Climatology is, to a large degree, the study of the statistics of our climate. The powerful tools of mathematical statistics therefore find wide application in climatological research, ranging from simple methods for determining the uncertainty of a climatological mean to sophisticated techniques which reveal the dynamics of the climate system.

The purpose of this book is to help the climatologist understand the basic precepts of the statistician's art and to provide some of the background needed to apply statistical methodology correctly and usefully. The book is self contained: introductory material, standard advanced techniques, and the specialized techniques used specifically by climatologists are all contained within this one source. There is a wealth of real-world examples drawn from the climate literature to demonstrate the need, power and pitfalls of statistical analysis in climate research.

This book is suitable as a main text for graduate courses on statistics for climatic, atmospheric and oceanic science. It will also be valuable as a reference source for researchers in climatology, meteorology, atmospheric science, and oceanography.

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Statistical Analysis in Climate Research

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Preface

The tools of mathematical statistics find wide application in climatological research. Indeed, climatology is, to a large degree, the study of the statistics of our climate. Mathematical statistics provides powerful tools which are invaluable for this pursuit. Applications range from simple uses of sampling distributions to provide estimates of the uncertainty of a climatological mean to sophisticated statistical methodologies that form the basis of diagnostic calculations designed to reveal the dynamics of the climate system. However, even the simplest of statistical tools has limitations and pitfalls that may cause the climatologist to draw false conclusions from valid data if the tools are used inappropriately and without a proper understanding of their conceptual foundations. The purpose of this book is to help the climatologist understand the basic precepts of the statistician's art and to provide some of the background needed to apply statistical methodology correctly and usefully.

We do not claim that this volume is in any way an exhaustive or comprehensive guide to the use of statistics in climatology, nor do we claim that the methodology described here is a current reflection of the art of applied statistics as it is conducted by statisticians. Statistics as it is applied in climatology is far removed from the cutting edge of methodological development. This is partly because statistical research has not come yet to grips with many of the problems encountered by climatologists and partly because climatologists have not yet made very deep excursions into the world of mathematical statistics. Instead, this book presents a subjectively chosen discourse on the tools we have found useful in our own research on climate diagnostics.

We will discuss a variety of statistical concepts and tools which are useful for solving problems in climatological research, including the following.

- The concept of a sample.
- The notions of exploratory and confirmatory statistics.
- The concept of the statistical model. Such a model is implicit in every statistical analysis technique and has substantial implications for the conclusions drawn from the analysis.
- The differences between parametric and non-parametric approaches to statistical analysis.
- The estimation of 'parameters' that describe the properties of the geophysical process being studied. Examples of these 'parameters' include means and variances, temporal and spatial power spectra, correlation coefficients, empirical orthogonal functions and Principal Oscillation Patterns. The concept of parameter estimation includes not only point estimation (estimation of the specific value of a parameter) but also interval estimation which account for uncertainty.
- The concepts of hypothesis testing, significance, and power.

We do *not* deal with:

- *Bayesian statistics*, which is philosophically quite different from the more common *frequentist* approach to statistics we use in this book. Bayesians, as they are known, incorporate *a priori* beliefs into a statistical analysis of a sample in a rational manner (see Epstein [114], Casella [77], or Gelman et al. [139]).
- *Geostatistics*, which is widely used in geology and related fields. This approach deals with the analysis of spatial fields sampled at a relatively small number of locations. The most prominent technique is called *kriging* (see Journel and Huijbregts [207], Journel [206], or Wackernagel [406]), which is related to the *data assimilation* techniques used in atmospheric and oceanic science (see, e.g., Daley [98] and Lorenc [258]).

A collection of applications of many statistical techniques has been compiled by von Storch and Navarra [395]; we recommend this collection as complementary reading to this book and refer to its contributions throughout. This collection does not cover the field systematically; instead it offers examples of the exploitation of statistical methods in the analysis of climatic data and numerical experiments.

Cookbook recipes for a variety of standard statistical situations are not offered by this book because they are dangerous for anyone who does not understand the basic concepts of statistics. Therefore, we offer a course in the concepts and discuss cases we have encountered in our work. Some of these examples refer to standard situations, and others to more exotic cases. Only the understanding of the principles and concepts prevents the scientist from falling into the many pitfalls specific to our field, such as multiplicity in statistical tests, the serial dependence within samples, or the enormous size of the climate's phase space. If these dangers are not understood, then the use of simple recipes will often lead to erroneous conclusions. Literature describes many cases, both famous and infamous, in which this has occurred.

We have tried to use a consistent notation throughout the book, a summary of which is offered in Appendix A. Some elements of linear algebra are available in Appendix B, and some aspects of Fourier analysis and transform are listed in Appendix C. Proofs of statements, which we do not consider essential for the overall understanding, are in Appendix M.

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