surface stress is supported by viscous shear and the flow is aerodynamically smooth; when  $Re_r > 2.0$  the flow stress is given by viscous transfer and the flow is aerodynamically rough (Fairall et al., 1996). The typical roughness Reynolds number for the conditions of Titan is  $Re_r \sim 0.31$ . Decreasing the friction velocity  $u_*$ , the roughness Reynolds number  $Re_r \rightarrow 0.11$ , and the surface roughness  $z_0 \rightarrow 0.11 \eta_{\text{air}}/\rho_{\text{air}} u_*$ . Increasing  $u_*$ , the roughness Reynolds number increases, and the surface roughness  $z_0 \rightarrow \alpha u_*^2/g$ . In the case of the friction velocity  $0.035 \text{ m s}^{-1}$  and  $Re_r \sim 0.31$ , the surface roughness is given by both the terms of Eq. (14).

We compute that, for an atmospheric reference height of  $z_r = 1 \text{ m}$  and a Charnock constant of 0.01, for a liquid hydrocarbon body on the surface of Titan the transfer coefficient  $K \sim 0.0016$  for a wind speed of  $0.1 \text{ m s}^{-1}$  and  $K \sim 0.0013$  for a wind speed of  $1 \text{ m s}^{-1}$ . When a Charnock constant of 0.035 is instead adopted,  $K$  becomes 0.0015 for a wind speed of  $1 \text{ m s}^{-1}$  and does not change at all for a wind speed of  $0.1 \text{ m s}^{-1}$ . This confirms the modest (<15%) influence of the uncertainty in Charnock constant on the transfer coefficient. The choice of the reference height in the low atmospheric layers does not change the results of the bulk aerodynamic method. We adopt a reference height of  $1 \text{ m}$  because the Huygens Probe collected measurements after landing within a meter of the actual surface.

### 2.1.5. Evaporation rate and surface temperature of a lake

The evaporation depends on the wind speed, air humidity, ground temperature, and composition of the hydrocarbon mixture. We consider a range of temperatures corresponding to a plausible (but as yet unmeasured) seasonal variation in temperature near the surface. Fig. 2 shows the evaporation rate of methane and of a mixture of methane, ethane and nitrogen and the change of lake surface elevation (given by the evaporation rate divided by the density) in a temperature range of 85–100 K for wind velocities of  $0.1 \text{ m s}^{-1}$  (dotted) and  $1 \text{ m s}^{-1}$  (solid). The density of liquid methane is  $453.4 \text{ kg m}^{-3}$  and of liquid ethane is  $654.1 \text{ kg m}^{-3}$  at a temperature of 92.5 K (Younglove and Ely, 1987).

Lorenz (2006) has determined the wind in the lowest 0.5 m of the atmosphere from the post-impact cooling of the Huygens probe, suggesting an upper limit of  $0.25 \text{ m s}^{-1}$  at that time and place. The presence of sand dunes on the Titan surface (Lorenz et al., 2006a) shows that the wind at least sometimes exceeds the  $0.5\text{--}1 \text{ m s}^{-1}$  saltation threshold (Lorenz et al., 2006c). In our studies here, we assume the wind velocity near the surface ranges between  $0.1$  and  $1 \text{ m s}^{-1}$ . The evaporation rate (Fig. 2) is computed in a range of wind velocity of  $0.1\text{--}1 \text{ m s}^{-1}$ .

The evaporation of the methane causes rapid cooling of the lake surface and depressing of the lake surface temperature. This cooling is counterbalanced by downward transport of sensible heat from the atmosphere into the lake. We determine the equilibrium surface temperature of a lake as follows. The sensible heat flux from the lake into the atmosphere is given by (Fairall et al., 1996)

$$F_h = \rho_{\text{air}} c_{p,\text{air}} K_h (T_{\text{lake}} - T_{\text{air}}) u_r, \quad (20)$$

where  $c_{p,\text{air}}$  is the air specific heat ( $c_{p,\text{air}} = 1004 \text{ J kg}^{-1} \text{ K}^{-1}$  is the specific heat of the nitrogen),  $K_h$  is the transfer coefficient of the sensible heat,  $T_{\text{lake}}$  is the surface temperature of the lake, and  $T_{\text{air}}$  is the air temperature. Note that, as expected, a lake temperature greater than the air temperature leads to a positive  $F_h$ , indicating a sensible heat flux from the lake into the atmosphere; similarly, a lake temperature colder than the air temperature leads to a negative  $F_h$ , indicating an energy flux from the atmosphere into the lake. We take  $K = K_h$ , indicating that turbulence acts similarly in the transport of moisture as in the transport of heat (see the discussion on transfer coefficients in Fairall et al., 1996). The saturation vapor humidity is a function of the lake temperature  $T_{\text{lake}}$  and is given approximately by

$$q^*(T) = q_0^* e^{(L/R)(1/T_0 - 1/T_{\text{lake}})}, \quad (21)$$

where  $q_0^* = q^*(T_0)$  and  $T_0$  is a reference temperature, where  $L$  is the latent heat of methane vaporization. A lake is in equilibrium with the atmosphere when the latent heat flux balances the sensible heat flux  $LE + F_h = 0$ . Note here that positive evaporation rates ( $E > 0$ ) imply latent heat fluxes from the lake into the atmosphere. Therefore, in this energy balance, we expect  $LE > 0$  and  $F_h < 0$  (the upward latent heat flux is balanced by the downward sensible heat flux). The full energy balance should also include the absorbed solar radiation and absorbed and radiated infrared energy fluxes, but these fluxes sum to

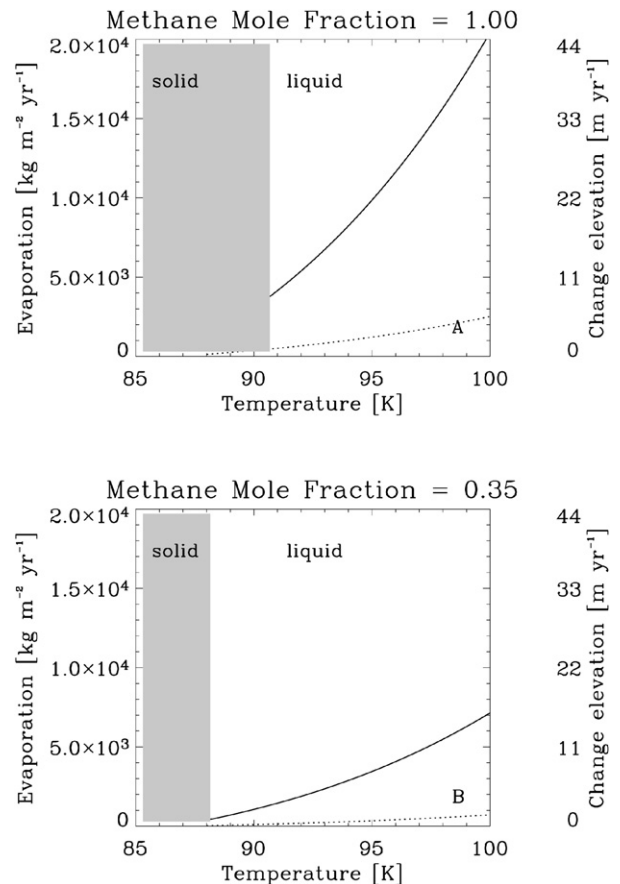


Fig. 2. Evaporation rate (left y-axis) (Eq. (6)) and change of lake surface elevation (right y-axis) of methane (A) and of a mixture of methane, ethane and nitrogen (B), in a temperature range of 85–100 K for a wind velocity of  $0.1$  and  $1 \text{ m s}^{-1}$  (dotted and solid curves, respectively). For a pure liquid methane body at the temperature of 91 K the evaporation rate for a wind speed of  $1 \text{ m s}^{-1}$  is  $5 \times 10^3 \text{ kg m}^{-2} \text{ yr}^{-1}$  (A) and for a mixture of methane (mole fraction 0.35), ethane (mole fraction 0.60) and nitrogen (mole fraction 0.05) is  $1.5 \times 10^3 \text{ kg m}^{-2} \text{ yr}^{-1}$  (B). The change of lake surface elevation is given by the evaporation rate divided by the density, where the density of methane is  $453.5 \text{ kg m}^{-3}$ .

$< 2 \text{ W m}^{-2}$  and can be neglected. Therefore, we compute the equilibrium surface temperature of a lake by

$$L(q^* - q) \cong -c_{p,\text{air}}(T_{\text{lake}} - T_{\text{air}}). \quad (22)$$

Fig. 3 shows the sensible heat flux  $F_h$  (dotted line) and the negative of the latent heat flux  $-LE$  (solid line) as a function of lake surface temperature. Both quantities are negative under realistic conditions where the lake is colder than the atmosphere. Equilibrium corresponds to the location where the solid and dotted curves cross (the lake gains thermal energy from the atmosphere at the same rate as it loses energy by evaporation). For an air temperature of 94 K and a methane mole fraction in the lake of  $\xi_{\text{CH}_4} = 0.35$ , the equilibrium temperature of the lake is  $\sim 91 \text{ K}$ . At this temperature, the evaporation of a lake with  $\xi_{\text{CH}_4} = 0.35$  and an air wind speed of  $1 \text{ m s}^{-1}$  is  $\sim 1.5 \times 10^3 \text{ kg m}^{-2} \text{ yr}^{-1}$  (Fig. 2), and the latent and sensible heat fluxes are  $\sim -20 \text{ W m}^{-2}$  (Fig. 3). For a pure methane lake, the methane evaporation decreases the surface temperature down to the melting temperature and, then, the lake freezes

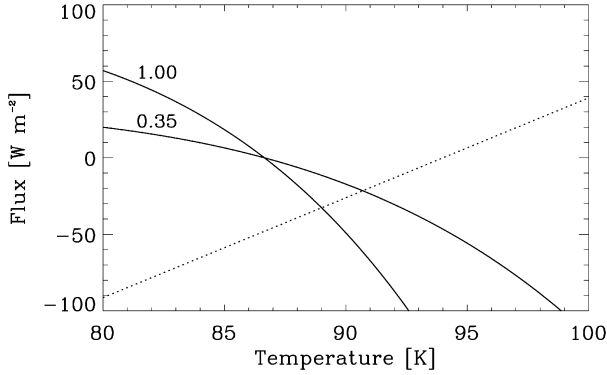


Fig. 3. Equilibrium temperature of the surface of a lake for a methane specific humidity of the air of  $4.92 \times 10^{-2}$  and a temperature of the air of  $T_{\text{air}} = 94$  K. The lake temperature would stabilize when the latent heat flux balances the sensible heat (computed using Eq. (22)). The figure shows the negative of the latent heat flux  $-LE$  in solid line and sensible heat flux  $F_h$  in dotted line. The equilibrium temperature of a lake with a methane mole fraction  $\xi_{\text{CH}_4} = 0.35$  is  $\sim 91$  K. For a pure methane lake (methane mole fraction = 1.00) the methane evaporation decreases the surface temperature down to the freezing temperature.

(Fig. 3). Hydrocarbons can freeze, depending on the temperature, the mole fraction of methane, and wind velocity (see the models in Figs. 2 and 3).

If a lake is present on the surface, the large evaporation of liquid hydrocarbons implies rapid changes of lake surface elevation (given by evaporation rate divided by density) of the order of  $\sim 3\text{--}10$   $\text{m yr}^{-1}$  for a temperature of 91 K (Fig. 2). Therefore, the shorelines of a hydrocarbons lake on the surface of Titan should experience large changes over time. For example, for a slope of  $10^{-2}$  (equivalent to a 100 m elevation change over a 10 km distance), lakes would retreat at up to several hundred meters to several kilometers per year. The altimeter profile in Elachi et al. (2005), on the other hand, shows a slope of 100 m in 100 km, or  $10^{-3}$ . For this value the rate of shoreline retreat would be up to  $\sim 30$   $\text{km yr}^{-1}$ . These estimates are upper limits to the change, because rainfall into the lake's watershed will supply methane back into the lake, counteracting the hydrocarbon evaporation. On the other hand, if lakes cover only a small fractional area of Titan, then a large fraction of the methane may fall as rain outside the lake's watershed. For a watershed diameter of 100 km and a mean tropospheric horizontal wind speed of  $u \sim 1$   $\text{m s}^{-1}$ , for example, this only requires the lag between evaporation and rain formation to exceed  $\sim 10^5$  s.

Our model predicts that the evaporation of hydrocarbons on the Titan surface is  $\sim 0.3 \times 10^3\text{--}5 \times 10^3$   $\text{kg m}^{-2} \text{yr}^{-1}$ , implying large changes over time of lake elevation of  $\sim 0.3\text{--}10$   $\text{m yr}^{-1}$ . Assuming a steady state where the average rate of evaporation and precipitation are equal, for a fractional area lake coverage of 0.004 and a lake elevation change of 10  $\text{m yr}^{-1}$ , we determine that the global precipitation rate on the surface of Titan to be 0.04  $\text{m yr}^{-1}$ . During a thunderstorm the first drops evaporate (Lorenz, 1993; Samuelson and Mayo, 1997) and increase the humidity of the air below, forming a saturated rain shaft through which subsequent drops can fall to the ground. Future modeling is required to determine how much, if any, rain can reach the surface.

Presumably, if lakes are disappearing in some regions, they are appearing in others, so shorelines could be moving in either direction. The rapid shoreline changes predicted here suggest that repeat Cassini observations of putative lake-like features should be performed at intervals of a year or more: any shoreline changes would provide evidence that candidate lake-like features are indeed lakes.

## 2.2. Lake coverage and tropospheric overturn

We show that the observations of the atmospheric methane relative humidity and convective clouds (clouds formed by upwelling motions in the atmosphere) frequency are consistent with a “desert planet,” containing only tiny fractional areal coverage of lakes.

General circulation model (GCM) results (Tokano et al., 2001, 1999) have shown that because the diabatic heating is weak in Titan's troposphere ( $< 10^{-7}$   $\text{K s}^{-1}$ ) compared to the Earth's, the circulation strength is weaker than on Earth. Moreover, these papers indicate that the characteristic tropospheric vertical wind speed is close to  $10^{-5}$   $\text{m s}^{-1}$ , with values reaching  $\sim 10^{-4}\text{--}10^{-3}$   $\text{m s}^{-1}$  in the convergence zone near the equator (Tokano et al., 2001). Moreover, Tokano et al. (2001) have shown that the maximum zonal wind speed in the troposphere is 3  $\text{m s}^{-1}$ . For a vertical wind speed of  $10^{-5}$   $\text{m s}^{-1}$  and a tropopause height of  $\sim 50$  km, the troposphere overturn timescale is then  $\sim 200$  years.

McKay et al. (1989) have demonstrated that the Titan atmosphere is almost, if not completely, in a state of global radiative equilibrium. The uncertainty in their models allows for up to 1% of the incident solar heat flux to be transported by convection in the lower 4 km of the atmosphere only. GCM results do not disagree with the assumption that the observed clouds are of convective nature (Tokano, 2005), even if the origin of the clouds is still not demonstrated in a definitive fashion. This might shorten the overturn time in the troposphere, although likely not by much. Thus we adopt 200 years for the overturn timescale  $\tau_{\text{over}}$ . The globally averaged tropospheric vertical mass flux [ $\text{kg s}^{-1}$ ] is given by

$$\dot{M} \cong \frac{p}{g \tau_{\text{over}}}, \quad (23)$$

where  $p$  is the atmospheric pressure. The globally averaged vertical flux of methane [ $\text{kg s}^{-1}$ ] is given by the evaporation rate of a hydrocarbon lake times the fractional area covered by the lakes

$$\dot{M}_{\text{CH}_4} \cong EA = \rho_{\text{air}} K (q^* - q) u_r A, \quad (24)$$

where  $A$  is the fractional area of Titan covered by lakes (defined as any area where methane can rapidly evaporate from the surface). Note that, in Eq. (24),  $q^*$  is the saturation humidity of the lake surface, which may be a few K colder than the air temperature (Section 2.1.5). The ratio between  $\dot{M}_{\text{CH}_4}$  and  $\dot{M}$  is, approximately, the specific humidity  $q$ . Therefore, we can write

$$\frac{\dot{M}_{\text{CH}_4}}{\dot{M}} \cong q \cong \frac{\rho_{\text{air}} K (q^* - q) u_r A g \tau_{\text{over}}}{p}. \quad (25)$$

Solving for  $q$ , we obtain

$$q \cong q^* \left[ 1 + \frac{p}{\rho_{\text{air}} K u_r A \tau_{\text{over}}} \right]^{-1} \cong q^* \left[ 1 + \frac{0.05}{A} \left( \frac{10 \text{ yr}}{\tau_{\text{over}}} \right) \right]^{-1}, \quad (26)$$

where the numerical estimate on the right uses  $\rho_{\text{air}} = 5 \text{ kg m}^{-3}$ ,  $u_r = 1 \text{ m s}^{-1}$ ,  $p = 1.5 \text{ bars}$ , and  $K = 0.0013$ . At constant  $A$ ,  $\tau_{\text{over}} \rightarrow 0$  implies  $q \rightarrow 0$ . In this case, the tropospheric overturning is so fast that there is insufficient time for evaporating methane to produce large relative humidities (any methane that evaporates quickly condenses in updrafts and gets rained out, leading to small atmospheric methane abundance). In the limit  $\tau_{\text{over}} \rightarrow \infty$ , on the other hand,  $q \rightarrow q^*$ . In this case, the overturning is extremely sluggish, so methane has plenty of time to saturate the troposphere. Similarly, at constant  $\tau_{\text{over}}$ , increasing (decreasing) the fractional lake area  $A$  increases (decreases) the total mass of evaporating methane, which increases (decreases)  $q$ .

Equation (26) shows that large relative humidities can be accommodated by small fractional lake coverage. For tropospheric overturning timescales determined from the GCM's of 200 years, a 50% relative humidity can result from lakes covering only 0.002 (0.2%) of the surface. If we assume a shorter turnover time, aided by tropospheric convection, the lake areal coverage must be larger to explain the observed relative humidity. The numerical estimate of Eq. (26) assumes a wind speed of  $1 \text{ m s}^{-1}$ . If the wind speed were  $0.1 \text{ m s}^{-1}$ , then the evaporation rate would be  $\sim 10$  times slower and the fractional lake coverage is correspondingly higher: 0.02 (2%) for the adopted GCM overturn time. Wind speeds between  $0.1$  and  $1 \text{ m s}^{-1}$  are a reasonable range for surface values based on the GCM models and in-situ measurements.

The seasonal variation of the air temperature can change the fractional lake coverage. The predicted seasonal variation of air temperatures near the surface of less than 1 K at low latitudes (Tokano and Neubauer, 2002) suggests that the results of this model, based on only one air temperature measurement from Huygens probe, represent an adequate description of the time and global average lake fractional area coverage. On other hand, the larger predicted seasonal variations of air temperature up to 4 K at the poles (Tokano and Neubauer, 2002), can induce larger seasonal changes in lake fractional areal coverage in the polar regions.

### 2.3. Probe landing site and fluvial processes

Three pieces of information are available at the probe landing site. First, the rounded cobbles and the size distribution of material suggest that liquids have transported material in this area (Tomasko et al., 2005). Second, there is the suggestion of scour beneath one of the cobbles, but no evidence that liquid fills this depression. It is entirely possible that on small scales liquid could disappear by infiltrating the ground rather than by evaporation.

In this connection, a third piece of information is that the heated inlet of the GCMS instrument (Niemann et al.,

2005) yielded methane (and ethane and other compounds) after landing, when it was embedded some centimeters into the ground. A study of the heat balance of the inlet pipe (Lorenz et al., 2006b) suggests that the ground was 'damp'—there was enough liquid methane present to remove heat from the inlet by conduction, convection and evaporation to limit the temperature rise of the inlet heater (much as damp sand on Earth 'feels' colder than dry sand at the same temperature, because it more effectively abstracts heat from one's hand).

Future work might attempt to model the diffusion of vapor through a porous regolith (much in the spirit of work on retention of ice in the martian regolith). However, the rate at which a soaked regolith dries out will depend on its porosity and particle size (which are not well-constrained) and in particular on the composition of the liquid. Since ethane was detected by the GCMS on the surface, it may be that the surface fluid has a substantial ethane mixing ratio, and its methane fraction is near to or is in equilibrium with the atmosphere above it in which case it could remain damp indefinitely.

In summary, there are some very interesting analogs with terrestrial hydrology and meteorology, although the data at hand do not permit much progress. If the surface is not porous, it would appear the last fluvial event occurred on the order of years or perhaps decades ago.

### 2.4. Surface/atmosphere interactions: lakes and volcanoes

Recently Roe et al. (2005) proposed that the spatially-persistent cloud feature they observed on Titan might come from outgassing of methane volcanoes, and that these volcanoes were also responsible for resupplying atmospheric methane against stratospheric photolytic destruction. To explain the atmospheric methane abundance, it is only necessary that the total atmospheric methane reservoir have been erupted within the last  $10^7$  yr. Here we argue that a very small areal coverage of preexisting methane lakes can supply the methane as well. For a current atmospheric methane column abundance of  $6000 \text{ kg m}^{-2}$ , the required methane volcanic outgassing rate is only  $6 \times 10^{-4} \text{ kg m}^{-2} \text{ yr}^{-1}$ . The evaporation rate from a lake is  $0.3\text{--}5.0 \times 10^3 \text{ kg m}^{-2} \text{ yr}^{-1}$ . Therefore, the volcanic outgassing required to explain the atmospheric methane reservoir is equivalent to lake evaporation if lakes cover only  $10^{-8}\text{--}10^{-7}$  of Titan's surface (corresponding to a lake area of  $8 \times 10^5\text{--}8 \times 10^6 \text{ m}^2$ ). Stated another way, even if only 0.1% of Titan is covered by lakes, the lake evaporation would exceed the required volcanic outgassing by a factor  $10^4\text{--}10^5$ . If any surface source for methane convective clouds exists (as emphasized by both Roe et al., 2005, and Griffith et al., 2005), then it is much more likely to result from an evaporating lake than from volcanism. We would therefore expect such lakes to be present in the vicinity of the persistent cloud feature reported by Roe et al. and Griffith et al.

## 3. Testing the hypothesis

We have demonstrated in a formal sense that the high relative humidity of  $\sim 50\%$  on the surface of Titan can result



from evaporation from lakes covering only 0.002–0.02 of the whole surface, and sustain a cycle of convective clouds and precipitation operating with a cycle time of centuries. Intense precipitation events can cause occasional intense rain and flash flooding, which would produce erosional features (channels and valleys) (Lorenz, 2000; Lorenz et al., 2005) despite the fact that Cassini–Huygens observations have shown a somewhat dry planet. After such events, liquid hydrocarbons would accumulate into ground depressions, forming lakes. Our model represents just one explanation for the methane relative humidity and surface state of Titan seen by Cassini and Huygens; alternatives are a near-surface methane reservoir resident in a porous crust, or no reservoir with a methane relative humidity that is declining in a secular fashion. The principal tests of our model lie in the existence of lakes with a surface areal coverage exceeding 0.2–2%, and time-variability in the abundance of liquid—hence shoreline level—in any lakes detected.

To date less than 10% of Titan's surface has been observed with the radar system at spatial resolution better than a kilometer; the coverage via optical remote sensing is substantially greater but at significantly poorer (kilometers) spatial resolution. Thus the optical remote sensing instruments—the Imaging Science Subsystem (ISS) and the Visible and Near-Infrared Mapper (VIMS)—are capable of seeing only relatively large lakes. Were a single circular lake to occupy 0.002% of the surface, our minimum coverage value, it would have a diameter of 400 km. The south polar lake-like feature is about 11% this size, but a number of smaller poorly defined dark features are present nearby. The poles have been particularly poorly covered with the radar; the T7 pass that would have extended to very high southern latitudes was truncated just beyond 60° S by a technical problem. Near the poleward end of the pass a bright area is embayed by a region that is much darker and hence potentially contains liquids (Elachi et al., 2006). Thus, there is circumstantial evidence that exposed liquids exist at high southern latitudes, but by the end of the prime mission much better constraints on liquid coverage at both poles should be available. As the revised version of this paper was being submitted to *Icarus*, the Cassini Radar Science Team announced the discovery of a series of what appear to be strong candidates for methane or methane–ethane-filled lakes at a latitude above 70° N (NASA Press Release 7.27.06 and Stofan et al., submitted for publication); further passes at high latitudes in both hemispheres will be required to determine the total areal coverage of such lakes.

The evaporation of hydrocarbons on the Titan surface is of the order of  $\sim 0.3 \times 10^3 - 5 \times 10^3 \text{ kg m}^{-2} \text{ yr}^{-1}$ , implying large changes over time of lake elevation of the order of  $\sim 0.3 - 10 \text{ myr}^{-1}$  and of the lake shorelines of the order of several hundreds meters to tens of kilometers  $\text{yr}^{-1}$ . Repeat observations of regions where candidate lake features have been seen by Cassini spacecraft remote sensing instruments early in the mission, such as at the south pole, are capable of revealing shoreline changes consistent with our model. The spatial resolution of the south polar image showing the large lake-like feature is marginal for this experiment, but the upper end of our shoreline change would be detectable over a few years.

Radar's 300 meter resolution provides a better chance to observe changes, and if the T7 "shoreline" in the high southern latitudes is indeed abutting an active lake system, we expect to see changes in its detailed pattern of embayments. North polar passes with the radar planned beginning in 2006 will provide a potential opportunity for establishing lake shoreline boundaries there as well, if lakes exist. The four year prime mission of Cassini could afford the chance to see changes if either pole could be reobserved late in the tour, but a possible extended mission of several years would provide a higher probability of seeing such changes.

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