Climate System Dynamics and Modelling

This book presents all aspects of climate system dynamics on all time scales from the Earth's formation to modern human-induced climate change. It discusses the dominant feedbacks and interactions between all the components of the climate system: atmosphere, ocean, land surface and ice sheets. It addresses one of the key challenges for a course on the climate system: students can come from a range of backgrounds. A glossary of key terms is provided for students with little background in the climate sciences, whilst instructors and students with more expertise will appreciate the book's modular nature. Exercises are provided at the end of each chapter for readers to test their understanding. This book will be invaluable for any course on climate system dynamics and modelling and will also be useful for scientists and professionals from other disciplines who want a clear introduction to the topic.

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Preface

The climate has a significant impact on life on Earth as well as on human activities. Temperature and precipitation strongly constrain the type of vegetation that can grow in a particular region. The design and location of houses depend on summer and winter temperatures and also on the probability of flooding. One single, late frost or a heavy hail storm could ruin an entire crop. Since the beginning of humanity, people thus have had to cope with climate and, if possible, to adapt to it. As a consequence, the various human civilisations have observed and tried to understand climate variations. They first provided mythological or religious explanations, often relying on weather lore to obtain forecasts. In parallel, climate has evolved as a science, elaborating more and more sophisticated representations of the observed phenomena. Such a description of climate now involves a very broad range of expertise corresponding to different domains of the sciences, including physics, chemistry, biology and geology.

A comprehensive analysis of all the components of the climate system (i.e., atmosphere, ocean, ice sheets, land surfaces, etc.) and of all the interactions between them is beyond the scope of any course or book. Here I provide only a relatively brief overview of the processes that rule the behaviour of the individual components. More detailed descriptions are provided in meteorology, oceanography and glaciology textbooks, for instance, with some suggestions for reading given in the reference section. *The focus of this book is on the interactions between the different elements of the climate system and on the main feedbacks that govern climate variability on all the time scales*. *On this basis, the first goal of this book is to analyse the dominant causes of past climate changes and to critically discuss the projections of climate change over the next centuries or millennia.*

Because of the complexity of the system, many analyses devoted to a quantitative estimate of climate change or climate variability rely on the use of comprehensive three-dimensional numerical models. Simple models are also widely applied to underline clearly the fundamental properties of the climate. *The second goal of this book is to give readers the basis on which to develop an understanding of how climate models are built and their specific interests and limitations and to provide key examples of their applications.*

This book is an extended version of an online resource available at www.climate.be/textbook. It was designed originally to support a course proposed to students in their first year of a master's program at the Université catholique de Louvain (Belgium). However, the book has been designed to also be followed by undergraduate students. Because the book covers a wide range of disciplines and is devoted to an audience with different backgrounds, some of the terms or concepts employed may not be familiar to everyone. An extensive glossary thus is provided for readers who feel the need for specific explanations. The corresponding terms are highlighted in **bold** in the text. Some sections include limited mathematical developments, but understanding them in detail is not required to follow the main arguments, which are always developed using words or diagrams. More generally, this book includes an extensive index and many cross-references between the various sections where related topics are discussed. This allows for dynamic navigation inside the text that encourages readers to focus on certain specific parts of interest whilst skipping others or leaving them for a later reading.

The references to textbooks and scientific papers have been chosen to provide up-to-date information that is complementary to the material included herein at an adequate level of complexity. Consequently, they do not necessarily correspond to the historical development of the concepts, but interested readers can consult them to gain more insight into the history of the field. The number of references is also strongly variable between the sections, being larger for subjects in rapid development and smaller for subjects that are only briefly discussed in the present framework. Finally, review exercises are available at the end of each chapter. They include questions that provide an overview of the most important elements covered in the corresponding sections so that readers can directly evaluate their understanding of the text.

A comprehensive understanding of climate modelling requires one to perform simulations on one's own. A very useful exercise thus is to code some of the equations proposed in the various sections, starting from the simplest. Because this may require a significant amount of work, some interactive models are proposed online (www.climate.be/climatebook). They are related to the material covered in this book, but they focus on some specific examples. They offer the opportunity to test the influence on model results of changes in parameters or of forcing. Specific quizzes are also available online that can be answered using those models.

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Main Symbols and Acronyms, Including Typical Values for Constants

α	Albedo
α_p	Planetary albedo (around 0.3 for present-day conditions)
α_T	Thermal expansion coefficient (kg m^{-3} K^{-1})
β_C	Concentration–carbon feedback parameter (PgC ppm^{-1})
β_S	Haline contraction coefficient (kg m^{-3} psu^{-1})
δ	Solar declination (in degrees or radians)
$\delta^{13}C$	Delta value for the relative abundance of ^{13}C in a sample (‰)
$\delta^{18}O$	Delta value for the relative abundance of ^{18}O in a sample (‰)
ΔQ	Radiative forcing (W m^{-2})
ΔR	Radiative imbalance at the top of the atmosphere (W m^{-2})
Δt	Time step
Δx	Spatial step
ε	Emissivity of an object
ε_{obl}	Obliquity (=23.45° presently)
γ	True anomaly (in degrees or radians)
γ_c	Climate–carbon feedback parameter (PgC ppm^{-1})
κ_c	Ocean heat uptake efficiency (W m^{-2} K^{-1})
ϕ	Latitude (on Earth, in degrees or radians)
ρ	Density (=1,000 kg m^{-3} for pure water, 917 kg m^{-3} for ice, around 1 kg m^{-3} for air at sea-level pressure)
ρ_f	Climate resistance (W m^{-2} K^{-1})
θ_s	Solar zenith distance (in degrees or radians)
λ	Longitude (on Earth, in degrees or radians)
λ_f	Climate feedback parameter
λ_i	Climate feedback parameter for variable x_i
λ_t	True longitude (in degrees or radians)
η	Sea-surface elevation
σ	Stefan-Boltzmann constant (=5.67×10^{-8} W m^{-2} K^{-4})
Γ	Lapse rate (K m^{-1})
τ_a	Infrared transmissivity of the atmosphere
$\tilde{\omega}$	Longitude of the perihelion measured from the vernal equinox (in degrees)
$\vec{\Omega}$	Angular velocity vector of the Earth ($\Omega = \left\Vert \vec{\Omega} \right\Vert = 7.292 \times 10^{-5}$ s^{-1})
AABW	Antarctic bottom water

AAIW	Antarctic intermediate water
ACC	Antarctic circumpolar current
A.D.	Anno Domini; year A.D. is the number of years since the beginning of the Christian (or Common) era
AGCM	Atmospheric general circulation model
AMO	Atlantic Multi-Decadal Oscillation
AOGCM	Atmosphere-ocean general circulation model
B.C.	Before Christ; year B.C. is the number of years before A.D. 1
B.P.	Before present, that is, before A.D. 1950
C	Condensation
CDW	Circumpolar deep water
CGCM	Coupled general circulation model
c_m	Specific heat capacity of medium m ($J\,K^{-1}\,kg^{-1}$)
C_m	Effective heat capacity of medium m ($J\,K^{-1}\,m^{-2}$)
CMIP	Coupled Model Inter-Comparison Project
c_p	Specific heat at constant pressure (=1,004 $J\,K^{-1}\,kg^{-1}$ for dry air)
CRE	Cloud radiative effect
c_v	Specific heat at constant volume (=717 $J\,K^{-1}\,kg^{-1}$ for dry air)
c_w	Specific heat of water (=4,180 $J\,K^{-1}\,kg^{-1}$ for pure water at 0°C)
DGVM	Dynamic global vegetation model
DIC	Dissolved inorganic carbon
DJF	December, January and February
e	Partial pressure of water vapour (Pa)
E	Evapotranspiration
EBM	Energy-balance model
ecc	Eccentricity (=0.0167 for present-day conditions)
EMIC	Earth model of intermediate complexity
ENSO	El Niño–Southern Oscillation
ERF	Effective radiative forcing
e_s	Saturation vapour pressure (Pa)
ESM	Earth system model
F_{diff}	Flux due to diffusion or conduction
f_f	Feedback factor
F_{fric}	Force due to friction
$F_{IR\downarrow}$	Downward longwave radiation at the surface ($W\,m^{-2}$)
$F_{IR\uparrow}$	Upward longwave radiation at the surface ($W\,m^{-2}$)
F_{LH}	Latent heat flux at the surface ($W\,m^{-2}$)
F_{SH}	Sensible heat flux at the surface ($W\,m^{-2}$)
F_{SOL}	Incoming solar radiation at the surface ($W\,m^{-2}$)
g	Acceleration due to gravity at the Earth's surface (=9.8 $m\,s^{-2}$)
GCM	General circulation model

g_T	Total feedback gain
GtC	Gigaton of carbon (10^{15} g of carbon)
H	Observation operator
HA	Hour angle
IPCC	Intergovernmental Panel on Climate Change
IRD	Ice-rafted debris
ITCZ	Intertropical Convergence Zone
J	Joule
JJA	June, July and August
K	Kelvin
ka	1000 years
K_H	Solubility (of CO_2)
kyr	1000 years
L_f	Latent heat of fusion of water (=334 kJ kg^{-1} at 0°C)
LGM	Last glacial maximum (around 21 kyr B.P.)
L_v	Latent heat of vaporisation of water (=2250 kJ kg^{-1} at 100°C, 2500 kJ kg^{-1} at 0°C)
m	Metre
MIP	Model Inter-Comparison Project
MOC	Meridional overturning circulation
MOS	Model output statistics
NADW	North Atlantic deep water
NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
nm	Nanometre (10^{-9} m)
NPO	North Pacific Oscillation
NPP	Net primary production
NPZD	Nutrient-phytoplankton-zooplankton-detritus model
OGCM	Ocean general circulation model
p	Pressure (Pa)
P	Precipitation
Pa	Pascal
PDE	Partial differential equation
PDO	Pacific Decadal Oscillation
PERH	Longitude of the perihelion measured from the autumn equinox (=102.04° in present-day conditions)
PETM	Paleocene-Eocene thermal maximum
PFT	Plant functional type
PgC	Petagrams of carbon (10^{15} g of carbon)
PMIP	Paleoclimate Modelling Inter-Comparison Project
PNA	Pacific North American pattern
ppb	Parts per billion
ppm	Parts per million
p_s	Surface pressure (Pa)
PSA	Pacific South American pattern

psu	Practical salinity unit
PW	10^{15} W
q	Specific humidity (kg/kg)
R	Earth's radius (=6,371 km)
R^*	Universal gas constant (=8.3143 J K^{-1} mol^{-1})
RF	Radiative forcing
RF_{TOA}	Net radiative flux at the top of the atmosphere (W m^{-2})
R_g	Gas constant for a gas g (=287.0 J K^{-1} kg^{-1} for dry air)
RH	Relative humidity
r_m	Mean distance between the Earth and the Sun (=1.5×10^{11} m)
RMS	Root mean square
R_{riv}	River runoff
R_v	Gas constant for water vapour (=461.4 J kg^{-1} K^{-1})
S	Ocean salinity
S_0	Mean total solar irradiance at mean Earth–Sun distance (~1,360 W m^{-2})
SAM	Southern Annular Mode
SLP	Sea-level pressure (Pa)
S_m	Soil moisture (metres of water)
SOI	Southern Oscillation index
S_r	Mean total solar irradiance at a distance r from the Sun
Sv	Sverdrup (=10^6 m^3 s^{-1})
T	Temperature (K)
t	Time
T_a	Air temperature (K)
TCR	Transient climate response
T_e	Effective emission temperature of the Earth (K)
T_s	Surface temperature (K)
TSI	Total solar irradiance (W m^{-2})
U	Internal energy per unit mass (J kg^{-1})
U_a	Wind velocity (m s^{-1})
$\vec{U}_{ice}$	Horizontal velocity vector for ice (m s^{-1})
$\vec{V}$	Velocity vector
W	Watt
WMO	World Meteorological Organisation
yr	Year
z	Altitude or depth, measured from the bottom upwards