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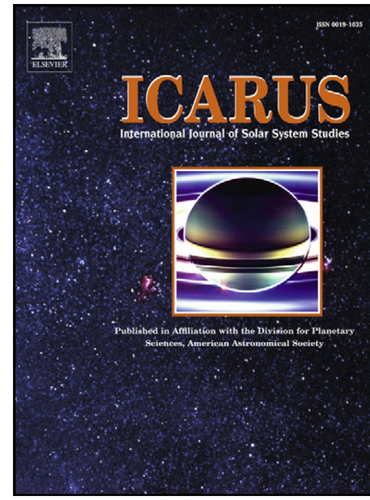

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A 3km Atmospheric Boundary Layer on Titan indicated by Dune Spacing and Huygens Data

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Abstract

Some 20% of Titan's surface is covered in large linear dunes that resemble in morphology, size and spacing (1-3km) those seen on Earth. Although gravity, atmospheric density and sand composition are very different on these two worlds, this coincident size scale suggests that the controlling parameter limiting the growth of giant dunes, namely the boundary layer thickness (Andreotti et al., 2009), is similar. We show that a ~3km boundary layer thickness is supported by Huygens descent data and is consistent with results from Global Circulation Models taking the distinctive thermal inertia and albedo of the dune sands into account. While the boundary layer thickness on Earth controlling dunes can vary by an order of magnitude depending on the proximity of oceans, which have very different thermal properties from dry land, the relative invariance of dune spacing on Titan is consistent with relatively uniform thermal properties near the dunes and no prominent variation with latitude is seen

Keywords

Titan; Meteorology; Geological Processes1. Introduction

Saturn's moon Titan was unexpectedly (Lorenz et al., 1995) discovered to have large areas covered in giant linear dunes (Lorenz et al., 2006). These dunes cover about 20% of the surface (Radebaugh et al., 2008; Lorenz and Radebaugh, 2009), almost exclusively in a band at the equator bounded by +/- 30^o latitude. The dunes were discovered in Cassini Radar images, and appear morphologically identical, and indeed rather similar in size, to large linear dunes on Earth, such as those in the Namib or Arabian deserts (e.g. Lorenz et al., 2006; Radebaugh et al., 2009.) An initial survey (Radebaugh et al., 2008) suggested typical lengths of 30-50km and a width of about 1km and spacing of 1-3km. In areas where the sand – likely composed principally of organic material (e.g. Soderblom et al., 2007) produced by atmospheric photochemistry of methane – is plentiful enough to blanket interdune areas, radarclinometry (shape-from-shading) has allowed their height to be measured to be about 150m (Lorenz et al., 2006). In another area, where exposed interdunes suggest sand is less plentiful, heights of 30-70m have been estimated (Barnes et al., 2008) from near-infrared images, and the dune spacing has a mean value of 2.1km.

Recent work has shown that there are two fundamental scaling parameters that control the size of sand dunes. The first is the so-called saturation length, i.e. the length over which the sediment flux relaxes towards its equilibrium value. This length defines the wavelength scale at which a flat sand bed will destabilize (Claudin and Andreotti, 2006) to form 'elementary' dunes (Elbelrhiti et al., 2005). To a first approximation, the grain inertia is the dominant mechanism in the saturation process, and the saturation length is itself proportional to the drag length $(\rho_s/\rho_f)d$, the distance over which a particle of size d, density ρ_s is accelerated to a velocity approaching that of the wind in air of density ρ_f. These elementary dunes, of size found to be ~$53(\rho_s/\rho_f)d$ (Claudin and Andreotti, 2006) can grow and coalesce to form progressively larger dunes, but the growth rate asymptotically declines as the dune spacing approaches the second scaling parameter, the thickness of the atmospheric boundary layer (Andreotti et al., 2009). The static stability at the top of this layer provides a 'capping' function, much as does the free surface of the water for subaqueous dunes, and limits the dune growth. On Earth, elementary dunes have a scale of ~20m, whereas on Titan (ρ_f ~5.4kg/m^3) the corresponding size (assuming organic 'sand' with ρ_s ~800kg/m^3, d~200μm is ~1.5m, far below the resolution of Cassini instrumentation. The dunes observed by Cassini are therefore 'giant' dunes, formed by the growth or aggregation of these smaller elementary bedforms. Dunes typically have heights about 12 times smaller than their spacing, and so the spacing limit due to the boundary layer also determines the maximum height of dunes, although attainment of this maximum height also requires a sufficient sand supply and time for growth.

In the absence of direct measurement of the boundary layer (which requires vertical profiling of the atmosphere), an effective proxy measure was determined by Andreotti et al. (2009) to be a scaling length of $\delta\Theta/\gamma$, where $\delta\Theta$ is the characteristic (seasonal) variation in potential temperature near the ground, and γ is the potential temperature lapse rate $d\Theta/dz$. This correlation appears to hold for over an order of magnitude of terrestrial dune sizes from coastal dunes of ~300m to giant continental dunes of ~3.5km, and the arguments are based on completely general fluid dynamics considerations. In this paper, we compare expectations from this correlation with the observed dune morphometrics on Titan and discuss the implications for the largely unknown meteorology of Titan.

Note that while the boundary layer thickness controls the limiting size of giant dunes, and also controls the size of helical roll vortices sometimes rendered visible by condensation forming long roll clouds, it should not be inferred (e.g. Hanna, 1969) that roll vortices necessarily form the dunes. The two observable effects represent a common cause, not cause and effect.

2. Observations of Dune Spacing

We made measurements on 4 image swaths from the Cassini RADAR instrument over areas where dunes appear as dark streaks on a brighter substrate and are thus easy to define (e.g. figure 1). Swaths projected at 128 pixels/degree (~350m/pixel) were studied in Adobe Photoshop by drawing a line of known length to guide the eye and counting by hand the number of dunes crossed.

Results are as follows : T21 (15^{o}S to 15^{o}N, Belet) dune spacings were 8.2, 9.2, 8.0 and 7.4 pixels, for an average of 8.2 pixels or 2.88 km. T25 (20^{o}S to 20^{o}N, Fensal, Aztlan) spacings were 7.7, 7.6, 8.5, 8.1 and 8.3 pixels, average 8.0 or 2.8 km. T41 (30^{o}S to 10^{o}N, Shangri-La near Huygens Landing site) spacings were 8.3, 7.2, 7.1, 8.8 and 8.4, leading to an average of 8.0 pixels or 2.8km, and T41 HiSAR (equator, Fensal) spacings were 10.2, 9.1 and 8.0, giving an average of 9.1 pixels or 3.19 km.

It is seen that there is remarkable uniformity among the observed Titan dune spacings in widely-separated regions, in contrast to the Earth where the scale size and spacing of giant dunes can vary by an order of magnitude. Barnes et al. (2008) report a mean spacing of 2.1km for dunes observed in Fensal (between

14°N and 17°N). Radebaugh et al. (2008) report occurrences of spacings of 1-2km, referring to some closely-spaced dunes (some apparently superposed on dunes with a slightly different orientation, perhaps suggesting a change in wind regime) in Belet, at around 6°S, 257°W and 8.5°S, 244°W. The Belet Sand Sea is particularly sand-rich, with sandy interdunes and little interruption to the dunes from topography or sand supply constriction. It may be noted that the broadside-on viewing geometry of these dunes in T8 (where the geometry of dunes was first recognized, Lorenz et al., 2006 – their figure 2 shows a radarclinometric profile of 9 dunes spanning 22km, or a mean spacing of 2.75km) may have been particularly favorable for detecting smaller dunes.

Thus although some examples of more narrowly-spaced dunes exist, the majority of observable dune spacings are 2-3km. There is no large-scale regional trend, nor an obvious variation with latitude. Since Andreotti et al. (2009) suggest dune growth is limited by the thickness of the boundary layer, this suggests that the Titan layer must have been 3km or more when the dunes were formed. In addition, many of Titan's interdune areas are clear of sand despite mass wasting processes; therefore, at least some of the dunes are likely active today (Barnes et al., 2008).

3. Huygens Probe Measurement of Boundary Layer Thickness

A single detailed profile of Titan's atmosphere exists, namely the in-situ measurements made by the Huygens Atmospheric Structure Instrument (HASI, e.g. Fulchignoni et al., 2005). This profile (figure 2) was acquired at around 9am local solar time, near 10°S, 192°W. The analysis by Tokano et al. (2006) noted a uniform region of potential temperature Θ between the surface and 300m altitude and therefore assigned the latter value as the thickness of a weakly convecting planetary boundary layer. However, as noted recently by Griffith et al. (2008), Θ is also near-constant over the regions 0.5-0.7 km and 1-2 km. They suggest that an original 2km boundary layer may have been modified by subsequent surface evaporation to produce the lower steps in Θ. We suggest instead that the 0.7 and 2km layer (possibly even a 3km inflection in the potential temperature profile shown in figure 2 - all these points are determined by inspection and thus must be considered somewhat subjective) are remnants of the boundary layer formed in previous days, the so-called ‘residual layer’ (Stull, 2008) while the convective boundary layer developing on landing day defines the most obvious 300m layer. One may risk over-interpreting a single profile of a temporally and spatially-variable atmosphere, but the Huygens data is the only direct measurement presently at hand. Our main point in this section of the paper has been to demonstrate that despite an earlier report, a typical boundary layer thickness of 2-3km is not inconsistent with the Huygens data. Radio occultations by the Cassini orbiter should yield refractivity profiles at several latitudes which may allow constraints to be placed on the boundary layer thickness. However, such results have not yet been published.

4. Global Circulation Model Predictions and Implications for Titan

Although Martian global circulation models (GCMs) are beginning to make headway on the question, Titan GCMs have not so far offered predictions of the thickness of the boundary layer as a function of location and season. The only predictive assessment was that of Allison (1992) who suggested a Titan boundary layer thickness of ~700m based on general scaling arguments.

However, we can use the heuristic $\delta\Theta/\gamma$ as a proxy for the boundary layer thickness and dune spacing. Further, in the absence of additional data, we must assume that the potential temperature variation can be equated to the thermodynamic temperature variation (i.e. $\delta\Theta \sim \delta T$). The data in Andreotti et al. (2009) show this to be correct to within ~20% for all the locations studied on Earth. For the relevant γ, we adopt the ~0.5 K/km seen in the lowermost few km of the Huygens profile (figure 2).

The GCM study by Tokano (2005) explores the seasonal variations in surface temperature on Titan as a function of surface type. He considers three globally-uniform surfaces, a bright ‘porous icy regolith’ (with albedo 0.38 and thermal inertia I= 334 $Jm^{-2}s^{-1/2}K^{-1}$), a rock-ice mixture with higher thermal inertia, and hydrocarbon lakes (with albedo 0.1 and a thermal inertia of 812 $Jm^{-2}s^{-1/2}K^{-1}$). As we now know, Titan's surface is very heterogenous, and none of these cases likely describes the sand seas. However, by comparing the different results, we can get a sense of what is plausible.

For the porous icy regolith, the equatorial surface temperature has an annual swing of about 1K, somewhat higher at 30^o latitude, and polar temperatures vary by about 4K. The amplitude of the near-surface atmospheric temperature cycle is about half as much. In fact, the sand seas will likely see a variation in temperature rather higher than this. First, the porosity of loose organic sands will be higher than the ~10% characteristic of a somewhat sintered regolith (the parameters were adopted from a self-compaction study by Kossacki and Lorenz, 1996) and so the density will be lower by a factor of ~2 and thus the thermal inertia will be at least 50% lower depending on the other details of the sand material. Second, because the sands are dark (with an albedo of around 5%) the absorbed insolation will be higher by about 50%. These two effects might be expected to combine to double the temperature variation. Thus we may estimate the low-latitude surface temperature variation at 2-4K with the boundary layer temperatures having δT at 1~2K. The hydrocarbon lake scenario, with an appropriately low albedo but higher thermal inertia than dune sands has similarly a surface low-latitude temperature swing of ~3K (note that latent heat effects of lake evaporation were not modeled, so in fact this scenario is a reasonable approximation of a sand sea, although it has a drag coefficient that may be small compared with that appropriate for a dune-covered terrain).

Taking these results together, it seems that δT of the order of 1-2K is not unreasonable, and thus $\delta T/\gamma$ of ~2-4km would be predicted, which is in encouraging agreement with the observed dune spacing, and the boundary layer thickness suggested by Huygens. In any case, further GCM simulation with more detailed surface properties are called for.

Recently Jennings et al. (2009) have reported surface temperature measurements across Titan from thermal infrared brightness temperatures in the 520 cm^{-1} window region using the Cassini Composite

Infrared Spectrometer (CIRS). They find equatorial temperatures of 93.7K, with the north (winter pole) ~91.7K and the south pole at around 92.4K. They also noted that the sand sea of Belet had a temperature about 1K higher than that of equatorial bright areas, supporting the argument above that the sands absorb more sunlight and are warmer as a result.

5. Conclusions and Implications for Titan

Titan's dunes prove to be an important diagnostic of that world's atmosphere. It has already been shown (Mitchell, 2008; Rannou et al., 2006) that the latitudinal extent of the dunes seems to be consistent with the transport of methane humidity away from low latitudes, and the prograde (West to East) sand transport implied by the dune morphology (Lorenz et al., 2006; Radebaugh et al, 2008; 2009; Lorenz and Radebaugh, 2009) poses some interesting challenges to circulation models, which expect low-latitude near-surface winds to be generally East to West. In this paper we have demonstrated that the scaling theory of Andreotti et al. (2009) seems to hold on Titan, namely that dune spacing may be controlled by the thickness of the atmospheric boundary layer, indicated to be 2-3km thick from Huygens data.

As befits a world of which some 20% is covered by dunes, Titan appears to have a climate with features in common with that of terrestrial deserts. Whereas the boundary layer, and thus the size of dunes, can be attenuated on Earth by the presence of nearby oceans with high thermal inertia – e.g. see the smaller dunes on the Namib coast (figure 3) compared with the larger ones inland, the dune spacing on Titan appears rather uniform, suggesting that the boundary layer may have a more or less constant limiting size over the low-latitude sand seas, whereas simulations might indicate that temperature contrasts should increase with latitude.

We note in closing that there is much to be learned by studying Titan's landscape and atmosphere : the complexity of the Huygens profile suggests that meteorological characterization of the boundary layer and its variations will be important and interesting. Further, the small drag length in Titan's thick atmosphere and resultant elementary dune size of ~1.5m suggests that imaging of resolution ~0.1m will be needed to adequately characterize the aeolian geomorphology on Titan.

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References

Allison, M. 1992, A preliminary assessment of the Titan planetary boundary layer, pp.113-118 in B. Kaldeich (ed), Proceedings of the Symposium on Titan, Toulouse, France, 9 –12 September 1991, ESA SP-338, European Space Agency, Noordwijk, The Netherlands, 1992

Andreotti, B., A. Fourriere, F. Ould-Kaddour, B. Murray and P. Claudin, 2009. Size of Giant Aeolian Dunes limited by the average depth of the Atmospheric Boundary Layer, Nature, 457, 1120-1123

Barnes, J.W., R.H. Brown, L. Soderblom, C. Sotin, S. Le Mouelic, S. Rodriguez, R. Jaumann, R.A. Beyer, R. Clark, P. Nicholson 2008. Spectroscopy, morphometry, and photoclinometry of Titan's dunefields from Cassini/VIMS. Icarus 195, 400-414.

Claudin, P. and B. Andreotti, 2006. A scaling law for aeolian dunes on Mars, Venus, Earth, and for subaqueous ripples. Earth and Planetary Science Letters, 252, 30–44

Elbelrhiti, H., P. Claudin, and B. Andreotti, 2005. Field evidence for surface-wave-inducedinstability of sand dunes. Nature, 437, 720–723

Fulchignoni, M., et al. 2005, In situ measuruments of the physical characteristics of Titan's environment, Nature, 438, 785–791

Griffith, C. A., C. P. McKay and F. Ferri 2008, Titan's Tropical Storms in an Evolving Atmosphere, Astrophysical Journal, 687, L41-L44

Hanna, S. R. 1969. The formation of longitudinal sand dunes by large helical eddies in the atmosphere, Journal of Applied Meteorology, 8, 874-883

Jennings, D. E., Flasar, F. M., Kunde, V. G., Samuelson, R. E., Pearl, J. C., Nixon, C. A., Carlson, R. C., Mamoutkine, A. A., Brasunas, J. C., Guandique, E., Achterberg, R. K., Bjoraker, G. L., Romani, P. N., Segura, M. E., Albright, S. A., Elliott, M. H., Tingley, J. S., Calcutt, S., Coustenis, A. and Courtin, R. 2009. Titan's Surface Brightness Temperatures, Astrophysical Journal Letters, Volume 691, L103-L105

Kossacki, K.J., Lorenz, R.D., 1996. Hiding Titan's ocean: densification and hydrocarbon storage in an icy regolith. Planetary and Space Science, 44, 1029-1037.

Lorenz, R. D. and J. Radebaugh, 2009. The Global Pattern of Titan's Dunes : Radar Survey from the Cassini Prime Mission, Geophysical Research Letters, 36, L03202

Lorenz, R. D., J. I. Lunine, J. A. Grier and M.A. Fisher 1995. Prediction of Aeolian Features on Planets : Application to Titan Paleoclimatology. J. Geophys. Res. 88, 26,377-26,386.

Lorenz, R. D. and 39 co-authors 2006. The Sand Seas of Titan: Cassini RADAR observations of Longitudinal Dunes. Science 312, 724-727.

Mitchell, J., 2008. The drying of Titan's dunes: Titan's methane hydrology and its impact on atmospheric circulation. J. Geophys. Res., Vol. 113, E08015

Radebaugh, J., R. Lorenz, J. Lunine, S. Wall, G. Boubin, E. Reffet, R. Kirk, R. Lopes, E. Stofan, L. Soderblom, M. Allison, M. Janssen, P. Paillou, P. Callahan and the Cassini Radar Team 2008, Dunes on Titan observed by Cassini Radar. Icarus 194, 690-703

Radebaugh, J., R. Lorenz, T. Farr, P. Paillou, C. Savage, C. Spencer 2009, Linear Dunes on Titan and Earth: Remote Sensing Comparisons, Geomorphology, in press

Rannou, P., Montmessin, F., Hourdin, F. and S. Lebonnois, 2006, The Latitudinal Distribution of Clouds on Titan, Science, 311, 201-205

Savage, C. and J. Radebaugh 2009, Titan as a laboratory for Linear Dune Formation, Abstract #1005, 40th Lunar and Planetary Science Conference, Houston, TX, March 2009.

Soderblom, L. and 26 co-authors, 2007. Correlations between Cassini VIMS spectra and RADAR SAR images: Implications for Titan's surface composition and the character of the Huygens Probe Landing Site, Planetary and Space Science, 55, 2025-2036.

Stull, R. B., 2008. An Introduction to Boundary Layer Meteorology, Springer, New York

Tokano, T. 2005. Meteorological assessment of the surface temperatures on Titan: constraints on the surface type. Icarus, 173, 222-242

Tokano, T., 2008. Dune-forming winds on Titan and the influence of topography, Icarus 194, 243-262.

Tokano, T., F. Ferri, G. Colombatti, T. Mäkinen & M. Fulchignoni, 2006. Titan's planetary boundary layer structure at the Huygens landing site, Journal of Geophysical Research, 111, E08007

Figure Captions

Figure 1. A section of the T41 Titan SAR swath at 180°W, 25°S, southeast of the Huygens landing site, showing typical dune spacing. Although bright topographic obstacles can interrupt the dunefield, the characteristic ~3km spacing is evident.

Figure 2. The near-surface potential temperature profile derived from Huygens data (Tokano et al., 2006) The constant Θ region 0-300m identified in that paper as the boundary layer is clearly seen (A); two additional steps in the profile at ~0.9km and ~2km (B,C) were suggested by Griffith et al. (2008) as suggesting a rather thicker, older boundary layer (C) had been modified subsequently (A,B). An additional inflection is seen at ~3.3km (D).

Figure 3. A 45x50km section of the Namib desert at 15°E, 25°S, observed by the Shuttle Imaging Radar (SIR-C) mission in 1994 (scene PR44419) – brightness is inverted for clarity. The dark South Atlantic Ocean is at left, with a strip of small coastal dunes (spacing 500-600m) grading into much larger linear dunes inland (spaced by 1.5-2.5km) , echoing the expected trend of the atmospheric boundary layer thickness

Figure 1

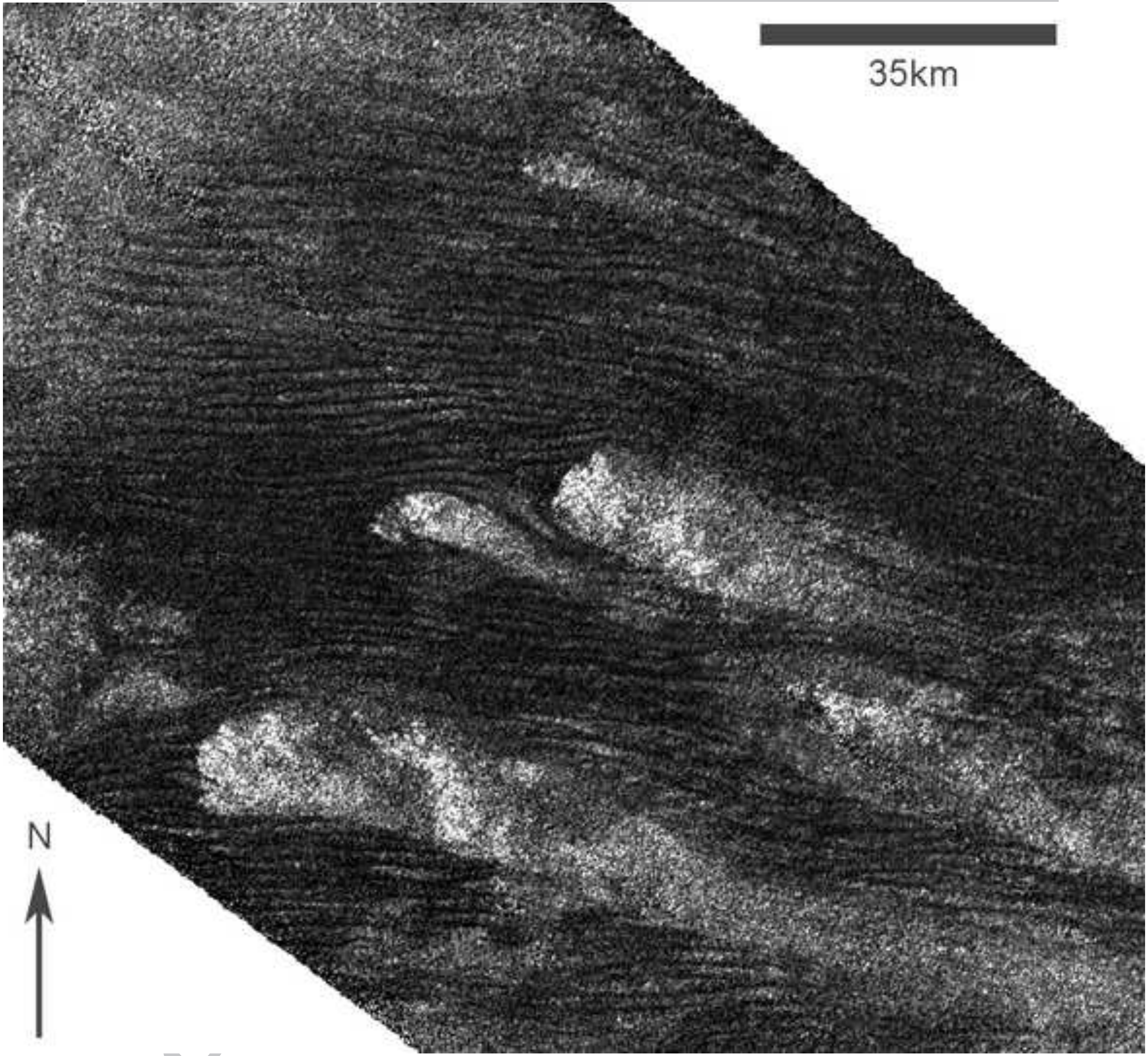
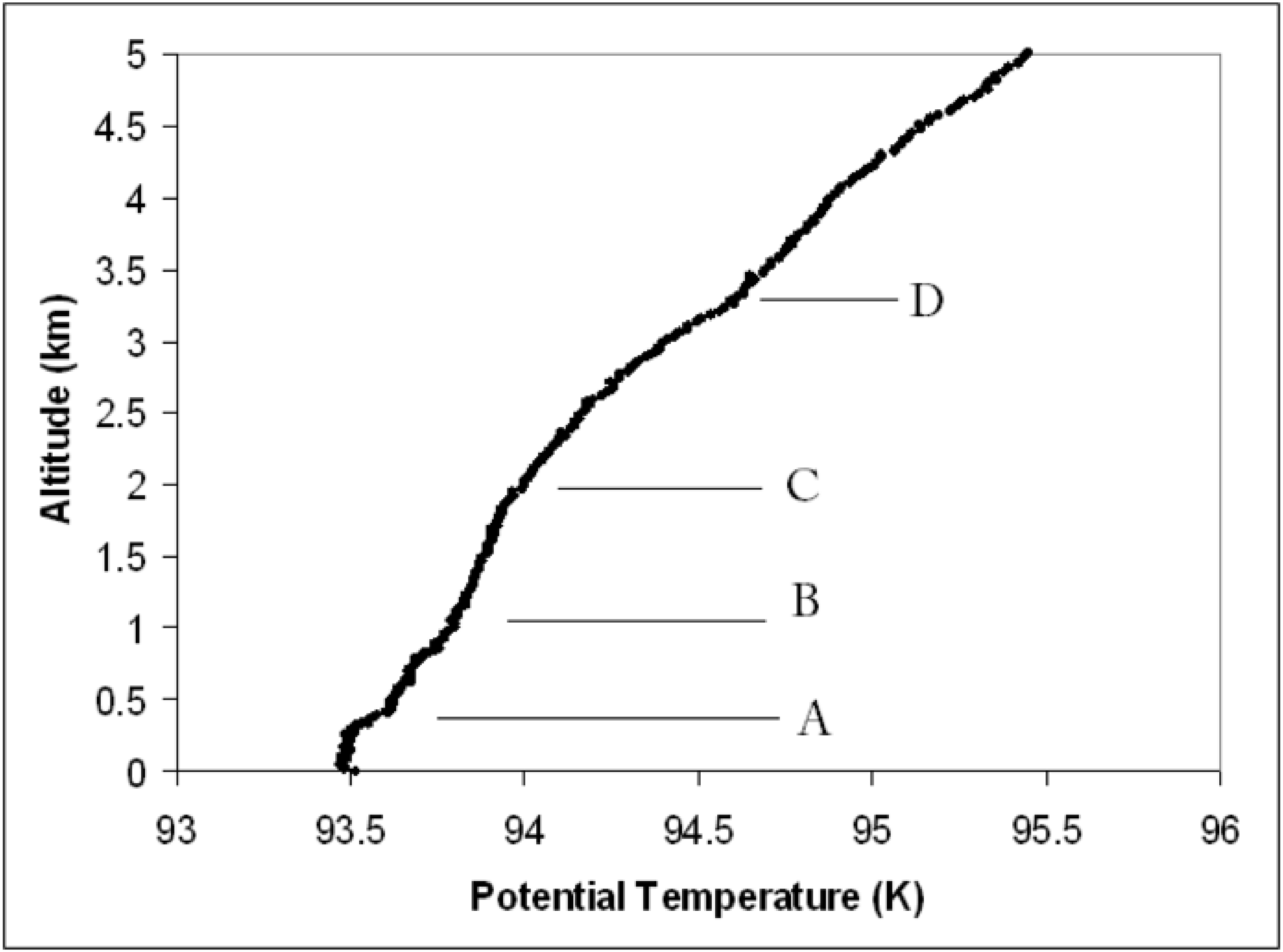


Fig 2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4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Altitude (km)
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93.5
94
94.5
95
95.5
96
Potential Temperature (K)
A
B
C
D

Figure 3