



Edited by
Ian Livingstone
Andrew Warren

AEOLIAN GEOMORPHOLOGY

A New Introduction

WILEY Blackwell

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Edited by

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Preface

Two decades after our first edition, we find aeolian geomorphology to be very much more vigorous. Our mandate is to organise and summarise the advances this vigour has brought.

While we alone wrote our earlier volume, we have now enlisted 16 new contributors, from four continents. The expansion in authors allows us to tap a much wider range of expertise and the insights of specialists. In some cases, as with 'dust', this allows us to separate contemporary lifting and transport of dust from its deposition 'loess', a process that took place over many thousands of years. In the case of 'dunes', we can now separate 'free' dunes (generally unvegetated) from 'anchored' dunes formed where there is a limited covering of plants. In the case of 'planetary landforms' we have introduced a topic that barely existed at the time of our first edition. All the chapters demonstrate huge advances in field observation, measurement, and mathematical modelling. Many, particularly Chapter 8 on sand seas, show the impact of greatly enhanced and accessible remote sensing; others (as in Chapter 6 on active dunes) bear the impact of improvements in field techniques; yet others (especially Chapter 5 on loess) show the power of greatly improved laboratory techniques.

Few aeolian processes operate in isolation from other geomorphological process

domains, as on slopes and coasts, in rivers, glaciers, and periglacial environments, let alone the related geological processes that operate over much greater time-scales. The full understanding of most aeolian processes requires knowledge of the processes that pre-sort sediment to sizes that can be moved by the wind. In their turn, aeolian processes deliver sediment to fluvial, marine, or glacial processes. These interactions take place over a range of temporal or geographical scales. At a small scale, the deposition of aeolian dust stimulates other geomorphological processes such as the development of rock varnishes or stone pavements. At a very much larger scale, crustal uplift may stimulate erosion that may find its way to places from which it is removed by the wind. Our authors have highlighted many of these interactions and overlaps between geomorphological domains. Our hope is that a fuller appreciation of aeolian processes will broaden our understanding of the evolution of whole physical landscapes, the goal of all geomorphologists.

We believe that the 12 chapters provide a comprehensive new introduction to aeolian geomorphology. We are indebted to all our authors for contributing their expertise.

Ian Livingstone, 'Whitstable'
Andrew Warren, Farringdon

1

Global Frameworks for Aeolian Geomorphology

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1.1 Introduction

This chapter locates aeolian geomorphology in four global frameworks, arranged in increasing scale. The first is the framework of contemporary winds, from local to annual. The second is the changing erosivity of the wind and the erodibility of the surface during recent geological history. The third, digging deeper into the past, is the framework of the preparation and supply of sand and dust to the wind. The fourth, covered very briefly, is the yet wider and older framework of plate-tectonics. Box 1.1 is a short early history of aeolian geomorphology.

1.2 Wind

Chapter 2 of this book, 'Grains in Motion', covers the shortest, smallest and most fundamental of aeolian rhythms, leaving larger-scale processes and their longer rhythms to be introduced in this chapter.

1.2.1 Wind Systems with Daily Rhythm and Local Scale

1.2.1.1 Dust Devils

The scientific term, dust devil, is a close translation of *Dhūla kā śaitāna* in the North Indian languages from which it was borrowed. Most dust devils blow in daytime,

reach diameters of a few metres, last for a few minutes and travel a few hundreds of metres; a few are larger, longer-lived and further-travelled. Some dust devils leave shallow tracks, most do not (see also Chapters 4 and 11).

1.2.1.2 Haboobs

A haboob (هَبُوب, 'blustery wind' in Sudanese Arabic) is, in the contemporary climatological literature, a dusty, mobile thunderstorm that develops when and where warm, moist air is taken to otherwise hot, dry, sparsely vegetated, dust-yielding environments, as in central Sudan and Arizona. A 'cold pool' develops at ground level within the thunderstorm and this pulls a strong downdraft. When the downdraft hits the ground, it bursts out horizontally at velocities of up to 20 ms^{-1} . These gusts raise a large amount of dust from the surface, if it is available. The outer edge of the dust cloud is often a sharply-defined, mobile 'wall' of dust. Most haboobs develop late in the day and last for less than a day. A haboob in Arizona on 5 July 2011 maintained a width of $\sim 10 \text{ km}$, but elongated to $\sim 80 \text{ km}$, as it moved slowly east-south-eastward (Raman et al. 2014). Haboobs carry and redeposit large amounts of dust, some held down and redistributed by the accompanying rain (see also Chapter 4).

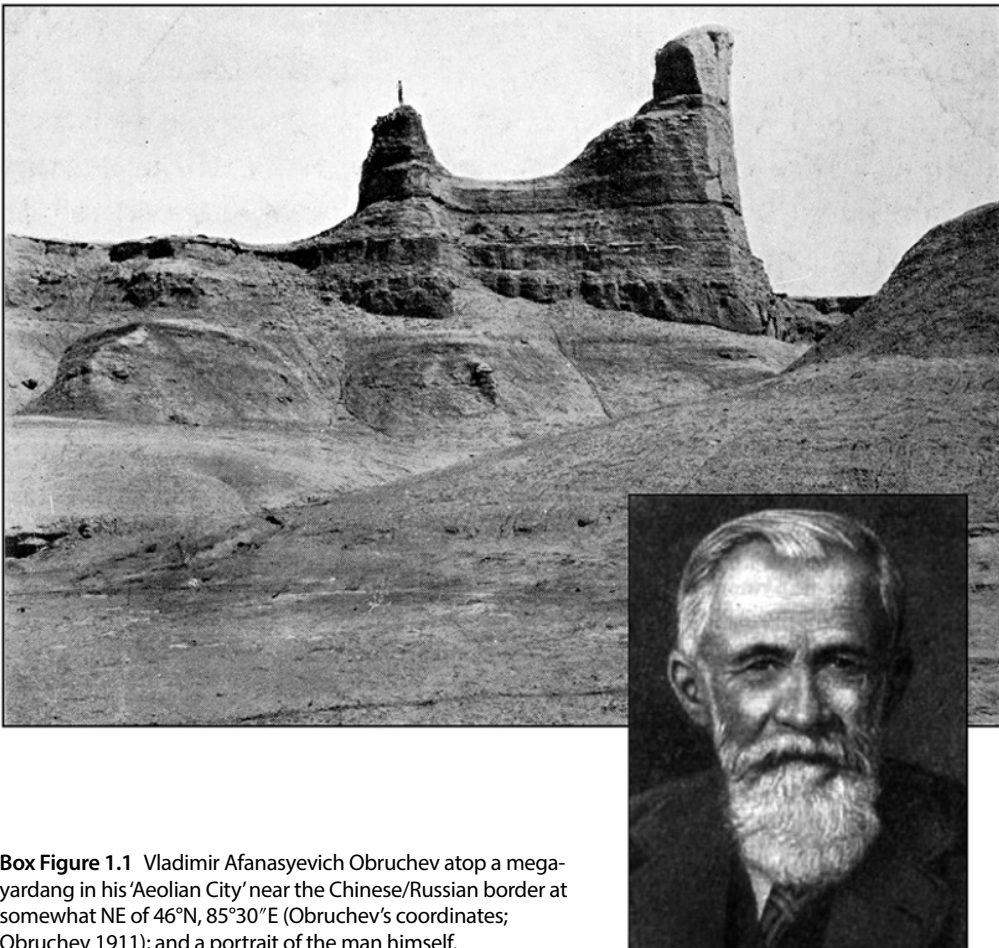
Other 'cold pool' phenomena operate and lift dust in three other situations. First, density currents flow down mountain slopes,

Box 1.1 A Short Early History of Aeolian Geomorphology

It was not until the late nineteenth century, even the early twentieth century, that a significant number of geo-scientists acknowledged that the wind was a major geomorphological agent. Rivers had been recognised in that role early in the century, particularly by Charles Lyell in his influential *Principles of Geology* (1875, first edition 1830). Lyell maintained that loess had been deposited by a flood, even the biblical Flood, not as dust, and ignored more obviously aeolian landforms. Despite pioneers like Udden (1894), Berg could still maintain that loess was a deep soil as late as 1916.

The principal catalyst to the aeolian enlightenment was the opening-up of the world in the

late nineteenth century, particularly its deserts. But experience, alone, was insufficient to come to a defensible interpretation. Keyes (1909), well acquainted as he was with the deserts of the western USA, could still assert that the wind could level mountains. More astute interpretation of direct observation, now of the Chinese loess, led both by von Richthofen (e.g. 1882), and the more influential 'aeolianist', Obruchev (e.g. 1895, Box Figure 1.1), to conclude that it was a deposit of aeolian dust. Obruchev's observations on the deserts of central Asia, which he traversed on horseback, included wind-eroded terrain, and the dust-filled skies he experienced, strengthened his belief in the power of the wind. He went



Box Figure 1.1 Vladimir Afanasyevich Obruchev atop a megalaydang in his 'Aeolian City' near the Chinese/Russian border at somewhat NE of 46°N , $85^{\circ}30'\text{E}$ (Obruchev's coordinates; Obruchev 1911); and a portrait of the man himself.

further to propose that loess-sized particles could have been created either by glacial grinding, which is non-aeolian (much debated; Chapter 4); or by the grinding of wind-driven sand (a fully aeolian process), an idea which, although contested for decades, is enjoying rebirth (Crouvi et al. 2010). The location of some 'desert loess' (in southern Tunisia) is shown on Figure 1.12. The early study of loess is further discussed in Chapter 5.

First-hand experience and critical interpretation also had a crucial role in shaping opinions about desert dunes. The pioneers here were a succession of French observers of the sand deserts of northern Africa, beginning with Rolland (e.g. 1890), who had been sent to reconnoitre the route of a trans-Saharan railway through southern Algeria. Rolland argued that the dunes he saw, some large, were wholly the work of the wind, and had been aligned by the wind. He even speculated about the sources of the dune sand, and the distribution of sand seas, questions still asked. Rolland's ideas were developed by later French geomorphologists, particularly Aufrère (1930), whose work reached an international audience. There were still some blind alleys in the search for explanations of dunes, such as Vaughn-Cornish's wave theory (Goudie 2008), but in

the 1930s two major revolutions in aeolian geomorphology were about to break.

In the early twentieth century, although it was generally accepted that the wind could erode, move, and deposit sediment, few asked how it did so. The gap in knowledge was dramatically narrowed by Bagnold (e.g. 1941), who, like Obruchev, had traversed many wind-formed landscapes, in his case in south-west Asia and north-eastern Africa, and now travelling by motor car (Bagnold 1990). As an engineer, Bagnold focused mathematical modelling and experiments onto aeolian processes (Bagnold 1941; more in Chapter 2). He was probably the first to use a wind tunnel to study the movement of sand, and more certainly the first to study the mechanism of sand movement in the field (Box Figure 1.2). His wind tunnel was replicated by the Wind Erosion Research Unit in Kansas (see Chapter 12). In the Soviet Union, Znamenski (1958), who also replicated Bagnold's design of wind tunnel, quoting him as "Bagnolg". Bagnold's book is still the most commonly cited source in aeolian geomorphology. Development of many his ideas had to wait for decades (Chapter 2). One of his few excursions into application is described in Box 12.1 in Chapter 12. Bagnold is quoted in most of the chapters in this book.

Box Figure 1.2 Ralf Adger Bagnold measuring the wind-speed profile and the flux of sand, near 'Uweinat in southwestern Egypt in February 1938. Source: Photograph: R.F. Peel.



Wind measurements being made with my multiple manometer in a sand storm near Gilf Kebir, 1938. The sand collector is in the middle ground. Photograph by Ronald Peel.

The early twentieth century also saw a slower, more diffuse revolution, driven by the discovery of large areas of inactive aeolian terrain, as a by-product of the growing realisation of the extent of Pleistocene climatic change in other fields of geomorphology. Pioneers in the study of these terrains and deposits included Cailleux (e.g. 1936) in respect of mainly northern Europe (but also some more exotic places); others worked on evidence from West Africa (summarised in Grove and Warren 1968), and yet others in North America, for example, Leighton (1931) on loess. At first, the dating of these 'fossil' landscapes had to rely on stratigraphy and palaeontology, a problem that was overcome, first, by radiocarbon dating (Libby

1952), and three decades later by luminescence dating, which is better suited to generally inorganic aeolian material, and has a much greater historical reach (Chapters 5 and 10). Other methods, like the use of cosmogenic isotopes, came still later and have even greater historical reach (Vermeesch et al. 2010).

Many more techniques have now made significant contributions to aeolian geomorphology: remote sensing, which has opened new vistas on dune form, and the local generation and the global movement of dust (Chapter 4), mathematical modelling of the movement of sediment and of the form of dunes (Chapter 6) and much more, as explained in the chapters that follow.

and some of these raise dust on the plains below. On the southern slopes of the Atlas Mountains in Morocco, these events occur about eleven times in a year, between April and December; they have the same spatial scale as haboobs (Emmel et al. 2010). Second, similar density currents may bring momentum and feed dust to the landward phases of sea breezes (discussed later). Third, cold pool atmospheric outflows are the main mechanism for raising dust in the central Sahara (Allen et al. 2013). None of these events leaves an obvious pattern on the ground.

1.2.1.3 Low-Level Jets

Low-level jets are strong winds limited to a small area. The two examples described here are from the drylands. Both are constant in direction and strongest at night.

On the Pampa la Hoja in southern Peru (just south-west of Arequipa, marked on Figure 1.5), a low-level jet is sometimes active over a plain with an area of ~ 50 km downwind by ~ 4 km (Lettau and Lettau 1978). The Pampa is a plateau with very little relief that slopes gently up towards the east and which is virtually free of vegetation. The jet drives small, widely dispersed, very symmetrical, fast-moving barchan dunes eastward over the pampa ($16^{\circ}41'S$; $71^{\circ}51'W$;¹ eye altitude

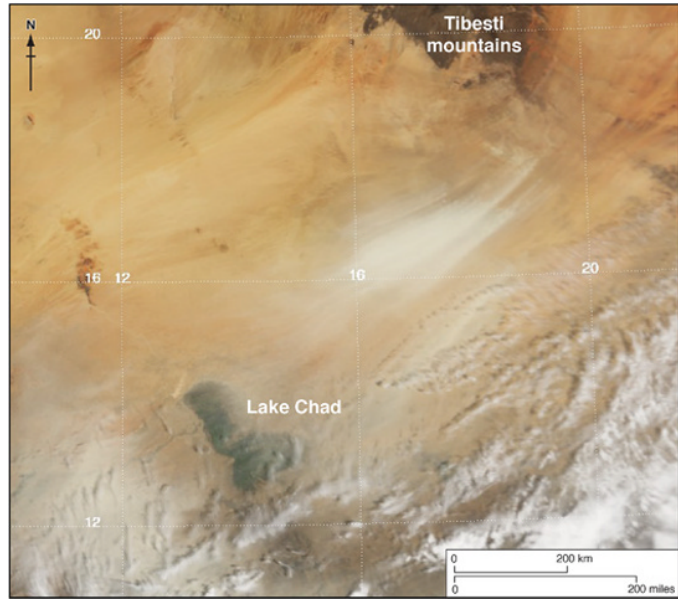
2.5 km^2). The movement of the barchans is so closely related to the wind-speed, that the Lettaus could use their movement as anemometers (there is more on the movement of barchans dunes in Chapter 6).

The Bodélé low-level jet in northern Chad blows in another very dry part of the world (Figure 1.1, located on Figure 1.12). It boasts two aeolian superlatives: the dustiest place on Earth (Warren et al. 2007) and the fastest dunes on Earth (Vermeesch and Drake 2008). There is more on this in Chapter 4.

1.2.1.4 Sea Breezes

Sea breezes (Figure 1.2) blow onto any coast that has a large enough contrast between the thermal capacities of the land and of the water. They are thus more active in summer, at low latitudes, on warm coasts washed by cool currents, and on landmasses above some a minimum size, depending on local contrasts in temperature. They blow onto the coasts of oceans, seas, and lakes (selected locations on Figure 1.5). Sea breezes on the shores of smaller bodies of water, like Lake Erie, reach only a few kilometres inland (Sills et al. 2011). On the south-western coast of Western Australia, where, in summer, there is a strong contrast in temperature between

Figure 1.1 The Bodélé low-level jet in operation, raising a cloud of dust from the now-dry surface of a Holocene Lake. (MODIS true colour composite (channels 3, 4, and 1) image for 12:45UTC, 4 March 2005). See insert for colour representation of this figure.



the ocean and the land, the sea breeze reaches over 600 km, east to Kalgoorlie.

Sea breezes blow on-shore in the morning, their velocity peaking at a sharply defined 'sea-breeze front'. At night, the wind is seaward and gentler (Furberg et al. 2002). Tsoar (1983) followed a linear seif dune (Chapter 6) in Sinai as it grew under the influence of a sea-breeze in summer and the Westerlies in winter. His site was some 60 km inland (in the direction of the breeze). In summer the sea-breeze front arrived dependably, suddenly and to a welcome, at lunch time.

Sea breezes help to build dunes behind many other coasts, as in Oregon (44° 04' 15 N; 124° 07' 33 W; Hunter and Richmond 1988); and Lençóis Maranhenses in north-eastern Brazil (02° 30' S; 42° 52'; eye altitude 20 km; Parteli et al. 2006). On the Makran coast in Pakistan, and probably on other steep coastal hinterlands, the seaward phase of a sea breeze may be strengthened by a cool density current (see Section 1.2.1.2), which carries small plumes of dust out to sea.

1.2.1.5 Hurricanes, Cyclones, Typhoons

Hurricanes (Carib: *Hurican*) (Figure 1.3) in the Atlantic, tropical cyclones in the Indian

Ocean and South Pacific, or typhoons in north-western Pacific (台風 in Japanese) are everyday names for the same phenomenon. Diameters are ~300 km, varying considerably between hurricanes and their state of development. Wind speeds also vary widely, between and within hurricanes; in which, at their worst winds can reach at least 80 m s^{-1} .

Hurricanes form over the ocean where it is warm enough, which is, roughly, within 5° of the Equator; and where there is a source of vorticity, such as a thunderstorm. Some hurricanes sweep along shorelines, bringing different wind speeds from place to place and time to time, as did the very destructive Hurricane Sandy along the coasts of New Jersey and New York State in 2012 (Figure 1.3). Others travel at a more acute angle to the shore, their velocity dropping rapidly inland, as did Hurricane Katrina on the Louisiana coast in August 2005. If still at sea, hurricanes travel towards the appropriate pole and decelerate.

The high winds, huge waves, torrential rainfall, and storm surges of hurricanes can move great quantities of sand from coastal dunes, taking it inshore, along-shore or off-shore. This damage is usually repaired before

Mean hourly hodographs averaged over all sea breeze days for each station

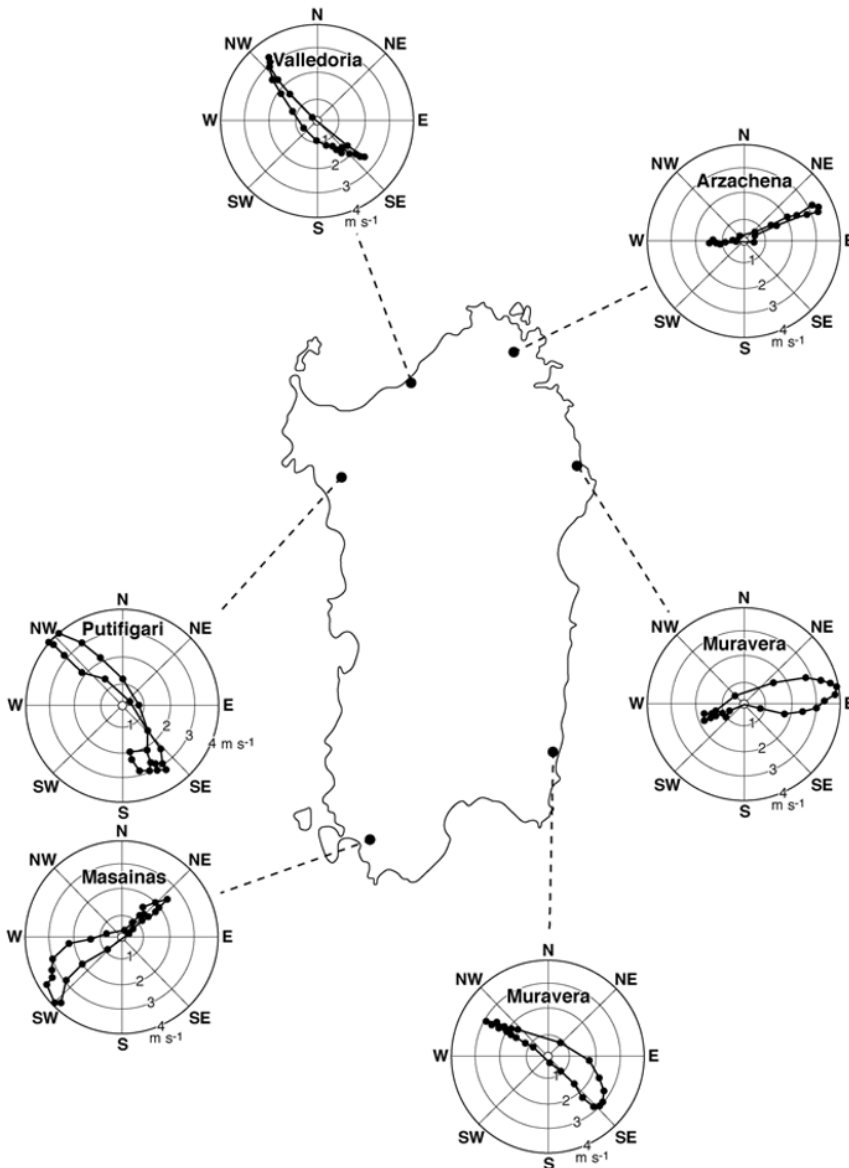


Figure 1.2 Sea breezes on the Sardinian Coast. Source: A selection from Furberg et al. (2002).

the next hurricane attacks by onshore sea breezes (see Section 1.2.1.4), as on the coast of Texas, after the attack by Hurricane Alicia in 1983 (Houser et al. 2015). But, as the Earth warms, attacks may have already become more frequent, and thus allow less time for

recovery. The global distribution of hurricanes has already moved towards the poles (Stephens 2011). Wind-driven waves, despite their aeolian origin, are generally classified as ‘coastal’ rather than as aeolian geomorphological processes.

Figure 1.3 Hurricane Sandy off the Atlantic coast of the USA in October 2012. Glimpses of the east coast of the USA that it attacked can be seen.



1.2.1.6 Mountain Winds

Mountain winds may sometimes reach the same velocity as severe hurricanes but few do. They occur in all global wind systems. There are four types of mountain wind.

First, on high mountains, high winds may blow for days and many are strong. They lift and carry large quantities of snow, which they build into cornices in the lee of ridges. They also form wind-erosional features or *sastrugi* on ice-free and snow and ice surfaces (see Chapter 3). On gently sloping ground they build snow dunes.

Second, are the winds that are accelerated through mountain gaps. North of Rawlins, Wyoming, strong winds blow through a ~5km-wide defile through a range of hills, through which they drive very fast-moving parabolic dunes (see Chapter 8) (42°12'N; 107°04'W eye altitude 12km; Gaylord and Dawson 1987). Other defiles in Wyoming hold more fast-moving dunes.

Third, katabatic or 'downslope' winds, *sensu stricto*, are driven by differences in air density, most related to differences in temperature (as between high and low ground). Examples are the Santa Ana in southern California, and the Berg winds in South Africa (both named on Figure 1.5; the

association of high winds downwind of mountain ranges, worldwide, is shown on Figure 1.8). Chapter 6 briefly describes the effects some of these winds have on dune form. Velocity is greater in winds that have steeper descents, and in constricted valleys and passes. These winds are, in general, strongest in winter (Muhs et al. 1996 p. 129). East of the Rockies, katabatic winds reach ~700km over the plains beyond. Chapter 6 briefly describes the effects on dune form of katabatic winds blowing over the steeply scarp edge of the African Plateau. The fiercest katabatic winds blow down the steep slopes of the Antarctic and Greenland ice plateaux (van den Broeke et al. 1994), driven by the great masses of very cold, very dense air on the plateaux (Figure 1.4).

In the San Geronio Pass in California, the Santa Anna hurled sand, and thus eroded blocks of Lucite in an 11-year experiment (Sharp 1980). Katabatic winds in Antarctica reach much greater velocities, and carve out huge fields of wind-erosional features in ice (*sastrugi*, see Chapter 3) (Bromwich et al. 1990) and drive a unique aeolian landform on the coast: dunes formed of pebbles with diameters of about 1.9cm, which, it is claimed, could only have been moved by

Wind roses for Halley and automatic weather stations C2 and C4

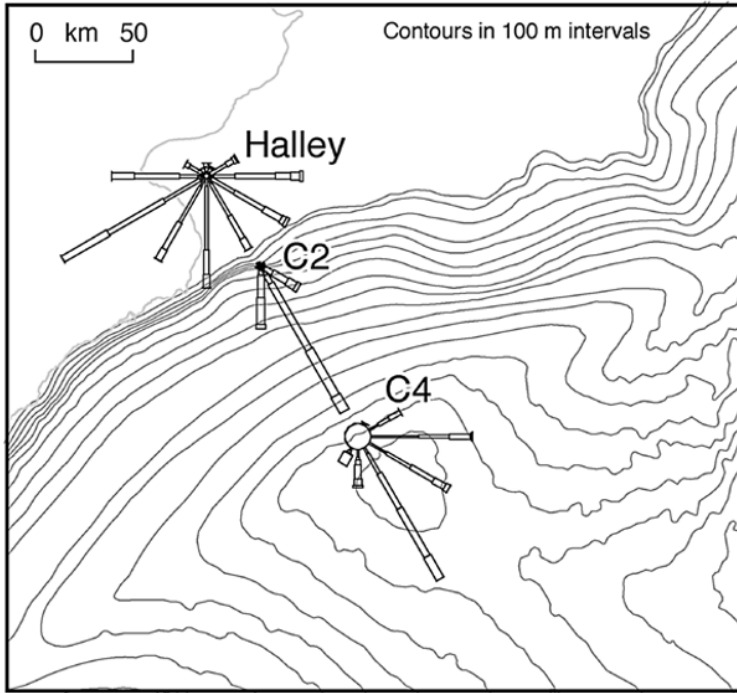


Figure 1.4 A wind rose for a station experiencing katabatic winds descending from the Antarctic Plateau (Renfrew 2004). Wind speeds in 5 m s^{-1} bins from 0.1 to 30 m s^{-1} .

winds of $>54 \text{ m s}^{-1}$ (Bendixen and Isbel 2007). In the Pleistocene, katabatic winds formed ventifacts on the margins of the expanded ice sheets (see Chapter 3).

Fourth, föhns are *sensu lato* katabatic, in that they blow downhill, but they develop only where and when warm, wet air, as in a cyclonic system, releases its moisture as it climbs up the upwind, generally western or southern, slope of a mountain massif, to descend in the lee as a warm, dry wind, which may carry dust (as in the Alps, where the name belongs). Föhns on the western Canadian prairies (locally: ‘Chinooks’) have eroded distinctive gullies on the bluffs of the Old Man River near Lethbridge in Alberta ($49^{\circ} 40' \text{N}$; $112^{\circ} 51' \text{W}$, eye altitude 14 km). The gullies on either side of the river are aligned with the Chinook, rather than with usual the dendritic pattern of fluvial tributaries. Beaty (1975) believed that the

gullies were relics of stronger Chinooks of the past. Many Alpine föhns carry and deposit dust taken from North Africa by cyclonic systems.

1.2.2 Wind Systems with Annual Rhythms and Semi-Global Scale

1.2.2.1 Westerlies

The Westerlies are active between approximately 30° and 60° , north and south (Figure 1.5). They carry cyclonic (frontal, low-pressure) systems, in which the winds are strongest in winter. In these systems, winds are very variable in direction (Figure 1.6). Most Westerlies carry enough moisture to ensure that the land surfaces over which they blow are protected by vegetation, which reduces erosion to a very low level (Figure 1.7).

There are places and situations, nonetheless, where and when the westerlies move

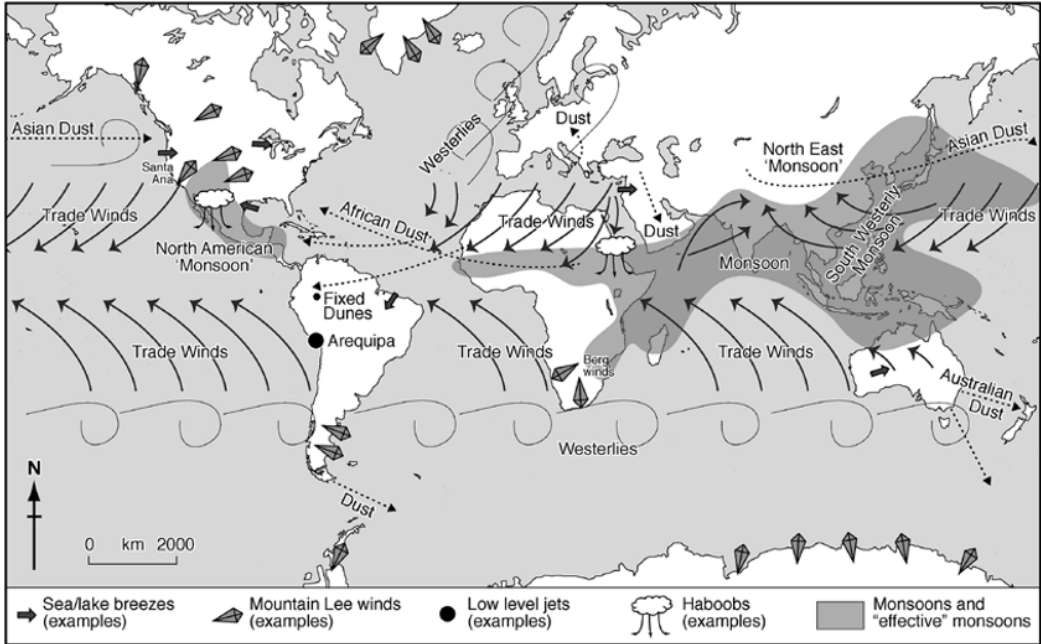


Figure 1.5 Global and selected local wind systems, dust pathways, etc.

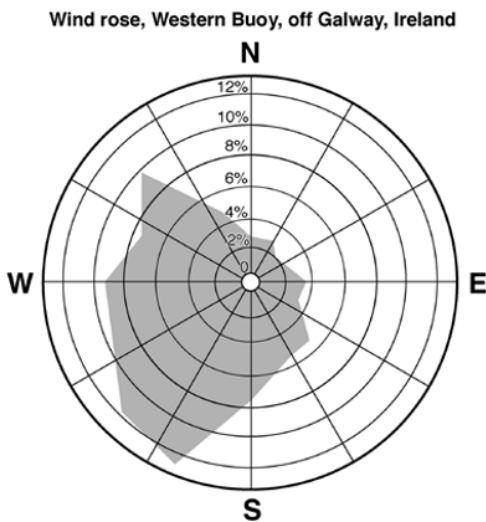


Figure 1.6 Typical wind rose for the Westerlies: at the 'Western Buoy' off Galway on the west coast of Ireland, showing a dominantly south-westerly flow, but also the great spread of wind directions, associated with the passage of low-pressure systems. Percentage figures on this, and subsequent wind roses, are for the percentage of annual observations of winds from that sector.

sand and raise dust. Large amounts are moved, for example, on west-facing macro-tidal shores, as on the coasts of Oregon, Chile, Ireland, and France (Figure 1.8). Many of these coasts also experience macro-tidal seas, which regularly expose large areas of bare sand to the wind. Much of this sand is blown ashore to coastal dunes. In southwestern France, Late Pleistocene and Holocene Westerlies drove coastal sand 125 km inland (Bertran et al. 2011). Inland, smaller amounts of sand are blown to dunes in the dry parts of Iceland and Patagonia (Mountney and Russell 2004; Del Valle et al. 2008). The westerlies also move sand and dust when they encounter sandy soil on fields cleared for cultivation (see Chapter 12).

On their southern flanks, the Westerlies also carry large quantities of dust, although much less than the Harmattan. The first of these areas is in the Mediterranean, where the tracks of the frontal systems shift south, most often in the winter or spring. There, they meet the dry, sparsely vegetated,



Figure 1.7 Global land cover, the principal global control of wind erosion. Darker areas have more land cover. Unless disturbed, all land except those with the sparse vegetation in arid lands, is protected from wind erosion and transport. Source: Based on: <http://www.esa-landcover-cci.org/?q=node/158>.

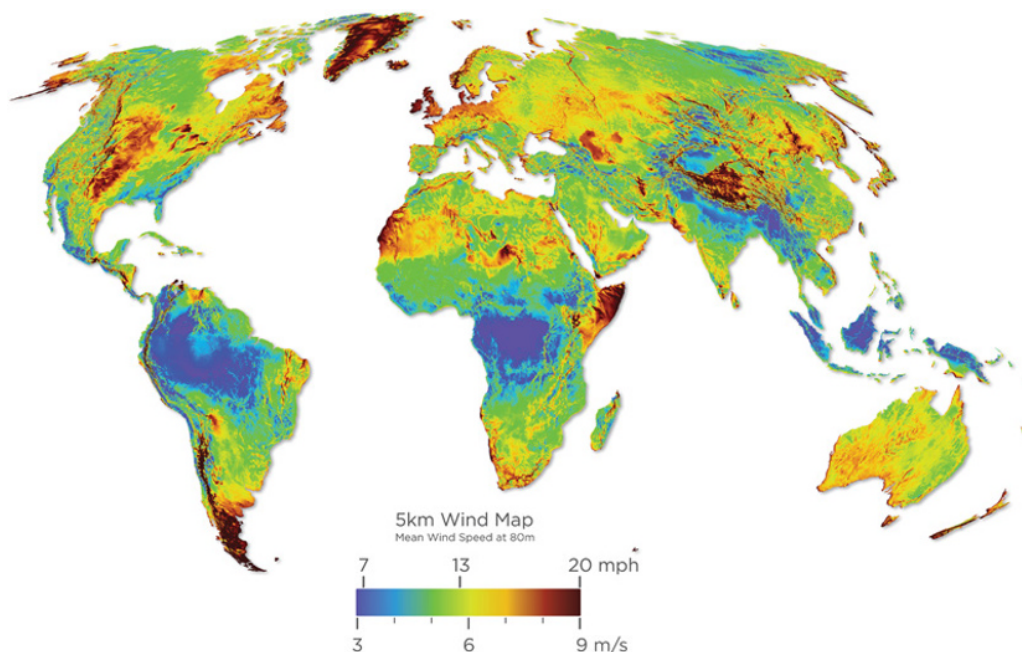


Figure 1.8 Global distribution of wind speed. The map shows average annual wind speed at 80 m above-ground at a 5 km spatial resolution. Wind-speed declines towards the ground, at a rate determined by, among other things, surface roughness (a much fuller explanation is given in Chapter 2). Thus, the map shows only the global pattern of relative differences in wind speed. The map is available at: http://www.3tier.com/static/ttcms/us/images/support/maps/3tier_5km_global_wind_speed.pdf. The average wind speeds are based on over 10 years of hourly data developed with computer model simulations that create realistic wind fields. The wind speed dataset compares well with observations from over 4000 NCEP-ADP network stations. Source: The second section of this caption is a shortened version of text provided by Vaisala Inc., 2001. See insert for colour representation of this figure.

dust-yielding parts of North Africa (Figure 1.5.). When they reach Europe, the best-known term for these dusty winds is the *Sirocco* (of which more later in Section 1.4.4); or in Libya they are *Ghibli* (جبلي); and in Egypt and in the Levant, *Khamsin* (خمسين) or the *Sharav* (שרב). Dust is also raised by cyclonic systems on their southern flanks in North America and Australia (see Chapter 4). The main beneficiaries of this dust are soils on the northern flanks of the tracks of these cyclones (Yaalon 1997). Some of the dust joins föhn winds (see Section 1.2.1.6), and some escapes further north to southern England, as it did on 12 December 2015, and sometimes beyond.

Winter frontal dust storms also plague Iraq, Iran, and northern Arabia, but the better-known and dustier wind, also blowing from the west, is the summer *Shamal* (شمال), a wind that is driven by the difference between high pressure in the west and monsoonal low-pressure in the east. Winter and summer in these areas, westerly winds are accelerated as they come up against the mountains of southern Turkey and Iran before they meet the very dry and dusty alluvial plain of southern Iraq (Hamidi et al. 2013), as the intruders in the Second Gulf War discovered to their cost.

Yet more dust is raised on the pole-ward flanks of the Westerlies, as in eastern Iceland (Mountney and Russell 2004), and Patagonia. In the Patagonian winter, some of this dust joins cyclonic systems in the Westerlies to become the dusty *Pampero*, which is strongest in early summer, and may reach southern Brazil.

1.2.2.2 The Trade Winds

The Trades blow between approximately 30° and 10°, north and south (Figures 1.5 and 1.9). ('Trade' is apt in an aeolian-geomorphological context as it meant 'movement' in old English.) In the sub-tropics, their pathways curve towards the equator in both hemispheres, clockwise in the north, anticlockwise in the south. In the eastern Sahara, the curve is made visible by the borders of sand seas,

barchan-dune 'trains', and wind-eroded features, which are evident even on small-scale scenes on Google Earth, creating the most unmistakable aeolian imprint of the wind on the Earth's land surface.

The Trades probably move much more sand than any other wind system, local or global (their nearest competitor is probably the north-east monsoon in western China, see Section 1.4.4). They are fastest and steadiest on the Atlantic coasts of Morocco and Western Sahara (Figure 1.8), where they drive trains of fast-moving barchans (Elbelrhiti 2012; Figure 1.5 and Chapter 6); and in parts of the Western Desert of Egypt (Stokes et al. 1999), where they blow sand into the oases of El Kharga (Chapter 12, Box 12.1), and blew for the first field measurement of blowing sand by Brigadier Bagnold in 1938 (Box Figure 1.2).

The Trades are strongest in winter, when their trajectories move bodily towards the equator. They weaken in summer, as they are nudged towards the poles by the monsoons (Section 1.2.2.4). Figure 1.9 shows seasonal variation in direction and strength of the Trades, which may explain the extensive

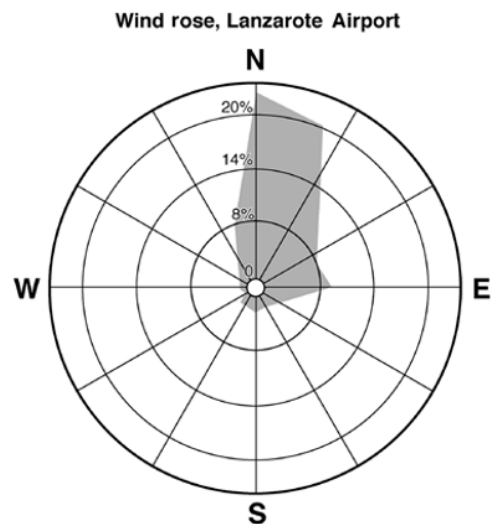


Figure 1.9 Wind rose for the airport in Lanzarote, showing the extraordinarily directional steadiness of the Trade Winds. The two close peaks represent a small, seasonal shift in wind direction.

areas of linear seif dunes in much of the central Sahara (Warren 1972) (seif dunes are explained in Chapter 6). Climate change appears to be accelerating the Trades (Zheng et al. 2016).

1.2.2.3 The Harmattan

The word 'Harmattan' comes from Akan, the language of parts of Ghana and Côte d'Ivoire. In the southern Sahara/northern Sahel and in the early part of the year, the Trades curve round to become easterlies, and become the Harmattan (Figure 1.5). This wind lifts dust from many surfaces, but most comes from dry lakes, the biggest being the Bodélé (see Section 1.2.1.3). This dust: (i) darkens the sky over much of West Africa (find Accra on Google Earth; if the date when the image was taken was in March or April, it will probably be hazy); (ii) fertilises otherwise poor Sahelian soils, adding to them, by one measurement, $\sim 2000 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (Drees et al. 1993; Herrmann et al. 1996; Chapter 12); (iii) crosses the Atlantic; (iv) to fertilise the Amazon rainforest; and (v) occasionally reaches Ecuador, Florida, and even the American Mid-West (Bristow et al. 2010). Finally, (vi) dust accumulated on the floor of the Atlantic shows that the Harmattan has been blowing since the Cretaceous (Lever and McCave 1983).

1.2.2.4 Monsoons

Monsoons (Figure 1.5) (موسم, 'rainy season' in the original Arabic) are now in most climatological terminologies: low-latitude weather systems in which winds reverse in direction during the annual cycle, bringing rain summers and dry winters. The summer wind is the 'wet monsoon'; the winter wind, the 'dry monsoon'. In effect, the monsoons are sea breezes (above) writ large.

In the summer, haboobs (Section 1.2.1.2) are common on the dry margins of wet monsoons. For example, the North American monsoon (Figure 1.5) breaks over the north of Central America and parts of the dry US south-west. On the equatorial sides of the monsoons, heavy rains feed dense canopies of

vegetation (Figure 1.7), which, if undisturbed, allow little loss of dust to the wind. Quite the reverse: many wet monsoons wash dust out of the atmosphere.

There are two dry monsoons: one warm, one cold. The warm one blows in summer, over north-eastern Somalia and southern Oman (Figure 1.5) where it drives small fields of barchan dunes (Wiggs 1993). It is an extension of the East African monsoon or a precursor of the Indian monsoon.

In north-eastern Asia, the North-West Monsoon comes from the east, from the dry heart of Asia (Figure 1.5). It carries dust raised by cyclonic systems (Jugder 2005). In the Gobi Desert of Mongolia, long-term analysis of weather data shows that dust storms occur, on 30–37 days in the year (Natsagdorj et al. 2003). A study using the Nd–Sr ratio of dust has shown that many of the main sources are sand seas (Jiedong et al. 2009).

When the north-west monsoon reaches north-eastern China in winter, it is dry, biting cold, and very dusty. Figure 1.10 shows the annual alternation of wind directions at Beijing Airport (the dry north-west monsoon in winter and the wet 'south-western'

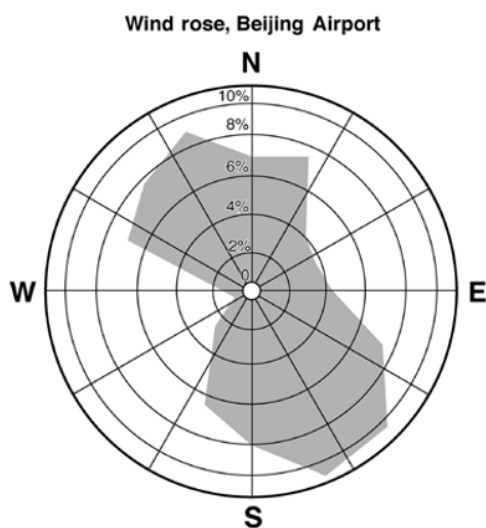


Figure 1.10 Wind rose for Beijing Airport, showing the alternation between the dry and dusty north-east monsoon in winter and the wet South-western monsoon (here south-easterly) in summer.

monsoon in summer, twisted in at its northern limit here to a south-easterly). The phenomenally thick loesses in parts of China were built by this wind in the Holocene, Pleistocene, and before (see Chapter 5). On its contemporary traverse over north-eastern China, the wind picks up industrial pollution. The toxic mix is then swept over Korea and Japan, where, as *Kosa* (黄砂) or 'yellow sand', it has a long written-history (Uematsu et al. 2002). It then crosses the North Pacific to western North America, much depleted by its contribution to deep sea sediments, but with some pollution in tow (Figure 1.5).

1.2.3 The Calmer Globe

On Figure 1.8, the calmness of most of the equatorial belt is striking, but even if there were strong winds, they could move little sediment beneath dense, tall vegetation (Figure 1.7), watered by abundant rainfall. Yet, as recently as the Holocene, sand was moved in places now covered by these dense forests (discussed shortly).

1.3 Rhythms of Erosivity and Erodibility from the Semi-Decadal to Hundreds of Thousands of Years

1.3.1 Multiannual Rhythms

Multiannual rhythms, most of which are driven by ocean-surface processes, create variations of wind speed, dust transport, and rainfall at any one site. The strongest and best known of these rhythms is the El Niño Southern Oscillation (ENSO), in which sea-surface temperature oscillates between the western and eastern Pacific. The periodicity of severe ENSO events is very variable, but usually in the range of two to seven years. Other multiannual ocean-based oscillations include the North Atlantic Oscillation (NAO), the Arctic and the Antarctic Oscillations.

Good correlations have been found between severe ENSO events and increased

deposition of dust on the floor of the Pacific itself (Marx et al. 2009), and with dust-raising in the south-western United States (Okin and Reheis 2002); Chapter 12 discusses the relationship between the ENSO and the Dust Bowl in the Great Plains. Its effects may be felt in Europe and beyond. The North Atlantic Oscillation (NAO), like the ENSO, has also been found to have increased the activity of coastal dunes in Europe (Clarke and Rendell 2006); as has the Southern Oscillation in northern Brazil (Maia et al. 2005). The Antarctic Oscillation, surprisingly, pulses in the same rhythm as dustiness in parts of China (Ke and Wang 2004).

1.3.2 Century-Scale Rhythms

Century-scale rhythms or events with return periods of centuries, like the 'Little Ice Age' (c.1350–c.1850), have a spatial range that is uncertain, but may be at least hemispherical (Szkornik et al. 2008; Jinhua and Wang 2014). Accelerated winds in these systems built coastal and inland dunes and raised dust, some of which reached Antarctica (Mosley-Thompson et al. 1990).

1.3.3 Orbitally-Forced Rhythms

Very much longer climatic rhythms are driven by the combined effect of several of Earth's movements in space, known sometimes as the 'Milankovich' cycles. Although challenged by others, Milankovich's theory of temperature variations and his calculations, by and large, have been upheld (Fagan 2009). Individual cycles are regularly cyclic, but their combination creates complex temporal patterns of solar radiation, and hence temperature, on the Earth's surface. The Pleistocene was a period when the rhythms collaborated to create a sequence of cooler periods, each lasting ~100 000 years (the Glacials), in which ice sheets covered large parts of North America and Europe. They alternated with shorter, warmer periods in some interglacials. There were many smaller

variations in temperature within each of these periods, especially those at 40 000-year and 20 000-year cycles, not all of which were directly related to the solar input. The climatic impacts of shorter cool events, such as the ‘Heinrich Events’, which lasted ~1000 years, include dune formation in the Negev of Israel (Roskin et al. 2011).

Aeolian activity was radically changed in these fluctuations. First, winds that were accelerated by the topographic obstruction of the enlarged ice sheets in both Europe and North America, lifted, carried, and deposited more loose sediments than did the gentler winds of the interglacials (more in Chapters 5 and 10). They also excavated huge wind-parallel ridges or ‘mega-yardangs’ in the American Mid-West (Zakrewska 1963), and Hungary (Sebé et al. 2011; Figure 1.11). Second, the directions of some of the winds near the ice caps were reversed (Chapter 3).

Third, and more significantly, massive alternations of wet and dry conditions drove massive shifts in global vegetation zones, which then drove major alternations in aeolian activity. In some of the wet periods, many areas that now are desert were covered in savannah or grassland, allowing early man to move out of Africa; in other places, deserts shrank or disappeared. In the drier periods,

even in the Holocene, places now covered by closed-canopy rainforest were dry and free enough of vegetation to allow dune formation, as in the upper Amazon Basin (Carneiro Filho et al. 2002, located on Figure 1.5).

The chronology of these dry/humid sequences in southern Africa, and the uncertainties encountered when trying to date them, are described in Chapter 10. The following account is much less detailed (and less analytical) and refers only to northern Africa and western Europe.

In northern Africa, the least ambiguous evidence for these fluctuations is in the aeolian sands and dune patterns that are now in areas where rainfall is greater than ~250 mm (annually). If undisturbed, these areas are capable of sustaining wooded savannah (Figure 1.12) and even agriculture (zoom into and away from 12°53'N; 30°41'E, to see mega-dune patterns in an agricultural landscape, well south of the 250 mm isohyet) (Warren 1970).

Close to the present edge of the desert, in Mauritania, there is much more accurate evidence of three Late Pleistocene and Holocene periods of dune formation (Figure 1.13). Dune-building periods were interspersed with periods of stability and soil formation. The winds in each dune-forming phase came from a slightly different direction (Lancaster

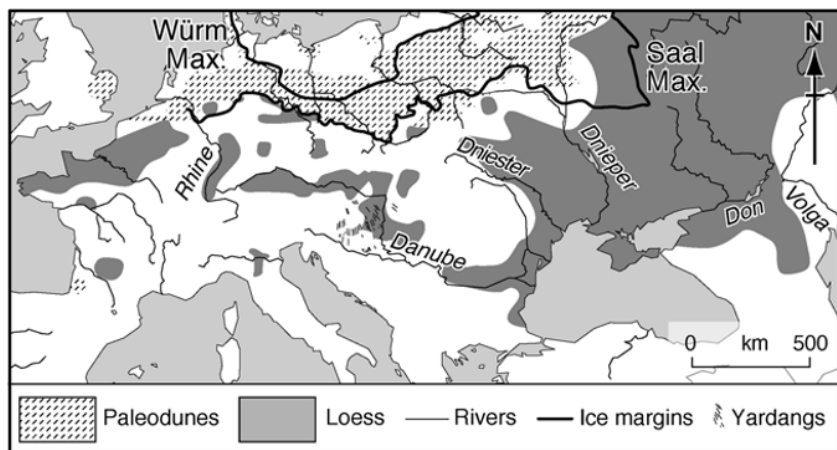


Figure 1.11 Europe: Distribution of sandy and loessic soils, associated rivers, selected limits of glaciations in part of Europe and some yardangs of Pleistocene Age (various sources).