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NOTE
Titan's Snowline

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We show that the "snowline" altitude on Titan, above which the condensed nonideal methane–nitrogen phase is solid, is lower (∼14 km) near the equator than at high latitudes (∼19 km). This counterintuitive result derives from the thermodynamic behavior of the binary condensate. The snowline altitude is an operating constraint on future Titan missions where icing would pose a ceiling on atmospheric flight. These snowline altitudes are higher than likely topography, suggesting that optically bright regions on Titan are not due to veneering caused by methane frost deposition.

Key Words: **Titan; meteorology; ices; atmospheres-structure.**

Introduction. Titan's atmosphere participates in a hydrological cycle like the Earth's, but with much less vigor owing to the reduced sunlight (Lorenz 2000a, Lorenz and Mitton 2002). The working fluid, methane, is considerably more volatile than water, as it must be to act as a "volatile" at Titan's cold temperatures. Its behavior is complicated by the fact that methane forms a (nonideal) solution with the dominant atmospheric gas, nitrogen, which lowers its freezing point. Previous work (Thompson 1985, Kouvaris and Flasar 1991, Thompson *et al.* 1992) has pointed out that the binary mixture should freeze at altitudes of around 14 km and above.

In this paper, we reexamine the freezing altitude question, motivated largely by observations (Samuelson *et al.* 1997) that indicate latitudinal variations in methane mixing ratio and surface temperature. These imply that there is no single altitude at which the condensate will freeze—the "snowline" will depend on latitude, and perhaps season.

Methane frost or snow has been suggested as an explanation for the bright region on Titan's leading hemisphere (Coustenis *et al.* 2002) and for alleged bright polar caps (Combes *et al.* 1997). The snowline altitude permits an assessment of the topography required for such an explanation, which is at odds with at least the previous thermodynamic studies cited above.

Recent observations (Griffith *et al.* 2000) of rapidly evolving clouds on Titan suggest that precipitation occurs—the snowline determines at what altitude falling hailstones melt. This altitude may be an important factor in controlling the size of falling hailstones.

Finally, future plans for post-*Cassini* Titan exploration (Lorenz 2000b, Hall *et al.* 2002) may involve aerial vehicles such as airships or helicopters. Operation of such vehicles at high altitudes allows them to exploit Titan's zonal winds (which increase with altitude) and thus transit large longitude ranges at low propulsive cost. However, operation above the snowline opens the hazard of icing; it is therefore important to understand better the allowable range of operating altitudes.

Method. In recent years, far-infrared spectra from the *Voyager 1* encounter have been analyzed in detail (Courtin 1995, Samuelson *et al.* 1997, Courtin and Kim 2002—see also Flasar *et al.* 1981, Hunten *et al.* 1984, Flasar and Conrath 1992). The later analyses have pointed both to methane supersaturation in the upper troposphere and to latitudinal variations in both temperature and methane abundance. Specifically, the "equatorial" near-surface atmospheric CH_4 mole fraction appears to be 0.06 and the "polar" value around 0.02, while the corresponding surface temperatures are about 93 and 89 K. Tropopause temperatures are approximately invariant with latitude, around 71 K. Here we explore how these variations affect the snowline.

Three-phase equilibrium of binary mixtures is rather complex: see the methane–nitrogen phase diagram presented by Thompson (1985). One starting point for consideration of the problem is the specification of the liquidus temperature $T_{\text{liq}}(X_{\text{CH}_4})$, below which freezing begins, where X_{CH_4} is the mole fraction of methane in the condensed phase. This is adequately approximated by straight line segments namely $T_{\text{liq}} = 63$ K ($X_{\text{CH}_4} < 0.2$) and $T_{\text{liq}} = 56 + 35X_{\text{CH}_4}$ ($0.2 < X_{\text{CH}_4} < 1.0$). The solidus temperature $T_{\text{sol}}(X_{\text{CH}_4})$ can be similarly specified, $T_{\text{sol}} = 63$ K ($X_{\text{CH}_4} < 0.55$) and $T_{\text{sol}} = 29 + 62X_{\text{CH}_4}$ ($0.55 < X_{\text{CH}_4} < 1.0$). Nitrogen acts as an antifreeze to methane.

For equilibrium with the atmospheric methane abundance, we can use the polynomials of Kouvaris and Flasar (1991)—these are easier to use than the near-equivalent, but more complicated, formalism of Thompson *et al.* (1992). Specifically, we use the 90-K polynomial, as the difference between this and other temperatures is small, and this is the temperature for which the range of permitted X_{CH_4} is the largest. We find the partial methane pressure divided by its saturation value, i.e., $P_{\text{CH}_4} = y^* P_{\text{SAT(CH}_4)}$

$$y = 0.6879 + 0.3487x - 0.2451x^2 + 0.0970x^3 + 0.2874x^4 + 0.0251x^5 - 0.2082x^6, \quad \text{with } x = 2.05191X_{\text{CH}_4} + 1.02914,$$

where $P_{\text{SAT(CH}_4)}$ is given by the expression $P_{\text{SAT(CH}_4)} = 34{,}543 \exp(-1145.705/T)$ with the pressure in bar and temperature T in Kelvin. This simple expression (due to McKay—see Lorenz *et al.* 1999) yields a result within 5% of the more elaborate expressions by Brown and Zeigler (1982) over the temperature range of interest 70–100 K.

Taking equatorial and polar conditions above we find $X_{\text{CH}_4} \sim 0.3$ and ~ 0.1 respectively. The corresponding liquidus temperatures are only 67 and 63 K, so the formation of frost at the surface is impossible. In fact, the abundant nitrogen in Titan's atmosphere prevents any frost formation below 700 mbar—this is most easily visualized by the three-phase line shown in Fig. 1, adapted from Kouvaris and Flasar (1991). In a pure nitrogen atmosphere, the frost point is at around 100 mbar, the saturation vapor pressure of liquid nitrogen at its freezing point (63 K); for pure methane where the freezing point is 91 K, the pressure has a similar value. Any attempt to cool higher-pressure reservoirs of these gases will only result in condensation of the vapor until the pressure has dropped below 100 mbar. For a methane–nitrogen mixture, the maximum three-phase pressure of 700 mbar occurs at 82 K for a liquid of $X_{\text{CH}_4} = 0.8$.

The altitude at which this occurs can be determined by comparing an atmosphere profile with the three-phase curve. Titan's tropospheric temperature profile (see, e.g., Lellouch and Hunten 1997) can be described with good accuracy

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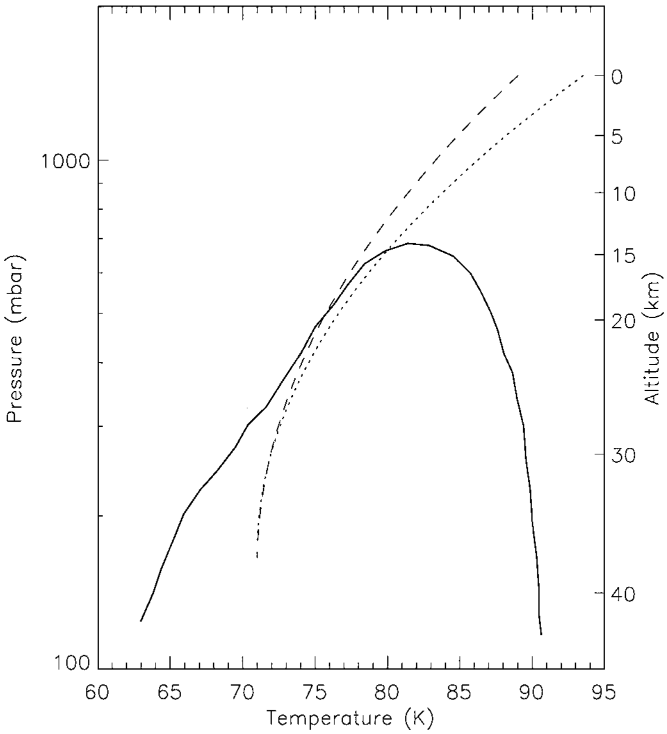

FIG. 1. Three-phase line from Kouvaris and Flasar (1991). Above the solid curve only liquid and vapor coexist—frost is thermodynamically unstable. The dotted and dashed curves are models of Titan's atmospheric temperature profile with tropopause temperatures equal to 71 K and surface temperatures of 93 and 89 K, respectively. Note that they cross the phase curve to the left of the peak, at altitudes of 14 and 19 km.

by a parabolic function, i.e., $T(z) = T_{\text{surf}} - Bz + Cz^2$ with B and C being constants and z the altitude in kilometers. We specify the profile with two independent parameters, namely the surface and tropopause (40 km) temperatures, T_{surf} and T_{trop}, respectively. Forcing the profile to pass through T_{trop} with a slope $dT/dz = 0$ at 40 km then requires $B = (T_{\text{surf}} - T_{\text{trop}})/20$ and $C = B/80$. The pressure at a given altitude is specified simply as $P(z) = P_{\text{o}} \exp(-z/H)$, where the scale height H is set at 18.7 km (an average throughout the troposphere) and P_{o} is the surface pressure of 1.5 bar (the slight difference in scale height due to temperature and methane abundance variations can be ignored.) Curves with $T_{\text{surf}} = 93$ and 89 K, and $T_{\text{trop}} = 71$ K for both are overlain in Fig. 1.

Results and discussion. As noted in prior work (Kouvaris and Flasar 1991, Thompson 1985) the equatorial profile crosses the freezing line at 14 km. As an aside, we wonder whether it is coincidence that the Titan profile meets the freezing line almost at the peak (highest pressure, lowest altitude) of the freezing line. Interestingly, the profile meets the freezing line slightly to the left of the peak. Because of this, the cooler atmosphere profile, representing high-latitude conditions, meets the freezing line at a lower pressure. In other words, methane–nitrogen ice melts at a higher altitude at high latitudes than in the tropics. This runs contrary to the expectation we have from terrestrial experience (which would be satisfied if the profile met the freezing line to the right of the peak) that colder conditions lead to a lower snowline.

Coustenis *et al.* (2002) have argued that Titan's bright region may be bright because of cold or elevated terrain covered by methane frost. However, because the freezing line has a maximum at 700 mbar, a cold surface is not enough to form frost—it must be at low pressure too. Terrain of 14-km elevation seems unlikely to be attained by topography on Titan (see discussion in Smith *et al.* 1996). If the bright region is all at 10-km altitude, tidal forces would tend to rotate it to align with Saturn's gravity gradient. Furthermore, hemispheric-averaged brightness temperature measurements made at 3.5 cm show no evidence of a lightcurve (Grossman and Muhleman 1992)—i.e., the microwave emission from the bright terrain is the same as the dark terrain, again inconsistent with a large region of elevated topography.

Courtin and Kim (2002) have observed a "cold spot" (35°N, 20°W) with an infrared brightness temperature 3 K colder than other areas. A cloud is interpreted as the most likely explanation, although some deposit of low-emissivity material is possible. Courtin and Kim suggest a 5-km mountaintop, applying a tropospheric-average lapse rate, would be compatible with this observation, although perhaps only 2–3 km is more appropriate, since the *Voyager* radio-occultation profiles have a steeper lapse rate (~1.2 K/km, similar to our analytic fits above) near the surface. In any case, methane frost is not required to explain this feature, nor would the implied conditions permit it.

Samuelson and Mayo (1997) calculate the rates of methane rainfall required to balance upward eddy diffusion of methane, and show that steady-state supersaturation in the upper troposphere is indeed compatible with (occasional) precipitation. They model the growth and descent of hydrometeors in the atmosphere, considering that particles would grow to ~2-cm hailstones to an altitude of 12 km, where they would melt and break into smaller raindrops—see also Lorenz (1993). Tokano *et al.* (2001) have modeled the evolution of thunderclouds—even if a hailstone could grow rather larger, buoyed by an updraft in such a cloud (which would last only an hour or so), it would take an hour or so to reach the surface and so would melt before reaching it (since the thermal propagation time into a 3-cm hydrocarbon ice particle with thermal conductivity $k \sim 0.3$ W m^{-1} K^{-1} is only several hundred seconds). Thus even transient, nonequilibrium, deposits of methane hailstones seem unlikely.

Conclusions. The phase equilibrium of methane–nitrogen in the lower atmosphere of Titan has been investigated to explore the sensitivity of the freezing-point altitude on Titan. A counterintuitive result is that the snowline is at a lower altitude at low latitudes than at the cooler mid- and polar latitudes. Frost or snow cover as an interpretation for the large bright region on Titan appears to strain the constraints that currently exist.

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