Titan’s Lower Atmosphere

Caitlin Ann Griffith

Dept. of Planetary Sciences, Univ. of Arizona. Tucson, AZ, 85719 USA

Abstract. Saturn’s largest moon, Titan, sports an atmosphere 10 times thicker than Earth’s. Like Earth, the moon’s atmosphere is N₂ based and possesses a rich organic chemistry. In addition, similar to the terrestrial hydrological cycle, Titan has a methane cycle, with methane clouds, rain and seas. Presently, there is a revolution in our understanding of the moon, as data flows in and is analyzed from the NASA and ESA Cassini/Huygens mission. For example, seas were detected only this year. Here I will discuss the evolution of our understanding of Titan’s atmosphere, its composition, chemistry, dynamics and origin. Current open questions will also be presented. Studies of Titan’s atmosphere began and evolved to the present state in less time than that of a single scientist’s career. This short interlude of activity demonstrates the rigors of the scientific method, and raises enticing questions about the workings and evolution of an atmosphere.

Keywords: Titan, Atmosphere, Surface, Chemistry, Circulation, Atmospheric Dynamics, Atmospheric Structure, Origin and Evolution


A LITTLE HISTORIC BACKGROUND

Pre-Voyager

The presence of Titan’s atmosphere was first revealed by limb darkening, observed by J. Comas Solá in 1907. Roughly three decades later, the first compositional information arrived with the detection of methane vibrational absorption features at 8800 [1]. After another three decades, infrared photometry revealed emission features due to ethane (C₂H₆) and acetylene (C₂H₂), [2, 3, 4]. These detections suggested a rich photochemistry on Titan, initiated from the ultraviolet dissociation of methane. Ultraviolet data displayed a decrease in reflectivity from 6000 to 2600 [5, 6], hinting at the presence of a haze similar to that produced in the laboratory photolysis of methane-rich gases [7]. Additional near-IR data [8, 9] more fully characterized the methane features, allowing Trafton [8] to determine a column abundance of 2 km atm from his analysis of the 3ν₃ band at 1.1 µm. Hunten [10] re-analyzed this band, using the curve of growth by Wallace and Hunten [11], and concluded that, assuming a nitrogen-rich atmosphere, the pressure of nitrogen is 0.9 bar, corresponding to 63 km-amagat, and the mixing ratio of methane is 0.0025. However, radio measurements at 3.3 mm indicated a brightness temperature of 213±38 K [12], which far exceeds Titan’s effective temperature (Table I) and suggests an extremely strong greenhouse effect.

In the late 1970’s two models for Titan’s atmosphere emerged. The “inversion model”, consisted of 20 mbar of methane in vapor pressure equilibrium with a surface of methane ice [13, 6]. The surface pressure allowed for a column abundance that matched the near-IR data, and an effective temperature that allowed for a balanced radiation budget. A
high altitude haze is assumed to result from photolysis and cause the drop in the UV reflectivity of the planet. The surface was expected to be of uniform temperature, with the atmosphere acting as a thermostat. If any local region found itself cooler than the mean temperature, condensation would occur and warm the surface. Similarly, locally warm regions would evaporate until the mean temperature was reached. Thus the pole would never cool down. It was noted that since the poles receive less flux than the equator, there would be a steady migration of methane to the poles, a statically unstable situation. Glaciers were then postulated to exist, along with continual overturn of the surface, which prevented the surface from being paved over by haze sediments.

The second model of Titan consisted of a thick nitrogen-rich atmosphere with a surface pressure of 21 bars, i.e. 1,000 times that of first model, and a surface temperature of \( \sim 200 \) K [14]. The hot surface temperature explained the measurements of Titan’s brightness temperature at 3 mm [14]. In addition, the atmospheric pressure of 0.9 bar, derived from near-IR methane lines, was interpreted as pertaining to the air above an optically thick cloud layer rather than the surface [10]. The idea is that ultraviolet and visible radiation penetrates only down to the \( \sim 1 \) bar level, whereas millimeter radiation probes down to the hotter surface. By further modeling the pressure-induced opacity of \( \text{H}_2 \) and \( \text{N}_2 \), Hunten then determined a Rosseland mean absorption coefficient of \( A = 1.87 \times 10^{-7} \text{ cm}^{-1} \text{ amagat}^{-2} \). The pressure level for which the temperature equals the effective temperature was estimated to be that of unit optical depth, \( \tau = 1 \). This level, found to be 0.79 bar for no cloud and 0.61 bar for a cloudy atmosphere, defined the tropopause. Assuming an adiabatic lapse rate, Hunten found that a temperature of 200 K occurred at a pressure of 21 bars. This pressure defined the surface. Hunten further estimated the effective temperature to be 77 K from Titan’s albedo. In addition, he derived the hydrogen abundance by assuming it to be that for which its production by photolysis matches its loss through escape. A value of 0.47% was determined, which, in fact, is consistent with the recent value of 0.35% measured by Cassini (R. V. Yelle, private communication).

**Voyager**

The arrival of Voyager 1 to Titan in 1981 confirmed the existence of an immense atmosphere. The spacecraft flew behind Titan, while transmitting radio signals to Earth. The refraction of the radiation provides a measure of the density and thus temperature (for an assumed composition) of Titan’s atmosphere [15], and revealed a surface pressure of 1.44 bars. Voyager measurements at ultraviolet wavelengths indicated a \( \text{N}_2 \)-based atmosphere, where, as determined by infrared spectra, principally methane, as well as a plethora of organic species, exist as minor components, as predicted by Hunten [10]. The radio measurements upon which the 21 bar thick atmosphere was predicted turned out to be faulty. Instead the derived pressure inferred from the methane lines of 0.9 bar [10] is close to the real value of 1.44 bar. While it turns out that Titan does not have the methane-based atmosphere proposed by Danielson et al. and Caldwell [13, 6], some of the processes inherent to their model may be important. More recent studies of the thermodynamics of Titan’s atmosphere suggest that methane may regulate
polar temperatures [16, 17], and general circulation models suggest that methane might migrate and accumulate at Titan’s poles [18]. Table I compares a few basic properties of Titan to those of Earth. \[1 \ 2 \ 3 \ 4 \ 5 \ 6\]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Titan</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>2575 km</td>
<td>6378 km</td>
</tr>
<tr>
<td>Bulk Density</td>
<td>1.88 g cm(^{-3})</td>
<td>5.52 g cm(^{-3})</td>
</tr>
<tr>
<td>Surface gravity</td>
<td>1.35 m s(^{-2})</td>
<td>9.8 m s(^{-2})</td>
</tr>
<tr>
<td>Heliocentric Semi-major axis</td>
<td>9.54 AU</td>
<td>1 AU</td>
</tr>
<tr>
<td>Heliocentric Period</td>
<td>29.5 yr</td>
<td>1 yr</td>
</tr>
<tr>
<td>Length of day</td>
<td>15.95 days</td>
<td>1 day</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.029</td>
<td>0.0167</td>
</tr>
<tr>
<td>Axial Tilt</td>
<td>26.7°</td>
<td>23.4°</td>
</tr>
<tr>
<td>Bond albedo</td>
<td>0.2</td>
<td>0.29</td>
</tr>
<tr>
<td>Effective Temperature</td>
<td>82 K</td>
<td>255 K</td>
</tr>
<tr>
<td>Mean Surface Temperature</td>
<td>93.65 K</td>
<td>288 K</td>
</tr>
<tr>
<td>Surface Pressure</td>
<td>1.467 bar</td>
<td>1.013 bar</td>
</tr>
<tr>
<td>Air density</td>
<td>5.3 kg m(^{-3})</td>
<td>1.2 kg m(^{-3})</td>
</tr>
<tr>
<td>Column density</td>
<td>92 km am</td>
<td>8 km am</td>
</tr>
<tr>
<td>Specific heat, (c_p)</td>
<td>900 J K(^{-1})kg(^{-1})</td>
<td>1004 J K(^{-1})kg(^{-1})</td>
</tr>
<tr>
<td>Dry adiabatic lapse rate</td>
<td>1.3 K km(^{-1})</td>
<td>9.8 K km(^{-1})</td>
</tr>
<tr>
<td>Moist adiabatic lapse rate</td>
<td>0.5 K km(^{-1})</td>
<td>(\sim) 5 K km(^{-1})</td>
</tr>
<tr>
<td>Surface saturated mixing ratio</td>
<td>0.114</td>
<td>0.017</td>
</tr>
<tr>
<td>Pressure scale height</td>
<td>20 km</td>
<td>8.4 km</td>
</tr>
<tr>
<td>Brunt-Vaisala frequency</td>
<td>(3 \times 10^{-3}) s(^{-1})</td>
<td>(5 \times 10^{-3}) s(^{-1})</td>
</tr>
</tbody>
</table>

**TITAN’S CHEMISTRY**

Most of the species in Titan’s atmosphere owe their existence to a rich chemistry that originates primarily from the dissociation of methane (CH\(_4\)) by ultraviolet radiation in

---

1 Note that “am” in Table 1 refers to amagat, a unit of density frequently used in planetary astronomy. 1 km am = 2.68\(\times\)10\(^{24}\) molecules cm\(^{-2}\) or, assuming a mean molecular mass of 28 grams (approximately that of Titan’s atmosphere), 1 km am = 1250 kg m\(^{-2}\)

2 The surface temperature, pressure, density and moist lapse rate refer to the Huygens Probe measurements [19, 20]; the terrestrial surface temperature refers to the global mean.

3 The axial tilt for Titan refers to that of Saturn; Titan rotates in a plane defined by Saturn’s equator.

4 The moist terrestrial lapse rate assumes average temperatures.

5 Saturated mixing ratios and the scale heights were calculated for the given surface temperatures.

6 Eccentricity refers to Titan’s orbit about Saturn.
Titan’s upper atmosphere [21, 22, 23]. The chemistry is rather complicated. It is enriched by a nitrogen chemistry, caused by the dissociation of N₂ into N(^2D) and N(^4S) mainly by extreme ultraviolet light (λ < 1000 ) and secondarily by magnetospheric electrons. In addition, cosmic ray electrons are hypothesized to also dissociate nitrogen, forming N and NH, in Titan’s lower stratosphere, below 150 km altitude [21]. More recently, Cassini measurements of the ionosphere, above ~900 km, indicate that the ion chemistry plays a major role in the hydrochemistry [23].

Unlike the jovian planets, which also display a bounty of organic molecules due to methane photolysis, on Titan the resulting hydrogen escapes. Thus the chemistry proceeds irreversibly to the production of higher order carbon molecules. The organic byproducts are mixed in the thermosphere and stratosphere down to the ~100 km level, below which the temperature of the atmosphere decreases rapidly with decreasing altitude. At the cooler temperatures most of the byproducts condense. Their ultimate fate is their precipitation onto Titan’s surface.

A number of different disciplines are involved in the study of Titan’s chemistry. Laboratory experiments simulate the chemistry and determine chemical rate constants as well as the effects of UV irradiation and charge particle bombardment. Observational astronomers measure the composition using ultraviolet, infrared and submillimeter spectroscopy, as well as spacecraft samples. Chemists construct models of the atmosphere based on the laboratory and observational data.
Let’s consider first Titan’s measured composition. The initial ground-based photometry of the 1970s detected enough species, e.g. CH$_4$, C$_2$H$_6$, and C$_2$H$_2$, to suggest photochemistry. In the 1980s, roughly a dozen more species were detected on Titan from Voyager infrared and ultraviolet spectroscopy [25, 26, 27, 28, 29]. The composition was moreover found to vary with latitude [28, 30, 31]. Ground-based millimeter heterodyne spectroscopy resolves line shapes sufficiently to determine the vertical distribution of the species from the shape of the rotational lines (e.g. [32], [33]). The higher resolving power (R~1900) observations from the ISO satellite led to the detection of water [34].

Recently the NASA and ESA Cassini/Huygens mission better quantified the altitude and latitudinal variations in the stratospheric composition of the most abundant species [35, 36, 37, 38, 39, 40]. In addition, Cassini measured an entirely unknown process at levels above 1000 km altitude: the ionospheric chemistry. The newly measured thermospheric and ionospheric composition brings the total number of measured and inferred neutrals and ions in Titan’s atmosphere equals nearly 100 at present [41].

Since 2004, the Cassini spacecraft has been orbiting Saturn, making periodic passes close to Titan. During these passes (44 in the nominal mission which will end in 2008) many of the 12 instruments have been investigating the chemistry of Titan’s atmosphere and surface. The Ion and Neutral Mass Spectrometer (INMS) extracts samples of Titan’s atmosphere and measures the molecular masses of both ion and neutral species. Measurements made during Cassini’s close passes to Titan reveal the atmosphere’s composition from 1000 to 2000 km. The Cassini Plasma Spectrometer (CAPS) measures the flux of ions as a function of mass per charge (or energy per charge in the case of electrons), also in the thermosphere. Ultraviolet spectroscopy, measured by the Ultraviolet Imaging Spectrograph (UVIS), probes the atmospheric composition at 500-1000 km altitude. The highly variable composition of Titan’s stratosphere, between 100 and 500 km, is probed by the mid-infrared spectrometer (CIRS) on Cassini through the emission lines that Titan displays (Fig. 1). The Visual and Infrared Mapping Spectrometer (VIMS) measures the composition of the lower atmosphere and surface, as well as the HCN abundance up to 1000 km altitude. The CCD imager, ISS, provides photometric images useful for constraining the surface material and haze density. In addition, the Radar instrument identifies lakes and seas by their smooth surface and thus low signal at oblique angles.

In 2005, Cassini dropped the Huygens probe equipped with 6 instruments into Titan’s atmosphere. In situ measurements of the composition of Titan’s tropical atmosphere, below 160 km altitude, were accomplished by two instruments. The Gas Chromatograph Mass Spectrometer (GCMS) sampled the atmosphere and measured the vertical profiles of species throughout Huygens’ descent in the atmosphere. The Aerosol Collector Pyrolyser (ACP) sampled Titan’s haze at two altitudes, polymerized the solids, and ran the resultant gas through the mass spectrometer.

In Table II, we present the molar fractions of the most abundant species in Titan’s stratosphere. These rough averages over latitude are compared to the thermospheric composition. The implied variations in altitude, as discussed below, are indicative of

---

7 Stratospheric measurements of HCN & C$_2$N$_2$ refer to the north polar region, and H$_2$O to 400 km.
8 Thermospheric benzene abundance comes from R. V. Yelle, private communication.
Titan’s chemistry. The abundances in the lower atmosphere were derived from Voyager, Cassini, Huygens, and ISO infrared spectroscopy [28, 36, 37, 38, 39, 40] as well as ground-based submillimeter astronomy [33]. Abundances at altitudes of 500-1000 km come from spacecraft UV spectroscopy [29]. Thermosphere abundances, at 1000-2000 km altitude, are probed by in situ sampling of Titan’s atmosphere as Cassini flies by Titan [42, 23, 43].

<table>
<thead>
<tr>
<th>Species</th>
<th>At ~160 km</th>
<th>At 1100 km</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>N₂</td>
<td>0.98</td>
<td>0.97</td>
<td>[40, 42]</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.014</td>
<td>0.027</td>
<td>[40, 42]</td>
</tr>
<tr>
<td>H₂</td>
<td>0.004</td>
<td>0.004</td>
<td>[42]</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>2×10⁻⁵</td>
<td>1.2×10⁻⁴</td>
<td>[36, 42]</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>3×10⁻⁶</td>
<td>2.8×10⁻⁴</td>
<td>[36, 42]</td>
</tr>
<tr>
<td>HCN</td>
<td>7×10⁻⁷</td>
<td>2.0×10⁻⁴</td>
<td>[36, 23]</td>
</tr>
<tr>
<td>C₃H₈</td>
<td>5×10⁻⁷</td>
<td>2.3×10⁻⁶</td>
<td>[36, 42]</td>
</tr>
<tr>
<td>C₃H₄</td>
<td>1×10⁻⁸</td>
<td>4.0×10⁻⁶</td>
<td>[36, 42]</td>
</tr>
<tr>
<td>C₄H₂</td>
<td>2×10⁻⁹</td>
<td>1.0×10⁻⁵</td>
<td>[36, 23]</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>7×10⁻⁷</td>
<td>1.0×10⁻³</td>
<td>[36, 23]</td>
</tr>
<tr>
<td>HC₃N</td>
<td>4×10⁻⁸</td>
<td>4.0×10⁻⁵</td>
<td>[38, 30, 23]</td>
</tr>
<tr>
<td>C₂H₃N</td>
<td>1.5×10⁻⁹</td>
<td>3.0×10⁻⁶</td>
<td>[23]</td>
</tr>
<tr>
<td>C₂N₂</td>
<td>5×10⁻⁹</td>
<td>-</td>
<td>[30]</td>
</tr>
<tr>
<td>C₆H₆</td>
<td>3×10⁻⁹</td>
<td>&gt; 10⁻⁶</td>
<td>[36]</td>
</tr>
<tr>
<td>H₂O</td>
<td>8×10⁻⁹</td>
<td>&lt;3×10⁻⁷</td>
<td>[34, 23]</td>
</tr>
<tr>
<td>CO</td>
<td>4.7×10⁻⁵</td>
<td>-</td>
<td>[39, 44]</td>
</tr>
<tr>
<td>CO₂</td>
<td>1.5×10⁻⁸</td>
<td>-</td>
<td>[39, 28]</td>
</tr>
</tbody>
</table>

The Methane Chemistry

Calculations of Titan’s neutral photochemistry indicate chemical pathways that produce the most abundant byproducts of methane photolysis, ethane (C₂H₆) and acetylene (C₂H₂) [21, 22, 45]. Direct photolysis of methane involves photons of wavelengths between 1000 and 1600; with 90% of the absorption caused by the large flux of Lyman-α radiation at 1216. The optical depth of 1216 radiation is 7×10⁶ in Titan’s atmosphere. Thus methane photolysis occurs above ~900 km altitude, and is independent of the methane abundance, i.e. photon limited. The chemistry proceeds by breaking up the CH₄ in several ways:

\[ \text{CH}_4 + h\nu \rightarrow \text{CH} + \text{H}_2 + \text{H} \]
\[ \rightarrow ^3\text{CH}_2 + 2\text{H} \]  \hspace{1cm} (2)
\[ \rightarrow ^1\text{CH}_2 + \text{H}_2 \]  \hspace{1cm} (3)
rapidly followed by,
\[ ^1\text{CH}_2 + \text{N}_2 \rightarrow ^3\text{CH}_2 + \text{N}_2. \]  \hspace{1cm} (4)
The radicals react with CH\(_4\):
\[ \text{CH} + \text{CH}_4 \rightarrow \text{C}_2\text{H}_4 + \text{H}. \]  \hspace{1cm} (5)
Photolysis by photons of wavelengths \( \lambda < 1700 \) at \( \sim 800 \) km altitude leads to the production of the more stable molecule, acetylene (C\(_2\text{H}_2\)),
\[ \text{C}_2\text{H}_4 + \text{hv} \rightarrow \text{C}_2\text{H}_2 + \text{H}_2, \]  \hspace{1cm} (6)
which is also likely produced higher up (\( \sim 1000 \) km altitude) by:
\[ ^3\text{CH}_2 + ^3\text{CH}_2 \rightarrow \text{C}_2\text{H}_2 + \text{H}_2. \]  \hspace{1cm} (7)
Acetylene further reacts with \(^3\text{CH}_2\) to form allene (CH\(_3\)C\(_2\)H). Acetylene mixes down to altitudes of \( \sim 250-800 \) km where it is photolyzed to form C\(_4\)H\(_2\) and higher order polyacetylenes (C\(_{2n}\)H\(_2\)). These long chain solids likely precipitate to the surface. The production of ethane proceeds primarily at low altitudes (\( \sim 250 \) km), where the atmosphere is dense enough to enable 3 body reactions,
\[ \text{CH}_3 + \text{CH}_3 + \text{N}_2 \rightarrow \text{C}_2\text{H}_6 + \text{N}_2. \]  \hspace{1cm} (8)
Also at low altitudes (\( \sim 250 \) km), CH\(_4\) is photolyzed catalytically. The photolysis of C\(_2\)H\(_2\) produces C\(_2\)H, which reacts with methane
\[ \text{C}_2\text{H} + \text{CH}_4 \rightarrow \text{CH}_3 + \text{C}_2\text{H}_2. \]  \hspace{1cm} (9)
This method for breaking up methane is estimated from laboratory experiments to proceed at a rate nearly an order of magnitude greater than that of direct photolysis [23], because the longer wavelength photons that are involved are more copiously emitted by the Sun. The reaction rate depends on detailed knowledge of the C\(_2\)H\(_2\) profile, of which C\(_2\)H is a photochemical byproduct.
Because the CH\(_4\) chemistry is quite complicated, the best way to determine the photolysis rate of methane is to measure the H\(_2\) abundance and its escape rate in the upper atmosphere. Recent data from Cassini’s INMS indicate that the H\(_2\) mole fraction is \( 4 \times 10^{-3} \) at 1150 km altitude and the escape flux is \( 9.0 \pm 0.2 \times 10^9 \text{ cm}^{-2} \text{ s}^{-1} \), which equals the limiting flux at that altitude. Making the approximation that methane photolysis produces ethane, the break up of two methane molecules leads to the escape of one hydrogen molecule. The methane photolysis rate is thus \( 1.8 \pm 0.2 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \), a number similar to that used by Yung et al. (1984) of \( 1.5 \pm 0.2 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \).
The Nitrogen chemistry

The dissociation of N$_2$ into N($^2$D) and N($^4$S) produces mainly N$_2$. However some of the atoms react with hydrocarbons, at the $\sim$1000 km level to form HCN:

$$\text{N}^{(4S)} + \text{CH}_3 \rightarrow \text{HCN} + \text{H}_2$$ \hspace{1cm} (11)

$$\text{N}^{(4S)} + 3\text{CH}_2 \rightarrow \text{HCN} + \text{H}$$ \hspace{1cm} (12)

$$\text{N}^{(2D)} + \text{CH}_4 \rightarrow \text{HCN} + \text{H}_2 + \text{H}.$$ \hspace{1cm} (13)

Photolysis of HCN gives CN, which reacts predominantly with CH$_4$ to reform HCN. Thus HCN, the most abundant nitrile, is highly stable. Other abundant nitriles are C$_2$N$_2$ and cyanoacetylene (HC$_3$N), formed from reactions involving C$_2$H$_2$.

The ionosphere is a significant source of HCN through the production of N$^+$ and N$_2^+$, which charge exchanges with N, also forming N$^+$, which reacts with CH$_4$ to form HCN$^+$. The latter reacts with CH$_4$ to form H$_2$CN$^+$, which undergoes dissociative recombination:

$$\text{H}_2\text{CN}^+ + e^- \rightarrow \text{HCN} + \text{H}.$$ \hspace{1cm} (14)

Variations in the vertical composition of a species (Table II) provide an indirect measure of its sources, sinks and the vertical mixing of the atmosphere. This can be understood qualitatively by examining the 3 most abundant species in the lower stratosphere (C$_2$H$_6$, C$_2$H$_2$, HCN). Acetylene (C$_2$H$_2$) decreases in abundance dramatically from the thermosphere to the lower stratosphere, as does HCN. This trend reflects its formation in the thermosphere and its attrition in the stratosphere perhaps through polymerization and, for HCN, the high altitude ($\sim$80 km) at which it condenses. Ethane displays more similar mixing ratios in the thermosphere and stratosphere. It is produced in the lower atmosphere, and mixes to the thermosphere, where it is stable with respect to photolysis.

An interesting detection by Cassini’s INMS is that of benzene at 1100 km. Here its volume mixing ratio is at least 2 orders of magnitude higher than predicted. It’s precipitous drop in abundance to $\sim 10^{-8}$ at 180 km altitude, indicates that it chemically reacts with other constituents, perhaps incorporating itself in Titan’s haze.

The Haze

The chemistry leading to the composition of Titan’s haze is likely varied and complicated [46, 47]. This topic has been approached primarily with the production of solids in laboratory simulations of Titan’s chemistry. In addition, photochemical and more recently ion chemistry models have addressed the processes that cause polymerization.

Laboratory experiments simulate the production of solid organic material under a variety of pressures, temperatures and subjected to a range of energy sources, such as discharges, ultraviolet radiation and cold plasma. The solids that result have a C/H ratio of $\sim 1$ and a relatively small C/N ratio (between 1.5 and 11), which indicates that the nitrogen chemistry plays a strong role in the production of the haze [48].

One suggested pathway to large organic molecules is the polymerization of acetylene and cyanooacetylene (HC$_3$N), which has been investigated by Clarke and Ferris (1997).
The photodissociation of acetylene creates ethynyl radicals (C₂H) which produce long chain molecules through the reaction:

$$C_{2n}H_2 + C_2H \rightarrow C_{2n+2}H_2 + H.$$  \hfill (15)

Such “polyynes” have been identified in the process of soot production. They are photodissociated and form polyacetylene radicals (e.g. C₆H) which also build large organic molecules. The main obstacle against this process is the recycling of C₂H into C₂H₂ [47].

Nitriles have also been suggested as a source of Titan’s haze. Laboratory simulations of Titan’s chemistry produce a polymer that includes HCN [50]. The polymerization scheme is not well understood. Thompson and Sagan [51] suggest that it may involve the attachment of CN. Wilson and Atreya [47] find that one of the most abundant nitriles produced in the initial chemistry is C₂H₃CN. Khare et al. [52] note that the optical constants of Titan’s haze do not however resemble those of pure HCN polymers.

Polycyclic Aromatic Hydrocarbons (PAHs) can be found in circumstellar nebula and interplanetary dust particles. PAHs are compounds that consist of connected aromatic rings, such as benzene. While they generally form in high temperature conditions, PAHs are also created in laboratory simulations of Titan’s atmosphere [53, 54]. The production of PAHs might be caused by the addition of acetylene, HCN, and HC₃N on to the simplest aromatic hydrocarbon, benzene.

Studies of the chemistry that initiates haze production [47] suggest that the nitrile chemistry may predominate above 800 km in the production of Titan’s haze, while the PAHs may form at lower altitudes. Recent Cassini observations, discussed below, in fact implicate these two processes.

Yet, Cassini measurements increasingly point to ions as major players in the synthesis of Titan’s haze. Although CAPS measures electron densities that are similar to those inferred by Voyager, it also measures ions whose molecular mass exceeds 1000 amu, much larger than expected. Investigations of Titan’s chemistry prior to Cassini focused on the photochemistry; now models must be extended to include ion chemistry. In addition, INMS data of the ion population of Titan’s atmosphere at 1100 km altitude indicate the presence of four additional nitriles: NH₃, C₂H₃CN, C₂H₅CN, and CH₂NH, which were either unexpected or underestimated [23]. One of the species, C₂H₃CN, is thought to play a role in the production of Titan’s haze [47]. Unsaturated nitriles may facilitate the production of Titan’s haze, as they are expected to polymerize and form macromolecules. In addition, Cassini’s ACP instrument identified NH₃ and HCN as the main products from the photolysis of Titan’s haze. The nitrogen chemistry appears to be more extensive than previously realized.

The Chemistry of Titan’s Surface

A typical gas molecule produced by the photolysis of methane in the upper atmosphere diffuses down to lower levels reaching the 100 km level (0.01 bar), where the temperature drops from 150 K to 70 K at 40 km altitude (Fig. 2). As the gas molecules traverse this region they condense. The condensation altitude depends on the species.
Considering the abundances of ethane, acetylene, propane, and hydrocyanide and their vapor pressures, we find that they condense between 55 and 90 km altitude. Photochemical models indicate that the production rate of these condensates would form a layer several hundred meters deep, on average if methane were present in Titan’s atmosphere since its formation [21] (Table III). Models of the interior evolution indicate that methane outgassed early in the moon’s history as a result of accretional heating and the early overturn of the moon’s core [55]. Thus ethane and methane lakes were expected on Titan’s surface as Cassini closed in on Titan.

### TABLE III

<table>
<thead>
<tr>
<th>Species</th>
<th>Production</th>
<th>Depth*</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{C}_2\text{H}_6$</td>
<td>$6 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$</td>
<td>300 m</td>
<td>liquid</td>
</tr>
<tr>
<td>$\text{C}_2\text{H}_2$</td>
<td>$1 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$</td>
<td>100 m</td>
<td>solid</td>
</tr>
<tr>
<td>HCN</td>
<td>$6 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$</td>
<td>20 m</td>
<td>solid</td>
</tr>
<tr>
<td>$\text{C}_3\text{H}_8$</td>
<td>$6 \times 10^{-13}$ g cm$^{-2}$ s$^{-1}$</td>
<td>20 m</td>
<td>liquid</td>
</tr>
<tr>
<td>haze</td>
<td>$1.2 \times 10^{-14}$ g cm$^{-2}$ s$^{-1}$</td>
<td>60 m</td>
<td>solid</td>
</tr>
</tbody>
</table>

*Depth of global layer if produced for 4.5 Gyr at present rate.

Arguably, the biggest surprise upon Cassini’s arrival was Titan’s lack of oceans. At first, as the dark and light terrain came into view, it seemed that we had finally gleaned extra-terrestrial oceans. Nautical adventures in calm methane seas, under a pale orange sky, seemed imminent. But a few hours later, after frantically examining the VIMS spectra of the dark “seas”, we realized that in fact none of the pixels completely sampled a liquid surface. The spectra varied little in morphology between the dark and light terrains, suggesting no dramatic compositional variation across the disk. The next, much closer pass (at 1174 km distance as opposed to 341,500 km of the first) dashed any hopes of large lakes in the equatorial region.

Yet recently, passes over the polar regions, detected many dark regions north of 70N latitude that appear to be lakes. Moreover, in February of 2007 (a month ago from this writing), Cassini made its closest pass ever over the north pole, allowing RADAR to detect an immense and entirely featureless region with a low signal within the noise level that appears to be a deep sea of several hundred thousand square kilometers. It is larger than all of the Great Lakes on the Canada-US border combined. In addition, near the south pole ISS detected a well defined kidney shaped dark region about the size of Lake Ontario (64,000 km$^2$), one of the Great Lakes, after which the lake is named. The quantity of liquid in the lakes is not known, because only a fraction of the polar surface area has been sampled and the lake depths are not well constrained. Nonetheless, let us estimate the surface reservoir of methane by assuming that shallow lakes cover 10% of Titan’s surface north of 70° latitude. We use a depth of 15 m based on their transparency to RADAR wavelengths. In addition we estimate that the north polar seas, which display no transparency, have a depth of 75 m, because this is half the average altitude variation measured by DISR and the RADAR altimetry experiment [56, 57]. We assume that north polar seas extend roughly 400,000 km$^2$, that is 2-3 times the area of
these non-transparent seas observed by RADAR on February 22, 2007. The amount of methane in the seas and lakes is equivalent to a global layer of methane ∼0.5 m thick. If we further include Lake Ontario and assume a depth of 75 m, similar to that of its terrestrial counterpart (86 m), the surface liquid layer increases to 0.56 m. Thus there is not enough liquid to deduce that, if it were ethane, atmospheric methane has existed (and produced ethane) since the overturning of Titan’s core. A number of explanations have been proposed, but none confirmed. Possibly we simply haven’t looked in the right place, and there is a vast reservoir of ethane in Titan’s subsurface. Possibly, ethane reacts with other surface organics that form more complex organic material, which would then be spectroscopically indistinguishable from the haze sediments. Yet, no chemical scheme to this effect has been identified. Alternatively, Titan may have only recently outgassed methane, leaving the sediments of organic byproducts scarce. To explore this idea, we next examine ideas regarding the accretion of Titan and the resulting outgassing of its atmosphere.

**TITAN’S FORMATION**

Planets and satellites formed from the material in the primordial solar nebula, the elemental composition of which is expected to have resembled that of the Sun and the molecular cloud from which the Solar System originated (Table IV ⁹). The outer planets’ satellites accreted from the solids in the denser nebular regions surrounding the giant planets. Pressures in these circumplanetary nebulae are thought have been 5 to 8 orders of magnitude greater than that in the outer solar nebula.

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
<th>Element</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1</td>
<td>Mg</td>
<td>4.0×10⁻⁵</td>
</tr>
<tr>
<td>He</td>
<td>0.068</td>
<td>Si</td>
<td>3.8×10⁻⁵</td>
</tr>
<tr>
<td>O</td>
<td>6.9×10⁻⁴</td>
<td>Fe</td>
<td>3.4×10⁻⁵</td>
</tr>
<tr>
<td>C</td>
<td>4.2×10⁻⁴</td>
<td>S</td>
<td>1.9×10⁻⁵</td>
</tr>
<tr>
<td>Ne</td>
<td>9.8×10⁻⁵</td>
<td>Ar</td>
<td>3.8×10⁻⁶</td>
</tr>
<tr>
<td>N</td>
<td>8.7×10⁻⁵</td>
<td>Al</td>
<td>3.0×10⁻⁶</td>
</tr>
</tbody>
</table>

We obviously can not directly measure pressure and temperature of a planetary nebula that existed 4.5 billion years ago. Yet in 1974, Lewis [59] realized that the condensation temperatures of abundant species are insensitive to largely divergent assumptions regarding the pressure of the solar and sub-solar nebulae. Constraints on the bulk compositions of the terrestrial planets, Ceres and Vesta, the Galilean moons, and Titan could be derived from their densities [59], considering species formed from the most abundant

---

⁹ Solar composition, based on Cameron 1982 [58]
elements (Table V). The temperatures at which the inferred constituents condensed, and thus a profile of solar nebula temperatures was then inferred [59]. The resulting temperature as a function of distance from the Sun disagreed significantly with that of a nebula in radiative equilibrium with the Sun. Instead it suggested that the nebula was dense, convective, and opaque to the Sun, as hypothesized by Cameron and Pine [60].

In the formation of the outer planets’ satellites, the partitioning of N, C, and O determines the volatile state and the densities of the satellites. Roughly 15% of the oxygen is predicted to have been incorporated in the rock, with the rest of the oxygen divided between CO and H$_2$O [61]. Temperatures in the solar nebula estimated by Lewis [59] imply that, in thermodynamic equilibrium, CO and N$_2$ are more abundant than are methane and ammonia (NH$_3$) in the inner solar nebula. In the cooler outer nebula, where the giant planets accreted, CH$_4$ is more abundant than CO, and the NH$_3$ more prevalent than in the inner nebula, at thermodynamic equilibrium. Lewis and Prinn [62] indicate however that the chemistry that converts CO to CH$_4$ and N$_2$ to NH$_3$ was too slow relative to the radial mixing rates and the nebula evolutionary rates to produce significant amounts of NH$_3$ and CH$_4$. This consideration suggests that Titan’s N and C come from CO and N$_2$. Yet, Prinn and Fegley (1981) [63] argue that in the denser circumplanetary nebula, reactions are fast enough to realize thermochemical equilibrium. Thus Titan’s N and C might derive from CH$_4$ and NH$_3$.

### Table V

<table>
<thead>
<tr>
<th>Planet</th>
<th>Density (g cm$^{-3}$)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>5.4</td>
<td>60% iron-nickel alloy</td>
</tr>
<tr>
<td>Venus</td>
<td>5.2</td>
<td>potassium feldspar</td>
</tr>
<tr>
<td>Earth</td>
<td>5.5</td>
<td>below FeS, above FeO</td>
</tr>
<tr>
<td>Mars</td>
<td>3.9</td>
<td>below FeO, above serpentine</td>
</tr>
<tr>
<td>Ceres</td>
<td>2.7</td>
<td>serpentine</td>
</tr>
<tr>
<td>Vesta</td>
<td>3.6</td>
<td>serpentine</td>
</tr>
<tr>
<td>Ganymede</td>
<td>1.94</td>
<td>no methane</td>
</tr>
<tr>
<td>Callisto</td>
<td>1.85</td>
<td>no methane</td>
</tr>
<tr>
<td>Titan</td>
<td>1.88</td>
<td>has methane</td>
</tr>
</tbody>
</table>

**The Origin of Titan’s atmosphere**

Titan’s atmosphere is interesting in the context of the Solar System. Ganymede and Callisto, which share a similar density and size as Titan, have a similar bulk composition. They also have a similar gravitational field with which to retain an atmosphere. Still they have no stable atmosphere. The lack of neon in Titan’s atmosphere indicates that it was not captured from the solar nebula, which would have had similar cosmic abundances of N$_2$ and Ne [64] (Table IV). Instead Titan outgassed its volatiles, which
were accreted with the solid material in the subnebula. The atmospheric composition, i.e. the CH\textsubscript{4} and N\textsubscript{2}, evolved from ices containing N and C that accreted to form the moon.

Titan’s bulk density is indicative of the oxidation state of carbon. For example if CO was the primary carbon molecule, there would be less oxygen available to form water. In this case the rock to water ratio would be 75/25 [61]. Alternatively, if methane was the dominant species, the mass ratio would be 40/60, quite different [61]. The measured density of Titan suggests a value of 55/45. Perhaps some CO was present in the subnebula, or perhaps the mass ratio was raised by the escape of water [61].

Saturn’s subnebula is thought to have been cool enough to allow for the direct condensation of CH\textsubscript{4} and ammonia hydrates. The alternative carbon and nitrogen species, CO and N\textsubscript{2}, are too volatile to have condensed in pure form. They could have accreted either by being adsorbed onto the surfaces of ice, or by incorporating in water ice lattices as clathrates [63]. Both of these processes preferentially incorporate methane most readily, CO secondarily, and lastly N\textsubscript{2} [65]. If the CO to CH\textsubscript{4} ratio is less than 1, as indicated by Titan’s density, the nitrogen to methane ratio in water ice is smaller than 10\textsuperscript{-3} [61]. This value is much smaller than the ratio of nitrogen to methane (∼30) in Titan’s atmosphere, and also smaller than the ratio N\textsubscript{2}:CH\textsubscript{4}, that includes the methane needed to supply Titan with a lifetime of atmospheric methane (∼1/7). Thus the main source of nitrogen was postulated to be NH\textsubscript{3} [61], which then converted to N\textsubscript{2}, perhaps through photolysis [66, 67] or impact heating [68, 69].

The abundance of argon in Titan’s atmosphere provides a test for the original molecular form of nitrogen that supplied the atmosphere [65]. It turns out that Ar incorporates itself into clathrates with much the same probability as does nitrogen [65]. Lunine and Stevenson [65] find that if the N\textsubscript{2} derived from clathrates, the mixing ratio of argon must exceed 10\textsuperscript{-2}. Recently Cassini was able to constrain the origin of Titan’s atmospheric nitrogen: The INMS instrument measured an argon mixing ratio of less than 10\textsuperscript{-6}, indicating that N\textsubscript{2} derives from the condensation of NH\textsubscript{3} hydrates [42].

The Evolution of Titan’s atmosphere

Based on available phase diagrams for ammonia water systems, Lunine and Stevenson (1987) [55], modeled Titan’s interior structure and found that Titan’s final state after accretion consisted of an inner undifferentiated core, above which resided a layer of rock that differentiated from the NH\textsubscript{3}-H\textsubscript{2}O layer above it. An initial atmosphere formed from the outgassing of the outer layers; but it is thought to have been eroded away by solar EUV radiation, T-Tauri wind or early impacts. The only remaining methane was trapped in the core, which, with a radius estimated to be 1500 km, was large enough to contain sufficient methane to keep Titan’s atmosphere methane rich despite its photochemical destruction over 4.5 Gyr. The core is estimated to have overturned several 10\textsuperscript{8} years after Titan’s accretion, releasing the methane which then rose to the surface. During its passage through the overlying interior ammonia-water ocean, methane is enclathrated by the ocean to an extent that depends on the thickness of the ocean [55]. The available information regarding ammonia water systems indicated that much of the ammonia and
water formed an ice dihydrate layer leaving too small an ocean to trap the rising methane [55]. The methane consequently rose through cracks in the surface crust to form oceans of methane, coupled to an atmosphere in vapor pressure equilibriumph [55, 70].

Cassini did not detect vast oceans on Titan; the question regarding the origin of Titan’s atmospheric methane thus has been revisited. Using recent experimental data on methane clathrate stability [71, 72] and ammonia-water phase diagrams [73], Tobie et al. [74] address this question along with another puzzling attribute of Titan, the eccentricity of its orbit (Table I). Titan’s eccentricity is surprisingly high (0.029), giving rise to the question of how it could persist over geologic time without being tidally dissipated to a more circular one. Tobie et al. [74] consider the coupled evolution of Titan’s orbit and its interior. Their computation of the tidal dissipation and subsequent eccentricity decay over Titan’s evolution [74, 75] indicate that Titan’s orbit was more highly eccentric in the past, with an eccentricity of 5-30%. Titan’s present eccentricity is then a remnant of a past much larger eccentricity.

The new evolution model [74] examines Titan’s evolution following accretion, when, according to prior models [55], a subsurface liquid layer containing NH$_3$ and H$_2$O overlies a silicate layer, which surrounds an undifferentiated core containing a mixture of ice and rock. Consistent with former models [55], the overturning of the core releases methane, which rises and, if not previously in the form of a clathrate, becomes enclathrated by the water. Yet, based on stability diagrams derived from recent laboratory measurements, methane clathrates are expected to have been highly stable in Titan’s interior [73, 76]. The dissociation of clathrates requires specific temperature conditions which are reached only during specific periods of the moon’s evolution. As a result, much of the methane is enclathrated and slowly released in three episodes of methane outgassing. The early events occurred with the core overturn and, later, the onset of core convection, when Titan was < 1 Gyr and ~2 Gyr years old, respectively.

The third, recent, episode of outgassing is initiated by the freezing of the outer liquid layer. In this final stage, the presence of NH$_3$ is of vital importance because it acts as an antifreeze, allowing a liquid layer to survive ~4 Gyrs, thereby delaying the dissipation of Titan’s orbit, and the release of methane. Once the outer layer froze (within the past 0.1-1Gyr), Titan’s orbit evolved from a highly eccentric orbit to the one observed today. The thickening of the ice layer (crystallization of the ocean) incited convection which affected the clathrate layer and led to the dissociation of methane clathrates, thereby allowing methane gas to rise to the surface. This model argues that the methane in Titan’s atmosphere is relatively recent, and results from outgassing within the past 1 Gyr, rather than that during the core overturn ~4 Gyr ago.

Titan’s isotopic composition supports this hypothesis. The carbon isotopic ratio (C$^{13}$/C$^{12}$) is not elevated relative to the terrestrial value, therefore CH$_4$ did not languish in the atmosphere for a long enough time to experience measurable fractionation from escape. In contrast, the nitrogen isotopic ratio (N$^{15}$/C$^{14}$) is elevated and indicates fractionation from escape processes [40, 77]. The presence NH$_3$ in Titan’s interior, as proposed in early models [55], is now supported by the lack of argon in Titan’s atmosphere. While there is evidence of water ice on Titan’s surface [31, 78, 56], NH$_3$ has not been identified spectroscopically on Titan’s surface. Yet, such a detection is difficult because atmospheric methane obscures all but a few wavelength regions. In addition, water ice is highly absorptive in a number of these “windows”. These limitations may obscure all
but possibly the 2.0 $\mu$m features of Titan’s spectrum. In addition, there is no chemical evidence of the early outgassing events. That is, it is still not clear why liquid ethane is not abundant on Titan’s surface.

Cassini images indeed reveal a young surface with few craters, suggestive of recent global volcanic activity. Based on the number of craters, the surface is estimated to be $\sim$1 Gyr old [79]. Yet at present only a small percentage of Titan’s surface has been mapped. Additional mapping efforts (ongoing with Cassini) are needed to test the possibility that the crater count is consistent with the two proposed outgassing events at $<1$ Gyr and $\sim$2 Gyr.

Geological evidence for recent volcanism is indirect at present. There is a feature 30 km wide that has a morphology suggestive of a volcanic origin with multiple overlying flows [80]. Clouds, which rarely appear north of -60° latitude appear consistently in a band at -40° latitude. Their presence may in part result from Titan’s circulation [81], which is predicted have an upwelling branch at this latitude [18]. However, the clouds’ preference for $\sim$0° longitude has no explanation; it may result from outgassing [82].

Current efforts involving the Cassini mission aim to search for spectroscopic evidence of surface NH$_3$ ice, examine at high spatial resolution candidate cryovolcanic features, and search for a “smoking gun” cloud signature. Yet, it should be cautioned that sustaining Titan’s atmosphere through volcanic outgassing requires the release of only $\sim2 \times 10^7$ kg of methane each (terrestrial) year. Such an output may be dispersed into numerous small fumerols that are difficult to detect. Alternatively, we may simply miss the major outgassing events.

WEATHER AND CIRCULATION

Titan’s surface generally appears benign and familiar, shaped by weather, with lakes, fluvial channels, and dunes [56, 83, 84]. These terrestrial-like features result from Titan’s unique resemblance to Earth; similar to Earth’s hydrological cycle, the moon sports a methane cycle, with clouds, rain and lakes. Yet, the structure of Titan’s atmosphere differs strongly from Earth’s. Only 10% of the sunlight reaches the surface to fuel weather [85], compared to $\sim$60% on Earth. The moon’s atmosphere contains more methane, than Earth’s atmosphere has water; thus there is more latent heat available to fuel storms, if condensation occurs. Titan’s troposphere, because it is cool and massive, also responds slowly to daily and seasonal changes in solar forcing, with a radiative time constant of 138 yrs [86]. In contrast, Earth’s radiative time constant is much shorter than a year. Titan also lacks oceans, which are central to Earth’s climate, and instead stores much of its condensable matter in its atmosphere. As a result, Titan’s weather differs markedly from Earth’s. Evidence for this is given by the location of Titan’s large clouds, which presently reside either in a narrow band at 40° S latitude or within 30° of the south pole [87, 88, 89, 90, 91, 81]. Titan presents us with a deviant version of weather on Earth.
Temperature Profile

Arguably, the most important measurements of the Titan’s troposphere by the Voyager mission in 1980 (near northern spring equinox) were the thermal profiles, recorded by the Radio Occultation experiment during dawn and dusk at 8.5° latitude, 256° west longitude, and 6.2° latitude, 77° longitude, respectively [15]. These profiles are almost identical to that measured by Huygens in 2005 (a few years following south summer solstice) at -10° latitude, 192° west longitude [19]. The temperature profile manifests the atmosphere’s absorption and emission of radiation, and therefore the partitioning of solar energy in the atmosphere. Titan’s temperatures, analyzed with radiative transfer models [92, 85, 93], indicate that the lower troposphere cools mainly radiatively, giving rise to a decreasing temperature profile up to the tropopause at 40 km altitude. However, there is a significant greenhouse effect on Titan (Fig. 3), which increases the surface temperature by 21 K over the effective temperature [94]. Between ~40 and 200 km, the stratosphere warms as a result of the absorption of sunlight by haze and methane (Figs. 2, 3). These effects limit the surface insolation, and cools the surface by -9 K compared to the effective temperature [94]. At 200 km, radiative cooling to space competes with radiative warming, giving rise to a nearly isothermal temperature profile of ~176 K up to roughly 350 km altitude. Titan’s atmosphere cools above 350 km from emission by C$_2$H$_6$, C$_2$H$_2$ and HCN to form a mesopause at ~550 km [93].

Earth shows a similar atmospheric structure, however the radiative forcing is caused by different species. The lowest atmosphere cools mainly radiatively. Convection contributes ~7% of the cooling compared to ~1% on Titan (Fig. 3). The temperature minimum is correlated with changes in composition. The mixing ratio of stratospheric water is constrained to lie below that of ~1.3×10$^{-4}$ corresponding to the saturation pressure at the tropopause (assuming T=216 K, P= 0.2 bar). This vapor content is much lower than the surface value of 0.017 bar (at T=288 K, P=1 bar). The ozone concentration increases by an order of magnitude within the first couple of kilometers above the tropopause as it is formed from the photodissociation of O$_2$. Ozone absorbs radiation shortward of 320 nm, thereby heating the atmosphere to temperatures of ~270 K at 50 km altitude, the stratopause. Above this level, in the mesosphere, temperatures fall to a minimum of ~180 K at ~90 km altitude, as a result of cooling by CO$_2$ emission. Temperatures rise above roughly 90 km altitude, as the atmosphere absorbs extreme ultraviolet solar radiation, to temperatures as high as ~2000 K in the thermosphere.

General Circulation

Titan’s haze and, to a smaller extent, methane, absorb ~30% of the incoming radiation, thereby cooling the lower atmosphere. This process, termed as an anti-greenhouse effect [85] because haze is opaque to visible light and transparent to IR radiation, does not have a counterpart in Earth atmosphere (Fig. 3). It limits the power available on Titan to drive weather, by restricting the troposphere and surface insolation. The radiative effects of Titan’s haze are complicated because its thickness varies with latitude as a result of Titan’s general circulation [95]. Titan’s circulation also affects the latitudinal distri-
Temperature profiles of Earth’s and Titan’s atmospheres exhibit a similar structure. Shown here are the US Standard atmosphere for Earth (used for aircraft simulations) and Titan’s profile as measured by Voyager [15].

Distributions of organic molecules in Titan’s atmosphere, which therefore vary with season [96, 35], and change the radiative forcing of the atmosphere [97, 98].

The solar heating of the atmosphere varies with latitude and season, with less power at polar latitudes since the moon’s tilt with respect to the Sun is ~26.7°. If the atmosphere were in radiative equilibrium at each latitude there would be a ~15 K difference between the equatorial and 60° latitude surface temperature [99]. Instead, a roughly 3 K temperature difference was inferred from Voyager infrared spectra. The implied pole-to-equatorial mixing of air [99], is the atmosphere’s response to the differential solar insolation. In part as a result of the planet’s spin (Table I), zonal winds also arise, along with the occurrence of distinct cells of circulation. Thus, Titan’s circulation changes with season as a result of the seasonal variations in the solar insolation and atmospheric composition [100, 101, 18].

Since the radiative time scale of Titan’s troposphere is larger than Titan’s year, Titan’s circulation could be deduced to respond to the average seasonal insolation, which is greatest at the equator. The heating at the equator would then cause air to generally rise at the equator, and, upon reaching the stable tropopause, spread to higher latitudes, like the Hadley cell on Earth. Yet, except at equinox, when such a circulation is predicted...
FIGURE 3. A comparison of the partitioning of radiation in Earth’s and Titan’s atmosphere [85]. Unlike on Earth, Titan’s stratospheric haze (upper dark region) limits the insolation that reaches the surface. Convection (green arrows) plays a larger role on Earth than on Titan, and evaporation (blue arrows) strongly affects the terrestrial atmosphere, and likely Titan’s polar atmosphere.

[99], general circulation models (GCM) indicate a quite different average wind pattern for Titan’s lower atmosphere. Titan’s circulation is instead found to run generally from pole to pole, with rising air near the summer pole and its transport and subsidence near the winter pole [100, 18]. As the seasons change with the arrival of equinox a brief Hadley cell appears in GCM models with rising air in the tropics for a couple of (Earth) years, i.e. a small fraction of a Titan year (29.5 Earth years). Winds then return to follow a pole-to-pole circulation in the opposite sense.

This circulation appears to be largely affected by the warming of Titan’s surface, which although poorly illuminated nonetheless reacts faster than the atmosphere to the change in seasons. General circulation models that do not include changes in the surface temperature with season do not derive a pole-to-pole circulation [102]. Titan’s haze, which varies in density with latitude and season, also strongly affects the circulation [95, 18]. For example, in the winter night, haze radiates heat, thereby cooling the atmosphere and aiding subsidence. Only recently with the DISR experiment on the Huygens probe, has the solar absorption and scattering of Titan’s haze been measured [56]. This measurement will soon be incorporated into GCM models to better account for the effects of the haze. However, it should be noted that the haze was measured only in the tropics, and observations and GCM models indicate a very different density profile at the poles, with for example a high concentration of haze and photochemical condensates at the winter pole [86, 103, 104, 105, 106, 107, 18].

The meridional mixing of Titan’s air, as discussed above, is quite slow, with average
velocities of $\sim 0.04 \text{ cm s}^{-1}$ in the troposphere, and $\sim 5 \text{ cm s}^{-1}$ in the stratosphere [99]. In contrast, east-west or zonal winds with velocities of $\sim 10 \text{ m s}^{-1}$ are measured in the troposphere. The wind speeds increase to $\sim 220 \text{ m s}^{-1}$ in the stratosphere at particular latitudes, depending on the season. Zonal winds have been measured at 0.25 mbar by the shape of Titan’s atmosphere at this pressure level using measurements of the central flash of stellar occultations [108, 109]. Latitudinal temperature variations measure zonal winds at 100-250 km, i.e. $\sim 0.2$-10 mbar [99, 35]. Zonal winds arise in part from a coupling of the surface to the atmosphere, and in addition as a result of the latitudinal transfer of angular momentum by, for example, meridional circulation or non-axisymmetric eddies.

A simple consideration of the equation of motion provides some initial insight into Titan’s circulation. Consider a unit mass element of atmosphere, of density $\rho$, moving with velocity $\mathbf{V}$, in a pressure gradient, $\nabla P$, gravity, $g$, and friction force, $F$:
\[
\frac{d\mathbf{V}}{dt} = g - \frac{1}{\rho} \nabla P + F.
\] (16)

Generally one works with coordinates that are fixed to the planet’s surface, which makes the equation somewhat more complicated since planets rotate and are round. For example, the planet’s rotation gives rise to an apparent force, the “Coriolis force”. If we ignore vertical motions and neglect the curvature of the planet by ignoring terms proportional to the inverse radius of the planet, the equation simplifies to:
\[
\frac{d\mathbf{V}}{dt} = f \mathbf{V} \times \hat{z} - \frac{1}{\rho} \nabla P + F,
\] (17)

where $f = 2\Omega \sin \phi$, $\phi$ is the latitude, $\Omega$ the angular velocity of the planet’s rotation and $\hat{z}$ is a unit normal vector in the vertical upward direction. The coordinate system is now fixed to the planet, and motion occurs on a horizontal plane. Horizontal motions are generally faster than vertical motions. For an atmosphere on a rapidly rotating planet, such as Jupiter, with a spin just short of 10 hours, the first term in the Coriolis force cannot be ignored. We can consider large scale motion on the planet where the motion’s curvature and acceleration are small $\frac{d\mathbf{V}}{dt} = 0$. In that case, assuming no friction, the above equation reduces to:
\[
v = \frac{1}{f \rho} \frac{dp}{dx}, \quad u = -\frac{1}{f \rho} \frac{dp}{dy},
\] (18)

where $y$ is the coordinate in the northward direction, $x$ is that in the eastward direction and $v$ and $u$ are the associated velocities, respectively. Thus zonal winds, $u$, depend on latitudinal variations in the pressure as a result of the Coriolis effect. In effect, northward (southward) bound air in the northern hemisphere will move eastward (westward), as a result of its higher (lower) angular momentum around centers of high pressures or downwelling air. Likewise, around low pressure regions (cyclones), air moves counterclockwise in the northern hemisphere. In such geostrophic motion, the Coriolis “force” exactly balances the pressure gradient force.
Another convenient approximation, that of *cyclostrophic* winds, occurs when the Coriolis affect is small. Then assuming no friction:

\[
\frac{d\mathbf{V}}{dt} = -\frac{1}{\rho} \nabla P.
\]  

(19)

Considering motion with a radius of curvature of \(r\), this simplifies to:

\[
\frac{V^2}{r} = \frac{1}{\rho} \frac{dP}{dr}.
\]

(20)

The pressure gradient is the force that accelerates the circulation motion. Since this force must point towards the center, the center of cyclostrophic circulation is always a region of low pressure, as easily witnessed in the dust devils of the southwest, or the tornados of the midwest regions of the United States, which display a center of rising air. In addition, the circulation clearly can be either clockwise or counterclockwise.

The ratio of the magnitudes of the acceleration term to the Coriolis term, the Rossby number, \(R_o\), provides a good check of the appropriate approximation. Here:

\[
R_o \sim \frac{V^2/L}{fV} = \frac{V}{fL},
\]

(21)

and values less than 0.1 can be approximated as geostrophic motion with an error less than 10%. For example, Jupiter’s Great Red Spot (GRS) at 22° latitude is a storm system that rotates in the anticlockwise direction. It exhibits winds with speeds as high as 120 m/s and extends over a region of \(\sim 13,000 \times 30,000 \text{ km}^2\). Its Rossby number, \(R_o \sim 0.04\), indicates that the GRS is an anticyclone in geostrophic balance.

The Rossby number for Titan’s winds, approximated by taking \(L= 1000 \text{ km}\), \(V=200 \text{ m/s}\), and assuming a latitude of 30°, is \(R_o \sim 40\). Thus Titan’s winds are cyclostrophic. Without direct measurements, it was unclear whether they are prograde or retrograde. The direction of Titan’s winds was a particularly pressing question prior to the release of the Huygens probe. The tracking of the probe by the Cassini orbiter depended on constraining somewhat the east-west drift that the probe would experience upon descent. Measurements of the doppler shift of Titan’s \(\text{C}_2\text{H}_6\) emission lines over the east and west limbs indicated a prograde zonal circulation for Titan’s stratosphere [110].

Temperature variations are correlated with pressure variations in an atmosphere. Specifically, the change in the zonal winds with height is associated with latitudinal temperature gradients. This effect is expressed in the thermal wind equation, derived by combining equation 17 with that for hydrostatic equilibrium and taking zonal averages [111]:

\[
\frac{\partial}{\partial \ln P} [uf + u^2 \tan(\phi)r^{-1}] \sim \frac{R}{rm} \left( \frac{\partial T}{\partial \phi} \right) P.
\]

(22)

where \(\phi\) is the latitude.

Thus, horizontal temperature variations with, for example, seasonal changes, alter zonal winds. In addition, the latitudinal temperature fields (as measured by Voyager or
more comprehensively by Cassini) can be used to infer zonal winds [111, 35]. In 1989, during northern summer, the highest winds were found at −65° at the 0.25 mbar level [108, 109, 111]. In 2001, during southern summer the strongest jets were observed at 60° [112]. By 2005, these jets had migrated towards the equator, residing between 20-40° N latitude [35]. Thus, the zonal winds indeed vary with Titan’s seasons [35]. Flasar et al. [113] find that the coupling of latitudinal temperature variations and the winds (apparent in equation 22) results in a dynamical inertia that introduces a phase lag of an entire season (which exceeds the radiative relaxation time) to Titan’s stratospheric circulation.

High winds at the winter 60° latitude line may isolate polar air similar to the Antarctic polar vortex, which on Earth allows for the formation of the ozone hole. Similarly, the winter polar chemistry on Titan may be unique. The hydrocarbon species produced in the stratosphere are expected to be transported to the lower stratosphere at the winter pole, where they might concentrate during the winter as a result of the isolation [107, 18]. In addition, a modified chemistry may thrive in the polar night, one that allows for species that would otherwise have been destroyed by the UV dissociation [106, 105].

One of the big questions regarding Titan’s circulation pertains to the formation of winds that rotate faster than Titan’s surface, that is super rotating winds. Titan’s atmosphere at high latitudes exhibits strong latitudinal temperature gradients that explain the observed super-rotating winds. Yet, it is not clear how strong zonal winds form at the equatorial regions, where temperatures do not vary significantly. Potentially transient eddies transport angular momentum to the tropics from high northern latitudes [100]. Numerical models have also been able to produce tropical jets if a thick haze or cloud deck limits the surface insolation to the point that the temperature gradient is subadiabatic. The consequent lack of convection decouples the upper atmosphere to the surface friction, thereby enabling high zonal winds [114]. Yet, it is not yet clear if thick clouds or haze occurs during the tropics near equinox, when the tropical jets appear.

Current GCM models do not however resolve the details of convective systems, which occur on spatial scales much smaller than the grid systems. Finer grid models such as the regional atmospheric modeling systems (RAMS) are presently being adopted to Titan to understand cloud formation [115, 116].

Clouds and Convection

While there are no in situ measurements of atmospheric conditions within Titan’s storms, the temperature profile and humidity in stable areas, coupled with the overall cloud characteristics, provide some basic ideas regarding cloud formation. One key piece of information is the altitude change in the temperature, $dT/dz$, generally referred to as the lapse rate. Voyager and Huygens measured conditionally unstable lapse rates below $\sim 15$ km in Titan’s tropics [15, 117, 19]. That is, the temperature was found to decrease with increasing altitude faster than the moist adiabatic lapse rate but slower than the dry lapse rate. The profile implies that the atmosphere, if saturated, would be
unstable to convection. Yet, Voyager, and later Huygens, observations also indicate that the atmosphere is not saturated [118, 40]. The atmosphere was therefore stable at the latitude and season sampled by these spacecrafts. Nonetheless conditionally unstable profiles are typical of regions of cumulus activity on Earth, where temperatures manifest the combined effects of small areas of convection accompanied with larger regions of dry subsidence.

Convection and cloud formation require either that the atmosphere be humidified to saturation or that a parcel be physically raised above the altitude where it is cool enough to condense, called the lifting condensation level (LCL). Such forced lifting might occur in regions where air converges near the surface, or diverges aloft. A parcel might also be heated to the convection temperature so that it is buoyant enough to rise to the altitude where it becomes saturated. If the parcel rises sufficiently such that enough latent heat has been released to render the parcel buoyant, (i.e. to the level of free convection, LFC), it will further rise until its density matches that of the ambient atmosphere, called the level of neutral boundary (LNB).

Updrafts evolve rapidly enough so that they can be approximated as adiabatic, with an additional non-adiabatic process involving the mixing and entrainment of ambient air. To evaluate the stability of Titan’s atmosphere with respect to convection, we define a temperature that is conserved for adiabatic motions, the potential temperature, $\theta(z)$, at an altitude $z$. This is the temperature that a parcel of air, of temperature $T$ and pressure $P$, would have if it were moved adiabatically to some reference altitude, $z_s$, of pressure, $P_s$, generally taken to be the surface. For adiabatic motion of an ideal gas:

$$c_p dT = \frac{TR}{mP} dP. \tag{23}$$

Integrating this expression from $P=P$ to $P=P_s$, where $T = \theta$,

$$mc_p/R \int_\theta^T \frac{dT}{T} = \int_{P_s}^P \frac{dP}{P}, \tag{24}$$

or

$$\frac{mc_p}{R} \ln \frac{T}{\theta} = \ln \frac{P}{P_s}. \tag{25}$$

That is:

$$\left(\frac{T}{\theta}\right)^{mc_p/R} = \frac{P}{P_s}, \tag{26}$$

or

$$\theta = T \left(\frac{P_s}{P}\right)^{R/mc_p}. \tag{27}$$

The equivalent potential temperature, $\theta_e$, of a saturated atmosphere is defined as the potential temperature for the parcel where the warming of the parcel by latent heat is also considered.

$$\theta_e \approx \theta \exp(L_c q_s/c_p T). \tag{28}$$

The potential temperature gives us a measure of the stability of the atmosphere with respect to convection. Consider a quick (and thus adiabatic) and infinitesimal
displacement of a parcel of dry air. When displaced, a parcel immediately adjusts its pressure to the ambient atmospheric value. A comparison of air of different potential temperatures is equivalent to the comparison of air of different temperatures or densities when moved adiabatically to the same level. If the dry parcel when displaced has the same potential temperature as ambient air at the level it was transported to, then the parcel has the same temperature and density, and thus it does not budge; it is stable. Likewise if the lifted parcel’s $\theta$ exceeds the ambient value the parcel rises; it is unstable. If the lifted parcel’s $\theta$ is lower than the ambient value the parcel falls back to its original level; it is stable.

For a saturated atmosphere, we must consider the latent heat that warms the parcel upon ascent, therefore the equivalent potential temperature $\theta_e$. In turns out that the equivalent temperature of an atmosphere assuming saturation, that is $\theta_e^*$, provides an indication of stability in this case [119]. If a parcel is raised or heated such that its $\theta_e$ exceeds the ambient $\theta_e^*$, the parcel is buoyant. Note that this implies that the atmosphere is conditionally unstable if $d\theta_e^*/dz$ is negative and stable otherwise. Thus we need to know the the methane mixing ratio (or humidity) profile to evaluate the atmosphere’s stability. Voyager measurements did not uniquely determine the humidity profile. Yet Voyager radio occultation measurements indicated a surface humidity of at most 70%, the value needed to keep the lapse rate from exceeding the dry adiabatic value [118].

The temperature profile and (for the first time) the humidity profile of Titan’s atmosphere were measured by the Huygens Probe at -10° latitude and 192° longitude. From this data the $\theta_e^*$ profiles (black and red lines) and the surface value of $\theta_e$ (blue circle) are shown in Figure 5 (middle panel). The values of $\theta_e^*$ depend on the composition of the condensate (which sets the saturation methane abundance) and in the figure we consider both the methane condensates that contain dissolved N$_2$ (black line) and that do not (red line). Consider only for simplicity, the binary condensate (black line). It is apparent from the middle panel (Fig. 5) that air right above the surface is highly stable ($\theta_e$ (surface parcel) $\ll \theta_e^*$). Note that a parcel must be raised adiabatically (thus in a vertical path since $\theta_e$ is conserved) up to 9 km (the LFC) until it becomes buoyant and convects to the upper troposphere. The parcel rises a bit higher than $\sim 25$ km (the LNB), as a result of the momentum gained during ascent, assuming that the cumulus does not entrain ambient air. In comparison, the average LFC in regions of heavy convective activity (e.g. the US midwestern summers) typically occur 1.5 km above the surface. In the case of Midwestern summers, the surface heats sufficiently to raise surface air to the LFC, and cause afternoon thunderstorms. In comparison, on Titan the LFC is higher than on Earth, and the solar insolation and vertical winds much lower. This one measurement of Titan’s surface humidity might suggest cloudless conditions on Titan. Yet, for Titan, so far, we have only the temperature and humidity profile for one location. Therefore, let’s leave this aside for now, and consider additional measurements of Titan’s atmosphere.

In the mid-1990s there were two camps of thought regarding weather. One camp envisioned a “sunny” Titan: extraordinarily quiescent with with no clouds and potentially with highly supersaturated (150-200%) methane conditions above 15 km altitude, where the temperature profile was stable. This scenario was in part motivated by Voyager measurements of Titan’s 200-350 cm$^{-1}$ flux, which suggested an opacity structure indicative of supersaturated conditions [120, 121]. The Huygens’ measurement of the methane profile indicates, however, that saturation controls the humidity. It is still unclear what the
source of the additional opacity is at this wavelength. A further consideration was the composition of the haze; methane does not dissolve in the haze particles, thereby limiting the availability of condensation nuclei [120]. Yet, it was realized that ethane condenses on haze and methane on the ethane. The second camp envisioned a “stormy” Titan: one with clouds, rain and a landscape shaped by weather, as observed by Cassini. Yet, there is limited energy available in the troposphere for convection; instead the atmosphere appears to be largely in radiative equilibrium as shown in Fig. 3 [94].

In fact, we find that Titan lies somewhere in between these two personalities. Methane clouds were detected in 1995, through ground-based observations at near-IR wavelengths that sample Titan’s troposphere at spectral regions where methane absorption is weakest [122], as shown in figure 4. The clouds were hypothesized to be convective based on their altitudes and rapid temporal variability [123]. Yet clouds were found to be sparse, covering usually less than 1% of the disk [123]. The first ground-based images [87, 88] indicated that clouds reside mainly south of -70° latitude in 2000 until the present, and at 40° N latitude in 1995 [124]. Cassini observations confirm the presence of clouds predominantly at southern latitudes. At high resolution, the clouds appear to be composed of cells, reminiscent of cumuli, which supports a convective origin [125]. In addition, the clouds evolve vertically at the rate expected of adiabatic plumes [81]. The location of Titan’s clouds differs vastly from that on Earth, bringing up the question of whether cloud formation could also be somewhat exotic.

The propensity for the tops of the south polar clouds to appear consistently in the upper troposphere (near the likely LNB) suggests that parcels are lifted from the surface to the LFC, allowing them to rise to the upper troposphere. On Earth clouds are associ-
ated with regions of uplift, occurring preferentially near the equator at the rising branch of the Hadley cell and at high latitudes, where the polar front chisels up humid air from the tropics. The pole-to-pole circulation derived for Titan indicates a similar association, since most clouds are seen presently near Titan’s south pole, a region of circulation uplift. This correlation was shaken in 2005 by the detection of a band of smaller clouds at -40° latitude [91], which now appears to be a common occurrence [82, 81]. Yet, an updated GCM model that includes a greater opacity of haze at the pole came to the rescue; it predicts a rising circulation branch at -40° latitude as well as at the South Pole [18]. In effect, the haze concentration in the polar region obstructs sunlight from reaching the polar surface, thereby moving the Hadley cell to -40° latitude, and allowing for slantwise convection at the south polar region. Nonetheless, Titan’s circulation is still unable to entirely explain the cloud band because the clouds also have a longitude preference: they occur preferentially at 0°±30° longitude [82]. Clouds have also been observed, but not on a regular basis, at -14° and -33° latitude [125]. A recent Cassini VIMS image of Titan’s tropics at 0° longitude indicates the presence of a chain of mountains that rise 1.5 km above the low (∼150 m relief) hills of much of the surface. The association between the mountains and the clouds is unclear. The possibility of cryovolcanism has been suggested [82]. Yet this explanation does not explain why clouds develop at other longitudes at the -40° latitude band [81]. Thus a combination of updrafts and orographic, tidal and evaporative forcing has also been suggested [81]. Yet at present, the longitude preference mechanism is unclear.

Clouds are not common in Titan’s tropics, yet many washes appear, interspersed with vast dunes that extend for thousands of kilometers. It is possible that the dunes and washes are both currently forming, perhaps during different seasons. Alternatively, they were formed during different climates. To address this question, we examine the stability of Titan’s atmosphere. The only place on Titan where this is possible is at the Huygens landing site (at -10° latitude and 192° west longitude). As discussed above, the simultaneous measurements of the methane and temperature profiles allow us to calculate the equivalent potential temperature. Indeed Huygens landed in damp lake bed, at the base of hills that are carved by fluvial features. The GCMS inferred the soil’s dampness from the rise in the recorded methane abundance (relative to the atmospheric value) following landing [40, 84]. The evaporation rate on Titan’s surface, for the measured weak winds of ∼0.25-1 m s⁻¹ [126, 84], is roughly 5-17 m yr⁻¹ [17]. Since Titan’s atmosphere holds ∼5 m of CH₄, the dampness of the soil implies either rain in the past year or the past presence of a lake over a few meters deep.

A simple analysis of the Huygens GCMS and HASI data sets that assumes the condensation of pure methane suggests a perplexing profile: 45% humidity at the surface with a constant mixing ratio up to 8 km where the atmosphere is near 80% humidity. The atmosphere remains at ∼80% humidity up to 15 km, above which it rises to 100% humidity between 20-30 km altitude. It was not clear what causes the atmosphere to remain pegged at 80% humidity until Tokano et al. [20] explained the profile by realizing that nitrogen dissolves in methane at lower altitudes (below ∼20 km), where the methane is still liquid, and depresses the vapor pressure. Above 14 km methane condenses as a pure (or nearly pure) solid. In fact, such behavior was predicted for Titan by Thompson et al. in 1992 [127]. When nitrogen is included, it becomes apparent that the atmospheric humidity is ∼100% between 7 and 15 km altitude with respect to methane-nitrogen
FIGURE 5. Titan’s $\theta_\text{e}^*$ assuming saturation of CH$_4$-N$_2$ (black line) and pure CH$_4$ (red line) and non-ideal equation of state [127]. Three panels describe A) mid-tropospheric convection, B) forced uplift followed by convection of surface air, and C) convection in an 80% humid atmosphere. The dashed purple line shows the divide between pure CH$_4$ (above line) and CH$_4$-N$_2$ (below) condensation, although all parcels were assumed to condense as CH$_4$-N$_2$.

liquid condensation and $\sim$100% at 25-30 km for the condensation of pure methane ice, indicating that condensation controls the methane profile. This profile indicates a well mixed atmosphere below 7 km altitude.

As discussed above, Titan’s thermal profile is conditionally unstable below 12 km. While surface air has a low humidity of 45% and is therefore stable, the atmosphere is roughly saturated between 7 and 11 km and thus unstable to convection. As shown in the left panel of Figure 5, saturated air rises, to 21 km altitude, assuming the condensation of CH$_4$ and N$_2$. Note that the drops might freeze above 16 km altitude, exsolve the N$_2$, in which case the cumuli would finish their ascent somewhere between 16-21 km, depending on the, as yet unknown, microphysics. A weak convection cell is thus likely in Titan’s middle troposphere, with air rising between 7-11 km up to 14-21 km. Titan’s temperature profile thus suggests that the one diffuse cloud layer observed at 21 km altitude by Huygens’ DISR instrument [56] might be a remnant of mid-tropospheric convection.

The energetics of convection in Titan’s atmosphere can be estimated by integrating the buoyancy of the parcel over the altitude region in which the parcel is buoyant; that is from the LFC to the LNB altitudes. At the Huygens site, these values (for convection at 7 km altitude) are 7 km and 21 km respectively. The expression for the Convective
Available Potential Energy (CAPE) is:

\[
\text{CAPE} = \int_{z_{LFC}}^{z_{LNB}} \frac{g(T_p(z) - T(z))}{T(z)} dz,
\]  

(29)

where \( g \) is the acceleration of gravity (Table I) and \( T_p(z) \) and \( T(z) \) are the rising parcel’s temperature and the atmospheric temperature at the altitude \( z \). The calculated CAPE=200 J/kg is small indicating that the parcel’s density does not differ strongly from that of the ambient atmosphere over a large altitude range. Such a small CAPE does not indicate a method for making large (millimeter-sized) drops, suggesting instead that rain drops are 50-100 \( \mu \)m in size [128]. Unless the raindrops are in vapor pressure equilibrium with an atmosphere having \(~\)50% ethane humidity and \(~\)45% methane humidity, such raindrops would not reach Titan’s surface [129]. Titan’s atmosphere thus presently appears too stable to have carved the fluvial features seen at the Huygens landing site.

At equinox (in 2010), an upward circulation branch is predicted at Titan’s tropics [18] that is potentially sufficiently vigorous to raise surface parcels up to their LFC. Yet such updrafts, with no change in the methane humidity and the temperature profile, would give rise to only very weak convection with a CAPE\(~\)100 J/kg [116]. Rainstorms would not be expected unless the humidity changed as well. Note the difference between \( \theta_e^*(z) \) and \( \theta_e(\text{parcel}) \) in the right panel of Figure 5. Barth et al. [116] find that the humidity must be 65% before strong rainstorms would form. In such a case, the CAPE=1000 J/kg [116]. Generally the most severe weather on Earth has a CAPE of 2500 J/kg, in comparison.

Tokano et al. (2005) find that the small change of roughly 0.1 K in Titan’s surface temperature from Voyager to Huygens observations is most consistent with a surface consisting of a porous icy regolith. For such a composition, diurnal variations in the skin temperature are predicted to be 3 K. However, the skin depth is only \(~\)9 m, and thus while a morning dew might result if the boundary layer is \(~\)9 m, much lower than 350 m measured by Huygens [19, 20], the troposphere is not affected. Instead these models predict that the near-surface temperature in the tropics (including 10° S latitude) changes by only 0.5 K throughout Titan’s year. Such temperature changes would alter the humidity at the Huygens landing site by only \(~\)3%, insufficient to cause severe weather.

Conceivably Titan’s tropical atmosphere might humidify from the evaporation of the north polar lakes, which presently emerging out of winter night, will experience increased solar insolation until north summer solstice. As discussed above, we estimate that an amount of liquid equivalent to a global coverage of 0.5 m resides north of 70° latitude. This approximation does take into account the possibility that the lakes might be rich in ethane. Considering the atmospheric component of methane, the Huygens probe measured an equivalent of 4.5 m of methane in the atmosphere. If the north polar region is 3 K cooler than the tropics, it holds 3.1 m of methane if saturated. Thus we estimate an equivalent total precipitable depth of 4 m of atmospheric methane. Despite the number of assumptions, Titan’s atmospheric component of methane likely exceeds that of the surface (Table VI).
An increase in the humidity of Titan’s tropics from 45% to 65% requires the addition of \( \sim 0.7 \text{m} \) of methane, an amount that is certainly within the error of the value of 0.56 m approximated above. Yet the evaporation and mixing of the north polar methane (if indeed enough exists) is fairly complicated. For reasonable temperatures and winds the rate of evaporation of 10 m/yr [17], ignoring evaporative cooling, is fast enough to evaporate a 75 m lake within a Titan season (of 7.5 Earth years). Yet, evaporation cools the atmosphere and effectively arrests evaporation unless further heated. We can estimate of the cooling due to methane evaporation:

\[
\Delta T = \frac{m_{\text{CH}_4}}{m_{\text{atm}}} \frac{L_{\text{CH}_4}}{c_p},
\]

where \( c_p \) is the specific heat of the atmosphere (Table I), \( L_{\text{CH}_4} = 5.35 \times 10^5 \text{J/kg} \) is the latent heat of vaporization for methane, \( m_{\text{atm}} = 1.15 \times 10^5 \text{kg m}^{-2} \) is the column mass of the atmosphere, and \( m_{\text{CH}_4} \) is the areal mass of the methane liquid. Here we ignore the effects of ethane and dissolved nitrogen. We find that 1 m of methane (equivalent to 454 kg m\(^{-2}\)) cools the atmosphere by 2.1 K. The evaporation of all of the lakes and seas north of 70\(^\circ\), equivalent to an average of 15 m of methane in this region (north of 70\(^\circ\) latitude), would require the amount of energy equivalent to decreasing the polar temperature by 32 K. Equivalently, evaporation of 15 m of methane north of 70\(^\circ\) requires \( 3.66 \times 10^9 \text{J m}^{-2} \). The question arises as to whether this energy comes from the heating of the atmosphere during summer.

We estimate from a radiative transfer calculation that assumes the haze profile and methane absorption of McKay et al. [85] that 6% of the sunlight at the top of Titan’s atmosphere reaches Titan’s surface, on average, at 80\(^\circ\) at north summer solstice. This value is smaller than that of 10% estimated from disk averaged calculation because of the larger slant path through the atmosphere. At north summer solstice, the incident irradiation at the top of the atmosphere, 14.76 W m\(^{-2}\) is indirect and thus diminished by \( \cos(80^\circ - 26.7^\circ) \). The surface irradiation at north summer solstice is 8.8 W m\(^{-2}\). An overestimate of the summer heating can be made by assuming an insolation at the surface equal to that at summer solstice, 0.06 \times 8.8 \text{ W m}^{-2} = 0.53 \text{ W m}^{-2} persists for half a Titan year \( (4.64 \times 10^8 \text{ s}) \). The total energy available to evaporate the lakes in the summer is then \( 2.46 \times 10^8 \text{ J m}^{-2} \); that is an order of magnitude less than needed.

Thus summer heating at the poles is insufficient to evaporate the lakes. As suggested by Dave Stevenson [16], evaporation regulates Titan’s polar temperature, which must warm through the mixing of drier air from lower latitudes to allow further evaporation. We consider the heating of the entire summer hemisphere, with the idea that atmospheric dynamics mixes warm tropical air to the poles to counter evaporative cooling. The

### TABLE VI

<table>
<thead>
<tr>
<th>Condensible</th>
<th>Earth</th>
<th>Titan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (m(^3))</td>
<td>( 1.4 \times 10^{18} )</td>
<td>( 4.6 \times 10^{14} )</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.001% (2.5 cm)</td>
<td>81% (4 m)</td>
</tr>
<tr>
<td>Surface</td>
<td>99.998% (2.7 km)</td>
<td>9% (0.6 m)</td>
</tr>
</tbody>
</table>
percentage of sunlight that reaches the surface ranges from 6\% to 10\%, from the pole to
the equator, assuming the haze and methane opacities of McKay et al. [85]. Summing
the summer heating at latitudes from the equator to the pole over half a year (spring to
fall equinox), this time more accurately accounting for the variation of the insolation
with season, we find that the summer hemisphere gains \(2.7 \times 10^{21}\) J of energy at the
surface. This energy falls short of that needed to evaporate the lakes \(9.3 \times 10^{21}\) J, even
though it was assumed that all of the heating went exclusively into evaporation at the
north pole. Since a fraction of the energy will be invested in atmospheric dynamics
and local heating, it appears that meridional mixing of air will evaporate the lakes only
if they contain significantly less methane than we estimate. The additional dynamical
constraint that the pole to equator mixing time is slower than a Titan year, consistent
with the atmosphere’s large radiative time constant [99], further indicates that lakes are
permanent features of the polar regions.

Since the solar insolation on average is a maximum at the equator, air cycles to the
polar region, where, during winter, methane condenses out. A simple consideration of
the energy balance at Titan’s surface, thus suggests, in agreement GCM models [18], that
methane is transported to the poles where it largely remains. Thus the humidification
of Titan’s tropics to 65\% by summer evaporation of the north polar lakes does not seem
likely. Additionally the Huygens’ landing site (at 10° S latitude) lies closer to the south
pole, which has warmed from summer heating.

An alternative explanation for Titan’s tropical fluvial features is that they did not result
from current conditions, nor from a change in season. Instead the channels may have
formed from a past wetter climate. This explanation is consistent with the detection
of dry rivers and lake beds at all latitudes, including the north polar region [83]. It is
also consistent with the finding that some of the lakes in the north pole appear to have
evaporated from a larger lake bed. In addition, the presence of dunes [84] and washes in
the equator may be explained by postulating that Titan’s climate was wetter in the past,
at which time there was extensive rainfall and rivers, while in the present arid climate
dunes are forming.

The fate of north polar methane, whether it moves about Titan with the seasons or
migrates permanently to the polar regions upon outgassing will be partially answered
with future Cassini and ground-based observations. If the tropics become more humid,
and experience a Hadley cell circulation (with equatorial updrafts) at equinox (2010)
perhaps we will witness large tropical storms, which may explain the equatorial fluvial
features. Alternatively, we may detect no significant cloud activity, consistent with the
results of recent general circulation models [18] and the simple estimates above.

FUTURE STUDIES

At present the Cassini mission is in full swing, with new information on Titan “beamed
back” to Earth every 2-3 weeks, after each Titan flyby. Currently evidence for an
extensive ion chemistry is emerging from the presence of heavy ions of thousands of
atomic mass units in the thermosphere. The synthesis of data from the CAPS and INMS
instruments will further elucidate thermosphere’s ion and neutral chemistry, which prior to Cassini was unknown and thus largely ignored. Cassini is presently mapping Titan’s surface with RADAR, ISS and VIMS measurements to produce an inventory of its liquid coverage and geological features. Analysis of near-IR surface spectra aim to constrain the composition of the organic material deposited on the surface as well as its coverage over the water ice rich bedrock. Near-IR observations are able to inventory the clouds and their morphologies. The seasonal change in the stratospheric composition and temperatures are presently being measured with mid-IR measurements [35]. Perhaps in 2010, we will witness rainstorms over the Huygens landing site, indicating an increase in humidity in the tropics, and perhaps not.

Yet, it is still not clear when and how methane was supplied to Titan’s atmosphere, and the length of time that Titan’s atmosphere has, over its history, contained methane. Thus the total production of ethane and other higher order hydrocarbon material is unknown, as are the precise reactions that dominate the chemistry, and whether these reactions occur predominantly in the thermosphere or the stratosphere. The chemistry of organic surface sediments, the manifestation of Titan’s active geology, and the weather effects on Titan’s surface are not constrained.

The Cassini-Huygens mission will not entirely characterize Titan’s complex world. The Huygens probe measured the opacity, winds, temperature and methane profiles at -10° latitude, 192° west longitude. These measurements indicate the energy partitioning of the atmosphere, its stability and composition, yet they were measured at only this one place. In addition, the present mission will obtain only limited information of the composition of Titan’s surface because it is being investigated through near-infrared spectroscopy at a spectral resolution that is too low to resolve many candidate surface species. Further, the Cassini Radar instrument, which is mapping surface liquids on Titan, will image less than 45% of Titan’s surface at by the end of the extended mission. Investigations of Titan’s chemistry are limited by the mass range of the GCMS on the INMS instrument, which measures species of atomic mass less than 100.

As a result of these anticipated omissions, scientists worldwide are exploring the possibility of a future mission to Titan [130, 131]. It has been noted that Titan’s atmosphere, with its high density and cool conditions, lends itself to hot air balloons. Balloons can be powered for several Earth years with a Radioisotope Thermoelectric Generator (RTG) and allow for detailed analysis of the troposphere and surface, over a range of terrains. Even though a balloon drifts passively, its trajectory may be controlled in part through its elevation [131]. A range of latitudes may be sampled through the deployment of more than one balloon. Instruments that are being considered for the balloon include temperature and pressure sensors, high spectral resolution near-IR spectrometers, a GCMS, and a chemistry package that might be lowered to Titan’s surface. Such a mission would require an orbiter, which could be outfitted with a RADAR, near-IR spectrometer, a microwave sounder and perhaps a mass spectrometer that has a high mass range.

Yet, returning back to the present, the study of Titan over the past 40 years demonstrates the dramatic evolution in understanding of a world that resembles Earth. It combines the excitement of exploration with the rigors of scientific method. Particularly exciting to this field at present is that basic questions are now framed, but few answered. That is, we are, in many ways, just beginning an exploration of a foreign world. One can almost imagine being the young botanist on the Beagle.
ACKNOWLEDGMENTS

I thank Paulo Penteado, Gabriel Tobie, and Veronique Vuitton for their helpful comments regarding the manuscript.

REFERENCES


