Titan's lakes chemical composition: Sources of uncertainties and variability

D. Cordier, O. Mousis, J.I. Lunine, S. Lebonnois, P. Rannou, P. Lavvas, L.Q. Lobo, A.G.M. Ferreira

1. Introduction

The surface of Saturn's hazy-shrouded moon Titan had long been proposed to be at least partly hidden by oceans or seas, on the basis of the stability of liquid methane and ethane at the surface (Flasar, 1983; Lunine et al., 1983; Lorenz et al., 2003). The presence of a global ocean on Titan was excluded from ground-based radar observations in the mid 1990s (Muhleman et al., 1995). In mid 2006, dark, lake-like features of a range of sizes were detected at Titan's north polar region by the Cassini RADAR (Stofan et al., 2007). The chemical composition of these lakes remains, however, poorly determined. Spectra of the southern hemisphere lake Ontario Lacus have been obtained by the visual and infrared mapping spectrometer (VIMS) aboard Cassini but the only species that has been firmly identified is C2H6 (Brown et al., 2008). The difficulty in determining the composition of the lakes is essentially due to the presence of a large atmospheric fraction of CH4 that impedes this molecule's identification in the liquid phase present on the surface, irrespective of the value of its mole fraction. However, methane is indirectly inferred in Ontario Lacus by the secular decline of the lake extent over the Titan summer.
assumed that the liquid phase existing on Titan contains a
et al., 1989; McKay et al., 1993; Tokano, 2005). These models
elaborated in the pre-Cassini years (Lunine et al., 1983; Dubouloz
1989; Dubouloz et al., 1989; McKay et al., 1993; Tokano, 2005). These models
suggested that the liquid phase existing on Titan contains a
mixture made from $C_2H_6$, $CH_4$ and $N_2$, and a large number of
dissolved minor species.

On the other hand, the Cassini–Huygens measurements have improved our
knowledge of the structure and composition of Titan’s atmosphere. In
particular, the gas chromatograph mass spectrometer (GCMS) aboard
Huygens and the Cassini composite infrared spectrometer (CIRS) provided
new atmospheric mole fraction data (see Niemann et al., 2005, and Table 1).
Moreover, near-surface brightness temperatures and corresponding
estimates for physical temperatures in the high latitudes at which
numerous lakes are found have now been determined (Jennings
et al., 2009). These atmospheric and surface conditions have been
recently used to recompute the solubilities of the different
compounds in the hydrocarbon lakes (Cordier et al., 2009, hereafter
C09). The same model has also been employed to explore the
possibility of noble gas trapping in the lakes of Titan in order to
provide an attempt of explanation of their atmospheric depletion
(Cordier et al., 2009).

The assumptions considered by C09 are similar to those made
by Dubouloz et al. (1989) (hereafter DUB89): in both cases, lakes
are considered as nonideal solutions in thermodynamic equili-
brium with the atmosphere. However, neither DUB89 nor C09
have taken into consideration the influence of uncertainties on
the data used as inputs in their models. Indeed, some thermo-
dynamic data are measured at much higher temperature and
extrapolated down to temperatures relevant to Titan’s conditions.
Precipitation rates are also supposed to vary with respect to
latitude, longitude and time. In this work, we investigate the
influence of thermodynamic uncertainties, and in a lesser extent,
the geographic influence of the variation of precipitations on the
lakes composition. In the latter case, we restrict our study to a
supposed north/south poles asymmetry in chemical composition.

In Section 2 we detail our lake–atmosphere equilibrium
model. Section 3 is dedicated to the study of the influence of
uncertainties on thermodynamic data (vapor pressures, molar
volumes, enthalpies of vaporization and parameters of interac-
tion) on the resulting lakes composition. In Section 4, simulations
are conducted with the use of precipitation rates derived from a
version of the IPSL1 two-dimensional climate model of Titan’s
atmosphere (Crespin et al., 2008) and allow comparison between
chemical composition of south pole and north pole lakes. Section
5 is devoted to discussion and conclusions.

2. Description of the lake–atmosphere equilibrium model

Our model is based on regular solution theory and thermo-
dynamic equilibrium is assumed between the liquid and the
atmosphere. This equilibrium, which is expressed by the equality of
chemical potentials, can be written as follows (Eq. (1) of
DUB89):

$$Y_k^L = \Gamma_k X_k P_{vp,k}$$

where $P$ is the total pressure at Titan’s surface, $Y_k$ and $X_k$
respectively the mole fractions of the $k$ compound in the
atmosphere and in the liquid, and $P_{vp,k}$ its vapor pressure. The activity
coefficient $\Gamma_k$ (dimensionless) of the $k$ compound is given by
(frame of the regular solution theory—see Poling et al., 2007)

$$R T \ln \Gamma_k = V_{m,k} \sum_i \sum_j (A_{ik} - A_{ij}) \phi_i \phi_j,$$

where

$$A_{ij} = (\delta_i - \delta_j)^2 + 2 \eta_i \delta_i \delta_j \delta_j,$$

and

$$\delta_i = \left(\frac{\Delta H_{ij} - RT}{V_{m,i}}\right)^{1/2}$$

is the Hildebrand’s solubility parameter of the $i$th compound. The value of this parameter is given by

$$\delta_i = \left(\frac{\Delta H_{ij} - RT}{V_{m,i}}\right)^{1/2},$$

where $\Delta H_{ij}$ (J mol$^{-1}$) is the enthalpy of vaporization and
$V_{m,i}$ (m$^3$ mol$^{-1}$) the molar volume. $\delta_i$ represents a measure of
the molecular cohesion energy of the pure component $i$. It depends on
the nature and the strength of intermolecular forces (hydrogen bond,
etc.) between molecules of the same species. In general, two
components $i$ and $j$ with $\delta_i$ and $\delta_j$ presenting close values, have a
high solubility. Beside this, the $\delta_i$’s parameters represent the effects of
interactions between molecules of different species. These $\delta_i$’s are
empirically determined and are generally poorly known. The situation
$\delta_i = \delta_j$ and $\delta_i = 0$ corresponds to all activity coefficient equal to
one, in other words this is an ideal solution in which all intermole-
cular forces are negligible.

Our model also allows us to estimate the mole fraction of each
solid precipitate that is dissolved in the lakes of Titan. To this end,
we calculate the saturation mole fraction* $X_{sat}^{i}$ of the compound
$i$, which is given by (Eq. (7) of DUB89)

$$\ln (\Gamma^L X_{sat}^i) = \left(\frac{\Delta H_{sat} - RT}{V_{m,i}}\Gamma^L T_i - T_i\right),$$

where $T_i$ is the component’s melting temperature and $\Delta H_{sat}$ its
enthalpy of fusion. Our calculation procedure is then as follows:

1. The unknown $X_i$’s and $Y_i$’s are computed via the Newton–
Raphson method.

* See Niemann et al. (2009).
2. De Kok et al. (2007).
3. $N_2$ and $C_2H_6$ abundances have been calculated by C09 and correspond to a
ground temperature of 93.65 K. In Monte Carlo simulations presented here, the
mole fractions of $N_2$ and $C_2H_6$ are varying (see text).
2. Once the $X_i$'s have been determined, the $X_{sat}$'s are in turn calculated and compared to the $X_i$'s for each species. If for $i$ compound we get $X_{sat} < X_i$, then we fix $X_i = X_{sat}$.

3. We get new values of $X_i$'s and $X_{sat}$'s via the resolution of the nonlinear system.

4. The iterations are continued until we get a difference between $X_{sat}$ and $X_i$ lower than $10^{-6}$, value for which the numerical inaccuracy is clearly negligible, are compared to other sources of uncertainties.

The known $Y_i$'s are given in Table 1. The precipitation rates $\tau_i$'s represent the number of molecules of a given species, reaching the surface of Titan by unit of time and by unit of surface ($\text{molecules m}^{-2} \text{s}^{-1}$). The $\tau_i$'s used in C09 were derived from the photochemical models of Lavvas et al. (2008a,b) and Vuitton et al. (2008), and correspond to the main products of CH$_4$ and N$_2$ photolysis. These rates allow us to express each $i$ compound that falls from the atmosphere in the form

\[ X_i = \frac{\tau_i}{T_cT_H} \times X_{CH_4}. \] (7)

We also ensure that $\sum X_i = 1$ and $\sum Y_i = 1$. In this way, we get 15 unknowns and 15 equations, allowing the system to be solved. The thermodynamic data used in our calculations derive mainly from the NIST database.

3.3. Influence of vapor pressure uncertainties

Vapor pressures of species, for which Eq. (1) is written, are taken from the NIST database in the form of an Antoine’s law in the cases of N$_2$, CH$_4$, Ar and C$_2$H$_6$ or from a vapor pressure law given by Lide (1974) in the case of CO. In general the domains of validity of Antoine’s laws used in this work include the range of temperatures relevant for Titan’s lakes (i.e. 90 ± 3 K). For instance, in the cases of CH$_4$ and C$_2$H$_6$, the lower boundaries are 90.99 and 91.33 K respectively, implying moderate extrapolations for temperatures slightly below ∼ 90 K.

On the other hand, evaluating the accuracy of Antoine’s equations brought by the NIST database is not straightforward. To do so, we have first considered the case of N$_2$ for which NIST maintainers derived an Antoine’s equation from Edjeer and Thodos (1967). These authors published a Frost–Kalkwarf equation based on 180 experimental vapor pressure measurements derived from 13 references. The equation obtained by Edjeer and Thodos (1967) reproduces the experimental measurements with a deviation ranging between 0.13% and 2.04%. Comparing the vapor pressure computed with the NIST Antoine’s equation with the one given by Edjeer and Thodos (1967), we found differences reaching ∼ 10% for the lowest temperatures (i.e., around 67 K) and ∼ 1% for temperatures close to 90 K. Following a similar approach, we compared pressure computed with the NIST Antoine’s equation and original data from Carruth and Kobayashi (1973). We also made a comparison between our own fit and pressure data given by Lide (1974) for carbon monoxide. For the relevant temperature domain, the deviation for CH$_4$ remains between 0.1% and 1%, while the vapor pressure of CO reaches a deviation of about 9%. Consequently we have fixed the maximum errors on vapor pressures, for all relevant species (i.e., N$_2$, CH$_4$, Ar, CO and C$_2$H$_6$) to ± 10% relative to previously used values (see C09). This range should bracket all the vapor pressures expected for each compound. This approach allows us to explore a wide range of possibilities, including combinations which do not correspond to physical reality. In this sense, results corresponding to extreme deviations should be regarded as unlikely cases.

Table 2 gathers our results which are quantified by $\Delta P_{nai} = (P_{nai} - P_{sai})/P_{sai}$ and the relative standard deviation $\sigma^i$ (both expressed in percentage). $\Delta P_{nai}$ measures the total spread (over 10,000 computations of chemical compositions) of mole fraction values for a given species, including the results of the most unlikely combinations of synthetic errors. The relative standard deviation $\sigma^i$ is $\sqrt{\sum (X_i - \bar{X})^2 / \bar{X}}$ (the upper bar denotes the average value over 10,000 computations) shows how much variation or “dispersion” there is from the “average” $X_i$. Table 2 shows that $\sigma^i$'s differ strongly from $\Delta P_{nai}$'s. This feature corresponds to the signature of extremely narrow distributions of values around the average ones and can be explained by the non-linearity of the equations of our model. Indeed, synthetic errors are chosen with a uniform distribution but the resulting distribution of mole fractions is heterogeneous. The shapes of $X_i$'s distributions are shown in Section 3.5 in which errors for all thermodynamic inputs are taken into consideration.

Errors on vapor pressure mainly affect mole fractions of species for which Eq. (1) is written. This behavior is not surprising as Eq. (1) contains explicitly the vapor pressure. The entire set of equations being coupled, even a variation of one vapor pressure

\[ \text{http://webbook.nist.gov} \]

\[ ^{4} \text{CO data are unavailable in the NIST.} \]
Table 2

Results of Monte Carlo simulations showing the space of possible values for thermodynamic inputs explored randomly within a ±10% range centered on the nominal values used by C09. Xmin and Xmax are recorded for each species and results are presented in the form of Δs and relative standard deviations σ (see text). Xmax and xmin are shown only in the cases where the space of vapor pressures is explored. Δmix (σmix) refers to Monte Carlo simulations for which only vapor pressures are affected by synthetic errors. Δm (σm) and Δmix (σmix) and Δv (σv) refer to molar volumes, enthalpies of vaporization and interaction parameters li, respectively. Δmix (σmix) are resulting uncertainties when all thermodynamic quantities are considered with errors.

| Species | Xmin (Pvap) | X (Pvap) | Xmax (Pvap) | Δmix (%) | σmix (%) | Δv (%) | σv (%) | Δli (%) | σli (%) |
|---------|-------------|----------|-------------|----------|----------|--------|--------|---------|---------|
| N2      | 4.1 × 10^-3 | 4.9 × 10^-3 | 5.9 × 10^-3 | 37       | 8        | 792    | 94     | 2310    | 105     |
| CH4     | 8.3 × 10^-3 | 9.7 × 10^-3 | 1.1 × 10^-1 | 32       | 9        | 3467   | 61     | 570     | 63      |
| Ar      | 4.3 × 10^-3 | 4.9 × 10^-3 | 5.8 × 10^-6 | 31       | 7        | 333    | 53     | 557     | 56      |
| CO      | 3.5 × 10^-3 | 4.2 × 10^-3 | 5.1 × 10^-7 | 37       | 8        | 734    | 88     | 244     | 102     |
| C2H6    | 7.5 × 10^-1 | 7.6 × 10^-1 | 7.7 × 10^-1 | 3        | 1        | 50     | 96     | 9       | 17      |
| C3H8    | 7.3 × 10^-2 | 7.4 × 10^-2 | 7.5 × 10^-2 | 3        | 1        | 50     | 96     | 9       | 17      |
| C4H10   | 1.4 × 10^-2 | 1.4 × 10^-2 | 1.4 × 10^-2 | 3        | 1        | 50     | 96     | 9       | 17      |
| HCN     | 2.0 × 10^-2 | 2.2 × 10^-2 | 2.3 × 10^-2 | 16       | 4        | 156    | 50     | 167     | 56      |
| CO2     | 1.2 × 10^-2 | 1.2 × 10^-2 | 1.2 × 10^-2 | 3        | 1        | 50     | 96     | 9       | 17      |
| CH3CN   | 1.1 × 10^-2 | 1.1 × 10^-2 | 1.2 × 10^-2 | 3        | 1        | 50     | 96     | 9       | 17      |
| CO       | 2.9 × 10^-4 | 2.9 × 10^-4 | 3.0 × 10^-4 | 3        | 1        | 50     | 96     | 9       | 17      |
| C2H6     | 2.2 × 10^-4 | 2.3 × 10^-4 | 2.3 × 10^-4 | 3        | 1        | 50     | 96     | 9       | 17      |

affects the mole fractions of all the other species determined with our model. Note that the case of ethane is particular because its atmospheric mole fraction YC2H6 is an unknown of our mathematical problem, while atmospheric abundances of N2, CH4, Ar and CO are fixed by the observations. Compared to other compounds belonging to precipitated species HCN shows a relatively high Δmix (%) in this case, this is also due to the use of an equation (Eq. (6)) where vapor pressures play a role via Γ. Average values Xl differ slightly from previous results (C09).

3.2. Influence of molar volume uncertainties

Molar volumes have been estimated via Rackett’s method (see Poling et al., 2007). Tables 4–11 and pages 4.36–4.37 of Poling et al., 2007) present comparisons between measured molar volumes and estimated ones for some organic compounds at the boiling temperature. These comparisons show that maximum deviations typically reach the levels of a few percent. We then adopted a maximum “error” of ±10% for Monte Carlo simulations only applied to molar volumes. These simulations allow a sensitivity comparison with those performed for vapor pressure. Resulting Δmix and σmix are displayed in Table 2.

Similar to simulations related to vapor pressure, large differences between Δmix and σmix indicate a very narrow spread of molar fractions in lakes. As would be expected, species for which thermodynamic equations (1) are explicitly used show the highest deviations. As also shown by Table 2, a general trend is that molar fractions appear to be much more sensitive to molar volume than to vapor pressures.

3.3. Influence of enthalpies of vaporization uncertainties

The NIST and the literature provide numerous interpolation formulae for enthalpies of vaporization. Getting reliable estimates of their actual accuracy is not easy because the domains of validity of these formulae do not often include the ground temperature of Titan. For instance for C2H6, C3H8 and C4H8 extrapolations over about 100 K are required. However we have performed error estimates only for methane, ethane and argon. In the cases of methane and ethane, we compared the enthalpies of vaporization given by the NIST database (originally published by Majer and Svoboda, 1985) to those computed with the equations provided by Somayajulu (1988). For methane, in the temperature range of interest for the surface on Titan, we obtained differences lower than 1%. In the case of ethane, these differences are much more important and lie between 26% and 30%. Considering the work of Tegeler et al. (1999), we estimate an internal uncertainty of about 1% for the enthalpy of vaporization of argon. Again, in order to be consistent with others Monte Carlo simulations, we fixed the maximum “error” on the enthalpy of vaporization of each species to ±10%, a value which is well within the range of uncertainties found from comparisons. The results are displayed in Table 2 and show that the induced uncertainties on mole fractions are similar or higher than those obtained for the molar volumes.

3.4. Influence of li uncertainties

The interaction parameters li’s represent the interaction between molecules of different species and are essentially determined empirically. These parameters are fixed to zero in the case of interactions between the same molecules (if li = 0). In principle these li depend on temperature, however for typical nonpolar mixtures over a modest range of temperature, that dependence is usually small (see Poling et al., 2007). As stated by DUB89, they are unknown in many situations. In this work, as 13 species are taken into account in the liquid phase, we need to know 156 parameters (13 × 13 − 13 = 156; the 13 li being set to zero) and testing the possible influence of each of them in our system does not really make sense. Given the fact that the values of li range between ~0.02 (DUB89) and 0.09 (Poling et al., 2007), we have performed Monte Carlo simulations with these parameters set randomly between 0 and 0.10 (except li = 0). The sensitivity of mole fractions to li’s is presented in Table 2 and appears lower than in the cases of molar volume and enthalpy of vaporization.

3.5. Combination of all thermodynamic uncertainties

Here we have combined all sources of uncertainties (i.e. errors on P, V, ΔH, and li) and the results are represented by ΔAll and σAll in Table 2. The combination of uncertainties on thermodynamic data can induce mole fraction fluctuations up to a factor of ~100 for ΔAll and slightly lower than ~4 if we consider the relative standard deviation σAll. The distribution of mole fractions Xl is represented in the form of histograms in Figs. 1 and 2.

For each species, the range Xl,min − Xl,max has been divided into 100 intervals. For the k-th interval, the number Nk of mole fractions owning a given value has been normalized via Npeak = Nk/Npeak, where Npeak corresponds to the largest Nk. We stress that Npeak has a specific value for each compound.
Distributions are very narrow and clearly asymmetric. The smallest abundances are limited by $X = 0$. HCN is a particular case for which the highest abundances are limited by the saturation. Curiously, the HCN distribution presents a "residual tail" located at lake mole fractions between 0 and $\frac{1}{C_2H_8}$. If we consider case 1 of DUB89 (i.e. $T = 92.5$ K, $Y_{Ar} = 0$ and $Y_{CH_4} = 0.0155$), our results bracket the abundances found by these authors. For instance we find $\frac{1}{2} \times 10^{-5} \leq X_{CH_4} \leq 0.039$ while DUB89 got $X_{CH_4} = 0.018$. The case of methane is similar since we find $1.8 \times 10^{-5} \leq X_{CH_4} \leq 0.083$ whereas DUB89 inferred $X_{CH_4} = 7.3\%$. This illustrates the fact that differences between C09 and DUB89 are consistent with uncertainties caused by poorly known thermodynamic data.

One could argue that the choice of a maximum deviation of $\pm 10\%$ is arbitrary, even if that level of uncertainty has been discussed in previous subsections. Fig. 3 shows the sensitivity of $\sigma^*$ to the adopted maximum error for $N_2$, $CH_4$, $Ar$ and $CO$. As expected, the standard deviation increases with the value of the maximum error but this behavior appears to be nonlinear. During a Monte Carlo simulation, some combinations of errors yield to a non-convergence of the model, these occurrences corresponding more likely to unphysical situations and/or to an initial input (in practice the nominal solution for $T = 90$ K published in C09) in the Newton–Raphson algorithm which is too far from the solution of the system of the equations. In addition, a maximum error of $\pm 10\%$ in the thermodynamic data is probably an
overestimated value even if we do not really know how these data depart from the “real” ones. However, we consider that the most important point here was to address the sensitivity of the model to the different sources of uncertainties.

4. Influence of geographic variations of precipitation

On Earth, precipitation is almost entirely water, with the rate dependent on location and time. In the case of Titan, the situation is more complex because the slow sedimentation of stratospheric aerosols to the surface is key to filling the lakes with the dominant photochemical byproducts of methane as well as less abundant species.

Moreover, the sedimentation rates are also a function of location and time. In this section we restrict our study to the geographic dependence of lakes composition and more precisely to a possible south/north asymmetry as the distribution of lakes seems to be itself asymmetric (see Aharonson et al., 2009).

As mentioned in Section 2, the calculations are based on precipitation rates derived from a slightly improved version of Lavvas et al. (2008a,b) (hereafter LAV08) models that included the atmospheric profile of Titan’s atmosphere measured with the Huygens atmosphere structure instrument (Fulchignoni et al., 2005) and some updated reaction rates. In the following we refer to this set of precipitation rates as LAV09. These models are clearly inadequate for a geographical study, this is why we used a 2D models originally developed by Lebonnois et al. (2001). These authors used an analytic description of the meridional circulation of Titan’s atmosphere to take advection into account in a
two-dimensional photochemical model. This coupling between dynamics and photochemistry was subsequently improved by the implementation of the same photochemical model in the IPSL two-dimensional climate model (Crespin et al., 2008, hereafter LEB08).

Precipitates are included in our thermochemical model via the relation $X_i = (\tau_i/C_{CH_6}) \times X_{C_{CH_6}}$. At the first sight, one could believe that multiplying a given $\tau_i$ by an arbitrary factor $x_i$ yields a multiplication by $x_i$ of the resulting molar fraction $X_i$. This is not the case because the molar fraction of ethane $X_{C_{CH_6}}$ depends on all the other mole fractions. Indeed Eq. (1) depends on Eq. (4), and both equations are solved simultaneously. Hence, the influence of precipitation rates $\tau_i$ on mole fractions can only be estimated with a complete calculation. As these rates play a role in our set of equations via the ratios $\tau_i/C_{CH_6}$, we then consider these ratios instead of absolute $\tau_i$ values. For species available in LEB08’s models, we computed the time averaged ratios $\tau_i/C_{CH_6}$ results are displayed in Fig. 4, ratios deduced from LAV08 and LAV09 have been displayed for comparison.

While we have noticed in LEB08 data absolute precipitation rates have huge latitudinal variations, the ratios $\tau_i/C_{CH_6}$ do not exhibit such steep dependence in regions located poleward of latitudes around $\pm 60\degree$. In equatorial regions, the precipitation rates computed by LEB08 can be very small, implying that the ratio $\tau_i/C_{CH_6}$ probably has no great physical meaning in these regions. Fortunately, as hydrocarbon lakes have presumably been detected in polar regions, this observational evidence allows us to identify the questionable values.

With LEB08 polar ratios $\tau_i/C_{CH_6}$ we compute two sets of mole fractions: one for the south pole, another for the north pole. In both cases, the temperature and the pressure have been respectively fixed to 90 K and 1.467 bar. We did not find any significant differences between the composition of south and north lakes (i.e., differences of the order of 1%) excepted for $C_{CH_4}$ ($\sim 30\%$), $C_{CH_{10}}$, $CH_3CN$ and $C_6H_6$ (both around $\sim 20\%$). The north mole fractions being systematically larger than those computed for the south pole, this behavior corresponds to LEB08 large ratios at north pole (see Fig. 4). These results have to be considered carefully because even up-to-data 2D Titan’s atmosphere models have to be improved. For instance, LEB08 precipitation rates are in fact condensation rates. In this approach, when a given species is in an atmospheric layer where the local temperature corresponds to the saturation temperature of this species, then all the molecules in this layer are supposed to precipitate on Titan’s surface. In this picture, the microphysics of clouds is not taken into account. Models including this microphysics for a lot of species have to be developed.

5. Discussion and conclusion

Beside vapor pressures, molar volumes and other parameters already studied in previous sections, total pressure $P$ and temperature $T$ at ground level could have also an influence on lakes composition.

The influence of temperature has been already discussed in C09. The variations of ground pressure, as $P$ appears in Eq. (1), could change the thermodynamic equilibrium. Using the Cassini synthetic aperture radar (SAR) Stiles et al. (2009) have developed models of the topography of limited portions of the surface, finding surface heights typically in the range $-1500$ to $+1000$ m, yielding a maximum altitude difference of about 2500 m. More recently, radar altimetry analyzed by Wall et al. (2010) across Ontario Lacus and its surroundings shows a maximum amplitude of the altimetry echo center of mass of about $\sim 500$ m. This local determination is compatible with Stiles et al. (2009) work. HASI data (Fulchignoni et al., 2005) contain pressure records, measured on January 14th, 2005 during the Huygens probe descent. Between the Huygens landing site and an altitude of 2500 m, the pressure ranges between 1467 and 1296 hPa, i.e. a relative variation of 10%. By means of their 3D general circulation model, Tokano and Neubauer (2002) have investigated the

Fig. 4. (a–f) Solid lines: time averaged ratios $\tau_i/C_{CH_6}$ from LEB08 models represented as a function of Titan’s latitude. Dashed lines: the same ratios computed with the LAV09 model and taken from Vuitton et al. (2008) in the case of C6H6.
permeability of nonpolar molecules and are probably an inadequate formalism when polar components are in the solution. We recall that the mixture considered in this work includes two polar molecules: HCN (with a dipole moment of 2.98 D, which could be compared to the water dipole moment of 1.85 D) and acetonitrile CH₃CN (with a dipole moment of 3.84 D).

Our work stresses the great impact on predicted composition of uncertainties in the thermodynamic inputs. In the framework of our model, this influence appears to be more important than abundance differences between north and south pole lakes, assuming a maximum “error” level of ±10% considered in our Monte Carlo simulations. Our computations show also that the influence of pressure variations is purely negligible.

It is important to note that, in this work, we did not consider the seasonal variations of lakes chemical composition. Indeed, many phenomena could contribute to these variations, among which seasonal variations for short timescales and the Milankovitch cycle for longer timescales (see Aharonson et al., 2009). We stress that all these phenomena involve processes of evaporation/condensation of various species (in particular CH₄), which clearly represent non-equilibrium situations. A more realistic model will have to take into account these mass fluxes between lakes and the atmosphere (see Tokano, 2005) and incorporate a chemical model similar to the one used in the present work. Future works will have to integrate these two aspects of modeling to provide a more accurate description of lakes evolution.

We also underline the need for more realistic photochemistry models as already stated by Hébrard et al. (2007) among others. If we concentrate on the properties of the liquid of the lakes themselves, two kinds of approaches can be considered to make progress beyond what has been done here: (1) the development of more accurate thermodynamic data (measured in dedicated experiments and/or determined by ab initio computations); (2) Titan’s lakes in vitro simulations, in which one explicitly attempts to simulate Titan’s lakes through a liquid hydrocarbon mixture in contact with an atmosphere in a laboratory chamber. The second approach is surely more relevant because a model is not required to apply pure thermodynamic data, but the first approach may be more practical in the absence of a major experimental effort tied to proposed future missions to Titan like Titan Saturn System Mission (TSSM, see Matson et al., 2009) or Titan Mare Explorer (TiME, see Stofan et al., 2010), latter being dedicated to lakes study and analysis.

### References

Aharonson, O., Hayes, A.G., Lunine, J.I., Lorenz, R.D., Allison, M.D., Elachi, C., 2009. An asymmetric distribution of lakes on Titan as a possible consequence of orbital forcing. Nat. Geosci. 2 (December), 851–854.

Brown, R.H., Soderblom, L.A., Soderblom, J.M., Clark, R.N., Jaumann, R., Barnes, J.W., Sotin, C., Buratti, B., Baines, K.H., Nicholson, P.D., 2008. The identification of liquid ethane in Titan’s Ontario Lacus. Nature 454 (July), 607–610.

Carruth, C.F., Kobayashi, R., 1973. Vapor pressure of normal paraffins ethane through n-decane from their triple points to about 10 Mm Hg. J. Chem. Eng. Data 18, 115–126.
