Peter Knippertz
Jan-Berend W. Stuut *Editors*

Mineral Dust

A Key Player in the Earth System

Springer

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Editors
Peter Knippertz
School of Earth & Environment
University of Leeds
Leeds, UK

Institute for Meteorology and Climate Research
Karlsruhe Institute of Technology
Karlsruhe, Germany

Jan-Berend W. Stuut
NIOZ – Royal Netherlands Institute for Sea Research
Department of Marine Geology and Chemical Oceanography
Texel, The Netherlands

MARUM – Center for Marine Environmental Sciences
Department of Marine Sedimentology
University of Bremen
Bremen, Germany

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Preface

This is a book about mineral dust in the Earth's atmosphere. Atmospheric dust consists of tiny mineral particles, which mostly originate from soils in the arid and semi-arid parts of the Earth and can be transported over distances of many thousands of kilometres to be finally deposited on soil, plants and glaciers or into the ocean. Dust is a fascinating, truly interdisciplinary and rapidly growing research topic for many reasons. Dust storms are dramatic meteorological events that can have considerable impacts on human activities reaching from health and agriculture to industrial production, (air-)traffic and military operations. Dust changes the global energy and carbon budgets and thereby affects climate and even weather in multiple ways. The amounts of dust in the atmosphere, its sources and transport patterns have changed considerably through climate history, providing an important source of information for reconstructions. It is currently debated what role dust may play in manmade climate change. This book attempts to give a comprehensive overview of the full range of current dust research and the underpinning fundamental scientific concepts while at the same time explaining concrete applications of this science. It mainly addresses researchers from the postgraduate to the senior level, but at least parts of it should be useful for specialised teaching activities (e.g. summer schools).

The idea for this book was born in a recurrent session at the annual General Assembly of the European Geosciences Union (EGU) entitled "Aeolian dust: Initiator, Player, and Recorder of Environmental Change". Jan-Berend Stuut and Maarten Prins (both from the Climate division of EGU) started this session in 2004. It has successfully run every year since then with up to 60 contributions per session. Peter Knippertz was invited to join as a convener in 2008 to enhance the involvement of the Atmospheric Sciences division. Since then, the role of dust in climate and atmospheric sciences has been the backbone of the session, while participation from the soil science and geomorphology community has varied, as also reflected in changes to the convener group (Andreas Baas participating in 2008 and 2009, Sue McLaren joining in 2013). There are very few long-running, recurrent conference sessions or meetings solely dedicated to dust, such that this session has created an important interdisciplinary forum for this type of research. Over the years, a great number of internationally recognized experts on dust have attended and presented at the session, many of which are now authors of this book. Many presentations and the subsequent discussions have inspired new research and collaborations, and it has been a true pleasure to be involved in this activity over the years. We hope that the readers of this book will find it an inspiring and interesting lecture and that at least part of the fascination that brought the authors and editors of this book together in the first place can be conveyed on the following pages.

For those interested to learn more about aeolian dust, please visit the website of the International Society for Aeolian Research (ISAR) at www.aeolianresearch.org. The International Society of Aeolian Research was created to promote contacts among scientists undertaking research in aeolian processes, landforms, and modeling, to stimulate scientific research in aeolian topics and related fields, and to further the application of the results of such research into practical applications.

Personal Notes by the Editors

We, the editors, had a long discussion about how to write personal notes in the preface of this book. In the end we agreed that one important aspect should be to attempt to inspire the reader by telling how our careers developed and how the mixture of curiosity, enthusiasm, collaboration and pure chance have made our jobs so fascinating . . . .

Peter Knippertz

Looking back at my scientific career so far, it is interesting to reflect upon how I increasingly became involved in dust research. The initial spark was the extraordinary dust storm of 3–6 March 2004, which affected almost entire northern Africa for several days. By the time of this event I had just completed my PhD at the University of Cologne (Germany) on rainfall variability in northwestern Africa and had moved on to a postdoc fellowship at the University of Wisconsin–Madison (USA). The first Meteosat Second Generation satellite (Meteosat-8) had just become operational in time for this event on 29 January 2004. The extension to 12 channels, several of which in the infrared part of the electromagnetic spectrum, allowed for the first time visualizing dust plumes over land and water in a clear and consistent way with 15-min time resolution. Watching animations of this storm over and over again, I decided to conduct a detailed case study, which led to my first publication on dust (Knippertz and Fink, 2006, Quart. J. Roy. Meteorol. Soc.). After my return to Germany in 2005, I became involved with the SAMUM (Saharan Mineral Dust Experiment) project that brought me to Morocco and the Cape Verde Islands for dust-related fieldwork and led to numerous new contacts, collaborations and publications across Europe. In 2010, after my move to the University of Leeds (UK), I was granted my first own project on dust entitled "Desert Storms" through the European Research Council Starting Grant scheme, which allowed me to focus very strongly on meteorological aspects of dust uplift. Today, after another move back to Germany, dust science makes up an important part of my research portfolio, demonstrating how the invention of new technology (Meteosat) in combination with a spectacular single meteorological event (the March 2004 dust storm) can shape a research career for years. This book is yet another step in the growing importance that dust research has taken in my scientific interest and research work.

Of course, a book of this breadth of topics can hardly be assembled by one person alone. Therefore I am very grateful to Jan-Berend Stuut for the long-term fruitful and enjoyable collaboration, both for organising the EGU dust sessions and for editing this book. Only this collaboration made it possible to fully bridge the wide gap from dust particles acting as ice nuclei to the evolution of the Chinese Loess Plateau. I'm also thankful to the fantastic team of chapter authors that brought the fascinating range of dust research to life in this book. It is an honour to be an editor for such an excellent group of international experts, who have not only put together their own chapters but also contributed substantially by reviewing the chapters of others. I would like to thank the EGU for providing a great forum over the years to assemble the dust community at their annual meetings and all the scientists that have contributed to make the dust sessions lively and inspiring. Many of those have contributed significantly to my interest in and research on dust through fruitful collaborations and joint papers, and I won't be able to provide an exhaustive list here. To mention at least a few I would like to thank Andreas Fink for sharing the enthusiasm about the March 2004 storm and many other interesting meteorological events; Lothar Schütz, Konrad Kandler, Albert Ansmann and many others involved in SAMUM for opening the project up generously and widely for my participation; Amato Evan and Helen Brindley for giving me a better satellite perspective on dust; Martin Todd, Cyrille Flamant and Diana Bou Karam for fruitful discussions and joint papers; as well as my students, postdocs and colleagues at the Universities of Mainz (Carmen Emmel née Deutscher, Gregor Gläser) and Leeds (John Marsham, Bernd Heinold, Kerstin Schepanski, Carl Gilkeson, Sophie Cowie, Alex Roberts, Stephanie Fiedler, Bradley Jemmett-Smith) as well as at the Karlsruhe Institute of Technology (Florian Pantillon) for their fantastic research on dust and collaboration. Last but not least I am much obliged to those that funded this research over the past 10 years: the European Research Council (ERC), the German Science Foundation (DFG) and the Johannes Gutenberg University Mainz (JGU).

Leeds, UK
Karlsruhe, Germany
July 2014

Peter Knippertz

Jan-Berend W. Stuut

Ever since my Master's project, during which I tried to recognise and quantify wind-blown dust in marine sediments from the Indian Ocean, I have been fascinated by aeolian dust. Together with and supervised by Maarten Prins, we managed to characterise and quantify dust in marine sediments from both the Indian- and south-eastern Atlantic oceans, simply by studying the grain-size distribution of deep-marine sediments. A powerful proxy indeed! I continued studying mineral dust for my PhD studies offshore Namibia and established a reconstruction of environmental changes in south-western Africa. It turned out that climate in this part of Africa was related to ocean circulation but showed a pattern that was exactly opposite to the well-established paleoclimate records from the northern hemisphere. When looking at these records I am literally still amazed how the patterns in the grain size of the terrigenous sediments and those in the $\delta^{18}O$ of surface-ocean unicellular calcifiers line up so nicely although they are totally independent proxies! After finishing my PhD in 2001, I moved on to the University of Bremen, Germany, for a postdoc to study mineral dust in marine sediments offshore Chile to see if climate throughout the late Quaternary followed the same southern-hemisphere pattern, which it did! I thank both Gerold Wefer and Dierk Hebbeln for their unrelenting support and for giving me the freedom to go my own way “chasing dust” during two more postdoc phases in Bremen.

While studying dust in marine sediment archives, I found that it is quite possible and of vital importance to ground-truth observations inferred from dust deposits by comparing them with present-day processes of dust mobilisation, dispersal, and deposition. I am much obliged to Ralph Schneider who invited me to join his research cruise on board RV *Meteor* in 1998 to collect Saharan dust from the atmosphere while sailing from southern Spain to Gabon all along the west African coast. This was a typical example of being at the right place at the right time because we happened to sail through a few giant dust outbreaks: an amazing experience and probably a trigger similar to Peter’s observation of the March 2004 dust storm. For the first time we managed to combine the set of actual dust samples collected on board the ship with satellite data and the daily meteorological observations done by the German Weather Service on board the ship. By studying back-trajectories of the different air masses we located with the weather-balloon data, we managed to trace the different dust particles back to their sources. Many ship cruises and dust sampling campaigns later we still have more questions than answers regarding dust dispersal and deposition and also the marine environmental effects of dust deposition: enough work to be done!

One more colleague that played a critical role in my dusty career is Patrick De Deckker who picked up and stimulated my curiosity after the role of the southern hemisphere on global climate. Within weeks after we met, he managed to transfer our ideas into an ARC (the Australian NSF) proposal to study Australian dust sources. We got funded to go into the Australian outback to fingerprint the many different dust sources based on geology, mineralogy, chemistry and microbiology. These field trips were truly amazing and they broadened my horizon in many ways.

Another event that I think has been essential in shaping my dusty career is a project by the Dutch TV channel VPRO, who organised a trip on board the clipper *Stad Amsterdam* in 2010, retracing Charles Darwin’s travels on board HMS *Beagle*. They allowed me to participate in this cruise by installing a dust collector on deck sampling the atmosphere offshore the large deserts they passed, just like Darwin did. The trip made me aware of how easily scientific results can be misused to make money. On the ship I discussed a lot with a so-called geo-engineer who wanted to make money by fertilising the ocean with powdered iron ore in order to combat global warming. His motivation was based on John Martin's iron hypothesis which states that phytoplankton can sequester CO_2 from the atmosphere, and that there are certain iron-limited parts of the ocean in which phytoplankton can benefit from iron additions. These discussions convinced me of the fact that fundamental research is of vital importance for applied sciences as well and that great care should be taken when disturbing natural balances. As a result I am now working on three parallel projects in which we collect Saharan dust along a transatlantic transect between NW Africa and the Caribbean using tethered surface buoys and moored submarine sediment traps to study the marine environmental effects of dust deposition.

When I wanted to present my results in a big meeting like the European Geosciences Union, I found that actually there were no sessions in which my work fitted very well. As a result, the EGU program committee (by then still called EGS) was kind enough to allow Maarten Prins and me to organise our first dust session in Nice in 2004. It came down to us writing emails to invite people that we only knew from their dusty papers and ask them to join us in Nice to discuss mineral dust. The incredible thing was: virtually all these famous people (e.g., Grant McTainsh a.k.a. "Dr Dust", Joe Prospero, Ed Derbyshire, Martin Iriondo, Misao Mikami, Ina Tegen, Slobodan Markovic, Jean Robert Petit, Ludwig Zöller, Patrick De Deckker, Dennis Rousseau, Ian Smalley, to name a few) responded enthusiastically and came! From the first one on, our dust session was a great success with many very interesting contributions from almost all scientific disciplines one can think of related to mineral dust, which are also presented in this book. Throughout the years I had the pleasure to have worked together with different co-convenors (Maarten Prins, Andreas Baas, Peter Knippertz, Sue McLaren) and our sessions have been a continuous success, supported by many contributors presenting their fascinating work and ideas. I have enjoyed bringing people together in workshops and sessions like this and this book is just another result from this exercise of bridging gaps between scientific disciplines.

I wish to explicitly thank my co-editor Peter Knippertz who also put a lot of energy in organising the sessions in Vienna and came up with the idea to produce a state-of-the-art overview of the interdisciplinary studies of mineral dust in the form of this book.

Last but not least I would like to thank my direct dusty teammates in Bremen and at NIOZ, Inka Meyer, Conny Saukel, Carmen Friese, Malte Jäger, Felix Temmesfeld, Michelle van der Does, Laura Korte, Chris Munday, Geert-Jan Brummer, Esmee Geerken, Yvo Witte, Edwin Keijzer, and Bob Koster as well as generous funding by NIOZ and MARUM and by the German Science Foundation (DFG) through the DFG-Research Center/Cluster of Excellence "The Ocean in the Earth System", the Dutch Science Foundation (NWO), the Qatari Science Foundation (QNRF), the Australian Science Foundation (ARC), and the European Research Council (ERC).

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Jan-Berend W. Stuut

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Contents

Contributors

Matthew C. Baddock Atmospheric Environment Research Centre, Griffith School of Environment, Griffith University, Brisbane, QLD, Australia

Alex R. Baker Centre for Ocean and Atmospheric Sciences, School of Environmental Sciences, University of East Anglia, Norwich, UK

José Maria Baldasano Barcelona Supercomputer Center-Centro Nacional de Supercomputación (BSC-CNS), Barcelona, Spain

Sara Basart Barcelona Supercomputer Center-Centro Nacional de Supercomputación (BSC-CNS), Barcelona, Spain

Angela Benedetti European Centre for Medium-Range Weather Forecasts, Reading, UK

Francesco Benincasa Barcelona Supercomputer Center-Centro Nacional de Supercomputación (BSC-CNS), Barcelona, Spain

Gilles Bergametti LISA, UMR CNRS 7583 – Université Paris Est Créteil – Université Paris Diderot, Paris, France

Olivier Boucher Laboratoire de Météorologie Dynamique, Paris, France

Aikaterini Bougiatioti School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA

Laser Remote Sensing Laboratory, National Technical University of Athens, Athens, Greece

Philip Boyd University of Tasmania, Hobart, Australia

Otago University, Dunedin, New Zealand

Malcolm E. Brooks Met Office, Exeter, UK

Stephen R. Cattle Faculty of Agriculture and Environment, The University of Sydney, Sydney, NSW, Australia

Jen-Ping Chen Department of Atmospheric Science, National Taiwan University, Taipei, Taiwan

Isabelle Chiapello LOA, CNRS/Université Lille 1, Villeneuve d'Ascq, France

Peter R. Colarco NASA Goddard Space Flight Center, Greenbelt, MD, USA

Onn Crouvi Geological Survey of Israel, Jerusalem, Israel

Gilles Forêt LISA, UMR CNRS 7583 – Université Paris Est Créteil – Université Paris Diderot, Paris, France

Thomas E. Gill Department of Geological Sciences, University of Texas at El Paso, El Paso, TX, USA

Sunlin Gong Chinese Academy of Meteorological Sciences, Beijing, China

Vicki H. Grassian Department of Chemistry, University of Iowa, Iowa City, IA, USA

Eleanor J. Highwood Department of Meteorology, University of Reading, Reading, UK

Nicolas Huneeus Department of Geophysics and Center for Climate and Resilience Research, University of Chile, Santiago, Chile

Keith A. Hunter Otago University, Dunedin, New Zealand

Tim Jickells School of Environmental Sciences, University of East Anglia, Norwich Research Park, Norwich, UK

Luke Jones European Centre for Medium-Range Weather Forecasts, Reading, UK

Konrad Kandler Institute of Applied Geosciences, Technical University Darmstadt, Darmstadt, Germany

Peter Knippertz School of Earth & Environment, University of Leeds, Leeds, UK

Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany

Olga Laskina Department of Chemistry, University of Iowa, Iowa City, IA, USA

Sarah Lu National Centers for Environmental Prediction, College Park, MD, USA

Beatrice Marticorena Laboratoire Interuniversitaire des Systèmes Atmosphériques, UMR CNRS 7583, Universités Paris Est – Paris Diderot, IPLS, Créteil, France

Laurent Menut Laboratoire de Météorologie Dynamique, Paris, France

Ron L. Miller NASA Goddard Institute for Space Studies, New York, NY, USA

Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA

Jean-Jacques Morcrette European Centre for Medium-Range Weather Forecasts, Reading, UK

Suzette A. Morman United States Geological Survey, Denver, CO, USA

Daniel R. Muhs U.S. Geological Survey, Federal Center, Denver, CO, USA

Jane Mulcahy Met Office, Exeter, UK

Benjamin Murray Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, UK

Athanasios Nenes School of Earth and Atmospheric Sciences, School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, Atlanta, GA, USA

Institute of Chemical Engineering Sciences (ICE-HT), FORTH, Patras, Greece

Slobodan Nickovic Institute of Physics Belgrade, Serbia and University of Arizona, Tucson, AZ, USA

Carlos Pérez García-Pando Department of Applied Physics and Applied Maths, NASA Goddard Institute for Space Studies, Columbia University, New York, NY, USA

Jan P. Perlwitz NASA Goddard Institute for Space Studies, New York, NY, USA

Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA

Geoffrey S. Plumlee United States Geological Survey, Denver, CO, USA

Joseph M. Prospero Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL, USA

Jeffrey S. Reid Naval Research Laboratory, Monterey, CA, USA

Denis-Didier Rousseau Ecole Normale Supérieure, Laboratoire de Météorologie Dynamique, UMR CNRS-ENS 8539 & CERES-ERTI, Paris Cedex 5, France

Lamont-Doherty Earth Observatory, Columbia University, Palisades, USA

Claire L. Ryder Department of Meteorology, University of Reading, Reading, UK

Dirk Scheuvens Institute of Applied Geosciences, Technical University Darmstadt, Darmstadt, Germany

Michael Schulz Norwegian Meteorological Institute, Oslo, Norway

Thomas T. Sekiyama Japan Meteorological Agency/Meteorological Research Institute, Tsukuba, Japan

Jan-Berend W. Stuut NIOZ – Royal Netherlands Institute for Sea Research, Department of Marine Geology and Chemical Oceanography, Texel, The Netherlands

MARUM – Center for Marine Environmental Sciences, Department of Marine Sedimentology, University of Bremen, Bremen, Germany

Jimin Sun Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

Anders Svensson Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Taichu Y. Tanaka Japan Meteorological Agency/Meteorological Research Institute, Tsukuba, Japan

Ina Tegen Leibniz Institute for Tropospheric Research, Leipzig, Germany

Enric Terradellas Spanish Meteorological Agency, AEMET, Barcelona, Spain

Paul Vallelonga Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Douglas L. Westphal Naval Research Laboratory, Monterey, CA, USA

Marcelo A. Zárate Instituto de Ciencias de la Tierra y Ambientales de la Pampa (INCITAP), Avenida Uruguay 151, Santa Rosa, La Pampa, Argentina

Xiao-Ye Zhang Chinese Academy of Meteorological Sciences, Beijing, China

Chun-Hong Zhou Chinese Academy of Meteorological Sciences, Beijing, China

About the Editors

Peter Knippertz is an expert in meteorological aspects of dust storms. He received his Ph.D. in Meteorology from the University of Cologne (Germany) in 2003 and was a researcher at the Universities of Wisconsin-Madison (USA, 2003–2005), Mainz (Germany, 2005–2009), where he received his habilitation in 2008, and Leeds (UK, 2009–2013). In 2013 he moved to the Karlsruhe Institute of Technology (Germany), where he is now a Professor of Meteorology. He is currently leading a major 5-year project on dust emission funded by the European Research Council and a large European consortium on cloud-aerosol interactions in West Africa funded by the European Union.

Jan-Berend W. Stuut has been working on aeolian dust from a marine perspective since his Ph.D., which he received from Utrecht University (the Netherlands) in 2001. After his Ph.D., he worked as a postdoctoral researcher at the Research Center Ocean Margins and the MARUM – Center for Marine Environmental Sciences, both at the University of Bremen, focusing on marine archives of mineral dust. He then moved to the NIOZ – Royal Netherlands Institute for Sea Research in 2009 to further study modern dust deposition processes in and offshore deserts around the world. Since 2012 he is leading two projects on the marine environmental effects of Saharan dust funded by both the Dutch NSF (NWO) and the European Research Council (ERC). He is still affiliated to MARUM, Bremen, where he also leads a project on Saharan dust deposition in the Atlantic Ocean, funded by the German NSF (DFG).

Chapter 1
Introduction

Peter Knippertz and Jan-Berend W. Stuut

Abstract Mineral dust is a key player in the Earth system with important impacts on the global energy and carbon cycles, acting on timescales of minutes to millennia. Megatons of dust are lifted each year into the atmosphere by strong near-surface winds over the world's arid regions. Such winds can be generated by short-lived small-scale dust devils, cold outflow from thunderstorms up to continental-scale dust storms. The tiny dust particles can be lifted to great heights and transported thousands of kilometres across the globe. Once airborne, dust affects radiation and clouds and thereby also precipitation. Dust also alters chemical processes in the atmosphere and deteriorates air quality and visibility for aviation. Dust is removed from the atmosphere by gravitational settling, turbulence or precipitation. Deposition on plants, snow and ice changes the amount of reflected solar radiation. Iron and other nutrients contained in dust fertilise both terrestrial and marine ecosystems. Dust deposits in glaciers, soils and ocean or lake sediments constitute an important archive of past environmental changes. For the first time, this book gives a detailed account of the state of the art in the fascinating, highly interdisciplinary and dynamically evolving area of dust research including results from field campaigns,

P. Knippertz (✉)
School of Earth & Environment, University of Leeds, Leeds, UK

Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany
e-mail: peter.knippertz@kit.edu

J.-B.W. Stuut
NIOZ – Royal Netherlands Institute for Sea Research, Department of Marine Geology and Chemical Oceanography, Texel, The Netherlands

MARUM – Center for Marine Environmental Sciences, Department of Marine Sedimentology, University of Bremen, Bremen, Germany
e-mail: jbstuut@nioz.nl

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laboratory, aircraft, satellite, modelling and theoretical studies. This chapter gives a short introduction into the topic, placing several recent developments in dust research into a historical context.

Keywords Overview • History • Chapter • Publications • Observations • Modelling • Field campaigns • Player • Recorder • Environmental change

1.1 Why Study Dust?

Airborne dust, mostly emitted from soils in arid and semi-arid regions, is a key atmospheric constituent and represents an important natural source of atmospheric particulate matter. In comparison to soot from natural fires, sulphates from industrial exhaust, ash from volcanic eruptions and sea salt, dust is the most important aerosol by mass (Fig. 1.1).

Atmospheric dust is considered to be a harmful air pollutant causing respiratory diseases and infections, and in some regions dust can also contribute to trigger serious epidemics through carrying pathogens (De Deckker et al. 2008), such as foot-and-mouth disease in the UK (Griffin et al. 2001) and meningitis in the Sahel (Thomson et al. 2006). Significant dust events have a substantial economic impact as reduced visibility can affect air traffic, road transportation and military operations. The aerial erosion of soils is a major problem in agriculture (McTainsh et al. 1990). Reduced radiation at the surface has an impact on the output from solar power plants, especially those that rely on direct solar radiation (Schroedter-Homscheidt et al. 2013).

Dust also interacts with continental and maritime ecosystems by being a source of micronutrients (e.g. Okin et al. 2004; Jickells et al. 2005; Schulz et al. 2012;

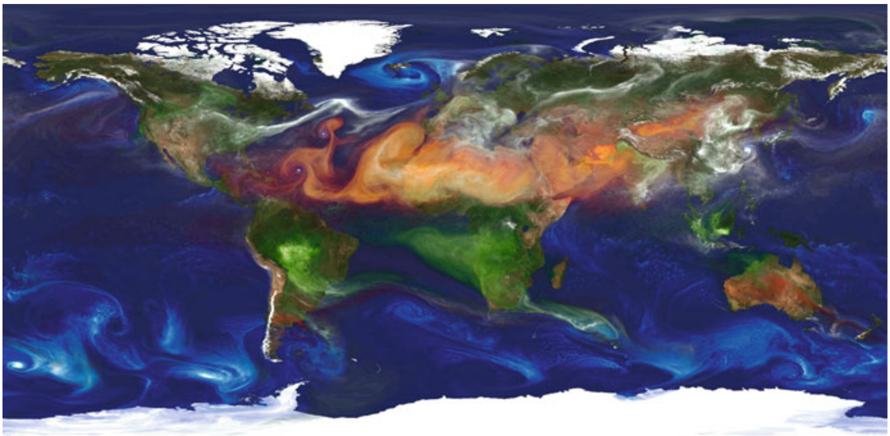

Fig. 1.1 NASA's GEOS-5 simulation, showing the four main aerosols: mineral dust from deserts (*red*), sea salt from spray (*blue*), soot and smoke from fires (*green*) and sulphate particles from fossil fuel combustion and volcanoes (*white*). Source: http://geos5.org

Martinez-Garcia et al. 2011). It has been hypothesised that the Amazon rainforest is fertilised significantly by Saharan dust (e.g. Bristow et al. 2010) and that the fertilising effect on the ocean is potentially so large that it plays an important role in global climate (Martin 1990).

In addition, dust plays an important role in different aspects of weather and climate dynamics, the Earth's radiative budget, cloud microphysics and atmospheric chemistry. The radiative heating of airborne dust modifies the energetics of the atmosphere, including possible modifications of easterly waves and tropical cyclone development over the Atlantic Ocean, downwind of the Sahara Desert (Karyampudi and Carlson 1988; Karyampudi and Pierce 2002).

As stressed by both the fourth and recent fifth assessment of the International Panel of Climate Change, the level of scientific understanding of the effects of aerosols, both natural and anthropogenic, on climate is generally low (Forster et al. 2007; Myhre et al. 2013). Considerable advances in the knowledge of dust mobilisation, dispersal and deposition as well as impacts of atmospheric dust have been made, but many open questions remain.

1.2 A Short History of Dust Research

Dust storms and atmospheric dust processes have attracted societal attention for millennia. In ancient Korea, for example, dust events caused concern because they were considered as God's punishment or a warning to the ruler. Historical records of dust observations are preserved from as early as the first century BC (Chun et al. 2008). Two millennia later, Alexander von Humboldt (1807) discussed how dust particles could be taken up into the atmosphere after viewing a wind spout in South America. Charles Darwin (1846) published the first scientific record of intercontinental transport of Saharan dust across the Atlantic Ocean. A Royal Society Colleague of Darwin had encountered Saharan dust along the African coast transported by the Harmattan winds much earlier, but he did not recognise that the 'troublesome sensation of prickling on the skin' he felt was probably caused by dust particles (Dobson 1781). Samples of dust collected by Darwin on the Beagle near the Cape Verde Islands were sent to Berlin, where they were analysed with regard to their microscopic content. Ehrenberg hypothesised that at least parts of the dust originated from a dry lake due to findings of freshwater diatoms and terrestrial plant material, thereby excluding volcanic sources as previously suggested (Ehrenberg 1849). In 1925 Sutton published a paper on the meteorology of haboob dust storms in Sudan, including a limited climatology based on surface station data. A few years later, Semmelhack (1934) described some details of the long-range transport and deposition patterns of mineral dust over the tropical Atlantic.

An important milestone of modern dust research was the publication of *The physics of blown sand and desert dunes* by Bagnold in 1941, which has been a main reference in the field of dust uplift ever since. The following 1940s–1960s saw a number of studies on dust emission and its dependence on soil characteristics (e.g.

Bisal and Hsieh 1966) and wind, including some work on dust devils (e.g. Sinclair 1969). Much of this was conducted in the field but also increasingly in wind tunnels (e.g. Marshall 1971). At the same time, researchers began to look more into characteristics of dust after long-range transport (Pitty 1968), while Policard and Collet (1952) published an early study of dust impacts on human health in the Sahara.

The first large field campaign with a dust component was the GARP Atlantic Tropical Experiment (GATE) during the summer of 1974, which included aerosol and turbidity measurements from a network of five land stations and ten ships. The 1970s also saw the advent of satellite technology capable of estimating dust loads from space (e.g. Fraser 1976). A number of publications authored by Prospero and Carlson discussed details of the transport of dust from Africa to America and its impacts on radiation (e.g. Carlson and Prospero 1972; Prospero and Nees 1976; Prospero and Carlson 1980), while Schütz and Jaenicke extensively analysed physical and chemical properties of dust particles sampled in the field (Schütz and Jaenicke 1974; Jaenicke and Schütz 1978). Work by Gillette and colleagues from the 1970s onwards established some of the concepts of dust emission still used today, such as sandblasting efficiency (e.g. Gillette 1974, 1977; Gillette et al. 1982). In 1979, Christer Morales edited a book entitled *Saharan dust: Mobilization, Transport, Deposition*. Based on a workshop held in Gothenburg, Sweden, this book gave a first comprehensive account of the state of the art in dust research at the time. In the following years, more detailed overviews were presented in two books by Pye (1987) and Goudie and Middleton (2006). In 2008, Shao published a book with a more specific focus on wind erosion.

In the 1980s many fundamental concepts of dust emission and deposition were developed further, including some classical work on dry and wet removal (e.g. Slinn and Slinn 1980; Giorgi 1988). Also during this time, Koopmann and Sarnthein conducted some pioneering work on Saharan dust deposited in the equatorial north Atlantic (Sarnthein and Koopmann 1980; Sarnthein et al. 1981; Koopmann 1981). This decade also saw the development of the first computer models for dust processes. While, for example, Lee (1983) looked specifically at the transport and removal processes of dust, Westphal et al. (1988) studied the importance of low-level nocturnal jets and the midlevel easterly jet on dust mobilisation and transport, using the first multidimensional, size-resolving, full physics numerical dust transport model. This implementation demonstrated the practicality of computer simulations of dust storms, as they are still used today.

The development of numerical dust models and the refinement of satellite retrievals have led to a rapid growth in the scientific interest in atmospheric dust over the past two decades. To illustrate this, Fig. 1.2 shows the development in publications and citations of papers on Saharan dust from 1985 to 2012. The number of publications per year grew exponentially from a handful of papers in the mid-1980s to almost 250 in 2009 with an even steeper increase in citations, as expected. This exponential increase corresponds to a doubling of the publication (citation) rate every 6 (4) years, which can be compared to the 11-year doubling time of the publication rate for climate change articles found by Stanhill (2001). These numbers are an impressive demonstration of the dynamic development of dust as a research topic of international relevance.