

Principles of Planetary Climate

This book introduces the reader to all the basic physical building blocks of climate needed to understand the present and past climate of Earth, the climates of Solar System planets, and the climates of the newly discovered extrasolar planets. These building blocks include thermodynamics, infrared radiative transfer, scattering, surface heat transfer, and various processes governing the evolution of atmospheric composition. General phenomena such as Snowball Earth states, habitability zones, and the Runaway Greenhouse are used to illustrate the interplay of the basic building blocks of physics. The reader will also acquire a quantitative understanding of such key problems as the Faint Young Sun, the nature of Titan's cold liquid-methane hydrological cycle, and the warm, wet Early Mars climate, in addition to phenomena related to anthropogenic global warming on Earth, Earth's glacial–interglacial cycles, and their analogs on other planets. Exploration of simple analytical solutions is used throughout as a means to build the intuition needed to interpret the behavior of more complex phenomena requiring numerical simulation. Where numerical simulation is necessary, all necessary algorithms are developed in the text, and implemented in user-modifiable software modules supplied in the online supplement to the book. Nearly 400 problems are supplied to help consolidate the reader's understanding, and to lead the reader towards original research on planetary climate.

This textbook is invaluable for advanced undergraduate or beginning graduate students in atmospheric science, Earth and planetary science, astrobiology, and physics. It also provides a superb reference text for researchers in these subjects, and is very suitable for academic researchers trained in physics or chemistry who wish to rapidly gain enough background to participate in the excitement of the new research opportunities opening in planetary climate.

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RAYMOND T. PIERREHUMBERT
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For Arnold E. Ross
who taught us to think deeply of simple things

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Preface

When it comes to understanding the whys and wherefores of climate, there is an infinite amount one needs to know, but life affords only a finite time in which to learn it; the time available before one's fellowship runs out and a PhD thesis must be produced affords still less. Inevitably, the student who wishes to get launched on significant interdisciplinary problems must begin with a somewhat hazy sketch of the relevant physics, and fill in the gaps as time goes on. It is a lifelong process. This book is an attempt to provide the student with a sturdy scaffolding upon which a deeper understanding may be built later.

The climate system is made up of building blocks which in themselves are based on elementary physical principles, but which have surprising and profound collective behavior when allowed to interact on the planetary scale. In this sense, the "climate game" is rather like the game of Go, where interesting structure emerges from the interaction of simple rules on a big playing field, rather than complexity in the rules themselves. This book is intended to provide a rapid entrée into this fascinating universe of problems for the student who is already somewhat literate in physics and mathematics, but who has not had any previous experience with climate problems. The subject matter of each individual chapter could easily fill a textbook many times over, but even the abbreviated treatment given here provides enough core material for the student to begin treating original questions in the physics of climate.

The Earth provides our best-observed example of a planetary climate, and so it is inevitable that any discussion of planetary climate will draw heavily on things that can be learned from study of the Earth's climate system. Nonetheless, the central organizing principle is the manner in which the interplay of the same basic set of physical building-blocks gives rise to the diverse climates of present, past, and future Earth, of the other planets in the Solar System, of the rapidly growing catalog of extrasolar planets, and of hypothetical planets yet to be discovered. A guiding principle is that new ideas come from profound analysis of simple models - thinking deeply of simple things. The goal is to teach the student how to build simple models of diverse planetary phenomena, and to provide the tools necessary to analyze their behavior.

This is very much a how-to book. The guiding principle is that the student should be able to reproduce every single result shown in the book, and should be able to use those skills as a basis for explorations that go wherever the student's curiosity may lead. Similarly, the student should have access to every dataset used to produce the figures in the book, and ideally to more comprehensive datasets that draw the student into further and even original analyses. To this end, I have set as a ground rule that I would not use reproductions of figures from other works, nor would I show any results which the student would not be able to reproduce. With the exception of a very few maps and images, every single figure and calculation in this book has been produced from scratch, using software written expressly for the purposes of this book and provided as an online software supplement. The computer implementations have pedagogy as their guiding principle, and readability of the implementation has been given priority over computational efficiency. A companion to this philosophy is what I call "freedom to tinker." The code is all in a form that can easily be modified for other purposes. The goal is to allow the student to first reproduce the results in the book, and then use the tools immediately as the basis for original research. In this, I have been much inspired by what the book *Numerical Recipes* did for numerical analysis. This book does not sell fish. Instead, it teaches students how to catch fish, and how to cook them. As gastronomical literature goes, the book before the reader is somewhat in the spirit of one of Elizabeth David's or Brillat-Savarin's extended pedagogical discourses on food (with recipes interspersed). My efforts to implement all the algorithms described in the present book and make them accessible to the reader also put me in mind of Julia Child's decade-long effort to winkle out and make explicit all the secret knowledge that makes the recipes in *Mastering the Art of French Cooking* actually work. Often, the most important things known to specialists and practitioners of such arts as radiative transfer or atmospheric escape are never committed to paper in a form that is recognizable to the uninitiated.

The software underlying this book was implemented in the open-source interpreted language Python, because it lends itself best to the design principles announced above. It has a versatile and powerful syntax but nonetheless is easy to learn. In my experience, students with no previous familiarity with the language can learn enough to make a substantial start on the computational problems in this book in only two weeks of self-study or computer labs. Python also teaches good programming style, and is a language the student will not outgrow, since it is easily extensible and provides a good basis for serious research computations. It will work on virtually any kind of computer, and because it is open-source the instructor does not have the bother and expense of dealing with licensing fees. I do hope that the student and instructor will fall for Python as madly as I have, but I emphasize that this book is not Python-specific. The text focuses on ideas that are independent of implementation. Specific reference to Python is confined to the online supplement and to the Workbook section of each chapter, where Python-specific advice is isolated in clearly demarcated *Python tips*. The instructor who wishes to make use of some other computer language in teaching the course will find few obstacles. The transparency and readability of Python is such that the Python implementations should provide a convenient aid to re-implementation in other languages. It is envisioned that MATLAB versions of most of the software will ultimately be made available.

In this book I have chosen to deal only with aspects of climate that can be treated without consideration of the fluid dynamics of the atmosphere or ocean. Many successful scientists have spent their entire careers productively in this sphere. The days are long gone when leading-edge problems could be found in planetary fluid dynamics alone, so even the student

whose primary interests lie in atmosphere/ocean dynamics will need to know a considerable amount about the other bits of physics that make up the climate system. There are many excellent textbooks on what is rather parochially known as “geophysical fluid dynamics,” from which the student can learn the fluid dynamics needed to address that aspect of planetary climate. That does not prevent me from entertaining a vision of adding one more at some point, as a sequel to the present volume. This sequel, subtitled *Things that Flow*, would treat the additional phenomena that emerge when fluid dynamics is introduced. It would continue the theme of taking a broad planetary view of phenomena, and of providing students with the computational tools needed to build models of their own. It would take a rather broad view of what counts as a “flow,” including such things as glaciers and sea ice as well as the more traditional atmospheres and oceans. We shall see; for the moment, this is just a vision.

Remarks on notation and terminology

Since I have in mind the full variety of planets in our Solar System and in extrasolar systems, there is the question of what kind of terminology to use to emphasize the generality of the phenomena. Should we create new terminology that emphasizes that we are talking about an arbitrary system, at the risk of creating confusion by introducing new jargon? Or should we adopt terminology that emphasizes the analogy with familiar concepts from Earth and our own Solar System? For the most part, I have adopted the latter approach, which leads to a certain amount of Earth-centric terminology. For example, if I sometimes refer to “the sun” or “solar radiation,” it is to be thought of as referring to whatever star the planet under discussion is orbiting, and not necessarily Earth’s Sun or even a star like it. In the same spirit, the term *solar constant* will be used to refer to the rate at which a planet receives energy from its star (as defined precisely in Chapter 3), regardless of what that star may be and where the planet may be located. One may thus talk about the solar constant for Mars, for Earth, for Gliese 581d, or for that matter the difference between Earth’s solar constant in June and July; from this remark, it is clear that the solar “constant” is a rather inconstant constant, but I will stick to the terminology since it has considerable familiarity within the field of climate physics. I will use the notation L_{\odot} to refer to the value of this quantity for the planet under consideration, and use the same \odot subscript to refer to all properties of a planet’s star and the electromagnetic radiation which emanates from it. The new notation is necessary in order to distinguish the value pertinent to a given planet from the specific *number* L_{\odot} which refers to the corresponding mean flux from the Sun itself, measured in the present era at a standard distance of 1 astronomical unit (roughly the Earth’s mean orbit). The reader should also be cautioned that astronomers usually use the symbol L to refer to a star’s *luminosity*, or net power output, rather than the flux as measured at some particular orbit. Since the luminosity of a star affects the climate of a planet only through the energy flux at the planet’s own orbit, however, I have taken the liberty of co-opting the symbol for this flux. Astronomers are free to think of the quantity as a form of apparent luminosity, seen from the planet’s orbit.

More proper terms would be *stellar radiation* and *stellar constant*, but those unfortunately call to mind starlight from the night sky and seem potentially confusing (though I will gradually break in the use of the terms to help the reader get used to the idea that there are a lot of stars out there, with a lot of planets with a lot of climates). The radiation from a planet’s star will also sometimes be referred to as *shortwave radiation*, to emphasize that it is almost invariably of considerably shorter wavelength than the thermal radiation by which a planet cools to space.

In a similar vein, “air” will mean whatever gas the atmosphere is composed of on the planet in question – after all, if you grew up there, you’d just call it “air.” When I need to refer to the specific substances that make up our own atmosphere, it will be called “Earth air.” All this is a bit like the way one refers to Martian “geology” and “geophysics,” so we don’t need to refer to Areophysics on Mars and Venerophysics on Venus when we are really talking about the same kind of physics in all these cases. Eventually, we will all need to learn to get used to terms like “periastron” as a generalization of “perihelion,” as the focus of the field shifts more to the generality of phenomena amongst planetary systems.

To improve the readability of inline equations, I will usually leave out parentheses in the denominator. For example, $a/2\pi$ is the same thing as $\frac{a}{2\pi}$, whereas I would write $(a/2)\pi$ or $\pi a/2$ if $\frac{a}{2}\pi$ was intended.

With few exceptions, SI units (based on kilograms, meters, and seconds) are used throughout this book. To avoid the baggage of miscellaneous factors of 1000 floating around, when counting molecules kilogram-moles are used, denoted with a capital, i.e. Mole. Thus 1 Mole of a substance is the number of molecules needed to make a number of kilograms equal to the molecular weight – one thousand times Avogadro’s number. There are a few cases where common practice dictates deviations from SI units, as in the use of millibars (mb) or bars for pressure when pascals (Pa) involve unwieldy numbers, or the use of cm^{-1} for wavenumbers in infrared spectroscopy.

Throughout the book we will most commonly use pressure as a vertical coordinate, and this raises some possibilities for confusion regarding the meaning of the word “above” applied to vertical position in an atmosphere, since low pressures occur at high altitudes and high pressures occur at low altitudes. The word “above” should always be understood in this context to refer to altitude. Thus, the phrase “layers above 100 mb” is to be understood as a shortcut for the more precise phrase “Layers whose altitude lies above the altitude of the 100 mb pressure level.”

How to use this book

The short exercises embedded in the text are meant to be done “on the spot,” as an immediate check of comprehension. More involved and thought-provoking problems may be found in the accompanying Workbook section at the end of each chapter. The Workbook provides an integral part of the course. Using the techniques and tools developed in the Workbook sections, the student will be able to reproduce every single computational and data analysis result included in the text. The Workbook also offers considerable opportunities for independent inquiry launching off from the results shown in the text.

There are four basic kinds of problems in the Workbook. Some calculations are analytic, and require nothing more than pen and paper (or at most a decent pocket calculator). Others involve simple computations, data analysis, or plotting of a sort that can be done in a spreadsheet or even many commercially available graphing programs, without the need for any actual computer programming. Many of these problems involve analysis of datasets from observations or laboratory experiments, and all critical datasets are provided in the online supplement to this book in a tab-delimited text format which can be easily read into software of any type. Students who have competence in a programming language, either from prior courses or because the instructor has integrated programming instruction into the climate sequence (as is done at the University of Chicago), have the option of doing these problems in the programming language of their choice. They should be encouraged to do so, since these simpler problems make good warm-up exercises allowing students to consolidate and hone their programming skills. The third class of problems requires actual programming,

but can easily be carried out from scratch by the student in the instructor's language of choice (perhaps with the assistance of some standard numerical analysis routines). While just about any language would do, I have found that interactive interpreted languages such as Python and MATLAB offer considerable advantages, since they provide instant feedback and encourage exploration and experimentation.

The fourth class of problem consists of major projects which would take a lot of time for the student to implement from scratch. Some of these become relatively straightforward, though, if the basic tools such as the moist adiabat routine of Chapter 2 or the "homebrew" exponential sum real gas radiation code of Chapter 4 are provided as tools the student can use in doing the problems. I have provided Python implementations of all such tools, but this is the class of problems that poses the greatest challenge for the instructor who has not adopted Python as the language of choice for instruction. It is highly recommended that the instructor take the time to re-code at least some of the critical tools in the language of choice if Python is not being used. I have provided algorithm descriptions in the text that are independent of the computer implementation, and examination of the Python code should also help. The object-oriented features and powerful list handling capabilities of Python mean that translations into languages that do not support these language features are apt to be more complicated and unwieldy, but still it is only the exponential sums radiation code that is likely to pose any real challenge to the instructor. It is an excellent training exercise to pursue the necessary code development as a team-project effort with a few enthusiastic graduate students, who can then serve as teaching assistants for the course.

There are just a handful of basic computational methods and computer skills needed to do the Workbook problems and to reproduce all the calculations in this book. None of the calculations requires any more computer power than is available on any decent laptop computer. The required numerical skills are outlined and exercised in the Chapter 1 Workbook section, which the student should master before proceeding to the rest of the book. I have not provided detailed discussions of basic algorithms like ordinary differential equation integration, interpolation, or numerical quadrature, since they are well described in the book *Numerical Recipes*, also available from Cambridge University Press. *Numerical Recipes* should be viewed as an essential companion to this book, though only a small part of the material in that opus is actually required for the problems that concern us here.

With very few exceptions, all the datasets needed to produce the figures in the text, or needed to do the data analysis problems in the Workbook sections, have been provided in the online supplement in plain text tabular form. These are organized into subdirectories according to the chapter to which the data is pertinent. These datasets can be plotted and analyzed using virtually any software. The only exceptions to the text format are a very few datasets used in making temperature and humidity maps in Chapters 7 and 9, which are too large to handle conveniently in text form. These datasets are in the machine-independent netCDF format, but they are not heavily used and it is not necessary to learn how to deal with this file format for the purposes of working through this book. The format is widely used for archiving numerical simulations and observations, so effort expended in this direction will be well repaid. It is very easy to read netCDF data using various packages written for use with Python, and not very hard to do it within MATLAB either.

For the foreseeable future, the online supplementary material can be downloaded from Cambridge University Press, at www.cambridge.org/pierrehumbert. The supplementary material, particularly the courseware, is meant to be somewhat viral, and so it should remain available over time (hopefully in improved and evolving forms) at various

open-source repositories and individual websites. This will no doubt be a mutable territory, and so the best way to locate such resources is to run suitably chosen keywords through a search engine.

There are three groups of Python courseware that are provided as part of the online supplement. Even non-Pythonista should be aware of what is there, since it is recommended that the same basic organization be adopted regardless of the computer language used for instruction.

- First, there are the basic courseware modules `ClimateUtilities.py`, `phys.py`, and `planets.py`. They should be placed in a publicly available directory which the students' Python interpreter will look for when loading add-on software (called `modules` in Python). The student should be able to read these files so as to get a better understanding of what they are doing, but it is not expected that the student will need to modify them.

`ClimateUtilities.py` provides basic graphics, input/output, data manipulation, and numerical analysis utilities. The modules `phys.py` and `planets.py` replace the data tables that typically appear on the endpapers and in the appendices of books such as this one. Being software rather than paper, they can include a more versatile level of data organization and can include functions as well as static data. However, since they are also human-readable text files, even the non-Pythonista can consult them in order to find needed data.

- Second, there are the *Chapter Scripts*, organized in subdirectories according to the chapter to which they pertain. These reproduce all the computations and figures appearing in the respective chapters, provide the means of further explorations, and also illustrate techniques needed to solve the Workbook problems. Some instructors will want to have the student refrain from examining the Chapter Scripts until they have had a go at implementing the ideas on their own, while others may want to make them immediately available as a study aid. Whenever they are made available, students are expected to have their own individual copies of these, as the basic intended use of these scripts is that the student will modify them and customize them, and re-run them as needed.
- Third, there are the *Solution Scripts*, which carry out solutions to selected Workbook problems. Access to these requires an instructor password, and they are intended to be doled out to students after they have turned in their own work.

The online supplement also includes Python tutorials, and various sample scripts illustrating numerical techniques and basic data analysis tasks. Software requirements and tips on installation are provided here as well. Solution write-ups for selected Workbook problems are also provided (instructor password required); these are for the most part language-independent, even where the calculations themselves were done in Python.

Although I have tried to rely primarily on calculations done with software that was written expressly for this book – and which the student can read, understand, and customize – at a few points I have found it necessary to make use of calculations carried out with a full-featured terrestrial radiation model. For this purpose I have used the `ccm` column radiation model from the National Center for Atmospheric Research. For the most part, I have designed the problems so that they can be done using various polynomial fits to calculations with this model; it is not strictly necessary for the student to have access to the model. Nonetheless, it is desirable that the student be able to reproduce the results on his or her own. A stand-alone FORTRAN version of the `ccm` radiation model can be downloaded from public sources and used to do the needed calculations, but to make life easier for the Pythonista, I have included as part of the courseware a user-friendly Python interface

to the ccm model, which makes it easy to use the model in conjunction with other Python computations. More details are provided in the online supplement.

Every author likes to think that their book will occasionally be perused from time to time even in a century or two. I think of this myself, when reading through the crumbling though still-illuminating pages of Arrhenius' work, or the less famous though equally crumbling (and still-illuminating) papers of Frank Verby. Whether the reader of the future (should I be so lucky) is absorbing this material through crumbling paper or neural implant, the text and equations will still in some sense be readable. One cannot dare to hope, however, that the associated software used in the computations for this book will still run on the hardware prevailing in the future, though one can hope that the underlying algorithms are eternal. Even the Python of 2050 is unlikely to look like the Python of 2010, if indeed the language still exists at all. For this reason, I have minimized the discussion of the detailed software implementation within the text, and left that to the supplementary online material. Surely, while Frank Verby's ideas on radiative transfer are still of interest, any description of the charts and graphical techniques for doing the calculations at the time would have at most historical interest. The associated Python software is meant to be not a static thing, but a living entity, which will be adopted, ported, and mutated by the community of users as necessary. It could well be that quantum computers of the next century will allow direct line-by-line calculations to replace all the approximate radiative fanciness developed in this book, but even then people will need a good set of example programs in order to help build an understanding of the underlying physics. Computation is not understanding. The calculations embodied in the suite of software upon which this book is built are intended to provide the nucleation point for understanding.

Prerequisites and suggested syllabi

Before tackling the material in this book, the student should have attained a good mastery of classical mechanics, such as is typically provided by a first-year college physics course or an advanced secondary school course. This is not so much because classical mechanics itself is heavily exercised in this book, as because classical mechanics introduces the student to the necessary kind of problem-solving skills, as well as building foundational concepts such as energy conservation and its use in problem-solving. It would also be useful for the student to have some familiarity with the basics of electromagnetism, including the concept of electric and magnetic fields and the forces they exert on charged particles; it is certainly not necessary for the student to have dealt with Maxwell's Equations in their full glory, though. The treatment of thermodynamics in this book is designed to be self-contained, though a student with some prior exposure to the subject in a physics course will be able to approach the material on a deeper level. There is some lightweight use of chemical kinetics and equilibrium in Chapter 8, but a self-contained, if minimal, introduction to the subject has been provided.

As for mathematics, all that is really required is a thorough understanding of single-variable differential and integral calculus, including first order ordinary differential equations. There is some use of second order differential equations in Chapters 5 and 7, but with help most students will be able to grasp the generalization even if they haven't formally studied the subject. The discussion of the diffusion equation in Chapter 7 makes use of a one-dimensional partial differential equation, but this material does not require a very deep understanding of the subject and for the most part can be grasped intuitively from a physical basis. In fact, for students who haven't before dealt with partial differential equations,

or who are rusty on the subject, this material and the associated problems serve as a good refresher. There is some optional material in the final chapter which exercises multivariable calculus more heavily, but the discussion is designed so that the details can be skipped if necessary.

It takes several courses to cover the material in this book, where by a “course” I mean 30 hours of lectures in a typical 10-week quarter, or 45 hours of lectures in a typical 15-week semester. Europeans using different quanta of instruction can calibrate the following accordingly.

For complete beginners, Chapters 2 and 3, with just a brief dip into the material of Chapter 1, plus all the necessary computer and algorithm preliminaries, fit in a one-quarter introductory course, though with little room for digressions. It is essential to introduce the students to some programming environment sophisticated enough to handle numerical differential equation integration. Even if most of the planetary history information in Chapter 1 is skipped, or left to self-study, the material in the Computational Toolkit section of the Chapter 1 Workbook should be covered, since it will be needed to do the rest of the problems. It usually works best to save lecture time by having the students learn programming and algorithms in lab or section meetings, supplemented by copious use of computational examples in the course of the lectures. When using Python, I find that students usually have enough basic skills to do the computational problems after about two weeks of such training; more advanced programming and numerical analysis skills can be introduced as needed. Besides covering the Computational Toolkit problems, it is a good idea to have the students work through the problems covering basic physics and chemistry, to get them up to speed on the fundamental concepts they will need to proceed; the “chemistry” covered in these problems is mostly a matter of understanding how to do problems involving molecular weight.

In a semester, or for students who already possess a good knowledge of either thermodynamics or basic computer skills, a bit more material can be fitted in. This could be a full coverage of the Earth and planetary history material of Chapter 1, a more thorough treatment of programming and numerical methods, or inclusion of the gray-gas portion of Chapter 4.

Chapters 4 and 5 can form the basis of a one-semester course for advanced undergraduates or beginning graduate students, but I have sometimes taken as much as a full quarter just to cover the material in Chapter 4 in depth, with plenty of time allowed for simulation projects using the material.

The material on surface energy balance in Chapter 6 is less fundamental to planetary climate than some of the other topics addressed, but it is something that everybody needs to know eventually. It could be paired naturally with Chapter 4 in place of scattering. My own preference is to truncate the material somewhat and teach it together with the material on the seasonal cycle and geographic variations in Chapter 7, which is truly fundamental and essential. One cannot begin to understand the issues surrounding Pleistocene ice ages without the material in this chapter.

Chapter 8, which deals with planetary formation and evolution of atmospheric composition – including feedbacks between climate and composition – can comfortably fit into a one-quarter course. It depends somewhat on material from previous chapters as a prerequisite, but the nature of the material is independent enough that with suitable presentation of background, it could be used in a stand-alone course. In a semester, the material could be supplemented with additional instruction on atmospheric chemistry, oceanic carbonate chemistry, or silicate weathering.

Chapter 9, which points the student toward an appreciation of the importance of fluid dynamical effects not considered as part of this book, can be worked in toward the end to fill out any of the above courses. It is a particularly good complement to the material in Chapter 7. Alternately, it can be left for the student to peruse at leisure, given that study of the other material has no doubt awakened considerable curiosity about what comes next.

The material is laid out in what seems to me to be the natural didactic order, but in view of the realities of teaching and the necessity of dividing the material up amongst multiple courses the instructor may wish to jump around a bit, so as to retain the students' interest. For example, Chapters 2 and 3 fit comfortably in a one-quarter course and provide the student with an introduction to thermodynamics and radiation, but adhering to that syllabus would leave the student without an appreciation of the important real gas aspects of CO₂ and water vapor. It is thus desirable to work in some of the more qualitative real gas material from Chapter 4, including the use of polynomial *OLR* fits in solving climate problems. These can be introduced as simply a drop-in replacement for σT^4 , once the qualitative underlying physics is explained. Similar opportunities abound, and I have tried to organize things so as to help out the instructor who wishes to wander nonlinearly through the subject matter.

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Notation

This is not a completely exhaustive list of symbols used in the text, but most of the important and frequently used ones are included. Note that some symbols are used for multiple purposes, according to context. In addition, some symbols have incidental alternate uses besides the major usages listed below.

<i>Units</i>	
m	Length, meter
cm	centimeter (0.01 m)
mm	millimeter (0.001 m)
μm	micron (10^{-6} m)
nm	nanometer (10^{-9} m)
pm	picometer (10^{-12} m)
km	kilometer (1000 m)
A.U.	Astronomical unit (mean distance of Earth from Sun, $1.496 \cdot 10^{11}$ m)
Parsec	Parallax-second ($3.08 \cdot 10^{16}$ m)
Light year	$9.46 \cdot 10^{15}$ m
kg	Mass, kilogram
Gt	gigatonne (10^{12} kg)
Mole	kilogram-mole, i.e. $1000 \cdot N_{\text{avo}}$ molecules
ppmv	Parts per million by count of molecules
s	Time, second
d, da	Standard Earth day (86 400 s)
sol	Standard Earth day
Hz	Frequency, 1/s
N	Force, newton (kg m/s^2)
Pa	Pressure, pascal (N/m^2)
bar	10^5 Pa, approximately one Earth atmosphere
mb	millibar (0.001 bar or 100 Pa)

J	Energy, joule (Nm)
kJ	kilojoule, 1000 J
attoJ	attojoule, (10^{-18} J)
W	Power, watt (J/s)
mW	milliwatt (0.001 W)
K	Temperature, kelvin
°C	Temperature, degrees Celsius

Physical and mathematical constants

k	Boltzmann thermodynamic constant, $1.38 \cdot 10^{-23}$ J/K
N_{avo}	Avogadro's number, $6.022 \cdot 10^{23}$. Number of molecules in the number of grams of a substance equal to the substance's molecular weight. Sometimes called the "Loschmidt number"
μ	Mass of a proton, approx. $0.001/N_{avo}$ or $1.66 \cdot 10^{-27}$ kg
R^*	Universal gas constant, k/μ or 8314.5 J Mol $^{-1}$ K $^{-1}$
c	Speed of light in vacuum, $3.0 \cdot 10^8$ m/s (Symbol also used for speed of sound in Chapter 8)
h	Planck's constant, $6.626 \cdot 10^{-34}$ Js
σ	Stefan-Boltzmann constant, $2\pi^5 k^4 / (15c^2 h^3)$, or $5.67 \cdot 10^{-8}$ W/m 2 K 4
G	Newton's gravitational constant, $6.674 \cdot 10^{-11}$ m 3 /kg \cdot s
L_{\odot}	Mean present Solar flux measured at 1 A.U. from the Sun, about 1365 W/m 2
K_{vk}	von Karman constant, 0.41
π	Ratio of circumference to diameter of circle, 3.14159...
e	Base of natural logarithms, 2.71828...

Variables and physical quantities

$B(\nu, T)$	Planck density in frequency space, expressed as function of frequency and temperature
C_D	Drag (bulk exchange) coefficient
C_H	Henry's law temperature constant
D	Diffusivity (thermal or mass)
H	Atmospheric density scale height (also used for weighting function in scattering calculation)
I	A general flux of radiation (sometimes per unit wavenumber or steradian, according to context)
$I(p, \hat{n}, \nu)$	Spectral irradiance at pressure p , in direction \hat{n} , at frequency ν
I_+, \bar{I}_+	Upward radiation flux; band-averaged upward flux
I_-, \bar{I}_-	Downward radiation flux; band-averaged down flux
J_{ν}	Photon flux at frequency ν
K_1	First carbonate equilibrium constant
K_2	Second carbonate equilibrium constant
K_H	Henry's law constant
K_{sp}	Solubility product constant
L	Latent heat

L_{\odot}	Stellar constant. Generalization of “solar constant” Incoming flux from a planet’s star, measured at the orbit. Time-dependent or mean, according to context.
M	Mach number (ratio of fluid velocity to speed of sound)
M	Generic colliding molecule
M, M_A	Molecular weight, of substance A
M_{\odot}	Stellar mass
OLR	Outgoing Longwave Radiation
OLR_{all}	All-sky OLR
OLR_{clear}	Clear-sky OLR
P	Phase function (Chapter 5)
Q_{abs}	Absorption efficiency
Q_{sca}	Scattering efficiency
R	Gas constant for some particular gas (R^*/M)
R, R_A	Gas constant, for substance A
Ri	Richardson number
S	Generic incident shortwave (stellar) radiation, averaged over appropriate portion of planet’s surface according to context
S	Line strength (intensity) (Chapter 4)
T	Temperature
T^*	Constant for radiative absorption temperature scaling
T_U	Temperature constant for Ebelmen–Urey reactions
T_{\odot}	Temperature of photosphere of star
T_s	Surface temperature
T_g	Ground temperature
T_{sa}	Surface air temperature
T_{skin}	Skin temperature
U	Wind speed at outer edge of surface layer
χ	Absorption or scattering cross-section, between molecules or between molecules and photons, according to context
χ_{ν}	Cross-section for collision with photon having frequency ν
Δ	Used to represent an increment of some quantity, as in ΔT for temperature difference
Γ	Gamma function
Ω	Angular rotation rate of planet
$d\Omega$	Differential of solid angle
Ω^+	Solid angle of upward hemisphere
Ω^-	Solid angle of downward hemisphere
Φ	Climate feedback factor (Chapter 3)
Φ	Escape flux, per unit surface area of planet (Chapter 8)
Φ^*	Limiting escape flux
Φ	Meridional heat transport (Chapter 9)
α	Albedo
α_g	Albedo of ground
χ	Collision cross-section
χ_{abs}	Absorption cross-section (per particle)
χ_{sca}	Scattering cross-section (per particle)
δ	Used with an isotope to indicate isotopic anomaly, e.g. $\delta^{18}\text{O}$
δ_{org}	Organic carbon isotopic anomaly
δ	Angle; subsolar latitude (Chapter 7)
δ	Angle; latitude of the Sun/star (subsolar/substellar latitude)

δ	Used to represent an increment of some quantity, usually presumed small, as in δr or δQ
δ	Depolarization factor (Chapter 5)
$\delta(x)$	Dirac delta “function” (Chapter 5)
ℓ	Characteristic length for impact erosion (Chapter 8)
ℓ	Mean free path (Chapter 8)
ℓ	Mass path for absorption
ℓ_s	Equivalent mass path for strong lines
η, η_A	Molar concentration, of substance A
γ	Angle; obliquity (Chapter 7)
γ	Line width (Chapter 4)
γ	Ratio of specific heats, c_p/c_v
γ, γ'	Numerical constants in two-stream scattering (Chapter 5)
γ_B, γ_{\pm}	Numerical constants in two-stream scattering (Chapter 5)
κ	Season angle (Chapter 7)
κ	Thermal conductivity
κ, κ_A	Absorption cross-section, of substance A
λ	Longitude in a geographically fixed coordinate system on a planet
λ	Wavelength
λ_{\odot}	Longitude of the subsolar/substellar point (“longitude of the sun”) in a geographically fixed coordinate system (Distinct from astronomers’ “ecliptic longitude”)
λ_c	Jeans escape parameter
L_{\odot}	Stellar luminosity
L_{\odot}	Luminosity of the Sun, (at present, if not qualified with a time argument)
\mathcal{H}	Longwave radiative heating per unit optical depth
H_v	Longwave radiative heating per unit mass
\mathcal{M}	Moist static energy per unit mass
\mathcal{T}	Transmission function
$\overline{\mathcal{T}}$	Band-averaged transmission function
ν	Frequency
ν_{max}	Frequency of maximum emission in frequency space
ω	Angular frequency of insolation cycle (Chapter 7)
ω_0	Single-scattering albedo
ϕ	Latitude
ρ	Density (sometimes subscripted according to species)
τ	Optical depth or thickness, sometimes as a function of wavenumber
τ^*	Optical thickness in normal direction
τ_{ν}	Optical thickness at frequency ν
τ_{∞}	Optical thickness of the entire atmosphere
τ	Generic thermal response time (Chapter 7)
τ_1	Diffusive thermal relaxation time scale (Chapter 7)
τ_D	Mixed layer thermal relaxation time scale (Chapter 7)
θ	Potential temperature
θ	Also used for propagation angle in radiative transfer
Θ	Scattering angle
\tilde{g}	Asymmetry factor in scattering
\hat{g}	An alternate form of asymmetry factor
ξ	Molar mixing ratio
ζ	Zenith angle

Notation

xxv

ζ	Non-dimensional boundary layer coordinate (Monin-Obukhov theory, Chapter 6)
a	Generic radius of a spherical body
a	Absorptivity (Chapter 3)
a_{sw}	Shortwave absorptivity of atmosphere
b	Multiple uses as a coefficient, but often used as a coupling constant (derivative of flux with respect to temperature), as in b_{ir} in Chapter 6.
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
e	Emissivity (Not to be confused with e as base of natural logarithms)
e_a	Effective atmospheric emissivity for back-radiation to ground (Chapter 6)
e^*	Surface cooling factor, $1 - e_a$ (Chapter 6)
e_g	Emissivity of ground (Chapter 6)
f_{org}	Organic carbon burial fraction
g	Acceleration of gravity (at surface, unless otherwise qualified)
g_s	Surface gravity
h	Hour angle (Chapter 7)
h	Relative humidity
h_t	Hour angle of the terminator
h_{sa}	Surface layer relative humidity
k	Generic equilibrium constant
n	Index of refraction (Chapter 5)
n	Particle number density (esp. in Chapter 8), often subscripted according to species or position, e.g. n_{ex} for exobase density.
n	Occasionally used for wavenumber ν/c . More commonly, ν is used and “wavenumber in 1/cm” is treated as an alternate unit of frequency
pH	$-\log_{10} [H^+]$ in aqueous solution.
p	Pressure
p_{CO_2}	Partial pressure of CO_2 , sometimes expressed as ppmv for Earth atmosphere
p_A	Partial pressure of substance A
p_s	Surface pressure
p_{rad}	Effective radiating pressure
p_{sat}	Saturation vapor pressure
p_{trop}	Tropopause pressure
q	Mass-specific concentration (also specific humidity)
q	Exponent in power law describing impactor distribution in Chapter 8
r, r_A	Mass mixing ratio, of substance A
r	Generic radius of a spherical object
r_\odot	Radius of star
r_c	Critical radius, transonic point (Chapter 8)
u	$h\nu/kT$
y	$\sin \phi$
z	Height of a pressure surface
