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Global circulation as the main source of cloud activity on Titan

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21 **Clouds on Titan result from the condensation of methane and ethane and, as on other planets,**
22 **are primarily structured by the atmosphere circulation¹⁻⁴. At present time, cloud activity mainly**
23 **occurs in the south (summer) hemisphere, arising near the pole⁵⁻¹² and at mid-latitudes^{7,8,13-15}**
24 **from cumulus updrafts triggered by surface heating and/or local methane sources, and at the**
25 **north (winter) pole^{16,17}, resulting from the subsidence and condensation of ethane-rich air into**
26 **the colder troposphere. General Circulation Models¹⁻³ predict that this distribution should seaso-**
27 **nally change moving from an hemisphere to another on a 15-year timescale, and that clouds**
28 **should develop under certain circumstances at temperate latitudes ($\sim 40^\circ$) in the winter hemi-**
29 **sphere². The models, however, have hitherto been poorly constrained and their long-term predic-**
30 **tions have not been observationally verified yet. Here we report that the global spatial cloud cov-**
31 **erage on Titan is in general agreement with the models, confirming that cloud activity is mainly**
32 **controlled by the global circulation. The non-detection of clouds at $\sim 40^\circ$ N latitude and the persis-**
33 **tence of the southern clouds while the southern summer is ending are, however, both in contra-**
34 **dition with models predictions. This suggests that Titan's equator-to-pole thermal contrast is**
35 **overestimated in the models and that Titan's atmosphere responds to the seasonal forcing with a**
36 **greater inertia than expected.**

37
38 The Visual and Infrared Mapping Spectrometer¹⁸ (VIMS) onboard Cassini provides a unique oppor-
39 tunity to regularly and accurately chart cloud activity from a close vantage point, hence with high spa-
40 tial resolution and good spectral coverage. We developed a semi-automated algorithm to isolate clouds
41 from other contributions in VIMS images (cf. Fig. 1) and applied it to 10,000 images of Titan. These
42 images encompass several millions of spectra, acquired during 39 monthly flybys of Titan between Ju-
43 ly 2004 and December 2007.

45 The total distribution of cloud events derived from our detections (Fig. 2) and the time variation of
46 their latitudinal distribution (Fig. 3a) indicates that cloud activity is clustered at three distinct latitudes
47 during the 2004-2007 period: the south polar region (poleward of 60°S), the north polar region (pole-
48 ward of 50°N), and a narrow belt centered at ~40°S. Individual detection maps are provided for each
49 flyby in the online supplementary information materials (Fig. S1 to S4).

50

51 Our study clearly shows the stability of the north polar cloud, which is systematically detected over
52 the 2004-2007 period. We observe this extensive meteorological system poleward of 50-60°N. All of
53 these clouds spectrally differ from the southern clouds, which are presumably formed by wet convec-
54 tion and made of large, tens of microns in size, liquid/solid methane droplets^{2,16}. They produce much
55 less signal at 5- μ m than any other cloudy features we detect elsewhere on Titan, indicating a lower
56 backscattering at 5- μ m. Given that complex indices of refraction of methane and ethane are not that
57 different at this wavelength, the difference in backscattering comes essentially from the particle size. A
58 relative lower backscattering at 5- μ m is consistent with north polar clouds composed of smaller, mi-
59 cron-sized, particles more probably made of solid ethane^{2,16,17}. We also detect small elongated clouds at
60 ~60-70°N in March and April 2007. Surrounded by the large north polar ethane cloud, these clouds are
61 thought to be convective methane clouds connected to the underlying lakes¹⁹. Their higher brightness
62 at 5- μ m confirms that they are similar to the methane clouds found in the southern hemisphere.

63

64 A few tropical clouds, thought to be rare during Titan's summer, are detected close to the equator
65 (~15°S) on 12 December 2006. Their areas never exceed 10,000 km². These clouds were therefore un-
66 detectable from ground-based observations. More details about tropical clouds are given in ref. (20).
67 We also observe more than one hundred isolated and transient temperate clouds near 40°S (Fig. 2 and
68 3a). Most of them are elongated in the east-west direction, as was previously reported^{7,8,13-15}, possibly
69 due to orographic waves over zonally oriented topography and/or shearing and stretching by strong

70 zonal winds of tens of meter per second⁷. This type of clouds appeared during two periods, in 2004 and
71 then regularly (on the two-thirds of the flybys) between July 2006 and October 2007. Between Decem-
72 ber 2004 and August 2006, temperate clouds have been observed very rarely (only in October 2005
73 (ref. 10) and January 2006 (this study)). This could be attributed to the combination of less frequent
74 Titan's flybys by Cassini and/or a momentary decline in cloud activity.

75

76 Our latitudinal and time distribution of clouds (Fig.3a) is compared with predictions of the atmos-
77 pheric Global Circulation Model from ref. (2) (IPSL-TGCM) which is, up to date, the only one to in-
78 clude a microphysical cloud scheme and thus predict the cloud cover (see Fig. 3b). Except for the lack
79 of winter mid-latitude clouds (40°N), we find that the main spatial characteristics of our cloud distribu-
80 tion are well reproduced by the IPSL-TGCM. Clouds appear in the model near 12 km altitude around
81 40° in the summer hemisphere (the southern hemisphere until 2009), associated to the ascending mo-
82 tion of the convergence zone of a Hadley-type cell¹⁻³. Clouds are also predicted very near the summer
83 pole (actual southern) where methane, driven from the warmer region below, condenses generating
84 convective structures^{2,21-23}. In the winter polar region, the cloud formation is related to the downwel-
85 ling stratospheric circulation, which drives an ethane and aerosol enriched stratospheric air into the
86 cold tropopause of the polar night (above 40 km). The observed stability of the north polar clouds is
87 interpreted, with the IPSL-TGCM, as the result of a constant incoming flux of ethane and aerosols from
88 the stratosphere²⁴, producing a mist of micron-sized droplets of ethane and other products which slowly
89 settles. However, present observations do not confirm the ~40°N clouds predicted by the IPSL-TGCM.
90 In the model, these clouds should result from the horizontal diffusive transport by inertial instabilities
91 of air, partially humid (RH=50%) in tropical regions, toward the colder north pole. At the altitude 12
92 km, where these clouds are formed, the model predicts $T_{80^{\circ}\text{N}} - T_{0^{\circ}} = -4\text{K}$. Such a contrast makes the air
93 to become saturated and to produce clouds around 40°N. The lack of such clouds in observations could
94 be explained by an actual equator to pole temperature contrast $T_{80^{\circ}\text{N}} - T_{0^{\circ}}$ of about -1.5K instead of the -

95 4K as predicted by the IPSL-TGCM. Such a small thermal contrast would allow air parcels with
96 RH=50% in tropical regions to move toward the pole without condensing. Conversely, it could also
97 enable the north polar region (where lakes are observed), saturated in methane, to wet the tropical re-
98 gions up to 50% humidity. If we consider the conditions at the surface, computations, including phase
99 equilibrium with N₂-CH₄ mixture, show that with an equator-to-pole contrast near the ground of -4.2K
100 (instead of -6.5K in the IPSL-TGCM), an air parcel at methane saturation near the pole (fed by lakes)
101 would be at 50% humidity if transported at tropics. Only 80% humidity would be needed at the north
102 pole if the temperature contrast at surface drops to -3 K, which is actually observed²⁵.

103

104 By contrast, the timing of the summer-hemisphere clouds as constrained by our observations is
105 poorly reproduced by the IPSL-TGCM. Fig. 3b shows that the southern cloud activity should gradually
106 decrease as the equinox approaches, as a consequence of a progressive change in the south polar circu-
107 lation pattern. This forecasted decline of southern meteorological activity is not supported by our data.
108 According to the IPSL-TGCM, the south polar clouds should have disappeared in mid-2005 and the
109 mid-latitudes clouds should have progressively faded out since 2005, whereas in our observations the
110 southern clouds are still present even late in 2007 and are particularly active at 40°S until mid-2007.
111 The significant latency to the predicted disappearance of summer clouds suggests that the response of
112 Titan's atmosphere to seasonal forcing presents certainly a greater inertia than expected. Yet, since
113 August 2007, south polar clouds' occurrences seemed to be less frequent in our data and the mid-
114 latitude clouds seemed to be scarcer. These very subtle declining trends may indicate that we are wit-
115 nessing the forthcoming seasonal circulation turnover as we approach the equinox, but with a different
116 timing pattern than forecasted by the IPSL-TGCM.

117

118 Fig. 4 shows that, between July 2004 and December 2007, the mid-latitude clouds are not uniformly
119 distributed in longitude, as already noticed during previous ground-based observations¹⁴ (December

120 2003-February 2005). The clouds' propensity for 0° longitude found in 2003-2005 was attributed to
121 localized geological forcings from the surface possibly related to an active cryovolcanic province¹⁴.
122 Yet, three years later, our distribution differs markedly, showing more structures (Fig. 4c). Contrary to
123 ref. (14), we observe mid-latitudes clouds at almost all longitudes with an excess at longitudes (from
124 60°E to 180°E corresponding to the leading hemisphere of Titan) where ref. (14) detected none. The
125 strong clouds' density peak, along with the secondary bump, both reported by ref. (14) have drifted
126 eastward by 30° with an estimated rate of $\sim 10^\circ$ by terrestrial year. In addition, we found two troughs at
127 longitudes facing Saturn (0°) and anti-Saturn (180°). Though the strong link of the clouds to the lati-
128 tude indicates that global circulation plays a major role in their formation¹⁻³, the wavy pattern of our
129 clouds' distribution suggests a secondary forcing mechanism. The 30° longitude shift in the cloud dis-
130 tribution between the periods 2003-2004 (ref. 14) and 2005-2007 (this study), as well as the loose cor-
131 relation of clouds with surface location, exclude surface geological activity as the primary triggering
132 mechanism. Both the drift in longitude and the discovery of two diametrically opposite minima rather
133 favour processes taking place in Titan's atmosphere, that we attribute to external forcing by Saturn's
134 tides. Saturn's tides are predicted to generate tidal winds in Titan's dense atmosphere, particularly sig-
135 nificant in the troposphere²⁶ at altitudes where temperate clouds are found to develop^{2,3,13-15}. These
136 winds manifest themselves as eastward travelling planetary-scale waves of degree-two and change
137 east-west direction periodically through the tidally locked orbit of Titan²⁶. In consequence, tidally-
138 induced winds periodically modify the convergence of air masses, mostly at two preferential longitudes
139 180° apart, potentially resulting in perturbations to cloud formations²⁶.

140 The extension of the Cassini mission possibly up to the summer solstice in 2017 and the
141 continuation of ground-based observations will feed the GCMs with further observational constraints.
142 The refined GCMs will provide a better knowledge of the global atmospheric circulation, which is
143 crucial for understanding the carbon-cycle on Titan.

144

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197

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

199

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205

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207 thors declare no competing financial interests. Correspondence and requests for materials should be addressed to S.R. (se-
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209

210

211

212 **Figure captions:**

213 **Figure 1: Method of spectral detection of Titan's clouds illustrated on a representative VIMS data**
214 **cube.** The VIMS onboard Cassini acquires a 352-channels spectrum from 0.3 to 5.1 μm for each pixel
215 of an image¹⁸. **(a)** shows a scatter plot of the 2.75 μm window integrated area versus the 5 μm window
216 integrated area of the VIMS color-image shown in **(b)** with Red=2.03- μm , Green=2.78- μm , Blue=5-
217 μm . The integrated window areas correspond to the integral of I/F within the spectral range shown in
218 gray in spectra. **(c)** and **(d)** correspond to the 2.75- μm and 5- μm integrated window area images re-
219 spectively, coded in grayscale (high values appear in bright). Characteristic spectra are inseted within

220 (a), showing clouds (red), limb (violet), typical surface (cyan) and a high 5- μm signal surface feature
 221 (Tui Regio²⁷) in green. "Surface" windows correspond to peaks at 1.27, 1.59, 2.03, 2.75 and 5 μm . Be-
 222 cause clouds are efficient reflectors and reduce the path-length of solar photons, their spectra present a
 223 brightening of all "surface" windows relative to other spectra. We found that the most robust spectral
 224 criterion to separate clouds' pixels from other contributions (surface and limb) is the simultaneous in-
 225 creased integrated areas of the 2.75- μm and 5- μm windows. Conservative, two-sigma thresholds on the
 226 integrated areas of these two windows are automatically calculated in order to isolate pixels corres-
 227 ponding to clouds (red triangles in (a)). We deliberately choose a conservative threshold to avoid false
 228 positives. This can lead to the rare non-detection of optically thin or low-altitude clouds, of clouds
 229 much smaller than a VIMS pixel, or of clouds that are too close to the limb. (e) shows the resulting
 230 cloud pixels detection (in red) which are then reprojected on a global map (see Fig. 2).

231

232 **Figure 2: Maps of Titan's clouds derived from VIMS observations from July 2004 to December**
 233 **2007.** Our detections are presented in cylindrical (top) and polar orthographic (bottom) projections.
 234 The colors of the clouds correspond to the date of each cloud observation. A VIMS grayscale mosaic of
 235 Titan's surface (adapted from RGB color composite global mosaics in ref. (28)) is used as background.
 236 Clouds are found to be distributed in three clustered regions: the two poles and the southern temperate
 237 latitudes. Only very few occurrences of clouds are found in equatorial regions. One cloud event is
 238 found on December 2005 just above a particularly interesting terrain thought to be of cryovolcanic ori-
 239 gin (Tui Regio²⁷) and may witness possible recent cryovolcanic activity.

240

241 **Figure 3: Latitudinal Titan's cloud coverage with time compared with Global Circulation Model³**
 242 **predictions. Top:** We reported here the latitudinal distribution of clouds we detected with VIMS ver-
 243 sus time from July 2004 to December 2007. The thin blue vertical lines mark the time of the VIMS ob-
 244 servations. The latitude extent of the clouds we detect is enhanced with thicker vertical lines, in blue

245 when in dayside and in green when in polar night. Isolated temperate clouds are colored in purple. The
 246 previous Cassini and ground-based observations reported in the literature are superimposed over our
 247 latitudinal distribution by colored dots and diamonds respectively. Our detections are in very good
 248 agreement with the previous observations. **Bottom:** Integrated Titan's cloud opacity above 10 km,
 249 summed each year, predicted by ref. (2)'s GCM (IPSL-TGCM) between 2004 and 2011. The thick
 250 black lines show the edge of the polar night. Spatial distribution of clouds forecasted by the IPSL-
 251 TGCM, confining clouds at the two poles and around 40°S, is in very good agreement with our obser-
 252 vations (see *top* and Fig. 2). On the contrary, the observed clouds timing is poorly reproduced by the
 253 IPSL-TGCM. In the time interval monitored by VIMS for this work, the IPSL-TGCM predict that the
 254 south pole cloud should vanish before the equinox for more than one year, and that the 40°S cloud belt
 255 should have reached a maximum of intensity between 2004 and 2007 and then should gradually vanish
 256 with the incoming circulation turnover. This seems to be lately observed by VIMS, with a significant
 257 delay (see text for details).

258

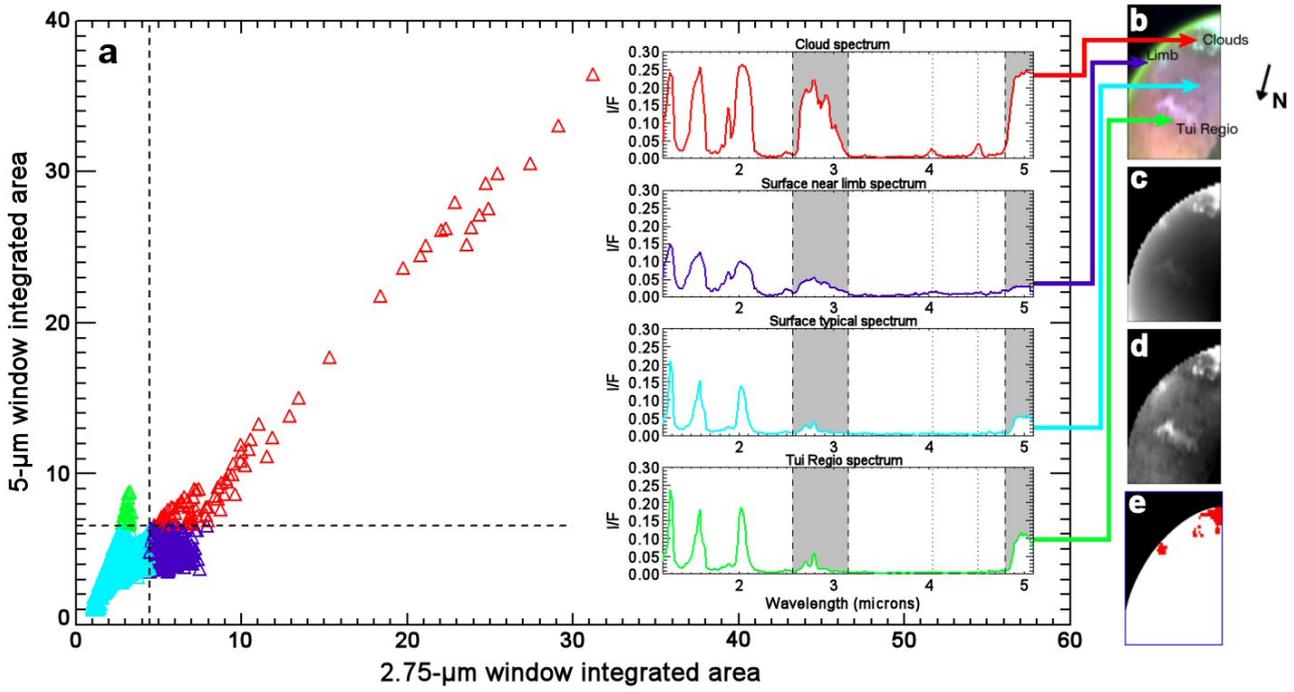
259 **Figure 4: The southern temperate clouds distribution in longitudes.** (*a*): The total number observa-
 260 tions that cover each 10° bin of longitude is shown with the solid red line for our study and the black
 261 dotted line for ref. (14). (*b*): The number of clouds observed by VIMS between July 2004 and Decem-
 262 ber 2007 (our study - solid red line) and ref. (14) between December 2003 and February 2005 (black
 263 dotted line) in each 10° bin of planetocentric longitude summed within 60°S and 0° of latitudes. Blue
 264 bars indicate the Poisson standard deviation for each VIMS clouds count. The statistics indicate that
 265 the overall shape of the longitudinal distribution is significant. (*c*): Normalized numbers of clouds
 266 (number of clouds divided by the number of observations) from ref. (14) and from this study are com-
 267 pared. Our distribution shows two minima at the sub- (0°E), where ref. (14) saw a maximum, and anti-
 268 Saturn points (180°E). Two others minima are also present in the neighbourhood of 70°E and -110°E
 269 longitude. But, due to Cassini's Saturn tour limitation, the detection of clouds was heavily precluded

270 here by particularly low spatial resolution (Fig. S5a) and very unfavourable conditions of observations
271 (resulting to high airmass – Fig. S5b), so that these two minima cannot be interpreted with confidence.

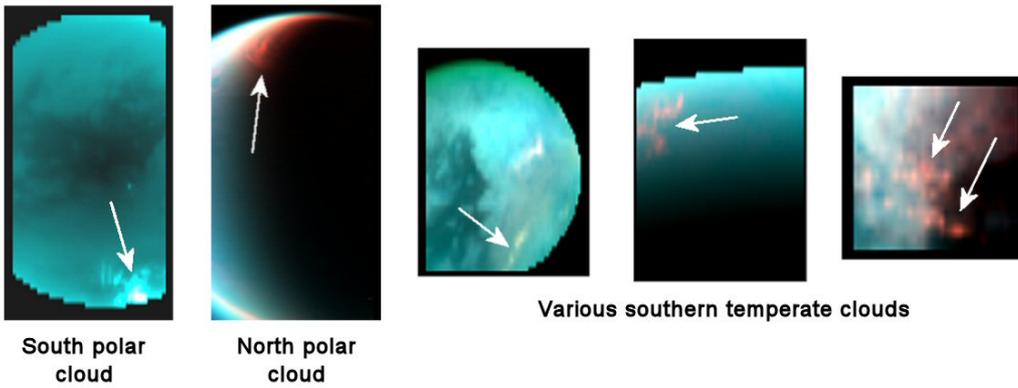
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Figure 1



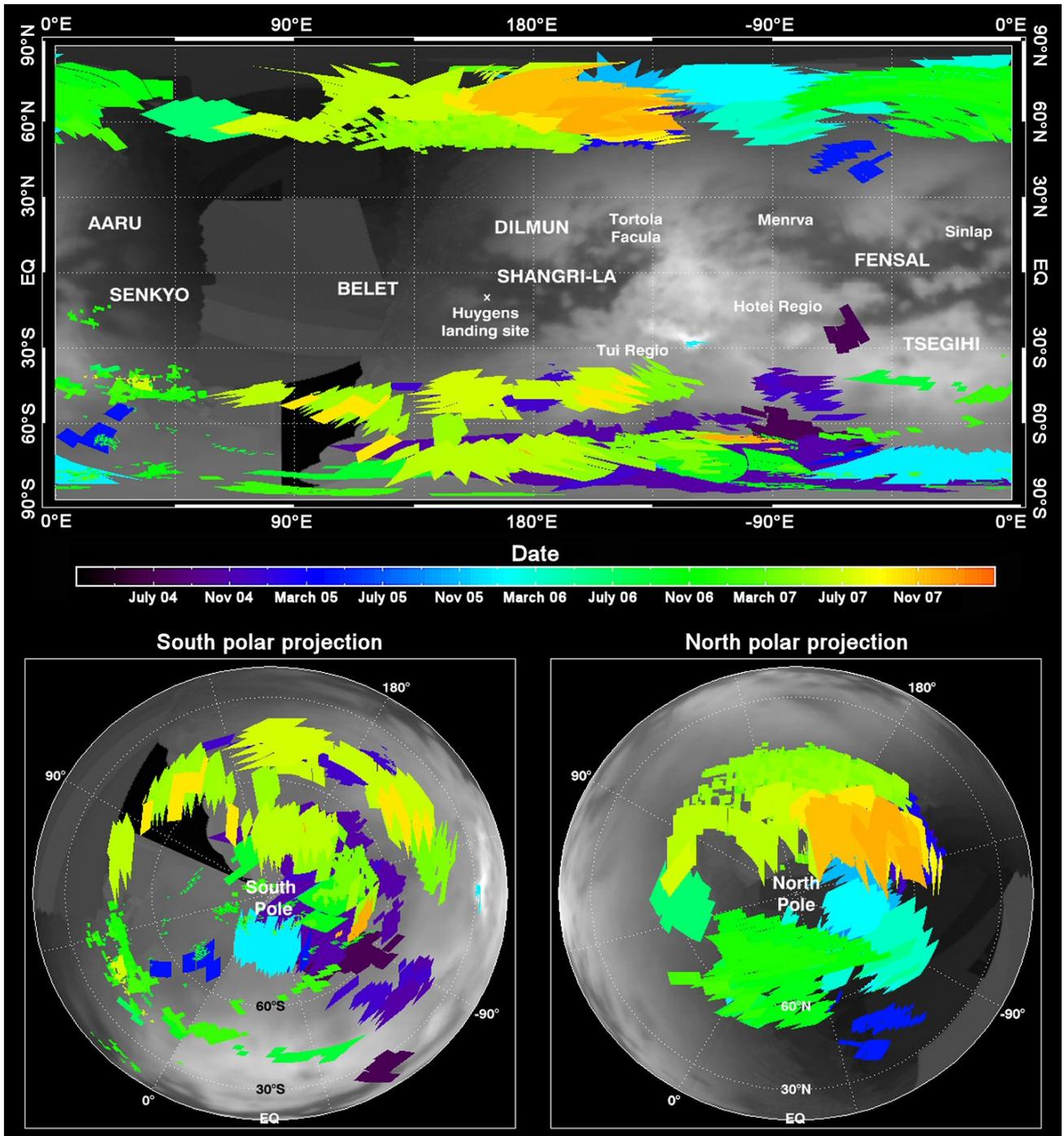
**Examples of Titan's clouds imaged by VIMS in the 2004-2007 period:
(RGB composites with RED=5- μ m, GREEN=1.6- μ m and BLUE=1.27- μ m)**



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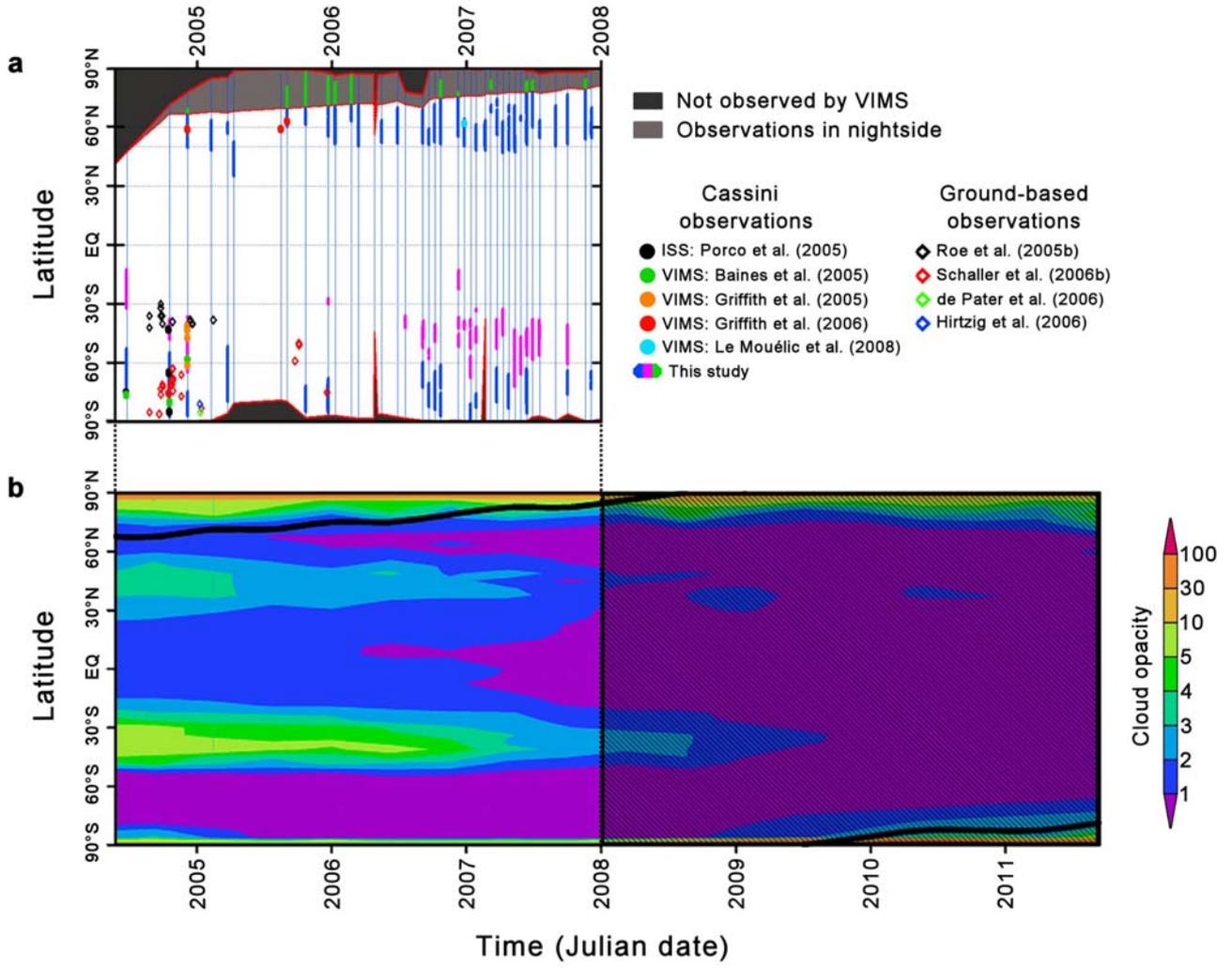
Figure 2



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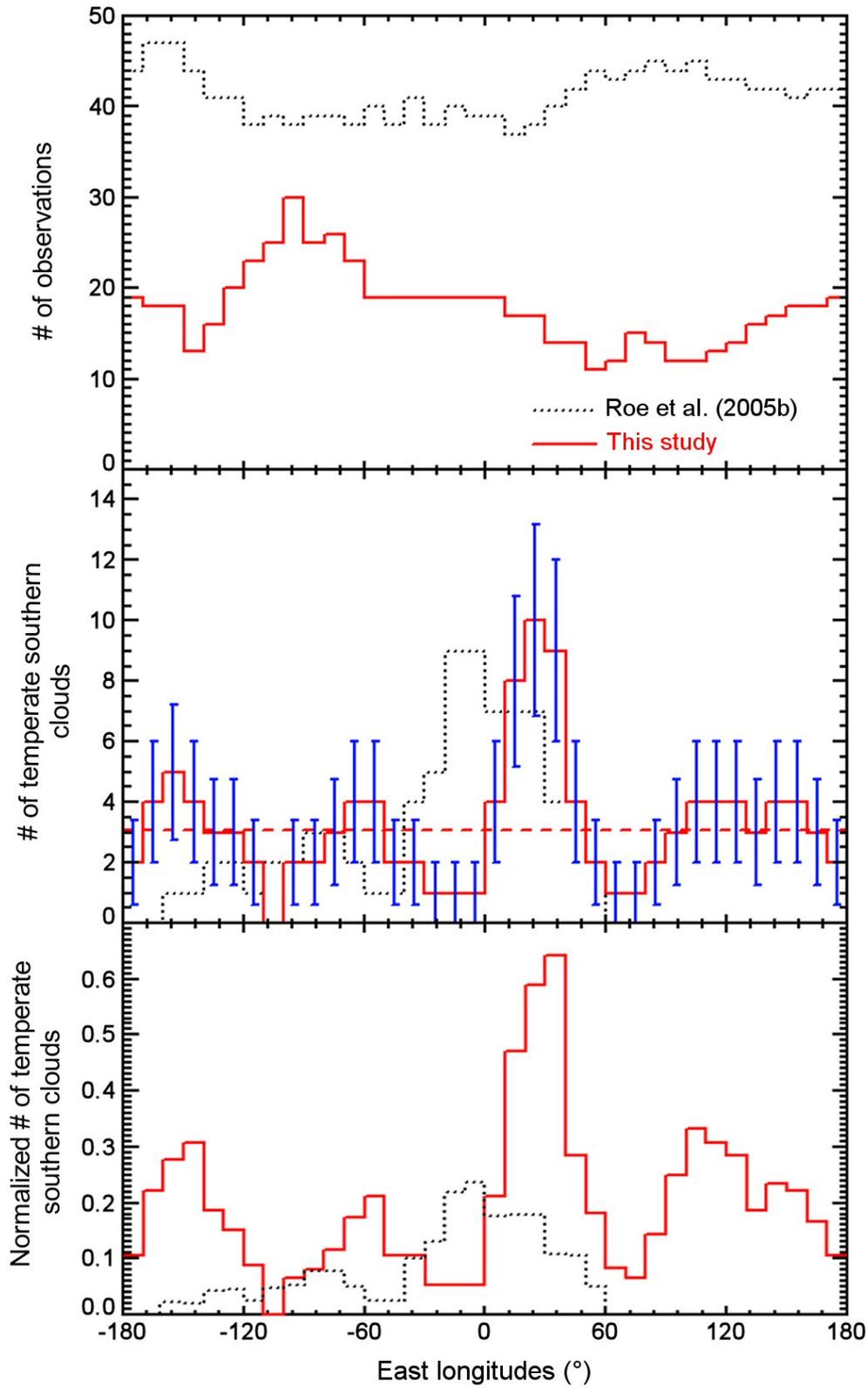
Figure 3



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Figure 4



287