Desert dunes and sand seas cover approximately 20% of the world’s arid zones and their morphology and patterning are an important diagnostic of environmental surface conditions not only on Earth, but also on other planetary bodies. Crescentic barchan dunes, for example, are indicative of a unidirectional sand-moving wind regime in low sediment supply conditions, whereas the appearance of linear dunes on the surface of Titan was interpreted as evidence of a bidirectional atmospheric flow regime that shapes granular surface material in its equatorial region.

The encroachment of moving desert dunes can threaten transportation infrastructure, agriculture, industry and settlements, either by burial under migrating dune bodies or by increased sand flux, and hence any change in the mobility and direction of migrating dunes can greatly alter the local risk assessment. Migrating dunes can be agents of desertification, as their passage leaves long-term detrimental impacts on soil productivity and ecological richness. They play a key role in dust emissions at globally important source regions, where the blasting impact of sand flux accompanying mobile dunes releases silt and clay particles into the atmosphere from underlying sediments in the surrounding area, an important climate-change feedback process.

A changing wind climate also plays a key role in the potential expansion of dune fields and sand seas, as well as the reactivation of currently dormant fields. An increase in wind-blown sand may trigger the transformation of a vegetation-controlled surface into mobile bare-sand dunes—particularly if accompanied by overgrazing or drought—and the potential release of dust harboured in the sediment. The subsequent increase in surface albedo from dark vegetation cover to bright bare sand can affect the regional radiation balance in a further climate-change feedback mechanism.

Understanding future changes in desert dune morphology, migration speed and direction has great socio-economic relevance. The recently completed Hotan–Ruqiang high-speed railway line in China, for example, includes 500 km of track along the southern Taklimakan Desert with US$205 million spent on measures for sand drift mitigation, and in the MENA (Middle East and North Africa) region railway projects worth US$53 billion are under way, some of which traverse major sand seas, such as the Riyadh–Jeddah ‘Saudi Landbridge’. Local road networks and agricultural patterns are adapted to current shapes and locations of dunes, whereas industrial infrastructure, cities, such as Nouakchott, Dubai and Sabha (Algeria), as well as archaeological sites, require continuous sand dune management. Existing measures...
A sand-moving wind regime can be quantified by the average scalar magnitude of drift potential (DP) vectors, proportional to the wind speed cubed above an initiation threshold, and the vector-resultant of the DPs, in magnitude (RDP) and direction (RDDir)\(^2\). DP reflects the overall capacity of the wind to shift sand, whereas RDP and RDDir quantify the net resultant sand displacement vector. The ratio RDP/DP quantifies the directional variability of the sand drift regime—values near unity indicate unidirectional regimes and small values indicate multiple wind vectors that together yield very little net movement of the sand. DP, RDP and RDDir are typically derived from meteorological records of wind speed and direction at a ten-minute temporal resolution that span periods of ten years or more to represent the wind climate\(^2\). Past comparisons between measured DP and observed sand sea activity\(^2\) suggested that low sand drift environments typically show DP < 27 m\(^3\) s\(^{-3}\), whereas high sand drift environments are associated with DP > 34 m\(^3\) s\(^{-3}\) (units are omitted henceforward, as per convention).

In this study we analyse wind data from Coupled Model Intercomparison Project Phase 6 (CMIP6) climate simulations to determine the projected changes, by the end of this century, in sand-moving wind regime parameters in the world’s arid zones under the SSP5-8.5 Shared Socio-economic Pathway emission scenario. We generated daily DP vectors from ten-minute wind speed distributions, which we derived from mean and maximum wind speed predictions, to calculate average DP, RDP and RDDir for the periods 2000–2015 and 2085–2100. We interpreted the projected changes in these parameters to infer shifts in speed and migration direction of mobile sand dunes, changes in dune shapes and pattern, and impacts on currently dormant dune fields.

**Fig. 1 | Phase diagram of desert dune types as a function of directional variability in sand drift.** Box-plot distributions of RDP/DP obtained from hindcast simulations for the period 2000–2015, for each of the four major desert dune types observed in satellite imagery across the arid zone. Notches indicate the medians, edges of the boxes define the 25th and 75th percentiles, whiskers extend to the distribution extremes (excluding the outliers marked as dots). The red vertical dashed lines indicate intersections of the percentile distributions between linear and barchan dunes at RDP/DP = 0.725 (in environments of low sand supply) and between transverse and star dunes at RDP/DP = 0.435 (in environments of high sand supply). Satellite imagery examples of the dune types with the wind regimes overlain are shown on the right. See Supplementary Section A for details on the dune survey. Credit: satellite imagery courtesy of Google Earth, copyright Maxar Technologies.

**Dune fields under current wind regimes**

We examined contemporary satellite imagery of the Earth’s surface in each cell of the CMIP6 climate simulation grid located in the arid zone to record the presence and areal extent of desert dunes and sand seas, their morphological types and an inferred net sand drift direction (Supplementary Section A). Google Earth Pro was used to visually explore the available imagery inside each of the 9,498 arid zone grid cells (typically with a pixel resolution of five metres or less) to record mobile desert dunes able to respond to changes in the sand drift regime on a decadal timescale, that is, dunes a few hundred metres in size or less. We differentiated between four major sand dune types\(^3\) (Fig. 1): (1) barchans, migrating crescent-shaped dunes with ‘horns’ pointing downwind; (2) transverse-crescentic dunes, migrating ridges of sand perpendicular to the prevailing wind; (3) linear-seif dunes, elongating ridges with single-threaded, sinuous crestlines that run parallel to the resultant sand transport direction and (4) star dunes, stationary accumulations of sand with multiple crestline arms that radiate outward in different directions. Statistics on areal extents and relative abundances per dune type are reported in Supplementary Table A1.

Comparison of our dune field inventory with sand-moving wind regime parameters extracted from the CMIP6 hindcast simulations for the start of this century (2000–2015) reveals that areas with mobile sand dunes experienced a median DP of 28, with extreme values of more than 90 at the 95th percentile of the frequency distribution. Although the traditional differentiation between low, moderate and high sand drift environments was previously based on a subjective classification of 13 desert regions\(^2\), we propose boundaries based on both the DP frequency distribution as well as on the mechanics of sand dune movement. We class low sand drift environments as those with DP < 10, a threshold value that equates to the annual turnover of a minimum size barchan dune (-10 m long)\(^3\) as well as the 25th percentile of the frequency distribution. At this threshold, minimum-size barchan dunes are able to adjust to an altered drift regime on a yearly timescale.
Fig. 2 | Changes in sand drift regime parameters in the global arid zones predicted for the end of this century. a–d. Predictions for the period 2085–2099 under the SSP5-8.5 climate change scenario, compared with the hindcast of the period 2000–2015, for changes in DP (a), RDP magnitude (b), directional variability in sand drift (c) and resultant drift direction (d). These maps are available as Google Earth layers in Supplementary Section D.
We class high sand drift environments as those with DP > 50, which equates to the 75th percentile of the distribution and is associated with the yearly turnover of a 25 m long dune. The latter threshold is similar to the traditional boundary (DP > 54) and 25 m is close to the mode (most common) length of terrestrial barchan dunes30, which means that at least half of all barchan dunes can adjust to an altered drift regime on a yearly timescale at this threshold. For the first 15 years of this century mean DP in the low sand drift environment was 4, in the moderate drift environment 28 and 80 in the high drift environment.

The formation of the four major dune types (barchans, transverse crescentic, linear self and star) depends on two variables: wind directional variability (quantified by RDP/DP) and sediment availability (quantified as an equivalent sediment thickness (EST))3. Our arid zone inventory of mobile desert dunes, mapped against the sand drift regime parameters for 2000–2015, yields frequency distributions of RDP/DP for each type that suggest a separation between barchans and linear dunes—both known to form at a low EST—and a separation between transverse-crescentic and star dunes—both known to form at a high EST (Fig. 1). Intersections of the percentile distributions indicate that at a low EST the boundary between barchan and linear dunes may be set at RDP/DP = 0.725, with barchans more common above this value (more unidirectional sand drift) and linear dunes below this value. At a high EST the cross-over between transverse-crescentic and star dunes is found at RDP/DP = 0.435, with star dunes more common below this value (a more multidirectional sand drift) and transverse-crescentic dunes at higher values. Of the arid zone active desert dune area, 29% experienced a multidirectional sand drift regime (RDP/DP < 0.435), 31% a bidirectional (0.435 < RDP/DP < 0.725) and 39% a unidirectional regime (RDP/DP > 0.725).

Future changes in sand-movement regime

A comparison of sand-moving wind regime parameters extracted from the 2000–2015 hindcast simulations and from SSP5-8.5 emission scenario simulations for the end of this century (2085–2100) indicate that 73% of the current desert dune areas are projected to experience a significantly different DP (P < 0.05). Around one-third of the desert dune area sees an increase in DP, the other two-thirds a decrease. Increases and decreases in DP beyond +10 and −10, respectively, are roughly balanced in areal extent (−7% each). Changes in RDP show a less skewed ratio of a 43% areal extent of increase and 57% of decrease, whereas the extent that experiences a rise in RDP greater than +10 is markedly higher (at 10%) than that experiencing a decline below −10 (2%).

In the aggregate, median DP across these areas declines by 12% (from 27.5 to 24.2), but RDP declines by only 3% (from 11.7 to 11.3). However, the spatial variability of these sand drift parameters greatly increases, with an 11% (for DP) and 13% (for RDP) rise in standard deviation. The more extreme values of sand drift are evident in higher 95th percentiles, which increase from 88 to 95 for DP, and from 72 to 77 for RDP. Transitions between the sand drift environment classes are small, with more than 90% of desert dune areas remaining in their class.

Directional variability in sand drift sees notable changes, as areas under multidirectional as well as unidirectional RDP/DP ratios shrink by 10 and 7%, respectively, but areas with bidirectional regimes expand by 19%. In three-quarters of active desert dune areas in moderate and high sand drift environments (that is, DP > 10), the RDDir changes by less than 10°, and 14% of these areas see a directional change of more than 15°, with 8% seeing a backing (anticlockwise) and 6% a veering (clockwise) trend. The changes in RDDir are statistically significant (P < 0.05) over 60% of the dune fields in moderate and high drift environments.

The global distribution across the arid zone of changes in the sand drift regime parameters by the end of this century (Fig. 2) reveals notable regions of interest. The most prominent feature is the increasing DP in a zonal band across the Central Sahara, the Horn of Africa, the Southern Arabian Peninsula and southeast Pakistan and Rajasthan. Conspicuous decreases in DP are visible in Patagonia, the Mediterranean Maghreb, Iraq, the Tibetan Plateau, Eastern Taklamakan and the Gobi Desert. The distribution of RDP changes in addition to those of DP shows a substantial increase in central Algeria and Libya, as well as moderate increases in central Western Australia. Large regions that experience little change or slight reductions in DP and RDP are North America, southern Africa and the Iran–Turkmenistan–Uzbekistan–Kazakhstan region. The small decreases across the American Great Plains region and the unchanging DP over the South African Kalahari Desert may alleviate concerns over the potential reactivation of vegetated dune fields in these regions31,32, and considerable decreases in and around Inner Mongolia may reduce the sand and dust storm hazards that affect northeast China. The consequences of combined changes in DP and RDP that affect the sand drift directional variability (RDP/DP) are most notable in the northern half of the Sahara, where directional variability turns more unidirectional, and the Sahel, where it turns more multidirectional; there is a strong contrast between Yemen and Oman, where it turns more unidirectional, and the Rub‘ al Khali, where it turns more multidirectional; large parts of the Australian interior experience a more unidirectional regime. Changes in RDDir for areas with DP > 10 are more dispersed, except for large parts of southern Australia where the direction tends substantially. The sand seas and desert dune fields particularly affected by changes in sand drift regime are listed in Table 1.

Analysis of simulations for the SSP1-2.6 scenario (which represents a less severe climate change impact) show that predicted changes in the sand drift regime are fully consistent with the SSP5-8.5 scenario across all the key regions, in proportion to the less severe climate forcing, as expected (Supplementary Information). We also analysed data

### Table 1 | Projected end-of-century changes in sand drift regime for select sand seas and desert dune fields

| Region                        | Changes                              |
|-------------------------------|--------------------------------------|
| Mauretania                    | Increasing sand drift (+15% DP) in more multi-directional regime |
| Western Sahara                | Increasing sand drift (+10% DPa and +10% RDP) |
| Grand Erg Occidental (Algeria) | Increasing sand drift (+40% RDP) in a more unidirectional regime |
| Grand Erg Oriental (Algeria)  | Decreasing DP (~13%), increasing RDP (≈60%), more unidirectional regime |
| Great Sand Sea (Libya–Egypt)  | Decreasing sand drift (~30% DP) |
| Bilma Sand Sea (Niger)        | Decreasing sand drift (~20% DP and ~25% RDP) |
| Bodélé Depression (Chad)      | Increasing sand drift (+20% DPa and +20% RDP) |
| Horn of Africa (Somalia)      | Increasing sand drift (+10% DP and +30% RDP) |
| Rub‘ al Khali (Saudi Arabia)  | Increasing sand drift (+15% DP) in a more multidirectional regime |
| Oman                          | Increasing sand drift (+100% DP and +150% RDP) in a more unidirectional regime |
| Thar Desert (India)           | Increasing sand drift (+30% DP and +30% RDP) |
| Taklamakan (China)            | Decreasing sand drift (~20% DP and ~20% RDP) |
| Gobi Desert (Badain Jaran and Tengger, China) | Decreasing sand drift (~20% DP and ~45% RDP) |
| Western Australia (Great Victoria and Gibson) | Increasing RDP (+45%) in a more unidirectional regime |

Changes for the period 2085–2100 relative to start-of-century (2000–2015), which include approximate increases and/or decreases over each region (see also Supplementary Section D). ‘Parameter trends present only in the high-resolution simulations discussed in the main text; also see Supplementary Section C.”
from lower-resolution simulations for three Tier-1 scenarios (SSP1-2.6, SSP2-4.5 and SSP5-8.5), which show consistency and proportionality in the changing sand drift regimes for most key regions in the arid zone, except for a few specific poorly reproduced trends over the Sahel (annotated as such in Table 1), which are likely a consequence of the lower spatial resolution, rather than an issue with the high-resolution results presented here (Supplementary Section C).

Future projections of increasing drought conditions suggest that the aridity in desert regions will remain the same if not intensify, whereas the desertification of drylands will expand. As the unvegetated state of sand seas and dune fields is strongly persistent even under ameliorating soil moisture conditions, there is little prospect for the future fixation of currently mobile desert dunes by vegetation or biocrust.

**Impacts on desert dunes**

Changes in sand drift regime can have four main impacts on desert dunes. First, a change in RDP affects their migration rate, particularly for barchan and transverse dunes, being proportional to RDP and inversely proportional to dune height. Figure 2 shows the Bodélé Depression experiencing the globally largest increase by the end of this century. The region currently already sees extreme RDP on the order of 300, reflected by the world’s fastest barchan dunes with heights of 20–40 m migrating at ~50 m yr⁻¹. The projected increase of 15–20% will see a commensurate speed-up (Fig. 3a), probably accompanied by further increasing dust emissions.

Second, a change in directional variability (RDP/DP) leads to dunes transforming in shape. Given their relatively small and self-contained size (hence short turnover time), the most likely shape change is for barchans to transform into linear-seif dunes under a wind regime with more directional variability (Fig. 3b). Roughly 18% of currently unidirectional sand dune areas see a transition to a bidirectional regime, which includes 39 grid cells where barchans are currently present (5% of the areal extent of barchan dune fields). Nearly 30% of dune areas currently under a multidirectional regime are projected to transition to a less variable (bidirectional) regime. This includes 23% of the areal extent that contains star dunes, which therefore are potentially subject to transforming into transverse dunes, although the large size of star dunes (typically many hundreds of metres in diameter) means that the changes in shape will be slow.

Third, a change in RDDir alters the direction of migration or elongation of dunes, particularly for barchans and linear dunes. Key changes in drift direction of more than 15°—which defines the transition between normal versus oblique dune orientation that causes key differences in airflow and sand transport interactions—are projected for 10% of the areas that experience moderate or high drift environments and currently contain barchans or linear dunes. Barchans can change...


direction as individual bedforms, and linear dunes may either be able to accommodate a reorientation \(^2\) or break up into rows of separate dunes if the drift direction shifts more perpendicular to the established crest line \(^3\). Migrating dunes that change course can particularly impact the human infrastructure and settlement developed around historic dune patterns, as illustrated in Fig. 3c. Changes in RDDir can also undermine the effectiveness of existing sand drift mitigating measures, such as sand fences, optimized for past sand drift regime parameters.

Fourth, major future increases in DP or RDP may initiate reactivation of dormant dune fields currently held down by vegetation—especially in regions where climatic change leads to increasing drought conditions—although the process is non-linear \(^4\) and both fully vegetated as well as fully mobile dune field states can be found under identical climatic conditions \(^5\). Of particular concern are western Australia and the Thar Desert. In the former, large areas of the Great Victoria and Gibson Desert are projected to experience a RDP increase on the order of 50%, whereas directional variability is set to reduce from RDP/DP values of around 0.35 (multidirectional) to around 0.60 (bidirectional). Combined with an expected reduction in soil moisture by the end of this century \(^6\), and the likely associated decrease in vegetation cover, the more focused RDP may trigger a reactivation of currently dormant linear dunes, accompanied by dust release from the disturbed sediment. The Thar Desert, meanwhile, is expected to see an increase in DP and RDP on the order of 25% under a highly unidirectional wind regime (Fig. 3d). Although the area is projected to receive increased monsoon rainfall \(^7\), socio-economic pressures may expose currently vegetated parabolic dunes to reactivation as well as expansion of the existing transverse-crescentic dune fields under the stronger DP.

Discussion

The predicted changes in sand drift regimes in the various regions around the globe are probably rooted in shifts in global atmospheric circulation and monsoonal systems, which alter the seasonality of sand-moving winds from contrasting directions. The origins of these changes are linked to the projected weakening and poleward expansion of the Hadley Cell due to global warming \(^8\), particularly in the Northern Hemisphere, together with changes in extratropical cyclone activity \(^9\) and monsoon systems \(^10\). In Fig. 4 we explore these regionally distinct impacts by comparing the projected changes in the sand drift vector for each typical month of the year for several locations. Changes in the West African monsoon are apparent in southern Mauretania (Fig. 4a), which sees a considerably increasing sand drift under stronger monsoonal westerly winds in July–September, whereas the northeasterly Harmattan winds during the dry winter months remain largely unchanged, which results in a key shift in RDDir that potentially threatens settlements in interdune areas. In northern Algeria (Fig. 4b), by contrast, the predicted decline in overall DP is due to decreases in the winter and spring northwesterlies (November–April), linked to the weakening of extratropical cyclone activity over the Mediterranean Sea. c. Oman (20.8362° N, 56.2675° E), showing impact of changes in the Indian South West monsoon. d. Western Australia (29.1812° S, 123.8048° E), showing the impact of the poleward displacement of storm tracks. Projected changes (current RDP + ΔRDP) are indicated numerically below each sand rose with the colour background in shades of red (ΔRDP > 0) or blue (ΔRDP < 0).
drift under the southeasterly trade winds. This yields a higher RDP in a more unidirectional sand drift regime.

Our finding of a global 12% decline in median DP over mobile desert dune areas is commensurate with a recent prediction of the average reduction in saturated sand flux by the end of this century for 45 sand seas46, and our projections of relatively small decreases in DP over most of central and western North America align well with regional models that indicate a 5% decline in the mean annual wind energy density for wind power generation47. Furthermore, the patterns of future changes in DP and RDP (Fig. 2) match closely those predicted from a previous generation of climate models for Africa and Australia48. Our results, however, reveal the great spatial variability in predicted changes in sand drift regime parameters—both increases and decreases in dune movement—and the potential impacts on desert dune morphology and migration in arid zones around the world. The projected changes in dune behaviour may have to be considered in future planning and management of sand dune encroachment hazards, and mitigation measures designed for current wind climate, such as sand fences and green belts, may locally become less effective—under a changing net sand drift direction, for example—or unnecessary, such as where dunes transform from a migrating to an elongating type. More precise and practical predictions of sand sea and dune field adjustments require a new generation of numerical models capable of simulating site-specific aeolian geomorphodynamics on a regional scale, rather than just for singular dunes46. Sand drift regime is one of the two key controls on dune dynamics, the other being sediment supply, in particular the role of vegetation restricting the movement of sand by wind. Climate change projections for most semi-arid zones generally predict increases in persistent drought conditions49, probably leading to a reduction in vegetation cover and expansion of desert dune activity in tandem with changes in the sand drift regime.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-022-01507-1.

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Methods
Data
We analysed gridded daily surface wind data for 15 years of hindcast (1 January 2000 to 31 December 2014) and 15 years of projected end-of-century (1 January 2085 to 31 December 2099) time periods generated by the HadGEM3-GC31-MM model\(^\text{50}\), a member of the most recent CMIP6 (ref. \(^\text{15}\)) for the SSPS-8.5 future scenario, a high emission scenario with high mitigation challenges but low adaptation challenges. The HadGEM3-GC31-MM model operates on a N216 grid with a nominal horizontal resolution of 60 × 90 km (spanning the globe over 432 columns in longitude and 324 rows in latitude) and an internal simulation timestep of 15 min (ref. \(^\text{55}\)). The time series are modelled as regularized as the mean of all daily-average DP magnitudes (of which there are 360 days × 15 yr × 4 model realizations = 21,600 values), whereas the RDP vector was calculated as the vector sum of all the daily-average DP vectors.

Calculation of sand drift regime parameters
For every day in each dataset a daily average DP vector was derived for each N216 grid cell from the four wind variables. The scalar magnitude of average DP is defined as:

\[
DP = \langle U^2 (U - U_t) \rangle, \quad U_t > 0
\]

where \(U\) is the surface wind speed at 10 m above the ground (m s\(^{-1}\)), and \(U_t\) is its threshold for the initiation of sand transport. We used a threshold of \(U_t = 6.2 \text{ m s}^{-1}\), which is equivalent to the impact threshold shear velocity for \(D_0 = 0.3 \text{ mm median grain size}\) quartz sand extrapolated via a logarithmic velocity profile from a Nikuradse roughness length \(z_0 = SD_{50}/30\) to the 10-m-height wind speed. This same threshold is typically used in DP studies\(^\text{3,5,28,29}\). As sand transport is a cubic function of wind speed that involves a threshold, the temporal resolution of wind data has a critical impact on DP estimates, progressively underestimating the DP with longer wind speed averaging times due to the filtering out of high wind speed events that contribute disproportionally to sand drift. The standard timescale for DP calculations is the 10 min temporal resolution of World Meteorological Organization wind speed recordings, but CMIP6 climate models only provide three-hourly wind speed data at best, which leads to an underestimation of DP by 10–35% (ref. \(^\text{3}^\text{,5}\)). Instead, we calculated the daily average DP from the reported daily mean wind speed and maximum wind speed by deriving a two-parameter Weibull probability density function (PDF) with a shape parameter, \(k\), and a scale parameter, \(\lambda\), where we equated the mean of the PDF to the daily mean wind speed, and we equated the \((1 - (1/96))\) percentile of the corresponding cumulative distribution function to the maximum wind speed, which is associated with an internal modelling time span of 15 min (96 such time spans in a day). The Weibull PDF is the statistical distribution that best represents meteorological wind speed data\(^\text{32,23}\). We took the thus-derived PDF to draw 144 random samples of 10 min wind speeds, averaged over 25 realizations, to calculate the DP magnitude using equation (1) (the difference between Weibull PDFs at a 15 min timescale versus a 10 min timescale is negligible).

The vector direction of the daily average DP was determined from the zonal and meridional daily averaged wind velocity reported for the grid cell, linearly interpolated from the Arakawa C grid used in HadGEM3 to the centroid of the cell to correspond with the DP magnitude. The overall DP in a grid cell for a 15 yr period was calculated as the mean of all daily-average DP magnitudes (of which there are 360 days × 15 yr × 4 model realizations = 21,600 values), whereas the RDP vector was calculated as the vector sum of all the daily-average DP vectors.

Testing of our ‘mean–max’ method to calculate DP magnitude on real-world 10 min meteorological data that spanned ~15 years and 25 stations indicated a root mean square error of only 2.4 units and an average 7% underestimation in comparison with full-scale granular calculations directly from the ‘raw’ 10 min data (Supplementary Section B), which suggests that the method is sufficiently robust for application to CMIP6 global climate model data. As the DP equation is the functional core of a traditional sand transport formula\(^\text{16}\), DP units can be converted into a sand flux using a suitable coefficient. For standard 0.3 mm median grain-size quartz sand, DP = 10 is equivalent to a saturated sand flux of 6.23 m\(^3\) m\(^{-1}\) yr\(^{-1}\) (assuming a sand bulk density of \(1,600 \text{ kg m}^{-3}\)). Some studies report DP values derived from wind speed data in knots (nautical miles per hour): note that one metric DP unit (m\(^3\) s\(^{-3}\)) is equivalent to 7.34 nautical DP units (‘knots-cubed’).

Comparison with ERA5 data
We compared DP values derived from the 2000–2015 hindcast simulations of the HadGEM3 model to DP values calculated from the ECMWF (European Centre for Medium-Range Weather Forecast) Reanalysis V5 (ERA5) surface (10 m height) wind data for the same period and the variables ‘10 m wind component’ (zonal) and ‘10 m wind component’ (meridional). ERA5 is a globally complete and consistent gridded reanalysis dataset with a high spatial resolution of ~30 km and temporal resolution of 1 h (ref. \(^\text{56}\)) and may be considered the best global dataset of past weather conditions\(^\text{57}\). ERA data were used successfully to replicate sand flux estimates derived from local meteorological station time series\(^\text{58}\), and HadGEM3 was previously found to have small anomalies with ERA5’s surface wind data compared with those of other CMIP6 models\(^\text{15}\). We used an approach to derive the daily average DP similar to our method for HadGEM3 data, except that we fitted a Weibull PDF through the 24 hourly scalar wind speed values from ERA5 and then resampled 144 wind speeds from that PDF to generate a 10-min-scale daily average DP. Note that wind speed data in ERA5 represent ‘instantaneous’ winds, not hourly averages, and so the PDF derived from these data does not filter out high wind speed events. The direction of the daily average DP vector was determined from the daily averaged \(u\) and \(v\) components.

As the ERA5 grid is at a higher spatial resolution than the N216 grid used in HadGEM3, the DP values at ERA5 grid nodes were linearly interpolated and upscaled to the areal-weighted average inside each N216 grid cell for comparison with the HadGEM3 results. The regression on DP values from ERA5 versus those from HadGEM3 for all the N216 land surface grid cells returned a goodness-of-fit \(R^2\) of 0.81 and a proportionality coefficient of 1.07, which we deemed sufficiently close to unity to avoid applying a scaling factor to the HadGEM3 results.

Dune field inventory
We used current satellite imagery in Google Earth Pro to visually assess the presence and estimate the areal extent of active desert dunes of four generalized types in each of the 9,498 grid cells of the HadGEM3 model domain located over land surface in the arid zone between +60° and −60° latitude. The arid zone was defined as the B zones in the Köppen–Geiger climate classification system, taken from Beck et al.\(^\text{59}\), and land surface grid cells were defined as containing 50% or more land fraction (as opposed to water). Mobile desert dunes were identified as having fully bare sand surfaces, sharp crest lines and slip faces, and showing a displacement or change in shape over multi-period imagery where available. We used a first-order classification to distinguish between four main desert dune types that are typically recognized\(^\text{60–62}\): barchan, transverse-crenscient, linear-seif and star dunes, and we only considered the spatial scale of individual dune bedforms that can respond to the decadal sand drift regime (a few 100 m or less), rather than large-scale sand sea structures, such as megadunes, draas and transgressive ridges that evolve over centuries. For each dune type present in a grid cell we estimated its areal extent in four classes: localized pockets.
(<10%), sparse (~30%), partial (~50%) and full (~80%) coverage. Where possible, we inferred the overall migration direction of the dunes from slip-face evidence and the spatial structure of dune fields, according to eight cardinal–ordinal compass directions (N, NE, E and so on). We found mobile desert dunes in 2,191 arid-zone grid cells, with barchan dunes present in 843, transverse-crescentic dunes in 1,441, linear-seif dunes in 1,008 and star dunes in 401. Further statistics are reported in the main text. See Supplementary Section A for further elaboration on the dune inventory, which includes many imagery examples.

**Sand roses**

Sand roses shown in the figures are generated following the conventions of Fryberger and Dean [53], based on the daily DP vectors (N = 21,600 for each grid cell). Each of 32 azimuth sectors (11.25° wide) shows the average daily DP from that direction, weighted by its time fraction. The sum of the weighted average daily DP over all sectors is equal to the overall DP for the whole 15 yr period. RDP vectors are indicated by red arrows in Fig. 3. Note that DP per sector indicates the direction the sand drift is coming from (as per a conventional wind rose), whereas the RDP vector shows the resultant direction that sand drift is moving toward.

**Statistical testing**

Statistical testing for significance was conducted on two sets of results: (1) changes in DP between 2000–2015 and 2085–2100, and (2) changes in RDDir between these two periods. In both cases, a test determined the statistical significance of the difference in the means derived from the 60 annual values (four replicates of 15 yr) of the variable from the hindcast simulations versus the 60 annual values from the end-of-century simulations, for each grid cell. For changes in DP, a t-test was applied as the data within each period were mostly normally distributed, but not assuming equal variance. For changes in RDDir, a one-way multivariate analysis of variance test was applied with the angular direction decomposed into two dependent coordinate variables, x and y, on the unit circle. Both types of testing assumed a statistical significance at the 95% level (P < 0.05).

**Data availability**

The source data analysed in this study are publicly available at the following sites: HadGEM3-GC31-MM in the CMIP6 repository from the World Climate Research Programme (https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/) and ERA5 hourly data on single levels from 1979 to present from the Climate Data Store—Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview). The datasets of predicted sand drift regime parameters generated in this study are available in the Supplementary Information as Google Earth layers. The datasets of the arid zone mobile dune survey and the sand drift regime parameters are further available in the repository https://doi.org/10.18742/c.6194551.

**Code availability**

Data processing and analysis scripts (written for Matlab) are available in the repository https://doi.org/10.18742/c.6194551.

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**Author contributions**

A.C.W.B. and L.A.D. conceived and designed the study, and collected and analysed the data. The manuscript was written and prepared by A.C.W.B.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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