Climate Risk Assessment and Management

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Table of contents

Welcome

Welcome to Climate Risk Assessment and Management, an online textbook **under construction** by James Doss-Gollin.

> ❗ Under Construction
>
> This textbook is a work in progress. Currently it's largely a brain dump, but I am building it out incrementally for use in my own classes. As I add and organize content, I will update the chapter status codes: (*planning*), (*draft*), (*revision*), and (*ready*). Contributions are welcome!

Motivation and Scope

History

This project emerged from two courses taught at Rice University by James Doss-Gollin: CEVE 543 focused on climate hazard and extremes and CEVE 421/521 focused on risk management.

Aim

The book is motivated by questions like

- What is the probability distribution of wind speeds that a building structure might experience?
- What will the probability distribution of extreme rainfall be in 2050, and what drives uncertainty in this estimate?
- What is the probability distribution of tropical cyclone losses across a regional portfolio?
- When, and how high, should a house be elevated to proactively manage future flood risk?
- What are robust, efficient, and equitable strategies for reducing flood risk in an urban area?

These questions span scales and sectors, yet they share fundamental challenges: characterizing extreme events, quantifying uncertainty, assessing risks, and making robust decisions when probability distributions are unknown or contested. Moreover, there is not a single correct answer to these questions, or a single method that will incontrovertibly answer them.

How to Use This Resource

The book is designed to be useful for practitioners, students, and teachers. Teachers may use individual chapters in their courses. Students may use it as a class text or reference. Practitioners may focus on specific chapters relevant to their work. Each chapter includes learning objectives and can be read independently, though some chapters build on concepts introduced in others.

Structure

- The **Preface** introduces the book's motivation and frames key challenges
- **Part 1** introduces key topics in probability, inference, Bayesian methods, optimization, machine learning, and Earth science. Rather than providing a comprehensive treatment, this part focuses on essential concepts and links to further resources.
- **Part 2** focuses on hazard **assessment**, namely modeling climate hazards and extremes. Material is organized around thematic applications and predictive tasks. The foundational idea is integrating information from noisy and/or biased sources to estimate the joint probability distribution of relevant hydroclimatic variables.
- **Part 3** risk management, which involves both mapping hazard to risk and designing interventions to manage these risks. Key ideas include the sequential nature of decisions, the pursuit of unclear and/or contested objectives, and the need to account for the sensitivity of estimated probability distributions (of hazard and of other relevant physical, social, and economic variables) to underlying models and assumptions.
- **Computational notebooks** written in Julia illustrate and complement the methods and concepts discussed in the text. While notebooks are referenced in the text, they are designed as standalone and self-contained resources.

Prerequisites

Basic probability and multivariate calculus, along with linear algebra, are sufficient mathematical foundations for this textbook. Some exposure to Earth science, hydrology, water resources, or related topics is strongly encouraged for context, though not strictly necessary for understanding methods. This book builds on a wide range of topics and methods in statistics, machine learning, optimization, and Earth science, and expertise in any of these areas may deepen your understanding, but is not necessary. No programming is required to read the book, but going through computational examples and applying methods to your own problems, which can substantially strengthen your understanding, does require programming.

Part I

About this book

License

Contributing

This textbook is a work in progress, and we welcome your contributions. Whether it's fixing a typo or proposing a new module, every suggestion helps. The easiest way to contribute is to fork the repository and submit a pull request. If you're not comfortable with that workflow, please open an issue on GitHub.

Citing

Please cite this resource as

```
@book{doss-gollin_textbook:2025,
  author = {Doss-Gollin, James},
  title = {Climate Risk Management},
  year = {2025},
  url = {https://jdossgollin.github.io/climate-risk-book},
}
```

In the future, we will move to stable releases with numbered versions.

Further Reading

Climate risk assessment and management are complex and interdisciplinary topics, and we are by no means comprehensive here. This page provides some helpful resources (textbooks, detailed online tutorials, and class websites) for your continued and supplementary study.

Inspiration

This textbook draws inspiration and content from several courses and lecture notes, and I am grateful to the instructors who have shared their materials with me.

- Upmanu Lall's Environmental Data Analysis course at Columbia
- Vivek Srikrishnan's Environmental Systems Analysis and Climate Risk Analysis classes at Cornell
- R. Balaji's Advanced Data Analysis Techniques (Statistical Learning Techniques for Engineering and Science) course at CU Boulder
- Alberto Montanari's collection of open course notes and lectures
- **Applegate and Keller (2015)** motivates this project and demonstrates problem-based learning.

Stats + ML basics

This book assumes familiarity with these topics, but these resources may be helpful as a refresher.

- **Blitzstein and Hwang (2019)** provides a thorough introduction to key concepts and ideas in probability. The book accompanies a free online course, Stat 110, which is a great resource for learning probability and statistics. Practice problems and solutions, handouts, and lecture videos are all available online.
- **Downey (2021)** offers an introduction to Bayesian statistics using computational methods. It's not environment focused but provides code and a clear explanation of core concepts.
- **Gelman (2021)** is a textbook designed for a first course on applied statistics. Clear and well-worked examples underpin discussion of fundamental ideas in statistical analysis and thinking about data.

Applications

There are lots of related books on catastrophe modeling, water resources research, geostats, statistical hydrology and related topics. Here is an incomplete list of some core references.

- **Naghettini (2017)** is a textbook on statistical hydrology that covers many of the same topics as this course. The statistical hydrology literature often obfuscates key ideas with complex notation and terminology, but this book is a helpful introduction to the field.
- **Helsel et al. (2020)** is a comprehensive introduction to water resources and hydrology, focusing on statistical methods for analyzing hydrologic data. Its methods are traditional, with less emphasis on machine learning or Bayesian methods and more attention to null hypothesis significance testing, but its case studies are well-worked and thoughtfully described.
- **Abernathey (2024)** is an excellent resource covering introductory topics in Earth and climate data science using Python, with an emphasis on foundational computations. These core computational concepts serves as a recommended prerequisite for more advanced material in this book.
- **Pyrcz (2024)** is a textbook focused on applied machine learning, with a particular focus on geostatistics. There's less focus on extremes, hydroclimate, and decision-making, but it provides very clear and interpretable explanations of many machine learning methods, including some that are not directly covered in this book.
- **Mignan (2024)** is a modern introduction to catastrophe risk modeling that covers a wide range of hazards, including hydroclimatic extremes, from a physics-based perspective. It provides a structured framework for quantifying hazard, exposure, and vulnerability, following industry-standard CAT modeling approaches. While broader in scope and more introductory in level, it complements this book's focus by illustrating foundational principles of probabilistic risk modeling in practice.

More Stats + ML

This book covers a broad set of topics in statistics, machine learning, and optimization. Most chapters could be a textbook of their own, and in fact many exist.

- **Friedman, Hastie, and Tibshirani (2001)** is a classic introduction to machine learning, which complements the Bayesian perspective nicely.
- **Jaynes (2003)** is a classic text on probability theory that you should read if you're interested in questions like "what is probability?"
- **Gelman et al. (2014)** and **McElreath (2020)** are the classic textbooks on Bayesian inference and provide a wealth of insight and detail. The Gelman textbook is a bit more dense while the McElreath book has a more conversational tone, but both cover similar topics.

- **Cressie and Wikle (2011)** provides a detailed exploration of hierarchical space-time models. There have been some computational advances since then that are worth keeping in mind before you apply these models directly, but it's a clearly written and overview.
- **Thuerey et al. (2024)** is a new textbook on physics-based deep learning, which is a rapidly growing area of research. It provides a comprehensive overview of the field, including theoretical foundations and practical applications. It covers topics, including neural operators and diffusion models, that are not covered in this course, but which are increasingly used in the climate risk space.
- **Bishop and Bishop (2024)** is a comprehensive, modern, and accessible start-to-finish textbook covering machine learning from basic probability through diffusion models.
- Michael Betancourt's writing page has detailed and mathematically rigorous explanations of many topics in Bayesian data analysis and probabilistic modeling.

Preface

What is climate risk?

Climate risks arise at the intersection of climate hazards, exposed systems, and vulnerability. They manifest when extreme or changing climate conditions—floods, droughts, extreme temperatures, sea-level rise, or shifting precipitation patterns—impact human and natural systems that are exposed and vulnerable to these conditions. The financial sector terms these "physical risks" to distinguish them from transition risks related to policy and market changes.

Climate risks span scales from the hyperlocal (a single building's flood exposure) to the global (climate impacts on agricultural productivity). They encompass immediate acute risks from individual extreme events and longer-term chronic risks from gradual climate changes. Crucially, climate risks are not solely natural phenomena but emerge from the complex interactions between climate hazards and the human systems—infrastructure, institutions, communities, and economies—that experience their impacts.

Climate risk is often defined as the product of hazard (probability that something will happen) and consequences (exposure and vulnerability). However, it's often helpful to start with the decisions we care about.

Risk management

The goal of assessing climate risks is to manage them, as is the focus of Part III. We manage climate risks by

- **building infrastructure**, such as seawalls, stormwater pipes, oyster beds, green roofs, dams
- **designing policy**, such as water pricing, land-use regulations, building codes
- **responding** to climate disasters through disaster response and recovery. While emergency management is beyond the scope of the book, disaster prevention (through infrastructure, policy, etc) and preparation (planning evacuation routes, assessing resource needs, etc) are problems that the tools of this class can inform.

A key insight from considering these applications is that climate risks are not natural phenomena, but occur at the intersection of natural and human systems. A second insight is that decisions about how to manage climate risks do not depend only on climate hazard, but also on human systems and values.

Exposure and vulnerability

Hazards do not create consequences by themselves. Hazards affect things that we care about, whether natural ecosystems, human homes, infrastructure systems, or something else. Quantitatively these are often described as exposure and vulnerability. However, this is not always a helpful framing because everything is exposed, to at least some degree, to climate hazards.

Climate hazard

Climate hazards have several key characteristics:

- **Location-specific impacts**: Specific weather patterns cause different things in different places—tropical cyclones cause extreme winds on the Gulf Coast, while persistent intense rainfall causes flooding in major rivers
- **Require Earth science and data**: Understanding hazards requires both physical process knowledge and empirical data
- **Variable focus on extremes**: Some applications care about extremes, but others (e.g., water management) care about shifts in the whole distribution
- **Multi-scale variability**: Characterized by variability across multiple spatial and temporal scales

What are good strategies?

The simple story

In principle, managing climate risks should be straightforward. If we had clear objectives and well-characterized uncertainty, there are **established mathematical formalisms for decision-making under uncertainty**. Notably, Bayesian Decision Theory provides an elegant framework: find the action a that maximizes expected utility

$$\mathbb{E}[U(a)] = \int U(a, s) p(s) ds,$$

where $U(a, s)$ is the utility of action a given s, and $p(s)$ is the over states of the world. The $\mathbb{E}[U(a)]$ represents the average utility we would expect from action a across all possible future states, weighted by their probabilities (see Chapter on Probability and Statistics for mathematical foundations).

With this framework and modern advances in operations research and optimization, we could frame climate risk management as a large-scale optimization problem. This might still be a challenging problem, requiring sophisticated optimization methods, large-ensemble Monte Carlo simulation, high-performance computing, and more, but fundamentally **there would be a right answer** that we could identify, at least seek to approximate.

Why this isn't enough

In practice, climate risk management defies this idealized approach for several fundamental reasons:

1. **Deep uncertainty**: Unlike textbook optimization problems, we rarely have well-defined probability distributions over future states. Climate risks involve poorly characterized, multiple, and interacting uncertainties spanning physical processes (climate projections), socioeconomic factors (development patterns, institutional capacity, human behavior), and their complex dependencies. The probability distributions we need span climate hazards, exposure patterns, vulnerability functions, and policy effectiveness—all evolving in ways that resist precise characterization.
2. **Large and poorly defined decision spaces**: The solution space includes not just individual projects but entire systems: infrastructure networks, policy portfolios, risk transfer arrangements, and adaptive management sequences. These decisions interact across scales, sectors, and time horizons in ways that resist comprehensive optimization.
3. **Contested objectives**: Different stakeholders hold different values about what we should optimize for—economic efficiency, equity, robustness, or flexibility. These objectives often conflict, and their relative importance is itself contested and evolving.

This brings us to a crucial insight: **we cannot simply frame climate risk management as a big optimization problem**. The field has witnessed an explosion of computational tools—climate models with ever-finer resolution, machine learning algorithms for processing vast datasets, and sophisticated visualization platforms for rendering complex projections. While these advances represent genuine progress, their proliferation has created new challenges for practitioners seeking to manage real-world climate risks.

The abundance of available tools does not automatically translate to better decisions. Indeed, the sophistication of modern computational approaches can obscure fundamental questions about problem framing, uncertainty characterization, and appropriate methods selection. Without solid conceptual foundations, practitioners may find themselves applying powerful tools inappropriately or mistaking methodological novelty for substantive insight.

The stakes of getting it wrong

The consequences of inadequate climate risk management are severe and diverse. **Infrastructure failures** occur when designs based on historical extremes prove insufficient for future conditions—leading to flooded neighborhoods when storm drains are undersized, or to costly over-design when extreme projections are treated as certainties. **Policy mistakes** compound these problems: development policies that ignore flood risks concentrate vulnerable populations in harm's way, while overly conservative regulations can stifle economic development without commensurate risk reduction benefits.

Financial miscalculations affect both public and private sectors. Insurance companies that underestimate climate risks face catastrophic losses, while those that overestimate risks price themselves out of markets. Infrastructure investors struggle to balance climate resilience against cost constraints, often erring toward solutions that prove either inadequate or prohibitively expensive. These failures cascade across scales: a poorly designed local drainage system contributes to regional flood management challenges, while flawed national climate risk assessments misguide infrastructure investment priorities across entire countries.

This book

This book develops both the technical tools and conceptual frameworks needed for climate risk management:

- **Part I** provides the statistical, optimization, and machine learning foundations that enable rigorous analysis of climate risks and decision alternatives
- **Part II** focuses on characterizing climate hazards and their uncertainties, emphasizing the integration of multiple imperfect information sources
- **Part III** addresses the transition from hazard to risk and the design of management strategies under deep uncertainty

Throughout, we emphasize that technical sophistication must be coupled with conceptual clarity about the nature of climate risks and the limits of optimization approaches. The goal is not to abandon quantitative analysis, but to use it more wisely—focusing computational power where it adds most value while acknowledging the irreducible uncertainties that require adaptive, robust approaches to climate risk management.

This book aims to teach readers how to **apply** tools from applied mathematics, statistics, and machine learning to answer questions such as

- What is the probability distribution of some relevant hazards or variables, such as (rainfall, wind, flood, temperature, streamflows) at a specific location?
- How do these probability distributions change in the next 50 years?

- How uncertain are these estimates and what specific mechanisms drive these uncertainties?
- What is the distribution of annual losses of a portfolio of assets exposed to one or many climate risks?
- What are trade-offs between up-front costs and future damages for decisions like how high to elevate a house?
- What are robust strategies for sequentially hardening infrastructure against climate risks?
- What are trade-offs between flood and drought protection for managing a reservoir?

While Part I does provide building blocks, they are intended to be self-contained references rather than a comprehensive overview to applied math, statistics, computer science, machine learning, and operations research. Instead, it aims to give you "just enough" context to think carefully about how to apply tools from these fields to climate risk management challenges.

What this book is not

This book focuses on the technical foundations of climate risk assessment and quantitative decision-making under uncertainty. While we address design requirements, social dimensions, and stakeholder considerations throughout—recognizing that technical tools can significantly inform these challenges—there are important aspects of climate risk management that require specialized expertise beyond our scope.

This book will **not** primarily teach you how to:

- **Manage reputational and transition risks**: While we focus on physical climate risks and their quantitative assessment, organizations also face complex risks from changing policies, markets, and stakeholder expectations that require specialized risk management expertise
- **Design and implement adaptive organizations**: While we cover adaptive management strategies and robust decision-making frameworks, the organizational design and management expertise needed to implement these approaches in practice requires additional specialized knowledge
- **Facilitate stakeholder processes**: While the quantitative tools we teach can strongly support consensus building by clarifying trade-offs and uncertainties, the facilitation, negotiation, and collaborative governance skills needed to lead stakeholder processes require specialized training
- **Develop communication strategies**: While we emphasize how to interpret and present quantitative risk assessments, developing effective communication strategies for diverse audiences—policymakers, communities, investors—requires specialized expertise in science communication and public engagement

- **Navigate implementation challenges**: While we address policy design and infrastructure planning from an analytical perspective, the practical challenges of construction management, regulatory processes, and community engagement require domain-specific expertise

This is an interdisciplinary text that draws insights from multiple fields and acknowledges the social, political, and institutional contexts that shape climate risk management. However, our primary focus remains on the quantitative and analytical foundations that can inform—but not replace—the broader expertise needed for effective practice.

Part II

I: Foundations

1 Fundamentals of Climate Science

Learning objectives

After reading this chapter, you should be able to:

- Identify key statistical characteristics of climate hazards (fat tails, non-stationarity, multi-scale variability)
- Understand why traditional statistical approaches often fail for climate extremes
- Recognize the decision-theoretic foundation for climate risk assessment
- Grasp the key physical processes driving climate variability and change
- Understand sources of uncertainty in climate projections and their implications for risk assessment

1.1 Climate and the water cycle

Climate refers to "the slowly varying aspects of the atmosphere–hydrosphere–land surface system." The water cycle plays a key role in our climate system, connecting atmospheric processes with terrestrial and oceanic systems.