NONLINEAR AND STOCHASTIC CLIMATE DYNAMICS

It is now widely recognized that the climate system is governed by nonlinear, multi-scale processes, whereby memory effects and stochastic forcing by fast processes, such as weather and convective systems, can induce regime behavior. Motivated by present difficulties in understanding the climate system and to aid the improvement of numerical weather and climate models, this book gathers contributions from mathematics, physics, and climate science to highlight the latest developments and current research questions in nonlinear and stochastic climate dynamics. Leading researchers discuss some of the most challenging and exciting areas of research in the mathematical geosciences, such as the theory of tipping points and of extreme events including spatial extremes, climate networks, data assimilation, and dynamical systems. This book provides graduate students and researchers with a broad overview of the physical climate system and introduces powerful data analysis and modeling methods for climate scientists and applied mathematicians.

CHRISTIAN L. E. FRANZKE is a research scientist at the University of Hamburg. His research interests include nonlinear atmospheric and climate dynamics, weather and climate risks, dynamics of extreme events, and stochastic and multi-scale modeling. He has developed new methods for the nonlinear analysis of paleoclimate data, station data, and climate model data, and has developed nonlinear stochastic climate models.

TERENCE J. O'KANE is an Australian Research Council Future Fellow, a principal research scientist (CSIRO Oceans and Atmosphere), and Adjunct Professor in Mathematics at the University of Tasmania. His research interests include the statistical mechanics and dynamics of geophysical flows, climate dynamics and variability, ensemble prediction and data assimilation, and time series analysis. He has worked on all aspects of weather prediction including the theory, modeling, and operational implementation of ensemble systems. In 2013 he was awarded the J. H. Michell Medal by the Australian Mathematics Society for outstanding research.

NONLINEAR AND STOCHASTIC CLIMATE DYNAMICS

Edited by

CHRISTIAN L. E. FRANZKE
University of Hamburg, Germany

and

TERENCE J. O'KANE
CSIRO Oceans and Atmosphere, Hobart, Australia

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Contents

Figures

Cambridge University Press
978-1-107-11814-0 — Nonlinear and Stochastic Climate Dynamics
Edited by Christian L. E. Franzke , Terence J. O'Kane
Frontmatter
More Information

Cambridge University Press
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Contributors

Dr. Tamás Bódai
Meteorological Institute and Center for Earth System Research and Sustainability
University of Hamburg
Grindelberg 7
20144 Hamburg
Germany
tamas.bodai@uni-hamburg.de

Prof. Armin Bunde
Institut für Theoretische Physik III
Heinrich-Buff-Ring 16
D-35392 Giessen
Germany
Armin.Bunde@physik.uni-giessen.de

Dr. Susanna Corti
Institute of Atmospheric Sciences and Climate
National Research Council
Bologna, Italy
s.corti@isac.cnr.it

Prof. Daan T. Crommelin
CWI
PO Box 94079, 1090 GB,
Amsterdam,
The Netherlands
and
Korteweg-de Vries Institute for Mathematics
University of Amsterdam
P.O. Box 94248

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More Information

1090 GE Amsterdam
The Netherlands
daan.crommelin@cwi.nl

Prof. Michel Crucifix
Université catholique de Louvain
Earth and Life Institute (ELIC)
Place Louis Pasteur 3, SC10 - L4.03.08
BE-1348 Louvain-la-Neuve
Belgium
michel.crucifix@uclouvain.be

Prof. Peter Ditlevsen
Niels Bohr Institute
Juliane Maries Vej 30
DK-2100 Copenhagen O, Denmark
pditlev@nbi.ku.dk

Dr. Jonathan F. Donges
Research Domain I - Earth System Analysis
Potsdam Institute for Climate Impact Research
Telegrafenberg A31
14473 Potsdam
Germany
and
Stockholm Resilience Centre
Stockholm University
Kräftriket 2B
114 19 Stockholm
Sweden
donges@pik-potsdam.de

Dr. Reik V. Donner
Research Domain IV - Transdisciplinary Concepts & Methods
Potsdam Institute for Climate Impact Research
Telegrafenberg A31
14473 Potsdam
Germany
reik.donner@pik-potsdam.de

Prof. Steven B. Feldstein
Department of Meteorology

The Pennsylvania State University
503 Walker Building
University Park, PA
16802 USA
sbf1@meteo.psu.edu

Dr. Jorgen S. Frederiksen
CSIRO Oceans and Atmosphere
Aspendale 3195
Victoria
Australia
jorgen.frederiksen@csiro.au

Dr. Christian L. E. Franzke
Meteorological Institute and Center for Earth System Research and Sustainability
University of Hamburg
Grindelberg 7
20144 Hamburg
Germany

Jun.-Prof. Susanne Gerber
Johannes Gutenberg University Mainz
Faculty of Biology and Center for Computational Sciences in Mainz (CSM)
Gebäude 2413, Staudinger Weg 9, Raum 05-513
55128 Mainz, Germany
gerber.sj@gmail.com

Prof. Georg A. Gottwald
School of Mathematics and Statistics
The University of Sydney
Sydney, 2006 NSW, Australia
georg.gottwald@sydney.edu.au

Prof. John Harlim
Department of Mathematics
Department of Meteorology and Atmospheric Science
The Pennsylvania State University
214 McAllister Building
University Park, PA 16802, USA
jharlim@psu.edu

Prof. Illia Horenko
ICS
Universita della Svizzera Italiana
Via G. Buffi 13
6900 Lugano Switzerland
illia.horenko@usi.ch

Dr. Terence J. O'Kane
CSIRO Oceans and Atmosphere
Castray Esplanade
Hobart TAS 7000
Australia
Terence.O'Kane@csiro.au

Dr. Vassili Kitsios
CSIRO Oceans and Atmosphere
Aspendale 3195
Victoria
Australia
Vassili.Kitsios@csiro.au

Dr. Guillaume Lenoir
Université catholique de Louvain
Earth and Life Institute (ELIC)
Place Louis Pasteur 3, SC10 - L4.03.08
BE-1348 Louvain-la-Neuve
Belgium
guillaume.lenoir@uclouvain.be

Dr. Joseph Ludescher
Institut für Theoretische Physik III
Heinrich-Buff-Ring 16
D-35392 Giessen
Germany
Josef.Ludescher@theo.physik.uni-giessen.de

Dr. Takahito Mitsui
Université catholique de Louvain
Earth and Life Institute (ELIC)
Place Louis Pasteur 3, SC10 - L4.03.08
BE-1348 Louvain-la-Neuve

Belgium
takahito.mitsui@uclouvain.be

Dr. Franco Molteni
European Centre for Medium-Range Weather Forecasts
Shinfield Park
Reading RG2 9AX
United Kingdom
franco.molteni@ecmwf.int

Dr. Didier P. Monselesan
CSIRO Oceans and Atmosphere
Castray Esplanade
Hobart TAS 7000
Australia
Didier.Monselesan@csiro.au

Dr. Balu T. Nadiga
Los Alamos National Lab, MS-B296
Los Alamos, NM 87545, USA
balu@lanl.gov

Dr. Mathieu Ribatet
IMAG
Université de Montpellier
4 Place Eugène Bataillon
34095 Montpellier Cedex 5
FRANCE
mathieu.ribatet@umontpellier.fr

Dr. James S. Risbey
CSIRO Oceans and Atmosphere
Castray Esplanade
Hobart TAS 7000
Australia
James.Risbey@csiro.au

Prof. David M. Straus
George Mason University
118 Research Hall, MSN 2B3

Fairfax, VA 22030
USA
dstraus@gmu.edu

Prof. Nicholas W. Watkins
Centre for the Analysis of Time Series
Tower 1, 11th Floor
London School of Economics and Political Science
Houghton Street
London WC2 2AE, UK
N.Watkins2@lse.ac.uk

Dr. Marc Wiedermann
Research Domain IV - Transdisciplinary Concepts & Methods
Potsdam Institute for Climate Impact Research
Telegrafenberg A31
14473 Potsdam
Germany
and
Department of Physics
Humboldt University of Berlin
Newtonstraße 15
12489 Berlin
Germany
marcwie@pik-potsdam.de

Dr Meelis J. Zidikheri
Australian Bureau of Meteorology
GPO Box 1289
Melbourne
Victoria 3001
Australia
m.zidikheri@bom.gov.au

Preface

Unquestionably the climate system is a highly nonlinear and complex system characterized by the communication of coherent information across a multitude of scales and exhibiting on occasion abrupt transitions between periods of relative stability. Given the importance of the potential societal impacts of anthropogenic influences, knowledge of both the past and future evolution of the climate system is of utmost importance. As a consequence there has been increased demand for predictions on the timescales from seasons to decades. To underpin predictive models beyond the timescales of synoptic weather forecasts, there is a huge need for applied mathematical, statistical, network, and complexity approaches to further our understanding of where predictive skill resides in the climate system.

The nonlinear, stochastic, and multiscale nature of the problem makes development of a foundational theoretical basis for climate variability and predictability a distinct challenge. Mathematicians, geoscientists, and fluid dynamicists are by nature attracted to the "hard problems" and this is reflected in the growing richness of approaches and increasing numbers of interdisciplinary mathematical and geoscience researchers attending the Nonlinear Processes sessions of the two big geosciences unions, the European Geoscience Union and the American Geophysical Union and dedicated conferences like SIAMs Mathematics of Planet Earth.

Traditional climate science has understood many important aspects of the climate system by linearizing the equations of motions and by making Markovian and Gaussian assumptions in combination with a deterministic view of the climate system. However, there is increasing observational evidence that the climate system is highly nonlinear, non-stationary, and non-Gaussian and that in many areas memory (non-Markovian) effects are important. These effects render our ability to make skillful predictions based on linear methods highly problematic. It has been shown that stochastic parameterizations can significantly improve ensemble prediction and data assimilation schemes. More generally, stochastic methods are particularly well suited for the analysis of high dimensional, non-stationary multiscale systems of which the atmosphere and ocean are two paradigmatic examples. Furthermore, stochastic methods have been shown to become crucial to understanding the impact of small-scale growing disturbances on the large-scale quasi-stationary structures manifest in the climate.

While physics, mathematics, and statistics contribute more and more to a nonlinear and stochastic view of the climate system, these communities still do not have a very close relationship with the climate science community, in part due to a lack of dedicated journals and books at the intersections of these communities. This book aims to link these communities and to give graduate students and interested scientists an accessible entry into nonlinear and stochastic climate dynamics by highlighting the latest developments and current research questions.

The contributions in this book cover the latest developments in this exciting research area of climate dynamics. The first two chapters deal with the particularly nonlinear (nonsecular) trends evident in the paleoclimate record. We begin with the chapter (1) by Crucifix et al. discussing how the nonlinearity of the climate system hampers predictions of the future climate, and in particular, the onset of the next ice age. The slow dynamics of ice ages feature the nonlinear interaction of ice sheets, the deep ocean, and carbon cycle dynamics. One important conclusion of this contribution is the usefulness of stochastic parameterizations in climate modeling. The second chapter by Ditlevsen discusses predictability in the climate system using the ice core record. The Greenland ice cores show a number of abrupt changes which are nonlinear responses inherent in the climate system and which can be interpreted as being tipping points. Ditlevsen shows that the predictability of tipping points depends on their dynamical origin and whether they are bifurcation (deterministic chaos) or noise induced. While the underlying dynamics of the transitions might not be exactly known, early warming systems for tipping points might still have some predictive skill.

The so-called teleconnection patterns or persistent regime states of the large-scale atmosphere and ocean are perhaps the most well recognized and most important area of nonlinear climate dynamics. In chapter 3 Feldstein and Franzke review the history and dynamics of atmospheric teleconnection patterns and regime states. For instance, the importance of the North Atlantic Oscillation teleconnection pattern and its surface impacts has been known since the time of the Vikings in the 12th century. Additionally, surface impacts of teleconnection patterns are associated with extremes of heat and cold, and have application for statistical downscaling, long-range predictions and paleoclimate reconstructions. While there is currently no comprehensive theory of teleconnection patterns, Feldstein and Franzke review the current understanding of the mechanisms driving them. Straus et al. (Chapter 4) extend the focus on atmospheric regimes considering their link to weather and the large-scale circulation including an examination of cluster methods used to identify regime states. This close link is particularly important for long-range predictions and impact studies.

While it is well recognized that regime transitions in climate systems are often initiated by an instability in the flow, predictability and the mechanisms underlying regime transitions are in general not well understood. Nadiga and O'Kane (Chapter 5) present the results of a regime and predictability study in an idealized barotropic vorticity model that admits low-frequency regime transitions between zonal and dipolar states. They consider perturbations that are embedded onto the system's chaotic attractor under the full nonlinear dynamics as nonlinear generalizations of the leading (backward) Lyapunov vector and where transitions between regimes are initiated by weak stochastic forcing of the large-scale modes.

Donner et al. (Chapter 6) take a particular nonlinear view on preferred atmospheric circulation patterns by applying network theory. In their contribution they point out similarities between network approaches and more traditional methods, which are mainly based on assumptions of linearity and stationarity, like Empirical Orthogonal Functions (EOFs). While the previous approaches are mainly aiming for preferred or recurring patterns, Horenko et al. (Chapter 7) discuss methods for identifying persistent patterns which likely are more predictable. Their non-parametric variational approach is especially suited for multiscale data and does not make assumptions about the underlying dynamics of the regime states and their evolution, i.e. stationarity.

A recent and exciting development is the use of stochastic methods in climate research. Gottwald et al. (Chapter 8) present the fundamentals of a stochastic climate theory. They show that the Mori-Zwanzig formalism, well-known from statistical physics, predicts the presence of memory effects in reduced order models. This implies that subgrid scale parameterizations for numerical weather and climate prediction models should include time-history effects. The current generation of operational weather and climate prediction models rarely consider such effects in parameterizations of subgrid processes. Gottwald et al. also review current methods to empirically estimate the coefficients for stochastic reduced order models. Frederiksen et al. (Chapter 9) review the development of a family of systematic parameter free approaches to subgrid scale parameterizations based on stochastic modeling and closure-based representations of the effects of subgrid turbulence in large eddy simulations of turbulent fluids including memory and non-Gaussian effects. Harlim (Chapter 10) presents the latest developments in data assimilation demonstrating that stochastic parameterizations are a particularly promising Ansatz for mitigating the effects of model error in data assimilation.

Bunde and Ludescher (Chapter 11) introduce the concept of long-memory in their contribution. Long-memory processes are those whose autocorrelation function decays according to a power-law. That memory effects are important in the climate system was already discussed in the chapter by Gottwald et al. (Chapter 8). The long-memory characteristic implies that perturbations can be long-term persistent. This property hinders the detection of significant climate trends. In particular, Bunde and Ludescher show that the first-order autoregressive process currently popular in trend testing are inadequate and that long-memory methods have to be used. The authors also show that long-memory also leads to the clustering of extreme events. While Bunde and Ludescher focus on Gaussian processes, Watkins (Chapter 12) surveys methods which simultaneously are long-memory and have heavy tails, i.e. have severely non-Gaussian distributions.

Ribatet (Chapter 13) presents the latest developments in the study of spatial extremes and the application of max-stable processes. Bodai (Chapter 14) uses a dynamical systems approach to extremes. In this approach the attractor dimension is related to the parameters of the classical extreme value distributions, well-known from statistical extreme value theory. He discusses the link between extreme value statistics and the geometrical properties of the attractor in both high-dimensional systems and in very low-dimensional settings where the fracticality of the attractor prevents the system from having an extreme value law.

In summary, this book provides, perhaps for the first time, an accessible overview on nonlinear and stochastic climate dynamics at the leading edge of research. We hope to contribute with this book to a fruitful interaction between the mathematical, physical, and climate science communities.

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