How often does it Rain on Titan? R. D. Lorenz[1] and E. P. Turtle[1].

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Introduction: We are privileged to live on one of only two worlds in the solar system on which liquids rain onto a solid surface : Titan is the other. Here we show that simple energy balance, numerical models of global and mesoscale circulation, ground- and space-based observations of clouds, and Cassini observations of surface change, are all consistent with Titan rains lasting 2-100 hours occurring at ~100-1000 year intervals globally, but 10-100 hours each Titan year (30 Earth years) at the poles. Implications for observations by Cassini and possible future missions are discussed.

Energy Balance Arguments: As noted prior to Cassini [1,2], the global surface energy balance at Titan expresses only ~0.1% of the top-of-atmosphere insolation as convection. Every raindrop that falls in a hydrological cycle must in turn be evaporated, and expressing this convective flux (~0.015 Wm^{-2}) as latent heat implies 1-2cm of rainfall on average per Earth year (compared with ~1m on Earth.) The moisture content of the atmosphere (~5m methane liquid equivalent on Titan, ~2cm on Earth) defines a characteristic rainfall amount or limit, and adopting a 'relaxation oscillator' model, dividing this by the flux above yields a typical interval between rain storms of ~1 week on Earth and ~100-1000 years on Titan [5]. But these are global average values - in fact the seasonal cycle on Titan concentrates rainfall in polar summer.

Cloud Cover Observations: Compared to the Earth, where average cloud cover is of the order of 50-65%, Titan is relatively cloud-free. A 2001-2003 Keck imaging survey of 16 nights yielded cloud coverage of 0.2-0.6% [3]. A groundbased spectroscopic monitoring campaign [4] indicated an average of 0.3% cloud cover on 138 nights over 2.2 years. These measurements are in reassuring accord with theoretical models relating convective heat flux to expression as moist plumes and cloud cover, which suggested ~0.2-1% cloud cover [5]

However, it is known that many of these clouds appear around the summer pole. If we define the polar region as the area poleward of 60° latitude (where most clouds have been detected), then the summer pole corresponds to only ~7% of Titan's total area, and thus the average cloud cover over the summer pole is higher by a corresponding factor, or 2.5-7.2%.

Numerical simulations of cloud convection (e.g. [6]) show cloud systems around 150km across have cores wherein updrafts and precipitation are concentrated are only ~20km across, or about 1-2% of the area of the cloud. Multiplying these observed or inferred fractions together, the fraction of the southern summer polar atmosphere occupied by updrafts or raincells is of the order of 0.02-0.15%.

Probability of Rainfall: Simulations (e.g. [7,8]) indicate that ~1000 kg/m^2 of methane precipitation may occur at the poles throughout the Titan summer season, with up to ~2000 kg/m^2 locally. Note that these amounts (equivalent to 2-4m of rainfall) are rather in excess of the global long-term average.. The two values may be reconciled by noting that clouds, and by implication rainfall, are much more frequent at the poles than elsewhere – multiplying the 2-4m of polar rainfall by the 15% of Titan's surface in the polar regions yields 0.3-0.6m per Titan year, in good agreement with the global energy limit.

Mesoscale simulations of individual storm systems (e.g. [5,9]) suggest that precipitation rates in methane rainstorms may be of the order of 20-200 kg/m^2 per hour for a few hours. Thus, for 2000 kg/m^2, there are in all a few to a few tens of storms totaling 10-100 hours of rainfall during the summer season of ~50,000 hours, or in other words it rains only ~0.01-0.1% of the time.

Rain Observations: Cassini has observed two events of surface darkening associated with cloud activity; these are best interpreted as rain events. In 2004 Arrakis Planitia (34,000km^2, 80°S, [10]) and in 2010 Concordia Regio (510,000km^2, 20°S [11]). Together, these represent ~0.7% of Titan's surface, in 6 years. Crudely, 100% of the surface would then be rained on in 6*100/0.7~860 years. In reality of course, the Cassini record is unlikely to be complete ('missing' events might be estimated by assuming that rain cells, as on Earth, follow a power-law size distribution – as for dust devils on Mars and Earth [12]) and thus the recurrence interval will be somewhat shorter. However, the order of magnitude is remarkably consistent with the other considerations herein.

Implications for Cassini Observations: Large-scale cloud and surface darkening observations have already been successful and monitoring continues. Cloud-tops ascending at rates of 2-4 m/s in large clouds, but up to 8-10 m/s in smaller more discrete cloud features were observed in southern summer high latitudes in VIMS data in 2004 [13]. As we move into northern summer, opportunities for such measurements (which can be made over wide areas) will likely increase. RADAR, as on Earth, has the ability to peer through clouds and detect rain unambiguously, and one short (2s) dedicated nadir-pointed cloud-sounding observation using a special altimetry mode established an upper limit on winter drizzle [14]. If 5~10 similar point observations are made in northern polar summer, as the Cassini Solstice Mission might permit, there is a ~1% chance of detecting rain (clearly this type of observation is best done from a Titan orbiter!). Detection over larger areas (but with lower sensitivity) may be possible in other Cassini radar modes, or in radio occultation data, but is at best a speculative possibility.

Effects on a Descending Probe: A parachute-borne vehicle on Titan would likely spend ~1 hour descending through Titan's troposphere, as did Huygens. Even in polar summer, the foregoing arguments suggest that a rainstorm would be encountered during descent with a probability of less than ~0.2% (rather less than the corresponding probability on Earth).

Were this to occur, effects would in any case be benign : simple ESD protection (standard for aircraft) can protect against triboelectric charging or lightning (and were adopted for Huygens). In fact methane is a poor dielectric and an extensive 72-flyby search for lightning on Titan has proved negative [15]. Unlike for a lifting wing, the aerodynamics of a bluff body descending at terminal velocity are not significantly affected by any methane ice formation, which would in any case melt off below about 14km. (In fact, some of the early work on Titan raindrops [16] was motivated by consideration of the size and amount of supercooled drops that could be present, a few kg of which might freeze onto the Huygens probe.) Were the probe at a descent speed V~10 m/s to encounter the diverging winds (5km thick at ~10 m/s [9]) in the anvil of a convecting cloud, the trajectory is displaced ~50/V or only ~5 km – i.e. a fast-descending probe will simply punch through the winds without moving far horizontally.

Lander observations of Rainfall : In contrast to a brief descent in the atmosphere, a long-lived surface lander in polar summer has a reasonable expectation of observing rainfall. As an example, the proposed TiME (Titan Mare Explorer) mission would spend 96 days (6 Titan days) on Ligeia Mare in 2023. In addition to detection of rain by in-situ meteorology measurements (P, T, humidity [17] and sound), rainfall might be remotely detectable via passive sonar (on Earth rainfall at sea makes a spectrally-distinctive contribution to the underwater background noise), and by camera observations. Imaging from the surface could observe convecting cloud evolution, rain shafts or even rainbows [18] (and note that in 2023 cloud observations may be possible over the full diurnal cycle - the polar summer sun at Ligeia will vary between +20^o and -6^o elevation – thus it will always be daytime or civil twilight. Ironically, TiME will not see nautical twilight, when the horizon is visible at sea on Earth, is when the sun is at -12^o elevation).

If rain shafts are considered to be ~10km wide[6,9], and are observable at distances of ~20km (the distance dune features were observable from Huygens; illumination and atmospheric opacity are the constraining factors—cloud tops at 40km are in line-of-sight at a distance of some 450km) then the area observable is a circle of ~1200km^2, or ~10x the area of the rain itself. Thus for events that occur ~10 times at a given point in polar summer (50,000hrs), we might expect a 50% chance for a lander to be rained on directly in a 2500hr mission, but that its camera could observe nearby rainfall an expected ~5 times.

The corresponding sampling area for rain being in the line of sight from a lander to Earth or the sun is a thin wedge ~450x10km or ~5x the camera observation area. Thus a rain shaft might be sunwards (and detectable in sun observations) dozens of times in the mission. Because communications with Earth must in any case be at S- or X-band (where the wavelength is several times the raindrop size), the radio cross section of Titan raindrops is quite small [14] and while careful calibration of the radio signal strength may permit an 'occultation' detection of rainfall (though of course communication may take place on only a fraction of the time), the attenuation will not be large and can be accommodated in downlink margins (rain on Earth is a more significant factor and is encountered on all planetary missions – data on Ligeia from Cassini flyby T64 was lost on redundant downlinks due to rain in Madrid on two consecutive days!). Since rain shafts will likely be advected across the line of sight at a few m/s, an occultation would last only 1-3 hours, rather less than a typical DSN pass.

Conclusions: Models and data converge on estimates of the typical recurrence interval and amount of rainfall on Titan. These allow predictions for future Cassini observations and possible future missions.

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