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Temperature Lapse Rate and Methane in Titan's Troposphere

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We have reanalyzed the Voyager radio occultation data for Titan, examining two alternative approaches to methane condensation. In one approach, methane condensation is facilitated by the presence of nitrogen because nitrogen lowers the condensation level of a methane/nitrogen mixture. The resulting enhancement in methane condensation lowers the upper limit on surface relative humidity of methane obtained from the Voyager occultation data from 0.7 to 0.6. We conclude that in this case the surface relative humidity of methane lies between 0.08 and 0.6, with values close to 0.6 indicated. In the other approach, methane is allowed to become supersaturated and reaches 1.4 times saturation in the troposphere. In this case, surface humidities up to 100% are allowed by the Voyager occultation data, and thus the upper limit must be set by other considerations. We conclude that if supersaturation is included, then the surface relative humidity of methane can be any value greater than 0.08—unless a deep ocean is present, in which case the surface relative humidity is limited to less than 0.85. Again, values close to 0.6 are indicated. Overall, the tropospheric lapse rate on Titan appears to be determined by radiative equilibrium. The lapse rate is everywhere stable against dry convection, but is unstable to moist convection. This finding is consistent with a supersaturated atmosphere in which condensation—and hence moist convection—is inhibited.

1. INTRODUCTION

Titan, the largest moon of the planet Saturn, is the only moon in the Solar System with a substantial atmosphere. Our primary information on the temperature and pressure near the surface of Titan derives from analysis of the refraction of the Voyager radio waves as the spacecraft passed behind Titan at two locations (Lindal *et al.* 1983, Lellouch *et al.* 1989). Because the refractivity of a gas is a function of density and composition, self consistent inversions of the density, temperature, and pressure profiles of Titan's atmosphere can be derived from the occultation data. For a pure N_2 atmosphere, the inversion is unique and implies surface temperatures of 94.0 and 93.9 K and surface pressures of 1.495 and 1.498 bar for ingress and egress, respectively (Lindal *et al.* 1983). However, when CH_4 is included there is no longer a unique solution and the inversion depends on the surface humidity and vertical profile of CH_4 (Flasar 1983, Lellouch *et al.* 1989).

Previous analyses have assumed that the CH_4 concentration is limited by its saturation vapor pressure. In this paper we reconsider this assumption in two ways: first by allowing for the effects of N_2 on CH_4 condensation, and second by allowing for CH_4 supersaturation. We then derive new limits for the range of possible temperature solutions and associated concentrations of CH_4. We also consider the implications of the presence of moist convection.

Following the work of Lindal *et al.* (1983), Flasar (1983) was the first to consider the effect of CH_4 on the inversion of the Voyager radio occultation data. Based on the assumption that CH_4 is limited by its saturation value, they found that the lapse rates are unstable to dry convection for surface humidities of CH_4 larger than $\simeq$0.7. This upper limit on the CH_4 at the surface is consistent with the presence of a C_2H_6–CH_4–N_2 ocean which could be the source of the CH_4 destroyed, and the sink for the C_2H_6 produced, in the atmosphere (Lunine *et al.* 1983).

In addition to dry convection, moist convection has also been used to limit the range of inversions of the occultation

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data. Eshleman (1983) pointed out that the profiles determined from both radio occultation data sets yield temperature lapse rates in the troposphere that would be unstable to moist convection, although they would be stable against dry convection. He suggested that this finding implies that CH_4 never saturates in Titan's troposphere, which in turn implies that the surface relative humidity is less than 0.2. However, Hunten *et al.* (1984) discussed this issue and suggested that—similar to the Earth—the troposphere of Titan may have only local regions of moist convection, and the average lapse rate would therefore be intermediate between a moist and a dry rate. This requires that Titan experiences weather and patchy clouds—implying an active and heterogenous troposphere.

If Titan's troposphere is heterogeneous, then temperature profiles should vary with location, and clouds should be present. However, both the similarity of the two radio occultation profiles obtained on Titan (Lindal *et al.* 1983) and theoretical models suggest that Titan's troposphere may be uniform with latitude and season—arguing against local weather. In this context, it is relevant to note that the radio occultation observations sample two regions of differing surface reflectivity in the near-infrared (Smith *et al.* 1996) indicating that the similarity is probably not due to a coincidence of geography. The ingress data were taken above a dark terrain—a candidate region for the possible CH_4–C_2H_6 lakes—which would be highly absorbing. In contrast, egress data were taken above a more highly reflective region of Titan's surface. Note furthermore that localized moist convection would imply the presence of cloud systems. However, the evidence for clouds on Titan is thin. Courtin *et al.* (1995) found that clouds were not needed to fit the IRIS data near 200 cm^{-1} and if present, that the optical depth was less than 0.7, which is consistent with the results of Toon *et al.* (1988). McKay *et al.* (1989) also found that the agreement between thermal structure calculations and observations improved slightly with the presence of clouds. Again, however, the clouds had to be either patchy or thin (visible optical depth $\leq$2). Griffith *et al.* (1991), based on observations in the near infrared (2 μm), also concluded that tropospheric clouds were patchy or thin.

In all the various analyses of the occultation data discussed above, the relative humidity was computed with respect to pure CH_4 condensation. However, in Titan's troposphere condensation occurs as a mixture of CH_4 and N_2 (Thompson *et al.* 1992), and the condensate includes both CH_4 and N_2. This has potentially important implications for the inversion of the occultation data because the presence of N_2 reduces the relative humidity at which CH_4 condensation occurs by $\simeq$20%. (In this paper "relative humidity" is always defined with respect to saturation of pure CH_4.) The presence of other gases—H_2 and Ar—affects the inversion of the radio occultation data as well. Their concentration must be independently determined in order to invert the occultation data.

In addition to the Voyager occultation data, the other key data that can yield information about the troposphere of Titan are the Voyager observations of Titan's thermal emission (IRIS). Courtin *et al.* (1995) recently analyzed the thermal emission spectra using improved methods for collision-induced absorption. They concluded that the percentage of H_2 is 0.1 $\pm$ 0.04 and placed an upper limit on Ar of 6%. Strobel *et al.* (1993), using different data, placed an upper limit on Ar of 10%. Courtin *et al.* (1995) also concluded that CH_4 must be supersaturated in Titan's troposphere by up to about 140% (1.4 times saturation) in order to fit the thermal spectrum.

An interesting and persistent feature of the IRIS analyses is the problem of fitting the spectrum near 300 cm^{-1}. Samuelson (1983) found that to fit the IRIS data required more CH_4 absorption in the troposphere than a saturated profile could provide, and he suggested that clouds were responsible for the increased opacity. Toon *et al.* (1988) found a similar need for increased opacity near 300 cm^{-1} but concluded that clouds were not a consistent explanation. Instead, they postulated a correction factor that increased the value of the absorption coefficient for N_2–CH_4 collision-induced opacity by a factor of 2. However, the recent work of Courtin *et al.* (1995) is based on improved methods for computing the relevant absorption coefficients (Borysow and Tang 1993). They also found that increased CH_4 opacity was required and that clouds were not a consistent explanation, but concluded that uncertainty in the absorption coefficients was not a plausible explanation. This led to the suggestion that CH_4 was present in the troposphere at supersaturated levels. An increased CH_4 amount produced the same effect as increasing the absorption coefficient.

The extra tropospheric opacity at 300 cm^{-1}—presumably from CH_4—is needed not only to match the IRIS observations, but also to obtain the observed thermal structure. This region of the spectrum is key to the greenhouse effect on Titan (McKay *et al.* 1991). Removing this excess opacity reduces the computed surface temperature (McKay *et al.* 1989).

There are at least two ways in which CH_4 supersaturation can be caused in Titan's troposphere. First, condensation may be kinetically inhibited due to the insolubility of the likely condensation nuclei (tholin) in CH_4 and C_2H_6 (Raulin 1987, McKay 1996) resulting in CH_4 concentrations several times saturation (Courtin *et al.* 1995). Alternatively, eddy transport of CH_4 upward from the surface may be effective at maintaining a constant mixing ratio against an inefficient condensation removal process. In either case, the presence of supersaturated concentrations of CH_4 has important implications. In this paper we consider how CH_4 supersaturation affects the results obtained from the inversion of the radio occultation data. We then explore the possible link between CH_4 supersaturation and the apparent lack of moist convection on Titan.

2. INVERSION METHOD

We use the temperature and pressure profile for pure N_2 determined by Lindal *et al.* (1983) as the basis for computing the profile for an arbitrary gas mixture. The iterative procedure we use is that outlined in McKay *et al.* (1989), except that the equation of state is determined using the Soave modification of the Redlich–Kwong equation of state (Reid *et al.* 1987). This equation of state (RKS) was chosen from among several possibilities because it predicts the behavior of N_2—CH_4 mixtures at the pressure and temperature range of interest on Titan to within 1% of experimental data—less than the error of other cubic equations of state (Knapp *et al.* 1982). The dry lapse rate is computed including real gas effects by the formula (Kasting 1988)

$$\frac{d \ln T}{d \ln P} = \frac{P}{C_p} \left.\frac{\partial V}{\partial T}\right)_{P,N} \tag{1}$$

or, in terms of altitude,

$$\frac{dT}{dz} = -\frac{mgT}{C_p V} \left.\frac{\partial V}{\partial T}\right)_{P,N}, \tag{2}$$

where T is temperature, P is pressure, V is the specific volume, C_P is the specific heat at constant pressure, N refers to number, z is altitude, m is the mean molecular weight, and g is the acceleration of gravity. On the first iteration, the temperature profile is taken to be that of Lindal *et al.* (1983), from which a refractivity profile is determined. Using this temperature profile, the mixing ratio of CH_4, H_2, and Ar (if included) is determined. This results in a new value for the density which alters the temperature and pressure profile corresponding to the refractivity data. This new temperature is then used in the next iteration. This is repeated until the temperature has converged everywhere in the troposphere to within 0.001 K.

We determine the CH_4 concentration by specifying the relative humidity at the surface, as well as the H_2 and Ar mixing ratios. In our nominal CH_4 profile, the mixing ratio of CH_4 is required to be uniform with altitude except where it would exceed 100% humidity. For our nominal humidity of 0.6, the mixing ratio at the surface is 7%; saturation conditions exist from 5.5 to 32 km, and the stratospheric mixing ratio is 1.7%. The H_2 mixing ratio is 0.1% and Ar is set to zero. The surface temperature is 93.3 K and the surface pressure is 1.44 bar. Following Courtin *et al.* (1995) we also consider CH_4 supersaturations of 140% humidity and larger.

The numerical model was developed using a high-level software modeling too, SIGMA (Keller *et al.* 1994), developed at NASA Ames. SIGMA supports model building in the physical sciences using diagrammatic data flow charts and drawing upon a knowledge base of information pertaining to the scientific domain being modeled. The system allows the user to construct a model by specifying only the physical variables and equations involved—in a manner similar to sketching a blackboard flow chart of a model. The Titan study was one of the test applications of the SIGMA approach during its development at Ames.

3. RESULTS

Our first result, presented in Fig. 1, is to duplicate the work of Flasar (1983), who found that for surface humidities greater than about 0.7, the derived lapse rate exceeded the dry adiabatic limit for CH_4 profiles that followed the saturation law. This is illustrated in Fig. 1 for a surface humidity of 0.8. Note that the unstable region is not at the surface, but instead occurs from about 2 to 4 km altitude. These solutions are considered unphysical since convection would efficiently act to lower the lapse rate to the adiabatic value. Figure 2 extends this analysis to other values of the surface relative humidity. In the top panel of Fig. 2, we have plotted the maximum lapse rate in the troposphere, as well as the dry adiabatic lapse rate associated with the altitude at which the maximum occurs. The results for the ingress and egress profiles are similar, but we plot both results because the difference between them is an indication of the error in the data. This is particularly true for the vertical profiles as shown in Fig. 1. Including argon at levels consistent with the upper limits results in even more unstable lapse rates for high humidities (>0.8), but does not significantly change the humidity at which unstable lapse rates first occur. When a mixture of CH_4 and N_2 is considered, condensation occurs at a lower relative humidity of CH_4 (Thompson *et al.* 1992). As shown in the top panel of Fig. 2, when CH_4 condensation is determined by saturation of the binary mixture (CH_2–N_2) during inversion of the radio occultation data, the first occurrence of unphysical lapse rates is lowered from a surface relative humidity of 0.7 to 0.6.

We now allow for CH_4 supersaturation in the troposphere. Figure 2 (middle) shows the maximum lapse rate in the troposphere when CH_4 is allowed to reach 140% saturation in the inversion procedure. For both the ingress and egress profiles, there are no unphysical profiles for any value of the surface relative humidity. The unstable lapse rates indicated for relative humidities over 0.7 in the saturation limited case shown in the top panel of Fig. 2 do not exist when 140% supersaturation is allowed. The

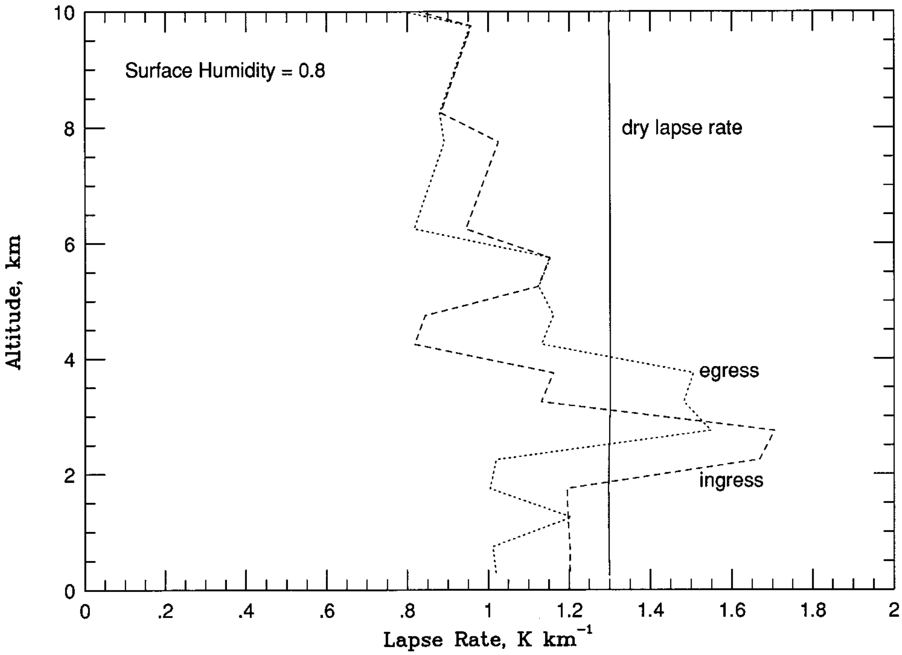

FIG. 1. Vertical profile of lapse rate determined from Voyager ingress and egress radio occultation data for CH_4 surface relative humidity of 0.8, H_2 mixing ratio of 0.1%, and no Ar. CH_4 is limited to its saturation value determined by condensation of pure CH_4. The dry adiabatic lapse rate is shown as the solid line. All values computed with RKS equation of state (see text). The lapse rate is unstable in the range 2–4 km.

bottom panel of Fig. 2 shows the same results, but for no condensation of CH_4 at all. Without condensation, the mixing ratio of methane—even throughout the stratospheric region—is constant and equal to the surface value. Again in this case, there are no unphysical solutions. Including argon does not change the results.

In Fig. 3, we show the inverted temperature profiles for a value of the surface humidity of 0.6, similar to the nominal values of Toon *et al.* (1988), Lellouch *et al.* (1989), and Courtin *et al.* (1995). Saturation of CH_4 is limited to unity and occurs from 5 to 35 km altitude. When condensation as a mixture of CH_4 and N_2 (Thompson *et al.* 1992) is included, condensation occurs at a slightly lower altitude, 3 km (Thompson *et al.* 1992). Also shown in Fig. 3 is the moist lapse rate computed for the condensation of the binary CH_4 and N_2 based on Thompson *et al.* (1992). The moist lapse rate is shown for all altitudes even though condensation is only expected above about 3 km.

4. DISCUSSION

Since we have argued that supersaturation of CH_4 in the troposphere removes the limit on the surface relative humidity derived from the radio occultation data, it is interesting here to review the published constraints on CH_4 in Titan's atmosphere. There has not been a direct determination of CH_4 in Titan's troposphere or CH_4 condensate clouds. This is in contrast with Titan's stratosphere for which CH_4 emissions at 7.7 μm provide a direct indication of the amount of CH_4, although one that is conflated with temperature (Lellouch *et al.* 1989). Nonetheless, as listed in Table I, various methods have been used to infer the tropospheric CH_4 concentration and, in particular, the relative humidity at the surface.

The highest upper limit to the relative humidity at the surface of Titan follows directly from thermodynamical arguments. If Titan's surface is covered by an ocean then, as shown by Thompson (1985), the relative humidity must be less than about 0.85. This constraint derives from the fact that the total pressure in equilibrium with a mixture of CH_4 and N_2 (and C_2H_6) decreases as the mole fraction of CH_4 is increased. This decrease in pressure with increasing CH_4 is because CH_4 has a lower vapor pressure than N_2. At low CH_4 mole fractions, the surface pressure of a CH_4 and N_2 mixture would be too high, and C_2H_6 must be added to the mixture. If there is a negligible mole fraction of C_2H_6, then as the CH_4 mole fraction increases, a point is reached (at CH_4 mole fraction 0.85) where the total pressure is just equal to the observed pressure. Any further increase in the CH_4 mole fraction reduces the total pressure to below the observed value. This limit is only reached in the case of a very deep ocean diluting any photochemically produced C_2H_6. The upper limit of 0.85 on the CH_4 mole fraction in the ocean gives essentially the same limit on the surface humidity of CH_4, because the activity coefficient for the mixture is close to unity. Thus, 0.85 is the

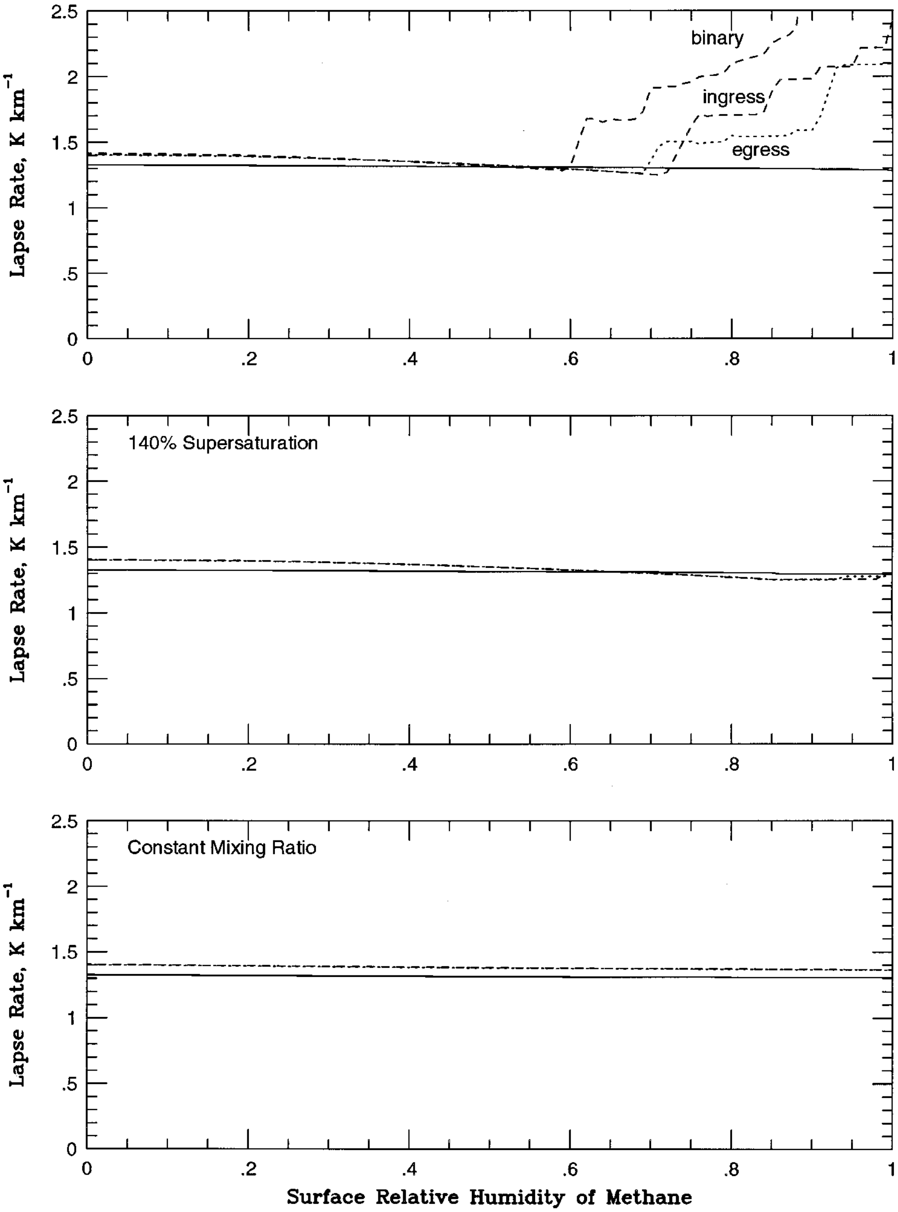

FIG. 2. (Top) Maximum tropospheric lapse rate versus surface relative humidity of CH_4 for Voyager ingress (dashed lines) and egress (dotted line) profiles. Solid line is the adiabatic dry lapse rate at the altitude at which the maximum lapse rate occurred. Profiles are stable (within error of ± 0.1) for humidities less than $\simeq 0.7$. CH_4 is limited to its saturation value determined by condensation of pure CH_4. Also shown is the lapse rate for the ingress profile computed with CH_4 limited by condensation of a binary CH_4–N_2 mixture. In this case unphysical solutions are obtained for humidities greater than $\simeq 0.6$. (Middle) Ingress and egress profiles as in (top), but for CH_4 allowed to reach 1.4 times saturation. (Bottom) Ingress and egress profiles as in (top), but for no CH_4 condensation—the CH_4 mixing ratio is constant with altitude.

limit on the surface relative humidity of CH_4 with an ocean present, as listed in Table I.

The radio occultation data (Flasar 1983) coupled with stratospheric emissions (Lellouch *et al.* 1989) have been used previously to indicate an upper limit to the CH_4 humidity of 0.7, with a nominal value of 0.66 (Lellouch *et al.* 1989). Lower limits to the CH_4 humidity follow from the radio occultation data, combined with the 7.7-μm stratospheric emissions and Voyager IRIS data. Once the tropospheric mixing ratio falls below about 0.2, CH_4 is no longer saturated at the tropopause, and the stratospheric CH_4 mixing ratio should then be equal to the tropospheric value. The minimum value for the stratospheric mixing ratio of CH_4 implies a surface relative humidity of more than 0.04 if argon is present (at 27%) and above 0.08 if argon is not included in the analysis (Lellouch *et al.* 1989), as listed in

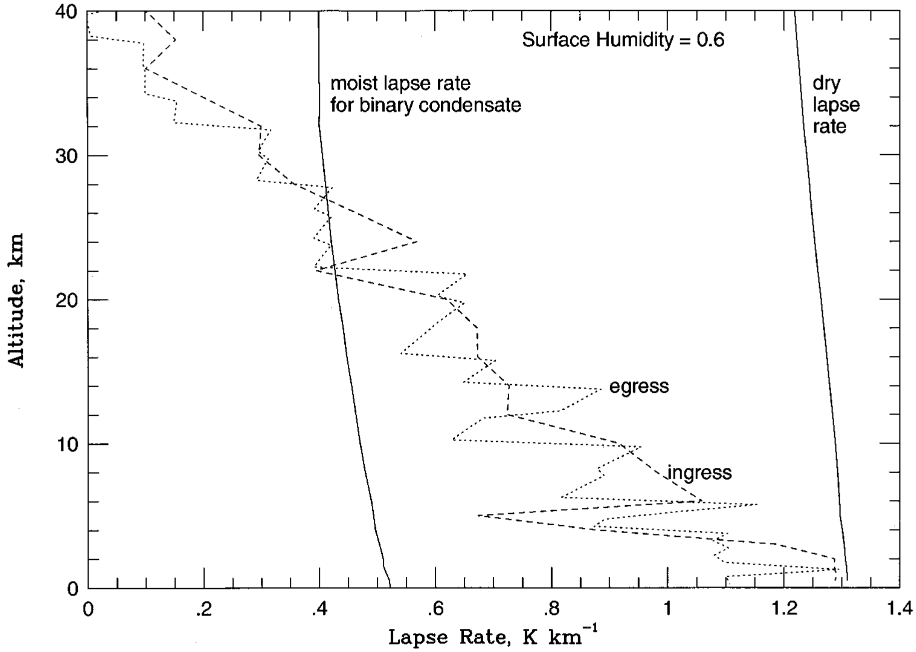

FIG. 3. Vertical profile of lapse rate determined from Voyager ingress and egress radio occultation data for CH_4 surface relative humidity of 0.6, H_2 mixing ratio of 0.1%, and no Ar. CH_4 is limited to 100% relative humidity throughout the profile. The dry and moist adiabatic lapse rates are shown as the solid lines. Data values and dry lapse rate are computed with RKS equation of state (see text); the moist lapse rate calculation includes the effect of the N_2–CH_4 binary. The lapse rate is stable with respect to dry convection, but unstable with respect to moist convection.

Table I. Voyager IRIS observations at 300 cm^{-1} further constrain the lower limit, indicating a value of 0.6 for non-supersaturated conditions (Toon *et al.* 1988, Courtin *et al.* 1995).

In this study we have found that when the Voyager occultation data are analyzed with condensation of the binary CH_4–N_2 included, the upper limit on the surface humidity falls to 0.6. The lower limit remains unchanged. If supersaturation is included, then no upper or lower limit on the surface relative humidity of CH_4 is deduced from the radio occultation data. Any value that is above the stratospheric minimum of 0.08 discussed above is allowed. However, if an ocean is present, then this implies an upper limit on the surface humidity of CH_4 of 0.85. A relative humidity of 0.6 is consistent with all studies presented above.

As shown in Fig. 3, Titan's temperature profile derived from the Voyager occultation data is unstable against moist

TABLE I
Tropospheric CH_4

Surface humidity	Basis for conclusion	Reference
<0.7	Voyager occultation, dry lapse rate	Flasar (1983)
<0.2	Voyager occultation, moist lapse rate	Eshleman *et al.* (1983)
No constraint	Localization of moist lapse rate	Hunten *et al.* (1984)
<0.85	$CH_4/N_2/C_2H_6$ thermodynamics (ocean only)	Thompson (1985)
>0.6	IRIS data near 300 cm^{-1}	Toon *et al.* (1988)
0.66	Voyager occultation and 7.7-μm data	Lellouch *et al.* (1989)
	Voyager occultation, 7.7-μm data	Lellouch *et al.* (1989)
>0.04	(a) Minimum stratospheric value with Ar	
>0.08	(b) Minimum stratospheric value without Ar	
>0.6	IRIS data near 300 cm^{-1}	Courtin *et al.* (1995)
$\simeq$140% ($z \simeq$ 15–30 km)		
<0.6	Voyager occultation, dry lapse rate with binary condensation	This study
No upper limit	Voyager occultation, dry lapse rate with supersaturation	This study

convection. This result is obtained for any reasonable equation of state used to analyze the data and regardless of the CH_4 humidity profile used—either binary condensation or supersaturation. As pointed out by Eshleman *et al.* (1983), it appears clear that neither the ingress nor egress profiles show moist convection, even though condensation and moist convection should be occurring if the surface humidity of CH_4 on Titan exceeds about 0.2. One possible explanation (Hunten *et al.* 1984) is that, by analogy with the Earth, moist convection only occurs in localized regions on Titan. However, as discussed above (see also Courtin *et al.* 1995), other evidence suggests that Titan's troposphere is more uniform laterally and more quiescent than that of the Earth. Consistent with the suggestion of a quiescent troposphere is the possibility that condensation of CH_4 does not occur in Titan's troposphere, thus resulting in the supersaturations required by Courtin *et al.* (1995). Under this scenario, Titan's troposphere acts as a noncondensable gas and the convective limit is set by the dry adiabatic lapse rate only. The moist lapse rate does not apply. Courtin *et al.* (1995) suggested that supersaturation of CH_4 on Titan could result from the low number of condensation nuclei and the high contact angle between the tholin material and CH_4.

Without condensation present, Titan's lapse rate might be expected to follow the dry lapse throughout the troposphere. As seen in Fig. 3, however, this is not the case. As pointed out by Samuelson (1983), Titan's lapse rate is essentially the radiative equilibrium profile. Detailed nongray radiative convective models have shown that this is indeed the case (McKay *et al.* 1989).

Tropospheric clouds would be direct evidence for CH_4 condensation. Previous studies based on the thermal structure (McKay *et al.* 1989), the IRIS data (Toon *et al.* 1988, Courtin *et al.* 1995), and near infrared observations (Griffith *et al.* 1991) are all consistent with no tropospheric clouds. Clouds—if present—must be very thin or patchy.

The virtual absence of condensation in Titan's atmosphere and a temperature lapse rate unstable to moist convection could generate interesting effects. Awal and Lunine (1994) looked at moist convection in Titan's atmosphere triggered by dry convective activity in the lowermost layer of the atmosphere. It is expected that a convective zone must exist, since the radiative equilibrium solution results in a finite temperature discontinuity at the surface. Convective activity that penetrates up into the layer of condensation (about 3 km) would be expected to grow throughout the troposphere and possibly into the stratosphere if it carried sufficient condensation nuclei to allow for CH_4–N_2 condensation. These plumes were estimated to cover $<10^{-5}$ of Titan's globe. As suggested by Awal and Lunine (1994), moist convective plumes on Titan could be a very rare but still important source of vertical transport of CH_4.

5. CONCLUSIONS

We have considered two important—and mutually exclusive—atmospheric effects in the analysis of the Voyager radio occultation data: (1) the enhanced condensation of CH_4 when coupled with N_2 and (2) the possibility that CH_3 is supersaturated and is effectively noncondensing. We have compared the derived lapse rates to the dry and moist adiabats. Our main conclusions can be listed as follows:

1. The condensation of the binary CH_4–N_2 occurs at a lower relative humidity of CH_4 than for pure CH_4. This effect lowers the upper limit of surface humidity derived from the radio occultation data. The upper limit is 0.7 when only CH_4 is considered and is reduced to 0.6 when the effects of N_2 are included.
2. If CH_4 condensation is inhibited and supersaturations of 140% or more result, then the Voyager occultation data do not result in any upper limit on the surface relative humidity of Titan.
3. There is no convective zone in Titan's troposphere. Titan's tropospheric lapse rate is stable with respect to dry convection and closely follows the radiative lapse rate.
4. Titan's tropospheric lapse rate is unstable with respect to moist convection. Considering the indications that Titan's lower atmosphere is laterally uniform, this is a further indication that CH_4 condensation is inhibited.

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