1 Details of Titan Cloud Observations

Increased cloud activity on Titan was first observed in IRTF data from April 13, 2008 UT but could have begun as early as April 9, 2008 UT. After detecting cloud activity with the IRTF, we subsequently observed Titan with the Gemini North Telescope using the facility's near-infrared camera with the the natural guide star adaptive optics system. Table 1 provides details of the brightnesses and extents of clouds in the Gemini images. Fractional brightness is defined as the increase in brightness in the H2 (1–0) filter (2.11 microns) compared with cloud-free observations. The brightest clouds occurred on April 14 and April 28, when Titan's flux at 2.11 microns increased by 7 and 9 percent, respectively (Supplementary Table 1). In contrast, observations taken on over one hundred nights from 2005-2008 showed fractional brightness variations of less than 0.5%[7, 25].

Large, short-lived cloud outbursts on Titan have been observed on two previous occasions (1995[22] and 2004[23]). The maximum areal coverages of the clouds on Titan's disk were comparable in all three events ($\sim$10%), but the maximum cloud brightnesses of the 2008 event were at least a factor of 2 lower than the previous large cloud events. Comparing the K-band IRTF spectra from the 2008 event with the UKIRT spectra from the 1995 event[22], we find that the wavelengths at which both spectra deviate from cloud-free nights are comparable ($\sim$2.17 microns). However,

Table 1. Titan Cloud Details

Date	Cloud Latitude	Fractional brightness	Extent (10^6 km^2)
2008-Apr-14	-29	0.070	2.4
2008-Apr-15	-27	0.060	3.6
	-58	0.003	0.6
2008-Apr-16	-25	0.009	1.0
	-72	0.009	0.9
2008-Apr-17	-63	0.003	1.0
2008-Apr-18	-19	0.004	0.3
2008-Apr-20	-17	0.007	0.9
	-64	0.002	0.4
2008-Apr-21	-70	0.018	2.2
2008-Apr-22	-72	0.015	2.0
2008-Apr-24	-41	0.003	0.6
2008-Apr-25	-36	0.007	1.1
2008-Apr-28	-15	0.002	0.2
	-25	0.046	0.8
	-36	0.045	1.6
2008-May-01	-15	0.001	0.2
	-68	0.007	1.3
2008-May-02	-72	0.005	0.7
2008-May-08	-16	0.004	0.9

precise comparison of the spectra from these two events is hindered by the fact that the latitudes of the 1995 clouds are unknown.

2 Rossby waves on Titan

The dispersion relation of Rossby waves on a mean zonal flow with velocity U that varies slowly with latitude is

$$\omega = Uk - k\frac{\beta + Uk_d^2}{k^2 + l^2 + k_d^2}. \tag{S1}$$

Here, ω is the wave frequency, k and l are the zonal and meridional wavenumbers, k_d is the deformation wavenumber, and $\beta = 2\Omega\cos(\phi_0)/a$ is the planetary vorticity gradient, with planetary angular velocity Ω and planetary radius a (e.g., ref. 30). For simplicity, we have assumed the flow domain to be vertically homogeneous (because detailed information about the thermal structure of Titan's troposphere is not available). We have also made the β-plane approximation of considering motion on a plane tangent to the planet at latitude ϕ_0, though what follows remains approximately valid when full spherical geometry is retained[31].

To estimate the deformation wavenumber k_d in Titan's troposphere, we take the Brunt-Väisälä frequency $N \sim 3 \times 10^{-3}\,\mathrm{s}^{-1}$ inferred from Voyager radio-occultation and IRIS measurements[32,33] as representative of the troposphere. For the (baroclinic) deformation radius $L_d = NH/f$, with Coriolis parameter $f = 2\Omega\sin(\phi_0)$ and scale height $H = 20\,\mathrm{km}$, this gives $L_d \sim 9300\,\mathrm{km}$ at $\phi_0 = 45°$ latitude. The external (barotropic) deformation radius $L_d = \sqrt{gH}/f$ is an order of magnitude larger. Therefore, the midlatitude deformation radius is at least a factor ~ 4 larger than the planetary radius ($a = 2575\,\mathrm{km}$), and we can neglect the deformation wavenumber $k_d = 1/L_d$ compared with the effective horizontal wavenumber $(k^2 + l^2)^{1/2}$.

Moreover, if we take the mid-tropospheric zonal wind $U \sim 3\,\mathrm{m\,s^{-1}}$ inferred from the descent of the Huygens probe into Titan's low-latitude troposphere[34,35] as representative of the troposphere as a whole, the term $Uk_d^2 \sim 4 \times 10^{-14}\,\mathrm{m^{-1}\,s^{-1}}$ is more than an order of magnitude smaller than $\beta = 2.5 \times 10^{-12}\,\mathrm{m^{-1}s^{-1}}$ at $\phi_0 = 45°$ latitude. Hence, we neglect effects of a finite deformation radius and set $k_d \approx 0$. This amounts to considering barotropic (deep) Rossby waves, with dispersion relation

$$\omega \approx Uk - \frac{\beta k}{k^2 + l^2}. \tag{S2}$$

Assuming the mean flow to be slowly varying with latitude means that we neglect the modification of the absolute vorticity gradient by the meridional curvature of the mean flow. If the mean zonal flow in Titan's troposphere varies on the planetary scale, this modification is of order $U/a^2 \sim 5 \times 10^{-13}\,\mathrm{m\,s^{-1}}$, which is a factor ~ 5 smaller than β (that is, the Rossby number of the mean flow is ~ 0.2); hence, the modification is likely small (though how precisely the zonal flow on Titan varies with latitude is unknown).

The zonal and meridional group velocities implied by the dispersion relation (S2) are

$$u_g = \partial_k \omega \approx \frac{\omega}{k} + \frac{2\beta k^2}{(k^2 + l^2)^2}, \tag{S3}$$

$$v_g = \partial_l \omega \approx \frac{2\beta k l}{(k^2 + l^2)^2}. \tag{S4}$$

We assume that Rossby waves on Titan are excited by a stationary source, so that they are stationary themselves ($\omega = 0$). In this case, the dispersion relation (S2) implies that their effective horizontal wavenumber is the stationary Rossby wavenumber

$$K_s = (k^2 + l^2)^{1/2} = (\beta/U)^{1/2}. \tag{S5}$$

As the waves propagate meridionally into regions of different mean zonal flow U and different β, the meridional wavenumber adjusts so that $l^2 = K_s^2 - k^2$ (ref. 31). Substituting for the meridional wavenumber in the group velocities (S3) gives the group velocities of stationary Rossby waves

$$u_{gs} \approx \frac{2\beta k^2}{K_s^4}, \tag{S6}$$

$$v_{gs} \approx \pm\frac{2\beta k(K_s^2 - k^2)^{1/2}}{K_s^4}. \tag{S7}$$

For small wavenumbers $k < K_s$, the waves can propagate meridionally; for large wavenumbers $k \geq K_s$, the waves are trapped near their source latitude.

The cloud features we observe appear to originate at $\sim 15°$S latitude and propagate with a meridional velocity of 3–$8\,\mathrm{m\,s^{-1}}$. At $15°$S and assuming $U \sim 3\,\mathrm{m\,s^{-1}}$ as before, the nondimensional stationary Rossby wavenumber is $K_s a \approx 2.8$. Thus, long waves with wavenumbers $k \lesssim 3$ can be expected to be able to propagate meridionally from a low-latitude generation region, whereas shorter waves will be trapped near the generation region. At $15°$S, waves with zonal wavenumber $k \approx 2$ have an eastward zonal group velocity $u_{gs} \approx 3.9\,\mathrm{m\,s^{-1}}$ and a similar meridional group velocity $v_{gs} \approx \pm 3.3\,\mathrm{m\,s^{-1}}$, both roughly consistent with the observed propagation of the cloud features. The meridional group velocity will vary gradually with latitude as β and U vary, but the observed propagation of the cloud features appears to be consistent, at least in an order-of-magnitude sense, with the propagation of planetary Rossby waves.

Mean meridional winds in Titan's troposphere inferred from the Huygens descent and from Titan models[34,35] are at least an order of magnitude smaller than the observed meridional propagation velocity of the cloud features, so advection of the cloud features by mean circulations can be ruled out. (Mean meridional circulations occur on timescales comparable to radiative timescales; hence, they cannot advect cloud features on timescales of Earth days from Titan's tropics into high latitudes.) Other waves that may propagate meridionally are not consistent with the observations. For example, the internal gravity wave speed $NH \sim 60\,\mathrm{m\,s^{-1}}$ is about an order of magnitude faster than the propagation speed we observe, external gravity waves would be even faster, and tidal waves appear to be associated only with weak meridional winds in the troposphere[37]. Planetary Rossby waves offer the most likely mechanism for how the cloud features we observe propagate meridionally. Similar poleward propagation of planetary Rossby waves generated in low latitudes occurs in Earth's troposphere[31, 38].

Supplementary References

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