

## Title

# The Land-Atmosphere System

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## Reasons for writing

Our aim is to produce a textbook that can meet the needs of interdisciplinary courses that are not currently well served by the many published discipline-focused textbooks. The subject of land-atmosphere interactions is rapidly growing in the Earth Sciences, with profound consequences for agriculture, hydrology and climate change research, among others. It lies at the heart of the water-food-energy nexus (<http://www.unwater.org/water-facts/water-food-and-energy/>; <http://www.fao.org/energy/water-food-energy-nexus/en/>) and is the core topic of the World Climate Research Programme's Global Energy and Water Exchanges project (GEWEX; <http://www.gewex.org/>) and the international Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS; <https://ileaps.org/>) programme of FutureEarth.

From personal experience, we have seen graduate and advanced undergraduate courses on this subject proliferate in the last decade as academic researchers seek to train a generation of scientists in this topic. Courses covering the subject of the land-atmosphere system lie in a number of different departments, making it difficult to teach coherently such an interdisciplinary topic. As described below, we feel there is not an adequate textbook on this subject, one that truly conveys its interdisciplinary nature and contents in a comprehensible way. We propose such a textbook based on our own knowledge and experience.

## Content

We envision a truly interdisciplinary textbook bridging hydrology, ecology, meteorology, climate, geography, environmental science, soil science and biogeochemistry. The book will emphasize the interlocking elements that define the atmosphere and Earth's surface as a singular system.

The Land-Atmosphere System is highly interconnected and web-like. Thus, the topic does not lend itself easily to the linear narrative of a book. Realizing also the varied levels of technical prowess across disciplines, and our own belief that it is necessary to combine reductionist knowledge of details with the "big picture", we plan to organize the book in three tiers with links and pointers across the tiers. The first tier, "Systems", is broad, descriptive, and organized by global climate regimes. It includes evidence of why we study the Land-Atmosphere System. The total Land-Atmosphere System is composed of these individual systems. Each chapter points to elements within the second tier, "Principles", which describes the physical processes and components that are important building blocks, and shows how each system functions. The third tier is the most technical, "Physics & Mathematics" – the majority of the equations are here, as are details of how principles are represented numerically in various models. An outline is attached below, along with annotated outlines of the first two tiers.

We realize our proposed organization of the book is rather unconventional, in that we do not lead with the fundamental nitty-gritty, but instead with the broad views. This is a deliberate choice – we feel it is

important to illustrate why the student should be interested and concerned with the Land-Atmosphere System in the first place. That is, to show the large systems in which the processes operate, the context in which principles and physics apply, before drilling down to the very discipline-level, reductionist perspective at which the physics and the numerical models operate. In fields like mathematics, physics, engineering, biology, etc., one traditionally learns the fundamentals before being allowed to apply them or often even glimpse their applicability in complex systems. As a matter of science communication and pedagogy, we propose to start with the larger environmental systems and dismantle them from tier 1 to tier 3 in the book, rather than describe the components separately *in vacuo* and then assemble them. We feel this provides a more enduring attraction and motivation to the topic, advancing a more holistic perspective to the Land-Atmosphere System, and to the environment in general.

Within each of the first two tiers there will be pointers to the more detailed information in the next tier down, sort of like subroutines within a computer program. This leads the student down the path of discovery and understanding, and allows the student to “come back up for air” as well. In fact, we feel the duality of top-down and bottom-up viewpoints should be bridged to optimize understanding. In a nutshell, one analyzes to see the details clearly, and one synthesizes to see clearly how each detail connects to others. We believe this approach removes barriers to thinking about how individual elements may affect (and be affected by) the system in which they exist.

Each tier is introduced with a chapter explaining the structure, concepts and theory of our approach in that tier, and what the reader needs to know and keep in mind to get the most out of the material. Each section of a chapter will start with a glossary of terms introduced therein, and conclude with a summary of concepts to have been learned and a problem set of questions, sorted based on difficulty level.

A particular focus of the book will be on models as a tool for understanding. Problem sets in the first and third tiers will be built around conceptual and numerical models respectively, with problems in the second tier being a mixture of the two. Conceptual models are essential for understanding the complexities of the land-atmosphere system. Numerical models lie at the heart of so much research, forecasting, and, through bodies such as the Intergovernmental Panel on Climate Change (IPCC), policy. Numerical models are also the tools of prediction and projections, and thus invaluable to understand.

The course of the book is based on CLIM714/614, a graduate level class in the Climate Dynamics program at GMU which Dirmeyer has taught beginning in 1999. It reflects the evolution of what has been found successful, particularly as MS and PhD students have enrolled from diverse departments including Atmosphere Ocean and Earth Sciences, Environmental Science and Policy, Geography and Geoinformation Science, and Civil Engineering. A point is made at the beginning of the course that students should be self-aware, understand their own strengths and weaknesses especially in terms of being “right or left brained”, take advantage of their strengths and work on their weaknesses. The best scientists are balanced, and this book will foster development of that balanced approach.

## **Readership and Level**

We envision the book as a primary text for interdisciplinary courses at the graduate or advanced undergraduate level, and a recommend resource in a wide range of Earth science courses. The book will also be a valuable resource for research scientists and other professionals in fields associated with the topic, who never had such a singular resource before. Most readers will be familiar with some content in

the book but unfamiliar with other content – the book structure will facilitate learning of the new subject matter by comparison to the presentation of the familiar.

Students using this book are expected to be well grounded in basic science and mathematics courses. Calculus is a prerequisite; differential equations would be helpful. Having elementary physics, biology and chemistry courses would also be recommended, as would courses in numerical methods and computer science. However, we feel that a balanced educational approach drawing on intuitive and creative talents as well as the “nerd” is essential for synthesis and understanding of such a diverse interdisciplinary topic. The textbook will cultivate *both sides of the brain*.

Material learned from this textbook would aid students in preparation and execution of research (particularly important for graduate studies), synthesizing knowledge across traditional disciplines to acquire a “big picture” of the interrelationships in the Land-Atmosphere System. A better understanding will be gained of how work within one discipline interacts with other disciplines and the larger systems (e.g., how land management can have feedbacks on climate, or how extreme weather events have consequences for hydrology).

## **Competing and comparable books**

One of the closest comparable books is also from CUP: Ecological Climatology by Gordon Bonan. The 3<sup>rd</sup> Edition was recently completed. We have both known Gordon for many years, and Dirmeyer had several chats with him about textbook writing in his office in September. While his book contains a great deal of useful and relevant information, the book also has an ecological focus. We endeavor to have a truly interdisciplinary flavor to our book, that will help bridge gaps as well as be more approachable and comprehensible. The market for Ecological Climatology is probably a subset of our proposed book.

The other most comparable book is Terrestrial Hydrometeorology by Jim Shuttleworth (Wiley/Blackwell). This book is quite comparable in the level of detail within its scope, which is somewhat narrower than our proposed scope. Shuttleworth's book focuses on the water and energy cycles, and not the carbon cycle or ecology except at a very superficial level. Although it is mainly centered on the water cycle, it does not delve much into surface or subsurface hydrology. Lastly, it is only lightly *textbook-ish*; there is a chapter at the end where a few questions and solutions are presented, but only 10 questions are posed covering 25 chapters. We both also have known Jim for a long time, and know he intended this book as a career summary in textbook form more than a textbook *per se*.

Principles of Environmental Physics (Fourth Edition by Monteith and Unsworth) is an excellent foundational book that we will build upon, but has a *reductionist* quality whereas we are aiming at a more holistic, synthesis approach. Other books tend to be less comprehensive (e.g., Transport in the Atmosphere-Vegetation-Soil Continuum by Moene & van Dam; CUP) or firmly based within a single discipline (e.g., Hydrology by Wilfried Brutsaert; CUP). Most other books are either highly descriptive or very technical, not achieving the balance we feel is necessary.

## **Electronic supplements/products**

Problem sets will tend toward having the students use, and in some cases develop, models and parameterizations of processes discussed in the textbook. We are still discussing and experimenting

with formats. For the last 7 years, Dirmeyer has used Excel-based homework sets in his graduate class. Excel was a convenient neutral platform that was familiar to most students despite diverse backgrounds and departments. However, the idea of avoiding licensed software is very appealing, and we are considering using Python as a versatile, open-source platform. In any case, having starter code, data sets, completed code solutions and instructor materials online is very appealing to us and would facilitate hands-on student learning. For the advanced undergraduate level, point-and-click interfaces might be preferred, but at the graduate level we envision students having access to source code and doing further coding themselves. Python is platform-agnostic, object-oriented, and somewhat less parochial than alternatives like R or (not free) MatLab.

## About the authors/editors

**Paul Dirmeyer** is a Full Professor at George Mason University (GMU) and Senior Research Scientist at the Center for Ocean-Land-Atmosphere Studies (COLA) in Fairfax, Virginia, USA. He conducts research on the role of the land surface in the climate system. This includes the development and application of land-surface models, studies of the impact of land surface variability on the predictability of climate, interactions between the terrestrial and atmospheric branches of the hydrologic cycle, and the impacts of land use change on regional and global climate. He is heavily involved in national and international research projects and programs, as well as service through professional organizations. He is a Fellow of the American Geophysical Union (AGU) and American Meteorological Society (AMS). He is Editor of the AGU Journal of Advances in Modeling Earth Systems (JAMES), has a World of Science h-Index of 44 and a Google Scholar h-Index of 59. He teaches a graduate course in Land-Atmosphere Interactions at GMU. More information including full CV and publication list are at <https://cos.gmu.edu/aoes/profile-paul-dirmeyer/>.

**Eleanor Blyth** is Science Head for Hydro-Climate Risks and directs the Land Surface Science Group at the Centre for Ecology and Hydrology (CEH) in Wallingford, UK. She develops and applies numerical models of the land surface as used in hydrologic, weather forecast and Earth system models. She has expertise in the relevant processes of evaporation, soil processes, soil freezing, snow processes, runoff generation and photosynthesis and uses data to develop and test model representation of these processes. She leads the development and application of the Joint UK Land Environment Simulator (JULES), which is used operationally in the UK Met Office weather prediction model and the Hadley Centre's Earth system model. She is currently spearheading the NERC-funded Hydro-JULES programme to build a three-dimensional community model of the terrestrial water cycle to underpin hydrological research in the UK. She is also co-Chair of the international Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS) programme of FutureEarth and hosts its international project office at CEH. See <https://www.ceh.ac.uk/staff/eleanor-blyth> for more information.

## Time-frame for completion

We believe writing can be completed in about 2 years. Artwork and particularly development of problem sets and solutions will add significant time – at least a year.

## Length and figures

~600 pages; we feel color figures will be essential. We are not fond of color plates grouped in the middle of a book and would prefer all figures be in their appropriate chapters.

# Book Outline

## Frontmatter

1. Dedications and acknowledgements
2. Philosophy of this book; views from various perspectives gives fuller understanding

## Tier 1: Systems

<b>I. Systems as a concept</b>
I.1 Models of systems; components, inside vs. outside the box
I.2 Conceptual vs physical vs statistical models
<b>II. Global climate system</b>
II.1 Brief climate primer: precip, temperature, and their variability
II.2 Land cover types: trees (woody), grass (non-woody), bare soil, snow&ice; anthro/ managed: crops, pasture, urban
II.3 Carbon cycle and climate
II.4 Where is global climate affected by land? And in a general sense, why? Sets up rest of book.
<b>III. Tropics</b>
III.0 Definition of tropics
III.1 Evergreen forests & rainfall – what's happening above ground
III.2 Soils and inundated areas – what's happening below ground
III.3 Human disturbance / CC and implications
<b>IV. Subtropics (incl. seasonally)</b>
IV.0 Definition of subtropics
IV.1 Semi-arid vegetation
IV.2 Semiarid hydrology
IV.3 Carbon – not much
IV.4 Monsoon systems; wet and dry seasons
IV.5 Deserts & desertification
<b>V. Temperate Zone</b>
V.0 Definition
V.1 Thermal seasons & deciduous vegetation
V.2 Managed landscapes
V.3 Temperate hydrology
V.4 Carbon in temperate zones
<b>VI. Boreal and Arctic Zones</b>
VI.0 Definition(s) boreal & arctic, climate and vegetation; link to ice ages
VI.1 Vegetation, snow and air – what happens above ground
VI.2 Freezing soils – permafrost, wetlands, carbon budgets
VI.3 Climate change and implications
<b>VII. Past, present and future climate and extremes</b>
VII.0 Drivers and evidence of variability
VII.1 Climate controls on vegetation, soils, water & energy
VII.2 Changes in extremes – role of the land

## Tier 2: Principles

<b>A. Scientific process</b>
A.1 Scientific method
A.2 Search for processes, linkages, causality, understanding
A.3 Differentiate from engineering (solutions), statistics (relationships)
<b>B. Climate forcings</b>
B.0 Mean climate overview
B.1 Cycles: diurnal and annual
B.2 Planetary and orbital variations
B.3 Intraseasonal-decadal variability
B.4 Extremes and trends
<b>C. Feedbacks and coupling</b>
C.0 Conceptualization and scales
C.1 Land states and fluxes (coupling - land)
C.2 PBL growth and cloud formation/convection (coupling – atmosphere)
C.3 Mesoscale systems ( $L \rightarrow A$ )
C.4 Atmospheric transport ( $A \rightarrow L$ )
C.5 Carbon cycle feedbacks
<b>D. Physical structure and processes</b>
D.0 Components and linkages
D.1 Radiative exchange
D.2 Heat exchange
D.3 Water exchange – precip, soil moisture, evaporation, interception, transpiration, hydrology
D.4 Snow & ice processes
D.5 Soil physics – soil moisture and heat flow and freezing
<b>E. Biogeochemistry</b>
E.0 Carbon in the land system
E.1 Carbon in vegetation
E.1.1 Photosynthesis and plant respiration
E.1.2 Phenology
E.1.3 Vegetation dynamics, disturbance and adaptation
E.2 Carbon in the soil
E.2.1 Inputs and transformations
E.2.2 Biological outputs
E.2.3 Non-biological outputs

## Tier 3: Mathematics / Physics

<b>1. Numerics of physical models</b>
1.1 Common mathematical forms
1.2 Discretization
1.3 Parameterization
1.4 Scales
<b>2. States (stores), fluxes and parameters</b>
2.1 Energy – theory, models and observation
2.2 Water – theory, models and observation. Include frozen water.
2.3 Momentum– theory, models and observation

2.4 Carbon (and Nutrients) – theory, models and observation
2.5 Horizontal fluxes
<b>3. Diffusion and turbulent exchange across a gradient</b>
3.1 Turbulence – relationship with height from surface
3.2 Aerodynamic resistance
3.3 Stability correction
3.4 Canopy sub-layer
<b>4. Principles of radiation</b>
4.1 Shortwave – diffuse, direct, albedo
4.2 Longwave – from sky, land, within canopy, absorption bands
<b>5. Soils</b>
5.1 Darcy-Richards – water retention curves
5.2 Freezing soils
5.3 Pedotransfer functions
5.4 Mineral, organic and oxy-soils
<b>6. Photosynthesis and respiration</b>
6.1 C <sub>3</sub> and C <sub>4</sub> photosynthesis
6.2 Plant respiration
6.4 Soil respiration
6.5 Plant growth – carbon allocation

## Appendices

1. Units, constants, etc.
2. Master glossary
3. References
4. Index

Imbedded Boxes on:

1. Instrumentation / measurement for each + a primer on satellites
2. Historical notes and anecdotes, to illustrate the human process of science
3. Interesting tangents not central to the course