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# Impacts of Sand and Dust Storms on Oceans

## *A Scientific Environmental Assessment for Policy Makers*

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Global Partnership on Nutrient Management GPNM

GPA Global Programme of Action for the Protection of the Marine Environment from Land-based Activities

GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

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# Contents



## List of tables and figures

### List of tables



### List of figures

# Glossary

| | |
|---|---|
| aerosol | minute particles suspended in the atmosphere |
| algal bloom | large proliferations of microalgae involving up to millions of cells per litre |
| archaea | type of microbe that emits carbon dioxide into the atmosphere via the process of respiration |
| aspergillosis | disease that affects coral; also known as sea fan disease |
| autotrophy | mode of nutrition that uses solar radiation as the energy source; the dominant form of autotrophy is photosynthesis |
| bioaerosol | minute particles from plant or animal matter, or from microorganisms, suspended in the atmosphere (e.g. bacteria, pollen, spores) |
| bioavailability | measure of the amount of an element available to organic life |
| biogenic | produced or brought about by living organisms |
| biological carbon pump | process by which photosynthetically produced organic matter in the ocean is exported from the surface to depth by a combination of sinking particles, vertical mixing and transport by animals |
| calcification | build-up of calcium salts |
| combustion | the process of burning |
| cryosphere | portion of Earth's surface that is frozen throughout the year |
| cyanobacterium | major type of photosynthetic bacteria that contain a bluish pigment |
| desiccation | loss of moisture leading to extreme dryness |
| dinoflagellate | one-celled aquatic organism |
| eutrophication | excessive load of nutrients in a body of water |
| glacial–interglacial cycles | fluctuation between Ice Ages (glacials) and periods of warmer climate (interglacials) |
| gyre | large system of circulating ocean currents formed by the Earth's wind patterns and the forces created by the planet's rotation |
| heterotrophic bacteria | type of microbe that emits carbon dioxide into the atmosphere via the process of respiration |
| heterotrophy | mode of nutrition that uses carbohydrate as the sole source of energy |
| Ice Age | see 'glacial–interglacial cycles' |
| immunosuppression | partial or complete suppression of an immune response |
| marine snow | decaying material sinking from upper waters to the deep ocean |
| oligotrophic | low in nutrients and relatively unproductive in terms of aquatic animal and plant life |
| pathogenicity | the property of causing disease |
| pelagic | relating to the open sea |
| photic zone | layer of the ocean reached by enough sunlight to allow plant growth |
| photochemistry | chemical effects of light |
| photophysiological | physiology of processes (e.g. photosynthesis) that involve light |
| red tide | algal bloom that discolours the surface of the sea |
| septicaemia | a serious infection of the bloodstream |
| solubility | property of a substance to dissolve in a liquid |
| symbiont | organism living in symbiosis with another |
| trace metal | element that normally occurs at a very low level in the environment |
| troposphere | the lowest region of the atmosphere |

# Acronyms and abbreviations

| | |
|---|---|
| AOD | aerosol optical depth |
| AVHRR | Advanced Very-High-Resolution Radiometer |
| CBD | Convention on Biological Diversity |
| DMS | dimethyl sulphide |
| GESAMP | Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection |
| HAB | harmful algal bloom |
| HNLC | high-nutrient, low-chlorophyll |
| LNLC | low-nutrient, low-chlorophyll |
| MEA | Multilateral Environmental Agreement |
| ppm | parts per million |
| SDG | Sustainable Development Goal |
| SDS | sand and dust storms |
| SST | sea surface temperature |
| UNCCD | United Nations Convention to Combat Desertification |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| WMO | World Meteorological Organization |

## Note on units of mass:

g (grams) are used throughout this report for consistency.
Gg (Gigagram) = one thousand tonnes.
Tg (Teragram) = one million tonnes

Satellite view North Africa and South of Europe. Sahara dust over Atlantic ocean and fires in Portugal. Elements of this image furnished by NASA.
Photo by elRoce

## List of chemical symbols and elements

| Symbol | Element |
|---|---|
| Al | aluminium |
| Ca | calcium |
| Cd | cadmium |
| Co | cobalt |
| Cu | copper |
| Fe | iron |
| K | potassium |
| Mg | magnesium |
| Mn | manganese |
| N | nitrogen |
| Ni | nickel |
| P | phosphorus |
| Pb | lead |
| Si | silicon |
| Ti | titanium |
| Zn | zinc |

Haboob dust storm in the Arizona desert
Photo: John D Sirlin, at Shutterstock

## Foreword

Links between oceans and land are innumerable. Each year sand and dust storms (SDS) carry an estimated half a billion tonnes of minerals, nutrients and organic and inorganic matter to oceans from the world's deserts and semi-deserts. This material helps drive biogeochemical cycles, including nitrogen, carbon and sulphur cycles, that are necessary for Earth system functions.

Desert dust is a principal driver of oceanic primary productivity, which forms the base of the marine food web and fuels the global carbon cycle. The fertilizing effect of desert dust is thought to have an impact on algal blooms and may contribute to *Sargassum* seaweed mats. Potential links have also been identified between microorganisms, trace metals and organic contaminants carried in desert dust and some of the complex changes on coral reefs observed in numerous parts of the world.

This report sums the current state of knowledge on these important connections. This knowledge, though imperfect, has significant implications for a number of Sustainable Development Goals (SDGs), particularly SDG 14 on Life Below Water and SDG 15 on Life on Land. Publication of this report is timely, coming at the start of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), as well as the United Nations Decade on Ecosystem Restoration (2021–2030). The restoration of degraded land can reduce sand and dust emissions and is recognized as a strong vehicle for driving implementation of the United Nations Convention to Combat Desertification (UNCCD). The interlinkages between SDS and marine productivity, and hence biodiversity, will inform discussions at the Conferences of the Parties to various United Nations conventions, such as the United Nations Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC), and the UNCCD.

Sound environmental policy must be based firmly on good science. One of the clear messages from this report is the simple fact that many aspects of the impacts of SDS on the oceans are only partially understood. Despite the limited knowledge, the impacts of SDS on oceans—their ecosystem functions, goods and services—are potentially numerous and wide-ranging, thus warranting continued careful monitoring and research.

Jian Liu
**Director, Science Division**
**United Nations Environment Programme**

Plumes of desert dust blowing from the Sonoran Desert and Baja California, north-west Mexico
Photo: NASA on The Commons

# Executive summary

Sand and dust storms (SDS) are common in deserts and semi-deserts when strong winds blow over dry soils with little or no vegetation. Dust generated by SDS is often raised high into the atmosphere and transported over long distances, frequently over the oceans. These atmospheric events are important for ecosystem functioning, with a wide range of effects on the Earth system. Given the hazards they pose to society, and the threats implied to the achievement of several Sustainable Development Goals (SDGs), they have also become an issue of increasing concern to governments and the international community.

SDS vary in frequency and intensity over multiple timescales. They are highly seasonal and can vary significantly from year to year. They also respond to drought periods and other drivers such as El Niño–Southern Oscillation and the North Atlantic Oscillation. Deserts in the northern hemisphere (northern Africa; the Middle East; south-west, central and north-east Asia) are the largest and most persistently active SDS sources, with smaller, less active sources located in North and South America, southern Africa, Australia and Iceland. The relative importance of naturally emitting wind erosion sources, as compared with those significantly influenced by human action—largely via poor agricultural management and excessive water use—is unclear, but the Sahara is the world's largest source of desert dust. It produces around 55 percent of all global dust emissions, with marked effects on the North Atlantic Ocean, the Caribbean Sea, the Mediterranean Sea and the Red Sea.

Each year, SDS carry an estimated average of half a billion tonnes of minerals and nutrients, organic and inorganic matter to the oceans. This desert dust has a range of effects on marine biodiversity. Dust provides a major source of externally supplied nutrients and trace metals. These elements are essential for all life forms and their atmospheric supply can exert control over ocean primary production via single-celled organisms collectively known as phytoplankton. This key metabolic process drives biogeochemical cycles in the oceans, including the carbon, nitrogen, sulphur, phosphorus and silicon cycles.

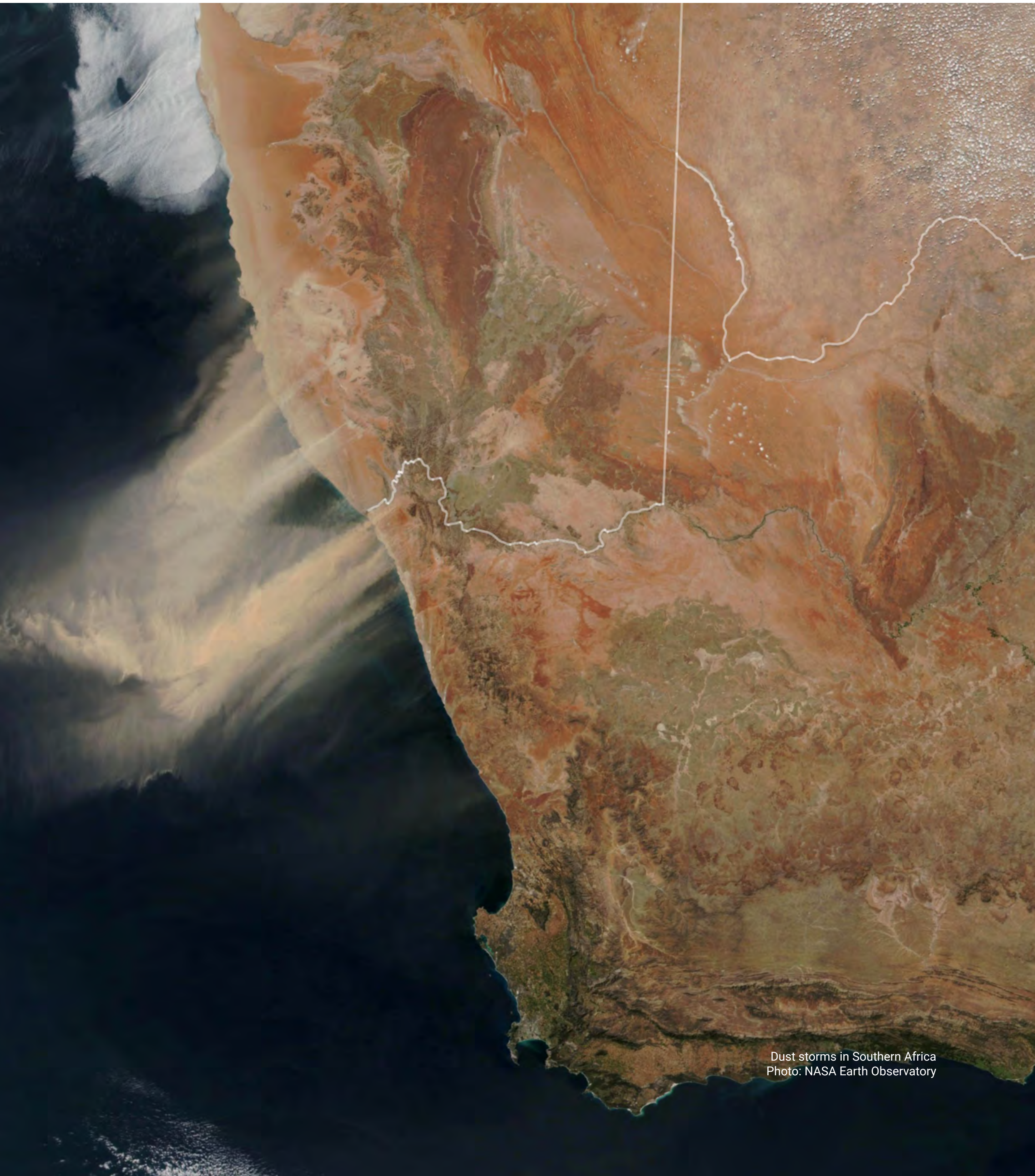
The fertilizing effect of desert dust is also thought to have an impact on algal blooms, which are an important food source for marine life, although some—dubbed harmful algal blooms (HABs)—may have detrimental effects on human health and economic activity. Dust deposition may also play a role in the unusually large blooms of floating *Sargassum* seaweed mats that have been noted since 2011 in the Caribbean Sea and the Atlantic Ocean along the coastlines of western Africa and Brazil. The cause of these blooms is a matter for debate, but nutrients in desert dust may enhance the growth of *Sargassum*.

Links have been found between desert dust and coral reef systems. The health of such reefs responds to numerous, frequently interlinked issues, but disease has been important in recent worldwide coral reef declines, and a number of diseases that affect coral are associated with microorganisms carried in desert dust. Dust deposition may be one of a range of influences that stress coral reefs, reducing their resilience to other factors that can cause their health to deteriorate.

Dust has significant impacts on weather and climate in several ways. One impact probably occurs indirectly via dimethyl sulphide (DMS) released from phytoplankton fertilized by iron-rich desert dust, which creates local climate feedbacks via additional cloud condensation nuclei. Dust also exerts indirect impacts on the climate system due to the part it plays in the global carbon cycle—a role stemming from further interactions between desert dust and the microorganisms responsible for primary production. The 'biological carbon pump' results in carbon being sequestered into the oceans from the atmosphere, with consequent feedback effects on climate. This occurs through carbon dioxide and nutrients being transformed into organic carbon, which sinks to the deep ocean, decomposes and becomes buried in sediment. The Southern Ocean, where primary productivity is limited by iron deficiency, could be particularly important in the operation of the biological carbon pump.

There are still considerable uncertainties around how SDS interact with the oceans and consequences for other parameters of the Earth system. This report highlights critical areas for further monitoring and study and where research can inform appropriate policy development. Understanding SDS and the long-range transport of desert dust to oceans is relevant to the three Rio conventions: the Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC), and the United Nations Convention to Combat Desertification (UNCCD).

It also has significant implications for a number of SDGs, particularly SDG 14 on Life Below Water and SDG 15 on Life on Land, and demonstrates the interdependencies between the SDGs. This report's publication is timely, coming at the beginning of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), as well as the United Nations Decade on Ecosystem Restoration (2021–2030).



Dust storms in Southern Africa
Photo: NASA Earth Observatory

Fishing vessel at sea
Photo: Bjoern Wylezich at Shutterstock

# 1. Introduction

Large quantities of small particles are eroded by wind from soil surfaces in many parts of the world to generate sand and dust storms (SDS). These events are most common in deserts and semi-deserts because soils in these areas are typically dry and unconsolidated, with little or no vegetation cover; conditions that enable the erosion of surface sediment by wind. These atmospheric events have a wide variety of effects on the hydrosphere, lithosphere, biosphere, atmosphere and cryosphere and they are important for ecosystem functioning. Hence, the dust cycle has been recognized as an integral part of Earth system science (Shao *et al.*, 2011; Knippertz and Stuut, 2014).

On land, SDS represent a significant hazard to human society, not only in deserts and semi-deserts, but also to people living beyond these dryland regions because dust haze is often transported over large distances (Kellogg and Griffin, 2006). There are numerous consequences for human populations, including threats to agriculture, health, electricity generation, and the transport industry (Middleton, 2017). These hazardous impacts have brought SDS to the attention of the United Nations General Assembly, resulting in the adoption of resolutions entitled "Combating sand and dust storms" in 2015 (A/RES/70/195), 2016 (A/RES/71/219), 2017 (A/RES/72/225), 2018 (A/RES/73/237) and 2019 (A/RES/74/226). Also notable are UN Environment Assembly resolution 2/21 and United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) resolution 72/7, both concerning SDS. These resolutions recognize the threats posed by SDS to livelihoods, the environment and the economy and acknowledge that they can hinder the achievement of several Sustainable Development Goals (SDGs).

Significant quantities of these mineral dust particles (hereafter, simply 'desert dust', 'dust particles' or 'dust') emitted from land surfaces are deposited episodically on the oceans. One of the first western scientific papers to address the relationships between desert dust and the marine environment was published by Charles Darwin, who observed Saharan dust deposited on his ship in the Atlantic Ocean in the early 19th Century (Darwin, 1846). Dust has impacts on marine biogeochemistry, primary productivity, carbon storage and deep-sea sedimentation. Its deposition brings nutrients to ocean surface waters and the seabed, in places enhancing primary production, with impacts on the global nitrogen, carbon and sulphur cycles. In coastal waters in particular, nutrients in desert dust can in some circumstances trigger algal blooms. Although these blooms are an important food source for much marine life, they can sometimes be harmful to marine wildlife, human health and economic activity. Potential links have also been identified between constituents of desert dust and some deleterious changes monitored on coral reefs in numerous locations worldwide.

This report examines the state of knowledge of how SDS impact marine ecosystems. These impacts, both direct and indirect, are inevitably also relevant to human society. In part, the impacts may be hazardous, but the perception of any threats should be balanced by an appreciation of the significance of desert dust to the Earth system. Actions to implement the recommendations presented at the end of this report should also take into account all aspects of SDS impacts on marine ecosystems.

Sandstorm in Jordan
Photo: Ahmad A Atwah at Shutterstock

# 2. Sand and dust storm definitions

Small particulate matter found in the atmosphere can be derived from numerous sources. Such material includes sea salt, volcanic dust and industrial pollutants, but this report is concerned with particles that are eroded by wind from land surfaces. The distinction between sand storms and dust storms is not clear-cut since there is a continuum of particle sizes in any storm, comprising clay-sized (less than 4 micrometres, or μm, in diameter); silt-sized (4 to 62.5μm); and sand-sized (62.5μm to 2 mm), adopting the commonly used standardized grade scale described by Wentworth (1922).[1] The World Meteorological Organization (WMO) defines a dust storm or sand storm as an ensemble of particles lifted to great heights by a strong and turbulent wind that reduces visibility, normally assessed at 1.8 m above the ground, to less than 1,000 m.

In mineralogical terms, sand and dust particles from the low- to mid-latitudes are mainly composed of quartz, clay minerals (including illite, smectite, chlorite and kaolinite), feldspar, plagioclase, calcite and iron oxides (such as hematite and goethite) (Shi *et al*., 2005; Formenti *et al*., 2008; Nowak *et al*., 2018). Dust particles from the high latitudes may have significantly different mineralogy. In chemical terms, sand and dust are composed of silicon dioxide ($SiO_2$), aluminium oxide ($Al_2O_3$), iron oxide ($Fe_2O_3$ and FeO), calcium oxide (CaO), magnesium oxide (MgO) and potassium oxide ($K_2O$), with their relative abundance dependent on the sediment in the source area (Krueger *et al*., 2004).

Other biochemically important elements commonly present in trace quantities in desert dust include titanium (Ti), manganese (Mn) and copper (Cu). Generally, the concentrations of most major elements (Si, Al, Fe, Mg, Ca, K, in approximate order of importance) replicate the composition of the upper continental crust, although there is considerable variability between samples (Lawrence and Neff, 2009). Many SDS source areas also contribute a variety of salts, appreciable quantities of organic matter, microorganisms (such as fungi, bacteria and viruses), and pollutants derived from anthropogenic activities such as industry and agriculture (Goudie and Middleton, 2006). The airborne particles of biogenic origin, including fragments from living organisms (such as pollen and spores), also include elements derived from plant and animal matter, such as nitrogen (N) and phosphorus (P) (Gross *et al*., 2016; Stockdale *et al*., 2016).

Material entrained from the land surface can be lifted to considerable altitudes and transported great distances by high-altitude winds. This long-distance transport results in individual dust events affecting huge areas, in some cases more than 100,000 km$^2$. Sand storms, however, have typically more localized effects, including sand dune encroachment. Hence, most of the SDS impacts on the oceans stem from dust particles rather than sand.

Sand particles
Photo: jorik at Shutterstock

[1] In air quality and aerosol research literature, the terms 'fine aerosols' (~<1 μm) and 'coarse mode' (>1 μm) are also frequently used.

Remnant of the desiccated Aral Sea
Photo credit: Patrick Schneider/ Unsplash

# 3. Dust storm sources, transport pathways and deposition

The locations of major contemporary SDS source areas are generally known (although knowledge about them is still imperfect) and there is substantial information on long-distance desert dust transport (Ginoux *et al*., 2012). Comparatively, dust deposition is less well known since measurements are relatively few and incomplete, although modelling is helping to fill this gap (Shao *et al*., 2011).

## 3.1. SDS sources

Earth's main present-day sources of desert dust have been identified using observations from terrestrial meteorological stations and an array of sensors carried by satellites. These sources are primarily in northern hemisphere desert regions, forming a broad swathe of territory that is often dubbed the Dust Belt (Prospero *et al*., 2002), stretching from the Sahara in western Africa across the Middle East and deserts of south-west and central Asia to the Taklimakan and Gobi Deserts of north-east Asia. Lesser—though locally important—sources are in other desert regions, including in the Americas (for example Mojave, Sonoran, Nazca and Atacama Deserts), southern Africa (Namib and Kalahari Deserts) and the deserts of Australia (Ginoux *et al*., 2012). Most of these source areas are in low latitudes, but an estimated 5 percent of global desert dust is emitted from high-latitude sources. These include the Patagonian Desert in Argentina and Antarctica in the southern hemisphere; Iceland, Greenland, and parts of the North American sub-Arctic such as Alaska and the Yukon in the northern hemisphere (Bullard, 2017).

Within these broad dryland areas, dust sources are often highly localized and specific. Typical dust-producing desert surfaces include large internal drainage basins, ephemeral dry lakes,[2] alluvial deposits, and piedmont alluvial fans (Figure 3.1). In high latitudes, glacial outwash plains are characteristically rich in dust-sized material. Many sources produce dust naturally, but erosion also occurs in environments where human mismanagement has rendered them susceptible to wind action. Such conditions arise in lake beds that have dried out due to excessive water use, a classic example being the Aral Sea in Kazakhstan and Uzbekistan (Issanova *et al*., 2015). Enhanced wind erosion can also occur in poorly managed and abandoned farming areas, as Moridnejad *et al*. (2015) report from parts of Iraq and Syria.

Indeed, a compilation of data from sedimentary archives extracted from many parts of the world suggests that dust emissions have at least doubled over the past ~250 years, a period that has seen the creation and widespread expansion of 'industrial agriculture' (Hooper and Marx, 2018). Nonetheless, making the distinction between anthropogenic effects and natural drivers of wind erosion is not a straightforward task, even in well-documented locations (Middleton, 2019). As Webb and Pierre (2018, p. 286) put it, "While the impacts of land use activities and land management on aeolian processes can be profound, the interactions are often complex and assessments of anthropogenic dust loads at all scales remain highly uncertain."[3]

The scale of wind erosion sources that are significantly influenced by human activity is therefore debatable, with estimates of their relative contribution to global dust emissions ranging from <10 percent (Tegen *et al*., 2004) to >50 percent (Mahowald and Luo, 2003). This high degree of uncertainty is attributable both to the aforementioned complexities and to the relative lack of detailed information on many dust source areas (UNEP, WMO, UNCCD, 2016). Ginoux *et al*. (2012) suggest that 75 percent of global dust emissions come from natural sources, with anthropogenic sources accounting for 25 percent, although this assessment indicates significant regional variability, with the authors concluding that anthropogenic dust emission sources make a larger contribution (75 percent) in Australia. These proportions are not fixed, since wind erosion rates vary over time and space. At anthropogenic sources, greater amounts of sediment are eroded on occasion due to mismanagement, often in combination with adverse climate conditions (McLeman *et al*., 2014), or less sediment is produced when subject to successful wind erosion control practices (Middleton and Kang, 2017).

2 Ephemeral lakes, which are often high in salts, have many regional names, including chott, sebkha, salar, playa and pan.

3 Future trends in dust emissions as a result of human-induced climate change are equally uncertain. They will depend on numerous factors, not least changes in atmospheric circulation and precipitation totals, timing and patterns. Such dust emission changes are also likely to vary geographically (Jia *et al.*, 2019).

Figure 3.1. Plumes of dust blowing north-easterly over the south-west Atlantic from alluvial point sources in Patagonia, Argentina

Source: NASA MODIS image

The world's largest source of desert dust is widely regarded to be the Sahara Desert, which produces an estimated 55 percent of all global dust emissions (Ginoux *et al*., 2012), and its most active dust source: the Bodélé Depression, site of an ancient lake bed (Goudie and Middleton, 2001). Overall, total emissions of desert dust to the global atmosphere are estimated to range from 1,000 to 3,000 Tg per year, or 1 to 3 billion tonnes (see for example Miller *et al*., 2004; Tegen and Fung, 1994; Huneeus *et al*., 2010). Most of these estimates are produced using models because actual measurements are geographically scarce and temporally infrequent, although the use of geostationary satellites is improving our capacity to monitor dust emissions.

## 3.2. Long-distance dust transport

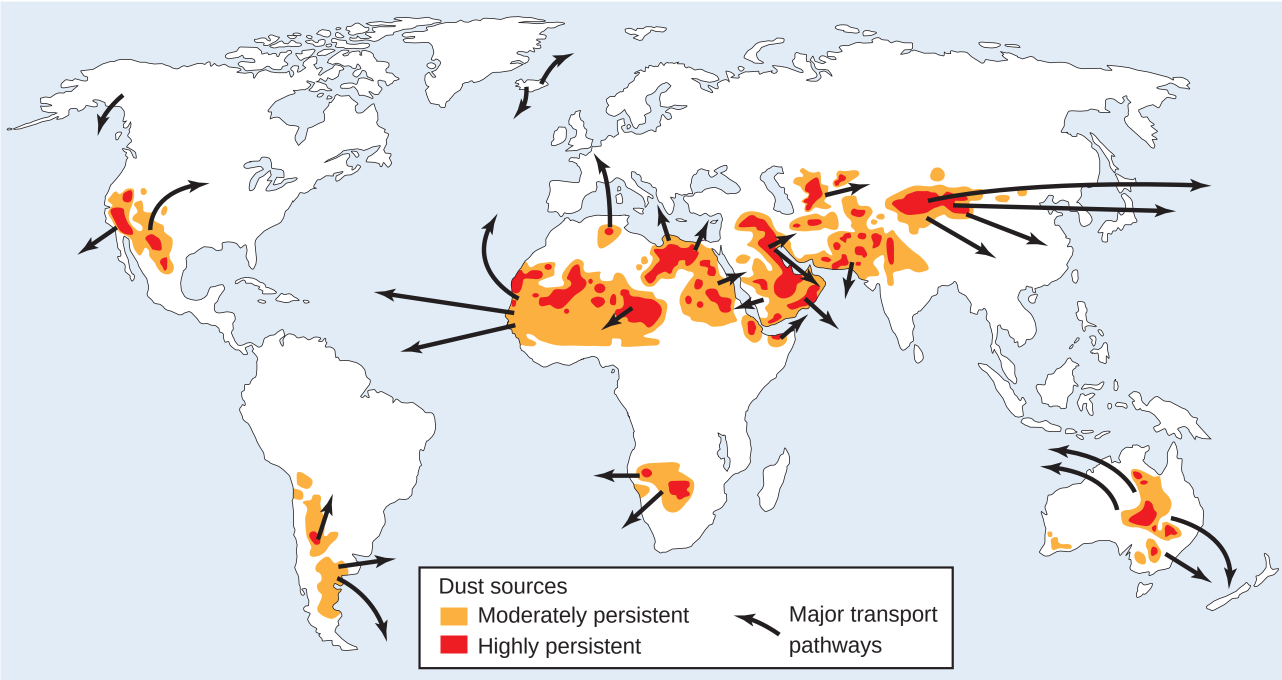
Many studies have noted that desert dust is frequently transported through the troposphere over great distances (>1,000 km), hence affecting biogeochemical conditions far from dust sources. Such long-distance transport tends to be dominated by fine dust particles, with diameters typically smaller than ~20μm, simply because larger particles settle out sooner due to gravitational forces. However, long-distance transport events can also include aggregates of fine particles and single sand-sized particles (>62.5μm) that may comprise an important part of the total mass delivered to remote oceans (van der Does *et al*., 2018).

The global pattern of major dust transport pathways, most of them over the oceans, is depicted in Figure 3.2. Dust events can also incorporate other material picked up in the atmosphere through which they pass (Meskhidze *et al*., 2005). In some world regions (for example north-east Asia and southern Europe), dust haze typically combines with a variety of anthropogenic pollutants during transport (Luo *et al*., 2020).

Many of these long-distance dust flows are highly seasonal and can vary significantly from year to year. Most soil material transported from deserts in China and Mongolia across the Bohai Sea and out over the North Pacific is mobilized during the spring months (March–May). Dust from sources in southern Mesopotamia is commonly transported down the Arabian Gulf by the north-westerly Shamal, a dust-laden wind that blows from February to October. Much Saharan dust is transported south-westward by the Harmattan wind that prevails between October and April. The westward trajectory of Saharan dust events transported over the North Atlantic also shifts with the seasons. Saharan dust monitored at Cayenne, French Guiana, in South America peaks in March and April, while the peak months for Saharan dust at Miami, Florida, USA, in North America are July and August.

The intensity and frequency of SDS also fluctuate over longer timescales, responding to drivers such as drought (Middleton, 1985), El Niño–Southern Oscillation (Banerjee and Kumar, 2016) and the North Atlantic Oscillation (Moulin *et al*., 1997). The quantities of North African dust transported to the Caribbean increased markedly in the early 1970s, a rise attributed largely to the drought prevailing in the Sahara/Sahel region (Prospero and Lamb, 2003).

**Figure 3.2.** Global sources of desert dust and pathways of long-distance transport.




Source: Adapted from Muhs *et al*., 2014.

After peaking in the early 1980s, trans-Atlantic dust flows from western Africa decreased by about 10 percent per decade (between 1982 and 2008), based on measurements of dust aerosol optical depth (AOD) over the mid-North Atlantic from the Advanced Very-High-Resolution Radiometer (AVHRR) satellite-borne instrument. This declining trend, which persisted throughout both summer and winter (Ridley *et al*., 2014), was viewed by Wang *et al*. (2012) as part of a multi-decadal co-variability of North Atlantic sea surface temperature (SST) and Sahelian precipitation and dust, while Kim *et al*. (2017) highlighted the strong correlation between surface wind speeds over the Sahara and the decreasing dust emission trend.

## 3.3. Dust deposition

There are three principal ways in which dust is deposited: by settling due to the force of gravity; through turbulent dry deposition, or via the scavenging of particles in raindrops ('wet deposition'). In *situ* measurements of dust deposition to the open ocean are even less common than such measurements over land (Schulz *et al*., 2012), but estimates of dust inputs (i.e. dry + wet deposition) to the world oceans are around 500 Tg annually (Jickells *et al*., 2005). Annual total deposition rates to major world oceans, derived mostly from modelled data, are shown in Table 3.1. Maximum dust deposition per unit area (about 10 g $m^{-2}$ $yr^{-1}$) occurs in parts of the North Atlantic (from

**Table 3.1.** Desert dust deposition rates over the oceans

| Ocean | Deposition (Tg yr−1) | Reference |
|---|---|---|
| North Atlantic | 202 | Jickells *et al*. (2005) |
| Indian Ocean | 118 | Jickells *et al*. (2005) |
| North Pacific | 72 | Jickells *et al*. (2005) |
| Mediterranean Sea | 40 | Guerzoni *et al*. (1999) |
| South Pacific | 29 | Jickells *et al*. (2005) |
| South Atlantic | 17 | Jickells *et al*. (2005) |
| Arctic Ocean | 6 | Shevchenko and Lisitzin (2004) |
| All oceans | 477 | Mahowald *et al*. (2010) |

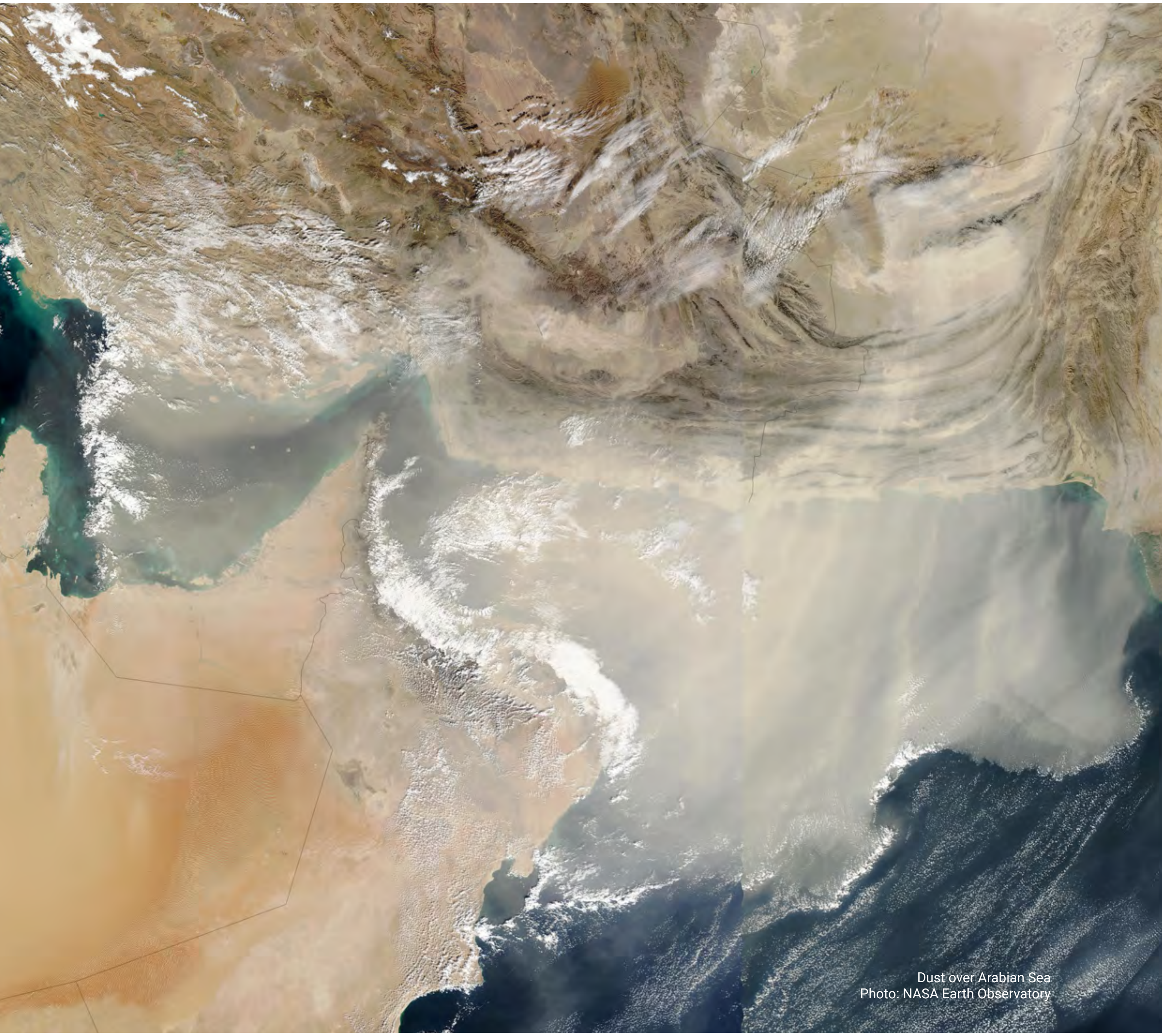
Source: Guieu *et al*. 2014a

Saharan dust) and in parts the North Pacific (dust originating from north-east Asia).

Globally, dust emissions are approximately one tenth of the mass of material delivered to the oceans by rivers, although the relative importance varies greatly by region (Bullard and Baddock, 2019). Dust flux exceeds fluvial sediment flux in North Africa (six times higher) and the Middle East (twice as high), and they are the same order of magnitude in Australia. Elsewhere, dust emissions are either negligible, as in

Europe, or far exceeded by riverine transport to the oceans. It is also important to note that atmospheric input to the oceans takes place over a very large spatial scale, while riverine input tends to be much more localized along the coast.

The significance of the Sahara as a source of windborne sediment—especially to the North Atlantic, the Caribbean Sea, the Mediterranean Sea and the Red Sea—is outlined for many marine issues in the forthcoming chapters. The presence of submicron (<1μm) Saharan dust in suspension in the uppermost waters of the Mediterranean is also one possible explanation for the sea's unusually green colour (Claustre *et al*. 2002)[4], and a large, lobe-shaped area of iron oxide-rich sediment on the seabed off north-west Africa is testament to the longevity of the Saharan dust source and the trans-Atlantic transport pathway (Balsam *et al*., 1995).



Dust over Arabian Sea
Photo: NASA Earth Observatory

4 Other hypotheses attribute this effect to the presence of coccoliths (calcium carbonate platelets, a few μm in diameter, secreted by certain organisms), or the Mediterranean's unique phytoplankton community structure.

Barracuda
Photo: Rich Carey at Shutterstock

Algal blooms on a beach
Photo: smspsy at Shutterstock.

# 4. Dust and biodiversity

## 4.1. Ocean primary production

Desert dust generated by SDS provides a major source of externally supplied nutrients and trace metals to the oceans (Mahowald *et al*., 2018). These elements are essential for all life forms and their atmospheric supply can exert control over ocean primary production (Jickells and Moore, 2015). The effect on marine primary productivity occurs principally through the impacts of dust-borne nutrients on single-celled photosynthetic organisms collectively termed 'phytoplankton', which are responsible for the vast majority of new organic material production in marine waters. Inputs from atmospheric deposition at some oceanic locations have been shown to induce phytoplankton growth, enhance the fixation of nitrogen, and change phytoplankton species dynamics. These inputs can also intensify carbon sequestration via the biological pump and affect ocean dimethyl sulphide (DMS) emissions, in turn affecting cloud albedo (see chapter 5).

### 4.1.1. Phosphorus, nitrogen and iron

The nutrients best studied in these respects are the macronutrients phosphorus (P) and nitrogen (N), and the micronutrient iron (Fe), all of which can play a significant role in marine primary production.[5] Field observations, experiments (both in the laboratory and in situ), and numerical modelling simulations have established links between atmospheric deposition of dust and increases in ocean chlorophyll concentrations, a proxy for phytoplankton biomass (Jickells *et al*., 2005; Doney *et al*., 2007; Gallisai *et al*., 2014). There are two main ways in which the deposition of nutrients available in desert dust can stimulate the growth of phytoplankton in the oceans, if the receiving ecosystem is limited by an element present in the dust deposited:

- directly, by supplying P and/or Fe, alleviating limitation by these nutrients
- indirectly, when dust supplying P and/or Fe stimulates N fixation, alleviating N limitation

The growth of marine primary producers such as phytoplankton, which form the base of the ocean's food web, is controlled by the availability of light and nutrients, and the nutrient in shortest supply relative to cellular requirements limits primary production. Iron, which is a particularly important micronutrient limiting primary production, is commonly available in dust mobilized from arid regions (see chapter 2) and desert dust represents the most important source of iron from the atmosphere to the open oceans (Mahowald *et al*., 2018).

Oceanographers recognize two broad regimes in which nutrient limitation in upper ocean waters affects phytoplankton. Certain areas are characterized by high levels of macronutrients (i.e. nitrogen and phosphate) but biological production that is paradoxically low. In these so-called high-nutrient, low-chlorophyll (HNLC) marine areas, the relative lack of the micronutrient iron is thought to often limit productivity.[6] This has been shown by a number of laboratory and in situ experiments where chlorophyll concentrations in surface waters increased proportionally to the addition of iron (Boyd *et al*., 2007). These areas are predominantly at high latitudes and include the vast Southern Ocean and the sub-Arctic North Pacific Ocean. Although Fe is the main limiting factor in these HNLC areas, there is an ongoing debate on the geographical patterns and importance of co-limitation by vitamins and micronutrients other than iron (Moore *et al*., 2013; Hutchins and Boyd, 2016).

In contrast to HNLC areas, some 60 percent of the global ocean (including the Caribbean and Mediterranean seas, and the subtropical oceanic gyres—large systems of circulating ocean currents) is oligotrophic, comprising areas that are characterized as low-nutrient, low-chlorophyll (LNLC). In these LNLC regions, dust-supplied phosphorus and iron, either on their own or in combination, have had demonstrable effects on phytoplankton growth, both directly (by alleviating nutrient limitation) and/or indirectly (by P and/or Fe stimulating N fixation). These impacts have been studied in various locations, including the Mediterranean Sea (Guieu *et al*., 2014b), the Caribbean Sea (Chien *et al*., 2016), the Yellow Sea (Liu *et al*., 2013) the Gulf of California (Arellano-Torres *et al*., 2020) and the subtropical North Atlantic gyre (Neuer et al., 2004).

5 Dust also plays a role in the world ocean silica (Si) cycle, with important implications for marine primary production (Tréguer and De La Rocha, 2013).
6 Other possible reasons for the surprisingly limited phytoplankton growth in these areas include light limitation and grazing pressure.

Generally, desert dust is considered to be an important source of the macronutrient P,[7] particularly in oligotrophic parts of the open ocean where there is little input from other new nutrient sources such as rivers, groundwater discharge or sediment resuspension (Jickells *et al*., 2005).

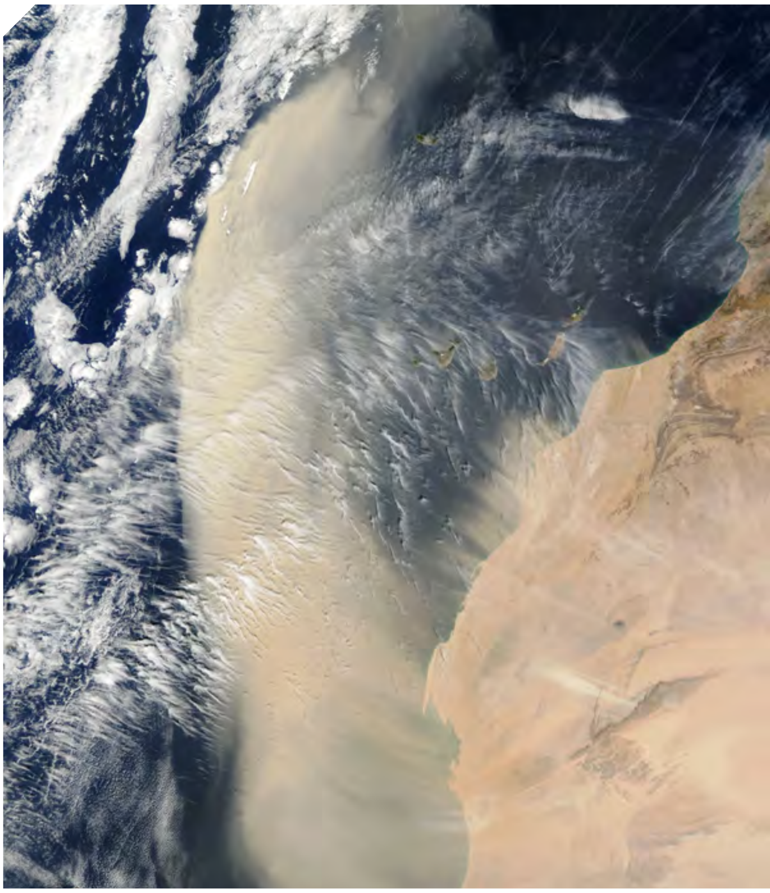
One area where productivity is considered to be colimited—by Fe and P—is the tropical North Atlantic, where the addition of Saharan dust has been shown to stimulate N fixation, presumably by supplying both Fe and P (Mills et al., 2004). The tropical North Atlantic receives large amounts of Saharan dust, principally during the summer months via wet deposition (van der Does *et al.,* 2020). The observation that nitrogen-fixing organisms (for example, Trichodesmium, a marine cyanobacterium) are much more abundant in the tropical North Atlantic than in the tropical South Atlantic (where dust inputs are low) is another piece of evidence to support links between desert dust inputs and marine biogeochemical responses.

In a study of phytoplankton response to the input of desert dust in the north-west Pacific Ocean, Zhang *et al.* (2019) found that the addition of dust changed the relative importance of phytoplankton of different body sizes, the so-called size structure of the phytoplankton community, with a shift towards larger cells with increasing dust deposition. Similarly, strong changes in phytoplankton abundance and bacterial community composition were measured in response to Saharan dust deposition events in the subtropical western Atlantic (Borchardt *et al.,* 2020). Shifts in phytoplankton size structure have also been noted in experimental work on dust inputs to marine ecosystems (for example, Lekunberri *et al*., 2010). Phytoplankton size structure influences the trophic organization and food web dynamics of pelagic ecosystems (Finkel *et al*., 2009).

However, the above generalizations on links between dust-derived nutrient inputs and marine primary production are not necessarily universal. The influence of dust on fertilization in the equatorial Pacific is disputed (Jacobel *et al*., 2019) and dust deposition is also a source of particles that can scavenge iron, so that in some areas the addition of dust can result in a decrease of dissolved Fe (Ye and Völker, 2017). Evidence is equivocal for phytoplankton responses to dust deposition in Australian waters (Gabric *et al*., 2010; Mackie *et al*., 2008) leading Cropp *et al*., (2013) to adopt a climatological approach to the issue, analysing a 20-year record of air parcel trajectories from Australia's major dust source, the Kati Thanda-Lake Eyre Basin. These authors suggested that the biological response of ocean waters to dust-derived nutrients varies seasonally and that marine biological receptivity to the nutrients delivered in dust is often not in synchrony with the timing of dust deposition in the Tasman Sea and Southern Ocean south of latitude 45°S.

In lower latitudes, where biological receptivity extends throughout the year, Ohde and Siegel (2010) observed time lags of up to 16 days between Saharan dust storm events and enhanced chlorophyll-a concentrations off north-west Africa, where coastal upwelling provides a more significant nutrient supply. This study over the period 2000–2008 also found that out of 57 strong dust storms assessed (an example is shown in Figure 4.1), just six events were clearly related to enhanced phytoplankton growth. Episodic dust storms also provide an input of nutrients to phytoplankton blooms in the highly productive

**Figure 4.1.** A huge outbreak of Saharan dust over the Atlantic coast of Mauritania spreading north-westward on 4 March 2004



Source: NASA MODIS

[7] By contrast, dust itself is a minor source of nitrogen delivery to the ocean (Jickells *et al.,* 2017).

Arabian Sea. Banerjee and Kumar (2014) assessed chlorophyll-a during the winter monsoon period and concluded that some blooms, but not all, could be attributed to dust deposition events. In the Arabian Gulf, no close temporal coupling between dust storms and productivity was found by Al-Najjar *et al.* (2019), but they still highlighted the importance of dust as a source of nutrients to the ecosystem. Their study concluded that the dust rapidly sinks to the seabed where the nutrients Fe and P are liberated through iron reduction. Nutrient liberation from the seabed is slow and its transport from the seabed to the photic zone by circulation processes is irregular.

Further questions are raised by Torfstein and Kienast (2018) in their four-year study of high-resolution records of chlorophyll concentrations and desert dust concentrations in the oligotrophic Gulf of Aqaba, in the northern Red Sea. They found no significant correlation between dust and chlorophyll concentrations, even allowing for possible time lags between cause and effect. This finding applied to both seasonal dust activity and individual dust events, suggesting that the role of dust as a control on productivity in the Gulf of Aqaba may have been overestimated.

Another complicating factor in attempts to assess links between dust deposition and marine primary productivity occurs in areas where desert dust becomes mixed with anthropogenic atmospheric pollutants. For instance, Meskhidze, Chameides and Nenes (2005) used a model to compare two dust plumes from the Gobi Desert, one of which appeared to stimulate enhanced phytoplankton growth in the North Pacific Ocean, while the other did not. They found that the dust event that increased phytoplankton growth had been acidified by a relatively large amount of atmospheric sulphur dioxide pollution from industrial plants in China (see section 4.1.3).

## 4.1.2. Other trace elements

A suite of other trace metals commonly contained in desert dust also have implications for marine productivity. Some of the most significant metals in this respect are zinc (Zn), cobalt (Co), nickel (Ni), manganese (Mn) and copper (Cu), all of which comprise significant components of key enzymes for marine phytoplankton and bacteria physiology (Jickells and Moore, 2015). Indeed, some studies suggest many of these elements could be responsible for co-limitation of marine phytoplankton or bacterial growth, although the evidence is equivocal (Moore *et al.*, 2013). By contrast, certain elements such as Cu are toxic at high concentrations to some plankton and may therefore inhibit biological productivity (Paytan *et al.*, 2009). In several cases, desert dust is the primary atmospheric source of these trace metals to the oceans (Table 4.1).

As with N, P and Fe, understanding the precise role of desert dust is further complicated by other aerosol sources of trace metals, including anthropogenic combustion. In a recent review of aerosol trace metal impacts on marine microorganisms, Mahowald *et al.* (2018) suggested available estimates indicate that desert dust dominates for Al, Ti, Mn and Fe, although combustion sources (both biomass fires and industrial processes) may also contribute to those elements and may be particularly important for Cu, Zn and Pb.

**Table 4.1.** Aerosol metal sources to the atmosphere (Gg yr-1)

| Metal | Anthropogenic | Dust | Fire | Biogenic | Sea spray | Volcanic | Total |
|---|---|---|---|---|---|---|---|
| Aluminium | 3,000 | 80,000 | 2,000 | 200 | 1,000 | 5,000 | 90,000 |
| Titanium | 2 | 8,000 | 6 | | | | 8,000 |
| Manganese | 10 | 900 | 20 | 30 | 2 | 40 | 1,000 |
| Iron | 700 | 50,000 | 1,000 | 200 | 200 | 9,000 | 60,000 |
| Copper | 30 | 20 | 20 | 3 | 10 | 9 | 100 |
| Zinc | 60 | 60 | 100 | 5 | 50 | 10 | 300 |
| Cadmium | 3 | 0 | 0 | 0.2 | 0 | 9 | 10 |
| Lead | 100 | 6 | 30 | 2 | 5 | 4 | 200 |
| Sum | 4,000 | 140,000 | 3,000 | 400 | 1,000 | 14,000 | 160,000 |

Source: Mahowald *et al.*, 2018.

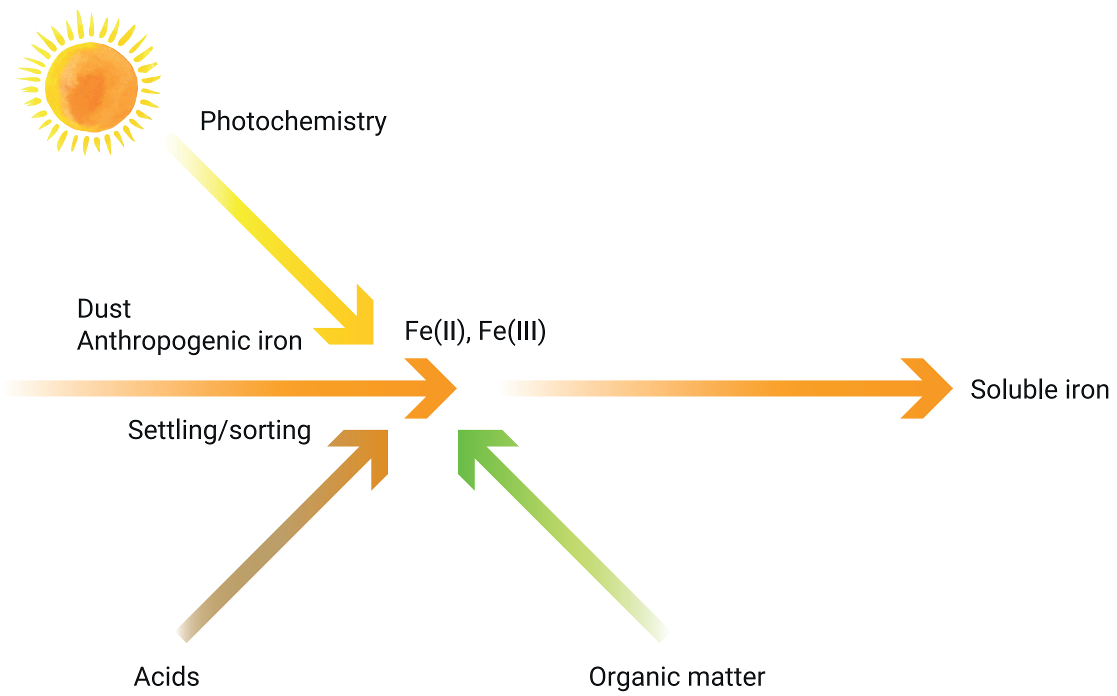
### 4.1.3. Bioavailability of elements

The biological impact of desert dust deposited in the oceans depends on a number of factors, not least the composition of the dust and of the sea water where deposition occurs. The amount of material deposited and the bioavailability of the elements present in the dust are similarly critical. Bioavailability is not well-understood. Indeed, Schulz *et al*. (2012, p.10391) describe it as "one of the most poorly understood aspects of the entire global dust cycle", but it is influenced at least in part by the solubility of the various dust-elements and solubility is therefore used as a proxy for bioavailability (Jickells, Baker and Chance, 2016).

The majority of atmospheric nitrogen—both organic and inorganic—inputs to the oceans, from desert dust and many other sources, appear to be both soluble and bioavailable (Okin *et al*. 2011). By contrast, most of the phosphorus and iron carried in desert dust are present as minerals that are not immediately soluble in water, and therefore are not bioavailable (Tagliabue *et al*., 2017). Recently, much work has been done to understand the change in speciation and solubility of phosphorus in dust during long-range transport (for example, Stockdale *et al*., 2016; Shi *et al*., 2019), but the literature on how trace metals in dust particles are converted to a soluble form has a predominant focus on iron (Baker and Croot, 2010). These studies have identified a range of complex chemical processes affecting particles during atmospheric transport (Figure 4.2). Dust particles remain in transit for periods lasting from hours to weeks and during this time they are exposed to sunlight and to acidic compounds (for example, sulphuric acid [$H_2SO_4$], nitric acid [$HNO_3$] and organic acids such as oxalic acid [$C_2H_2O_4$]). Solubility can be modified by chemical reactions that take place on the surface of individual dust particles or while passing through cloud droplets. The size of dust particles affects iron solubility (Baker and Jickells, 2006) but its overall impact on iron solubility in bulk aerosol is small (Shi *et al*., 2011). This atmospheric processing of iron and how it is represented in global biogeochemical numerical models has been a focus for work by the United Nations Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) Working Group 38, 'The Atmospheric Input of Chemicals to the Ocean' (Myriokefalitakis *et al*., 2018). One outcome of this work is the realization that combustion processes may be more important than once thought in the solubility of aerosol iron in the ocean (Ito *et al*., 2019).

Some of the critical changes that can occur during transport over great distances and over long periods

**Figure 4.2.** Atmospheric processes that can modify the solubility of iron (both as oxidized iron, Fe(III), and the more soluble reduced Fe(II) form) from dust during transport through the atmosphere.




Source: Adapted from Jickells and Moore, 2015.

are indicated in Figure 4.3, constructed from analysis of Saharan dust samples collected at three locations (Greece, the mid-Atlantic Ocean and Bermuda) at different transport length and timescales (although not along a single atmospheric flow path). With increased transport time, atmospheric processing appears to influence the form of iron minerals and oxidation state in the dust, resulting in enhanced aerosol acidity (as measured by pH) and increased aerosol-iron solubility.

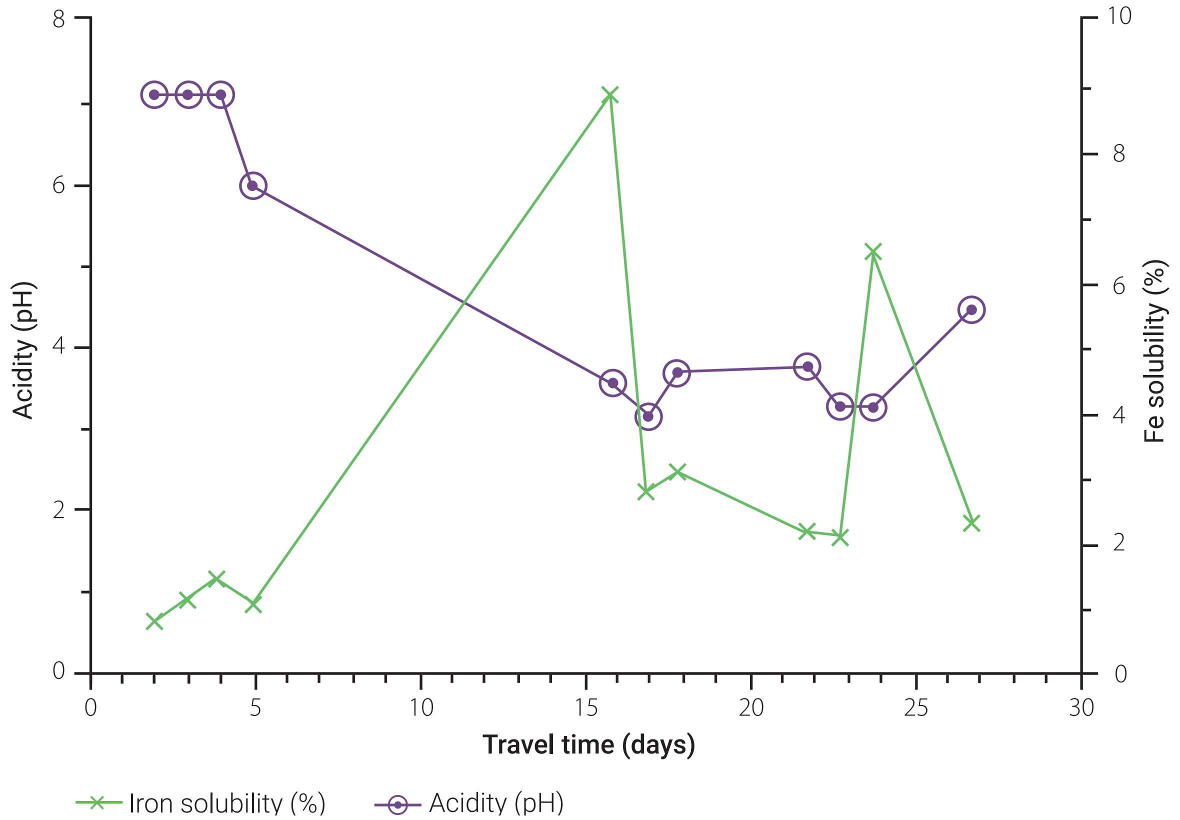
Reactions associated with atmospheric acidification are also enhanced in areas where desert dust mixes with pollution from industrial and biomass-burning regions (Ito and Shi, 2016). For example, industrial pollutants from North America complicate the processing of Saharan dust in the Caribbean (Sedwick, Sholkovitz and Church, 2007), and desert dust from China and Mongolia transported to the South China Sea and other parts of the North Pacific is typically mixed with industrial aerosols from China (Guo *et al*., 2012). Ito *et al*. (2016) have demonstrated that the impact of increased soluble iron supply to the oceans on productivity and carbon export may have contributed to the observed expansion of oxygen depletion in many marine regions of the world, with important consequences for ecosystems and biogeochemical cycles (Laffoley and Baxter, 2019).

Anthropogenic pollutants also frequently contain nutrients. High concentrations of nitrogen detected in Saharan dust flows over the tropical North Atlantic, for instance, are probably not derived from Saharan soils, but reflect emissions from highly populated areas of Europe drawn south under the influence of the prevailing air flow, as suggested by Savoie, Prospero and Saltzman (1989), who also highlight a possible secondary contribution from anthropogenic and biomass-burning emissions in North Africa. The dust-derived nutrients and the nutrients derived from anthropogenic sources travel together through the atmosphere and are deposited in combination, but their sources are quite different.

## 4.2. Dust and algal blooms

The introduction of dust-borne nutrients to ocean waters—which may increase their productivity (see section 4.1) —can sometimes enhance the growth of algal blooms. These algal blooms provide an important source of food for marine life, although

**Figure 4.3.** Acidity and iron solubility for Saharan dust plumes.




Source: Adapted from Longo *et al.* 2016.

some blooms may lead to detrimental effects on human health and economic activity. Other marine issues that have proved damaging to society, including a number of diseases and unprecedented blooms of floating seaweed mats, have also been related to desert dust deposition.

### 4.2.1. Harmful algal blooms

Microscopic planktonic algae, which represent an important food source for filter-feeding shellfish and the larvae of crustaceans and finfish, can in some situations have negative effects, resulting in severe economic losses to aquaculture, fisheries and tourism, as well as major environmental and human health impacts. Large proliferations of microalgae, so-called 'algal blooms' involving up to millions of cells per litre, can at times discolour the surface of the sea, an effect dubbed 'red tides'. That said, while red tides are most visible, it is important to note that discolouration of the water is not a prerequisite for a harmful algal bloom (HAB). Hallegraeff (2003) identifies three types of HAB:

- Those that grow so dense that they cause indiscriminate kills of fish and invertebrates through oxygen depletion.[8]
- Those containing species that produce potent toxins that reach upper-trophic level marine wildlife and humans through the food chain.[9]
- Those containing species that are non-toxic to humans but harmful to fish and invertebrates, particularly in intensive aquacultural systems.

The impact of HABs on the health of wild and cultured organisms has been described for many species, including mollusks, crustaceans, fish, sea turtles, birds, marine mammals and corals (for example, Núñez-Vázquez *et al*., 2011; Broadwater, Van Dolah and Fire, 2018).

Where and when an algal bloom occurs is dictated by a complex interaction of meteorological and biogeochemical factors. Most algal blooms are entirely natural events, and the input of desert dust is widely regarded to be an important regulator of many blooms—both harmful or otherwise—although nutrient pollution from anthropogenic sources that degrades water quality is also a critical factor in many nuisance cases (Walsh and Steidinger, 2001). In the Gulf of Mexico, nutrients supplied by inputs of iron-rich Saharan dust are thought to promote nitrogen fixation by marine cyanobacteria (*Trichodesmium* spp.) which in turn provide the biologically usable nitrogen needed to sustain HABs caused by the toxic marine dinoflagellate *Karenia brevis*. Walsh *et al*. (2006) suggest the negative effects of Saharan dust have persisted since at least the late 1520s, when the Spanish explorer Álvar Núñez Cabeza de Vaca observed that the local indigenous American shellfish harvest was suspended seasonally on what are now Texas beaches. Walsh *et al*. (ibid.) also propose that a similar chain of potential causation links desert dust from the Simpson, Gobi, Great Western and Kalahari deserts to toxic HABs in coastal habitats of Australia, China, Japan, New Zealand and South Africa. Similarly, dust deposition was identified as one of the factors explaining a red tide event that lasted for more than a year in 2008–9 in the Arabian Gulf (Zhao and Ghedira, 2014).

In the East China Sea, where more than 30 algal bloom events are recorded annually, dust blown from the Loess Plateau in China provides iron and phosphate to coastal waters (Tian *et al*., 2018). Both elements are essential nutrients for the metabolism of Cryptomonas sp. and Prorocentrum micans Ehrenberg, two important algae species in the region's HABs. These authors found a significant correlation ($r2 = 0.98$, $p < 0.01$) between the timing of large-scale HABs (>300 $km^2$) and long-distance dust transport events with a lag time of a few days during the months (March – September) when HABs are most frequent. These months also have ideal sea temperature conditions for the growth of algae in the East China Sea.

### 4.2.2. *Sargassum* invasion

Another marine issue where dust deposition may play a role stems from the unusually large blooms of floating *Sargassum* seaweed mats[10] that have been noted since 2011 in the Caribbean Sea and the Atlantic Ocean along the coastlines of West Africa and Brazil (Schell, Goodwin and Siuda, 2015). These drifting *Sargassum* mats provide an important habitat for a wide range of species in the open ocean, but close to shore they can disrupt shipping, fishing and tourism, with considerable negative impacts on the economies of coastal communities (Figure 4.4).

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[8] Particularly dense blooms can also cause damage/death through direct contact (e.g. clogging of gills), so that even when the water is oxygenated there are fish kills.

[9] Causing a range of gastrointestinal and neurological illnesses in people.

[10] Floating mats are mainly composed of two species: *Sargassum* natans and *Sargassum* fluitans.

**Figure 4.4.** Clearing a beach of *Sargassum* at Playa del Carmen, Mexico

Source: Kamira/Shutterstock.com

The cause of these mass *Sargassum* blooms continues to be a matter for debate, but the hypotheses include enhanced nutrient loading—from coastal upwelling, land-based anthropogenic sources and/or from desert dust—and the effects of climate change and variability (Oviatt *et al*., 2019; Wang *et al*., 2019). Enhanced eutrophication caused by very high nutrient loads flushed out to sea from agriculture and other land uses in the Amazon Basin is one of the triggers put forward by Louime, Fortune and Gervais (2017). This effect may be boosted by nutrients brought in via dust from the Sahara (Pawlik, Burkepile and Thurber, 2016), although there is also evidence to suggest that nutrients derived from biomass burning in Africa are more effective than dust in stimulating *Sargassum* seaweed growth (Barkley *et al*., 2019). The belief that the main nursery for mass *Sargassum* blooms is located off the West African coast (Putman *et al*., 2018), as opposed to the Sargasso Sea, as once thought, may lend credence to the importance of African nutrient sources—whether derived from dust, upwelling or biomass burning—given that deposition from Africa is greater on the eastern side of the North Atlantic.

## 4.3. Microbial pathogens

The triggering effect of an increased supply of iron delivered in desert dust could apply to other organisms previously kept in check by nutrient limitations. These include opportunistic marine microbial pathogens, including *Vibrio*, a bacterium. There are many species of *Vibrio* in the oceans and only a few of these are considered pathogenic, but those that are pathogenic can cause disease in humans (for example, cholera, shellfish-associated gastroenteritis) and marine organisms. Westrich *et al*. (2016) demonstrated that *Vibrio*, which are typically rare in pelagic waters, respond rapidly to inputs of iron-rich Saharan dust in the Caribbean and subtropical Atlantic where their relative abundance increased from around 1 percent to around 20 percent of the total microbial community within 24 hours. A similarly swift increase in *Vibrio* abundance was also detected in the open ocean by Westrich *et al*. (2018) who were able to evaluate the in situ response to the arrival of multiple distinct dust events in the tropical mid-Atlantic Ocean. These authors point out that the ecological roles of such microorganisms are largely unknown, especially in the open ocean, but they are thought to contribute to the stability and function of the ecosystem (Shade *et al*., 2014).

A growing number of studies have also demonstrated that pathogens present in desert dust can be transported great distances around the planet in a viable state (for example, Brown and Hovmøller, 2002; Prospero *et al*., 2005; González-Martin *et al*., 2014; Maki *et al*., 2019). Microorganisms in dryland soils are highly resistant to desiccation, temperature extremes, conditions of high salinity and exposure to ultraviolet radiation, and are therefore typically able to survive in the atmosphere for many days. In an early review of the possible implications, Griffin and Kellogg (2004) highlighted potential links between a disease outbreak in Caribbean sea urchins *(Meoma ventricosa)* and bacteria isolated from Saharan dust events sampled in the Virgin Islands in the Caribbean Sea, as well as septicaemia in a loggerhead turtle *(Caretta caretta)* found off the Canary Islands and a bacterium cultured from aerosolized dust collected in Mali. Research into these desert-derived bioaerosols still has many basic questions to answer. Griffin and Kellogg (2004) suggested a significant fraction (20–30 percent) of the very diverse population of microorganisms -viruses, bacteria, and fungi- transported in desert dust comprises species capable of causing disease, and disease outbreaks, in a wide range of organisms, both terrestrial and marine, though data on specific microbes in SDS known to cause disease in people and animals are still lacking. Of course, it can be assumed that dust has always moved through the Earth's atmosphere, but these authors warned that in addition to native dust constituents, dust-associated toxins of human origin may also impact the health of downwind ecosystems through direct (toxin accumulation) or indirect (immunosuppression) means.

## 4.4. Dust and coral reef systems

The links between desert dust and coral reef systems are numerous and varied. They include the direct and indirect effects of nutrients, trace metals, microorganisms and other organic matter carried in desert dust and deposited in the oceans. One of the most direct effects is the incorporation of dust particles into coral skeletons during growth, a phenomenon that also integrates a record of past environmental conditions that can be reconstructed with appropriate techniques (for example, Mukhopadhyay and Kreycik, 2008). One body of research has established links between desert dust and the health of coral reef systems in some parts of the world, particularly in the Caribbean, where a notable decline in coral reef health in the late 1970s and 1980s coincided with a period of high volumes of Saharan dust being transported across the Atlantic (Shinn *et al*., 2000). Indeed, Shinn *et al*. (2000) highlighted the fact that individual years of maximum dust flux into the Caribbean correlated with synchronous Caribbean-wide reef mortalities.

Although the health of coral reefs responds to numerous, frequently interlinked factors, including overexploitation, coastal development, overfishing, pollution, invasive species, ocean acidification, as well as increasing SSTs, disease has undoubtedly been an important factor in recent coral reef declines worldwide (Thurber *et al*., 2017). Several diseases that affect corals are associated with microorganisms carried in desert dust, with high dust deposition rates having a potentially smothering effect on corals. This is one of various factors that stresses reefs and reduces their resilience to other factors, resulting in a deterioration of their health.

### 4.4.1. Disease

Microorganisms carried in desert dust have been implicated as causal agents of a number of diseases that affect coral, notably aspergillosis, black band disease, white pox and white plague (Garrison *et al*., 2003). Aspergillosis (also known as sea fan disease because it primarily affects two types of sea fans, *Gorgonia ventalina* and *Gorgonia flabellum*) is one of the most extensive coral diseases in the Caribbean (Figure 4.5). Its causative agent, the fungus *Aspergillus sydowii*, is widely found in soils and is also salt tolerant and capable of growing in the sea. *Aspergillus sydowii* has been found in Saharan dust samples taken in the Caribbean and from diseased sea fan corals in the region (Garrison *et al*., 2003). Experimental work supports the causal link: when healthy sea fans were inoculated with *Aspergillus* spp. isolated from dust samples in the Caribbean the infected corals produced Aspergillosis-like disease morphology (Weir-Brush *et al*., 2004). A possible mechanism for the effect of sea fan disease on the coral host was suggested after researchers studied an extensive *Aspergillus sydowii* marine fungal bloom on the eastern Australian seaboard following a large dust storm that occurred in September 2009 (Hayashi *et al*., 2016). Bioassays revealed adverse effects on the photophysiological performance of the coral reef dinoflagellate *Symbiodinium*, the coral symbiont that plays essential roles in coral fitness and energy production.

Another disease identified in the Caribbean and elsewhere is black band disease, one of the earliest reported of the diseases known to affect coral reef organisms. In this case, the relationship between the disease and desert dust appears to depend heavily on the iron content of the dust, which facilitates the pathogenicity of the black band cyanobacterium (Garrison *et al*., 2003). White plague (also known as white syndrome) is also suspected to cause maximum damage to Caribbean coral reefs when combined with iron-rich dust (Garrison *et al*., 2003). The link between desert dust and white pox is less definitive. Garrison *et al*. (2003) proposed that the disease may be introduced to coral reefs via the atmospheric transport of soil material, though other pathways are also suggested, including river discharge.

General understanding of the diseases that affect coral, their causative agents and pathogenesis is still limited (Sheridan *et al*., 2013), partly because coral diseases were only initially identified and reported in the 1970s, firstly on reefs in the Caribbean and the Florida Keys and subsequently on reefs worldwide. Hence, in the case of links to desert dust, not all agree on the causes (Rypien, 2008) and many details remain obscure. As Mera and Bourne (2018) note, compromised coral (host) health is not always due to one specific causative agent, with diseases often

**Figure 4.5.** A sea fan coral (Gorgonia ventalina) infected with Aspergillus sydowii

Multifocal purple annular lesions are indicative of infection.
Source: Ernesto Weil.

resulting from complex interactions between the host, causative agents and the physical environments in which they occur.

## 4.4.2. Smothering

High rates of desert dust deposition may have a smothering effect on corals, both through elevated sedimentation rates and high turbidity in the water, which may stress reefs. Coral polyps are capable of physically removing sediment, but doing so requires energy that is then unavailable for skeletal growth or reproduction (Rogers, 1990). Reef zones where sedimentation rates are high may display relatively lower species diversity, with some less sediment-tolerant species absent, less live coral and lower coral growth rates.

However, a contrasting effect of high dust loads has been suggested in the Red Sea. Using an atmospheric model to study the impacts on regional climate, Osipov and Stenchikov (2018) concluded that dust in the atmosphere plays an important role in the energy balance, thermal, and circulation regimes in Red Sea waters. Dust appeared to modulate the flows of heat and salt in the Red Sea, which are particularly important for the region's extensive coral reef ecosystems.

## 4.4.3. Reef resilience

The simple presence of pathogens in dust does not necessarily result in a coral succumbing to disease. However, the subsequent physiological stress produced by the combination of enhanced dust transport, nutrient enrichment and SST anomalies may act to encourage the proliferation of a disease (Shinn *et al.*, 2000). In this way, the deposition of dust may undermine the resilience of coral reefs to disturbances. Again, the Caribbean has been a focus of research in this regard. Several hypotheses have been suggested to explain the relatively low resilience of Caribbean coral reefs, with some establishing a link with the Caribbean's high rates of Saharan dust deposition.

Roff and Mumby (2012) put forward a range of ideas to explain the Caribbean's relatively low resilience. One of these depends on inputs of Saharan dust to account for the suggestion that HABs occur more readily in the Caribbean than in other regions. These authors propose that the input of bioavailable iron (Fe2+) in desert dust over millennia could have reduced iron limitation in Caribbean algae, thus facilitating their ability to bloom when other enabling conditions are met. The HABs impede incoming solar radiation and weaken coral immunity. Pawlik *et al*. (2016) propose another possible sequence of events in the Caribbean, by linking dust with dissolved organic carbon and the growth of sponges and seaweeds, which compete with corals for space.

Garrison *et al*. (2003) offer a wider perspective on potential stressors, highlighting that the mixes of anthropogenic atmospheric pollutants often found in dusty air masses—including pesticides, excreted antibiotics, combustion products and metals—may also alter the resistance of coral reef organisms to disease pathogens, affect reproduction or the survival rate of larvae, interfere with calcification or act as toxins, potentially initiating a cascade of effects. As these authors suggest, the effects of atmospherically transported and deposited chemical contaminants on coral reefs at the molecular, cellular, organismal and system levels are still very poorly understood (Garrison *et al*., 2003).

Skaftafell glacier, Vatnajokull National Park in Iceland
Photo: Guitar at Shutterstock

# 5. Dust and global climate

Desert dust significantly impacts weather and climate in various ways (Schepanski, 2018). Dust affects the energy balance of the Earth system through the scattering, absorption and re-emission of radiation in the atmosphere, as well as through modifications to the optical properties of clouds and snow/ice surfaces. Dust particles serve as nuclei for cloud formation, with their chemical composition affecting the acidity of rainfall. Over the tropical North Atlantic Ocean, dust from the Sahara has a cooling effect on SSTs, which plays a role in modifying wind fields and the development of hurricanes (Lau and Kim, 2007). Another indirect way in which dust may induce a climate-regulating mechanism is via DMS released from phytoplankton fertilized by iron-rich dust (see chapter 4). Dust also exerts indirect impacts on the climate system due to its role in the global carbon cycle, which stems from further interactions between desert dust and the microorganisms responsible for primary production.

## 5.1. The sulphur cycle: dimethyl sulphide production

When desert dust is deposited on the ocean surface, the nutrients it supplies are used by various marine microorganisms that perform the key metabolic processes driving the biogeochemical cycles in oceans. A major natural source of sulphur to the atmosphere is produced by marine plankton that emit the trace gas DMS, which produces cloud condensation nuclei in the marine troposphere, backscattering incoming radiation, increasing the albedo of low-altitude clouds and potentially cooling the atmosphere (Charlson *et al*., 1987). Deposition of iron-rich desert dust that can fertilize the growth of DMS producers is one mechanism that probably influences DMS-related climate feedbacks (Henriksson *et al*., 2000; Gunson *et al*., 2006), although more recent work has disputed the mechanism of this biologically-mediated climate feedback (Quinn and Bates, 2011).

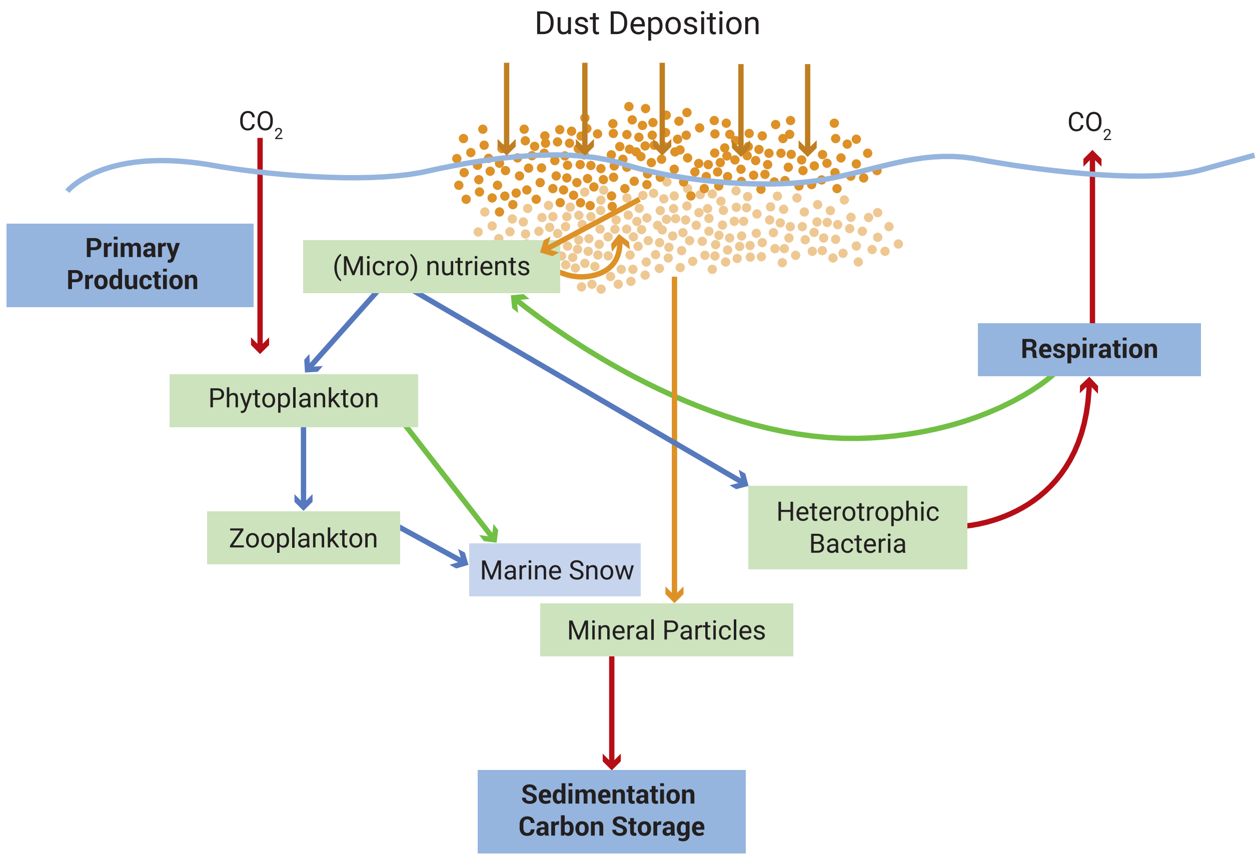
## 5.2. The carbon cycle: sequestration via the biological carbon pump

Changes to biogeochemical cycles in oceans have the potential to influence atmospheric carbon dioxide concentrations, which also results in climate feedbacks. The interaction with atmospheric carbon occurs principally in two opposite ways (Guieu *et al*., 2014b). The input of nutrients with dust can stimulate primary production by phytoplankton in the sunlit upper levels of the oceans, using carbon dioxide from the atmosphere for photosynthesis. Conversely, the nutrients can be used by a range of non-photosynthetic microbes—including archaea and heterotrophic bacteria—that emit carbon dioxide into the atmosphere via the process of respiration.

Carbon is sequestered into the oceans from the atmosphere when and where there is a net production of organic material due to an imbalance between primary production and respiration, which depends on numerous factors and varies over a range of spatiotemporal scales (Moore *et al*., 2013). For example, a field experiment in coastal waters of the Mediterranean found that both primary production and community respiration were stimulated by inputs of Saharan dust and its associated phosphorous, but the net result of low-dust additions was an initial switch towards heterotrophy, or respiration, whereas the net result of high dust additions was a shift towards autotrophy, or primary production (Lekunberri *et al*., 2010).

Much of the organic material newly produced by phytoplankton forms the basis of oceanic food chains, but a small proportion dies and sinks below the upper water level along with other falling debris, including the faecal pellets of zooplankton. This decaying material, often referred to as ‘marine snow’, provides food for many deep-sea creatures and is remineralized to nutrients and inorganic carbon at depth (Turner, 2015). An even smaller proportion of this sinking debris becomes buried in sediments (Ducklow *et al*., 2001). In this way, there is an overall sequestering of carbon from the atmosphere into the deep ocean, reducing atmospheric carbon dioxide in the process. The transformation of carbon dioxide and nutrients into organic carbon, its sinking into the deep ocean, its decomposition at depth and the incorporation of some carbon into sediment—and

**Figure 5.1.** The biological carbon pump showing how dust deposition affects stocks (green boxes) and fluxes (blue boxes) which result in an overall sequestration of carbon in deep ocean sedimentation.




Source: Adapted from de Leeuw *et al*., 2014

eventually rocks—is known as the biological carbon pump (Figure 5.1). Through this mechanism, carbon is sequestered for periods ranging from weeks to hundreds and even millions of years in the case of rocks, with oceans maintaining the atmospheric carbon dioxide concentration around 200 ppm lower than it would be if there was no life in the oceans.[11]

Dust is thought to play an additional role in the operation of the biological carbon pump. Dust particles that sink below the ocean surface can be incorporated into organic aggregates, making them larger and denser so that they effectively act as ballast, resulting in increased sinking velocities and therefore aiding the transport of organic matter to the deep ocean (van der Jagt *et al*., 2018). Dust also contributes indirectly to another similar mechanism that helps transport carbon to the deep ocean. The shells of diatoms, which are rich in silica—a key constituent of dust—provide another form of ballast to marine snow (Tréguer *et al*., 2018).

The overall impact of the two main effects of dust deposition on oceanic carbon sequestration —via nutrients that enhance primary productivity and the ballasting effect of mineral particles—was assessed in the central Atlantic Ocean by Pabortsava *et al*. (2017). These authors measured sediment particulate organic carbon flux over a two-year period using sediment traps to a depth of 3,000 m in the dust-rich central North Atlantic gyre and the dust-poor South Atlantic gyre. Comparing the two areas, they concluded that carbon fluxes were twice as high in the dust-rich North Atlantic gyre, which also had a higher proportion of primary production exported to its depths. The ballasting effect of dust particles was proposed as one explanation for this marked difference in carbon flux, though the authors also noted another possibility: that the two phytoplankton communities are very different, partly due to SDS stimulated nitrogen fixation in the North Atlantic, which may cause (or at least contribute to) the differences seen in sedimentation between the

11 Predictions by numerical models that couple the climate system and carbon cycle indicate a declining ocean carbon sink with human-induced warming.

two regions. The high-latitude North Atlantic Ocean, where productivity is affected by dust from Iceland, is another area where the sequestration of atmospheric carbon is important (Achterberg *et al*. 2018).

## 5.3. Dust in the Southern Ocean over glacial–interglacial cycles

The operation of the biological carbon pump may have been more efficient during the glacial periods of Earth's history. Over the past 800,000 years, Earth's climate has varied throughout glacial–interglacial cycles lasting around 100,000 years each, with these cycles characterized by higher and lower temperatures and greenhouse gas concentrations during interglacial periods and glacial periods, respectively (Jouzel *et al*., 2007). A number of factors are related to these changes, one of which is thought to be dust.

One hypothesis—supported by evidence from ice cores and marine sediment cores—proposes that high atmospheric concentrations of iron-rich dust deposited in oceans during glacial periods may have enhanced phytoplankton growth, thus lowering the atmospheric carbon dioxide level during those periods by 10–20 ppm (Martin, 1990). The effect of this is thought to have been most pronounced in HNLC areas of the ocean, particularly the Southern Ocean, where productivity is limited by iron deficiency.

The dominance of the Southern Ocean in large-scale atmospheric carbon dioxide drawdown is debatable, not least because the southern hemisphere does not have major continental dust sources in the present day. However, there is considerable evidence from deep-sea sediment cores to indicate that atmospheric dust loads have varied significantly over glacial–interglacial time scales, with increased dust deposition to the oceans being a feature of glacial stages (Rea, 1994). Dust concentrations in low latitudes may have been more than two times present-day loads (Winckler *et al*., 2008), though a high-resolution record of dust from an ice core in East Antarctica, which provides an undisturbed climate sequence over the past eight glacial–interglacial cycles, indicates that dust fluxes from South American dust sources during glacial periods may have been as much as 25 times higher than their present level (Lambert *et al*., 2008). There is also an argument that dust originating from glacial sources at high latitudes display elevated levels of bioavailable iron and therefore has more potential to influence ocean productivity and in turn the global carbon cycle (Shoenfelt *et al*., 2017).

Coastal delta sediments in northeast Greenland
Photo: Daniel Carlson at Shutterstock


Traditional Zanzibar dhow
Photo: Sun_Shine at Shutterstock

# 6. Policy implications

This report has demonstrated the importance of SDS for marine ecosystem functioning as well as the wide range of SDS effects on the Earth system, both direct and indirect, actual and potential. Nonetheless, considerable uncertainties remain and the state of knowledge of how SDS impact marine ecosystems, their goods and services, is incomplete. These imperfections in general understanding have significant implications for the science–policy interface on SDS.

More monitoring and basic research are still needed. Critical areas for continuing study include the uncertainties identified in earlier chapters on how desert dust impacts marine biodiversity and global climate. Further development of dust cycle models at global and regional scales is also required, as is their integration with climate change models. Developing this understanding will contribute to the achievement of targets under SDG 14 on Life Below Water.

It is also critical that more appreciation is given to the balance between potentially hazardous impacts of desert dust deposition over the oceans and the effects recognized as part of necessary Earth system functions. Recognizing the relevant consequences of these effects is necessary for efforts to reverse the cycle of decline in ocean health and to create improved conditions for sustainable ocean development, prime motivations behind the United Nations Decade of Ocean Science for Sustainable Development (2021–2030).

More efforts are also needed to assess the relative importance of naturally emitting wind erosion sources and those significantly influenced by human action. Land-based human activities—particularly unsustainable agriculture and other land uses that result in desertification, including poor water management—can result in enhanced dust emissions that frequently impact marine ecosystems great distances away. Many governance mechanisms do not accommodate impact pathways crossing between land and sea.[12] However, policies designed to tackle land degradation are relevant here, including ecosystem restoration projects that help mitigate SDS sources. The United Nations Decade on Ecosystem Restoration (2021–2030) provides an apt framework to focus this type of work. In this way, efforts made towards achieving SDG 15 on Life on Land, including target 15.3 on land degradation neutrality (LDN), will contribute to ocean health.

In the wider policy context, the connection between land and sea highlighted in this report demonstrates the importance of integrated thinking on the Earth system and the interdependencies between the SDGs. The need to account for interactions among goals has been emphasized as critical to maximizing long-term moves towards sustainability (Nash *et al*., 2020). Understanding SDS and the long-range transportation of desert dust to oceans has implications for the international community and government signatories of several multilateral environmental agreements (MEAs). The relevance is clear for the three Rio conventions: the United Nations Convention on Biological Diversity (CBD), the United Nations Framework Convention on Climate Change (UNFCCC), and the United Nations Convention to Combat Desertification (UNCCD). Further improvement in scientific knowledge of how SDS interact with the oceans and the consequent impacts on other parameters of the Earth system will inform appropriate policy development in all these fields.

[12] See the United Nations Environment Programme (UNEP) International Resource Panel (IRP) report "Mapping the Impacts of Land-Based Activities on Coastal Resources in Support of the Sustainable Blue Economy" (forthcoming).

Red tide flowing to the coast of Yamaguchi prefecture in Japan
Photo: tak-photo at Shutterstock

# 7. Conclusions and recommendations

## 7.1. Conclusions

1. SDS are important to ecosystem functioning and have a wide range of effects on the Earth system.
2. SDS vary in frequency and intensity over multiple timescales, responding to seasonal climate variability, drought periods and other drivers, such as El Niño–Southern Oscillation and the North Atlantic Oscillation.
3. Desert regions in the northern hemisphere (northern Africa, the Middle East, south-west, central and north-east Asia) contain the largest and most persistently active sources; smaller, less active sources are located in North and South America, southern Africa, Australia and Iceland.
4. The Sahara is the world's largest source of desert dust, producing some 55 percent of all global dust emissions, with marked effects on the North Atlantic Ocean, the Caribbean Sea, the Mediterranean Sea and the Red Sea.
5. The relative importance of naturally emitting wind erosion sources and those significantly influenced by human action is unclear.
6. Desert dust provides the largest atmospheric source of certain trace metals—iron, manganese, titanium, aluminium—to oceans, which have significant implications for marine microorganisms.
7. Desert dust provides the primary external source of iron to offshore waters, although controls on iron aerosol solubility are poorly understood.
8. Desert dust deposited on ocean surfaces influences key metabolic processes driving the biogeochemical cycles in the oceans, including carbon, nitrogen, sulphur, phosphorus and silicon cycles.
9. The fertilizing effect of desert dust is thought to have an impact on algal blooms and may have an impact on *Sargassum* seaweed mats.
10. The very diverse population of highly resilient microorganisms transported in desert dust is not well-documented, but includes species capable of causing disease in many marine organisms, including coral reefs.
11. The Southern Ocean, which is characterized by large areas with high nitrate but low chlorophyll surface concentrations, is particularly sensitive to the input of dust and iron.
12. Dust input to oceans during glacial periods may have suppressed atmospheric carbon dioxide compared with interglacial periods.

## 7.2. Recommendations

1. Encourage further research into the understanding of SDS sources and emissions, including assessment of the relative importance of naturally emitting wind erosion sources and those significantly influenced by human action.
2. Promote the establishment of a network of study sites across different oceans to take long-term measurements of dust in the marine atmospheric boundary layer.
3. Encourage further development of models of the dust cycle at global and regional scales, including better simulation of processes of dust emission, transport and deposition.
4. Promote ecosystem restoration projects that can help mitigate SDS sources by providing wind erosion protection to susceptible soils (for example, Africa's Great Green Wall).[13]
5. Encourage research into the interactions between natural desert dust constituents and dust-associated toxins of human origin and how they may impact the health of downwind marine ecosystems.
6. Encourage research into the interactions between desert dust constituents deposited in oceans and indirect impacts on human health.

[13] See www.greatgreenwall.org/.

7. Encourage research into the processes affecting the bioavailability of phosphorus and iron carried in desert dust and assess the combined effects of different stressors (warming, pH, ultraviolet radiation, etc.) on the response of ecosystems to dust deposition.

8. Promote the implementation of coordinated field experiments involving both atmospheric and marine measurements to address the processes and role of dust, iron and phosphorus fertilization on marine biogeochemistry and climate.

9. Promote assessments of the economic value of damage caused by SDS which will enhance policy development and mitigation efforts.

10. Enhance the science–policy interface on SDS to support implementation of relevant resolutions and decisions taken at the Conferences of the Parties of the UNCCD, the United Nations Environment Assembly and other relevant MEAs, in particular to address SDG 14 on Life Below Water and SDG 15 on Life on Land, including target 15.3 on LDN.

Loggerhead sea turtle *Caretta caretta*
Photo: Pete Niesen at Shutterstock

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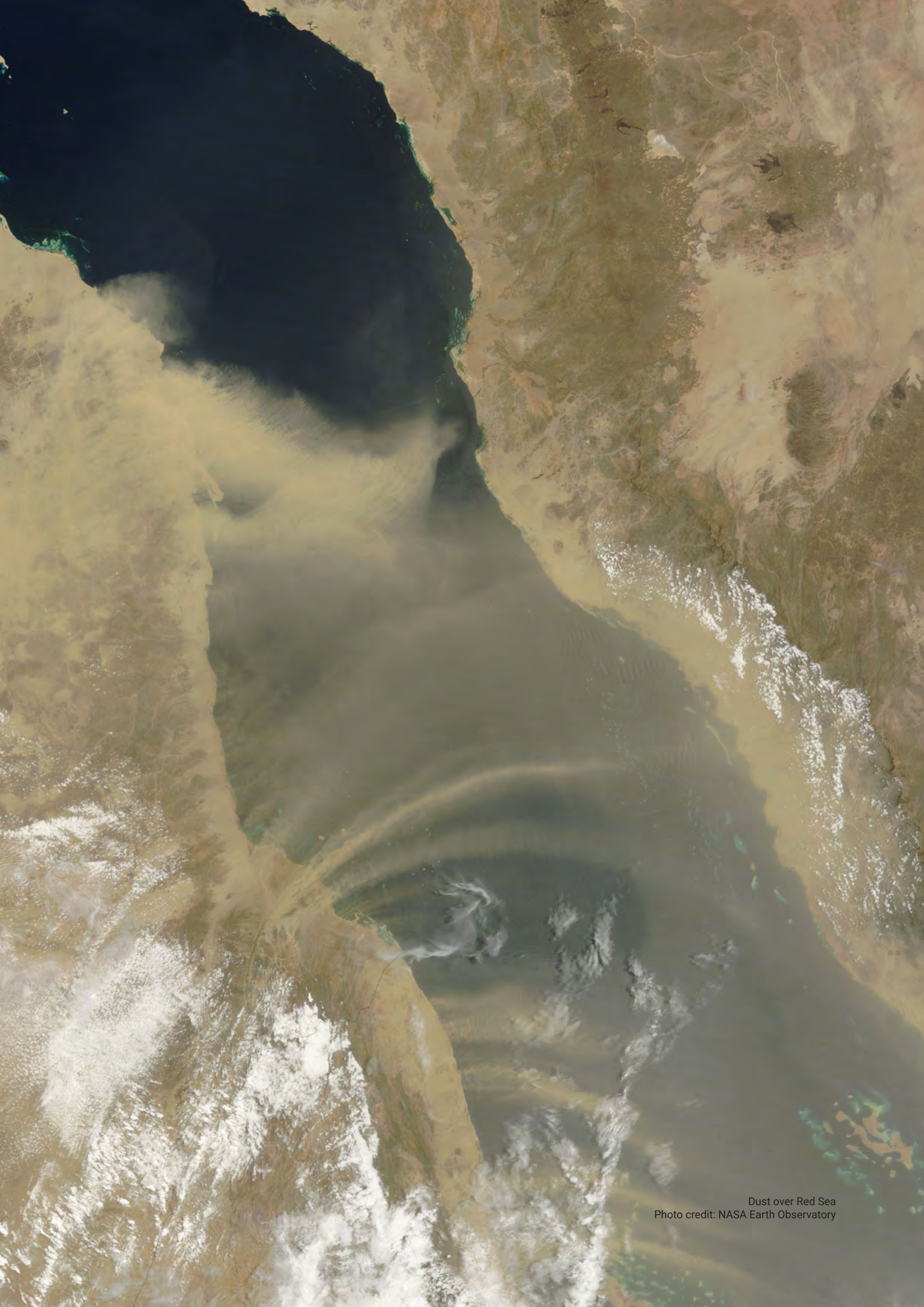

Dust over Red Sea
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