1 Introduction

Climate is changing and will continue to change. Societies and ecosystems are affected by and often depend on climate and its variability. Already in 1992, the United Nations Framework Convention on Climate Change stated that all parties shall "cooperate in preparing for adaptation to the impacts of climate change" (United Nations 1992). Over the last decades, several countries have developed national adaptation strategies. The EU strategy on adaptation to climate change (European Commission 2013), for instance, acknowledges the need to take adaptation measures at all levels ranging from national to regional and local levels. The Global Framework for Climate Services (GFCS), established in 2009, sets out to develop and communicate climate information to "enable better management of the risks of climate variability and change and adaptation to climate change" (http://www.wmo.int/gfcs/vision). In short, there is an urgent demand for scientifically credible climate change information, in particular at the regional scale (Hewitt et al. 2012). One approach to obtain information about regional climate change is downscaling of global climate projections. In fact, a plethora of different data products have already been made available via internet portals.

Yet the provision of regional climate change information is one of the big challenges in climate science (Schiermeier 2010) and still a subject of essentially basic research (Hewitson et al. 2014). A *Nature* editorial prominently pointed out that "certainty is what current-generation regional studies cannot yet provide" (Nature 2010). Kundzewicz and Stakhiv (2010) argue that climate models have originally been developed to guide mitigation decisions. They could provide a broad picture of global climate change but would not yet be skillful to serve as input for regional adaptation planning. Kerr (2011*b*) brings forward a range of arguments which have been issued against current downscaling practice, and, in a later piece (Kerr 2011*a*), discusses the challenges of providing actionable climate information.

Against this background, the book at hand attempts to provide a reference for a range of approaches and methods often summarised as statistical downscaling. At the same time, the book aims to put the more technical issues of statistical downscaling into the broader context of user needs, regional climate modelling uncertainties and limitations, and good scientific practice. To begin with, we would like to sketch the scientific idea of statistical downscaling and then give some guidance on how to best approach this book.

CAMBRIDGE
Cambridge University Press
978-1-107-06605-2 — Statistical Downscaling and Bias Correction for Climate Research
Douglas Maraun , Martin Widmann
Excerpt
More Information

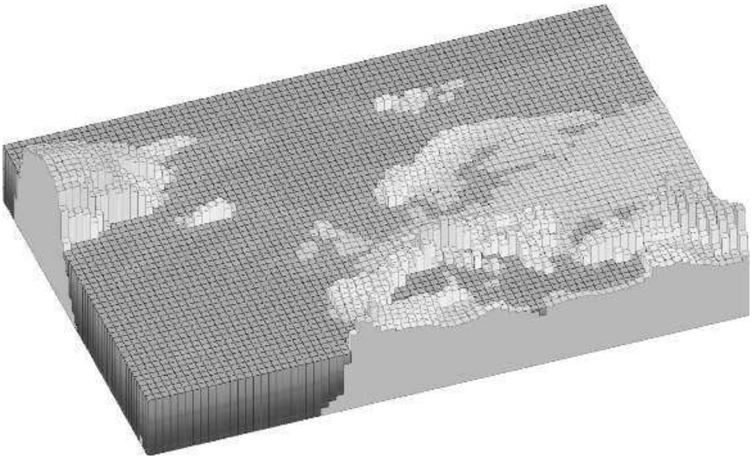

Figure 1.1 Landmask and elevation model of a typical state-of-the-art GCM. The horizontal resolution is approximately $1.13^\circ \times 1.13^\circ$. Adapted from Figure 1.4 (bottom panel AR4), Solomon et al. (2007).

1.1 Statistical Downscaling and Bias Correction in a Nutshell

On the 18th of July 2009, heavy rains fell in the city of Graz, Austria. The soil was still saturated from a wet spell in late June, such that the city's streams burst their banks, and several districts were flooded. Hydrologists, engineers and city planners might all be interested in the risk of such a flooding to happen again: it depends on the precipitation history over the preceding weeks, on the intensity of the rainfall event and on its spatial-temporal distribution. But all these users of climate information are more and more concerned not only with risk in present climate but also with potential changes of risk in a warmer future climate.

Much of our knowledge about future climate change stems from projections with global general circulation models (GCMs). For instance, the ensemble simulations carried out within the coupled model intercomparison project (CMIP, Meehl et al. 2007*a*, Taylor et al. 2012) have been the backbone of many prominent messages published in the last Intergovernmental Panel on Climate Change (IPCC) assessment reports (e.g. Meehl et al. 2007*b*, Collins et al. 2013). But even state-of-the-art GCMs still have a rather coarse resolution (Figure 1.1). As a consequence, regional-scale topography and meteorological processes, in particular those responsible for many types of extreme events, are not represented by these models.

The idea of downscaling is to bridge the gap between the large spatial scales represented by GCMs to the smaller scales required for assessing regional climate change and its impacts. Two major types of downscaling exist: in dynamical downscaling, a high-resolution regional climate model (RCM) is nested into the GCM over the domain of interest (Rummukainen 2010). In statistical downscaling, empirical links between the large-scale and local-scale climate are identified and applied to climate model output.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-06605-2 — Statistical Downscaling and Bias Correction for Climate Research
Douglas Maraun , Martin Widmann
Excerpt
More Information

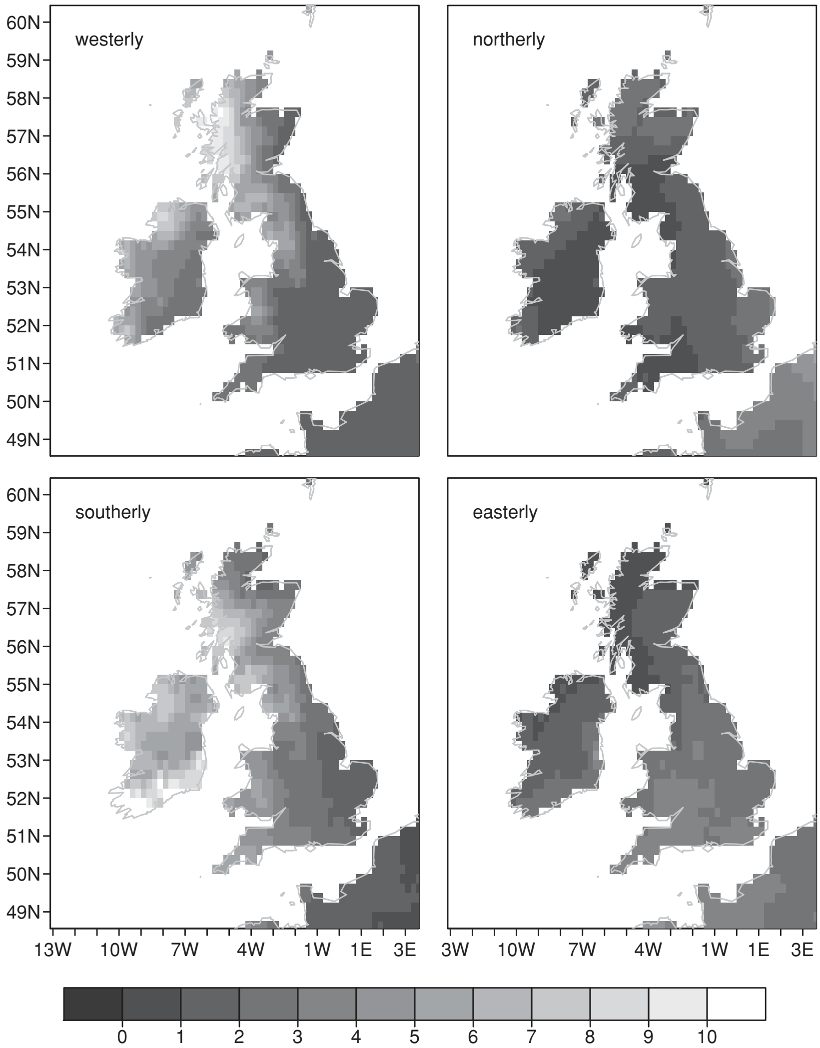

Figure 1.2 Precipitation composites [mm/day] on the British Isles for selected Lamb weather types (Lamb 1972), which describe the main atmospheric circulation patterns over the British Isles. Based on E-OBS daily data (Haylock et al. 2008) and the Lamb weather types from the Climatic Research Unit (Jones et al. 2013) for the period 1950 to 2016.

Figure 1.2 illustrates such an empirical relationship for the British Isles. The panels show the average precipitation which falls under four different situations of the large-scale atmospheric circulation: in case of a westerly flow, the highest precipitation is expected along the west coast of Ireland and Great Britain. Highest intensities occur in particular in the western Scottish Highlands – the South East of England is typically dry under such conditions. Northerly airflow instead brings cooler air, which typically carries less moisture. Precipitation intensities are thus lower – with relatively high values in the exposed regions of Northern Scotland, the North East of Ireland and East

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE
Cambridge University Press
978-1-107-06605-2 — Statistical Downscaling and Bias Correction for Climate Research
Douglas Maraun , Martin Widmann
Excerpt
More Information

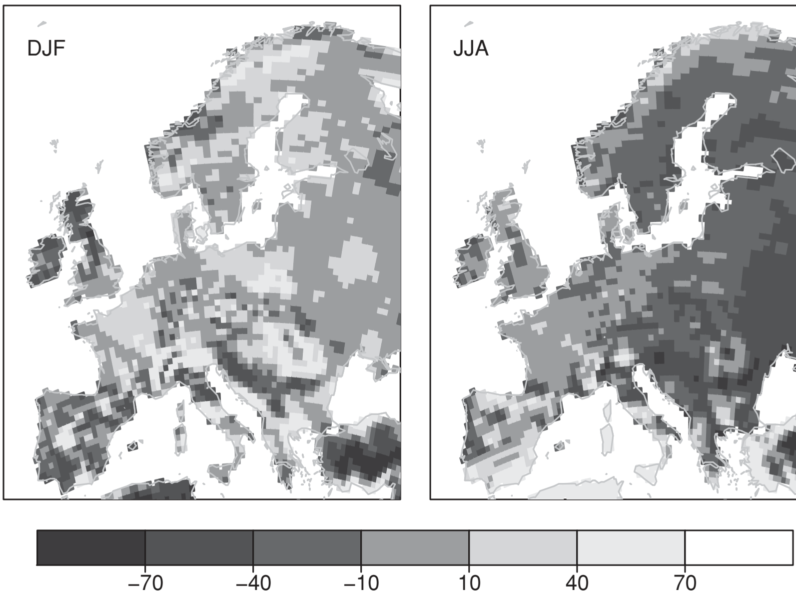

Figure 1.3 Relative precipitation bias [%] of the RCM RACMO2 (van Meijgaard et al. 2008), driven by the GCM EC-EARTH (Hazeleger et al. 2010) compared to E-OBS data (Haylock et al. 2008), for the period 1971–2000. Left: winter; right: summer.

Anglia. If the flow arrives from the south, precipitation is highest in the South of Ireland but also along the west coast of Great Britain. Finally, easterly flow brings higher intensities to the East coast and to the hills of South-West England and Wales, the first orographic barrier in the south of Great Britain. Other such situations – called weather types in meteorology – would also be associated with typical precipitation patterns. Thus, knowing the large-scale flow, one can predict the regional distribution of precipitation, including the effects of regional orography. Applying this empirical relationship to the large-scale circulation simulated by a GCM would thus downscale the GCM and generate regional-scale precipitation fields. In statistical downscaling jargon, this would be a weather-type-based perfect prognosis model. Under the assumption that the empirical link between large-scale circulation and local precipitation remains valid in a future climate, one could apply the model to generate regional precipitation projections.

But even if a GCM would resolve the climate processes relevant for a particular user, the simulated climate would typically still substantially deviate from real-world climate. In fact, even after dynamical downscaling the simulated regional climate is in general biased compared to observations. Figure 1.3 shows the relative error between simulated and observed mean winter (left) and summer (right) precipitation climate. The simulation has been conducted with the RCM RACMO2, driven by the GCM EC-EARTH, two well-performing climate models. In some parts of Europe, the relative error is below 10%, but in many regions it exceeds plus or minus 70%. Impact modellers often cannot use such simulations directly; they demand some form of statistical post-processing to adjust the model output towards observations. Again, one could establish an empirical

© in this web service Cambridge University Press www.cambridge.org

Cambridge University Press
978-1-107-06605-2 — Statistical Downscaling and Bias Correction for Climate Research
Douglas Maraun , Martin Widmann
Excerpt
More Information

link: here the ratio between the simulated and the observed mean precipitation. Applying this scaling factor to the simulation, one would "remove" the model bias. This bias correction procedure is a simple form of model output statistics. Under the assumption that the correction function is applicable in a future climate, one could post-process future precipitation projections.

The terms "statistical downscaling" and "bias correction" are used differently in different communities and countries. Many US researchers use the terms essentially interchangeably. In other countries, climatologists often reserve the term "statistical downscaling" or even "empirical statistical downscaling" for the first approach, which we call perfect prognosis. The term "bias correction" is used by dynamical downscalers and hydrologists exclusively for the second approach, but some users of empirical statistical downscaling would claim that also their approaches are bias correcting. Recently, some authors began to argue that bias correction, as it does only post-processes model output, should better be called bias adjustment. And being slightly meticulous, one could even argue that many statistical methods from either approach do not generate time series representing local climate – that is, they are not really downscaling. We therefore decided to follow a semi-pragmatic approach. In general, and in particular when we compare the two approaches, we use the terminology originally proposed by Klein and Glahn 1974: we call the first approach perfect prognosis (PP) and the second model output statistics (MOS). The key advantage is that these terms are precisely defined and at the same time get more and more used across disciplines. But since most MOS approaches in this book are mere bias corrections, we often use this simpler term. The term "statistical downscaling" is used rather colloquially to subsume both approaches.

1.2 How to Read This Book

We hope the book will prove useful for different audiences, each with its specific backgrounds and needs. One could approach the book simply by reading it in the given order or use selected chapters as reference. In particular, these would be the technical chapters on statistical methods (Chapter 6) and dynamical modelling (Chapter 8), the different downscaling approaches (Chapters 11–14), and finally the evaluation and performance (Chapters 15 and 16).

Readers who are new to the field or who are mainly interested in using and interpreting downscaling results may instead start reading the book from Chapter 18. This chapter provides a condensed summary of how to best apply statistical downscaling in practice: what are important issues to be considered? Which methods are useful in which context? How could one deal with uncertainties? In each section, the reader is then directed towards more in-depth discussions in the preceding parts of the book. We will sketch these in the following.

Part I provides both a broader context and the necessary technical background. In Chapter 2 we introduce climate and weather phenomena governing regional climates. After a historical overview (Chapter 3), we discuss the main assumptions, requirements and concepts of downscaling (Chapter 4). User needs are reviewed and discussed in

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-06605-2 — Statistical Downscaling and Bias Correction for Climate Research
Douglas Maraun , Martin Widmann
Excerpt
More Information

Chapter 5. Chapters 6 to 9 provide background in statistical modelling, a summary of observational data and dynamical climate modelling and a discussion of their limitations and uncertainties.

Part II is the core of the book and introduces the overall structure of downscaling methods (Chapter 10), as well as the major approaches PP, MOS, weather generators and combinations of these approaches (Chapters 11–14). Each of these chapters provides an overview of widely used methods as well as their structural limitations and the assumptions underlying their use.

Part III discusses the performance of statistical downscaling and regional modelling and its use in practice. A general framework for the evaluation of regional climate projections is presented in Chapter 15 and a synthesis of actual performance in Chapter 16. The ongoing debate of the applicability of downscaling is critically reviewed in Chapter 17. Finally, Chapter 18 provides a synthesis of the book and guidelines for the use of downscaling in practical applications.

© in this web service Cambridge University Press www.cambridge.org