Exploring Planetary Climate

This book chronicles the history of climate science and planetary exploration, focusing on our ever-expanding knowledge of Earth's climate, and the parallel research underway on some of our nearest neighbors: Mars, Venus and Titan. From early telescopic observation of clouds and ice caps on planetary bodies in the seventeenth century, to the dawn of the space age and the first robotic planetary explorers, the book presents a comprehensive chronological overview of planetary climate research, right up to the dramatic recent developments in detecting and characterizing exoplanets. Meanwhile, the book also documents the discoveries about our own climate on Earth, not only about how it works today, but also how profoundly different it has been in the past. Highly topical and written in an accessible and engaging narrative style, this book provides invaluable historical context for students, researchers, professional scientists, and those with a general interest in planetary climate research.

RALPH D. LORENZ is a planetary scientist at the Johns Hopkins Applied Physics Laboratory. He has worked for the European Space Agency on the Huygens probe to Titan, and has been involved in many NASA and international space projects, including Cassini, Mars Polar Lander and the Japanese Venus Climate Orbiter. He enjoys visiting exotic locations on Earth – from the Arabian Desert and Alaska to Vanuatu and New Zealand – to learn about processes on other worlds, notably dust devils, sand dunes and volcanoes.

"A detailed, historical account of the development of climate science on Earth and on neighboring planets, written by a top researcher in the field. I myself learned a lot from this book. Lorenz combines a thorough knowledge of the literature on climate science with first-hand experience in planetary exploration and a good grasp of the underlying physics. A must-read for all those who are interested in this topic."

James Kasting, Pennsylvania State University

"This is a wide-ranging overview of the entire history of planetary climate research, starting with ancient Greece and finishing with the latest solar system and exoplanet discoveries. Written by a pioneer in outer solar system exploration, it is a very entertaining read, full of colorful anecdotes and interesting asides. I recommend it to anyone interested in an overview of this fascinating topic or in space exploration generally."

Robin Wordsworth, Harvard University

"[This] book . . . is remarkable in many ways. As a planetary climate specialist myself, I am impressed by Lorenz's exhaustive knowledge and thorough understanding of climate processes . . . But what I like most is the storytelling and his description of how scientists make progress and mistakes. As a result, anyone interested in the great history of sciences, as well as in the small but meaningful stories of space exploration, will enjoy this text."

François Forget, CNRS, France

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A History of Scientific Discovery on Earth, Mars, Venus and Titan

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Foreword

Having worked with Ralph on mission proposals to Saturn's moon Titan as well as on the Cassini RADAR team, I am quite familiar with his exceptionally broad expertise, and his unusual ability to distill complex concepts into straightforward explanations. Anyone who knows him is also always prepared to hear historical factoids which illustrate that not only does he understand an engineering or scientific problem, he also knows the history behind how the answer has been puzzled out over time (although he has a suspicious ability to tie most work back to Scottish scientists and engineers!). In this book, Ralph turns these talents to the history of planetary climate, to the benefit of us all.

To the general public, discussions of climate change seem to have started around the time of Al Gore's 1992 book *Earth in Balance*, and therefore seem to have some sort of murky, political origin. As Ralph ably lays out in this book, the history of trying to understand how Earth's climate works stretches back well over a thousand years, with our understanding accelerating as we obtained the capability to make more sophisticated and precise measurements. The potentially damaging effects of increasing carbon dioxide in our atmosphere through the burning of fossil fuels was argued within the scientific community for many decades before the current scientific consensus was reached. This long history of inquiry by hundreds of individuals over centuries makes for fascinating reading, but also serves to help the reader understand why scientists feel confident, and very alarmed, about the pace of climate change, its current and very visible effects on this planet, and the model predictions of what will come if we do not decarbonize the world's economies.

The book also puts the Earth in context: part of the reason we understand our own climate so well is that we have been able to study the climates of Venus, Mars and Titan. These other solar system bodies have helped us to understand the forcings on planetary climates, including the role of greenhouse gases. These other worlds have helped us understand that planetary climates can change radically over time, which helps inform our search for life beyond Earth. Early Mars and Venus may both have supported life, with extensive surface water oceans, before they became too cold or too hot, respectively. As we begin our study of planets around other stars, searching for Earth 2.0, our understanding of planetary climates will undoubtedly continue to evolve. Ralph's excellent summary of what we know based on our own solar system illustrates our strong foundation as we look further outward, and also our strong basis for concern as we look homeward.

Ellen R. Stofan
Former Chief Scientist, NASA

Preface

I was 11 years old. It was 1980, my first week at the King Edward VI Grammar School in Stratford-upon-Avon, England – the same institution at which William Shakespeare had some centuries before learned his small Latin and less Greek. Indeed I had a Latin class that week, but also an hour of Physics. Our Physics teacher had the class – all boys, in uniform suits and ties and required to wear caps in town – copy down from the blackboard into our exercise books a table of the (nine!) planets, with their size, mass, distance from the Sun, length of their year, and their surface temperature (in some cases only recently measured). Our attention was drawn to the systematic order of things, how the temperatures declined with distance from the Sun. This all made sense to me. "I want to be a physicist", I told Mr Hurlbut as we trooped out of the class.

In fact, I didn't become a physicist exactly. I knew, especially after the Voyager encounter with Uranus, the Challenger disaster (which brought some reality to aspirations of becoming an astronaut) and especially the daring close encounter of the European Giotto spacecraft with comet Halley – all of which happened in the first three months of 1986 – that I wanted to work in planetary exploration. I ended up studying for a degree in Aerospace Systems Engineering, and that got me, with exceptional good fortune, into my first job, working as a young engineer for the European Space Agency. This was at the beginning of the Huygens project, a joint endeavor with NASA to send a probe to Saturn's moon Titan. I subsequently became more of a physicist after all (but with some geology,[1] chemistry and other topics thrown in – when I am asked my profession, these days I say "planetary scientist"). Frequently I have been confronted with

[1] Actually, I have never sat in a formal geology class. I have, however, been on many field trips with the planetary sciences graduate students at the Lunar and Planetary Lab, at the University of Arizona. These gave me a love of desert landscapes, and an ability to at least fake some understanding of geological processes.

engineering questions of what the spacecraft or instrument I am working on is going to observe, or how it will be affected by the planetary environment it is in.[2] These basic-sounding questions, such as “What is the probability the Huygens probe will be struck by lightning?” or “How strong is the wind on Mars?”, turn out to be very, very difficult to answer, but enormously interesting to consider scientifically. Many of these questions led me to explore planetary climate in one way or another.

I had written a couple of books about my work on Titan, and chatting with Ingrid Gnerlich, my editor at Princeton University Press, she suggested that planetary climate would be a good subject for a book. I heartily agreed – although I then got substantially distracted with other projects for several years. That delay, however, has made the subject all the more interesting.

First, Titan is now rather better understood as Cassini’s observations have seen seasonal change, seen clouds and rain come and go, and showed a dramatic difference between north and south in the extent of its lakes and seas – a fundamentally climate-related question.

Second, the growing number of extrasolar planets shows that there is a vast realm of planetary possibilities, with different sizes, masses, atmospheres, stars and orbital configurations. All, however, are subject to the same laws of physics, which let us explore which of these worlds might be habitable, motivating study of climate more generally.

And third, our own climate continues to evolve. As I worked on the book and carbon dioxide concentrations climbed above 400 ppm, an international agreement was reached in Paris to attempt to limit temperature rise to 2 K.

This book largely confines itself to the four principal climates in our solar system – those of Earth, Mars, Venus and Titan. The last of these, formally speaking, is not a planet, but it acts like one and has more interesting processes going on than many actual planets. I largely avoid the giant planets Jupiter and Saturn, and the ice giants Uranus and Neptune, for a couple of reasons. First, they don’t have accessible surfaces, so there is nothing really for a climate to affect – no sand dunes, no river valleys, etc. Second, rather than having “no climate”, in a sense they each have an infinite number of climates – since there is no surface, one level in their thick atmosphere is as significant as any other. If you feel too cold, descend into the warm depths. Lacking infinite patience, but mostly for the first reason, I have not covered them except in passing, although I recognize they are very interesting from a purely fluid-mechanics standpoint.

[2] My ruminations on the difference in outlook between the scientific and engineering profession were published recently: R. Lorenz, Engineers are Dogs, Scientists are Cats, *Aerospace America*, pp. 40–43, June 2018.

There are several moons and an ex-planet that have borderline climates, in particular Triton and Pluto. Their atmospheres are tens of thousands of times thinner than that of Earth. While some layers of haze are present on Pluto, and wind streaks and even plumes seen on Triton, their climates are of limited practical significance. In fact, Pluto turned out to be a lot more interesting than I had expected, but the data from New Horizons' encounter will take years to digest. Similarly, relatively little can be said about individual exoplanets. While their collective study is a burgeoning field, it is not one in which I am regularly immersed, and so my review of these developments is really only a cursory guide to the state-of-the-art, but should serve to provide some literacy and context for further reading.

One of the most enriching pleasures of writing a book is that it sets a framework and motivation for learning things. In fact, I had planned to write something of a textbook about planetary climate itself, but as I wrote what was going to be an introductory chapter or two for historical context, I found the history itself to be a rich and interesting story. My instinct is that if I find something interesting, hopefully readers may do also, and so the history itself became the focus of the book. Other books have since emerged (see Further Reading) that amply fill the textbook need, and so I have indulged my instincts to concentrate on how our ideas about climate have evolved and how our knowledge of planetary environments and our own past climate has been won.

As well as telling a story, I hope the book will serve as a springboard for further study, and I have attempted to be generous in documenting sources, resources and directions for further reading with numbered references, although no book of this length could hope to cite every relevant work on a topic this wide. The attentive reader will have already noted I also have a propensity to make parenthetical amplifications – included as footnotes. My excuse is that reality is not perfectly linear, so the text describing it cannot be only one-dimensional – the notes are literary fracticality. Also, in describing parallel threads of endeavor, it is impossible to be strictly chronological – the text is obliged to hop back and forth in time somewhat in order to retain at least a punctuated equilibrium of topic.

I should caution that, while the book is written essentially as a history, I am not trained as a historian. I hope I have applied the necessary degree of scholarship in researching events long before my time. I have known at least some of the scientists involved in the era of planetary exploration (Chapter 5 onwards) and am somewhat familiar with the literature. Since 1990 or so (Chapter 7 onwards) I have become a protagonist myself, writing some of the papers, and reviewing others, so the account thereafter cannot be considered totally objective. Inevitably, my own contributions receive more attention than others, but I hope the story is balanced overall. In trying to tell a story that spans centuries, I have likely failed to do full justice to the large body of work that has emerged in the past two decades about the planet Mars, but again, hope that I have provided most of the highlights.

I have been fortunate to have worked with many talented individuals over the years on topics related to planetary climate. They are too many to list here, although many will become obvious on examining the notes. Reviewers for Princeton University Press and Cambridge University Press provided important comments that improved the text, Margaret Patterson's attentive copyediting made for a much more polished product, and the enthusiasm of Emma Kiddle at Cambridge is much appreciated. A few colleagues deserve mention, however, for kindly commenting on early chapters (Laura Kerber, Jani Radebaugh and Mark Bullock), and especially Conor Nixon for bravely subjecting himself to a draft of the whole text. Kevin McGouldrick provided helpful remarks on the first four chapters (published in abridged form as "Planetary Climate before the Space Age" on Createspace). Their stabilizing feedback prevented some runaway text. Any errors in what remains, however, are mine alone.

Special acknowledgement is due to Elizabeth Turtle, who not only provided encouragement and critical comment on the text, but has patiently tolerated her husband littering the living room with higher piles of books and papers than usual, only to substitute complaints about "never getting time to write books" with complaints about how long the book was taking to write. Her love brings warmth to a cold universe.