

## The Atmosphere and Climate of Mars

Humanity has long been fascinated by the planet Mars. Was its climate ever conducive to life? What is the atmosphere like today, and why did it change so dramatically over time? Twelve spacecraft have successfully flown to Mars since the Viking mission of the 1970s and early 1980s. These orbiters, landers, and rovers have generated vast amounts of data that now span a Martian decade (~18 years). This new volume brings together the many new ideas about the atmosphere and climate system that have emerged, including the complex interplay of the volatile and dust cycles, the atmosphere–surface interactions that connect them over time, and the diversity of the planet’s environment and its complex history. Including tutorials and explanations of complicated ideas, students, researchers, and non-specialists alike are able to use this resource to gain a thorough and up-to-date understanding of this most Earth-like of planetary neighbors.

ROBERT M. HABERLE is a senior scientist in the Space Science and Astrobiology Division at NASA Ames Research Center. His main research interests center around the atmosphere and climate of Mars: past, present, and future. He has been involved in multiple NASA missions to Mars including Pathfinder, Mars Global Surveyor, and the Mars Science Laboratory, and he has promoted and developed landed network mission concepts for atmospheric science.

R. TODD CLANCY is a senior scientist with the Space Science Institute of Boulder, Colorado, and his research has focused on observational studies of atmospheres of the Earth, Venus, and Mars.

FRANÇOIS FORGET is a CNRS senior scientist in Paris, where he studies the past and present climate of Mars. He has been heavily involved in the ESA missions Mars Express and Exomars 2016, and is a member of the NASA Mars Reconnaissance Orbiter (MRO) and Insight science teams.

MICHAEL D. SMITH is a senior scientist in the Planetary Systems Laboratory of NASA’s Goddard Space Flight Center. His research interests include the meteorology and dynamics of planetary atmospheres, radiative transfer, and remote sensing techniques, and he has been an active participant for more than 20 years on the science teams of eight past, current, and future spacecraft missions to Mars.

RICHARD W. ZUREK is chief scientist for the Mars Program Office at the Jet Propulsion Laboratory (JPL), California Institute of Technology. He also serves as the project scientist for the Mars Reconnaissance Orbiter (MRO), and is involved in the development and implementation of new missions to Mars.

**Cambridge Planetary Science***Series Editors:*

Fran Bagenal, David Jewitt, Carl Murray, Jim Bell, Ralph Lorenz, Francis Nimmo, Sara Russell

*Books in the series:*

1. Jupiter: The Planet, Satellites and Magnetosphere<sup>†</sup>  
Edited by Bagenal, Dowling and McKinnon  
978-0-521-03545-3
2. Meteorites: A Petrologic, Chemical and Isotopic Synthesis<sup>†</sup>  
Hutchison  
978-0-521-03539-2
3. The Origin of Chondrules and Chondrites<sup>†</sup>  
Sears  
978-1-107-40285-0
4. Planetary Rings<sup>†</sup>  
Esposito  
978-1-107-40247-8
5. The Geology of Mars: Evidence from Earth-Based Analogs<sup>†</sup>  
Edited by Chapman  
978-0-521-20659-4
6. The Surface of Mars  
Carr  
978-0-521-87201-0
7. Volcanism on Io: A Comparison with Earth<sup>†</sup>  
Davies  
978-0-521-85003-2
8. Mars: An Introduction to its Interior, Surface and Atmosphere  
Barlow  
978-0-521-85226-5
9. The Martian Surface: Composition, Mineralogy and Physical Properties  
Edited by Bell  
978-0-521-86698-9
10. Planetary Crusts: Their Composition, Origin and Evolution<sup>†</sup>  
Taylor and McLennan  
978-0-521-14201-4
11. Planetary Tectonics<sup>†</sup>  
Edited by Watters and Schultz  
978-0-521-74992-3
12. Protoplanetary Dust: Astrophysical and Cosmochemical Perspectives<sup>†</sup>  
Edited by Apai and Lauretta  
978-0-521-51772-0
13. Planetary Surface Processes  
Melosh  
978-0-521-51418-7

Cambridge University Press

978-1-107-01618-7 — The Atmosphere and Climate of Mars

Edited by Robert M. Haberle , R. Todd Clancy , François Forget , Michael D. Smith , Richard W. Zurek

Frontmatter

[More Information](#)

14. Titan: Interior, Surface, Atmosphere and Space Environment  
Edited by Müller-Wodarg, Griffith, Lellouch and Cravens  
978-0-521-19992-6
15. Planetary Rings: A Post-Equinox View (Second edition)  
Esposito  
978-1-107-02882-1
16. Planetesimals: Early Differentiation and Consequences for Planets  
Edited by Elkins-Tanton and Weiss  
978-1-107-11848-5
17. Asteroids: Astronomical and Geological Bodies  
Burbine  
978-1-107-09684-4
18. The Atmosphere and Climate of Mars  
Edited by Haberle, Clancy, Forget, Smith and Zurek  
978-1-107-01618-7

† Reissued as a paperback

# THE ATMOSPHERE AND CLIMATE OF MARS

ROBERT M. HABERLE

*NASA Ames Research Center, Moffett Field, California, USA*

R. TODD CLANCY

*Space Science Institute, Boulder, Colorado, USA*

FRANÇOIS FORGET

*Laboratoire de Météorologie Dynamique, CNRS, Université Pierre et Marie Curie, Paris, France*

MICHAEL D. SMITH

*NASA Goddard Space Flight Center, Greenbelt, Maryland, USA*

RICHARD W. ZUREK

*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*



CAMBRIDGE  
UNIVERSITY PRESS

Cambridge University Press

978-1-107-01618-7 — The Atmosphere and Climate of Mars

Edited by Robert M. Haberle, R. Todd Clancy, François Forget, Michael D. Smith, Richard W. Zurek

Frontmatter

[More Information](#)

## CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

4843/24, 2nd Floor, Ansari Road, Daryaganj, Delhi - 110002, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9781107016187](http://www.cambridge.org/9781107016187)

DOI: 10.1017/9781139060172

© Cambridge University Press 2017

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2017

Printed in the United Kingdom by TJ International Ltd, Padstow, Cornwall

*A catalogue record for this publication is available from the British Library.*

*Library of Congress Cataloging-in-Publication Data*

Names: Haberle, Robert M. | Clancy, R. Todd. | Forget, François. |

Smith, Michael D., 1966– | Zurek, Richard W., 1947–

Title: The atmosphere and climate of Mars / [edited by] Robert M. Haberle,

NASA-Ames Research Center, R. Todd Clancy, Space Science Institute,

Boulder, Colorado, François Forget, Laboratoire de Météorologie

Dynamique, Paris, Michael D. Smith, NASA-Goddard Space Flight Center,

Richard W. Zurek, Jet Propulsion Laboratory, California.

Description: Cambridge: Cambridge University Press, 2017. |

Series: Cambridge planetary science; 18 |

Includes bibliographical references and index.

Identifiers: LCCN 2017001528 | ISBN 9781107016187 (hardback: alk. paper)

Subjects: LCSH: Mars (Planet) – Atmosphere. | Mars (Planet) – Climate. |

Planets – Atmospheres.

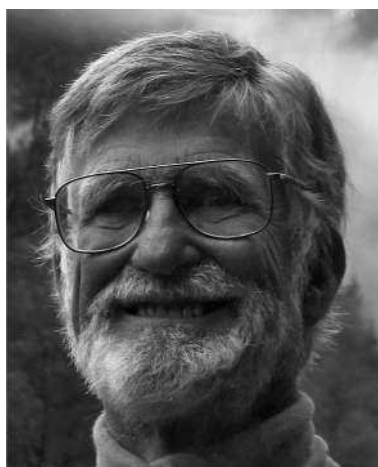
Classification: LCC QB643.A86 A86 2017 | DDC 551.50999/23–dc23

LC record available at <https://lcn.loc.gov/2017001528>

ISBN 978-1-107-01618-7 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

## DEDICATION



This book is dedicated to the memory of Conway B. Leovy (1933–2011), a true planetary scientist and believer in comparative study of any planet or moon known to have an atmosphere: Earth, Mars, Venus, Titan, and the Solar System’s gas giants.

He was fortunate to finish his academic training as space probes were first being launched to the planets, and he was an intellectual leader on many Mars flight science teams, starting with the imaging teams of the Mariners 6 and 7 flyby missions, the Mariner 9 Orbiter, the Viking Lander Meteorology Teams, and the Mars Reconnaissance Orbiter Mars Climate Sounder investigation. His goal was to apply the rapidly developing theory of dynamical meteorology, including advances in numerical simulation, and the growing sophistication of atmospheric radiation models and input databases, to interpret the new data being returned from space. While at the Rand Corporation, Conway pioneered – with Yale Mintz at UCLA – the application of general circulation models to atmospheres other than Earth, but he did not stop there during a long tenure as a professor of atmospheric science and geophysics at the University of Washington, Seattle. His successful research on ozone depletion in the Earth’s stratosphere, the effects of vast dust storms on the Mars atmosphere, and the momentum balance on slowly rotating Venus and Titan were just some of the activities for which he was recognized as a Fellow of the American Meteorological Society and as recipient of the Gerard P. Kuiper Prize of the AAS Division for Planetary Sciences.

Expert in many disciplines, Conway was an inspiration to his colleagues and to the many students he mentored (several of whom are authors contributing to this book). He was an avid environmentalist, a dedicated family man, and possessed a kindness, generosity, and modesty not normally found in such intellectual giants. We miss his presence still, but his inquisitive spirit and exceptional integrity continue to inspire us. If here, he would ask us what we had learned and what interesting questions remain. For Mars, this book is our answer.

## CONTENTS

	<i>List of Contributors</i>	page xi
	<i>General Acknowledgments</i>	xiii
1	Introduction ROBERT M. HABERLE, R. TODD CLANCY, FRANÇOIS FORGET, MICHAEL D. SMITH, RICHARD W. ZUREK	1
2	Understanding Mars and Its Atmosphere RICHARD W. ZUREK	3
3	History of Mars Atmosphere Observations PHILIP B. JAMES, PHILIP R. CHRISTENSEN, R. TODD CLANCY, MARK T. LEMMON, PAUL WITHERS	20
4	Thermal Structure and Composition MICHAEL D. SMITH, STEPHEN W. BOUGHER, THÉRÈSE ENCRENAZ, FRANÇOIS FORGET, ARMIN KLEINBÖHL	42
5	Mars Clouds R. TODD CLANCY, FRANCK MONTMESSIN, JENNIFER BENSON, FRANK DAERDEN, ANTHONY COLAPRETE, MICHAEL J. WOLFF	76
6	Radiative Process: Techniques and Applications MICHAEL J. WOLFF, MIGUEL LOPÉZ-VALVERDE, JEAN-BAPTISTE MADELEINE, R. JOHN WILSON, MICHAEL D. SMITH, THIERRY FOUCHET, GREGORY T. DELORY	106
7	The Martian Planetary Boundary Layer PETER L. READ, BORIS GALPERIN, SØREN E. LARSEN, STEPHEN R. LEWIS, ANNI MÄÄTTÄNEN, ARAKEL PETROSYAN, NILTON RENNÓ, HANNU SAVIJÄRVI, TERO SIILI, AYMERIC SPIGA, ANTHONY TOIGO, LUIS VÁZQUEZ	172
8	Mesoscale Meteorology SCOT C. R. RAFKIN, AYMERIC SPIGA, TIMOTHY I. MICHAELS	203
9	The Global Circulation JEFFREY R. BARNES, ROBERT M. HABERLE, R. JOHN WILSON, STEPHEN R. LEWIS, JAMES R. MURPHY, PETER L. READ	229

x *Contents*

10	The Mars Dust Cycle	295
	MELINDA A. KAHRE, JAMES R. MURPHY, CLAIRE E. NEWMAN, R. JOHN WILSON, BRUCE A. CANTOR, MARK T. LEMMON, MICHAEL J. WOLFF	
11	The Water Cycle	338
	FRANCK MONTMESSIN, MICHAEL D. SMITH, YVES LANGEVIN, MICHAEL T. MELLON, ANNA FEDOROVA	
12	The CO <sub>2</sub> Cycle	374
	TIMOTHY N. TITUS, SHANE BYRNE, ANTHONY COLAPRETE, FRANÇOIS FORGET, TIMOTHY I. MICHAELS, THOMAS H. PRETTYMAN	
13	Atmospheric Photochemistry	405
	FRANCK LEFÈVRE, VLADIMIR KRASNOPOLSKY	
14	Upper Neutral Atmosphere and Ionosphere	433
	STEPHEN W. BOUGHER, DAVID A. BRAIN, JANE L. FOX, FRANCISCO GONZALEZ-GALINDO, CYRIL SIMON-WEDLUND, PAUL G. WITHERS	
15	Solar Wind Interaction and Atmospheric Escape	464
	DAVID A. BRAIN, STANISLAV BARABASH, STEPHEN W. BOUGHER, FIRDEV S DURU, BRUCE M. JAKOSKY, RONAN MODOLO	
16	Recent Climate Variations	497
	FRANÇOIS FORGET, SHANE BYRNE, JAMES W. HEAD, MICHAEL A. MISCHNA, NORBERT SCHÖRGHOFER	
17	The Early Mars Climate System	526
	ROBERT M. HABERLE, DAVID C. CATLING, MICHAEL H. CARR, KEVIN J. ZAHNLE	
18	Future Prospects	569
	ROBERT M. HABERLE, R. TODD CLANCY, FRANÇOIS FORGET, MICHAEL D. SMITH, RICHARD W. ZUREK	
	<i>Index</i>	570

*A color plate section can be found between pages 402 and 403*



## CONTRIBUTORS

STANISLAV BARABASH

Swedish Institute of Space Physics, Kiruna, Sweden

JEFFREY R. BARNES

College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, Oregon, USA

JENNIFER BENSON

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

STEPHEN W. BOUGHER

Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA

DAVID A. BRAIN

Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA

SHANE BYRNE

Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA

BRUCE A. CANTOR

Malin Space Science Systems, San Diego, California, USA

MICHAEL H. CARR

United States Geological Survey, Menlo Park, California, USA

DAVID C. CATLING

Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA

PHILIP R. CHRISTENSEN

School of Earth and Space Exploration, Arizona State University, Tempe, Arizona, USA

R. TODD CLANCY

Space Science Institute, Boulder, Colorado, USA

ANTHONY COLAPRETE

NASA Ames Research Center, Moffett Field, California, USA

FRANK DAERDEN

Royal Belgian Institute for Space Aeronomy, Brussels, Belgium

GREGORY T. DELORY

Space Sciences Laboratory, and Center for Integrative Planetary Sciences, University of California, Berkeley, California, USA

FIRDEVS DURU

Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA

THÉRÈSE ENCRENAZ

LESIA, CNRS, Observatoire de Paris, Meudon, France

ANNA FEDOROVA

Space Research Institute, Russian Academy of Sciences, Moscow, Russia

FRANÇOIS FORGET

Laboratoire de Météorologie Dynamique, CNRS, Université Pierre et Marie Curie, Paris, France

THIERRY FOUCHET

LESIA, CNRS, Observatoire de Paris, Meudon, France

JANE L. FOX

Department of Physics, Wright State University, Dayton, Ohio, USA

BORIS GALPERIN

College of Marine Science, University of South Florida, St Petersburg, Florida, USA

FRANCISCO GONZÁLEZ-GALINDO

Instituto de Astrofísica de Andalucía, IAA/CSIC, Granada, Spain

ROBERT M. HABERLE

NASA Ames Research Center, Moffett Field, California, USA

JAMES W. HEAD

Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, Rhode Island, USA

BRUCE M. JAKOSKY

Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA

PHILIP B. JAMES

Space Science Institute, Boulder, Colorado, USA

MELINDA A. KAHRE

NASA Ames Research Center, Moffett Field, California, USA

ARMIN KLEINBÖHL

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

VLADIMIR KRASNOPOLSKY

Institute for Astrophysics and Computational Sciences, Catholic University of America, Washington, DC, USA

xii *Contributors*

YVES LANGEVIN

Institut d'Astrophysique Spatiale, CNRS, Université Paris-Sud, Orsay, France

SØREN E. LARSEN

Risø National Laboratory, Technical University of Denmark, Roskilde, Denmark

FRANCK LEFÈVRE

Laboratoire Atmosphères, Milieux, Observations Spatiales, CNRS, Université Pierre et Marie Curie, Paris, France

MARK T. LEMMON

Texas A&amp;M University, College Station, Texas, USA

STEPHEN R. LEWIS

Department of Physical Sciences, The Open University, United Kingdom

MIGUEL LOPÉZ-VALVERDE

Instituto de Astrofísica de Andalucía, IAA/CSIC, Granada, Spain

ANNI MÄÄTTÄNEN

Laboratoire Atmosphères, Milieux, Observations Spatiales, CNRS, Paris, France

JEAN-BAPTISTE MADELEINE

Laboratoire de Météorologie Dynamique, IPSL, Université Pierre et Marie Curie, Paris, France

MICHAEL T. MELLON

Southwest Research Institute, Boulder, Colorado, USA

TIMOTHY I. MICHAELS

SETI Institute, Mt. View, California, USA

MICHAEL A. MISCHNA

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

RONAN MODOLO

Laboratoire Atmosphères, Milieux, Observations Spatiales, CNRS, Guyancourt, France

FRANCK MONTMESSIN

Laboratoire Atmosphères, Milieux, Observations Spatiales, CNRS, Guyancourt, France

JAMES R. MURPHY

Department of Astronomy, New Mexico State University, Las Cruces, New Mexico, USA

CLAIRE E. NEWMAN

Ashima Research, Pasadena, California, USA

ARAKEL PETROSYAN

Space Research Institute, Russian Academy of Sciences, Moscow, Russia

THOMAS H. PRETTYMAN

Planetary Science Institute, Tucson, Arizona, USA

SCOT C. R. RAFKIN

Southwest Research Institute, Boulder, Colorado, USA

PETER L. READ

Atmospheric, Oceanic and Planetary Physics Department, University of Oxford, United Kingdom

NILTON RENNÓ

Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, Michigan, USA

HANNU SAVIJÄRVI

Department of Physics, University of Helsinki, Helsinki, Finland

NORBERT SCHÖRGHOFER

Institute for Astronomy, University of Hawaii, Honolulu, Hawaii, USA

TERO SIILI

Earth Observation Division, Finnish Meteorological Institute, Helsinki, Finland

CYRIL SIMON-WEDLUND

Department of Radio Science and Engineering, School of Electrical Engineering, Aalto University, Espoo, Finland

MICHAEL D. SMITH

NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

AYMERIC SPIGA

Laboratoire de Météorologie Dynamique, CNRS, Université Pierre et Marie Curie, Paris, France

TIMOTHY N. TITUS

Astrogeology Science Center, United States Geological Survey, Flagstaff, Arizona, USA

ANTHONY TOIGO

Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, USA

LUIS VÁZQUEZ

Departamento de Matemática Aplicada, Facultad de Informática, Universidad Complutense de Madrid, Madrid, Spain

R. JOHN WILSON

NASA Ames Research Center, Moffett Field, California, USA.

PAUL WITHERS

Astronomy Department, Boston University, Boston, Massachusetts, USA

MICHAEL J. WOLFF

Space Science Institute, Boulder, Colorado, USA

KEVIN J. ZAHNLE

NASA Ames Research Center, Moffett Field, California, USA

RICHARD W. ZUREK

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

## GENERAL ACKNOWLEDGMENTS

The editors gratefully acknowledge support for this project from NASA's Planetary Science Division, the Jet Propulsion Laboratory/California Institute of Technology, and the Centre National de la Recherche Scientifique.