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In Titan’s atmosphere, the second most abundant constituent, methane, exists as a gas, liquid and solid, and cycles between the atmosphere and the surface. Similar to the Earth’s hydrological cycle, Titan sports clouds, rain and lakes. Yet, Titan’s cycle differs dramatically from its terrestrial counterpart, and reveals the workings of weather in an atmosphere that is 10 times thicker than the Earth’s atmosphere, that is two orders of magnitude less illuminated, and that involves a different condensable. While ongoing measurements by the Cassini–Huygens mission are revealing the intricacies of the moon’s weather, circulation, lake coverage and geology, knowledge is still limited by the paucity of observations. This review of Titan’s methane cycle therefore focuses on measured characteristics of the lower atmosphere and surface that appear particularly perplexing or alien.

Keywords: planetary atmospheres; Titan; weather

1. Summary of current observations

Titan’s methane cycle plays out largely below the tropopause at 45 km (figure 1). As on the Earth, the tropopause’s low temperature limits the abundance of the surface-supplied condensable at higher altitudes. Yet, on Titan, the tropopause saturation pressure of methane, $P_{\text{CH}_4}$ $\sim$ 0.015, is relatively high, well exceeding that, $P_{\text{H}_2\text{O}}$ $\sim$ 10$^{-5}$, of water on Earth. Sufficient methane therefore mixes into the stratosphere where it is destroyed irreversibly by ultraviolet solar radiation to produce higher order organic material. These by-products mix down to the lower atmosphere and precipitate, with a few exceptions, onto the surface. As a result, organic sediments accumulate on Titan’s surface at a high enough rate to form a layer approximately 0.5 km thick, most of which is liquid ethane, over the course of Titan’s lifetime of approximately 4.5 Gyr (Lunine et al. 1983; Yung et al. 1984). Thus, Titan’s climate continually evolves. Sediments accumulate on the surface to be buried through cryo-volcanic resurfacing (Mousis & Schmitt 2008) and potentially chemically altered (Atreya et al. 2006). The moon’s slow drying of methane follows periodic resupply episodes of cryo-volcanic outgassing (Lunine & Stevenson 1985; Sotin et al. 2005; Tobie et al. 2006; Lopes et al. 2007).

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One contribution of 14 to a Discussion Meeting Issue ‘Progress in understanding Titan’s atmosphere and space environment’.
Measurements below Titan’s troposphere are limited largely to radar surface observations (Elachi et al. 2005), near-infrared spectral images of Titan’s surface and clouds (e.g. Griffith et al. 1991; Brown et al. 2002, 2006; Roe et al. 2002; Porco et al. 2005), three temperature profiles of Titan’s tropical atmosphere (Lindal et al. 1983; Fulchignoni et al. 2005) and one measurement of Titan’s methane abundance profile (figure 2) at the probe landing site (Niemann et al. 2005). The drift of clouds and of the Huygens probe provide a few spotted measurements of tropospheric zonal winds, and indicate prograde winds of 10–35 m s\(^{-1}\) at 20–40 km that decrease with altitude to speeds less than 1 m s\(^{-1}\) below 5 km altitude (Bird et al. 2005; Griffith et al. 2005; Porco et al. 2005; Folkner et al. 2006). Upper atmosphere measurements also bear on the topic, particularly temperature maps (Flasar et al. 2005), and the latitude profiles of minor species (e.g. Coustenis & Bézard 1995; Lebonnois et al. 2001; Vinatier et al. 2006), wind measurements through occultation and Doppler observations (e.g. Hubbard et al. 1993; Sicardy et al. 1999, 2006; Bouchez 2004; Kostiuk et al. 2005; Zalucha et al. 2007) and the haze density (Lorenz et al. 1999; Rannou et al. 2006) that manifest Titan’s general circulation. The atmospheric opacity structure further establishes the solar energy partitioning, including the surface insolation (figure 3).

With only one humidity profile and a handful of temperature and wind soundings, the dearth of observations curbs the present knowledge of Titan’s atmosphere. Thus, this review stays close to the data. We focus on three characteristics, or ‘curiosities’, of Titan’s atmosphere and surface that distinctly differ from their terrestrial equivalents. Thermodynamic, radiative transfer and general circulation studies are invoked to explain Titan’s and the Earth’s weather as manifestations of the different fundamental properties of these atmospheres.
Three curiosities

The ground-based detection of methane clouds in Titan’s atmosphere (Griffith et al. 1998) provided the first indications of active weather and deep convection (Griffith et al. 2000). Subsequent images revealed that clouds resided near the South Pole (Brown et al. 2002; Roe et al. 2002) and later, unexpectedly, in a band centred at $\pm 40^\circ$ latitude (Roe et al. 2005a). These two specific cloud locations, now confirmed by many additional observations (Gendron et al. 2004; Gibbard et al. 2004; Adamkovics et al. 2005; Griffith et al. 2005; Porco et al. 2005; Hirtzig et al. 2006), contain the majority of clouds, which cover usually approximately 1 per cent of Titan’s globe, although occasionally a single system can cover approximately 10 per cent of the globe (Griffith et al. 1998; Schaller et al. 2006b). By contrast, water clouds cover approximately 50 per cent of the Earth. The infrequency of clouds on Titan probably stems from the limited power available at the surface, approximately 1 per cent (figure 3), to drive convection (McKay et al. 1991; Lorenz et al. 2005). Images of Titan have been recorded from 1998 to 2008, which span a sizeable fraction of Titan’s year (29.5 Earth years), surrounding the south summer solstice, in October 2002. Comparisons of these images indicate a diminishing incidence of South Polar clouds coupled with a greater occurrence of mid-latitude clouds (Bouchez & Brown 2005; Schaller et al. 2006a), and suggest a coupling of the cloud locations to seasonal circulation.

(a) Three curiosities

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In addition, the latitude of these clouds contrasts that of the cloud detected in the 1995 Hubble Space Telescope data at 40° latitude during the northern autumnal equinox (Lorenz 2008; Lorenz et al. 2008). To date, few tropical clouds have been detected. These include the tenuous cloud observed at 21 km altitude by the Huygens probe (Tomasko et al. 2005), a handful of optically thick small clouds (Porco et al. 2005). The first curiosity is the cloud locations on Titan’s globe, their regularities and exceptions.

Radar observations suggest that deep (non-transparent) lakes are confined to the polar regions, while at equatorial latitudes, vast dunes are interspersed with dendritic features (Lorenz et al. 2006; Barnes et al. 2007; Stofan et al. 2007). The Huygens probe fortuitously landed in a damp lake bed fed by washes, which sits in a dune field (Tomasko et al. 2005; Soderblom et al. 2007a,b). Near-IR spectroscopy indicates further that water ice, which makes up half of Titan’s bulk material, is exposed despite the sediments of organic material produced in Titan’s stratosphere (Coustenis et al. 1995; Griffith et al. 2003; Soderblom et al. 2007a). The second curiosity is the latitudinal pattern of surface features, with, for example, lakes confined to the poles and washes coexistent with dunes in the tropics.

Titan’s temperature and methane abundance profiles reveal the stability of its atmosphere to convection and consequent cloud formation. The Huygens gas chromatograph mass spectrometer (GCMS) instrument measured an atmospheric humidity of 45 per cent above a damp surface. The mixing ratio is constant at 0.049 up to the level, approximately 8 km, where the temperature

Figure 3. Radiative balance of (a) Titan’s tropical atmosphere (McKay et al. 1991) differs from that of (b) the Earth, largely owing to the moon’s stratospheric haze that absorbs 40% of the sunlight. Consequently, only 10% of the radiation reaches Titan’s surface, providing little power for convection (wiggly line) and evaporation (light line). Both atmospheres have strong greenhouse effects. The evaporative flux is unknown for Titan and therefore missing in the figure. The solar fluxes at Earth and Titan are 1370 and 15 W m⁻²; one-quarter of which, 342 and 3.7 W m⁻², respectively, are the globally averaged insolations at the top of these atmospheres.

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is cold enough to be saturated. The atmosphere is saturated with respect to \( \text{CH}_4\text{–N}_2 \) condensation at 8–16 km, and pure \( \text{CH}_4 \) ice at 25–30 km, with an intermediate mixing ratio in between these two regions (Tokano et al. 2006a), as shown in figure 2. This profile is markedly simple, and, in fact, it is just that assumed in simple models of Titan’s atmosphere prior to Cassini (McKay et al. 1989; Thompson et al. 1992). But such profiles are rarely seen on Earth (figure 2). The third curiosity is the perfect methane profile, and the damp surface despite a cloudless sky.

### 2. Titan’s temperature and methane profiles

Titan’s temperature profile has been measured, to date, only three times. On 12 November 1980, near the northern spring equinox, Voyager determined the temperature structure at dawn (at \( -8.5^\circ \text{ latitude, 256^\circ west longitude} \)) and at dusk (at \( 6.2^\circ \text{ latitude, 77^\circ west longitude} \)). The thermal profile was measured through the refraction of radio waves relayed to the Earth and occulted by Titan’s atmosphere as Voyager went behind Titan and re-emerged (Lindal et al. 1983). On 15 January 2005, a little over 2 years past the south summer solstice, the Huygens atmospheric structure instrument (HASI) measured, \textit{in situ}, the temperature profile at the probe landing site, at \( -10^\circ \text{ latitude, 192^\circ west longitude} \) (Fulchignoni et al. 2005). The profiles match each other to within the error of the data of approximately 0.5 K. The HASI measurements revealed for the first time the details of the profile at low altitudes. Temperatures follow those of an adiabatically rising parcel (i.e. the dry lapse rate) below 300 m; this lower region thus defines the current planetary boundary layer (Tokano et al. 2006b). A couple of additional altitude regions below 2 km approach the dry lapse rate, suggesting that dry convection has occurred up to 2 km altitude in the past (Griffith et al. 2008). Above 2 km, the atmosphere is stable with respect to dry convection.

Titan’s methane abundance profile has been measured only once; these data were recorded by Huygens’ GCMS at the probe landing site (Niemann et al. 2005). While Cassini will record additional temperature profiles at a variety of latitudes using radio occultation measurements similar to Voyager, another methane profile requires another trip to Titan. This unique measurement therefore deserves careful analysis in concert with the temperature profile, both recorded on a summer afternoon in Titan’s tropics.

The humidity at Titan’s surface indicates that surface parcels, if lifted, become saturated at 6 km, the lifting condensation level (LCL; Tokano et al. 2006a). Condensation and the release of latent heat aids convection above this altitude. The measured lapse rate is slightly steeper than the wet lapse rate with respect to \( \text{CH}_4\text{–N}_2 \) condensation at several altitude regions below approximately 15 km (Griffith et al. 2008). Since the atmosphere at 8–15 km is saturated (Tokano et al. 2006a), these regions are unstable with respect to wet convection (Griffith et al. 2008). Parcels that are nudged upwards convect and rise to altitudes anywhere between 15 and 26 km, depending on the microphysics. Such convection forms clouds, and may explain the thin cloud layer detected by the Huygens Descent Imager/Spectral Radiometer instrument at 21 km altitude (Griffith et al. 2008). Yet, convection at the probe landing site is weak, with a small convective
available potential energy (CAPE) ≤ 120 J kg⁻¹ (Griffith et al. 2008). The temperature and methane profiles indicate an atmosphere too stable to produce enough rainfall presently (Tokano et al. 2006a; Barth & Rafkin 2007), or with changes in seasons (Griffith et al. 2008), to form the washes at the landing site.

Conditions at the probe landing site are not conducive to the convection of surface air to the upper troposphere (Tokano et al. 2006a), because updrafts are too weak to raise parcels up to the level of free convection (LFC) of approximately 9 km, where they become buoyant and convect freely. Surface heating at the equinox (in 2010) may raise the parcels to the LFC. However, the resultant convection would also be weak, CAPE ≤ 180 J kg⁻¹, and heavy rainstorms unlikely (Griffith et al. 2008). The strength of convection and the CAPE of Titan’s tropical atmosphere can only be enhanced with an increase in humidity (Griffith et al. 2008). Detailed convection models for Titan indicate that rainfall will occur if the atmospheric humidity is increased to at least 60 per cent at the surface (Hueso & Sánchez-Lavega 2006; Barth & Rafkin 2007).

(a) Temporal humidity variations and the stability of polar lakes

On Earth, the humidity in the lower troposphere varies throughout the day and season from dry conditions to a nearly saturated atmosphere, as shown for two randomly chosen temperature profiles for Tucson, Arizona (figure 2). These rapid variations are powered ultimately from the solar insolation (342 W m⁻², globally averaged), of which 57 per cent reaches the surface, 7 per cent is available for convection and 22 per cent, on average, i.e. 75 W m⁻², for evaporation (figure 3). This power well exceeds that, approximately 7 W m⁻², needed to evaporate an entire atmospheric column of water in a three-month season (figure 3). The Earth’s surface contains 2.7 km, globally averaged, of liquid water, sufficient to supply the entire inventory of vapour, approximately 2.5 cm, in the atmosphere.

Variations in the atmospheric humidity on Titan are, by contrast, limited by the low power, the low methane surface supply and the high methane vapour pressure (Griffith et al. 2008). Titan’s atmospheric methane content, equivalent to 5 m of liquid at the probe landing site (Tokano et al. 2006a), is high owing to the large saturation vapour pressure and scale height. Thus, a large mass of methane must evaporate, by terrestrial standards, to significantly change the humidity. Ample power is needed to this effect. On Titan, however, 10 per cent of the incident sunlight reaches the surface (McKay et al. 1991; Tomasko et al. 2008), and only 1 per cent, or 0.037 W m⁻², powers convection (figure 3). The evaporation rate is unknown, and probably depends on the terrain. Yet, even the entire globally averaged surface flux, i.e. 0.37 W m⁻², falls short of the 4 W m⁻² power needed to evaporate a full column of Titan’s methane in its long 7.4 Earth year summer. If 1 per cent of the power is available for evaporation, then only 7 cm of methane evaporates in half a Titan year. By contrast, changes in the ethane humidity, requiring little energy, are probably more common (table 1). These numbers suggest that large-scale variations in Titan’s methane humidity in the lower troposphere may be energy limited.
The polar lakes are estimated to contain at least $3 \times 10^4$ km$^3$ of methane (Lorenz 2008; Lorenz et al. 2008). While their compositions (i.e. the methane and ethane content) are unknown, it is likely that they contain enough methane (above $2 \times 10^4$ km$^3$) to increase the humidity in the Northern Hemisphere by 15 per cent. Yet radiative transfer derivations of the summer heating of the North Pole indicate that the power is sufficient to evaporate only $2.8 \times 10^3$ km$^3$ of methane, enough to increase the humidity of the hemisphere below 8 km to only 2 per cent (Griffith et al. 2008). This is an upper limit, since it is not clear that polar methane efficiently transports to the equator over the time scale of a season. The methane column abundance in the tropics therefore does not change significantly with season, barring cryo-volcanism, and the measured abundance by Huygens is probably representative of Titan’s tropical atmosphere.

Vertical redistribution of methane could result from seasonal cooling and condensation in the upper atmosphere. For example, a cooling of 2 K above 23 km would condense enough methane to saturate the atmosphere between 4 and 8 km (Griffith et al. 2008). Yet such a redistribution of methane, even if seasonal, is not indicated by the Huygens profile. Instead, the steady decrease in methane with height, below 8 km, points to the surface, where methane is most abundant, as the atmosphere’s source.

(b) Damp landing site

Huygens measured a damp surface (Niemann et al. 2005), which, given the relatively dry atmosphere (45% humidity), poses the question of whether there was recent rainfall. Tenuous clouds predicted by general circulation models (GCMs) to result from temperature variations create methane cirrus of radii less than 0.9 mm and thus virga rather than rainfall (Barth & Toon 2004; Rannou et al. 2004; Graves et al. 2008). Microphysical models of convective systems indicate the production of virga, with few larger surface-prone particles (Barth & Rafkin 2007; Graves et al. 2008; Griffith et al. 2008). Possibly this drizzle replenishes the surface liquids at a rate of 5–50 mm yr$^{-1}$ (Rannou et al. 2006;
Tokano et al. 2006a; Barth & Rafkin 2007) comparable with the evaporation rate (Mitri et al. 2007), which is slow, on average, owing to the low insolation (Griffith et al. 2008).

Alternatively, methane is in near vapour pressure equilibrium above a surface solution, a condition that Titan’s atmosphere tends towards as it dries of methane in the absence of volcanism. Such a concoction would contain the principal by-product of methane photolysis, ethane (Lunine et al. 1983), which was detected in the South Polar lake-like feature, Ontario Lacus (Brown et al. 2008). In vapour pressure equilibrium, a liquid containing 39 per cent methane, 54 per cent ethane and 7 per cent nitrogen (Thompson et al. 1992) provides an atmosphere with the measured methane mixing ratio of 0.049 (Niemann et al. 2005) and an ethane mixing ratio, $1.4 \times 10^{-5}$, close to that, $10^{-5}$, measured at 160 km altitude (Vinatier et al. 2006). The Huygens GCMS detected evidence for the presence of ethane on Titan’s surface, from a rise in the count rate following landing (Niemann et al. 2005). Yet, whether equilibrium conditions persist will be tested with Huygens GCMS measurements of the atmospheric ethane content.

3. Cloud locations

Since the year 2000, Titan’s clouds frequent primarily the South Polar region and a thin band centred at $-40^\circ$ latitude. Their time variability, cumuli morphology and altitudes indicate a convective origin (Griffith et al. 2000, 2005; Porco et al. 2005). Initially, the presence of highly variable clouds in an atmosphere whose radiative time constant of approximately 138 years (Smith et al. 1981; Flasar 1983) exceeds a Titan year was somewhat surprising. The first images provided an explanation as they indicated that clouds reside at South Polar latitudes, which receive the highest daily averaged solar insolation (Brown et al. 2002; Roe et al. 2002). These data suggested that cloud formation results from the solar heating of the surface, which, unlike the atmosphere, responds within the time scale of a Titan season (Brown et al. 2002). Thereby, warmed, surface parcels convect, cool and condense in the upper troposphere.

The detection of the $-40^\circ$ latitude clouds (Roe et al. 2005a) was unexpected since the daily surface insolation is not exceptional at this latitude. These mid-latitude clouds furthermore, unlike the South Polar clouds, were initially found to prefer several longitudes, centred at $0^\circ$ and $90^\circ$ (Roe et al. 2005b). These longitudes do not point to forcing by Saturn’s tides, which significantly affect Titan’s dynamics (Tokano & Neubauer 2002). One possible explanation for these clouds is that they represent the ‘smoking gun’ of volcanoes (Roe et al. 2005b). Yet, visual and infrared mapping spectrometer observations indicate that an abrupt change in the haze opacity also occurs at $-40^\circ$, suggesting that Titan’s general circulation changes, giving rise to upwelling at this latitude (Griffith et al. 2005). A general circulation model now predicts the presence of an upwelling branch and the occurrence of clouds at $-40^\circ$ latitude (Rannou et al. 2006).

1 Titan’s long radiative time constant stems from the thickness of its atmosphere (with a column density of 92 km amagat as opposed to 8 km amagat on Earth) and its low effective temperature of approximately 82 K.
Yet the details of cloud formation are not understood, because the atmospheric methane and temperature profiles are unknown at middle and high latitudes where clouds prevail. Conditions at the Huygens landing site are not conducive to the formation of the clouds observed at $-40^\circ$ latitude (Griffith et al. 2008), which reach heights of approximately 45 km. Instead, a more humid lower atmosphere is indicated, if these clouds are convective, as suggested by their morphologies (Griffith et al. 2005). Detailed models of the formation of Titan's South Polar clouds also point to conditions exceeding 80 per cent humidity (Hueso & Sánchez-Lavega 2006). Such a moist environment may occur at the summer poles by lake evaporation powered by the large increase in the surface insolation (Griffith et al. 2008). Whether this occurs or not depends on the ethane content in the lakes, which, if abundant, would limit the vapour pressure of methane. Yet the humidification of the $-40^\circ$ latitude region through the evaporation from the lakes would require a precise transport of methane to lower latitudes near the surface, since there is insufficient power to evaporate the lakes and humidify the entire disc north and including $-40^\circ$ latitude. An unstable lower troposphere could be produced by the evaporation of surface liquids too shallow to have been detected by Cassini radar measurements. Alternatively, the lower atmosphere may be humidified by the transfer of methane from the upper to the lower troposphere, such that variations in Titan's upper tropospheric temperature induce condensation, virga and evaporation of methane in the undersaturated atmosphere below 8 km. Such a possibility will be in part tested with temperature measurements by the Cassini radio occultation experiment, currently in progress.

Few clouds have been observed in Titan's tropical atmosphere. These include small isolated clouds in the Southern Hemisphere (Porco et al. 2005) and clouds at the landing site at 21 km altitude (Tomasko et al. 2005), which can be explained by the weak mid-troposphere convection cell evident from the Huygens methane and temperature data (Griffith et al. 2008). Clouds above 35 km have not been observed at tropical latitudes. Thus, currently, it seems that deep convection, as indicated by cloud heights, occurs only at high polar latitudes in the summer.

(a) The importance of being ethane

Ethane, although only a minor species in Titan's atmosphere (table 1), can have a large effect on the methane cycle, because it also exists as a liquid, gas and solid. Its influence does not derive from its latent heat content, which is small by comparison with that from methane (table 1). Instead, ethane dissolves in methane liquid and, if plentiful as surface liquids, regulates the methane humidity as well as the distribution of liquid methane on Titan's surface.

The detection of ethane in Ontario Lacus (Brown et al. 2008) suggests that all of the polar lakes contain ethane. Ethane is produced in the stratosphere, transported downwards to the winter polar region (Rannou et al. 2006), condenses above the polar tropopause (Griffith et al. 2006) and mixes down to the surface (Barth & Toon 2004). In addition, Huygens GCMS measurements suggest that the tropical surface is damp with respect to ethane and methane (Niemann et al. 2005). Possibly, there are small shallow (several metre) ethane–methane pools in the tropics, which are transparent to radar sounding.
If ethane is prevalent as a liquid on Titan’s surface, methane would then evaporate most rapidly from dry land and accumulate in the ethane-rich lakes. These lakes would then contain the surface reservoir of methane. In addition, they would regulate the methane content in the atmosphere. Such ethane-rich lakes could contribute to cloud formation, such that under windy conditions, methane evaporates from the lakes thereby forming clouds specifically over the shallow and unseen bogs. The repeated past presence of clouds at \(-40^\circ\) latitude and \(0^\circ\) longitude, indicating a preference for clouds at a specific place, could result from the presence of shallow lakes.

Similarly, significant ethane in the polar lakes would regulate the methane humidity, thereby controlling the atmospheric stability; albeit the presence of South Polar clouds points to a humid atmosphere (Hueso & Sánchez-Lavega 2006). If, alternatively, the lakes contain less than approximately 40 per cent ethane, summer heating of the polar region is sufficient to significantly humidify the polar surface, thereby causing deep convection and cloud formation (Griffith et al. 2008). Yet, it is unclear whether ethane plays a major role in the methane cycle since the ethane content of the atmosphere has not been measured. It is interesting that there have been no detections of an ethane mist, since relatively little power is needed to evaporate ethane and raise it to its LCL (table 1).

4. Latitude distribution of surface features

Dunes extending thousands of kilometres are ubiquitous in Titan’s tropics, within \(\pm 30^\circ\) of the equator (Lorenz et al. 2005; Barnes et al. 2007; Radebaugh et al. 2008). Poleward of \(60^\circ\) latitude, radar-dark patches indicate the presence of lakes, which extend for hundreds of kilometres (Stofan et al. 2007). Optical and radar images of the South Polar region also reveal lakes poleward of \(-75^\circ\) latitude; however, as the South Pole has not yet been extensively mapped, the lake coverage is poorly known. Lakes have not been detected on Titan’s surface within \(-50^\circ\) and \(50^\circ\) latitude. These observations suggest the presence of different climates as experienced on Earth. Terrestrial sand dunes and deserts, e.g. the Namib and Sahara deserts, prevail at specific latitudes, concentrating around the \(-25^\circ\) and \(25^\circ\) latitude bands. While oceans extend from the North to the South Pole, the major river basins, e.g. the Amazon and Danube, are more numerous near the equator, and approximately \(50^\circ\) latitude.

(a) Methane migration

The Earth’s rivers prevail at latitudes of greater occurrence of precipitation, which, in turn, correlates with the Earth’s circulation. The equator experiences updrafts and condensation associated with the Hadley circulation; and slantwise convection, connected with the polar front, develops at high latitudes. Evaporation transpires preferentially at more arid latitudes approximately \(25^\circ\) north and south of the equator, where the circulation causes subsidence and associated warming. On average, water vapour blows out of the Southern Hemisphere and into the Northern Hemisphere. This would lead to the accumulation of water in the Northern Hemisphere, if the nearly pole-to-pole oceans did not counteract this effect with a flow of water into the Southern Hemisphere.

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For Titan, where global ocean currents do not balance the atmospheric transport of the condensable, the question arises as to whether the methane is transported by the circulation over long time scales to accumulate at specific latitudes. Titan’s cloud and circulation patterns suggest that, currently, methane moves from the Northern to the Southern Hemisphere, where rain prevails. Yet the moon’s circulation will change dramatically, causing a Hadley cell circulation briefly at the equinox (in 2010) before flipping the pole-to-pole circulation to incur updrafts in the north and subsidence in the south (Hourdin et al. 1995; Mitchel et al. 2006; Rannou et al. 2006). The long-term effect, according to a most recent GCM calculation, is the accumulation of methane at Titan’s poles (Rannou et al. 2006). Polar lakes are stable against evaporation because there is insufficient daily and seasonal surface insolation variations to evaporate them (Griffith et al. 2008). The non-detection of tropical lakes and prevalence of tropical dunes further support the hypothesis that the poles are wet at the expense of drying the tropics.

Yet the fluvial features in the tropics suggest rainfall. The morphology of the south-flowing ‘washes’ north of the Huygens landing site indicates a comprehensive drainage system in the highlands that results from rainfall (Soderblom et al. 2007b). This terrain exhibits slopes as high as 30°, suggesting a formation more recent than the time scale for wind erosion (Soderblom et al. 2007b). The actual landing site is a flood plain that runs east to west, which appears to have been vigorous enough to mould rounded cobbles (Soderblom et al. 2007b). The formation of oases such as this one, interspersed among dunes, is unclear. Current conditions, as evident from Titan’s temperature and methane profiles, are not conducive to rain (Tokano et al. 2006a; Barth & Raftkin 2007; Griffith et al. 2008). Seasonal updrafts predicted at tropical latitudes (Mitchel et al. 2006; Rannou et al. 2006) may lead to greater cloud formation, as seen at −40° latitude and near the South Pole. Yet, without an increase in humidity, the atmosphere will remain only weakly unstable; thus, mildly convective clouds extending to approximately 26 km rather than deeply convective rainstorms that reach the tropopause are expected (Griffith et al. 2008). Cryo-volcanism could locally humidify the atmosphere and instigate rainstorms, although evidence is lacking for their presence at the locations of the dendritic features. The washes may be a relic of a wetter climate in the past; however, ruggedness of the terrain suggests youth.

5. Titan’s weather: a deranged version of the Earth

Titan’s methane cycle differs from the Earth’s hydrological cycle. Current research indicates that the dissimilarities stem from the fundamental properties of these bodies. Titan’s slow spin rate allows for a pole-to-pole circulation; its orbital period (29.5 Earth years) affects long seasons; and its distance to the Sun lowers the solar heating two orders of magnitude. Titan’s large atmospheric mass contributes to a large radiative time constant. The chemistry of the atmosphere, particularly the presence of methane, strongly differentiates Titan from the Earth. The photolysis of methane and the production of haze causes the atmosphere to be optically thick and limits surface insolation to 10 per cent, and

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the power for convection and evaporation to approximately 1 per cent of the incident sunlight. Clouds are therefore sparse, by terrestrial standards. The saturation vapour pressure of methane allows the atmosphere to accumulate over two orders of magnitude more condensables than possible on the Earth, thereby endowing the atmosphere with a greater latent heat potential. As on Earth, clouds appear to follow updrafts in Titan’s circulation, and thereby frequent latitudes uncommon to their terrestrial counterparts. However, studies of Titan’s atmosphere are still young. The effects of ethane are unknown; the methane abundance profile has only been measured at one place and one time; the depth and composition of the oceans cannot yet be measured; the atmospheric opacity is ill constrained at the poles; the dampness of the tropical surface is unconstrained except at the probe landing site (figure 4). Local incongruities, such as surface puddles, orographic winds, outgassing and methane vents, are entirely uncharacterized. This lack of information limits our understanding of the energy partitioning at the surface, the thermodynamic effects of ethane, the surface forcing of the circulation, the local dynamical conditions and the local stability of the atmosphere. Present studies may almost appear to predict the workings of Titan’s methane cycle from an analysis of the hydrological cycle and

Figure 4. Hierarchy of knowledge and deduction. The top white bubbles indicate fundamental properties of Titan’s atmosphere that determine Titan’s weather. These properties of Titan’s orbit, and the atmosphere’s chemical, radiative and thermodynamical properties, affect (as shown by the arrows) the dynamics, the atmospheric and the surface distribution of methane and ethane (grey bubbles), which, in turn, control the weather. Here, $T_R$ is the radiative time constant and $T_S$ is the duration of a season. The fundamental characteristics that are poorly constrained across the disc (outlined in black) profoundly affect our understanding of the circulation, latent heat effects, surface–atmosphere interface, the structure of the polar atmosphere, the formation and evolution of clouds and the long-term transport of methane. Attributes that are currently observable are outlined in grey. Note that local effects, such as volcanism and orographic winds, which influence cloud formation, are poorly constrained and not included here.
the replacement of Earth’s fundamental properties with those of Titan. Yet, this uncomplicated impression may be superficial as it is based on a handful of observational data.

**Appendix A. Growth of the boundary layer**

The time scale, $T_{PBL}$, for the growth of the planetary boundary layer is estimated by assuming that all of the globally averaged surface insolation goes into sensible heat, $H_s$. This value is an overestimate for both Titan and the Earth, as shown in figure 3. The sensible heat warms and mixes the lower atmosphere to form a growing layer of uniform potential temperature and composition. For a quiescent atmosphere, one can estimate this process thermodynamically. A boundary layer of height $Z_B$ and approximate constant density, $\rho$, and $c_p$ experiences a change in virtual temperature, $T_v$, with time of $d T_v/d t = H_s / Z_B c_p \rho$. This layer grows such that its height occurs at the intersection of its constant potential temperature and the ambient potential temperature: $d Z_B / d t = (d T_v / dt) / (d T_v / dz + g / c_p)_{amb}$. Based on Titan’s thermal profile (Fulchignoni et al. 2005), the difference between the dry and measured lapse rates (the denominator) is approximately 0.26 K km$^{-1}$, roughly one-fifth of the lapse rate between the surface and 6 km. For the Earth, the ambient lapse rate is also assumed to be 20 per cent less steep than the dry value.

**References**


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