Supplementary Methods

Measurement of position

The dune contours are measured with hand-carrying Garamin GPS receivers. The resolution, checked at reference points, is of the order of 4 m for the whole figure 1. We report the positions of the dunes shown on figure 1 in Supplementary Table. Depending on the size of the dune, the GPS points are spaced by 5 m to 20 m. The aerial photographs are taken with a Leica Geosystems camera on 240 mm x 240 mm films, with a lens of focal 88 mm or 152 mm. They are digitalized at 60 pix/mm, which, depending on the altitude of the plane, gives finally a resolution between 20 cm/pixel for a field of 2.7 km and 70 cm/pix for a field of 10 km. The global position of the camera (latitude, longitude, altitude and the three Euler angles) is determined from the GPS positions of various landmarks (road, relief, cliff, track…) visible on the photographs. This procedure ensures a global positioning of any visible point within a resolution of less than 4 m. To take series of pictures from low altitudes (between 50 m and 200 m), we used a stabilised kite with a digital Leica camera (2240 pix x 1680 pix) Using a mosaic of pictures, we typically obtain photographs showing a field of 200 m x 500 m with a resolution of the order of 5 cm/pix.

Measurement of propagation speed

The displacement can be measured within a resolution of few meters by using either two GPS contours or one GPS contour and an aerial photograph. This guarantees a precision that is less than a percent for the velocity (red points on figure 2a). For the waves, we mark with sticks the crest of the slip face — when it exists — or otherwise the steepest slope line and measured the horizontal displacement within few centimetres. While they are still measured within few percents, the wave propagation speeds (black points on figure 2a) are more scattered than the dune propagation speed, due to the short timescale (few tens of hours) over which they are averaged.
Measurement of height profile

For an accurate measurement of the height variations $\delta h$ associated to the wave (figure 2a), we need to reach a precision of the order of the centimetre on a length scale of 100 m horizontally and 10 m vertically. Using side view digital photographs, we first measure the horizontal and vertical positions of different fluorescent markers along the cut line — two of which giving the scale — within a global resolution of 20 cm. We also measure the angle (within 0.2°) and the distance (within 5 mm) between sticks all along the profile. Combining these three sets of measurements, we extract the profile $h(x)$ from least square fits of these data sets.

Measurement of erosion rate and sand flux

We define the integrated mass sand flux $q_m$ which is the overall mass of sand which crosses a unit horizontal length per unit time — whatever the altitude and the velocity of the grains. The integrated volume flux $q$ is defined as the ratio of $q_m$ to the dune density $\rho_{\text{dune}} = 1530 \text{ kg/m}^3$. $q$ is of the order of 100 m$^2$/year. The conservation of matter directly relates $q$ to the erosion rate as $\partial_t h + \partial_x q = 0$, which gives $q = q_0 - \int \partial_x h \, dx$.

The erosion is measured using 20 cm, 50 cm and 100 cm long sticks buried down to a gauge line in the sand. The accuracy is mainly limited by the presence of aeolian ripples, few millimetres in height. Compensating this small scale bed form, the erosion (typically 100 mm) is measured within a resolution of 2 mm.

To determine the sand flux saturation length (figure 3b), we simply integrate minus the erosion rate, starting from the upwind edge of the sand sheet. The integration of measurement errors leads to a random walk like drift, which is partly responsible for the oscillations of the plot. For the flux profile of figure 2b, as for the height profile (see above), we correct this drift with independent measurements of $q$ at the top and bottom of secondary slip faces. Behind these slip faces, the wind is generally not sufficient to sustain transport so that they behave as perfect integral sand traps. Hence, $q$ vanishes at the bottom of the slip face and can be deduced at the crest from simple geometrical considerations ($q = c H$ for pure propagation). Compared to regular sand traps, this technique is non intrusive and insures both accuracy and lack of systematic errors.
Measurement of wind velocity and saturated sand flux

The wind velocity over the flat ground is measured with three cup anemometers at 10 m, 20 m and 40 m fitted with a wind vane, located next to the dune field in Tarfaya (27°54’N, -12°55’W). The corresponding time series for the shear velocity $u_*$ and the wind direction $\theta$ were acquired at a rate of one data point per hour during one year (each point is averaged over one hour). The saturated sand flux $Q$, which is the maximum amount of sand that can be transported by the wind, is controlled by $u_*$. We obtain the time series for $Q$ using calibration curves provided by J.D. Iversen and K. Rasmussen (Sedimentology 46, 723-731, 1999), which, for $d=180$ μm, can be fitted by

$$Q = 13 \frac{\rho_{air}}{\rho_{dune}} \sqrt{\frac{d}{g}} \left( u_*^2 - u_{th}^2 \right)$$

with a good approximation $^{14}$. $Q$ vanishes below the threshold shear velocity $u_{th} = 0.1 \sqrt{\frac{\rho_{sand}}{\rho_{air}} g d}$ with $\rho_{sand} = 2550$ kg/m$^3$ and $\rho_{air} = 1.2$ kg/m$^3$.

Measurement of the increase in velocity and flux between the ground and the brink

The speed-up factor — the increase of velocity between the ground and the brink — is measured with two cup anemometers placed at 13 cm from the bed, just above the saltation layer$^{2-4}$. The values found on six dunes, ranging from 1 m to 8 m high, do not present any systematic dependence on the dune height, but are dispersed around the average value $s=1.45$. The corresponding increase of flux between the ground and the brinks $a$ is deduced from the wind time series $u_*(t)$:

$$a = \frac{\int \left( s^2 u_*(t)^2 - u_{th}^2 \right) dt}{\int \left( u_*^2 - u_{th}^2 \right) dt}.$$ Integration over the year 1999 gives $a=2.7$. 
Averaged and maximum sand flux roses

The averaged sand flux rose (figure 1) is computed by integration over one year (1999) of the saturated flux for each compass direction (30° wide bins). The maximum sand flux rose is defined as the maximum Q for each compass direction, i.e. the maximum of all the values averaged over one hour.

The averaged sand flux rose is a standard tool to characterise the wind regime. An index of the directional variability of the wind is given by the ratio of the resultant drift potential (RDP) to the drift potential (DP)\(^{15}\). The DP is the integral of \(\left| \bar{Q}(t) \right| \) and gives 88.8 m\(^2\)/year for 1999 whereas RDP is the modulus of the integral of \(\bar{Q}(t)\) and gives 80.6 m\(^2\)/year for the same year. We obtain a RDP/DP of 0.91 (slightly less, 0.89, for the flux/velocity relationship commonly used\(^{15}\)), which corresponds to a narrow unimodal wind regime in the classification proposed by Fryberg and Dean\(^{15}\).

The region around Tarfaya (Atlantic Sahara) is thus comparable to other regions on Earth where the wind regime is unidirectional (RDP/DP of 0.87 in Walis Bay, Namibia, 0.91 in Chimbote, Peru, 0.92 in Bulgan, Mongolia, and 0.97 in Aranau, Brazil). However, the maximum sand flux rose introduced here shows that the intermittent events (storms), which can be as large as ten times the average, are much more isotropically distributed.

Scaling of dune and wave velocities on the saturated flux

In order to compare the propagation of dunes in different places and under different meteorological conditions, the speeds have to be rescaled by a reference flux. It is natural to choose the saturated flux on solid ground \(Q\) averaged over the period of time considered. The dune data points of figure 2a (red points) thus display \(c/Q\) as a function of the dune height \(H\). Since the flux increases almost linearly along the stoss slope up to \(aQ\) at the crest the reference flux for a wave at altitude \(z\) is \(aQ \ (z/H)\). The wave data points of figure 2a (black points) thus display \(cH/(aQ \ z)\) as a function of the wave amplitude. For this purpose, the factor \((z/H)\) is measured on side view photographs and \(aQ\) is estimated from the propagation of neighbouring dunes.
Supplementary Table

Most recent measurement of the position (hollow of the slip face) of the main dunes displayed on figure 1

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Supplementary Figures

Photographs of dunes featuring surface waves in various fields all over the world.

a) Small amplitude waves on a 7 m high barchan, Atlantic Sahara, Morocco. (credits B. Andreotti)

b) Unstable barchan (~ 8 m high) presenting secondary slip faces, Atlantic Sahara, Morocco. (credits Thierry Kunicki)

c) Target dune (~2 m high) after the collision shown on Fig. 1g, Atlantic Sahara, Morocco. (credits B. Andreotti)
d) Permanently unstable barchan (mega-barchan, 640 m wide), Atlantic Sahara, Morocco.
   (credits Thierry Kunicki)

e) Unstable barchan (mega-barchan, 10 km wide), Argyre Planitia crater basin, Mars.
   (credits ESA/DLR/FU; Berlin (G. Neukum))
f) Unstable dune in southwestern Egypt, near Bir Misaha.
   Courtesy of the U.S. Geological Survey
   (credits Carol S. Breed, U.S. Geological Survey, Desert Studies Group, Flagstaff, 1984,

g) Chain destabilization of barchans, Sechura desert, Peru.
   Courtesy of the U.S. Geological Survey

h) Unstable barchan, inland of Semanco Bay, Peru.
   Courtesy of the U.S. Geological Survey

k) Nucleation of waves on a star dune, Namibia.
   (credits B. Andreotti)

l) Nucleation of waves on a climbing dune, Namibia.
m) Barchans in Jericoacoara, Brazil.

n) Weakly unstable barchan ridges, Lençóis Maranhenses, Brazil
o) Array of permanently unstable dunes (mega-dunes), Rub Al-Khali, Saudi Arabia
   (credits George Steinmetz)

p) Permanently unstable dunes (mega-dunes), Rub Al-Khali, Saudi Arabia.
   Image provided by NASA GSFC Earth Sciences (GES) Data and Information Services Center
   (DISC) / Distributed Active Archive Center (DAAC).
   (from Geomorphology from Space eds. N. M. Short and R. W. Blair, Nasa publ., 1986,
   http://disc.gsfc.nasa.gov/geomorphology/GEO_8/GEO_PLATE_E-2.HTML#FigE-2.3)