Horizontal structures and dynamics of Titan’s thermosphere
I. C. F. Müller-Wodarg,1, R. V. Yelle2, J. Cui2 and J. H. Waite3

Abstract.
Observations by the Cassini Ion Neutral Mass Spectrometer (INMS) measure the latitude and height structure of N2 and CH4 densities in Titan’s thermosphere between 1000 and 1600 km altitude. We have used the observations to construct an empirical model that describes the mean state of the thermosphere in the northern hemisphere, ignoring local time and longitude changes. The principal features in the INMS data are well reproduced by this simple latitude-height model. We find a pronounced oblateness in the thermosphere, with densities above 1100 km altitude increasing by around 70% from the northern (winter-) pole to the equator, resulting in isobaric surfaces being ±45 km higher over the equator than at the northern pole. Thermospheric temperatures derived from the densities are nearly isothermal above 1200 km at 146±13 K but near 1000 km altitude reach 167±6 K at the equator and 132±6 K near the pole. Using our Thermosphere General Circulation Model with this thermal structure imposed, we derive thermospheric horizontal wind speeds reaching 200 m s−1, with primarily poleward flow at equatorial latitudes which, northward of around 60°N, is accompanied by a band of prograde zonal winds of up to 150 m s−1. At high latitudes diverging horizontal winds generate regions of strong subsidence with vertical velocities of up to -30 m s−1. We find thermospheric dynamics to be sensitive to coupling from below. CH4 abundances are enhanced in the northern polar region, which may result from transport by thermospheric winds.

1. Introduction
Before the arrival of Cassini/Huygens at the Saturnian system, the most detailed observations of Titan’s thermosphere were made by the Voyager 1 Ultraviolet Spectrometer solar occultation experiment and dayglow measurements in November 1980 [Broadfoot et al., 1981], yielding thermospheric densities of N2, CH4 and C2H2 in the morning and evening terminators at near-equatorial latitudes, from which exospheric temperatures of 196±20 K and 176±20 K were inferred, respectively [Smith et al., 1982]. A comprehensive reanalysis of these data by Verwack et al. [2004] revised the original density values by Smith et al. [1982] and inferred lower temperatures of 153-158 K. On January 14, 2005, the Huygens probe descended through Titan’s atmosphere, with its Atmospheric Structure Instrument (HASI) measuring total atmospheric density below 1400 km altitude by recording the deceleration of the probe by atmospheric drag. These measurements were carried out at near-equatorial latitudes, giving the first continuous profile of atmospheric density from the thermosphere to the troposphere of Titan. The derived pressure scale heights yielded atmospheric temperatures which in the thermosphere ranged from around 140-200 K, with strong oscillations of up to around 10 K amplitude around a mean temperature value of ~175 K [Falcighigni et al., 2005]. In December 2004 the Cassini Ultraviolet Imaging Spectrometer (UVIS) observed two stellar occultations and derived vertical profiles of CH4 and minor hydrocarbon species between around 450 and 1600 km altitude near latitudes of 36°S and 35-75°N [Shemansky et al., 2005].

On October 26, 2004, the Cassini spacecraft carried out its first in-situ measurements of Titan’s upper atmosphere down to a closest approach altitude of 1174 km. During this and the following targeted low altitude flybys the Ion-Neutral Mass Spectrometer (INMS) instrument on board the spacecraft [Waite et al., 2004] measured altitude profiles of neutral atmospheric constituents at an unprecedented level of detail, both in terms of species characteristics and spatial resolution. Analyses of the two earliest flybys inferred exospheric temperatures of 149±3 K near 39°N at the evening terminator [Waite et al., 2005; Yelle et al., 2006] and between 154–162 K near 74°N close to midnight local time [Müller-Wodarg et al., 2006; De La Haye et al., 2007]. These early analyses of the INMS measurements suggested an unexpected trend of temperatures in Titan’s thermosphere, with larger values in locations of lower solar EUV energy deposition. As pointed out by Müller-Wodarg et al. [2006], these analyses of density profiles from any single flyby were however potentially affected by horizontal structures in Titan’s thermosphere, introducing an uncertainty in the temperature determination that could not be resolved with the available datasets.

Between 2005 and 2007, the INMS measured thermospheric densities during 13 targeted flybys, a dataset that allows for the first time a more comprehensive determination of horizontal structures on Titan. This study will present an analysis of the INMS dataset available to date, constructing an empirical model that describes the latitude-height profiles of N2 and CH4 densities between 1000 and 1600 km altitude in Titan’s northern hemisphere. We will use this information to constrain dynamics in the thermosphere and investigate how winds affect the distribution of constituents such as CH4. Section 2 will describe the data reduction and empirical model, in Section 3 we will analyze the latitudinal structures of density and temperature, Sections 4 and 5 will present calculations of thermospheric winds and investigate horizontal variations of CH4 mole fractions. Our results are discussed in Section 6.
2. Observations and empirical model

2.1. The Titan flyby trajectories

The INMS measurements used in this study were taken during 13 targeted Titan flybys which occurred between April 16, 2005 (T5) and June 13, 2007 (T32). Main characteristics of the flybys are shown in Figure 1 and listed in Table 1. All flybys considered here sampled only the northern hemisphere of Titan. Altitudes of closest approach (C/A) ranged from 950 km (T16) to 1025 km (T5), latitudes at C/A ranged from 30.36°N (T25) to 85.50°N (T16). As shown in the top left panel of Figure 1, 5 of the closest approaches occurred in the daytime sector, but most solar zenith angles in the dusk sector were larger than 80°, implying that the majority of measurements were taken during dusk or night conditions. Due to the uneven coverage of dayside and nightside passes, we will in this study not investigate local time changes in the thermosphere. Similarly, the majority of flybys occurred within the 60°E to 60°W longitude sector (bottom left panel), so we will not attempt to study longitude variations.

Figure 1 illustrates the geographic coverage of INMS measurements considered in this study. At altitudes above around 1300 km most latitudes from the equator to around 80°N are well sampled, whereas below that height the regions equatorward of 15-20° are poorly sampled. In this study we consider only data taken below 1600 km altitude.

2.2. Data Reduction

In this paper, we examine Cassini Ion Neutral Mass Spectrometer (INMS) data obtained in the Closed Source Neutral (CSN) mode, which is specifically designed for measurements of unreactive neutral species detected in the atmosphere of Titan or other INMS targets [Waite et al., 2004]. The data consists of a sequence of ratios of counting rate versus mass-to-charge ratio, m/z, from m/z=1 to 99 amu per electron charge. In all flybys and for all channels relevant to this work, the INMS samples Titan’s upper atmosphere with a time resolution of ~0.9 sec, corresponding to a spatial resolution of ~5.4 km along the spacecraft trajectory, for a typical flyby velocity of 6 km s^{-1} relative to Titan.

The INMS data can be analyzed in two ways. For major constituents in Titan’s atmosphere (N₂, CH₄), density profiles can be obtained directly from counts in relevant mass channels (usually the channels of main peaks in their cracking patterns) as a function of altitude [Yelle et al., 2006]. In contrast, analysis of minor constituents (C₂H₂, C₂H₆, etc.) requires careful modeling of mass cracking patterns in the observed full mass spectrum. The full mass spectrum is usually obtained by integrating the counts in all channels over a particular altitude range. The spectral analysis used to determine minor species densities is described elsewhere [Waite et al., 2005; Cui et al., 2007]. Here, we present the methodology used in determination of major species densities.

The INMS flight unit (FU) was calibrated prior to launch with a small number of reference gases, including N₂ and CH₄. In our analysis, these sensitivities are used to infer number densities from count rates. However, the N₂ and CH₄ gases are mixtures of their isotopes and isotopic ratios may differ in the atmosphere of Titan and Earth and may vary with altitude. It is therefore necessary to determine sensitivities for N₂, ¹⁴N¹⁴N, CH₄ and ¹³CH₄ separately, allowing for the possibility of different isotope ratios on Titan. Details of the procedure are described in Cui et al. [2007]. Here, we concentrate exclusively on the main isotopes.

The INMS has both a high gain counter (C(1)) and a low gain counter (C(2)). The C(1) counts in channels m/z=28, 29 and 16 are used to determine the densities of N₂, ¹³N¹⁴N, CH₄ and ¹³CH₄ when possible. However, the C(1) counter for channel 28 becomes saturated below ~1,300 km in all flybys and is likely to be saturated for channels 14, 15, 16 and 29 at low altitude passes. When this happens we determine densities either from C(2) counts of the main peak channel or alternatively from C(3) counts in other channels where the cracking pattern of the species shows sufficiently large counts. For the former case, the C(2)/C(1) conversion factor has to be determined. For the latter case, calibration between density values determined from different channels is required to ensure consistency. This may be associated with the fact that the dissociative ionization of a molecule imparts the dissociation fragments with excess kinetic energy which may affect the way that the fragment ions are transmitted through the ion optics of the INMS. In all cases, we assume that the densities inferred from the main peak channel of a given species are correct, to which we calibrate densities determined from other channels.

The cracking pattern of N₂ has peaks at m/z=28 and 14, produced by N₂₂ and N⁺ ions. To derive N₂ densities, we use C(2) counts in channel 28 below 1,100 km (where C(1) counts in channels 14 and 28 are both saturated), we use C(1) counts in channel 28 above 1,300 km where it is not saturated, and we use C(1) counts in channel 14 below, 1,100 and 1,300 km (where C(1) counts are saturated in channel 28 but not in channel 14). The switch to counts in channel 14 for the density determination at intermediate altitudes is based on the consideration that C(1) counts in channel 14 are always much higher than C(2) counts in channel 28 and therefore have a higher signal-to-noise ratio.

For calibration of N₂ densities derived from different channels, we calculate the ratio of the N₂ density determined from channel 28 to that determined from channel 14 between 1,300 and 1,600 km for each flyby. The lower boundary is selected to ensure that C(1) counts are not affected by saturation. Counts of channel 14 are contributed by both N₂, CH₄, and ¹³N¹⁴N, and the contributions from CH₄ and ¹³N¹⁴N have to be subtracted for an accurate determination of N₂ densities from this channel. Here CH₄ densities are calculated from C(3) counts in channel 16, and ¹³N¹⁴N densities from C(1) counts in channel 29. Based on the above procedure, we obtain a N₂ scaling factor for channel 14, which varies by 5% from flyby to flyby and has an average value of 0.79.

The C(2)/C(1) conversion factor for channel 28 can in principle be determined by taking the average ratio of C(1) counts to C(2) counts at the same altitudes where the C(1) counter is not saturated for channel 28. However, C(2) counts are very low in regions where C(1) counts are not saturated, making it difficult to estimate the conversion factor from counts in channel 28 directly. Instead, we use the procedure described above to determine N₂ densities above 1,100 km from C(1) counts in channel 14, and then predict the corresponding C(1) counts in channel 28. Here the N₂ scaling factor for channel 14 as determined above has been used for calibration. With the predicted C(1) counts and measured C(2) counts in channel 28, the C(2)/C(1) conversion factor can be calculated accurately, assuming that it is a constant for each flyby. This conversion factor varies by 6% from flyby to flyby, with an average value of 5.470.

As an example, we show in Figure 2 the altitude profile of N₂ densities calculated from C(1) (black crosses) and C(2) (blue squares) counts of channel 28, as well as C(1) counts (red plus signs) of channel 14, for the inbound measurements taken at the T16 flyby (July 22, 2006). The dotted lines mark the position of the N₂ densities switch from one algorithm to another.

The cracking pattern of CH₄ has peaks at m/z=12, 13, 14, 15 and 16, produced by CH₃⁺ ions where z ranges from 0 to 4. In most cases, the CH₄ densities can be determined accurately from C(1) counts in channel 16. The contribution
from $^{13}$CH$_4$ to m/z=16 has to be subtracted, with $^{12}$CH$_4$ densities easily obtained from C$^{(1)}$ counts in m/z=17. However, the C$^{(1)}$ counter of channel 16 becomes saturated below ~1,100 km, and the CH$_4$ densities have to be calculated differently in that region. C$^{(2)}$ counts in channel 16 cannot be used since they are too noisy. Since C$^{(1)}$ counts in channels 14 and 15 may also be saturated at low altitudes and have large contributions from N$_2$ and $^{12}$N$^{14}$N, we use C$^{(1)}$ counts in channels 12 and 13 to determine CH$_4$ densities below 1,100 km. Counts in channels 12 and 13 are not contributed by CH$_3$H$_2$ and CH$_3$H for and channel 13, $^{13}$CH$_4$ provides an additional contribution. All these minor contributions have to be subtracted. While $^{12}$CH$_4$ densities are easily obtained from C$^{(1)}$ counts in channel 17, an estimate of C$_2$H$_2$ and C$_2$H$_4$ is uncertain since these two species have complex cracking patterns. Counts in channels 24, 25 and 26 can in principle be used to constrain densities of C$_2$H$_2$ and C$_2$H$_4$, with minor contributions from other hydrocarbons (C$_2$H$_6$, C$_3$H$_8$, C$_4$H$_{10}$, etc.) ignored. However, the cracking pattern is not an issue for N$_2$ since its cracking pattern is very similar for channels 24, 25 and 26, in the sense that the branching ratios of C$_2$H$_2$ are approximately a factor of 3 higher than those of C$_2$H$_4$ for all these channels but the relative signals are the same. This implies that counts in these channels can only be used to constrain the linear combination of C$_2$H$_2$ and C$_2$H$_4$ densities, in the form of n$_{2C_2H_2} + \frac{1}{3}n_{2C_2H_4}$.

Assuming pure C$_2$H$_2$, counts in each of the channels 24, 25 and 26 give an independent estimate of the C$_2$H$_2$ densities. At any given altitude, the mean value is adopted and used to calculate the contribution from C$_2$H$_2$ to channels 12 and 13. With contributions from C$_2$H$_2$ and $^{13}$CH$_4$ subtracted, the remaining counts in these two channels can then be used to determine CH$_4$ densities. In the alternative extreme case in which we assume pure C$_2$H$_4$, we obtain similar densities of CH$_4$, consistent with the results for the pure C$_2$H$_2$ case within 1-sigma uncertainties. This similarity is mainly due to the fact that the contributions from C$_2$H$_2$ and C$_2$H$_4$ to channels 12 and 13 are small.

As for N$_2$, CH$_4$ densities determined from different channels have to be corrected to ensure consistency among densities in different altitude ranges. The scaling factors for CH$_4$ for channels 12 and 13 are obtained similarly to the adjustments to N$_2$ for channel 14 as described above. This results in a smooth CH$_4$ density profile for each flyby, which does not show any discontinuity at 1,100 km where the density contributions from channel 16 to channels 12 and 13. In our analysis, the average value of CH$_4$ density determined from channels 12 and 13 is used at any given altitude below 1,100 km.

N$_2$ and CH$_4$ density profiles are extracted from INMS data with the procedures described above, for both inbound and outbound measurements. The outbound measurements of some minor species are strongly affected by absorption from the walls of the instrument [Vuitton et al., 2007]. However, this is not an issue for N$_2$ and CH$_4$ at lower altitudes. A comparison between the inbound and outbound density profiles averaged over all flybys to smooth out horizontal variations shows that the inbound and outbound average profiles are nearly identical below ~1,800 km for both N$_2$ and CH$_4$, implying that the wall chemistry effect is not a concern for this study.

2.3. Empirical model of Titan’s thermosphere

2.3.1. Construction of model

A major difficulty in deriving atmospheric properties from any single flyby is the fact that the spacecraft moves both horizontally and vertically through Titan’s atmosphere. Typically the horizontal distance covered in Titan’s atmosphere is at least a factor of 5 larger than the sampled height range. While density measurements from single flybys are often displayed as a function of altitude, it is dangerous to interpret such figures as height profiles because horizontal structures in the atmosphere also affect the measured profiles. In order to overcome this difficulty, we have used measurements from all flybys shown in Figure 1 to construct an empirical atmosphere model, allowing separation of the horizontal and vertical structures.

The INMS measures the densities of N$_2$ and CH$_4$, but we use mass densities ($\rho$) and CH$_4$ mixing ratios (\chi(CH$_4$)) in order to construct the model and derive the N$_2$ and CH$_4$ densities from them. This is done as mass density is the important quantity for hydrostatic equilibrium, an important constraint assumed in the model for $\rho$. In constructing the model we define an altitude grid from 1000 to 1600 km with a step size of 10 km and a latitude grid from 0 to 90°N with a step size of 2°. Since INMS measurement heights in most cases do not coincide with the initial chosen altitude levels, we carry out log-linear interpolations in altitude of surrounding values of $\rho$ and \chi(CH$_4$) from relevant flybys on to the grid levels. Examples of resulting profiles are shown in Figures 3, 4 and 5 for altitudes 1030 km, 1200 km and 1590 km, respectively.

At each height level we fit the latitude variations with fourth order Legendre polynomials, shown as dashed lines in Figures 3, 4 and 5. Since measurements are limited to the northern hemisphere, only symmetric Legendre functions P$_0$, P$_2$ and P$_4$ are used. We thus obtain at each altitude a set of 3 Legendre polynomial amplitude values each for $\rho$ and \chi(CH$_4$). These amplitudes are plotted versus altitude in Figures 6 and 7. The left panels in both figures show the P$_0$ amplitudes, the middle and right panels are amplitudes of P$_2$ and P$_4$, respectively, plotted as fractions of P$_0$.

In order to obtain a model that can be used for any arbitrary altitude, we fit altitude dependent functions through the Legendre polynomial amplitudes, as shown in Figures 6 and 7. For P$_0$ amplitudes of $\rho$ and \chi(CH$_4$) we used third order polynomial functions of the form $A + Bz + Cz^2 + Dz^3$, where z the altitude (in km). The vertical profiles of P$_2$/P$_0$ in $\rho$ and \chi(CH$_4$) as well as P$_4$/P$_0$ in $\rho$ were fit with a hyperbolical function of the form $x = A + (B - A) \cdot tanh((z - C)/D)$, where $x = P_2/P_0$ and $P_4/P_0 \cdot P_0$. We fit $P_2/P_0$ \chi(CH$_4$) with a simple linear function $P_2/P_0 \cdot \chi(CH_4) = A + Bz$. The values for coefficients A-D are given in Table 2. These sets of coefficients define a simple model for the N$_2$ and CH$_4$ densities in Titan’s thermosphere. Since we used only INMS data from Titan’s northern hemisphere in constraining the Legendre polynomials, the model should not be applied to the southern hemisphere.

It should be noted that in constructing the empirical model we did not consider any changes with time in Titan’s atmosphere. The Cassini flybys used in this study occurred over a period of around 2.5 years, which allows for changes in season, solar EUV radiation and magnetospheric forcing to be visible in Titan’s thermosphere. Titan’s solar declination angle changed from -23.3° to -12.7° (Apr 10, 2007), so any seasonally induced variations will be smoothed in our model. To assess the variability of solar EUV flux, Table 1 lists the F10.7 cm flux (at 1 AU) for each flyby. The values show that we sampled Titan mostly at solar minimum conditions, at an average F10.7 cm flux value of 80 with a standard deviation of 21%. The solar EUV fluctuations, therefore are small and likely to cause minor variations in Titan’s thermosphere over the time span of the observations.

2.3.2. Atmospheric variability and model uncertainties

The empirical atmosphere model described in the previous section is an average representation of Titan’s thermosphere as a function of altitude and latitude. We see in
Figures 3, 4 and 5 the typical scatter of data points at different altitudes around the Legendre fit curves. Also shown in the figures are the standard deviations, calculated from the differences between data points and the fitted functions. Figure 8 shows the standard deviations of mass density and CH$_4$ mixing ratio as a function of altitude. While mass density uncertainties range from 10 to 50% between 1000 and 1600 km, those of CH$_4$ lie between 20 to 25%. Solid and dashed lines are third degree polynomial fits to the standard deviations, with coefficients listed as $\sigma_1$ and $\sigma_2$ in Table 2.

Two types of uncertainties affect the model, those inherent in the INMS measurements and those due to time and spatial variations in the atmosphere. Measurement errors by the INMS are due to counting statistics as well as overall calibration uncertainties and typically lie below 20%, implying that the deviations are due predominantly to local time, longitude or universal time variations not included in the model. Spatial variations in Titan's atmosphere not captured by the empirical model include local time and longitude changes. As can be seen from Figures 3, 4 and 5, no systematic trend with solar zenith angle is apparent in the data, but this may in large part be due to the uneven statistics, with most measurements having been made at zenith angles larger than 110$^\circ$. Similarly, longitude coverage of the measurements is at present insufficient to identify any longitudinal trends, which could result from standing waves or the magnetosphere interaction around Titan. As more measurements are made, future studies need to investigate these possible variations. Calculations by Müller-Wodarg et al. [2000], using a 3-D General Circulation Model (GCM) of Titan's thermosphere, found diurnal and hemispheric variability of up to 10-20 K in thermospheric temperatures resulting from solar EUV heating, largest above 1300 km. This is consistent with our finding here that the standard deviations of $\rho$ increase with altitude (Figure 8), so a large part of the spread may be due to diurnal changes in Titan's thermosphere driven by solar EUV heating on the dayside.

The presence of strong waves in Titan's atmosphere is discussed by Fulchignoni et al. [2005] and Müller-Wodarg et al. [2006]. Amplitudes of pressure and density perturbations in the thermosphere reached around 4-12%, consistent with the standard deviation of measurements near 1000 km, but much smaller than those higher up. Waves such as those identified by Müller-Wodarg et al. [2006] may therefore only partly explain the variability we find here. It should be noted, though, that the $P_2$ amplitudes of $\chi$(CH$_4$) in Figure 7 appear to contain wave-like variability with height, despite consisting of datasets scattered irregularly over time, which would be expected to 'wash out' many of the wave features. Variability in Titan's upper atmosphere may in part also be caused by changes in solar and magnetospheric forcing. In their calculations of Titan's thermal structure for solar minimum and maximum conditions, Müller-Wodarg et al. [2000] found that thermospheric temperature increased by up to 20 K at solar maximum. As seen in Table 1, the data were used in our study here at low solstice, particularly in the lower thermosphere. Thus, this could be evidence for a thermospheric response to a variable magnetospheric or wave forcing, but as the present time we have insufficient data on magnetospheric conditions or wave sources to investigate this further.

### 3. Latitudinal structures in Titan's thermosphere

#### 3.1. Mass densities

The empirical model allows us to quantify latitudinal structures of density in Titan's thermosphere. Figure 10 shows vertical and latitudinal profiles of mass density. The vertical density profiles (left panel) are shown for latitudes 0$^\circ$N (solid), 55$^\circ$N (dashed-dotted) and 80$^\circ$N (dashed) between altitudes 1000 and 1600 km. Near 1000 km (solid line) the latitudinal density variations are below 15% and thereby within the model uncertainties (see Figure 8), while a distinctive latitude shape evolves at higher altitudes. Near 1070 km (dashed-dotted curve) equatorial densities are roughly 40% larger than those near 80$^\circ$N. This latitudinal difference increases to around 70% above 1100 km and remains unchanged up to the upper boundary of our range (dashed curve). Model uncertainties between 1100 km and 1590 km range from 20 to 50% (see the error bars and Figure 8), so the latitudinal structures are larger than the model uncertainties, particularly in the lower thermosphere.

The Huygens Atmospheric Structure Instrument (HASI) measured decelerations of the probe during its descent through Titan's thermosphere on Jan 14, 2005, from which mass densities have been inferred [Fulchignoni et al., 2005]. The Huygens probe flew through thermospheric heights at equatorial latitudes of 9$^\circ$S. We find for the equatorial latitude of HASI observations that our densities at 1000 km altitude are 2.3 times the HASI values, while at the upper boundary of HASI observations (1380 km) our densities are 0.6 times the HASI values. Our empirical model mass densities agree with HASI near 1300 km. This comparison is valid for latitudes within around 20$^\circ$ of the equator, so any latitudinal motion of the probe along its descent trajectory will not affect the comparison. The differences, if real, may overall, the match between the model and observations is good. The difference between model and data is well within the model uncertainties, and the main features in the N$_2$ densities are reproduced. In particular, the difference between the inbound (blue) and outbound (red) values at T19 are well captured by the model. This shows that many of the observed differences between inbound and outbound density profiles can be explained reasonably well by latitudinal variations in Titan's thermosphere. The average trends of CH$_4$ are reasonably well captured, but some of the differences between inbound and outbound profiles are not present in the model. The empirical model can be regarded as a reasonable representation of Titan's average thermospheric structure in the winter hemisphere at low solar activity.

While the empirical model agrees reasonably well with measurements at most flybys so far, there are considerable differences at T18, T25 and T32, where discrepancies above 1100 km can reach up to a factor of 7. Interestingly, the T25 flyby has a trajectory very similar to that of T26 through Titan's atmosphere, but the measured densities differ considerably. Near 1500 km altitude N$_2$ densities are [N$_2$] $\sim 7.1 \times 10^6$ cm$^{-3}$ (T26) and [N$_2$] $\sim 1.7 \times 10^6$ cm$^{-3}$ (T25), roughly a factor of 2 larger at T25. Corresponding CH$_4$ mixing ratios at that height are 18% (T26) and 15% (T25). The cause of this discrepancy is not certain but the similarity in geometry strongly suggests that it must be a temporal variation. However, as seen from Table 1, the solar F10.7 cm flux was very similar during both flybys (74 and 70\times10^{-22} W/m$^2$/Hz). Thus, this could be evidence for a thermospheric response to a variable magnetospheric or wave forcing, but at the present time we have insufficient data on magnetospheric conditions or wave sources to investigate this further.
be signatures of strong local variations in Titan’s thermosphere not captured by the empirical model, such as waves, or other temporal changes in the thermosphere.

The mass density profiles of our empirical model show an oblateness to be present in Titan’s thermosphere, clearly dominating the horizontal variations detected by INMS. Using observations only from the TA and T5 flybys, Müller-Wodarg et al. [2006] inferred the presence of this bulge, but derived a factor of 3 decrease in density from 30°N to 70°N, around 4 times more pronounced than what we found in this study. Given the improved statistics of this study and the uncertainties in separating horizontal variations from vertical variations in the study by Müller-Wodarg et al. [2006], we expect our new value to be more reliable. However, a contributing factor to the smaller bulge found in this study may be changes in Titan’s thermosphere, given that the bulk of data used in this study were taken more than 1 year after those used by Müller-Wodarg et al. [2003] (see Table 1). The density bulge will be accompanied by a thermal bulge and vigorous dynamics, as discussed in the following.

3.2. Temperatures

Temperatures are not measured directly in Titan’s thermosphere, but can be derived from the INMS density measurements. The procedure consists of first deriving vertical profiles of atmospheric pressure followed by calculations of temperatures from the ideal gas law, using the calculated pressure and measured density. Pressures are calculated by integrating the weight of the atmosphere from the top down [Müller-Wodarg et al., 2006]. An upper boundary condition is needed for the temperature determination. We calculated this by evaluating the average density scale height between 1500 and 1600 km at each latitude.

The technique for calculating pressures assumes a vertical column integration in the atmosphere. The inherent difficulty in calculating pressures and temperatures for any given flyby lies in the fact that measurements are carried out along horizontal trajectories along which density changes not only with altitude but also horizontally. As a result, calculation of pressure from densities taken along any single trajectory have an error associated with them, which will affect the inferred temperatures [Müller-Wodarg et al., 2006].

Construction of the empirical model, as described in section 2.3, overcomes this problem. By combining the data from many flybys, we succeed in separating latitudinal from vertical variations, removing a significant source of uncertainty for the derived temperatures.

Temperature error bars are derived using the same procedure as Müller-Wodarg et al. [2006]. We derived a series of 10000 pressure and temperature profiles using the technique described above, each time allowing ρ to vary randomly, assuming a Gaussian distribution with a standard deviation equal to the error bar (Figure 8). At each location, this generates 10000 different pressure and temperature values, for which we calculate the standard deviations for the temperature profile.

Figure 11 shows temperatures of Titan’s thermosphere, as derived from the empirical model densities. The upper panel shows temperatures as a function of latitude and altitude. The bottom left panel shows vertical temperature profiles at latitudes 20°N (solid), 50°N (dashed-dotted) and 70°N (dashed). The bottom right panel shows temperatures at fixed altitude levels of 1030 km (solid), 1200 km (dashed-dotted) and 1590 km (dashed) with error bars super-imposed. Temperatures close to 1000 km vary strongly with latitude, reaching 167±6 K at the equator and 132±6 K near the pole. In contrast, Titan’s thermosphere appears nearly isothermal above 1200 km with an average temperature of 146±13 K. Exospheric temperature values are in good agreement with the previously derived value of 149±3 K for the TA flyby [Waite et al., 2005; Yelle et al., 2006]. For the latitude range covered by TA (∼25-42°N below 1600 km), we obtain an average value of T_{ex}=144±13 K. The good agreement of these values is due to the fact that TA covered a latitude and altitude range where atmospheric temperatures are virtually constant and latitudinal density variations small, below 8%. As a result, the contribution of horizontal variations in TA flyby data was small and variation of temperatures from the flyby data directly was accurate.

In contrast, the T5 flyby covered a latitude range (60°N-76°N) where horizontal density variations reach around 30%, so derivation of temperatures by either fitting vertical density curves to the observations or calculating pressures by downward integration becomes more problematic. For T5, Müller-Wodarg et al. [2006] derived an isothermal temperature value of 155 K. The study by De La Haye et al. [2007] derived T5 temperatures of 162 K (ingress) and 154 K (egress). When extracting temperatures of Figure 11 along the T5 trajectory we find values to range between 136-150 K, clearly lower than the previously derived values, which considered the T5 densities only. This illustrates the effects of horizontal density variations on derived temperatures. In addition, it shows that we cannot necessarily assume isothermal conditions along any given flyby.

Vertical profiles of temperature derived from the accelerometer measurements by HASI have suggested considerable variability of temperature with altitude on Titan. Large amplitude (10 K) waves around an average temperature value of 170 K dominate the structure between around 800 and 1000 km altitude, followed at higher altitudes by a sharp decrease to around 150 K near 1200 km [Fulchignoni et al., 2005]. While uncertainties remain at those altitudes depending on the choice of boundary conditions in those derivations, the general trend appears remarkably similar to our derived temperatures. Near-equatorial temperatures in our model at latitudes of the HASI measurements range from 170±6 K at 1000 km to 152±10 K at 1200 km. The sharp temperature gradient that we find at low latitudes between 1000-1200 km appears consistent with that detected by HASI.

The INMS measurements used in this study were taken during southern hemisphere summer conditions on Titan, the solar declination angle ranging from -23.34° (Oct 26, 2004) to -11.79° (June 13, 2007), so solar zenith angles increase towards the northern pole. Solar EUV heating, which forms one of the important energy sources in Titan’s thermosphere, will therefore be stronger at the equator than pole. Using a General Circulation Model of Titan’s thermosphere, Müller-Wodarg et al. [2003] calculated global temperatures in Titan’s thermosphere, assuming solar EUV heating as the only energy source. Their calculated dayside exospheric temperature decrease at solstice conditions from equator to the winter pole by 10 K above 1300 km and less at lower altitudes. As shown in Figure 11, the thermosphere above 1200 km appears to be nearly isothermal, but the uncertainty of ±15 K allows for seasonal variations with latitude consistent with those modeled. The TCCM calculations suggest that the observed temperature structure below 1200 km is likely not to be caused by solar EUV heating.

4. Dynamics of Titan’s thermosphere

The temperature and density structure derived in the previous section can be used to infer dynamics in Titan’s thermosphere. The thermal wind equation is used to derive wind speeds from the thermal structure, but this ignores some non-linear acceleration terms in the momentum equation and molecular viscosity, which have been shown to play an important role in Titan’s thermosphere [Rishbeth
et al., 1999; Müller-Wodarg et al., 2000). We therefore use a numerical rather than analytical approach to derive the dynamics consistent with the thermal structure.

We use a simplified version of the General Circulation Model by Müller-Wodarg et al. [2003] by imposing the thermal structure of Figure 11 and numerically solving the full 3-D momentum and continuity equations, but not the energy equation. Our vertical range is 960 km (2.67 × 10^10 Pa) to around 1700 km (5.7 × 10^10 Pa), with isothermal conditions assumed above 1500 km. In order to avoid any horizontal boundary discontinuities, we solve the equations pole-to-pole and assume the same thermal profiles in the northern and southern hemispheres, even though at present we have no observational constraints from INMS for the southern hemisphere. The full gas continuity equation is solved with molecular and eddy diffusion of the two main gases N_2 and CH_4 as well as optional gas transport by winds. We assume fixed mixing ratios at the lower boundary and optional escape flux for CH_4 at the upper boundary (see Section 5). This forces the other details of the model are described by Müller-Wodarg et al. [2003]. Because the momentum equation needs to be solved in 3 dimensions, we extend the 2-dimensional temperatures of Figure 11 to 3 dimensions by assuming equal temperatures at all local times for any latitude/height location. While the thermal structure thus varies with altitude and latitude only, the equations are still solved in 3 dimensions. The resulting winds are, of course, local time independent. We ran the model to steady state, which typically takes 1 Titan rotation for the dynamics and 10 Titan rotations for the composition.

In Figures 12 and 13 we show the three calculated wind components (meridional, zonal, vertical) as a function of altitude and latitude. The two figures show results from simulations for different assumed lower boundary conditions. Figure 12 shows a simulation assuming zero winds at 960 km, whereas Figure 13 shows a case of non-zero winds at the lower boundary.

When assuming zero winds at 960 km, and hence co-rotation of the atmosphere at that height with Titan’s surface, the dynamics in our simulation are entirely driven by the latitude and altitude gradients of pressure in the atmosphere. We see from the upper panel of Figure 12 that meridional winds are poleward, reaching maximum values of 200 m s^{-1} above 1100 km near 75°N. Above this height meridional winds are virtually constant with height and decrease below that, reaching zero values at 960 km due to our boundary condition. The latitudinal pressure gradients, via the large meridional winds, effectively drive a super-rotating eastward jet at high latitudes which varies little with altitude above 1000 km and peaks near 80°N with 130 m s^{-1}. Zonal winds decrease towards the equator. Zonal winds are not driven by accelerations from zonal pressure gradients (which are zero in our simulations) but primarily by curvature forces. The small radius of Titan and its atmosphere result in a more curved geometry than on planets like Earth and Venus, and thereby in enhanced curvature forces, whereas the slow rotation rate of Titan reduces the importance of the Coriolis term.

The divergence of the horizontal winds generates upward winds of 2 m s^{-1} near equatorial latitudes which turn to subsistence near 50°N, increasing towards the pole with vertical wind speeds of -30 m s^{-1} poleward of 80°N. Seen in the latitude-height plane, therefore, a large circulation cell is formed with upwelling over the equator, poleward flow and subsistence over the pole. A weak equatorward return flow at low altitudes (not seen in Figure 12) closes the flow. A considerable uncertainty is whether the base of the thermosphere super-rotates, as does Titan’s stratosphere [Hubbard et al., 1993; Flasar et al., 2005; Sicardy et al., 2006]. No direct observational constraints are currently available for the dynamics above 500 km. Upward propagating waves may considerably affect the momentum balance [Müller-Wodarg et al., 2006; Strobel, 2006] and either maintain the atmospheric super-rotation up to thermospheric altitudes or suppress it. To assess the influence of possible super-rotation on dynamics of the thermosphere, we carried out another simulation with our model, where we implemented a profile of super-rotating zonal winds at our bottom boundary (near 960 km). We adopted for our lower boundary the stratospheric winds derived by Achterberg et al. [2007] from observations by the Cassini Composite Infrared Spectrometer (CIRS) for around 500 km altitude. While zonal winds are likely to change between 500 and 1000 km altitude, our use of the profile by Achterberg et al. [2007] is sufficient to assess the sensitivity of thermospheric winds to the lower boundary condition.

Figure 13 shows thermospheric winds calculated with the super-rotating lower boundary condition. The circulation differs considerably from the previous calculation without lower boundary forcing (Figure 12), but some common features are present in both. Peak meridional (poleward) wind speeds occur roughly 25° poleward of those in the unforced case, near 55°N, reaching around 80 m s^{-1}, a factor of 2 smaller. Poleward of 55°N we now obtain a broad region of near-zero meridional winds. As expected, zonal winds are generally more strongly eastward than in the unforced case, but their peak values in the zonal jet are similar to the unforced case. The zonal jet is now broader in latitude and has moved equatorward by around 15° to 65°N. The region of strong polar subsistence found in our unforced calculations (Figure 12) has become weaker, with vertical winds lower than -10 m s^{-1}. The region of strongest subsistence no longer occurs over the pole but at 60-70°N.

In essence, the super-rotating lower boundary condition splits the single circulation cell we had found in the unforced case of Figure 12 into two cells. Upwelling occurs over the equator, with poleward flow and downwelling near 65°N. A second circulation cell is located poleward of that, with weak upwelling in the polar cap region and weak equatorward flow. The two circulation cells are thus opposite to one another and converge in the downwelling zone near 65°N. Eastward winds are above the diurnal rotation speed of the thermosphere (around 18 m s^{-1}) everywhere except in the polar region, so in this calculation Titan’s thermosphere is super-rotating everywhere.

The circulation patterns shown in Figures 12 and 13 are physically consistent with the thermal profile of Figure 11. The numerical calculations illustrate that thermospheric dynamics are not fully constrained by the thermal profile alone, but depend on the vertical coupling from below. We have investigated the influence of super-rotation from below, but, in addition, dynamics may be driven by accelerations due to dissipating waves. Observations by Cassini/Huygens have detected strong waves in Titan’s thermosphere [Fulchignoni et al., 2005; Müller-Wodarg et al., 2006] and model calculations have suggested potentially strong wave forcing to occur in the thermosphere [Müller-Wodarg et al., 2006; Strobel, 2006]. Since the problem of waves forcing is currently under-constrained by observations, we have not yet attempted to include it in our calculations, but the principle introduces another degree of freedom to dynamics. We will in the following explore additional possible observational constraints on thermospheric dynamics.

5. Latitude variations of CH_4

Methane is one of the principal gases in Titan’s atmosphere and important for the chemistry and energy balance. In Titan’s thermosphere CH_4 undergoes photolysis principally by solar Lyα radiation. As shown by Yelle et al. [2007], the time scale for Lyα photolysis of CH_4 at the height of
strongest absorption (near 850 km) is around $2 \times 10^7$ sec. The diffusion time scale at that altitude is around $3 \times 10^6$ sec. Assuming the horizontal and vertical wind velocities derived in Section 4, we find transport time scales of up to $1 \times 10^4$ sec. The numbers illustrate that the photolysis time scale for CH$_4$ in Titan’s thermosphere is significantly larger than dynamical time scales. We may therefore in the context of this study treat CH$_4$ as chemically inert and expect it to be redistributed in Titan’s thermosphere by the winds and diffusion. Inert constituents lighter than the mean molecular mass ($\sim 28$ to $25$ amu at 1000 to 1600 km altitude) such as CH$_4$ will accumulate in regions of subsistence. The response of the CH$_4$ distribution to transport by solar driven thermospheric winds on Titan was calculated by Müller-Wodarg et al. [2003] using their Thermospheric General Circulation Model. The study showed an accumulation of CH$_4$ on the nightside and winter hemisphere which resulted from the subsistence of winds there. We can therefore regard CH$_4$ as a tracer for atmospheric dynamics, so investigating its latitudinal distribution may help constrain thermospheric winds.

The upper panels of Figures 3, 4 and 5 show CH$_4$ mole fractions as a function of latitude. A clear trend is seen with CH$_4$ abundances increasing towards polar latitudes by up to around 60%. However, it is important to note that these values include the effect of the atmosphere’s oblateness, whereby isotropic levels are at lower altitudes towards the pole. We find isobaric levels to decrease in altitude by up to around 45 km from equator to pole between 1200 and 1600 km. This implies that along a level of constant altitude we sample regions of lower pressure at polar latitudes, and hence of larger CH$_4$ abundances due to the diffusive separation. This alone does not constitute a real change in composition. Rather, we need to investigate whether CH$_4$ mole fractions vary with latitude on an isobar surface.

In order to compensate for the atmospheric oblateness, dotted lines in the upper panels of Figures 3, 4 and 5 show the CH$_4$ mole fractions from the empirical model on levels of constant pressure located close to the plotted altitudes. The mole fractions on a constant pressure level vary less with latitude, by up to around 45%, which is smaller than the error bars. While the implication of this is that the current dataset does not allow us to identify a clear increase of CH$_4$ abundances towards the northern pole, there nevertheless remains a suggestive trend that CH$_4$ accumulates in the northern (winter-) polar region in Titan’s thermosphere. Such an accumulation of CH$_4$ would most likely be caused by subsiding winds, in agreement with our calculated dynamics, which showed downwelling at the northern polar latitudes.

In 1-D diffusion models the eddy coefficient is commonly treated as a free parameter which represents small-scale turbulence and larger-scale dynamics not resolved by the model. Previous studies of Titan’s atmosphere have derived the eddy coefficient by adjusting its value in order to match particle densities with observations, assuming zero or thermal escape flux at the top boundary. This yielded an eddy coefficient for Titan’s thermosphere of a few times $10^6$ cm$^2$ s$^{-1}$, orders of magnitude larger than that derived for any other planet in our solar system. Yelle et al. [2006] points out that the effects of an upper boundary condition of non-zero vertical flux in the continuity equation is similar to that of a large eddy coefficient, and combinations of large eddy coefficient with low escape flux or low eddy coefficient with large escape flux can produce the similar vertical distributions of constituents, introducing an uncertainty in the determination of the true eddy coefficient and escape rates. On Titan, the CH$_4$ measurements alone cannot solve this ambiguity, and an independent determination of the eddy diffusion coefficient is necessary. Recently, Yelle et al. [2007] from analysis of $^{40}$Ar data from Cassini/Huygens derived an eddy coefficient in Titan’s thermosphere of $3 \times 10^5$ cm$^2$ s$^{-1}$, an order of magnitude smaller than the value previously assumed.

Figure 14 shows CH$_4$ mole fractions in Titan’s thermosphere at latitude 60°N. The plot shows measurements by the INMS during flybys T5, T16, T18, T19, T21, T27, T28, T30 and T32 alongside values from our empirical model. Also shown in the figure are values from our diffusion model which we ran to steady state assuming an eddy coefficient of K = $3 \times 10^6$ cm$^2$ s$^{-1}$ and escape flux of $\Phi_{esc} = 2.77 \times 10^{15}$ cm$^{-2}$ s$^{-3}$ (relative to Titan’s surface). There is very good agreement between the empirical and diffusion models as well as the measurements. Given that no assumptions were made when constructing the empirical model, this good match represents an independent validation of the empirical model. Our diffusion calculations confirm the result by Yelle et al. [2007] and show that a large CH$_4$ escape flux is necessary to reproduce the observed distribution.

Recently, Strobel [2007] showed that hydrodynamic escape in Titan’s atmosphere could account for such loss rates, while both Jeans escape and nonthermal escape processes are insufficient by orders of magnitude. Hydrodynamic escape on Titan is driven primarily by the energy absorbed through solar EUV absorption and possibly by energy deposited in the thermosphere through magnetosphere coupling processes. No calculations have to-date been carried out to characterize the latitude variation of hydrodynamic escape on Titan. The high equatorial temperatures below 1200 km altitude could enhance hydrodynamic escape at those latitude, but the larger solar zenith angles in the northern (winter-) hemisphere imply that solar EUV absorption there occurs at higher altitudes, which could increase the proportion of absorbed energy driving escape. It is therefore at this stage unclear how the CH$_4$ escape rates on Titan change with latitude.

Vertical winds in the thermosphere add another layer of complexity to the problem since they also generate a vertical CH$_4$ flux in the thermosphere. Our derived vertical winds are weakly upward in the equatorial and low altitude regions, depleting CH$_4$ abundances there, while the subsistence at polar latitudes enhances CH$_4$ abundances. The combined effects of atmospheric dynamics and escape will determine the latitudinal distribution of CH$_4$, but at present the problem is still not sufficiently constrained to allow deriving thermospheric winds from the latitudinal variations of CH$_4$. We intend to further address this problem in future studies.

6. Discussion

Using the combined in-situ observations of thermospheric N$_2$ and CH$_4$ densities by the INMS during 13 Cassini flybys, we have constructed an empirical model of Titan’s thermospheric densities and temperatures. The reasonable agreement between observations and the model allow us to conclude that most features found to-date in the INMS along-trajectory densities of N$_2$ and CH$_4$ are well explained by latitude and height variations in Titan’s thermosphere. The most striking feature we find is the considerable oblateness of Titan’s thermosphere. Despite uncertainties in the derived dynamics, we find that this oblateness is likely to drive strongly super-rotating prograde jets at high latitudes in the northern (winter) pole. No consistent trend has to-date been identified with local time and longitude, which may in part be a result of the zonal winds which can ”wash out” zonal variations. However, local time and longitude sampling is sparse to date, and definite conclusions on the variability with these coordinates is not possible.

Another important consequence of the horizontal winds is the possibly strong subsistence in the polar regions. This
may via adiabatic processes have important effects on the thermal structure there. The combined effects of poleward winds and subsistence can accumulate lighter gases (including CH₄ and HCN) in the winter polar region. An enhanced presence of HCN in the winter polar region, if real, would lead to very effective radiative cooling in the region due to emissions in the rotational bands which play a key role in Titan's thermosphere [Yelle, 1991]. Recalculating the thermal structure of Titan's thermosphere will be important also at equatorial latitudes, where we found temperatures much larger than at the northern polar latitudes. This will help determine whether the latitudinal thermal structure that we find is a result of latitudinal variations in the net radiative heating rate.

Recent analyses of INMS densities have identified the presence of large atmospheric waves in Titan's thermosphere [Fulchignoni et al., 2005; Müller-Wodarg et al., 2006]. These may through dissipation in the thermosphere deposit significant amounts of momentum there, alterting thermospheric winds [Strobel, 2006; Müller-Wodarg et al., 2006]. Our calculations of dynamics did not consider waves as a source of momentum. This adds another uncertainty to the wind profiles we calculated from the density and temperature structure since our calculations assumed winds to be driven primarily by pressure gradients. While it is likely that present and future Cassini observations will not be able to further constrain this problem, future studies can explore the possible parameter space for thermospheric winds, taking into account also horizontal variations of composition.

Our calculations in Section 4 have shown thermospheric waves to be sensitive to the dynamics of the lower atmosphere. Recent measurements by the Cassini Composite Infrared Spectrometer (CIRS) through nadir and limb sounding of the atmosphere have obtained latitudinal temperature maps from around 5 mbar to 0.005 mbar, from which winds could be inferred via the gradient wind equation up to around 500 km altitude [Flasar et al., 2005; Achterberg et al., 2007]. These studies found zonal jets which peak between around 30-60°N near 0.1 mbar with values of up to 190 m s⁻¹, in reasonable agreement with stratospheric winds derived from ground-based observations of two stellar occultations in 2003 [Sicardy et al., 2006]. The CIRS wind maps show a decrease of wind speeds above the 0.1 mbar level, but nothing is known of wind speeds between around 500 and 1000 km altitude on Titan. This introduces an uncertainty into our derived horizontal wind profiles that cannot currently be resolved. We found the vertical velocities to be particularly sensitive to this lower boundary condition (Figures 12 and 13), which may importantly affect transport of constituents (CH₄, HCN) in the polar regions and adiabatic heating rates there. Our understanding of the high latitude thermosphere on Titan will thus be particularly sensitive to coupling from below.

In some cases, as discussed in Section 2.3.3, the match between our empirical model and observations is poor. Particularly interesting are the differences between T25 and T26 flyby. The spacecraft followed almost an identical trajectory through the atmosphere, the solar activity in both cases was similar (see Table 1), and furthermore the position of Titan relative to Saturn was almost identical. Data from the Cassini Magnetometer instrument (MAG) have shown little difference of the overall magnetic field configuration and variability in the vicinity of Titan during these two flybys (C. Bertucci, personal comm. [2007]), suggesting that the forcing from Saturn's magnetosphere was comparable during T25 and T26. A more comprehensive analysis of magnetospheric conditions during these flybys, including the wind characteristics of energetic electrons and ions (measured by the Cassini Plasma Spectrometer and Magnetospheric Imaging Instrument) will be important to determine any differences in magnetospheric forcing during these flybys. In the absence of evidence for an external forcing mechanism that could cause differences in the atmosphere as observed between T25 and T26, a further possibility is the presence of large scale waves in the atmosphere which might cause such behavior. Further studies are needed to investigate this.

Our study suggests Titan's thermosphere to be dominated by strong dynamics which are accompanied by an oblate shape of the atmosphere at those heights. This picture diverges considerably from the global structure predicted in the pre-Cassini era by General Circulation models which considered solar heating alone [Müller-Wodarg et al., 2000]. Much of this results from vertical coupling to lower altitudes, illustrating that the thermosphere of Titan cannot be regarded as an isolated system. Furthermore, we cannot at present evaluate the relative importance of various energy sources upon the thermosphere, solar EUV absorption, magnetospheric heating or vertical wave propagation. Further observations in the years to come are expected to enhance our understanding of Titan's atmosphere as a strongly coupled entity.

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References


I. C. F. Müller-Wodarg, Space and Atmospheric Physics Group Imperial College London, Prince Consort Road London SW7 2BW, UK. (i.mueller-wodarg@imperial.ac.uk)

R. V. Yelle and J. Cui, Lunar and Planetary Laboratory University of Arizona, Tucson, AZ 85721, USA. (yelle@lpl.arizona.edu, jcui@lpl.arizona.edu)

J. H. Waite, Jr., Southwest Research Institute, 6220 Culebra, San Antonio, TX 78228-0510, USA. (hwaite@swri.edu)
Table 1. Summary of Titan flybys used in this study. Altitudes at closest approach (C/A) are given in km, Latitude, longitude and solar zenith angles (SZA) are given in degrees. Longitudes are defined as positive west. The local times of C/A are given in Titan local solar time (LST). The F10.7 cm solar flux is given in units of $10^{-22}$ W/m$^2$/Hz for 1 AU. The location of Titan around Saturn is given in hours of Saturn Local Time (SLT), where for 12.00 SLT Titan is positioned between Saturn and the Sun and for 0.00 SLT Titan is positioned on the anti-sunward side of Saturn.

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Table 2. Coefficients describing the vertical change of amplitudes of Legendre polynomials $P_0$, $P_2$ and $P_4$ in Titan’s thermosphere between 1000 and 1600 km altitude as well as standard deviations. For $\rho$ ($P_0$), $\chi$(CH$_4$) ($P_0$) and standard deviations ($\sigma$) the coefficients A-D are for a third order polynomial of the form $x = A + B y + C y^2 + D y^3$, where $x$ is the respective quantity and $y$ the altitude (in km). For $\chi$(CH$_4$) ($P_2$/$P_0$), $\rho$ ($P_2$/$P_0$) and $\chi$(CH$_4$) ($P_4$/$P_0$) coefficients A and B are for a first order polynomial of the form $x = A + B y$. For $\rho$ ($P_2$/$P_0$), $\rho$ ($P_4$/$P_0$) and $\chi$(CH$_4$) ($P_4$/$P_0$) coefficients A-D are for a hyperbolical function of the form $x = A + (B-A) \cdot \tanh \{(y-C)/D\}$, where $x$ is again the respective quantity and $y$ the altitude (in km). The fits resulting from these coefficients are shown in Figures 6 and 7 as dashed lines. Standard deviations are given as fractions of background values and are plotted in Figure 8 (as percentages).

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<td>981</td>
<td>59.39</td>
<td>1.65</td>
<td>1.60</td>
<td>129.79</td>
<td>81</td>
<td>13.66</td>
</tr>
<tr>
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<td>May 12, 2007</td>
<td>960</td>
<td>68.58</td>
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<td>1.53</td>
<td>121.73</td>
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<td>Jun 13, 2007</td>
<td>965</td>
<td>84.52</td>
<td>-1.24</td>
<td>1.31</td>
<td>106.93</td>
<td>71</td>
<td>13.56</td>
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Figure 1. Trajectories of the Cassini spacecraft during targeted Titan flybys between Apr 16, 2005 (T5) and Apr 10, 2007 (T28). Only the paths of Cassini below 1600 km altitude are shown. Solid (blue/black) lines denote the inbound path, dashed (red/gray) are outbound legs. The points of closest approach to Titan are marked with green points. In order to illustrate the coverage of INMS observations used in this study, only the locations are marked where measurements were returned from by the INMS.
Figure 2. The $N_2$ density profile for inbound measurements during the T16 flyby (July 22, 2006). Above 1,300 km, $N_2$ densities are determined from $C^1$ counts in channel 28 (black crosses); between 1,100 and 1,300 km, densities are determined from $C^1$ counts in channel 14 (blue squares) and below 1,100 km, densities determined from $C^2$ counts in channel 28 (red plus signs). Densities from both $C^1$ counts in channel 14 and $C^2$ counts in channel 28 have been calibrated to those from $C^1$ counts in channel 28 (see text).
Figure 3. Methane mixing ratios (upper panel) and mass densities (lower panel) at 1030 km altitude, as observed by the INMS during multiple flybys (T5-T32) and plotted as a function of latitude. Best fits of Legendre polynomials, as used in the empirical atmosphere model, are shown as dashed lines. Since measurements from all available local times are plotted, markers of data points distinguish the solar zenith angles, with stars indicating sunlit conditions (SZA < 90°), triangles indicating dusk conditions (90° ≤ SZA < 110°) and filled circles indicating conditions of darkness (SZA ≥ 110°). The standard deviations of data points around the fitted curves are shown in both panels. Dotted lines in the upper panel show Methane mole fractions on a level of constant pressure close to 1030 km determined by the empirical model, discussed in Section 5.
Figure 4. Same as Figure 3, but for an altitude of 1200 km.
Figure 5. Same as Figure 3, but for an altitude of 1590 km.
Figure 6. Amplitudes of the first 3 symmetric Legendre polynomials that best fit mass density in Titan’s atmosphere observed by INMS. Examples of Legendre polynomial fits are shown in Figures 3, 4 and 5. The left panel shows amplitudes of $P_0$ (in g/cm$^3$), the middle and right panels show amplitudes of the ratios $P_2/P_0$ and $P_4/P_0$. Also shown as dashed lines are the best fits to the points, using function coefficients given in Table 2 and described further in the text.
Figure 7. Same as Figure 6, but for CH$_4$ mixing ratios.
Figure 8. Standard deviations of CH$_4$ mixing ratios (stars) and mass density (dots) as a function of altitude. The values are fluctuations of measurements around the fitted Legendre polynomial curves, also shown in Figures 3, 4 and 5 as error bars. Dashed and solid lines are polynomial fits through the values, with coefficients given in Table 2. Standard deviations are given as percentages of the average background values.
Figure 9. Examples of comparisons between our empirical model and densities of N$_2$ and CH$_4$ observed by INMS in Titan’s upper atmosphere. Dots are the measurements and solid lines denote model values. Blue (black) lines/markers are for the inbound trajectory legs, red (gray) lines/markers are along the outbound trajectory. Also shown are uncertainty error bars on the model profiles.
Figure 10. Mass densities in Titan’s thermosphere, as given by our empirical model. The left panel shows vertical profiles at latitudes 0°N (solid), 55°N (dashed-dotted) and 80°N (dashed), illustrating the change with altitude of latitudinal variations. The right panel shows densities at fixed altitudes of 1000 km (solid), 1070 km (dashed-dotted) and 1150 km (dashed), normalized to their average values at each height. The latitudinal density structure is roughly uniform above 1100 km, as can be seen also in the left panel. Also shown are standard deviations of densities.
Figure 11. Temperatures in Titan’s thermosphere, as inferred from the empirical model atmosphere densities using the method described in the text. The upper panel shows temperatures as a function of latitude and altitude. The bottom left panel shows vertical temperature profiles at latitudes 20°N (solid), 50°N (dashed-dotted) and 70°N (dashed). The bottom right panel shows temperatures at fixed altitude levels of 1030 km (solid), 1200 km (dashed-dotted) and 1590 km (dashed). While the atmosphere is nearly isothermal above around 1200 km altitude, temperatures below 1100 km increase towards the equator. Error bars are also shown and smallest at the lowest heights.
Figure 12. Horizontal and vertical winds in Titan’s thermosphere, as derived with our General Circulation Model, assuming the thermal structure of Figure 11. The upper panel shows meridional winds (positive northward), the middle panel shows zonal winds (positive eastward) and the lower panel are vertical winds (positive upward). We assume zero winds at the model’s lower boundary (960 km).
Figure 13. Same as Figure 12, but assuming the stratospheric eastward winds of Achterberg et al. [2007] at the lower boundary (960 km).
Figure 14. Methane mole fractions in Titan’s thermosphere at latitude 60°N. Dots are measurements by the INMS during flybys T5, T16, T18, T19, T21, T27, T28, T30 and T32. The dotted line gives values from the empirical model, while the dashed line represents values from a diffusion model which assumes an eddy coefficient of $K=3 \times 10^7$ cm$^2$s$^{-1}$ and escape flux of $\Phi_{esc}=2.77 \times 10^9$ cm$^{-2}$s$^{-1}$ (relative to Titan’s surface).