Convective plumes and the scarcity of Titan's clouds

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[1] We show that simple thermodynamic models of convective plumes predict the area fraction of convective plumes (i.e., updrafts) in Titan's atmosphere to be ~12 smaller than on Earth. This result is in agreement with predictions by sophisticated dynamical models and with the relative tropospheric cloud cover, which is only ~1% on Titan. Rainstorms on Titan, being so rare, may be violent.
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1. Introduction: Titan Energy Balance

[2] Titan has a dense nitrogen atmosphere (surface pressure 1.5 bars, temperature 94 K) laden with an optically thick organic haze. *Samuelson* [1983] and *McKay et al.* [1989, 1991] showed that of the sunlight incident on the top of Titan's atmosphere, a substantial fraction is absorbed by stratospheric haze. A further fraction is absorbed by methane in the troposphere. Only around 10% of the incident solar radiation reaches the surface, of which about a fifth is reflected back to space. Thus the shortwave energy flux deposited onto the surface is approximately 8% of that at the top of the atmosphere (Figure 1).

[3] The troposphere is significantly opaque to thermal infrared radiation, leading to a strong greenhouse effect. The equivalent grey (Rosseland mean) thermal opacity is ~2.5 (compared with the Earth's of ~4), due principally to collision-induced absorption of N_2-CH_4, N_2-N_2 and N_2-H_2 [*McKay et al.*, 1989, 1991]; there is a window at around 19 microns (530 cm^{-1}) where the opacity is small and some photons escape to space. The overall global-average, annual-average energy balance is shown in Figure 1. In the average balance, the convective heat flux is estimated [*McKay et al.*, 1989, 1991] as only 1% of the top-of-atmosphere incident solar flux, in contrast to the Earth where the fraction is ~30%. We will return to these numbers later. In steady state, the atmosphere must convey the absorbed heat upwards, and increased opacity makes this more difficult to achieve by radiation alone: Earth's higher thermal opacity pushes a larger fraction of the upward flux from the surface through convection [*Lorenz and McKay*, 2003] rather than radiation.

[4] Caution is needed in that the 1% quantity mentioned above is calculated as the residual between much larger, but substantially model-dependent, fluxes of ~120% (see Figure 1.) It is likely to be correct only to an order of magnitude but it agrees with simple parameterizations [*Lorenz and McKay*, 2003]. (All these fluxes are relative to the incident solar flux on the top of the atmosphere, on average ~3.7 Wm^{-2}).

[5] In this paper, we explore how this convective flux may be manifested as convective plumes that are responsible for creating the dynamically-evolving and sparse clouds observed on Titan. We also consider some insights that Cassini observations may offer.

2. Convective Plumes and Cloud

2.1. Models

[6] How might the convective flux be manifested? The pole-to-pole Hadley cell indicated for Titan by GCMs [e.g., *Tokano et al.*, 1999] is in all probability a purely statistical flow, like the Hadley circulation of the Earth. The Hadley circulation is a statistical flow resulting from a small area fraction of upwelling plumes at low latitudes and widespread subsidence everywhere, but preferentially in midlatitudes. Indeed, except in regions of disturbed weather, the atmosphere in the upwelling branch of the cell is not moving upwards. Over most of the area of the ascending branch of the Hadley circulation, the air is subsiding and only in a few plumes is there upward motion. Statistically, these plumes have a higher speed and a larger area over the equator than at higher latitudes, and thus there is a net flow which we refer to as the Hadley cell. Similarly on Titan, we expect plumes over a small area fraction in the summer hemisphere and general subsidence elsewhere.

[7] These plumes are familiar to hang-glider and sailplane pilots as thermals. Their formation does not require moisture. However, some moisture is usually present, and an invisible convective plume is often capped with a cumulus cloud, as the rising warm (and moist) air cools adiabatically to the saturation point during its ascent (the altitude at which this occurs is the Lifting Condensation Level or LCL). At this point the plume's buoyancy may begin to be enhanced by the release of latent heat. *Griffth et al.* [2000] show how latent heat in Titan air of 60% surface relative humidity would accelerate a plume from 5.5 km altitude up to 20–25 km, a result also obtained with a more sophisticated cloud model by *Awal and Lunine* [1994] (hereinafter referred to as AL94). However, this moist convective process is a result of the dry plumes triggered at the surface and thus a continuum of moisture content may be considered. Note that "Moist" refers to processes involving condensation of water on Earth, and of methane in Titan's atmosphere.

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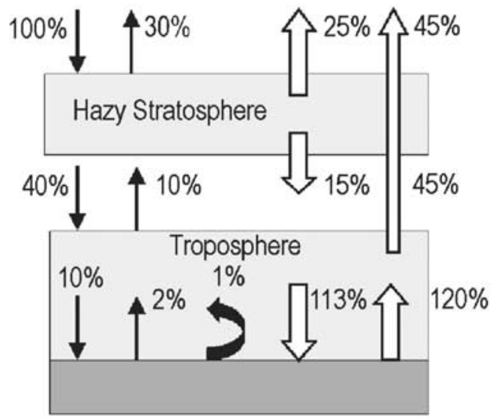

Figure 1. Globally-averaged, annually-averaged energy balance of Titan's surface and atmosphere, from *McKay et al.* [1991]. Fluxes are expressed as a percentage of the average incident top-of-atmosphere insolation 3.7 Wm^{-2}. Solid arrows are shortwave (solar) fluxes; open arrows are longwave (thermal) infrared fluxes. Curved solid arrow refers to convective flux, of $\sim$0.04 Wm^{-2}.

[8] The fractional area f covered by these plumes can be estimated using a heat engine theory for convection by *Rennò and Ingersoll* [1996] (hereinafter referred to as RI96). Their theory assumes (without considering moisture explicitly –the latent heat flux is part of the convective heat flux) that, steady-state convection is just strong enough that the work available from the heat engine balances the viscous dissipation opposing the convective motions (F_d). The work output is equal to the driving convective heat flux (F_{in}) multiplied by the thermodynamic efficiency of the convective heat engine (η), thus $F_d = \eta F_{in}$. The energy flux consumed by viscous dissipation is equal to the square of the plume's velocity w multiplied by the convective mass flux ($M_c = \rho f w$) and a utilization factor, μ. This term is the ratio of the frictional dissipation integrated along the convective streamline to the square of the convective velocity – RI96 give scaling arguments assuming a shallow atmosphere and homogenous and isotropic turbulence to yield $\mu \sim 16$. The convective mass flux, in turn, balances the subsidence mass flux, M_s. RI96 calculate the subsidence mass flux assuming that the tropospheric radiative cooling is balanced by the compressive warming due to subsidence. Using the Newtonian cooling rate approximation, they find $M_s = \Delta p/(g\ \tau_R)$ where p is pressure, and τ_R is the radiative time-scale. Assuming an opaque atmosphere radiating as gray body, RI96 obtain an expression for the radiative time scale, $\tau_R = c_p\ \Delta p/(g\ 8\ \varepsilon\ \sigma\ T_c^3)$, where c_p is specific heat at constant pressure, g is gravity acceleration, ε is the atmosphere effective emissivity assumed to be unity, σ is the Stefan-Boltzmann constant, and T_c is the average temperature at which the troposphere rejects heat to space: for this we choose the planet's effective temperature.

[9] Since, in steady state, the convective mass flux must balance the subsidence mass flux, the updraft area fraction is

$$f = (\mu/\eta)^{0.5} \cdot \left(8\sigma T_c^3\right)^{1.5} \cdot c_p^{-1.5} \cdot \rho^{-1} \cdot F_{in}^{-0.5} \qquad (1)$$

where η is an efficiency estimated to be $\sim$0.1, ρ is the density of the atmosphere.

[10] It follows that the velocity w of undiluted updrafts is

$$w = (\mu/\eta)^{-0.5} \cdot \left(8\sigma T_c^3\right)^{-0.5} \cdot c_p^{0.5} \cdot F_{in}^{0.5} \qquad (2)$$

with terms as before. For the terrestrial case with global/annual-averages $F_{in} \sim 100$ Wm^{-2}, $\rho = 1.2$ kgm^{-3} and $T_c \sim 250$ K gives $f \sim 7 \times 10^{-4}$ and $w \sim 10$ ms^{-1}, in reasonable agreement with terrestrial data (RI96).

[11] For the average on Titan, with $F_{in} \sim 0.04$ Wm^{-2}, $T_c \sim 82$ K, and $\rho = 5$ kg m^{-3}, we find $f \sim 5 \times 10^{-5}$ and $w \sim 1$ ms^{-1}. Thus, to a first order, plumes occupy $\sim$12 times less area fraction on Titan than on Earth, and are a factor $\sim$10 weaker in terms of velocity.

[12] In this calculation, we assume other terms remain the same. This is justified as follows. η is a Carnot efficiency $\Delta T/T$, with ΔT taken as roughly half the surface-to-tropopause temperature difference (94 K–72 K), and thus η for Titan on the same basis would be $\sim$0.1, as for Earth. The square root in the expressions above makes the results somewhat insensitive to changes in μ and η.

[13] An alternative formulation based on a dimensional analysis by *Craig* [1996] gives

$$f = (\mu/\eta)^{0.5} \cdot (\Delta h)^{-1.5} \cdot \rho^{-1} \cdot F_{in} \qquad (3)$$

where Δh is the excess enthalpy per unit mass transported by the convection.

[14] This expression depends explicitly on an assumed value for Δh. Figures 2a and 2b plot f for Earth and Titan as a function of Δh, with other parameters as before. It is seen that this expression agrees with the RI formula for Earth average conditions for $\Delta h = 2 \times 10^4$ Jkg^{-1}. In simple terms Δh is given by $\Delta h = c_p\Delta\Theta + \phi L$, where $\Delta\Theta$ is a temperature excess (i.e., the horizontal perturbation in temperature of the plume versus its surrounds) and ϕ is the mass fraction of condensible material with latent heat L (cf. AL94). In a dry atmosphere, all the enthalpy is associated with sensible heat and ϕ is zero; in moist convection, we may take as a limiting case ϕ as the difference between the mass fraction of the condensible at the surface and at the tropopause. This

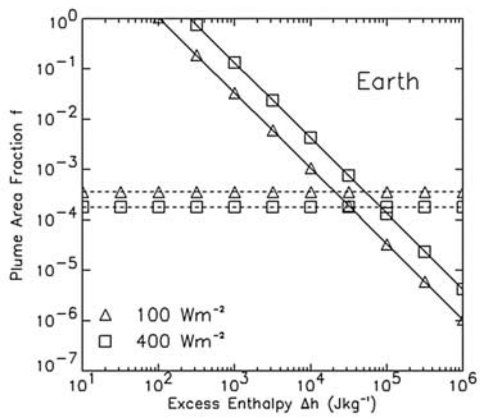

Figure 2a. Convective plume area for Earth average (Triangles) and summer (square) conditions from the RI formula (equation (1), horizontal dashed lines) and the Craig formula (equation (3), sloping solid lines).

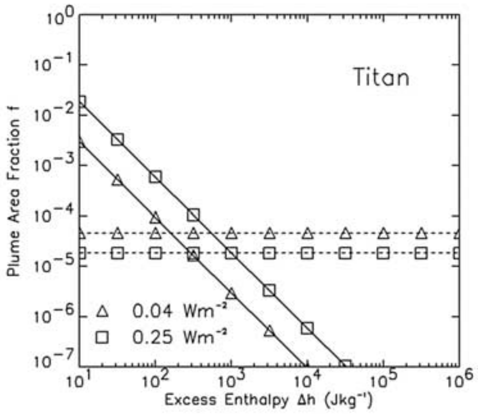

Figure 2b. As Figure 2a, but for Titan conditions.

terrestrial equivalent to a dry temperature excess of $\Delta\Theta$ ~20 K, or a condensible water vapor content of around 1%, or some intermediate combination of the two. These values are in good agreement with the known conditions for convection on Earth.

[15] Applying the formula for Titan average conditions, we find agreement with the RI formula for $\Delta h \sim 180$ Jkg^{-1}, corresponding to a $\Delta\Theta$ of 0.18 K. Expressed in terms of methane latent heat L = 5 $\times$ 10^5 Jkg^{-1}, this corresponds to condensation of only 0.04% of the atmospheric mass: by comparison, the methane abundance is 4~7% at the surface, and ~2% at the tropopause, suggesting maximum values ϕ = 0.02~0.05. Taking these extreme values gives $\Delta h \sim 1$–2×10^4 Jkg^{-1} and we recover the AL94 result of $f \sim 10^{-6}$–10^{-7}. To consider stronger convection in Titan's summer, we also give results for $F_{in} \sim 0.25$ Wm^{-2}. We justify this value with reference to the energy budget in Figure 1. At polar midsummer, the top-of-atmosphere insolation is double the average: assuming the haze and gas opacities remain the same, the shortwave flux onto the surface will also double to ~20% of the average, or 0.7 Wm^{-2}. The enormous heat capacity of Titan's atmosphere and its resultant long radiative time constant means that the downwelling longwave flux remains unchanged. This dense atmosphere is very effective at wicking away the heat deposited at the surface into plumes, and thus the convective heat flux is higher than average essentially by the increment in shortwave flux. This gives ~9% ~0.33 Wm^{-2} as an upper limit for polar midsummer.

[16] Updraft velocities for moist convection are comparable with the dry estimates above – for example, *Tokano et al.* [2001] estimate velocities of ~1 ms^{-1} in a convecting thunderstorm on Titan. AL94, with moisture-dominated plumes covering a very small area have velocities of up to ~10 ms^{-1}.

[17] Now, if the area of convective clouds is proportional to the area of plumes (a reasonable approximation, used in terrestrial models [e.g., *Ou*, 2001]), and noting that the Earth has a typical cloudiness of 50%, of which perhaps a third is due to convection, the convective cloud area on Titan seems likely to be a factor of 12 times smaller, or around 1%. Clearly this sort of scaling cannot work at large values of plume area, in that the cloud cover cannot exceed 100%, but for the small area coverage we predict for Titan, this limitation is not an issue.

[18] Although moist processes are not treated explicitly in the expressions above, moist process microphysics clearly plays a role in both Titan's and Earth's atmosphere. Irrespective of moisture's contribution, thermodynamic factors such as Carnot efficiency are independent of the working fluid of the convective heat engine – whether moist or dry. The application of these expressions to cloud areas may even be more robust than the plume areas themselves – a moister atmosphere can use latent heat transport to a greater extent, forming narrower plumes (larger F_{in}), but depositing more condensate above. The resultant cloud areas at the plume tops, taking the atmosphere as a whole, may therefore be rather insensitive to the moisture amount.

2.2. Cloud Observations

[19] Beneath the ubiquitous stratospheric haze, Titan has patchy tropospheric clouds. Disk-integrated spectroscopic measurements have pointed to cloud coverage of about 10% on several nights in 1995 [*Griffth et al.*, 1998] and around 1% on nights in 1998 [*Griffth et al.*, 2000]. The latter observation also showed that clouds vary on hourly time-scales. More recently, discrete clouds have been observed on Titan [*Roe et al.*, 2002; *Brown et al.*, 2002] at latitudes of 61–85 S, shortly prior to southern summer solstice. These clouds cover up to 2% of Titan's disk. The proximity of these clouds to the latitudes experiencing peak insolation has been noted, and suggests a convective origin.

[20] Additionally, a large (~10%) cloud feature has been observed (M. T. Lemmon et al., HST observations of Titan, 1994–1997: New surface albedo maps and detection of large-scale cloud activity, submitted to *Icarus*, 2004, hereinafter referred to as Lemmon et al., submitted manuscript, 2004) in Hubble Space telescope images acquired in 1995 (at southern spring equinox) at a latitude of 40 N. This single feature may be responsible for the 10% coverage inferred by *Griffth et al.* [1998], observed only a few weeks before.

[21] In addition to these detections, many dozens of observations have failed to detect cloud features (see Lemmon et al., submitted manuscript, 2004, for a compilation). Taken together, the observational data point to a time-averaged cloud coverage of the order 0.1 to 2%, a result in good agreement with our theoretical prediction above.

2.3. Violence of Storms: Titan as a Laboratory for Greenhouse Earth

[22] A principal limiting factor in the size of extreme storms on Earth is the availability of moisture in the atmosphere [e.g., *Trenberth*, 1999; *Allen and Ingram*, 2002] and thus in a greenhouse climate, the higher vapour pressure (or specific humidity) of atmospheric water at elevated temperatures permits more violent storms to occur. However, to a first order, the overall vigour of the hydrological cycle (as measured by the convective energy flux transporting the fluid substance upwards) is unchanged, and thus the precipitation flux conveyed in the now-permitted extreme events occurs at the expense of smaller precipitation events, which accordingly occur less often than before. The result is an unpleasant combination of more frequent droughts (since light rains occur less often) and of more frequent floods (since violent events become less rare.)

[23] Titan may represent an extreme example of this climate property. Although its hydrological cycle is weak

(the global average convective flux is ~2000 times smaller than Earth's, corresponding to ~0.5 cm of methane rainfall per Earth year [*Lorenz*, 2000]) Titan's atmosphere can store more latent heat [*Griffth et al.*, 2000].

[24] The column mass of methane on Titan exceeds 2000 kgm^{-2} (>2% of a 10^5 kgm^{-2} atmosphere) compared with ~100 kgm^{-2} of water on Earth (~1% of a 10^4 kgm^{-2} atmosphere.) These quantities, if they could be completely condensed, represent ~4 m and 10 cm of rainfall respectively – the meteorological turnover time for the relevant working fluids is therefore ~1 month for Earth, but a millennium for Titan. This picture seems to be supported by the supersaturation of methane in Titan's upper troposphere [*Courtin et al.*, 1995; *Samuelson et al.*, 1997] which suggests that there are significant kinetic barriers to condensation. Hence, like many desert regions on Earth, a location on Titan may experience rare, but very violent, rainfall [*Lorenz*, 2000]. We note that the Titan thundercloud model of *Tokano et al.* [2001] gives column masses of methane rain and graupel equivalent to surface thicknesses of around 20 cm and 80 cm respectively – representing a substantial fraction of the total atmospheric column, and centuries-worth of precipitation. Thus, although the methane hydrological cycle is weak overall, pluvial and fluvial erosion may nonetheless be significant forces of geomorphological change on Titan.

3. Cassini Observations

[25] Cassini has arrived after southern summer solstice (October 2002) and perihelion (July 2003). Imaging by Cassini's Imaging Science Subsystem (ISS) in near-infrared filters that probe to varying depths in Titan's atmosphere will provide detailed morphological constraints on cloud systems, and perhaps observe their evolution in detail. The Visual and Infrared Mapping Spectrometer (VIMS) will be able to place strong constraints on the opacity structure, and in particular the cloudtop altitude, of cloud systems, as well as more general information on the opacity structure of the haze and thus the energy deposition profile in the atmosphere. The Descent Imager and Spectral Radiometer (DISR) on the Huygens probe will significantly contribute to these areas too. Infrared sounding at 530 cm^{-1} using the Composite Infrared Spectrometer (CIRS) will sense the temperature of the top few microns of the surface, and measure the tropopause temperatures at other wavelengths. Several radio occultations during the Cassini tour will yield temperature profiles of the atmosphere near the surface at various latitudes.

[26] The scaling arguments presented in this paper concur with previous work arguing that convective plumes are rare – the Huygens probe is thus unlikely to encounter a strong updraft during its descent in January 2005.

[27] Although we anticipate a fantastic data return from Cassini, it will by no means completely survey Titan – we have argued convective events are rare. Each of the ~44 close flybys gives only a snapshot of Titan – Cassini is not well-disposed as a Titan monitoring platform. Thus it is important that groundbased observations of Titan, notably imaging and spectroscopy in the near-infrared to detect clouds, continues in earnest to put the Cassini encounters in context (the experience of the Galileo Probe's entering a 'hot spot', which was only known from groundbased support imaging, is sobering in this regard.)

[28] Finally, future spacecraft exploration of Titan should consider meteorology a key objective. Future missions might include in-situ exploration by aircraft or balloons, and observations from orbit using cloud-profiling radar and similar advanced instrumentation.

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References

Allen, M. R., and W. J. Ingram (2002), Constraints on future changes in climate and the hydrological cycle, *Nature*, *419*, 224–232.
Awal, M., and J. I. Lunine (1994), Moist convective clouds in Titan's atmosphere, *Geophys. Res. Lett.*, *21*, 2491–2494.
Brown, M. E., A. E. Bouchez, and C. A. Griffith (2002), Direct detection of variable tropospheric clouds near Titan's south pole, *Nature*, *420*, 795–797.
Craig, G. C. (1996), Dimensional analysis of a convecting atmosphere in equilibrium with external forcing, *Q. J. R. Meteorol. Soc.*, *122*, 1963–1967.
Courtin, R. D., D. Gautier, and C. P. McKay (1995), Titan's thermal emission spectrum: Re-analysis of the Voyager infrared measurements, *Icarus*, *114*, 144–162.
Griffth, C. A., T. Owen, G. A. Miller, and T. Geballe (1998), Transient clouds in Titan's lower atmosphere, *Nature*, *395*, 575.
Griffth, C. A., J. L. Hall, and T. R. Geballe (2000), Detection of daily clouds on Titan, *Science*, *290*, 509.
Lorenz, R. D. (2000), The weather on Titan, *Science*, *290*, 467–468.
Lorenz, R. D., and C. P. McKay (2003), A simple expression for vertical convective fluxes in planetary atmospheres, *Icarus*, *165*, 407–413.
McKay, C. P., J. B. Pollack, and R. Courtin (1989), The thermal structure of Titan's atmosphere, *Icarus*, *80*, 23–53.
McKay, C. P., J. B. Pollack, and R. Courtin (1991), The greenhouse and anti-greenhouse effect on Titan, *Science*, *253*, 1118–1121.
Ou, H.-W. (2001), Possible bounds on the Earth's surface temperature: From the perspective of a conceptual global-mean model, *J. Clim.*, *14*, 2976–2988.
Rennò, N. O., and A. P. Ingersoll (1996), Natural convection as a heat engine: A theory for CAPE, *J. Atmos. Sci.*, *53*, 572–585.
Roe, H. G., I. de Pater, A. Macintosh, and C. P. McKay (2002), Titan's clouds from Gemini and Keck adaptive optics imaging, *Astrophys. J.*, *581*, 1399–1406.
Samuelson, R. E. (1983), Radiative equilibrium model of Titan's atmosphere, *Icarus*, *53*, 364–387.
Samuelson, R. E., N. R. Nath, and A. Borysow (1997), Gaseous abundances and methane supersaturation in Titan's troposphere, *Planet. Space Sci.*, *45*, 959–980.
Tokano, T., F. M. Neubauer, M. Laube, and C. P. McKay (1999), Seasonal variation of Titan's atmospheric structure simulated by a general circulation model, *Planet. Space Sci.*, *47*, 493–520.
Tokano, T., G. J. Molina-Cuberos, H. Lammer, and W. Stumptner (2001), Modelling of thunderclouds and lightning generation on Titan, *Planet. Space Sci.*, *49*, 539–560.
Trenberth, K. E. (1999), Conceptual framework for changes of extremes of the hydrological cycle with climate change, *Clim. Change*, *42*, 327–339.

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