nature geoscience

LETTERS

PUBLISHED ONLINE: 8 DECEMBER 2014 | DOI: 10.1038/NGEO2323

Sand dune patterns on Titan controlled by long-term climate cycles

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Linear sand dunes cover the equatorial latitudes of Saturn's moon Titan and are shaped by global wind patterns[1–3]. These dunes are thought to reflect present-day diurnal, tidal and seasonal winds[1,3–6], but climate models have failed to reproduce observed dune morphologies with these wind patterns[4,6]. Dunes diagnostic of a specific wind[7,8] or formative timescale[9–11] have remained elusive[3,5,12]. Here we analyse radar imagery from NASA's Cassini spacecraft and identify barchan, star and reoriented dunes in sediment-limited regions of Titan's equatorial dune fields that diverge by 23° on average from the orientation of linear dunes. These morphologies imply shifts in wind direction and sediment availability. Using a numerical model, we estimate that the observed reorientation of dune crests to a change in wind direction would have taken around 3,000 Saturn years (1 Saturn year ∼29.4 Earth years) or longer—a timescale that exceeds diurnal, seasonal or tidal cycles. We propose that shifts in winds and sediment availability are the product of long-term climate cycles associated with variations in Saturn's orbit. Orbitally controlled landscape evolution—also proposed to explain the distribution of Titan's polar lakes[13]—implies a dune-forming climate on equatorial Titan that is analogous to Earth.

The remarkable similarity of wind-blown sand dunes on Earth, Mars, Venus and Titan (Fig. 1a–d) demonstrates that self-organization processes give rise to these landscape patterns independently of gravity, atmospheric pressure and sediment type. This property of dune pattern formation allows for the universal recognition of sand dunes and unambiguous evidence of surface winds capable of transporting sediment, but interpreting environmental conditions from well-organized patterns alone can lead to non-unique interpretations of a planet's wind climate (Supplementary Section 1)[5,14]. For example, some of our solar system's largest and most organized dune patterns have regularly spaced crest lines that extend for hundreds of kilometres across the equatorial regions of Saturn's moon Titan[1], but no consensus has emerged about the direction, number and cyclicity of dune-forming winds or the timescales over which the dunes change[5,6]. Uni-, bi- and multi-directional winds blowing from the east or the west and driven by diurnal, tidal, seasonal and storm-driven winds[1,3–6,15] have been suggested.

The persistence of dune patterns on landscapes and the orientation of dunes to wind cycles can be understood through the concept of dune reconstitution time[8,9,16,17], which is the forcing timescale needed to change dune orientation (Supplementary Section 1). Crest alignment to multiple flow directions arises where the duration of flow from a given direction is shorter than the dune reconstitution time[8,9,17] (Supplementary Fig. 3). If a dune is too large to reorient during any component of a wind cycle, the dune integrates the wind and the morphology reflects all winds during the cycle. This suggests that diurnal, tidal and seasonal wind cycles could be formative wind cycles, given Titan's large dunes and assumed slow migration rates[1,6]. However, a duty cycle greater than seasonal (for example, Milankovitch-scale) cannot be excluded as long as the flow is short relative to the dune reconstitution time.

The dune reconstitution time concept implies that changes in wind direction that are shorter in duration than the time needed to reorient Titan's largest dunes will not be apparent in the orientation of the largest dunes. These changes will, however, be reflected in smaller dunes, where the reconstitution time is short relative to variations in the wind. Here, we exploit the robustness of pattern self-organization and concept of dune reconstitution time by studying Titan's least organized and smallest dune patterns to discover landscape change (Fig. 1e). We newly identify dune types recognized as indicators of a multimodal wind regime and sediment-availability-limited transport conditions that allow us to estimate the dominant sediment-transporting wind directions and dune reconstitution timescales. We find that the timescales associated with the multimodal wind regime exceed the hypotheses favoured at present, which implies long-timescale climate cycles control Titan's dune field pattern evolution.

We examined Titan's four largest equatorial dune fields—Belet, Fensal, Senkyo and Shangri-La—by mapping ∼10,000 dune crest lines on Cassini synthetic aperture radar (SAR) imagery. The imagery was processed using a despeckle algorithm (Methods and Supplementary Figs 16, 19–21)[18] that permits identification of morphologic features approximately two to three pixels across (∼1 km), which is a finer scale than any previous dune mapping on Titan. In these radar images, dunes seem dark, implying a smooth surface, although radar glints off dune slopes may create bright areas. Dune-free regions have an overall lighter-toned, mottled texture, which implies radar scattering over a rough surface.

Our mapping showed two distinct dune crest line patterns—well organized and degraded. Well-organized crest lines extend unbroken for tens of kilometres, form a narrow distribution of wavelengths and have narrow interdune areas. We measured an average crest line length of 30 km and crest wavelengths of 3 km, as previously reported (Supplementary Fig. 19)[1,3]. We also identify regions of previously unmapped degraded linear dune patterns, which are defined by broken linear crest lines, a wide distribution of crest lengths and wavelengths, wide interdune areas and widespread dune-free regions (Supplementary Figs 1, 5, 9–12). Degraded crest line lengths range from a few to tens of kilometres and crest wavelengths average 4 km (Supplementary Fig. 19).

Within the degraded regions, we find barchan dunes with elongate horns (that is, crest terminations; Fig. 2b,d,e), which agrees with previous observations[19], and we newly identify star (Fig. 2a,c)

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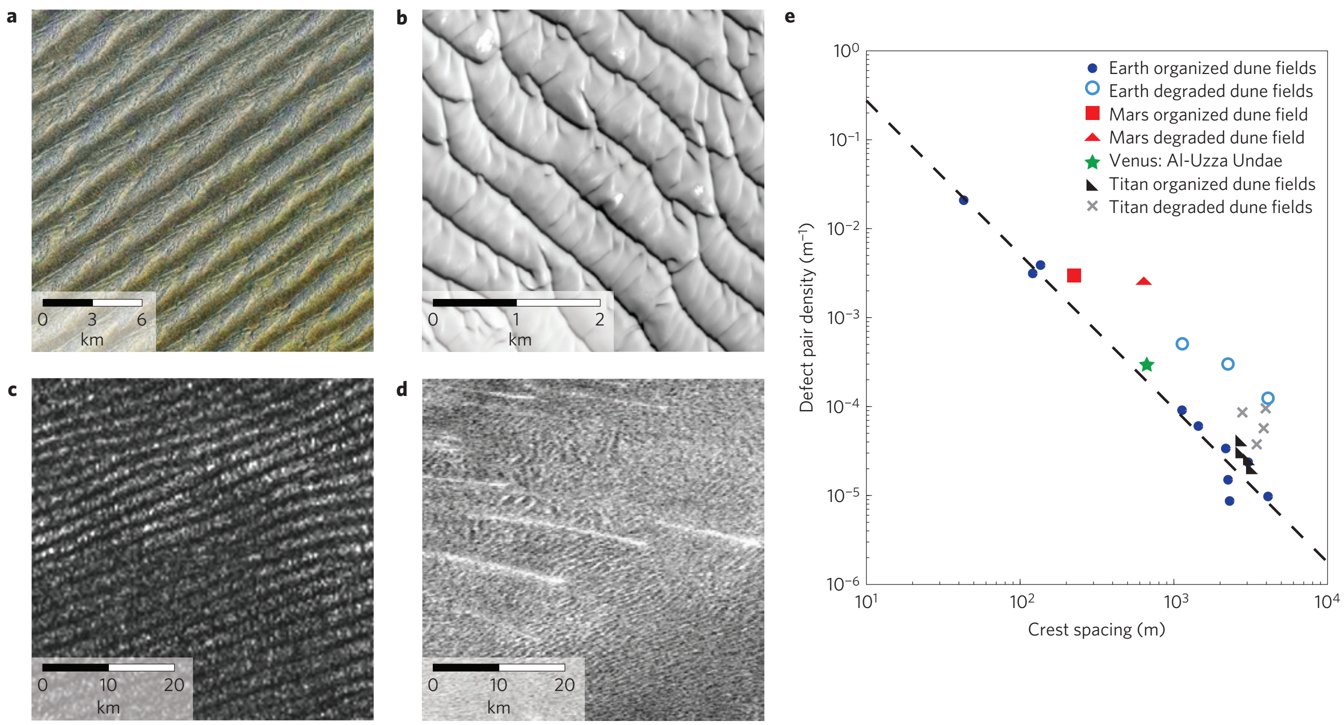

Figure 1 | Comparison of sand dune patterns in the solar system. a–d, Well-organized dune patterns on Earth (**a**), Mars (**b**), Titan (**c**) and Venus (**d**). **e**, Comparison between defect density ρ (given by $\rho = N/L$, where L is the total crest line length and N is the number of defect pairs[26]) and spacing shows well-organized patterns plot along a trend indicating patterns in equilibrium with formative conditions[30]. Degraded patterns fall off the trend with shorter crest lengths for measured spacing[30] (Supplementary Section 1 and Supplementary Fig. 2). Error bars are less than the symbol size. Supplementary Table 2 contains all image locations and north is up for all images.

and reoriented crest lines (Fig. 2d,e; refs 10,20). The barchan dunes occur *en échelon* along linear dune crests and as isolated dunes with crest lines oriented NW–SE (Fig. 2d,e). Star dunes are recognized by three or more crest lines that intersect at a central peak. Similar to the barchan dunes, the star dunes form along linear dune crests and as isolated forms (Fig. 2a,c). In less degraded areas, dunes superimposed on linear dunes and reoriented dunes diverge from the well-organized linear dune orientation by 23° (Figs 2d and 3). The same divergence in dune orientation persists across dune fields where this pattern occurs and matches the orientation of the barchan dunes.

This suite of dune morphologies is typical of multimodal winds (Supplementary Section 1 and Figs 3 and 4). Barchan dunes, including those with elongate horns, are found in wind regimes with which the divergence angle is low[7,8,16,21]. Star dunes, however, form in winds where the divergence angle between two or more modes of wind are around 90° (refs 8,22). The formation of barchan and star dunes along linear crest lines with a wide and regular crest spacing indicates that these are not immature dunes forming the developmental phases of linear dunes, but rather that the barchan and star dunes are reworking the linear dunes. The NW–SE orientation of the reoriented and barchan dunes indicates that these dunes are responding to the same change in conditions. The orientation of the dunes implies at least one wind mode from the southwest.

Barchan and star dunes surrounded by dune-free surfaces are typical of availability-limited sediment transport conditions, defined where the susceptibility of sediment to entrainment by the wind is low[16,23]. Factors that limit sand transport include increased surface roughness, such as pebble cover, which reduces the surface wind stresses, or surface stabilization by binding, cementation or moisture, which raise the threshold for transport[23]. Thus, the radar light-toned areas within the degraded dune fields could be bedrock, pebble or cobble lag, surface crusts, evaporites, or exposed dune cross-stratification.

Deflation to an availability-limited surface could explain the barchan and star dunes, where available sand is transferred to the dune. Broken crest lines, wide interdune areas and wide crest spacing in the degraded linear dunes, however, indicate a reduction of dune volume. We propose that sand from migrating dunes becomes trapped in damp surfaces (Supplementary Figs 13–15), as would occur with a relative rise in a near-surface liquid table. A net increase in regional liquid volume could occur by trapping precipitation and is consistent with recent observations of damp equatorial areas[24]. A change in surface moisture coincident with a shift in the wind explains the degraded linear dune patterns well and implies a pattern of change in aeolian activity analogous to Earth's sandy deserts, which experience humid (that is, less sand availability) conditions juxtaposed to dry (that is, more sand availability), windy conditions over glacial–interglacial timescales[25].

The key feature of our observations that can be used to place useful bounds on the direction and timescale of Titan's winds is the divergence in crest orientations (Figs 2 and 3). To examine reorientation timescales we use a geometric model to estimate the rate at which a crest line will adjust to steady state with a new wind regime (Methods)[26]. We input our measured crest line lengths and assume a maximum migration rate of ~1 m per Saturn year. This rate is based on sand flux calculations from GCM-modelled surface winds[6] (Supplementary Section 1 and Table 1). Using the average divergence angle between the linear and reoriented crest lines of 23° (Fig. 3b), the model predicts that the time to reorient the smallest dunes by this amount is around 3,000 Saturn years (Fig. 3a). The maximum time to reorient Titan's largest dunes is between 20,000 and 45,000 Saturn years.

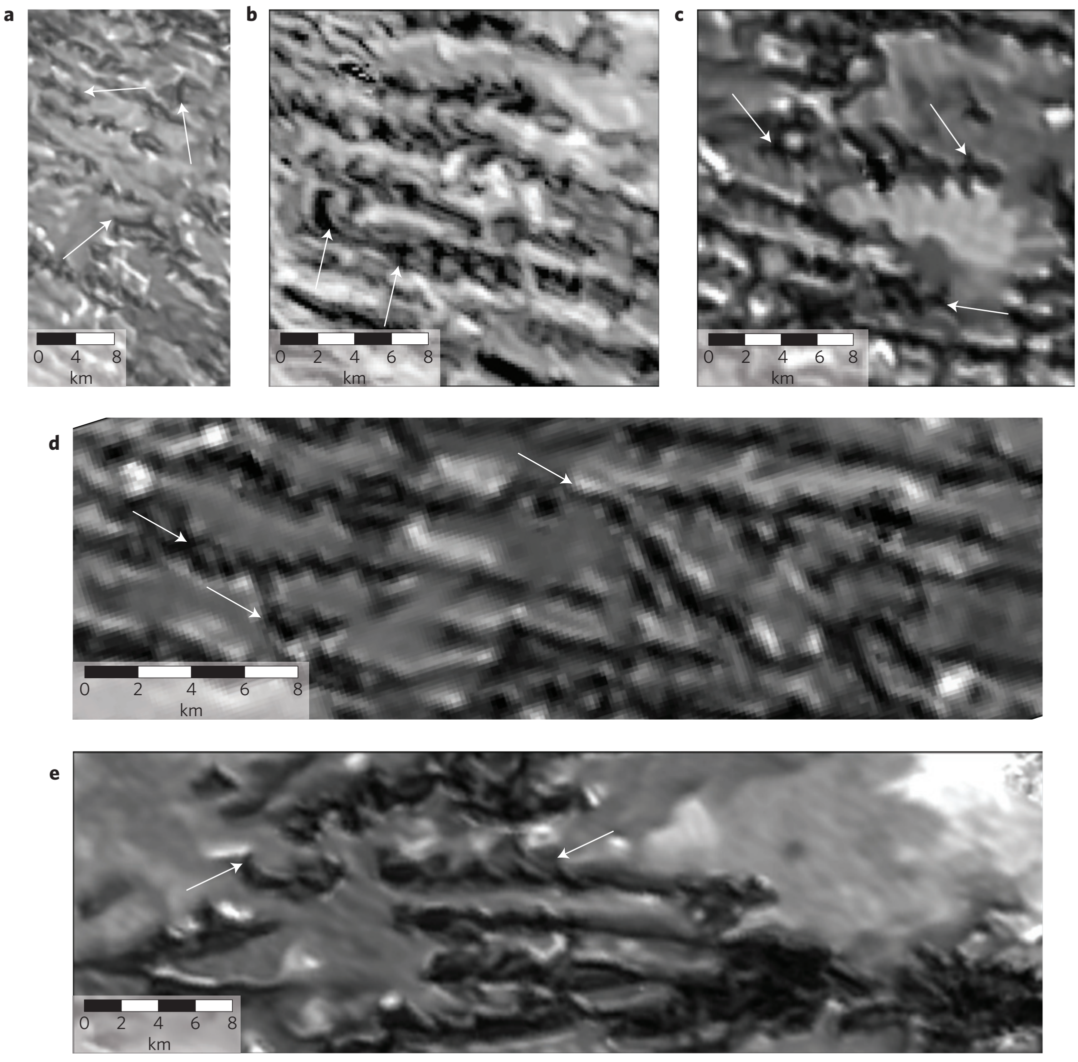

Figure 2 | Despeckled Cassini radar images of barchan, star and reoriented dunes. White arrows highlight type dune examples in each panel. **a**, Star dunes isolated and along linear crests in Belet Dune Field. **b**,**e**, Barchan dunes with elongate southern horns and reoriented crest lines indicating the influence of a second wind in Shangri-La Dune Field (**b**) and Senkyo Dune Field (**e**). **c**, Star dunes forming along linear dunes and as isolated dunes in Fensal Dune Field. **d**, Barchanoid and reoriented crest lines in Belet Dune Field. Supplementary Figs 17 and 18 show a comparison between despeckled radar and radar.

A shift in wind could have arisen as part of a long-term, cyclic multimodal wind regime on Titan. In this case, the wind cycle that generates the linear dunes must be longer than 3,000 Saturn years, but shorter than the timescale necessary to reorient the longest dunes. This range is significantly longer than seasonal and tidal cycles, but may relate to Milankovitch-scale cyclicity on Titan[13]. Titan's largest dunes could be oriented to an average of winds over all but the largest Milankovitch frequencies, whereas the small dunes reflect a recent mode of winds.

A long-term, cyclic climate that controlled the formation of Titan's dunes is similar to current models for the formation of large, complex linear dunes on Earth[27], where dunes formed or were significantly modified during the Last Glacial Maximum (~15,000 and 25,000 years ago) when Earth's subtropical desert climate was cooler and drier, and winds were stronger[25,27]. Many of Earth's dunes formed during this time are so large that the patterns have remained unaffected by the shift to modern winds during the Holocene (~11,000 years ago to present). In many areas, superimposed crest lines reflect the Holocene shift in winds[27]; a scenario that may be similar to the formation of reoriented dunes on Titan. Although untested on Earth, and as proposed here for Titan, some dunes may be in equilibrium with long-term, glacial–interglacial cycles, where the largest pattern does not reflect any given wind regime during a cycle, but rather integrated winds over multiple glacial periods.

Our measurements of dune type and orientation are evidence for a multimodal wind regime operating over thousands of Saturn years—a timescale that exceeds currently hypothesized wind cycles to explain Titan's dunes. We propose that Titan's equatorial aeolian landscape changes with variations in Saturn's orbit. This suggests a familiar model in which Titan's dune fields are like Earth's subtropical deserts, which are variably active throughout Milankovitch cycles but go through phases favourable to aeolian activity. Milankovitch-scale cycling of Titan's winds aligns the equatorial latitudes with Titan's high-latitude environments, where lakes and channels indicate a landscape modified over thousands of years[13,28,29]. The antiquity of Titan's dunes predicted by our analysis implies that the equatorial region has been favourable for aeolian activity over tens to hundreds of thousands of years allowing the accumulation and aeolian mobilization of sediment, perhaps driven

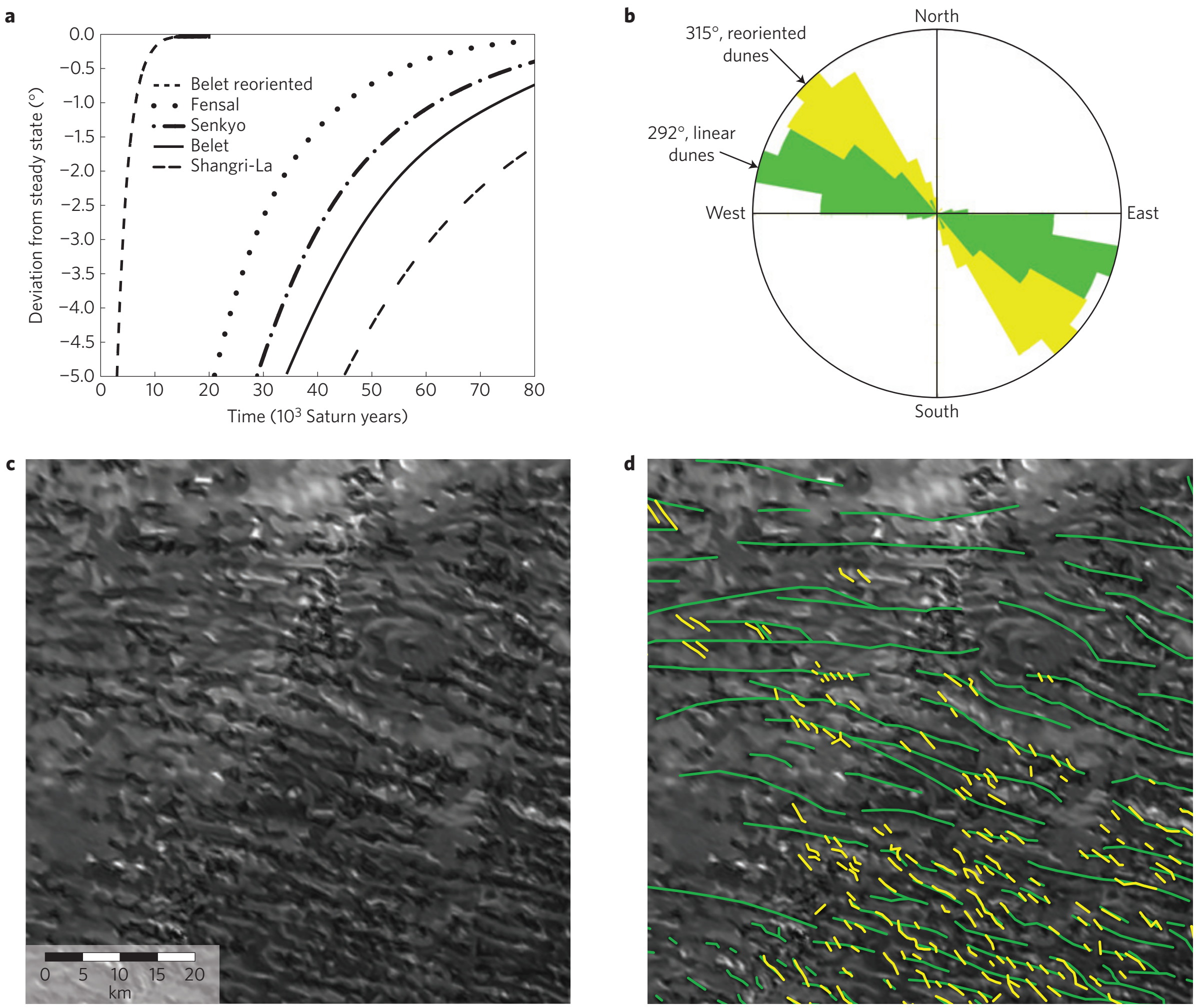

Figure 3 | Modelled dune reorientation timescales of Titan's dunes. a, Timescales required to reorient crest lines from 23° off steady state. Modelled solutions shown for the final 5° of reorientation. Reorientation in this asymptotic model is considered to be within 5° of steady state, which represents the error in determining the orientation for the smallest crest lines mapped in this study. **b**, Rose diagram showing 23° offset between linear dunes ($\bar{X}=292°$, $n=229$) and reoriented crest lines ($\bar{X}=315°$, $n=319$) mapped in **c**,**d**. Colours correspond to digitized crest lines in **d** and distinguish among the linear dunes (green) and reoriented dunes (yellow). **c**, Despeckled Cassini SAR image showing reoriented crest lines and linear dunes in Shangri-La Dune Field. **d**, Digitized crest lines of reoriented and linear dunes shown in **c**.

by degradation of nearby uplands or transport from the poles over similar timescales.

Methods

Cassini SAR images were processed using a non-local filtering approach to reduce noise and preserve structure. The technique averages similar pixels and assumes there are enough redundant pixels with identical noise-free values to reduce noise significantly. We use an adaptation of this approach to remove multiplicative speckle noise from Cassini SAR imagery[18]. The de-noised SAR images allow quantitative analysis of surface features down to two to three pixels. Dune crest lines were mapped at the smallest spatial resolutions feasible with the de-noised data, allowing the recognition of dunes a few kilometres in length. Crest lines were manually digitized within a geographical information systems geodatabase where crest line length is measured along the axis of the crest line from dune termination to termination. Crest spacing is measured perpendicular to the axis of the dune from crest line to crest line. Crest lines were mapped using both Cassini SAR (data available from the Planetary Data System (PDS) website at www.pds.nasa.gov) and de-noised Cassini SAR images to check the accuracy of crest line interpretations. Mapped crest line data were used in a geometrical model[26] that estimates dune reorientation timescales. The model predicts the timescale for a crest line out of equilibrium for a given wind to reorient to a new steady state. Within the model, crest lines reorient at a rate determined by the average migration rate of the dune, a proportional rate of defect (that is, dune termination) migration and the dune-field defect density, $\rho=N/L$, where L is the total crest line length and N is the number of defect pairs. Migration rates of dunes on Titan are unknown and we used an estimate of 1 m per Saturn year (~29.4 Earth years) based on fluxes calculated from wind data derived from global circulation models[6] and Earth analogues (Supplementary Table 1). The method used calculates mass sand flux from the zonal and meridional components of the surface winds using a standard flux equation and appropriate Titan boundary conditions. Ref. 6 does not apply a threshold shear velocity to the calculation—in other words, all winds contributed to the migration of the dune. Applying a threshold value would reduce the total number of effective winds and decrease the overall transport rates. The mass flux calculated from the wind speeds is translated into a volume flux and used in a standard mass-conservation bedform celerity equation. Based on the GCM-modelled migration rates and Earth analogues, our estimation of 1 m per Saturn year should be considered a maximum estimation of the migration rate, thus placing our bounds on the reorientation timescales as minimum.

Received 14 April 2014; accepted 13 November 2014; published online 8 December 2014

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Acknowledgements

Comments from C. Newman and T. Farr greatly improved our manuscript. This research was supported by NASA through the Cassini Data Analysis Program by grant NNX14AD52G to R.C.E. and A.G.H. A.L. thanks the French Space Agency (CNES) for its support. We thank C. McCormick, D. Parker and S. Troy at the University of Alabama and C. Ballard from University of California at Berkeley for assistance with mapping.

Author contributions

R.C.E. and A.G.H. contributed to the design, research, analysis and writing of the study. A.L. contributed the de-noised Titan data and manuscript editing.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.C.E.

Competing financial interests

The authors declare no competing financial interests.