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Is Titan Wet or Dry?

Abstract. *Titan's dense and cold nitrogen atmosphere contains a small amount of methane under conditions at least approaching those at which one or both constituents would condense. The possibility of methane and nitrogen rain clouds and global methane oceans has been discussed widely. From specific features of radio occultation and other Voyager results, however, it is concluded that nitrogen does not condense on Titan and that Titan has neither global methane oceans nor a global cloud of liquid methane droplets. Certain results indirectly support the conjecture that methane does not condense at any location. However, other considerations favor a methane ice haze high in the troposphere, and liquid and solid methane might exist on the surface and as low clouds at polar latitudes.*

Saturn's giant moon Titan is the only planet-sized body in the solar system known to share with Earth the characteristic of a predominantly nitrogen atmosphere (*1–4*). Many scientific and popular accounts propose that Titan shares another fundamental set of terrestrial features, namely global oceans, clouds, rain, snow, rivers, glaciers, and polar ice caps. In this scenario, methane plays the role on Titan that water does on Earth, being present as a liquid and a solid on the surface and in clouds and as a gas in the atmosphere (*1, 5*). In addition, it has been suggested that some of the atmospheric nitrogen itself condenses to the liquid phase (*6*).

Although the initial Voyager reports reinforced speculation about a "wet" Titan, current studies cast doubt on this interpretation and indicate instead that Titan is mostly "dry." The new evidence is based primarily on the Voyager radio occultation measurements as analyzed by Lindal *et al.* (*7*). While there is a global cloud cover, it might not include any condensed methane or nitrogen. Organic molecules, including complex hydrocarbons, are formed photochemically from methane and other constituents in the stratosphere and produce aerosol that obscures the surface to visual imaging (*8*). These particles are believed to settle to the surface, removing methane gas irreversibly from the atmosphere (*8*). Thus whether there are reservoirs of condensed methane depends on the evolutionary history of Titan's hydrocarbon and organic chemistry.

Figure 1 shows the average of the two atmospheric profiles from the Voyager radio occultation experiment. The two profiles, which are based on the assumption that the atmosphere consists entirely of nitrogen (*7*), apply to two positions within 10° latitude of the equator (assumed to be in Titan's orbital plane), one each near the morning and evening terminators at the time of the measurements. For the lowest 30 km of the atmosphere they have a temperature difference of less than 0.2 K (root-mean-square), suggesting a remarkable uniformity for Titan's equatorial troposphere.

The question of the influence of other constituents on the derived profile is discussed elsewhere (*1, 7, 9*). The values in Fig. 1 are near the low end of a possible range of about 4 K in actual equatorial temperatures because of uncertainty about the concentrations of minor constituents, particularly methane and argon. If there is very little argon, as we believe likely (*7*), then the proportion of methane would probably be less than a few percent, in which case the correct values would be very close to those shown in Fig. 1.

Measurements by the Voyager infrared instrument indicate about a 2 K reduction in surface infrared brightness temperature with increasing latitude and only a 2 K hemispheric difference at the wave number that is primarily sensitive to heights near the tropopause (*10*). However, since neither set of measurements includes regions within 20° of the orbital poles, global changes may be somewhat greater. We consider the profile shape in Fig. 1 to be representative, with up to a 3 K decrease for temporal and latitudinal effects and up to a 4 K increase for constituent uncertainties.

Also shown in Fig. 1 is the condensation temperature of nitrogen. It is about 5 K from the atmospheric curve at its closest approach, or a minimum of 2 K under the above uncertainties. We conclude that atmospheric nitrogen does not condense at Titan, either at the surface or in the atmosphere.

At every 4-km height interval up to 20 km in Fig. 1, we have superposed two short line segments representing certain theoretical slopes. In each case the steeper slope is for a nitrogen atmosphere that is saturated with methane and mixed vertically to produce a wet adiabat where the condensate moves with the gas. The accompanying percentages indicate the relative molar abundances of methane needed for saturation. The other segment is for a wet "pseudoadiabat" in which the condensate either does not mix away from where it condenses or else precipitates as rain or snow (*11*). Below about 10 km the slope of the actual curve is less steep than these theoretical segments.

The theoretical dry adiabat (no methane condensation) matches the measured curve for the lowest 4 km of the atmo-

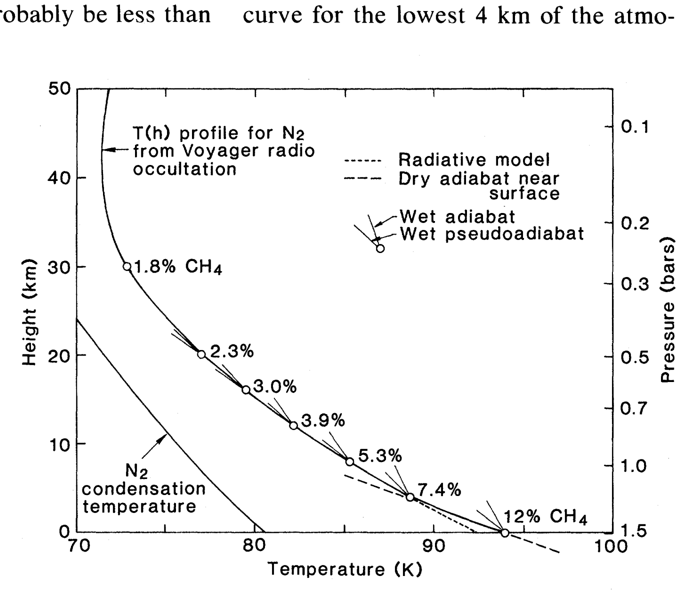

Fig. 1. Temperature as a function of height and pressure in the atmosphere of Titan (*7*), compared with the nitrogen condensation temperature, dry and wet methane adiabats, and a simple radiative model. Approximate relative methane molar abundances for saturation at a number of heights are shown. The point at 30 km is the cold trap.

Table 1. Clouds and condensates on Titan. Abbreviations: P, over at least some polar areas; E, over a substantial portion of the equatorial areas; G, over nearly all global areas.

Question	Yes	Maybe	Probably not	No
Liquid N_2 on surface				P, E, G
Liquid N_2 cloud or haze			P	E, G
Liquid CH_4 on surface		P	E	G
Liquid CH_4 cloud or haze		P	E	G
Solid CH_4 on surface		P		E, G
Solid CH_4 low cloud		P	E	G
Solid CH_4 high haze		P, E, G		
Other aerosol	P, E, G			

sphere (*7*). We take this as strong evidence that the equatorial lower atmosphere at the occultation points mixes vertically in this region and is not saturated with methane. That is, the methane is not abundant enough to condense as either liquid cloud particles (temperature above the triple point for methane, 90.7 K) or solid cloud particles (temperature < 90.7 K) at altitudes between 0 and 4 km. It follows that neither occultation point was over a methane ocean, since Flasar (*12*) has shown that if one were, the atmosphere at the surface would be within 2 percent of saturation and the so-called lifting condensation level (above which clouds would form under these conditions) would be less than 100 m (*13*).

Adding to these factors the apparent uniformity of the global troposphere leads us to conclude that methane oceans or surface ice and low-altitude clouds of liquid or solid methane particles are not the common global conditions for Titan. Such forms of methane might not exist at any location, although the lack of direct evidence means that they cannot be ruled out, particularly for polar latitudes.

The slope discontinuity near the 4-km level in Fig. 1 is reminiscent of those previously obtained at the level of the dense cloud layer in the middle atmosphere of Venus (*14*). However, we do not believe that this marks the base of a Titan cloud, since the measured change in slope appears to be too small and because the slope does not return to the dry adiabatic value at higher altitudes, as it does for Venus, after most of the condensate is removed. On the other hand, the change in slope and higher profile shape look very much like the transition from a dry adiabat to a higher region that is in radiative equilibrium. To illustrate this possibility, we computed simple radiative equilibrium models for a gray atmosphere heated from below, in which the infrared absorptivity is proportional to the atmospheric density. The short dashes in Fig. 1 illustrate the departure of such a simple model at low altitude, even though they overlie the measurements in the 5- to 15-km height range. This type of behavior is expected where there is a transition from a dry adiabat to radiative equilibrium at a height determined by the abilities of the two types of regions to conduct the required vertical flux of energy. That is, the observed curve appears to be a textbook example of this type of transition (*15*). If so, the local coincidence between the wet adiabats and the measured curve above about 10 km does not imply that there is condensation. The continually changing slope in the radiative region inherently includes values near these adiabats, even though vertical mixing does not occur and the concept of adiabats is not applicable.

More complete radiative computations have been made by Samuelson (*16*) on the basis of infrared measurements and the occultation profiles. They show a mass absorption cross section that decreases monotonically with height from about 5×10^{-5} m^2/kg at 5 km to a much smaller value near the tropopause (*16*). If methane ice clouds were contributing importantly to this absorption, one might expect the absorption to show a distinct increase with altitude at the saturation level. Since we have concluded that saturation does not occur between the surface and about 4 km, we take the lack of a noticeable discontinuity in absorption to be contributing but not conclusive evidence against methane saturation at greater heights at the occultation points. The global atmospheric uniformity then suggests that methane does not condense in any part of Titan's troposphere. If methane does not condense in the troposphere, then it does not condense at all.

The temperature profile in Fig. 1 provides a cold trap just below the tropopause that would result in a stratospheric methane molar abundance of 1.8 percent (the point at 30 km) if the methane abundance equals or exceeds this value in the troposphere. A stratospheric methane abundance lower than the minimum amount that would cause condensation at the altitude of the cold trap would mean that condensation does not occur at any height, including the surface. Taking into account the temperature uncertainties, we conclude that if the stratospheric methane abundance is less than about 1.3 percent, then methane does not condense anywhere.

Using ground-based observations of Titan and laboratory measurements, Hunten (*4*) derived stratospheric mixing ratios of 0.4 and 0.24 percent for two different cloud-top models (*17*). He stated that these results are uncertain by a factor of at least 2. However, larger stratospheric methane mixing ratios of 1 and 3 percent have been estimated by the Voyager infrared experiment team (*2*, *18*), but they are also only approximate. Thus the present evidence is not definitive.

We consider the lack of a clear indication of saturation in the temperature profile and the infrared absorption profile derived from it to be the best current evidence against condensation in the equatorial atmosphere. The observed atmospheric uniformity then suggests that methane does not condense at all. However, the production of an extended but tenuous haze of solid methane particles in the region of radiative equilibrium might not be detected by these means, so such a global haze remains a possibility. A methane ice haze high in the troposphere has been suggested on the basis of Voyager infrared measurements (*9*, *10*), but the possible infrared effects of this and other aerosols are not well known.

We summarize our conclusions in Table 1. They are generally more negative than would be inferred from previous discussions about atmospheric condensates on Titan.

If there is a surface reservoir of condensed methane, then the stratospheric methane and the production of more complex hydrocarbons and other organic molecules are maintained at a relatively steady level through the cold trap from a large surface supply. If not, then the methane molar abundances in the stratosphere and troposphere are the same, with the new methane needed to replace that lost by photochemical reactions presumably being supplied, perhaps episodically, by volcanism or other outgassing from Titan.

Any new spacecraft mission to Titan should take as a high priority the investigation of its surface characteristics, since they may be fundamentally different from those of any other planet or satellite. Dedicated radar and probe experiments are indicated, although even a limited mission might be able to use the spacecraft radio to detect surface conditions by directing transmissions toward Titan and receiving the scattered energy at Earth.

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6. One of us (V.R.E.) discussed this possibility at the Voyager press conference at the Jet Propulsion Laboratory on 13 November 1980.
7. G. F. Lindal *et al.*, *Icarus* **53**, 348 (1983). Fundamental characteristics of Titan determined from the Voyager radio science experiment include the following: diameter, 5150 km (40 percent of Earth's); density, 1.88 g cm^{-3} (34 percent); surface gravity, 1.354 m sec^{-2} (14 percent); and a nitrogen atmosphere with surface pressure, density, and absolute temperature 1.5, 4.5, and 0.33 times that of Earth's average atmosphere, respectively.
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14. Numerous authors [G. Fjeldbo, A. J. Kliore, V. R. Eshleman, *Astron. J.* **76**, 123 (1971); B. Lipa and G. L. Tyler, *Icarus* **39**, 192 (1979); V. R. Eshleman, D. O. Muhleman, P. D. Nicholson, P. G. Steffes, *ibid.* **44**, 793 (1980); P. G. Steffes and V. R. Eshleman, *ibid.* **46**, 127 (1981); and A. Seiff *et al.*, *J. Geophys. Res.* **85**, 7903 (1980)] have discussed the slope discontinuity in terms of a dry-to-wet adiabat transition involving carbon dioxide and sulfuric acid. On the other hand, J. B. Pollack, O. B. Toon, and R. Boese (*ibid.*, p. 8223) reproduced it with a model that does not include latent heat effects. In either case, however, the Venus atmospheric discontinuity is due to the cloud.
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Oceans on Titan?

Abstract. *If global oceans of methane exist on Titan, the atmosphere above them must be within 2 percent of saturation. The two Voyager radio occultation soundings, made at low latitudes, probably occurred over land, since they imply a relative humidity ≲ 70 percent near the surface. Oceans might exist at other low-latitude locations if the zonal wind velocities in the lowest 3 kilometers are ≤ 4 centimeters per second.*

Saturn's giant moon Titan is remarkable in that it has an atmosphere. Although nitrogen is the dominant constituent (*1, 2*), the presence of methane is well established (*2, 3*). Photolytic and catalytic dissociation of methane is rapid enough to deplete the total atmospheric abundance of methane in a time short compared to the satellite's presumed age, ~ 4.5 billion years (*4*). If the abundances of methane and other hydrocarbons currently observed in Titan's atmosphere typify those during much of its history, a source of atmospheric methane is required. Samuelson *et al.* (*5*) proposed that methane clouds also exist and provide much of the opacity in Titan's troposphere, because pressure-induced absorption by gaseous methane and nitrogen is unable to provide the infrared opacity required to account for the emission observed near 200 cm^{-1} (*6*). These considerations suggest that a reservoir of methane exists at Titan's surface, and the possibility of oceans of methane on Titan has been raised (*1, 7, 8*). In this report I examine the constraints that meteorology and the Voyager radio occulation data place on such hypothetical oceans.

An energy argument provides a lower limit on the amount of methane vapor above the surface of an ocean. Global radiative equilibrium models that are consistent with Voyager observations predict that between 13 and 33 percent of the solar irradiation is absorbed at Titan's surface (*9*). They also predict a temperature discontinuity of 1 to 3 K at the surface, which ensures that the net upward flux of thermal radiation balances the net downward flux of solar radiation. The discontinuity is unstable in the sense that the surface is warmer than the atmosphere just above it. In reality this instability generates turbulent fluxes of sensible and latent heat that provide much of the required upward energy flux and reduce the discontinuity in temperature predicted by the radiative models.

The flux of latent heat from an ocean surface can be expressed in terms of the bulk transfer relation (*10*):

$$H_L = \frac{n_a L}{\eta} C(q_s - q_a) \qquad (1)$$

where η is Avogadro's number, L is the latent heat of methane vaporization (*11*), and C is a bulk transfer coefficient. The quantity q_s denotes the mole fraction of methane saturated at the ocean surface (*12*); n_a and q_a denote total number density and the gaseous methane mole fraction at an "anemometer" level a few meters above the surface. For a positive flux of latent heat into the atmosphere, $q_a < q_s$. A globally averaged upper limit to the drop in methane abundance across the "surface boundary layer," $\Delta q = q_s - q_a$, follows from imposing an upper limit on H_L and a lower limit on C in Eq. 1. A plausible upper limit on H_L is the solar radiation absorbed at the surface: $H_L < 0.33\ S_0/4$, where S_0 is the solar constant at Titan. Since the surface layer is unstably stratified, C can be minimized by taking the free convection limit and including only the contribution to the stratification from $\Delta q > 0$ (methane is lighter than nitrogen), neglecting that from the drop in temperature: $C \geq 0.00214\ (\Delta q)^{1/3}$ m sec^{-1} (*13*). With these limits, Eq. 1 implies $(q_s - q_a)/q_s \leq 0.02$: the relative humidity of the atmosphere above the surface layer is ≥ 98 percent. The lifting condensation level (LCL), the height at which an ambient parcel of gas saturates when adiabatically lifted from the top of the surface layer, is ≤ 200 m. In Table 1 the lower atmosphere of Titan is compared with that in Earth's tropics. Typically, the relative humidity above the terrestrial surface layer is only 80 percent, and the LCL is situated 0.5 to 1 km above the surface. Although several factors contribute to these differences, one of the most important is the reduced value of the solar constant at Titan relative to Earth.