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Observational evidence for active dust storms on Titan at equinox

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Abstract: [230 words]

Saturn's moon Titan has a dense nitrogen-rich atmosphere with methane as its primary volatile. Titan's atmosphere experiences an active chemistry that produces a haze of organic aerosols that settle to the surface and a dynamic climate in which hydrocarbons are cycled between clouds, rain and seas. Titan's displays particularly energetic meteorology at equinox in equatorial regions, including sporadic and large methane storms. In 2009, near Titan's northern spring equinox, the Cassini spacecraft observed three distinctive and short-lived spectral brightenings close to the equator. Here we show from analyses of Cassini spectral data, radiative transfer modelling, and atmospheric simulations that the brightenings originate in the atmosphere and are consistent with formation from dust storms composed of micron-sized solid organic particles mobilized from underlying dune fields. Although the Huygens lander found evidence that dust can be kicked up locally from Titan's surface, our findings suggest that dust can be suspended in Titan's atmosphere at much larger spatial scale. Mobilization of dust and injection into the atmosphere would require dry conditions and unusually strong near-surface winds (about 5 times more than estimated ambient winds). Such strong winds are expected to occur in downbursts during rare equinoctial methane storms - consistent with the timing of the observed brightenings. Our findings imply that Titan – like Earth and Mars – has an active dust cycle, which suggests that Titan's dune fields are actively evolving by aeolian processes.

Main Text: [2725 words]

Along with Earth-based surveys, the close and frequent observations of Titan by the Cassini spacecraft, in orbit around Saturn since July 2004, allowed us to see down to Titan's surface and uncover evidence that the lowest part of its thick atmosphere experiences an exotic meteorological cycle analogous to Earth's hydrological cycle, involving methane evaporation, condensation into clouds[1-5], and rainfall[1,5,6]. Long-term monitoring campaigns have revealed that Titan's cloud coverage varies significantly with latitude and season[1-4]. General Circulation Models (GCMs) have suggested that the observed varying distribution of clouds is a natural consequence of the seasonally changing pattern of global atmospheric circulation[1-4,7-11]. This results in a net transport of methane from the tropics to the poles, drying the equatorial regions[7-11]. Titan's surface bears the marks of such climatic forcing through the presence of extensive and numerous liquid reservoirs and sustained cloud activity near the poles[1-4], and more arid conditions at equator, with intense, but relatively scarce meteorological activity[3-5,12,13] and widespread dune fields[14,15].

Indeed, only a few tropospheric clouds have been observed in Titan's equatorial regions[1-5,12,13]. Very close to spring equinox (August 2009), with a more direct solar illumination of the equatorial regions, clouds occurred near the equator a little more frequently and appeared to grow in size and energy, counting three major events in April 2008, September and October 2010[5,12]. This increase in cloud activity indicates that a very active equinoctial meteorology occurs in the equatorial regions, confirming GCM predictions during this short time interval[8-11]. Here we show new Cassini observations that illustrate the energetic meteorological conditions that prevail near Titan's equator during equinoxes and their possible impact on geomorphic processes.

Infrared equatorial brightenings at equinox

We report here singular and transient changes on Titan in the form of diffuse bright spots of unusual infrared color, that were detected by the Visual and Infrared Mapping Spectrometer (VIMS)[16] onboard Cassini. **Figure 1 and 2** show VIMS images and spectra of the only three events of this kind detected so far. They were observed during Titan flybys T56 (22 May 2009 – Titan solar longitude Ls = 357.9°), T65 (13 January 2010 – Ls = 5.3°) and T70 (21 June 2010 – Ls = 10.7°), all near in time to Titan's northern spring equinox (Ls = 0° by definition) (**Fig. S1a**). These observations revealed an intense and short-lived infrared brightening of large regions usually dark, very close to the equator. These brightenings lasted at least 11 to 14 hours (time during which the brightened areas are visible from Cassini orbit), but no more than 4 to 5 terrestrial weeks (less than three Titan days), since they only appeared in one flyby, except for the T70 event possibly still observable at T71 (7 July 2010). The three bright spots cover large areas, systematically over dune fields (≈420 000 km^2 over Senkyo, ≈250 000 km^2 over Belet and ≈180 000 km^2 over Shangri-La for the T56, T65 and T70 events respectively – **Fig. 1 and S1b**) and present a somewhat elongated shape in the zonal direction. Spectrally, these bright spots are observed only at the center and near-wings of the infrared atmospheric windows, suggesting surface or very low atmospheric features (**Fig. S2**). Their near-infrared (0.88-5.1 µm) spectra all present a pronounced positive slope (**Fig. 2**). They are brighter than the surrounding surface at wavelengths greater than 1.6-µm, particularly at 5-µm, and start dimming below 1.6-µm, fading almost totally at 0.93-µm, thus undetectable with the Imaging Science Subsystem (ISS) cameras onboard Cassini (**Fig. S3**). Note that the affected areas have similar spectra before and after the ephemeral brightening events (**Fig. 2**). The spectral characteristics of these brightenings differ significantly from those of all known examples of surface and atmospheric brightenings, such as tropospheric clouds or deposition of frost onto the surface (**Fig. S3**), which are bright and detectable in all near-infrared windows[2,3,6], revealing a substantial difference in nature (composition and/or altitude) and origin.

Evidence for large storms of organic dust

We investigate different possible explanations for these singular brightening events, considering both surface and atmospheric phenomena.

Given the particularly high brightness of these regions at 5-µm, we first examine the possibility of localized cryovolcanic hot spots. Considering that hypothetic eruptions on Titan are more likely effusive than explosive[17], the sudden apparition of these bright (hot?) spots over extensive areas is however hardly compatible with the slow outpouring and spreading of viscous lava flows. The timescale at which the T56, T65 and T70 events vanish is also difficult to reconcile with the timescale of cryolava cooling back to the average surface temperature of Titan, which has been calculated to be 1 to 2 orders of magnitude longer (≈100 to 1000 terrestrial days depending on the lava composition[18]) than the observed durations. Finally, calculations of the thermal emission of a hot surface (with temperatures ranging from 100 to 250 K) show that no temperature can satisfactorily explain the spectral slope observed between 1.6 and 5-µm for the three events (**Fig. S5**). Lava flows would also induce lasting surface changes, which are not observed.

Surface brightenings could be provoked by methane precipitation and subsequent freezing at the surface[5,6]. Such events have been reported by ISS and VIMS instruments in the wake of the 2010 September giant cloudburst[6] at roughly the same epoch and latitudes as the T56, T60 and T70 events. However, these precipitation-induced brightenings are characterized by an evolution timescale of several terrestrial months and a rise in flux in all atmospheric windows[6] (see an example in **Fig. S3**). None of the T56, T60 and T70 bright spots match those characteristics.

Finally, we explore the possibility that these local rises in brightness may have an atmospheric origin. To that end, we apply a radiative transfer model that simulates the scattering and absorption of sunlight by Titan's atmosphere, producing synthetic spectra for comparison with the observations.

Our radiative transfer model is an updated version of the model presented in detail in (ref. *19* and references therein), using the same atmospheric databases (haze and gases) and a similar methodology to derive haze optical depth and surface albedo (ref. *19* and Supplementary Information). The main novelty concerns the possibility to simulate an additional "cloud" layer composed of spherical particles in the lowest part of the atmosphere. This cloud is characterized by four parameters: top altitude, optical depth, particle effective radius and composition (either liquid methane or tholin-like organics analogous to airborne Titan's haze particles, presumably the main contributor to dune material composition[15, 19-24]).

We first retrieved "before" and "after" surface albedos at the same location as the T56, T65 and T70 bright spots from flybys closely bracketing them in time (see **Fig. 1 and 2**). As the surface is clearly visible in those observations, we perform the radiative transfer calculations without the additional cloud layer. The striking similarity of the "before" and "after" surface albedos at all wavelengths (**Fig. S4**) tells us that the brightening events have not substantially changed the properties of the surface.

These surface albedos were then used as inputs to model the "event" spectra extracted from the central and brightest pixel of the T56, T65 and T70 bright spots (**Fig. 2**). The "surface-only” model was unable to reproduce any of the event spectra, especially the high reflectance above 1.6-µm (**Fig. 3**). No enhancement in the local population of fractal aerosols or low altitude mist, both too dark in the infrared[19,25], especially at wavelengths greater than 2-µm[19], can better explain the observed spectra. We therefore searched for the best fits between observed and simulated spectra by adding a low altitude cloud, for various opacities, particle sizes, top altitudes and compositions. The inversions have been performed by using a **combination of Genetic and** Levenberg-Marquardt algorithm**s** (Supplementary Information).

In all cases, the best fits to the observed spectra over the full VIMS infrared range are provided by the addition of a cloud of solid organic particles. Those tholin-like clouds are found to be optically thin, with opacity ~0.5, composed of small particles (~5 microns in diameter), and confined at low altitude, with a maximum top altitude of ~10-14 km (**Fig. 3 and Table S5**).

We cannot completely exclude liquid methane clouds, despite systematic poorer fits, on the sole basis of fitting statistics (**Fig. 3 and Table S5**). However, the best retrieved parameters for methane clouds all point to unusually low top altitudes (10-13 km) and small droplet size (~5 microns), casting some doubts on the possibility of their physical existence. Cloud simulations using the TRAMS model[26,27] were therefore conducted at the time and location of the observed brightenings, in order to further investigate both methane convective and stratiform clouds as **possible** explanations. The details and results of the **cloud** model**l**ing studies are thoroughly discussed in the Supplementary Information. The radiative transfer modeling found that methane clouds, if real, should be restricted to altitudes below ≈13 km and probably lower (**Fig. 3 and Table S5**). At the season and location where the brightenings are observed, thermodynamics **suggest** that any methane clouds with a base below this level would be necessarily convective in nature and would extend to much greater altitudes. Depending on the relative humidity of Titan’s surface, the top altitude of such a convective cloud would reach at minimum 25 km. Moreover, we also calculated the microphysical properties (droplet size distribution and number density) of such clouds with the TRAMS model, still under the temperature and wind conditions at the equator and for the spring equinox, and it turns out that they are also completely inconsistent with the radiative transfer retrievals by several orders of magnitude**. TRAMS simulations lead indeed** to significantly optically thicker clouds than those possibly observed with VIMS **and considered in this study**. On their side, stratiform clouds below ≈13 km are not physically possible given the thermodynamic sounding. Stratiform clouds above 13 km may be possible, but they would be shallow and also inconsistent with the physical properties of the retrieved clouds. For all these reasons, methane clouds, either convective or stratiform, as retrieved by the radiative transfer mode**l**ling, are simply unphysical and must be rejected.

Gathering together all of the observations, including locations, directly above giant sand seas, timing, close to spring equinox when the strongest winds are expected to episodically blow, spectral characteristics, pointing to solid organics equivalent to the material constituting the dunes, and cloud dynamics, we conclude that the best, and only remaining explanation for these three bright spots **may be** short-lived dust storms composed of fine organic particles, smaller than sand-sized particles, lifted from the underlying dune fields.

Implication for equatorial near-surface winds at equinoxes

At local scale, it has already been demonstrated not only that dust **is likely to** exist on the surface of Titan, but also that winds less than 5 m/s **may** lift it: the penetrometer of the Huygens probe which landed near Titan's equator in 2005 indicated an uppermost thin (few mm) layer of soft/low-density material[28], and optical measurements showed dust around the probe for 2-4 seconds after impact[29]. This dust was **most possibly** lifted by the turbulent aerodynamic wake of the probe[29,30], which landed at 5.4 m/s. In our case, the **possibility for** large scale storms of dust has more significant implications for the atmospheric dynamics and sedimentology of the moon.

In order to investigate the possible onset of dust storms on Titan, we adapted models of sediment transport that were initially developed for Earth, Mars and Venus[31-33] to Titan's near-surface conditions. These models, based on semi-empirical or analytical calculations, allow us to predict the minimum friction velocity needed to initiate and sustain sediment transport (**Fig. 4** and Supplementary Information).

Dust can be emitted through three primary processes[34]: (i) direct aerodynamic lifting, (ii) indirect ejection from the surface by impacts of saltating sand particles, or (iii) lifting of sand-sized aggregates of dust particles that fragment upon impact on the surface. Our radiative transfer modelling points to particles in suspension with a diameter of ~5 microns. Aerodynamic lifting of such small particles, that experience large cohesive forces, requires a minimum friction velocity as high as 0.1 to 0.5 m/s (**Fig. 3**). Using the classical Karman's logarithmic wind velocity profile with a rugosity length of 5 mm, those friction velocities correspond to a wind blowing at ~2.5 to 11 m/s at 40 m altitude. Dust emission through saltation of sand particles (with an optimal size of 300 microns) would have a lower threshold friction velocity for lifting (~0.06 m/s) than that for dust (**Fig. 3**), requiring wind speed of ~1.4 m/s at 40 m altitude. However, compared to Earth and Mars, the lower gravity and higher fluid density on Titan substantially reduces the energy with which saltating particles impact the surface[34]. This implies that dust emission through saltator bombardment **may be** less efficient than it is on Earth and Mars (**Fig. S10**). Dust could also be emitted through the formation[35], lifting and fragmentation at impact of sand-sized aggregates of dust. Owing to their lower density, **such aggregates could present a threshold for lifting slightly below 1.4 m/s and be** more easily lifted than dust and sand particles[34]. Dust emission through this process would not necessarily involve active sand transport, an effect that has been observed directly on Mars[36]. In any case, micron-sized dust emission is systematically accompanied by the mobilization of larger particles, more easily unstuck from surface (**Fig. 4**). **Since** larger particles have higher fall velocity and will settle down rapidly, **they generally stay** confined close to the surface, while smaller particles can rise to higher altitudes and remain suspended for much longer time, generating the observed dust cloud. This is what can be observed on terrestrial and **M**artian dust storms and this can explain why the dust clouds we report here are dominated by the infrared signature of micron-sized particles.

Regardless of the process, dust injection into the atmosphere requires near-surface winds much stronger than the ambient averaged winds predicted to blow during equinoxes (maximum of ~0.3 m/s at 40 m altitude (e.g. ref *10*)). Only gusts, either appearing when considering wind statistics at high temporal frequency (i.e. capturing the turbulence associated with the equinoctial passage of the intertropical convergence zone[37]) or produced ahead of rare, but large methane storms, as simulated in mesoscale methane cloud models[38,39], can exceed 1 m/s at 40 m altitude and even reach 10 m/s for a few hours for the methane storms[38,39]. In both cases, gusts have the highest probability to occur during equinox in the equatorial regions, precisely when and where we **possibly** observe the dust storms. A few large equatorial storms have been observed very close to the equinox[5,12] (**Fig. S1a**). The most energetic of these **may** constitute the best, and timely, candidates for generating surface winds strong enough to inject organic dust into Titan's air (this mechanism would thus be analogous to Earth's "haboobs"). Their uncommonness **may** further explain the rareness of dust storm detections by Cassini. Such equatorial storms are also thought to sustain active sediment transport over the dunes and control their growth and orientation[38].

No equatorial methane storms have been yet detected preceding closely any of the T56, T65 and T70 events. But given the frequency of Cassini flybys of Titan (one per month in average) and the relative short living of methane storms (only a few to a few tens of hours), it is quite likely that those precursors have been missed and that we were only able to see the succeeding, and more persistent, dust cloud. In a same manner, no dust storms have been seen by Cassini after the gigantic methane storms observed in Titan’s equatorial regions in October 2010 (ref. *5*), but the fact that Cassini flew back by Titan only four months later may explain that, in that case, no dust storm could have been triggered or that we may have missed this event, if any.

The requirement of strong near-surface winds implies that dust lifting can be accompanied by saltation of the underlying dune sand. This constitutes additional clues for sand-saltating winds within currently active dune fields. This may only occur at equinoxes, every 14.7 terrestrial years. Besides the Earth and Mars, Titan would thus be the only other body in the Solar System where dust storms and aeolian activity over dune fields have been observed, indicating the complexity of the atmospheric dynamics and atmosphere-surface interactions at play on Saturn’s largest moon. The dust storms may also indicate an ongoing participation for dust within Titan's global organic cycle[35].

Data sources. VIMS data are available via NASA's Planetary Data System (PDS): http://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/Cassini/vims.html.

Data availability. The data that supports the analysis and plots within this paper and other findings of this study are available from the corresponding author upon request.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions S.R., S.L.M., J.W.B., J.B and G.V. discovered the brightening spots in the VIMS dataset and first emitted the dust storm hypothesis. S.R., T.A., M.H., L.M., P.R., C.A.G. and A.C. developed, adapted, ran the radiative transfer model and designed the inversion scheme including a low atmospheric layer of suspended particles. B.C., J.F.K., R.D.L., J.R., C.N. and S.C.P. helped with the wind and sediment transport calculations. J.F.K., C.N., T.C., O.B., and A.L. participated to the discussion of the geological implications of dust storms occurrence in Titan's atmosphere. C.S., R.H.B., K.H.B., B.J.B., R.N.C. and P.D.N. designed the planning of VIMS observations. S.R. drafted the manuscript with contributions from all authors.

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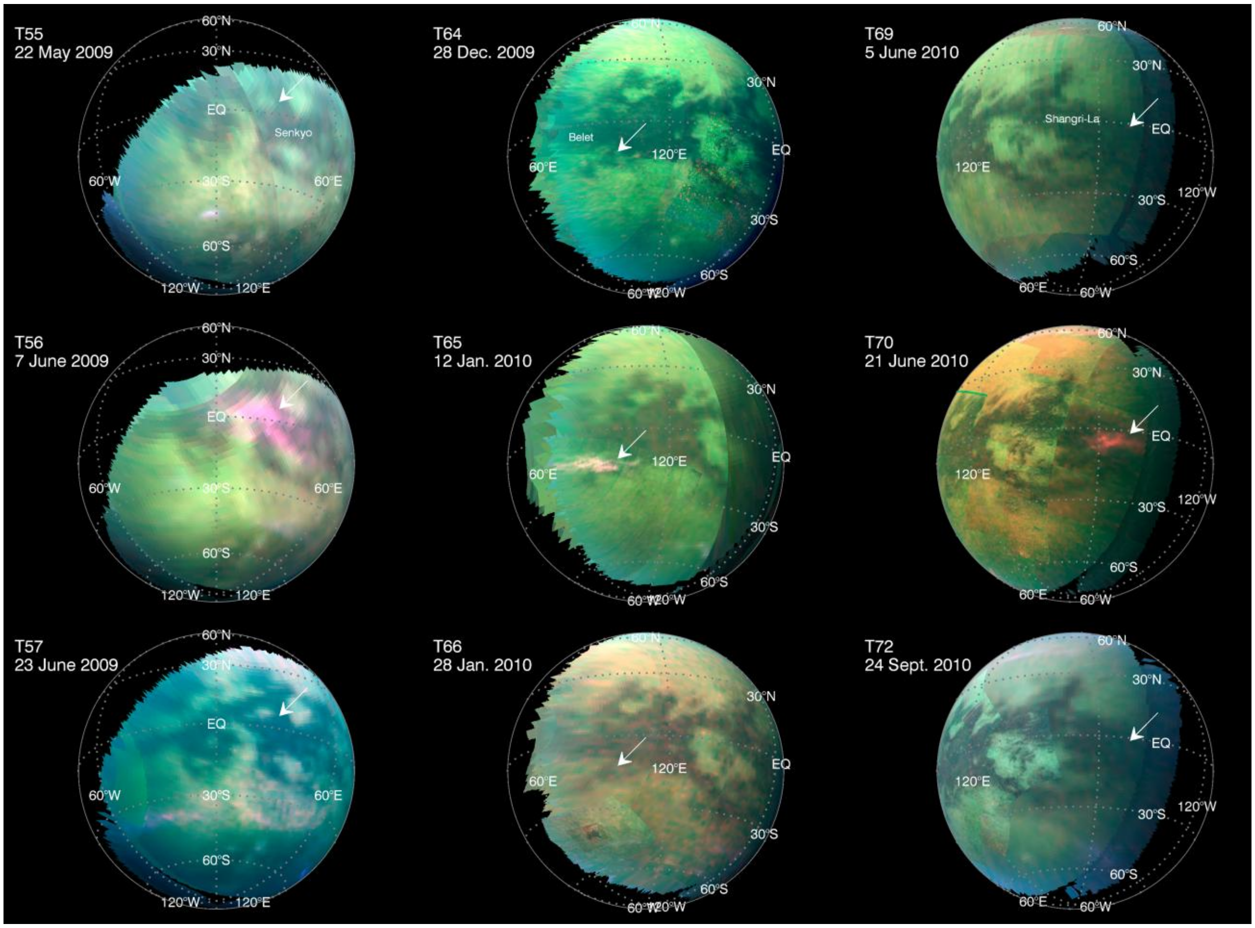

Fig. 1. VIMS color composite maps of Titan's singular brightening events that occurred in June 2009 (T56 flyby), January 2010 (T65) and June 2010 (T70). Each column presents a time series showing VIMS Titan images (using the same RGB coding, red being the average between 5 and 5.07-µm, green being 2-µm and blue one being 2.78-µm) acquired over the same area just before (top), during (middle) and immediately after the brightening (bottom) for each individual event. White arrows designate the location of the infrared brightenings, centered at ~24°E and ~2°S (T56), ~96°E and ~14°S (T65), and ~175°W and ~5°S (T70) and covering a large fraction of the Senkyo, Belet and Shangri-La sand seas respectively (see also **Fig. S1b**).

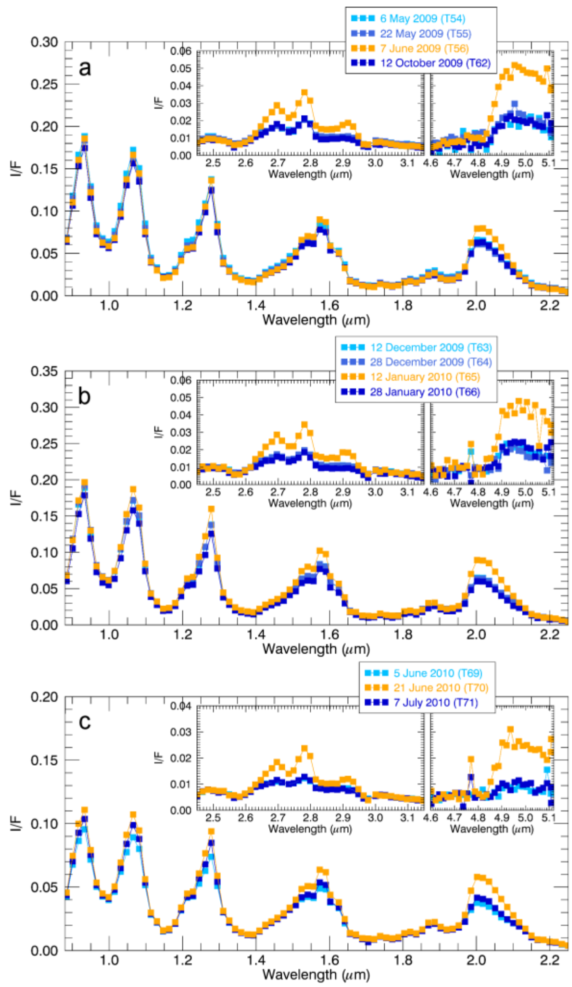

Fig. 2. VIMS infrared spectra of the brightening events that occurred at T56, T65 and T70 flybys. (a) The gold squares represent the infrared spectrum extracted from the brightest pixel in the central region of the brightening regions shown in **Fig. 1** for T56. This spectrum is compared with those extracted from the same location from flybys as close in time as possible, before and after the brightening event (blue tone squares). Same for T65 **(b)** and T70 **(c)**.

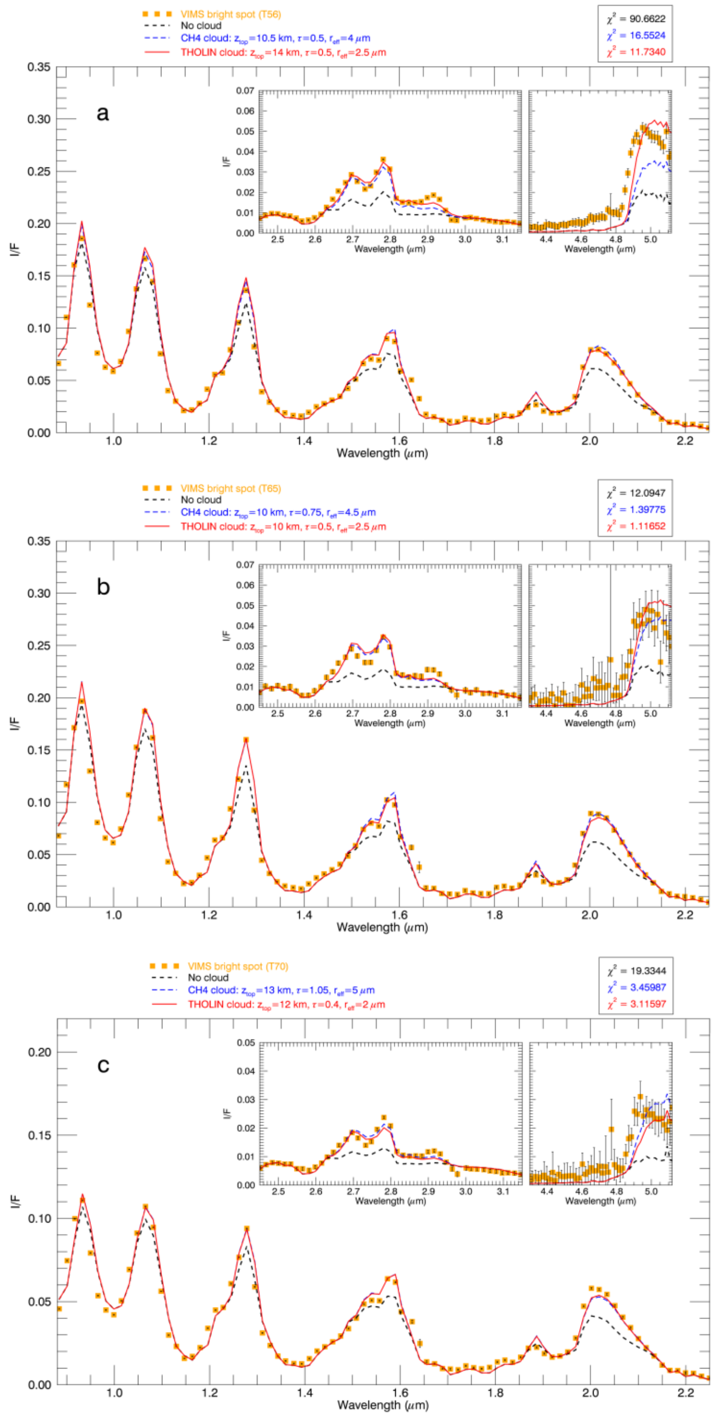

Fig. 3. Observed spectra of the brightest pixels of the T56 (a), T65 (b) and T70 (c) bright spots are compared with best-match calculated spectra. The observed infrared spectra are shown in yellow squares (identical to the yellow spectra shown in **Fig. 2**), along with their 1σ error bars calculated from the VIMS signal-to-noise ratio. We modelled spectra with no cloud

contribution (black dashed curves), with no satisfactory agreement with the observations. In all cases, the addition of a low altitude cloud composed of solid organic particles (red curves) provides the best fits over the full VIMS wavelength range. Despite systematic poorer fits, best fits for liquid methane clouds are also shown (blue dashed curves). Reduced χ^2 are indicated for the "surface-only", liquid methane and solid organic cloud models, along with the best retrieved parameters for the two kinds of clouds (**Table S5**).

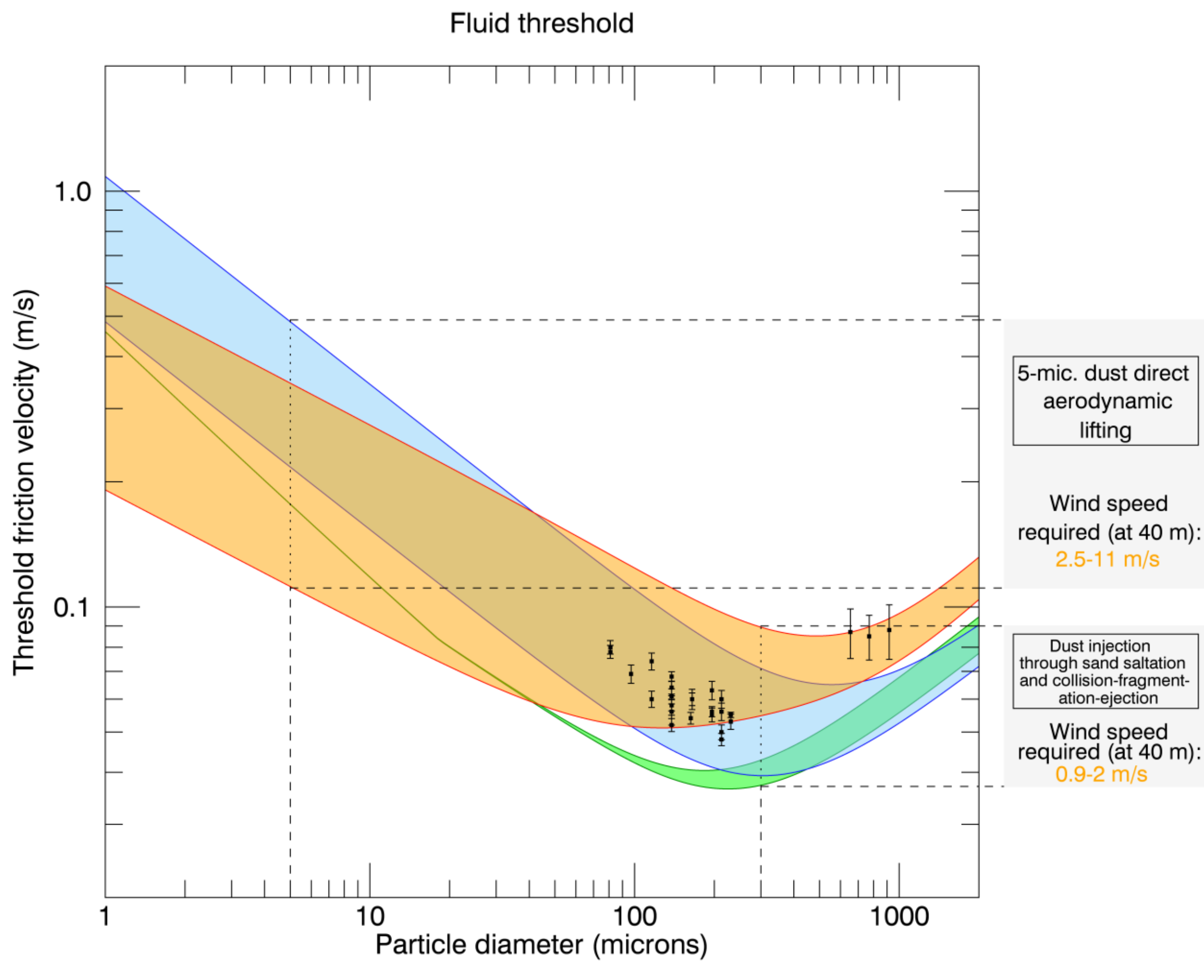

Fig. 4. Transport thresholds on Titan. Intervals of friction velocity at the fluid threshold computed from formulae given in ref. (*31*) (green area), ref. (*32*) (blue area) and ref. (*33*) (orange area) for a range of possible mass densities (800-1200 kg.m^{-3}) and interparticle forces (γ = 1-5.10^{-4} N/m) for Titan's surface material[32] (see **Table S6**). The calculated threshold curves are in very good agreement with recent wind-tunnel measurements under Titan's atmospheric and sedimentary conditions[40] (black squares with error bars). Range of needed near-surface wind speeds are given for 5-microns dust direct aerodynamic lifting and dust injection through saltation and collision-fragmentation-ejection processes respectively.