IMPACTS ANALYSIS FOR INVERSE INTEGRATED ASSESSMENTS OF CLIMATE CHANGE

D I S S E R T A T I O N

zur Erlangung des akademischen Grades
Doktor der Naturwissenschaften (Dr. rer. nat.)
in der Wissenschaftsdisziplin
Theoretische Physik

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät
der Universität Potsdam

von
Dipl.-Inform. Dipl.-Systemwiss. Hans-Martin Füssel
geboren am 24. April 1968 in Frankfurt am Main

Potsdam, im Oktober 2003

Abstract

This thesis describes the development and application of the impacts module of the ICLIPS model, a global integrated assessment model of climate change. The presentation of the technical aspects of this model component is preceded by a discussion of the sociopolitical context for model-based integrated assessments, which defines important requirements for the specification of the model.

Integrated assessment of climate change comprises a broad range of scientific efforts to support the decision-making about objectives and measures for climate policy, whereby many different approaches have been followed to provide policy-relevant information about climate impacts. Major challenges in this context are the large diversity of the relevant spatial and temporal scales, the multifactorial causation of many 'climate impacts', considerable scientific uncertainties, and the ambiguity associated with unavoidable normative evaluations. A hierarchical framework is presented for structuring climate impact assessments that reflects the evolution of their practice and of the underlying theory.

Integrated assessment models of climate change (IAMs) are scientific tools that contain simplified representations of the relevant components of the coupled society-climate system. The major decision-analytical frameworks for IAMs are evaluated according to their ability to address important aspects of the pertinent social decision problem. The guardrail approach is presented as an 'inverse' framework for climate change decision support, which aims to identify the whole set of policy strategies that are compatible with a set of normatively specified constraints ('guardrails'). This approach combines, to a certain degree, the scientific rigour and objectivity typical of predictive approaches with the ability to consider virtually all decision options that is at the core of optimization approaches. The ICLIPS model is described as the first IAM that implements the guardrail approach.

The representation of climate impacts is a key concern in any IAM. A review of existing IAMs reveals large differences in the coverage of impact sectors, in the choice of the impact numeraire(s), in the consideration of non-climatic developments, including purposeful adaptation, in the handling of uncertainty, and in the inclusion of singular events. IAMs based on an inverse approach impose specific requirements to the representation of climate impacts. This representation needs to combine a level of detail and reliability that is sufficient for the specification of impact guardrails with the conciseness and efficiency that allows for an exploration of the complete domain of plausible climate protection strategies. Large-scale singular events can often be represented by dynamic reduced-form models. This approach, however, is less appropriate for regular impacts where the determination of policy-relevant results generally needs to consider the heterogeneity of climatic, environmental, and socioeconomic factors at the local or regional scale.

Climate impact response functions (CIRFs) are identified as the most suitable reduced-form representation of regular climate impacts in the ICLIPS model. A CIRF depicts the aggregated response of a climate-sensitive system or sector as simulated by a spatially explicit sectoral impact model for a representative subset of plausible futures. In the CIRFs presented here, global mean temperature and atmospheric CO_2 concentration are used as predictors for global and regional impacts on natural vegetation, agricultural crop production, and water availability. Application of a pattern scaling technique makes it possible to consider the regional and seasonal patterns in the climate anomalies simulated by several general circulation models while ensuring the efficiency of the dynamic model components.

Efforts to provide quantitative estimates of future climate impacts generally face a trade-off between the relevance of an indicator for stakeholders and the exactness with which it can be determined. A number of non-monetary aggregated impact indicators for the CIRFs is presented, which aim to strike the balance between these two conflicting goals while taking into account additional constraints of the ICLIPS modelling framework. Various types of impact diagrams are used for the visualization of CIRFs, each of which provides a different perspective on the impact result space.

The sheer number of CIRFs computed for the ICLIPS model precludes their comprehensive presentation in this thesis. Selected results referring to changes in the distribution of biomes in different biogeographical regions, in the agricultural potential of various countries, and in the water availability in selected major catchments are discussed. The full set of CIRFs is accessible via the ICLIPS Impacts Tool, a graphical user interface that provides convenient access to more than 100,000 impact diagrams developed for the ICLIPS model. The technical aspects of the software are described as well as the accompanying database of CIRFs.

The most important application of CIRFs is in 'inverse' mode, where they are used to translate impact guardrails into simultaneous constraints for variables from the optimizing ICLIPS climate-economy model. This translation is facilitated by algorithms for the computation of reachable climate domains and for the parameterized approximation of admissible climate windows derived from CIRFs. The comprehensive set of CIRFs, together with these algorithms, enables the ICLIPS model to flexibly explore sets of climate policy strategies that explicitly comply with impact guardrails specified in biophysical units. This feature is not found in any other intertemporally optimizing IAM. A guardrail analysis with the integrated ICLIPS model is described that applies selected CIRFs for ecosystem changes. So-called "necessary carbon emission corridors" are determined for a default choice of normative constraints that limit global vegetation impacts as well as regional mitigation costs, and for systematic variations of these constraints.

A brief discussion of recent developments in integrated assessment modelling of climate change connects the work presented here with related efforts.

Keywords: Climate change, climate impacts, integrated assessment, guardrail approach, tolerable windows approach, inverse analysis, climate impact response functions, pattern scaling, ICLIPS

Zusammenfassung

Diese Dissertation beschreibt die Entwicklung und Anwendung des Klimawirkungsmoduls des ICLIPS-Modells, eines integrierten Modells des Klimawandels (“Integrated Assessment”-Modell). Vorangestellt ist eine Diskussion des gesellschaftspolitischen Kontexts, in dem modellbasiertes “Integrated Assessment” stattfindet, aus der wichtige Anforderungen an die Spezifikation des Klimawirkungsmoduls abgeleitet werden.

Das “Integrated Assessment” des Klimawandels umfasst eine weiten Bereich von Aktivitäten zur wissenschaftsbasierten Unterstützung klimapolitischer Entscheidungen. Hierbei wird eine Vielzahl von Ansätzen verfolgt, um politikrelevante Informationen über die erwarteten Auswirkungen des Klimawandels zu berücksichtigen. Wichtige Herausforderungen in diesem Bereich sind die große Bandbreite der relevanten räumlichen und zeitlichen Skalen, die multifaktorielle Verursachung vieler “Klimafolgen”, erhebliche wissenschaftliche Unsicherheiten sowie die Mehrdeutigkeit unvermeidlicher Werturteile. Die Entwicklung eines hierarchischen Konzeptmodells erlaubt die Strukturierung der verschiedenen Ansätze sowie die Darstellung eines mehrstufigen Entwicklungsprozesses, der sich in der Praxis und der zu Grunde liegenden Theorie von Studien zur Vulnerabilität hinsichtlich des Klimawandels wiederspiegelt.

“Integrated Assessment”-Modelle des Klimawandels sind wissenschaftliche Werkzeuge, welche eine vereinfachte Beschreibung des gekoppelten Mensch-Klima-Systems enthalten. Die wichtigsten entscheidungstheoretischen Ansätze im Bereich des modellbasierten “Integrated Assessment” werden im Hinblick auf ihre Fähigkeit zur adäquaten Darstellung klimapolitischer Entscheidungsprobleme bewertet. Dabei stellt der “Leitplankenansatz” eine “inverse” Herangehensweise zur Unterstützung klimapolitischer Entscheidungen dar, bei der versucht wird, die Gesamtheit der klimapolitischen Strategien zu bestimmen, die mit einer Reihe von zuvor normativ bestimmten Mindestkriterien (den sogenannten “Leitplanken”) verträglich sind. Dieser Ansatz verbindet bis zu einem gewissen Grad die wissenschaftliche Strenge und Objektivität simulationsbasierter Ansätze mit der Fähigkeit von Optimierungsansätzen, die Gesamtheit aller Entscheidungsoptionen zu berücksichtigen. Das ICLIPS-Modell ist das erste “Integrated Assessment”-Modell des Klimawandels, welches den Leitplankenansatz implementiert.

Die Darstellung von Klimafolgen ist eine wichtige Herausforderung für “Integrated Assessment”-Modelle des Klimawandels. Eine Betrachtung bestehender “Integrated Assessment”-Modelle offenbart große Unterschiede in der Berücksichtigung verschiedener vom Klimawandel betroffenen Sektoren, in der Wahl des bzw. der Indikatoren zur Darstellung von Klimafolgen, in der Berücksichtigung nicht-klimatischer Entwicklungen einschließlich gezielter Anpassungsmaßnahmen an den Klimawandel, in der Behandlung von Unsicherheiten und in der Berücksichtigung von “singulären” Ereignissen. “Integrated Assessment”-Modelle, die auf einem Inversansatz beruhen, stellen besondere Anforderungen an die Darstellung von Klimafolgen. Einerseits muss der Detaillierungsgrad hinreichend sein, um Leitplanken für Klimafolgen sinnvoll definieren zu können; andererseits muss die Darstellung effizient genug sein, um die Gesamtheit der möglichen klimapolitischen Strategien erkunden zu können. Großräumige Singularitäten können häufig durch vereinfachte dynamische Modelle abgebildet werden. Diese Methode ist jedoch weniger geeignet für reguläre Klimafolgen, bei denen die Bestimmung relevanter Ergebnisse in der Regel die Berücksichtigung der Heterogenität von klimatischen, naturräumlichen und sozialen Faktoren auf der lokalen oder regionalen Ebene erfordert.

Klimawirkungsfunktionen stellen sich als die geeignetste Darstellung regulärer Klimafolgen im ICLIPS-Modell heraus. Eine Klimawirkungsfunktion beschreibt in aggregierter Form die Reaktion eines klimasensitiven Systems, wie sie von einem geographisch expliziten Klimawirkungsmodell für eine repräsentative Teilmenge möglicher zukünftiger Entwicklungen simuliert wurde. Die in dieser Arbeit vorgestellten Klimawirkungsfunktionen nutzen die globale Mitteltemperatur sowie die atmosphärische CO_2-Konzentration als Prädiktoren für global und regional aggregierte Auswirkungen des Klimawandels auf natürliche Ökosysteme, die landwirtschaftliche Produktion und die Wasserverfügbarkeit. Die Anwendung einer "Musterskalierungstechnik" ermöglicht hierbei die Berücksichtigung der regionalen und saisonalen Muster des Klimaänderungssignals aus allgemeinen Zirkulationsmodellen, ohne die Effizienz der dynamischen Modellkomponenten zu beeinträchtigen.

Bemühungen zur quantitativen Abschätzung zukünftiger Klimafolgen sehen sich bei der Wahl geeigneter Indikatoren in der Regel einem Zielkonflikt zwischen der Relevanz eines Indikators für Entscheidungsträger und der Zuverlässigkeit, mit der dieser bestimmt werden kann, gegenüber. Eine Reihe von nichtmonetären Indikatoren zur aggregierten Darstellung von Klimafolgen in Klimawirkungsfunktionen wird präsentiert, welche eine Balance zwischen diesen beiden Zielen anstreben und gleichzeitig die Beschränkungen berücksichtigen, die sich aus anderen Komponenten des ICLIPS-Modells ergeben. Klimawirkungsfunktionen werden durch verschiedene Typen von Diagrammen visualisiert, welche jeweils unterschiedliche Perspektiven auf die Ergebnismenge der Klimawirkungssimulationen erlauben.

Die schiere Anzahl von Klimawirkungsfunktionen verhindert ihre umfassende Darstellung in dieser Arbeit. Ausgewählte Ergebnisse zu Veränderungen in der räumlichen Ausdehnung von Biomen, im landwirtschaftlichen Potential verschiedener Länder und in der Wasserverfügbarkeit in mehreren großen Einzugsgebieten werden diskutiert. Die Gesamtheit der Klimawirkungsfunktionen wird zugänglich gemacht durch das "ICLIPS Impacts Tool", eine graphische Benutzeroberfläche, die einen bequemen Zugriff auf über 100.000 Klimawirkungsdiagramme ermöglicht. Die technischen Aspekte der Software sowie die zugehörige Datenbasis wird beschrieben.

Die wichtigste Anwendung von Klimawirkungsfunktionen ist im "Inversmodus", wo sie genutzt werden, um Leitplanken zur Begrenzung von Klimafolgen in gleichzeitige Randbedingungen für Variablen aus dem optimierenden ICLIPS-Klima-Weltwirtschafts-Modell zu übersetzen. Diese Übersetzung wird ermöglicht durch Algorithmen zur Bestimmung von Mengen erreichbarer Klimazustände ("reachable climate domains") sowie zur parametrisierten Approximation zulässiger Klimafenster ("admissible climate windows"), die aus Klimawirkungsfunktionen abgeleitet werden. Der umfassende Bestand an Klimawirkungsfunktionen zusammen mit diesen Algorithmen ermöglicht es dem integrierten ICLIPS-Modell, in flexibler Weise diejenigen klimapolitischen Strategien zu bestimmen, welche bestimmte in biophysikalischen Einheiten ausgedrückte Begrenzungen von Klimafolgen explizit berücksichtigen. Diese Möglichkeit bietet kein anderes intertemporal optimierendes "Integrated Assessment"-Modell. Eine Leitplankenanalyse mit dem integrierten ICLIPS-Modell unter Anwendung ausgewählter Klimawirkungsfunktionen für Veränderungen natürlicher Ökosysteme wird beschrieben. In dieser Analyse werden so genannte "notwendige Emissionskorridore" berechnet, die vorgegebene Beschränkungen hinsichtlich der maximal zulässigen globalen Vegetationsveränderungen und der regionalen Klimaschutzkosten berücksichtigen. Dies geschieht sowohl für eine "Standardkombination" der drei gewählten Kriterien als auch für deren systematische Variation.

Eine abschließende Diskussion aktueller Entwicklungen in der "Integrated Assessment"-Modellierung stellt diese Arbeit mit anderen einschlägigen Bemühungen in Beziehung.

Schlagwörter: Klimawandel, Klimafolgen, Integrierte Bewertung, Fensteransatz, Leitplankenansatz, Inversanalyse, Klimawirkungsfunktionen, Musterskalierung, ICLIPS

Contents

List of Figures

List of Tables

Abbreviations

The following abbreviations are used throughout the text:

AEM	ICLIPS Aggregated Economic Model
AGMT	Annual global mean temperature
AOGCM	Coupled atmosphere-ocean general circulation model
CBA	Cost-benefit analysis
CEA	Cost-effectiveness analysis
CIRF	Climate impact response function
DAF	Decision-analytical framework
EOF	Empirical orthogonal function
FAO	Food and Agriculture Organization
GAMS	General Algebraic Modelling System
GCM	General circulation model (also: global climate model)
GDP	Gross domestic product
GHG	Greenhouse gas
GMT	(Annual) global mean temperature
IA	Integrated assessment
IAM	Integrated assessment model of climate change
ICEM	ICLIPS Climate-Economy Model
ICLIPS	Integrated Assessment of Climate Protection Strategies
ICM	ICLIPS Climate Model
IPCC	Intergovernmental Panel on Climate Change
IRF	Impulse response function
SCM	Simple climate model
SRES	IPCC Special Report on Emissions Scenarios
THC	Thermohaline circulation
UNFCCC	United Nations Framework Convention on Climate Change

Acknowledgements

This thesis could not have been written without the support, in different ways, by many people.

First of all, I would like to thank my supervisor Hans-Joachim ('John') Schellnhuber for providing me with excellent working conditions and for many stimulating discussions that have considerably shaped my thinking about the climate change problem. I am deeply indebted to him and to Ferenc Tóth for their pioneering work in the development of the guardrail approach and for the guidance that they have provided to the ICLIPS project.

Martin Claußen and Joseph Alcamo were so kind to serve as evaluators of this thesis, despite their many other commitments.

Gerhard Petschel-Held and Richard Klein encouraged me to set aside time to complete this thesis and gave me the freedom to actually do so, which I highly appreciate.

My colleagues Thomas Bruckner, Elmar Kriegler, Till Kuhlbrodt, Jürgen Scheffran, Kirsten Zickfeld, and Jürgen Kropp commented on earlier versions of the manuscript and served as experienced guides through the labyrinth of the *Promotionsordnung*.

I am extending special thanks to Jelle van Minnen, Frank Kaspar, and Georg Hooss, former collaborators in the ICLIPS project, who will find some of their ideas, models, and data used in this thesis.

Last but not least, I am grateful to my family who have always supported me on my way. My nephew Simon, now enjoying the third month of his life on Earth, does not know me yet without the manuscript of this thesis in my hands.

Introduction

Anthropogenic climate change, caused primarily by the emission of radiatively active gases into the Earth's atmosphere, is associated with substantial risks to ecological and social systems worldwide that call for societal response strategies. The overall objective of climate-related policies is to limit the total burden associated with mitigation of climate change, adaptation to climate change, and residual climate impacts. In the wording of the United Nations Framework Convention on Climate Change (UNFCCC), policies are required *"that would prevent dangerous anthropogenic interference with the climate system"*.

Despite a strong consensus on the need for scientific support to the decision-making about climate policies, there are —sometimes heated— debates about the appropriate roles of the science community and the policy community in this process. For instance, scientists are sometimes confronted with the expectation (or desire) of stakeholders that they provide 'magic numbers' which would 'objectively' specify disputed policy objectives. Major issues for scientists in this context are the incorporation of contentious value judgements in scientific analyses, the handling and communication of uncertain knowledge and outright knowledge gaps in a way that 'best' supports the decision-making process, and the use of context-dependent information outside the context in which it was originally obtained.

Climate change is probably the most controversial, and possibly the most complex topic where 'science for policy' is confronted with these challenges. The need for a new approach to the dialogue between science and policy is reflected, for instance, in the establishment of the Intergovernmental Panel on Climate Change (IPCC). While the IPCC has helped enormously to build a common understanding of the nature and importance of the climate problem and of the need and potential for societal responses, many scientific issues are still the subject of intense debate, including in non-scientific communities.

Major challenges for the formulation and implementation of effective response strategies to the threats caused by anthropogenic climate change are the global nature of the problem (but with significant regional heterogeneity in its causes and impacts), the availability of fundamentally different response options, the large number of decision-makers working at different levels whose coherent action is required for an effective solution, the pervasiveness of the problem with high stakes involved, the large uncertainties about many important aspects, the large inertia of key systems, and the strong links of the climate change problem, and of possible solutions, to other areas of international politics.

Integrated assessment models of climate change (IAMs) are scientific tools that aim at analyzing pertinent questions of decision-makers involved in climate policy formulation. These models are simplified representations of the 'relevant' components of the coupled global society-climate system that also need to consider the characteristics of the decision situation. IAMs combine methods, models, and data from different disciplines of the natural and social sciences. Given the diversity of response options, pertinent decision-makers, and characteristic spatiotemporal scales, no single IAM can address all of them equally well. While there are promising attempts to build modularized IAMs that can flexibly address different stakeholder needs, the majority of IAMs currently in use has been built to address the (perceived) needs of a limited group of stakeholders with a rather well-defined portfolio of decision options. A key issue for most current IAMs is to assist in the specification of long-term targets and strategies for the mitigation of climate change, as demanded by the UNFCCC.

Applications of IAMs take place in a specific decision-analytical framework, which has important implications for, i.a., the handling of different kinds of uncertainties and the consideration of (necessarily subjective) value judgements. Decision frameworks traditionally applied in climate policy can be classified into predictive approaches (with roots in system dynamics) and optimizing approaches (with roots in optimal control theory). Since the modelling requirements for these two types of analysis are quite distinct, IAMs typically can only be applied in either predictive or optimizing mode but not in both. A third category of decision-analytical frameworks are the satisficing approaches, which were first applied to the climate change topic in the form of tolerable windows and safe landing analyses. The guardrail approach (or simply 'inverse approach') to climate change decision support provides a consistent theoretical framework for these ideas. Its fundamental idea is to identify the whole set of climate policies that are compatible with certain normatively defined minimum requirements. A characteristic of the guardrail approach is the clear-cut separation between scientific analysis (which includes a characterization of the prevailing uncertainties) and normative judgements (such as the monetary valuation of a human life in different countries).

The deterministic version of the guardrail approach has been implemented in the ICLIPS integrated assessment model. The representation of impacts in 'inverse' IAMs such as the ICLIPS model faces various challenges. On the one hand, guardrail analyses, analogous to optimizing approaches, need to consider the full range of policy options. This can only be achieved if the dynamics of the system is represented by highly efficient reduced-form models. On the other hand, the specification of guardrails by decision-makers requires a portfolio of impact indicators that are both policy-relevant and scientifically valid. The level of detail needed at this end is more typical of predictive models. These two opposing requirements have strong implications for the feasibility of certain spatial and temporal scales of analysis, for the ability of inverse IAMs to consider non-climatic developments and adaptation, for the possibility to handle uncertainties and, in consequence, for the type of climate impacts (or 'reasons for concern') that can be appropriately considered.

One category of impacts that are amenable for guardrail analyses are large-scale singular events whose fundamental behaviour can be represented by a reduced-form model driven by a limited set of external forcings. Such a model has recently been built for the thermohaline ocean circulation, and there are ongoing efforts to simulate the Asian monsoon in a similar way. In contrast, the work described in this thesis is concerned with 'regular' impacts that would occur even if climate change proceeded smoothly. These impacts are represented in the ICLIPS integrated assessment model by climate impact response functions together with algorithms that enable their integration with the other model components.

The core of this thesis is the development and application of the impacts module of the ICLIPS model. The technical description of this work is preceded and complemented by a discussion of the sociopolitical context for climate-related decision support (as outlined above), which determines the requirements for integrated assessment modelling of climate change in general, and for the representation of climate impacts in particular.

Not all parts of this thesis have the same proximity to the scientific discipline within which it is submitted for evaluation. The author regards the broad disciplinary background of the work described here as a necessary consequence of the specific requirements of policy-related science.

This thesis in the context of normal and post-normal science

The fundamental objective of 'normal' science is to seek for truth, whereby consistency with empirical evidence is the ultimate quality criterion. However, model-based projections of the future evolution of open complex non-linear systems (such as the Earth's climate system) can never be 'correct' or 'true' in a narrow sense of the word. Furthermore, full empirical validation becomes impossible if the investigation is concerned with the long-term evolution of a unique system (such as changes to the Earth's climate caused by anthropogenic influences).

Since neither the objective nor the quality criterion of 'normal' science are fully applicable to assessments of future climate change and its impacts, both of them need to be modified according to the quality criteria of 'post-normal' science. Each disciplinary component applied in a policy-related interdisciplinary assessment (e.g., a disciplinary sub-model) is still required to adhere to the quality criteria of the respective discipline. The selection and integration of these components, however, should be guided by their *appropriateness* and *relevance* rather than by an —ultimately unrealistic— strive for *truth*.

Obviously, there is no absolute evaluation criterion for the appropriateness of a specific approach in policy-related science and for the relevance of the results achieved. Both of them are contingent on the respective policy context, and the evaluation also needs to consider the viability of 'better' alternatives. Consequently, in a situation where the only realistic alternative would be to abstain from an assessment, conducting an imperfect scientific assessment is likely to be the preferable option if the main imperfections and their implications for the results are clearly stated.

Research questions

The research described in this thesis addresses the following questions:

- How can climate impact assessments respond to the different information needs of climate-related decision-makers, given the considerable scientific uncertainties about future climate change and its impacts?

- What are the key requirements for the representation of climate impacts in integrated assessment models based on an inverse framework, and what are the advantages and shortcomings of different approaches to do so?

- How can the high-dimensional domains of regionally specific future climate scenarios be projected onto a few independent dimensions, such that they can be efficiently explored in inverse analyses of climate change?

- How can the results of impact simulations be aggregated and visualized in order to identify those regions and systems which are particularly sensitive to global climate change?

- What are the implications of uncertainties in climate projections derived from different general circulation models for the simulated climate impacts?

- What is the relative importance of different normative constraints for the climate policy space?

- What are the implications of the results from inverse analyses of climate change for climate policy?

Background of this thesis

Most of the research covered in this thesis was undertaken within the ICLIPS (Integrated Assessment of Climate Protection Strategies) project, an international research project initiated and guided by the Potsdam Institute for Climate Impact Research. (For a comprehensive description of the ICLIPS project, see Toth, 2003a.) As a consequence, some of the ideas and results presented here were developed by a closely collaborating interdisciplinary team. Describing exclusively the author's own contributions would, at some places, have left the reader with a 'patchy' picture of the overall topic. In order to present a self-contained thesis, some sections contain text based on the work of colleagues in ICLIPS that is deemed relevant for motivating the author's own work. The evaluation of the author's individual contribution is enabled by an explicit statement at the beginning of each chapter on the sources of the work presented therein.

The pronoun *we* is used throughout the text for the sake of grammatical consistency rather than to indicate the number of persons that were involved in the development of certain ideas or results.

The main contributions of the author of this thesis are

- the development of a conceptual framework for climate impact and adaptation assessments, which provides a consistent description of the key concepts and their relationships, and its application to characterize the evolution of the assessment practice and of the underlying theory (Section 2.2);
- the application of a pattern scaling technique to develop climate scenarios for the ICLIPS impact assessment, including an evaluation of the suitability of this approach, and the further development of a method for combining simulated climate anomalies with historical climate data (Section 3.3);
- the conceptualization of climate impact response functions (Section 3.4);
- the development of a suite of impact indicators on the basis of (suitably adapted) existing impact models (Section 3.5);
- the specification of various types of impact diagrams, each of which provides a different view on the high-dimensional result space of the impact models (Section 3.6.2);
- the development of two algorithms for the approximation of admissible climate windows by parameterized constraints that enable the application of climate impact response functions in guardrail analyses with the integrated ICLIPS model (Section 3.6.4);
- the development of an algorithm for the calculation of reachable climate domains with the ICLIPS climate model (Section 3.6.5);
- the development of the ICLIPS Impacts Tool, a graphical user interface that provides access to the full set of climate impact response functions developed for the ICLIPS model (Section 3.7);
- the production of a comprehensive set of climate impact response functions for natural vegetation (Section 4.2) and agricultural crop production (Section 4.3); and
- the application of climate impact response functions in guardrail analyses with the integrated ICLIPS model (Section 4.5).

This thesis is accompanied by a CD-ROM that contains the ICLIPS Impacts Tool. While this software is not part of the formal evaluation of this thesis, it may be useful for exploring model results that are not covered in the text.

Road-map to the text

Chapter 1 provides an introduction into the problem of anthropogenic climate change. Section 1.1 describes selected aspects of the physics of climate change; Section 1.2 gives an overview of the different types of impacts potentially caused by climate change; and Section 1.3 presents the principal societal response mechanisms.

Chapter 2 is devoted to the integrated assessment of climate change focussing on those issues that are relevant for the representation of climate impacts in integrated assessment models; Section 2.1 provides an introduction to the topic; Section 2.2 reviews the evolution of climate change impact and adaptation assessments, Section 2.3 discusses the major decision-analytical frameworks that have been applied in model-based integrated assessments of climate change; and Section 2.4 presents the structure and the main features of the ICLIPS integrated assessment model.

Chapter 3 describes the development of the impacts module of the ICLIPS model. Section 3.1 reviews the representation of climate impacts in IAMs based on ‘traditional’ decision-analytical frameworks; Section 3.2 describes the requirements and principle options for impacts modelling in ‘inverse’ IAMs; Section 3.3 presents the implementation of the pattern scaling approach for projecting future climate change in the ICLIPS model; Section 3.4 introduces the concept of climate impact response functions (CIRFs), which is central to the consideration of climate impacts in the ICLIPS model; Section 3.5 presents the impact indicators covered by the CIRFs and the various impact models applied in their computation; Section 3.6 describes the application of CIRFs and the algorithms developed for the integration of CIRFs into the ICLIPS modelling framework; and Section 3.7 presents the ICLIPS Impacts Tool, a graphical user interface that provides convenient access to the large set of CIRFs developed for the ICLIPS model.

Chapter 4 presents and discusses selected results of the ICLIPS model. Section 4.1 shows reachable climate domains determined with the ICLIPS climate model; Sections 4.2, 4.3, and 4.4 present CIRFs for natural vegetation, agricultural crop production, and water availability; and Section 4.5 discusses results of a guardrail analysis with the integrated ICLIPS model that includes an application of CIRFs for natural vegetation.

Chapter 5 summarizes the work presented in this thesis, discusses possible approaches for further development, and connects the work presented here with related efforts in the integrated assessment of climate change.

Chapter 1

The climate change problem

This chapter gives an introduction to the problem of anthropogenic climate change. Its main purpose is to provide a background for the work presented in the subsequent chapters for those readers who are less familiar with the topic. Section 1.1 describes selected aspects of the physics of climate change, Section 1.2 gives an overview of the different types of impacts potentially caused by anthropogenic climate change, and Section 1.3 presents the principal societal response options.

> *Section 1.1 summarizes information on anthropogenic climate change from the first volume of the IPCC Third Assessment Report (Houghton et al., 2001) and from other cited references. Section 1.2 reviews various existing classification schemes for climate impacts. Section 1.3 presents a summary by the author of this thesis of the different societal response options to the climate change problem. This work has been presented in a much broader context in Füssel (2002a).*

1.1 Science of anthropogenic climate change

This section describes the main characteristics of the climate system, the anthropogenic influence on the climate system, and the observed and projected effects of that influence on climate.

1.1.1 The climate system

The *climate system* is the complex system comprised of five major components of the Earth: the atmosphere, the hydrosphere, the kryosphere, the land surface (including the pedosphere), and the biosphere (see Figure 1.1). These interrelated and open sub-systems are linked through the fluxes of mass, energy, and momentum at different spatiotemporal scales. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings. These forcings may have natural causes (such as volcanic eruptions and solar variations) or anthropogenic causes (such as changing atmospheric composition and land-use change). *Climate* is usually defined narrowly as the statistical description of weather in terms of the mean and variability of relevant quantities in a region over a certain period of time. *Weather*, in turn, is the fluctuating state of the atmosphere, characterized by variables such as temperature, precipitation, cloud cover, and wind. The classical climate period, as defined by the World Meteorological Organization (WMO), is 30 years. However, longer periods are necessary to

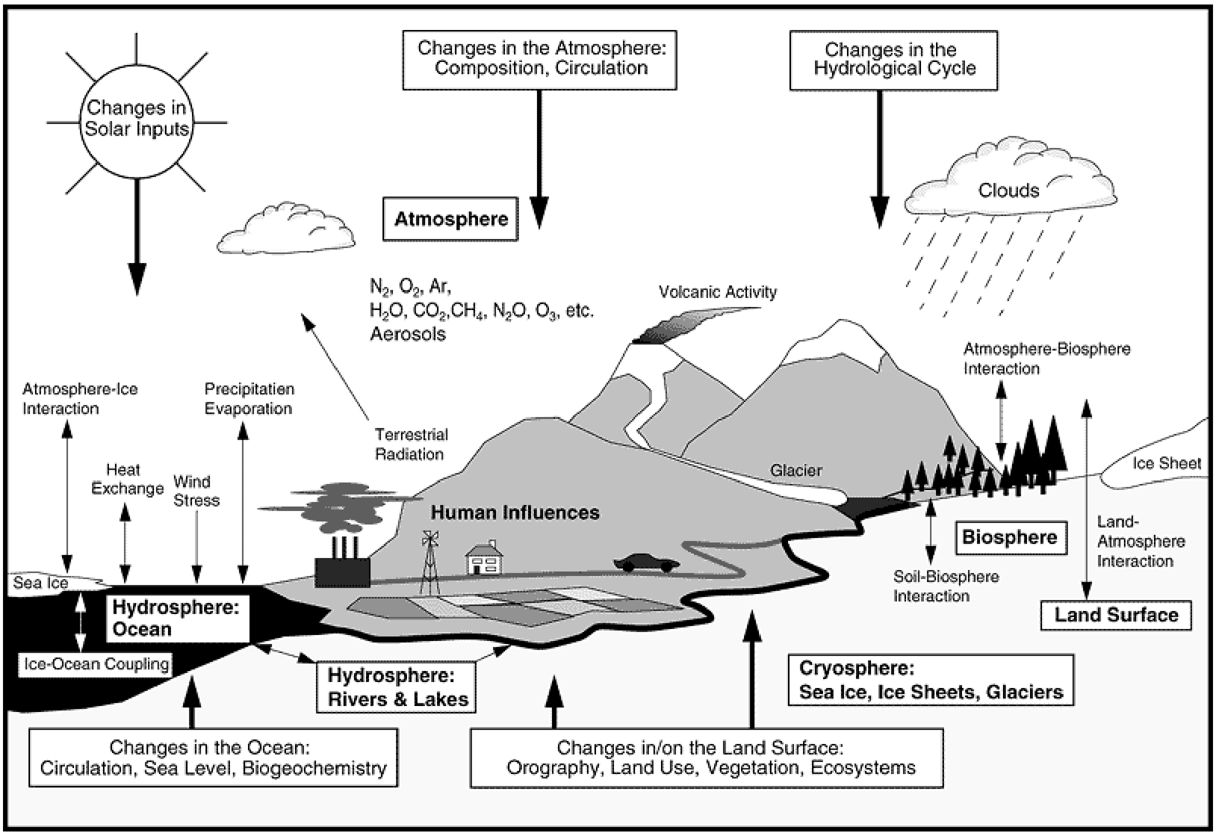


Figure 1.1: Schematic view of the components of the global climate system (bold), their processes and interactions (thin arrows), and some aspects that may change due to anthropogenic influence (bold arrows). Source: Baede et al. (2001)

identify some important climate features such as the distribution of 'extreme' weather events. Atmospheric climate is determined not only by atmospheric circulation but also by its interactions with the large-scale ocean currents and the land with its features such as albedo, vegetation, and soil moisture. A wider definition of climate thus refers to the state of the climate system as a whole, not just near-surface atmospheric conditions. Terrestrial climate varies spatially, depending on latitude, altitude, distance to the sea, land cover, orography, and other geographic features. Climate varies also on various temporal scales, even in the absence of external forcings ('internal climate variability').

Whilst the single most important factor determining the global climate is the level of solar irradiance at the tropopause, the radiative properties of the atmosphere and the surface are also influential. In particular, a number of trace gases in the atmosphere, such as water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3), affect the radiative balance by absorbing and emitting infrared radiation and/or short-wave radiation (see Figure 1.2). In the remainder of this text, we use the term (well-mixed) greenhouse gases (GHGs) to denote all these gases with the exception of water vapour. Even though the cumulative proportion of well-mixed GHGs in the atmosphere is below 0.1%, they significantly raise the temperature near the Earth's surface. Whilst the outgoing long-wave radiation of the atmosphere (235 Wm^{-2}) corresponds to an effective emission temperature of $-19\,^{\circ}C$,

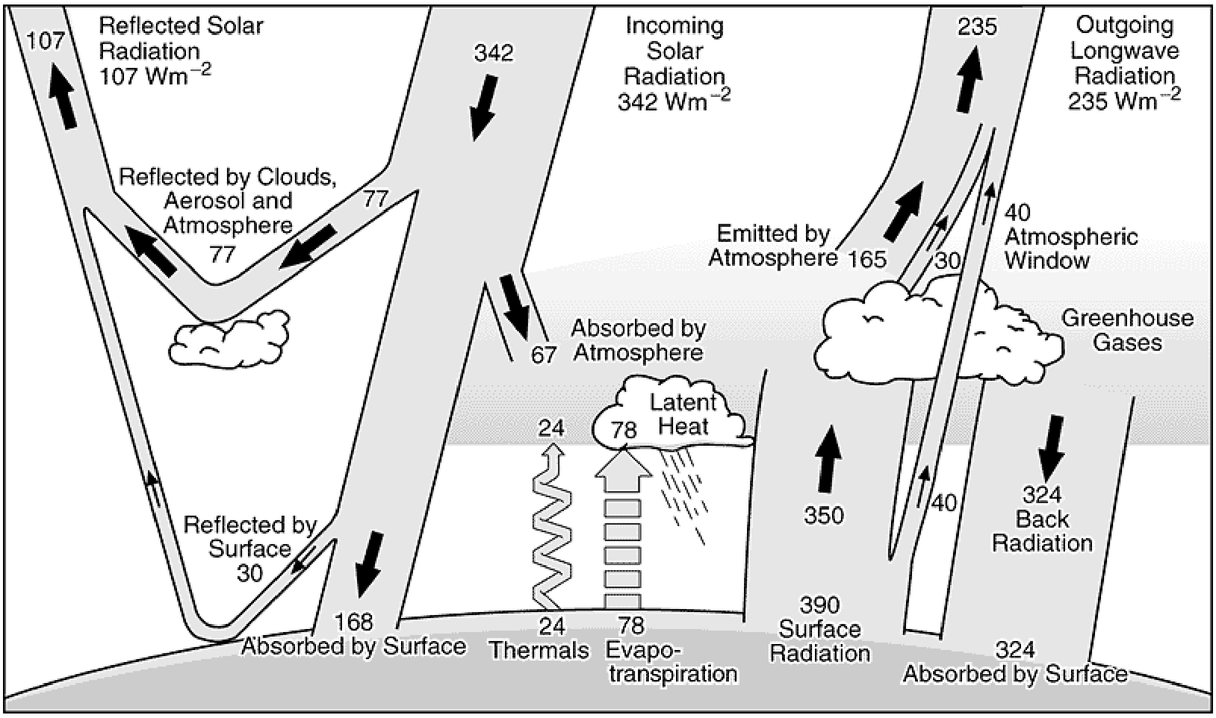


Figure 1.2: The Earth's global mean energy balance. Source: Baede et al. (2001)

the average temperature of the Earth surface is about $+14\,^{\circ}$Cdue to this *natural greenhouse effect*. The radiative balance of the atmosphere is also influenced in a complex way by various solid and liquid particles (aerosols), which exhibit significant spatial variability.

Any change in the components of the climate system or its interactions, or in the external forcing, may result in climate variations. This thesis is explicitly concerned with *anthropogenic climate change*, which is defined as a statistically meaningful variation in either the mean state of the climate or its variability, persisting for an extended period of time, which is caused by anthropogenic influences on the climate system. Climate impacts on ecological and social systems are determined by the 'total climate variability', which results from the interaction of natural climate variability and anthropogenic climate change. A separation of the natural and anthropogenic contribution is only possible on the basis of long time series, but not for specific weather events (including 'extreme' events). The distinction between these two factors of climate variability is nevertheless important because only the anthropogenically caused fraction is amenable to societal mitigation actions. The United Nations Framework Convention on Climate Change (UNFCCC; United Nations General Assembly, 1992) also restricts the term 'climate change' to that fraction of climate variability *"which is in addition to natural climate variability, and which is caused by human interference with the climate system"*, in particular by GHG emissions.

1.1.2 Anthropogenic influence on the climate system

Through the emissions of GHGs and aerosol precursors and through land use change, humankind has significantly modified the composition of the Earth's atmosphere since the industrial revolution (about

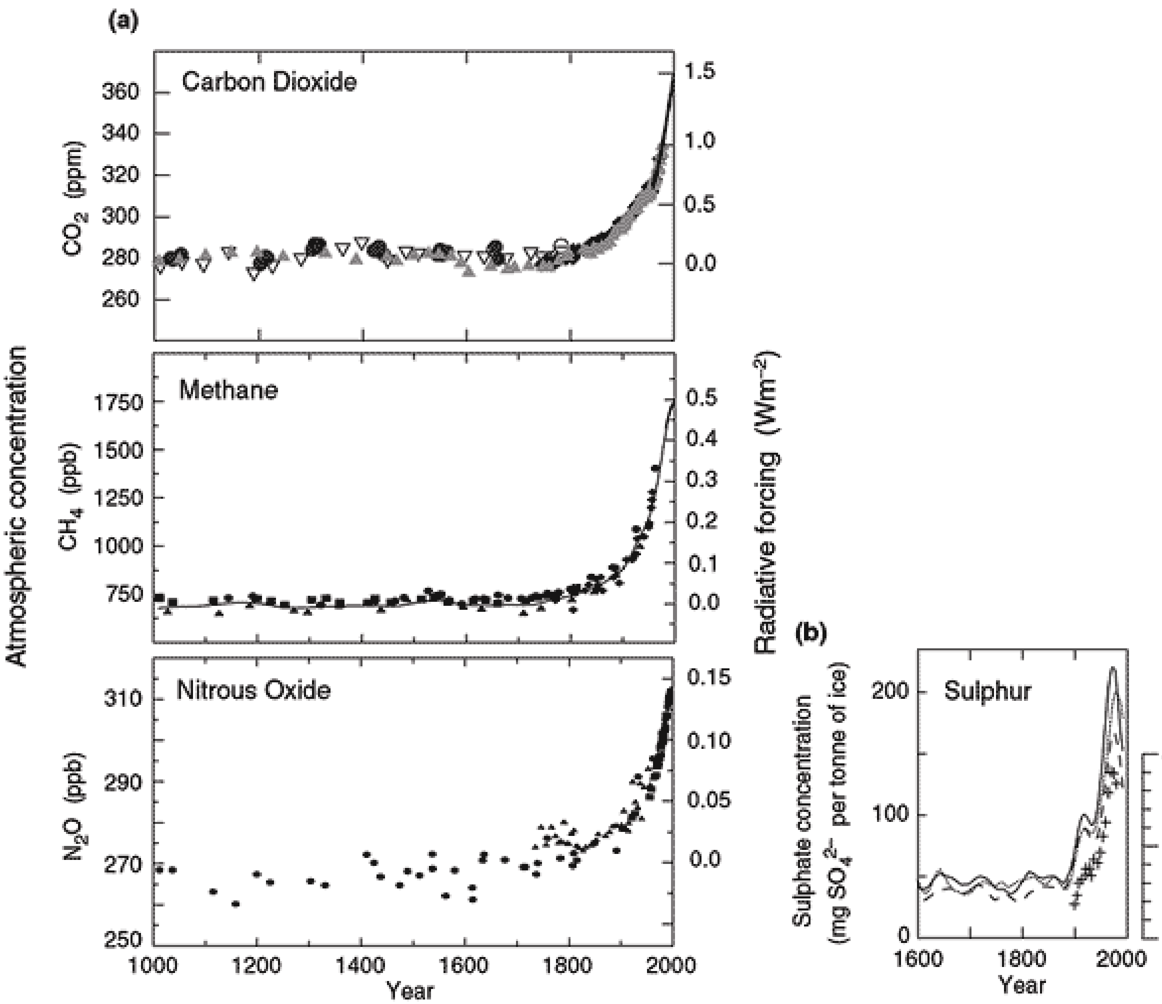


Figure 1.3: Records of changes in atmospheric composition. (a) Atmospheric concentrations of CO_2, CH_4, and N_2O over the past 1000 years. The estimated radiative forcing from these gases is indicated on the right-hand scale. (b) Sulphate concentration in several Greenland ice cores with the episodic effects of volcanic eruptions removed (lines) and total SO_2 emissions from sources in the US and Europe (crosses). Source: Albritton and Meira Filho (2001)

1750). Figure 1.3 shows the increase in atmospheric concentrations of the three most important well-mixed GHGs and of sulphate, the main precursor of anthropogenic aerosols, based on direct atmospheric measurements and on samples from ice cores and firn. The bulk of CO_2 emissions originates from fossil fuel burning. The rest is due to land-use change, especially deforestation, and cement production. CH_4 is emitted from natural gas activities, coal beds, landfills, and agriculture (rice paddies, ruminants). The main anthropogenic sources for N_2O are agriculture (nitrogen fertilizer, livestock), biomass burning, and industrial activities. Owing to their long atmospheric life-times (decades and longer), these GHGs are spatially well mixed. Aerosol precursors are emitted by fossil fuel and biomass burning. Their

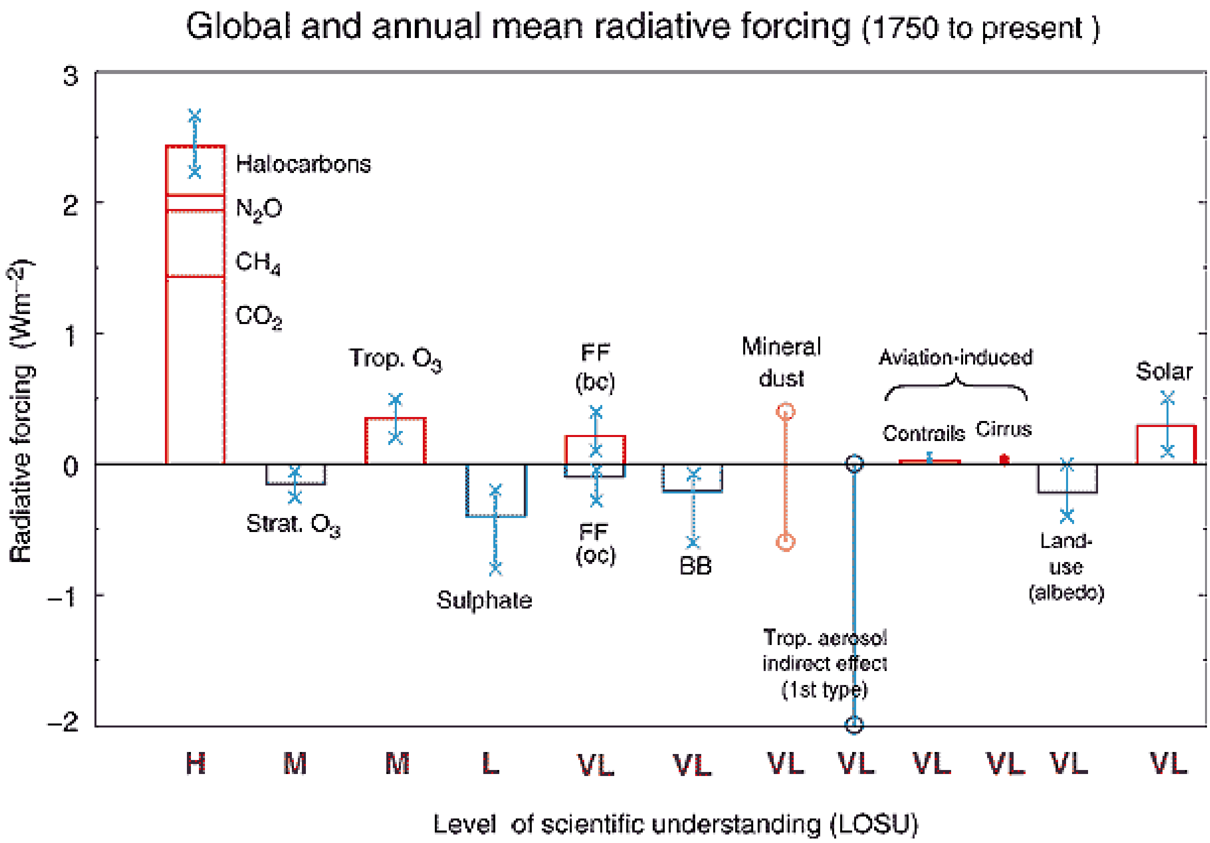


Figure 1.4: Global mean radiative forcings according to a number of agents for the period from pre-industrial to present (1750 to about 2000). The height of the rectangular bar denotes a central or best estimate value while its absence denotes no best estimate is possible. The vertical line about the rectangular bar with 'x' delimiters indicates an estimate of the uncertainty range. A vertical line without a rectangular bar and with 'o' delimiters denotes a forcing for which no central estimate can be given owing to large uncertainties. A 'level of scientific understanding' index is accorded to each forcing, with H, M, L, and VL denoting high, medium, low, and very low levels, respectively. Source: Ramaswamy et al. (2001)

much shorter atmospheric life-times (days to months) causes significant spatial (and temporal) variations whereby the highest concentrations are observed in the main industrialized regions of North America, Europe, and Southeast Asia.

The anthropogenic modification of atmospheric composition is associated with changes in in the radiative energy budget of the Earth's climate system denoted as *radiative forcing*. (For details on the radiative forcing concept, see Ramaswamy et al., 2001, Appendix 6.1.) Figure 1.4 summarizes the current knowledge about the anthropogenic influence on the Earth's radiative forcing. Two aspects deserve particular attention. First, the largest positive and best understood anthropogenic influence on radiative forcing are well-mixed GHGs, which account for an increased forcing of about 2.4 Wm^{-2}. Second, the potentially largest negative yet least understood factor is the indirect effect of tropospheric aerosols, whereby aerosols modify the microphysical and hence the radiative properties of clouds. The largely unknown size of the latter forcing (-2 to 0 Wm^{-2}) is a key source of uncertainty for the calibration of climate models. The sum of the individual bars in Figure 1.4 (except the last one) denotes the size of the anthropogenically *enhanced* greenhouse effect, which is in addition to the *natural* greenhouse effect. For comparison, the influence of solar irradiance change is indicated as well.

1.1.3 Observed response of the climate system

The proof that the climate system has already responded to the anthropogenic forcing requires two steps: first, the *detection* of climatic changes, and second, their *attribution* to anthropogenic perturbations, as opposed to internal climate variability or natural forcings. This section briefly summarizes the pertinent knowledge on these issues. Readers with particular interest in the detection and attribution problem are referred to the pertinent literature, as summarized in Folland et al. (2001) and Mitchell et al. (2001), respectively.

Climate was earlier defined as the statistical description of the whole climate system, or its atmospheric component. In practical terms, of course, only a limited amount of data about the climate system can be observed, processed, and thus be used for the detection of changes. Most statements about past and future climate change use the globally and annually averaged near-surface temperature (AGMT) as the primary proxy to describe the state of the global climate system. While the power of a scalar variable to describe a phenomenon as complex as global climate change is clearly limited, AGMT still represents the best available proxy in most contexts.

Figure 1.5.a depicts the variations of AGMT over the last 140 years. AGMT has increased over both the last 140 years and 100 years by $0.6 \pm 0.2\,^{\circ}$C, with an intermediate cooling period due to a masking of the GHG warming by 'cooling' aerosols. Figure 1.5.b extends this time series to the last millennium whereby geographical coverage is restricted to the Northern hemisphere due to limited data availability. The text notes that *"it is likely that the 1990s have been the warmest decade and 1998 the warmest year of the millennium"* (Houghton et al., 2001, p. 3). Other climatic changes observed during the 20th century that are consistent with model projections include a much stronger increase in night-time temperatures than in day-time temperatures, in winter and spring over summer and autumn temperatures, and in land surface over sea surface temperature. They also include significant precipitation changes that tend to increase the existing gradient between dry and wet regions, an accelerated rise in global average sea level, and wide-spread decreases in snow cover and ice extent. The noted changes in average climate characteristics are generally associated with substantial changes in the frequency and severity of 'extreme' climate events represented by the tails of the respective distribution.

Concerning the attribution of the observed changes, it is concluded in Mitchell et al. (2001) that 20th century climate was unusual, that the observed warming is inconsistent with estimates of internal climate variability, that the observed warming in the second half of the 20th century appears to be inconsistent with natural external forcing of the climate system, and that the vertical stratification of the observed warming is inconsistent with natural forcing whereas anthropogenic factors do provide an explanation of the 20th century temperature change. The knowledge is summarized as follows: *"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."* (Houghton et al., 2001, p. 10).

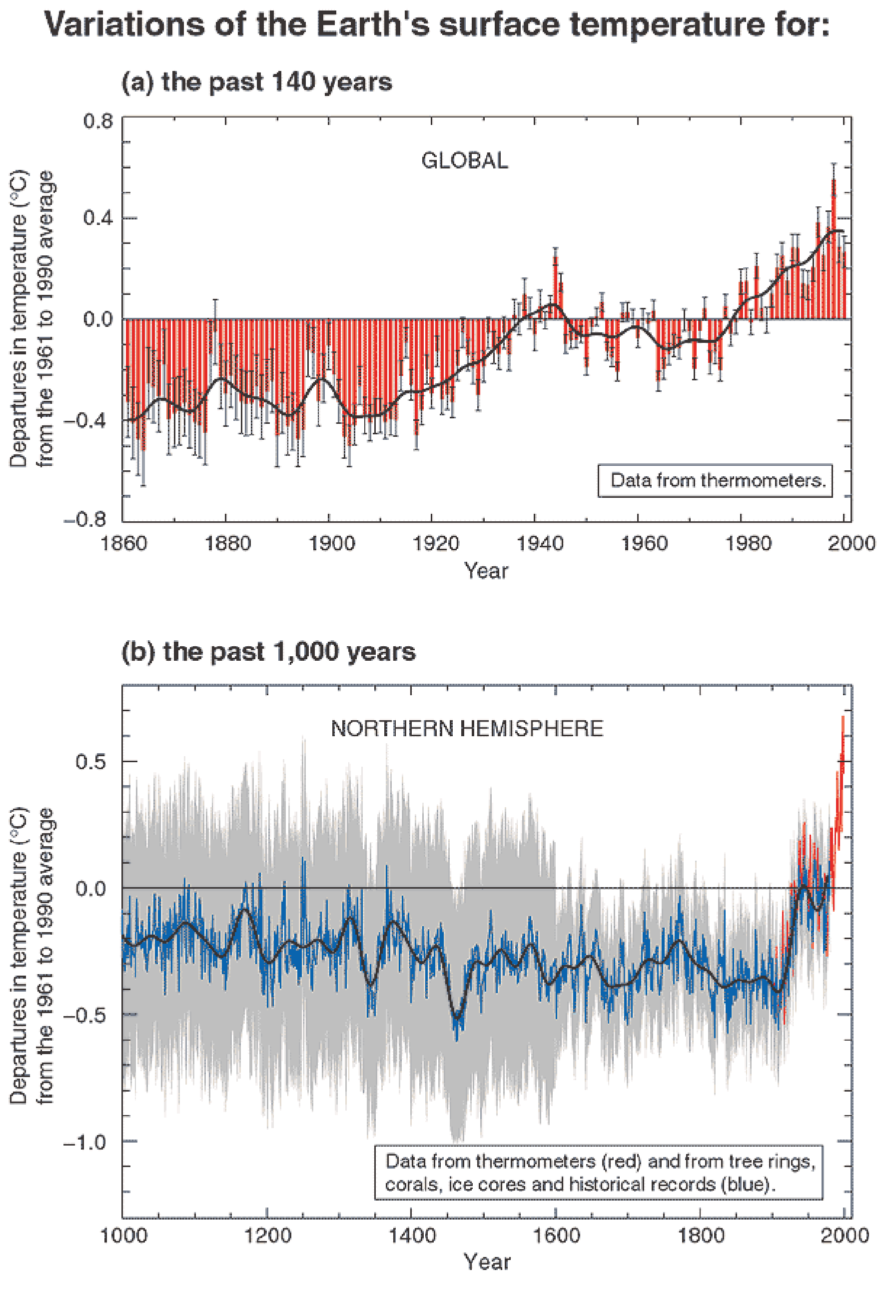


Figure 1.5: Variations of the Earth's surface temperature over the last 140 years and the last millennium. (a) The Earth's surface temperature is shown year by year (red bars) and approximately decade by decade (black line). Uncertainties in the annual data are represented by thin black whisker bars representing the 95% confidence range. (b) Additionally, the year by year (blue curve) and 50 year average (black curve) variations of the average surface temperature of the Northern Hemisphere for the past 1000 years have been reconstructed from 'proxy' data calibrated against thermometer data. The 95% confidence range in the annual data is represented by the grey region. Source: Houghton et al. (2001)

1.1.4 Projections of future climate change

This section briefly summarizes the available knowledge about future climate change. For a more detailed review, see Cubasch et al. (2001); Giorgi et al. (2001).

Projections of future climate change are based on simulations with numerical models, which are simplified mathematical representations of the Earth's climate system. A hierarchy of climate models is applied, which differ in their spatial and temporal resolution, their coverage of the various components of the climate system and their relationships, and the associated requirement for computing resources. At one end of the complexity spectrum, zero-dimensional energy-balance models ('simple climate models') are used to explore global temperature change in response to GHG emissions. These models are particularly useful for sensitivity analyses and in integrated assessment frameworks that require the evaluation of many different emission scenarios. At the other end, coupled atmosphere-ocean general circulation models (AOGCMs) simulate the global carbon cycle, the atmospheric chemistry of all relevant components of the atmosphere, and the horizontal and vertical fluxes of heat, mass, and momentum between many thousand atmospheric and oceanic grid boxes on time scales down to a few minutes. The abbreviation GCM traditionally stands for 'general circulation model'. However, it is now increasingly used to denote 'global climate model'. Some are spectral models and others use a fixed grid, but for convenience we will refer to the spatial element of any GCM as a 'grid box'. Other types of models are applied to estimate specific features of future climates. For instance, Earth system models of intermediate complexity may be used to understand important processes within the climate system, including their interactions and feedbacks, and to use this knowledge for simulations of future changes. All climate models are simplified representations of the actual climate system, which limit the accuracy and reliability of their projections. The primary trade-off to be considered in evaluations of their suitability in a specific context is the one between scientific detail and computational efficiency.

Projections of future climate change are always uncertain. The respective sources of uncertainty can be grouped into three broad categories.

Human choice: The freedom of human choice is the primary source of uncertainty about future GHG emissions in particular and about socioeconomic development in general. Many scenarios suggest steadily increasing GHG emissions during the 21st century and beyond. The IPCC has recently developed a number of future emission scenarios, denoted as SRES scenarios, that indicate the plausible range of future GHG emissions in the absence of an internationally coordinated climate policy (Nakicenovic and Swart, 2000).

Scientific uncertainty: Climate models used for investigating the effects of anthropogenic perturbations on climate are imperfect representations of the climate system. Limitations of these models include the need to parameterize sub-scale processes (i.e., processes that occur at spatiotemporal scales beyond the model resolution), a limited understanding of relevant processes, and insufficient calibration data.

System-inherent uncertainty: The long-term evolution of complex nonlinear systems, such as the climate system, is fundamentally unpredictable, even if the governing equations are perfectly deterministic. This unpredictability is obvious on the micro-level (i.e., for individual weather events). It may, however, extend to the macro-scale if the system evolves close to the boundary of two attractor basins. Despite these limitations, there is sufficient evidence to suggest that large-scale climate variations resulting from external forcings are at least partly predictable. This evidence includes the generally successful simulation of the climatic effects of forcing changes in the short-term (e.g., volcanic eruptions), in the mid-term (e.g., past anthropogenic GHG emissions), and in the long-term (e.g., changes in solar irradiance due to orbital changes).

Figure 1.6 shows the implications of the first two sources of uncertainty for changes in the mean climate. Figure 1.6.a depicts the anthropogenic emissions of CO_2, the single most important GHG, for the six "equally plausible" illustrative SRES emission scenarios. The other panels show the associated CO_2 emissions, CO_2 concentrations, anthropogenic SO_2 emissions, global mean temperature increase, and global mean sea level rise, respectively, as computed by a simple climate model tuned to various AOGCMs. The range of projected AGMT change between 1990 and 2100 for all SRES scenarios and all emulated AOGCMs is from 1.4 to 5.8 °C. For comparison, the AGMT difference between the last glacial maximum ($\sim 20,000$ years before present) and the present climate is around 5 °C(Folland et al., 2001). The uncertainty about future AGMT change is caused equally by differences between forcing scenarios and between climate models. The relative importance of scientific uncertainties is larger for most other climate parameters, such as regional climate changes, changes in precipitation and sea level, and changes in climate variability and extremes.

The response of the climate system to anthropogenic forcing includes the potential for 'rapid climate change', or 'large-scale climate singularities'. These terms are used to describe rapid large-scale changes in the climate system in response to gradual changes in its forcing. Singularities may result from a combination of the *nonlinearity* in functional relationships (e.g., the melting point of ice as a physical threshold in the climate system) and the *complexity* in the climate system, which gives rise to the possibility of positive feedback loops. Long-term observations as well as experimental studies indicate that smooth, or 'regular', behaviour is an exception rather than a rule in the dynamics of complex systems. Dansgaard-Oeschger oscillations (Dansgaard et al., 1993) as well as Heinrich events (Bond et al., 1992) are obvious examples of irregular behaviour of the climate system as a result of weak external forcing, which includes such 'unpleasant' features as hysteresis, irreversibility, and path dependence. Recently some important aspects of irregular climate change were successfully simulated with CLIMBER-2, a three-dimensional statistical-dynamical Earth system model of intermediate complexity (see, e.g., Claussen et al., 1999; Petoukhov et al., 2000). Since none of the simulations shown in Figure 1.6 includes the possibility of rapid climate change, these results do not cover the full range of uncertainties about future mean climate change.

Figure 1.7 shows the spatial patterns of projected changes in mean temperature and precipitation, and the reliability of these regional projections, for two forcing scenarios and two seasons. The spatial patterns of projected changes are largely consistent with the observed climate change during the 20$^{\text{th}}$ century. The confidence is greater for temperature than for precipitation projections, and it tends to be greater at higher latitudes than at lower latitudes.

Assessments of future changes in climate variability and extremes have been made possible only recently, primarily due to the increasing availability of comparable integrations with different GCMs and of ensemble integrations from single GCMs. For examples, see Kharin and Zwiers (2000); Räisänen and Palmer (2001); Milly et al. (2002). Changes in some aspects of climate variability are modelled consistently, such as increases in the frequency of extreme precipitation events across the globe. However, for many other 'extreme' phenomena, there is currently insufficient information to assess recent trends, and to make firm projections for the future.

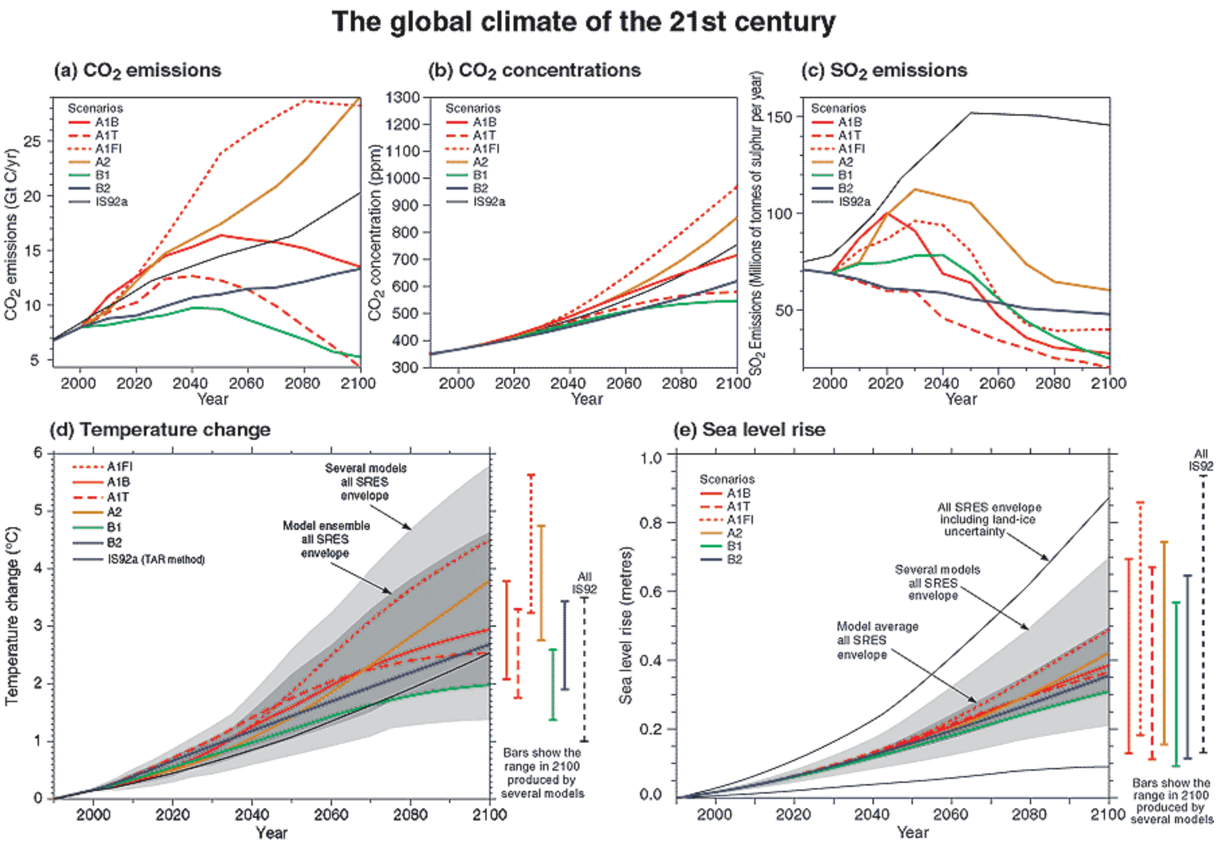
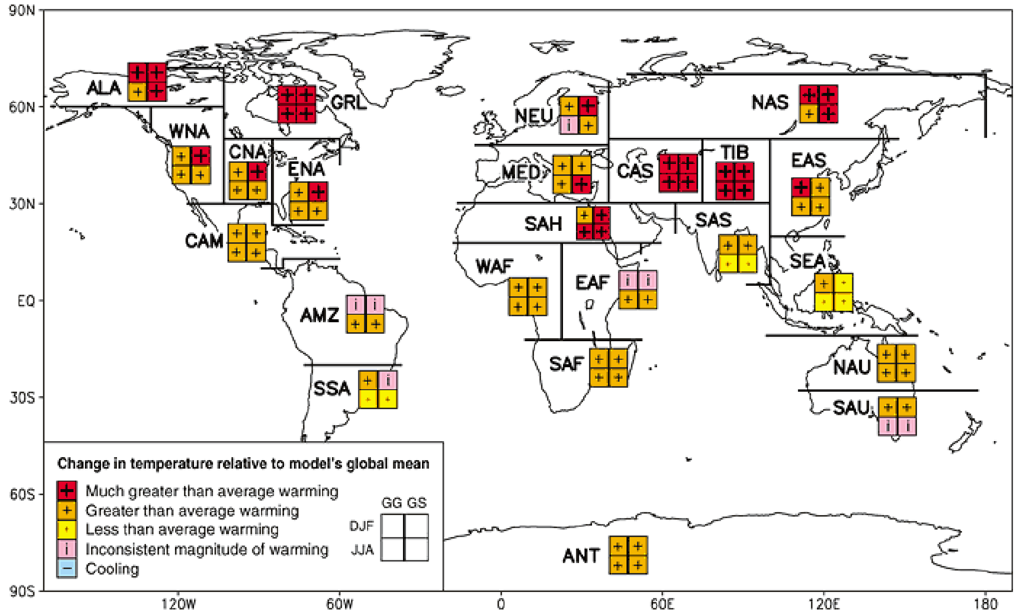
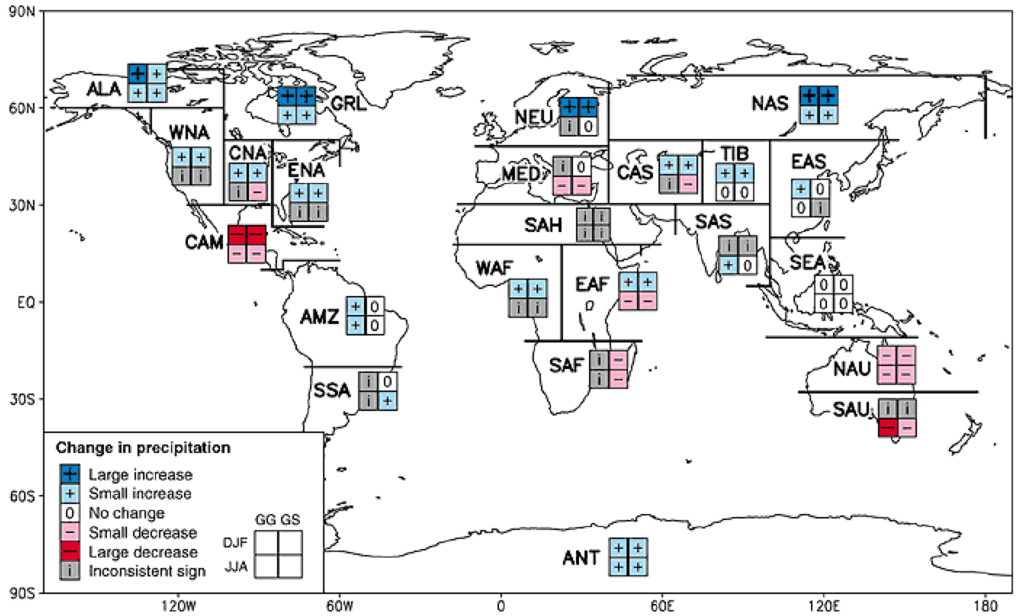


Figure 1.6: Global climate projections for the 21st century based on the six "illustrative" SRES emissions scenarios as computed by a simple climate model. (a) CO_2 emissions; (b) CO_2 concentrations; (c) anthropogenic SO_2 emissions; (d) temperature increase; (e) sea level rise (not allowing for uncertainty relating to ice dynamical changes in the West Antarctic ice sheet). The bars in (d) and (e) depict the range of results in 2100 for each of the six scenarios when the simple model is tuned to seven complex climate models (AOGCMs) with a range of climate sensitivities. The various shaded envelopes in (d) and (e) refer to the range of results for the full range of 35 SRES scenarios rather than the six 'illustrative' scenarios. The "Several models all SRES envelope" and the "Model ensemble/average all SRES envelope" show the results for the full range of scenarios for each of the seven model tunings and for their average, respectively. In (e), the former case is further split up according to the inclusion or not of land-ice uncertainty. Source: Houghton et al. (2001)

Model-based climate projections can be used to produce climate scenarios for investigating the impacts of anthropogenic climate change. Depending on the information needs of the impact assessment and the availability of pertinent models and data, a variety of methods is used to construct such climate scenarios, as illustrated in Figure 1.8 (see Mearns et al., 2001 for a review). These scenarios differ substantially in their coverage of different climate variables, in their temporal and spatial characteristics, and in the consideration of uncertainties. Some scenarios are restricted to deterministic projections of AGMT change from simple climate models, others focus on possible changes in current modes of interannual



(a)



(b)

Figure 1.7: Analysis of inter-model consistency in regional climate projections for two forcing scenarios and two seasons. GG is the greenhouse gas only case, and GS the greenhouse gas with sulphate case. In constructing the results, 'agreement' was defined as having at least four of the five GG models or three of the four GS models agreeing, whereby ensemble results were averaged into a single case. (a) Warming relative to each model's global warming; (b) precipitation change relative to baseline precipitation. Source: Giorgi et al. (2001)

climate variability such as the El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and still others use sophisticated downscaling methods to produce probabilistic projections of changes in several climate variables in a specific region.

Climate change projections may be scaled down to spatial scales below AOGCM grid size by using the AOGCM results as boundary conditions for nested regional climate models or as drivers for statistical downscaling models. A simpler method has been applied in many model-based climate impact assessments, including the ICLIPS model. Spatial patterns of climate anomalies derived from GCM experiments are scaled to the transient change in AGMT determined by a simple climate model and then superimposed onto the baseline climate. This 'pattern scaling' approach is shown in grey shading in Figure 1.8. Its application in the ICLIPS model is described in Section 3.3.

1.2 Impacts of climate change and reasons for concern

Many ecological and social systems are sensitive to the climatic variations associated with anthropogenic climate change. The most comprehensive review of the scientific knowledge on climate impacts is provided in the second volume of the IPCC Third Assessment Report (McCarthy et al., 2001). The changes in regional climate observed during the 20^{th} century have already been accompanied by widespread changes in a variety of systems, including hydrology, terrestrial and marine ecosystems, coastal zones, agriculture, fisheries, and human settlements. On the basis of hundreds of scientific studies, the IPCC concludes: *"The overall processes and patterns of observations reveal a widespread and coherent impact of 20th-century climate changes on many physical and biological systems"* (Smith et al., 2001, p. 927).

Assessments of climate impacts are a crucial source of information for the development of adequate societal response strategies. To facilitate the evaluation and aggregation of projected impacts, and the formulation of suitable responses, various classification schemes for categorizing climate impacts have been developed (Rothman et al., 2003). Many studies classify impacts according to the (economic) sector affected (such as agriculture, forestry, energy, water resources, health, tourism, etc.); a physical standpoint focusses on the affected system (atmosphere, aquatic systems, geologic systems, biological systems including humans, and built infrastructure); a productivist standpoint emphasizes the affected capital type (manufactured, human, social, and natural); and recent approaches emphasize the different (interlinked) constituents of human well-being (such as material welfare, health, social relations, security, freedom, and peace of mind).

In an effort to synthesize the current knowledge about climate impacts, and to structure the science-policy debate about objectives for international climate policy, Smith et al. (2001) distinguish five *"reasons for concern"* about climate change, which are meant as *"a way for readers to think about the seriousness of climate change impacts"*.

Risks to unique and threatened systems denote potential impacts on climate-sensitive systems confined to a narrow geographical range that can nevertheless affect other entities beyond their range, up to the global level. Examples include tropical glaciers, mangrove ecosystems, coral reefs and other biodiversity 'hot spots', and human settlements, in particular indigenous communities and the populations of low-lying small islands.

Aggregate damages refer to the overall economic or ecological implications of climate change at the global level, which may be denoted in monetary units or biophysical units. However, the spatial

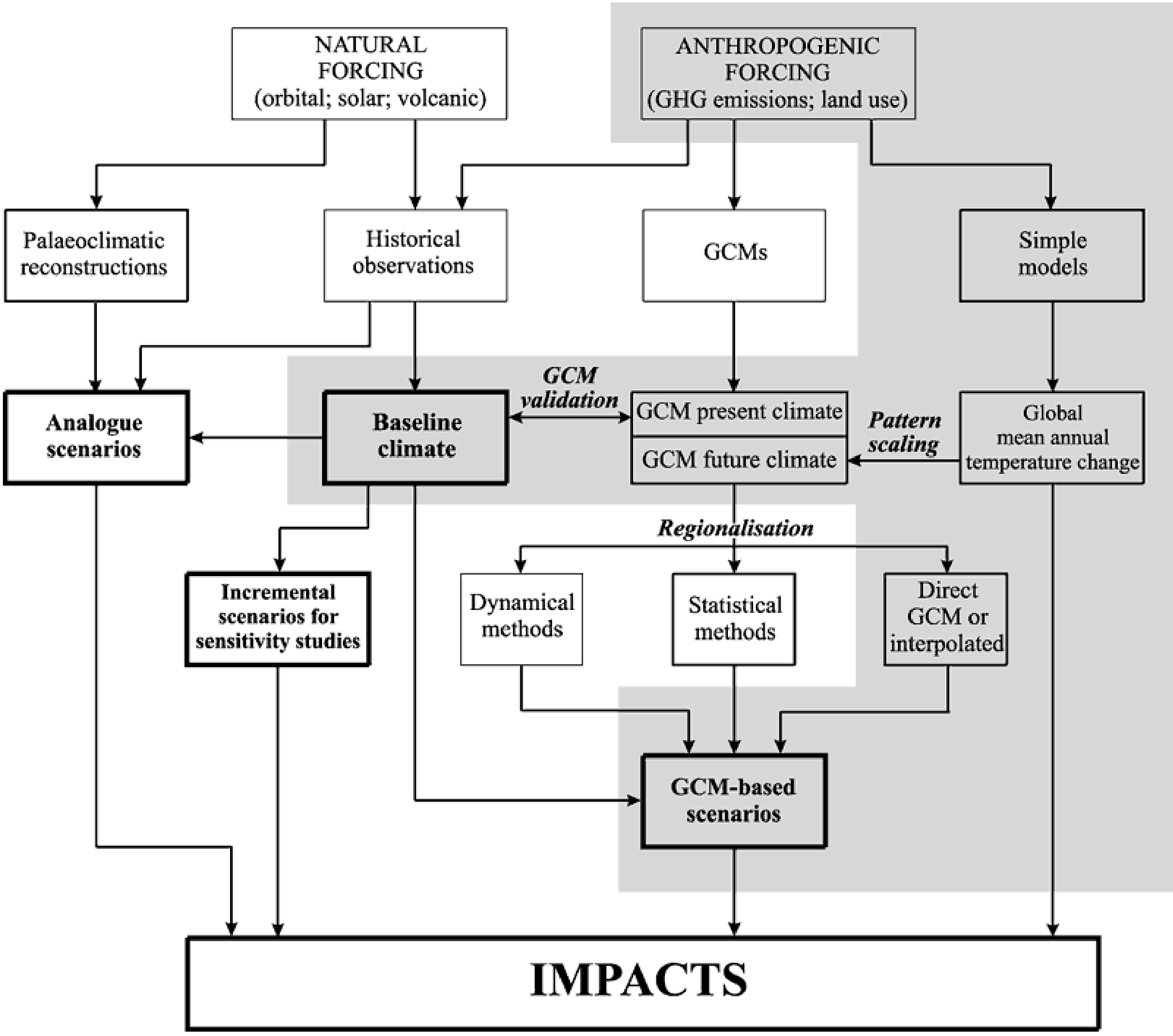


Figure 1.8: Some alternative data sources and procedures for constructing climate scenarios for use in impact assessment. Highlighted boxes indicate the baseline climate and common types of scenario. Grey shading encloses the typical components of climate scenario generators. Source: Mearns et al. (2001)

and temporal aggregation of impacts is generally not possible without value judgements. Noting that this category is usually interpreted from an economic, or at least anthropocentric, perspective, Leemans and Eickhout (2003) suggest to add an additional reason for concern, which relates to aggregated (regional and global-level) impacts on ecosystems.

The distribution of impacts refers to the heterogeneity of anticipated climate impacts across different regions and population groups. In particular, *"there is high confidence that developing countries will be more vulnerable to climate change than industrialized countries"* (Smith et al., 2001, p. 916).

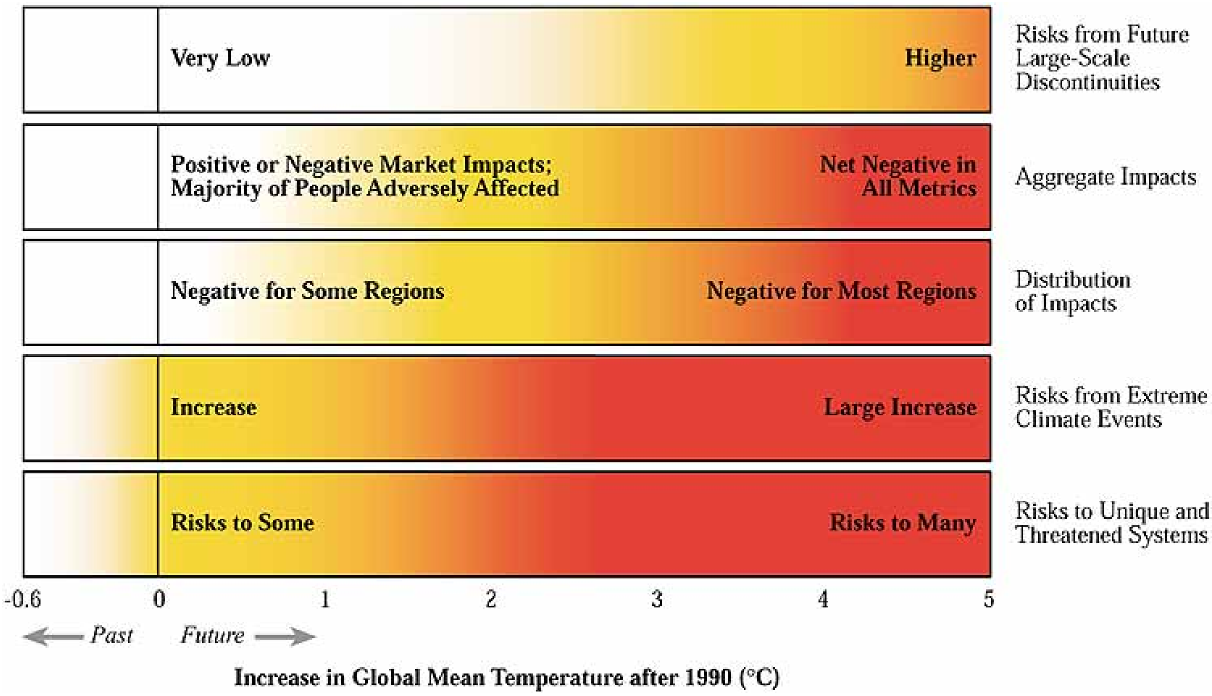


Figure 1.9: Impacts of or risks from climate change, by reason for concern. Each row corresponds to a reason for concern; shades correspond to severity of impact or risk. Global average temperatures in the 20th century increased by 0.6 °C and led to some impacts. Impacts are plotted against increases in global mean temperature after 1990. Source: Smith et al. (2001)

Risks associated with extreme weather events (e.g., floods, droughts, and storms) are likely to increase with climate change. Of course, the associated risks fall into one or more of the categories mentioned above. The reason for treating them separately is largely because these risks have been largely neglected in (quantitative) impact assessments, mostly due to a lack of suitable climate projections.

Risks of large-scale singular events denote the possibility that the global climate system may show singular responses to anthropogenic forcing, which could lead to rapid, large, and unexpected impacts on all spatial scales. The most ‘prominent’ large-scale singularities are a shutdown of the Noth Atlantic thermohaline circulation and a collapse of the West-Antarctic ice sheet, both of which have occurred in the past. The possibility of a run-away greenhouse effect due to a positive methane feedback (from thawing permafrost soils or destabilizing marine methane hydrates) falls into the same category. Any of these large-scale singularities would affect all other reasons for concern. In fact, most of them might well dominate impacts on unique and threatened systems, aggregate impacts, and distributional impacts, if they occurred. Since the low predictability of these events limits the potential for preventive adaptation, it is quite likely that large-scale singularities in the climate system would propagate as singularities along the causal cascade.

Figure 1.9 presents the synthesis of the IPCC impact assessment in a highly condensed form. Anticipated risks for each reason for concern are indicated qualitatively as a function of the change in global mean temperature (GMT). Among various possible indicators for climate change, GMT change was chosen as the most suitable one, taking into account the uncertainties along various parts of the cause-effect chain, the ability to consider transient as well as equilibrium impacts, and the dominating practice in the pertinent literature on climate impacts. Of course, the change in GMT cannot provide the full picture of anthropogenic climate change. It is also important to consider the rate of change, regional patterns of climate change, changes in other climate variables, and changes in higher moments of the distribution. Nevertheless, GMT change is a suitable proxy indicating the magnitude of many of these aspects.

An alternative yet related approach for structuring and quantifying the diverse risks associated with anthropogenic climate change was proposed by Jacoby (2003). That approach accounts for different scales, units, and degrees of aggregation by developing a portfolio of indicators, which consists of

1. global physical variables that can be analyzed in probabilistic terms, including the possibility of large-scale singularities,

2. impacts that can be measured at regional scale, preferably in natural units, and

3. exercises in monetary valuation of market and non-market impacts at the regional and global scale.

Schneider et al. (2000) classify climate impacts by suggesting “five numeraires” for climate impacts, which have become widely known as ‘Schneider metrics’. Parry et al. (2001), in contrast, use the number of people affected as the common denominator for a diverse range of climate impacts.

In this thesis, a comprehensive set of so-called climate impact response functions (CIRFs) is developed that represent the (simulated) relationship between key variables of global climate change on the one hand and selected indicators for global and regional impacts of climate change on the other hand. These CIRFs are then used by the ICLIPS climate-economy model to determine the set of climate protection strategies that are compatible with normatively defined ‘impact guardrails’. Figure 1.10 shows an exemplary CIRF that depicts the percentage of biomes worldwide that were simulated to become inviable across a range of changes in climate (indicated by global mean temperature) and CO_2 concentration. The purpose of showing this diagram is to provide the reader with a ‘picture’ of a CIRF that aids the understanding of the more technical discussion in later chapters. For a detailed explanation of this response surface and the methods used to determine it, the reader is referred to Chapter 3.

1.3 Societal response options

The substantial risks associated with anthropogenic climate change have motivated considerable interest in risk-reducing policies. The fundamental options for limiting the adverse impacts of anthropogenic climate change can be classified as follows:

Mitigation of climate change refers to confining global climate change by reducing the emissions of GHGs and/or enhancing their sinks.

Adaptation to climate change moderates the adverse effects of climate change through a wide range of actions that are targeted at the vulnerable system or population. The choice of a suitable adaptation strategy depends on the considered system and the types of climatic and non-climatic stressors that it is, or will be, exposed to.

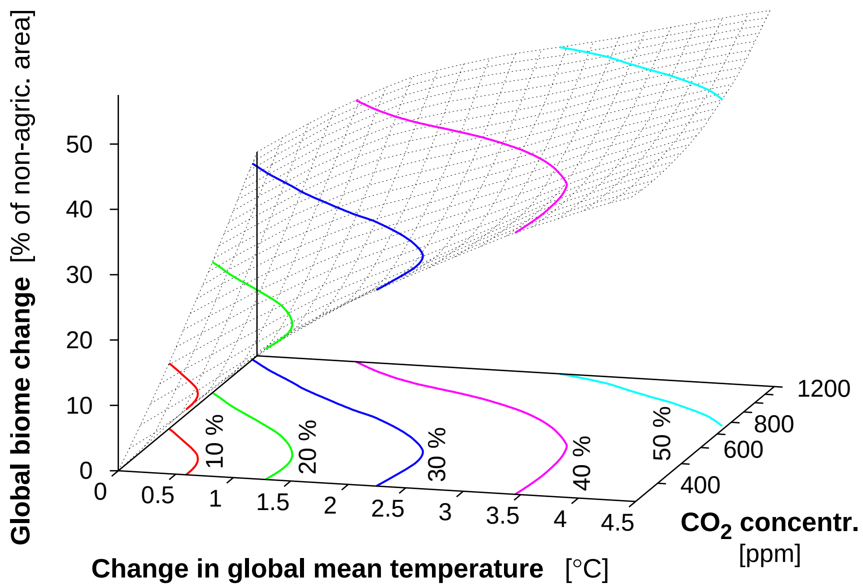


Figure 1.10: An illustrative climate impact response function showing the percentage of current biomes worldwide (on the vertical axis) that would become inviable across a range of changes in global climate and CO_2 concentration

	Mitigation of climate change	**Adaptation** to climate change
Target systems	All systems	Selected systems
Effectiveness	Certain	Less certain
Scale of effect	Global	Local to regional
Time until effect	Decades	Often immediate
Duration of effect	Centuries	Years to centuries
Secondary benefits	Sometimes	Often
Polluter pays?	Yes	Not necessarily
Monitoring	Relatively easy	More difficult

Table 1.1: Key characteristics of mitigation and adaptation

Information collection denotes measures that facilitate mitigation and/or adaptation by improving the pertinent information base. These measures include basic and applied scientific research, policy analysis, and efforts to improve data collection and exchange.

Key characteristics of mitigation and adaptation are summarized in Table 1.1. Mitigation has traditionally received much greater attention than adaptation in the climate change community, both from a scientific and from a policy perspective. Important reasons for the focus on mitigation are, first of all, that mitigating climate change helps to reduce impacts on all climate-sensitive systems whereas the potential of adaptation measures varies substantially across different systems and communities. It is, for instance, difficult to conceive how the population of Pacific coral atolls could ‘successfully’ adapt to substantial levels of sea-level rise. Second, reducing GHG emissions applies the polluter-pays principle whereas the need for adaptation measures will be greatest in developing countries whose historical contribution to anthropogenic climate change has been rather limited. Third, GHG emission reductions are relatively easy to monitor quantitatively, both in terms of their absolute amount and as deviation from an established baseline. It is much more difficult to measure the effectiveness of adaptation in terms of avoided impacts, or to ensure that international assistance to facilitate adaptation would be fully additional to existing development aid budgets.

In spite of the need for mitigation there are also convincing arguments for a more comprehensive consideration of adaptation as a response measure to climate change. First of all, given the amount of past GHG emissions and the inertia of the climate system, the Earth is already bound to some degree of climate change that can no longer be prevented even by the most ambitious emission reductions. Second, emission reductions take several decades to become fully effective whereas most adaptation measures have immediate benefits. Third, adaptations can be implemented on a local or regional scale, which makes them less dependent on the actions of others. Fourth, most adaptations to climate change also reduces the risks associated with current climate variability, which already constitute a significant threat in many regions now.

Anthropogenic climate change is an inherently global problem, which calls for a globally coordinated response. The UNFCCC and the Kyoto Protocol provide the legal framework for climate policy at the international level. The UNFCCC, which came into force in 1994, provides a framework for mitigation and adaptation actions, it imposes reporting requirements on all countries, and it establishes regular Conferences of the Parties. However, legally binding quantified mitigation objectives were only introduced in the Kyoto Protocol to the UNFCCC. The Kyoto Protocol was agreed in 1997 but its coming into force is still contingent on ratification by either the USA or the Russian Federation.

The work presented in this thesis is concerned with the development of integrated assessment models of climate change that focus on an operationalization of the objective of the UNFCCC, as specified in its Article 2:

> *“The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”*
> (United Nations General Assembly, 1992)

A few things are worth noting here. First, stabilization of atmospheric concentrations eventually requires very low net emissions of CO_2 (which does not have an atmospheric sink) yet allows for non-zero emissions of CH_4 and N_2O (which have an atmospheric sink). Second, the operationalization of this rather vaguely defined objective depends crucially on information from a wide range of climate change assessments. The classification of climate impacts into five reasons for concern (see Section 1.2) has been developed explicitly to provide a suitable framework for structuring the pertinent knowledge. Third, there is a consensus that any decision about what would constitute “dangerous anthropogenic interference with the climate system”, and which risk of failing to prevent a dangerous interference might be accepted, represents ultimately a value judgement that has to be made by the responsible political decision-makers in the presence of large uncertainties (Watson and the Core Writing Team, 2001). Thus, scientists can neither define whether a specific impact (or set of impacts) of climate change is ‘dangerous’, nor can they forecast with certainty at which level of climate change, or greenhouse gas concentrations, a specific impact would occur. Several decision-analytical frameworks for the interaction between the scientific and decision-making communities in the formulation of climate policies are explored in Section 2.3. For a detailed discussion of the scientific, economic, legal, and ethical aspects that are relevant for specifying long-term goals for climate policy consistent with the objective of the UNFCCC, the reader is referred, e.g., to Schröder et al. (2002).

Chapter 2

Integrated assessment of climate change

The term 'integrated assessment of climate change' denotes a broad range of efforts in which scientific knowledge from different disciplines, often combined with other types of knowledge, is applied to provide policy-relevant information for climate change decision-making. This chapter discusses selected aspects of the topic that are relevant for the representation of climate impacts in integrated assessment models. Section 2.1 gives an introduction to integrated assessment in general, and to its application in the climate change context. Section 2.2 reviews the evolution of climate change impact and adaptation assessments and presents a conceptual framework for structuring the different types of assessments. Section 2.3 reviews the major decision-analytical frameworks that have been applied in model-based integrated assessments of climate change. The guardrail approach to climate change decision support is described in some detail, including its mathematical foundations. Section 2.4 concludes this chapter with a presentation of the ICLIPS integrated assessment model (except the impacts module, which is described in detail in Chapter 3).

Section 2.1 is a review of key issues for the integrated assessment of climate change by the author of this thesis. Section 2.2 summarizes work by the author of this thesis from Füssel and Klein (2002a,b); Füssel (2002a). Section 2.3 presents the author's review of decision-analytic frameworks, which is largely based on publications of several members from the ICLIPS group (Toth and Mwandosya, 2001; Toth et al., 1997; Bruckner et al., 1999; Petschel-Held et al., 1999; Bruckner et al., 2003b; Kleinen et al., 2003) with minor contributions from the author. Section 2.4 on the ICLIPS integrated assessment model presents work from the ICLIPS group (Bruckner et al., 1999, 2003b; Toth et al., 2002, 2003a) with major contributions from the author.

2.1 Introduction

The overall objective of climate-related policies is to limit the total burden associated with mitigation of climate change, adaptation to climate change, and residual climate impacts. This general objective is taken up in the UNFCCC, whereby the focus lies on mitigation policies ("stabilization of greenhouse gas concentrations") and on the application of the 'polluter pays' principle ("common but differentiated responsibilities"). The implementation of the UNFCCC in general, and of its ultimate objective in particular, poses many intricate questions to science and international policymaking alike. Tackling these questions requires a problem-oriented transdisciplinary approach in a way that is generally described as 'integrated assessment' (IA). Rothman and Robinson (1997) describe IA as *"an attempt to provide a broad evaluation of impacts, costs, benefits and response options associated with multiple aspects of particular environmental issues"*. IA is distinguished from more traditional disciplinary science by two aspects: *"For a study to be integrated, it must reach beyond the bounds of a single discipline and consider more than [...] one aspect of the problem under consideration"*. The *assessment* dimension of IA is reflected in the purpose of IA *"to inform policy and decision-making, rather than to advance knowledge for its intrinsic value"* (Weyant et al., 1996).

IA has been developed to provide policy-relevant information about complex environmental problems. Hence, most IAs address strongly linked, complex, adaptive human-environment systems. The purpose of IAMs is not to forecast the future but to optimize current decisions. Therefore, the normative evaluation of facts and uncertainties generally plays an important role, and the relevance of certain aspects of the problem depends strongly on the (perceptions of the) respective decision-maker(s). Policy-related assessments are alternatively characterized as "mandated", "vernacular", "civic", and "post-normal" science (Funtowicz and Ravetz, 1992). Saloranta (2001) has shown that climate change science around the IPCC can, to a relatively large extent, be characterized as "post-normal".

Transdisciplinary assessments of the climate problem involve the crossing of various frontiers, in particular those between natural and social sciences, between descriptive and normative disciplines, between descriptive and normative aspects *within* disciplines, and between scientific and non-scientific knowledge (Schröder et al., 2002). However, actual assessments vary significantly in their use of 'non-scientific' and qualitative knowledge, and in the emphasis put on uncertainties and the complex rationality of the decision-making process.

IA applies a variety of tools and techniques, such as mathematical simulation models, expert panels, social discourses, simulation/policy exercises, and collaborative interdisciplinary research teams. Owing to the complexity of the problem, the long time horizon, and the global scope, IAs of climate change are dominated by the application of computer-based models.

Integrated assessment models of climate change (IAMs) are scientific tools that seek to provide advice to policy-makers involved in the decision-making process by providing a coherent synthesis of important aspects of climate change. They assemble knowledge from different disciplines to analyze the complex interdependencies between economic development, greenhouse gas emissions, climate change and its impact on various climate-sensitive systems. Depending on the particular model, the disciplines involved may include climatology, chemistry, ecology, agricultural science, epidemiology, risk analysis, economics, social geography, law, political science, game theory, ethics, and others. IAMs are exemplars of the "digital-mimicry principle", which is one of the key constituents of the "second Copernican revolution", a term suggested by Schellnhuber (1999) to denote recent scientific attempts *"to understand the 'Earth system' as a whole and to develop, on this cognitive basis, concepts for global environmental management"*.

Mathematical models are particularly useful to analyze the effects of system interactions and feedback mechanisms, and to provide indications of the potential range and magnitude of global climate change and of the scale of the interventions that are necessary to prevent or mitigate specific impacts. Limitations of formal models are an 'exclusionary bias' (i.e., a strong bias in favour of quantifiable information) and a bias of 'misplaced correctness' (i.e., the inadequate communication and use of uncertain or value-laden model results). In response to these problems, Funtowicz and Ravetz (1990) have developed the NUSAP (numeral, unit, spread, assessment, pedigree) system to describe qualitative and quantitative uncertainties in information that is relevant for policy-making. This scheme has recently been applied for the first time to a component of a complex IAM (van der Sluijs et al., 2002). It should be noted that the integration of disciplinary models into a transdisciplinary model introduces the possibility of 'new' errors, in addition to the shortcomings of individual model components, due to wrong coupling (such as incompatible spatial scales of climate and impact models) and to the omission of important components.

Major challenges for model-based IAs of climate change are:

- to determine which processes are important, and at which level of detail, to provide results that are relevant for particular policy problems;
- to account for different types of uncertainty, including the possibility of low-probability but potentially catastrophic events;
- to combine pertinent knowledge from different disciplines and sources, including qualitative and semi-quantitative knowledge;
- to account for relevant interactions across regions, sectors, and spatiotemporal scales;
- to account for non-climatic developments and the indeterminacy associated with them;
- to adequately consider autonomous and purposeful adaptive responses to climate change;
- to consider the scope of validity and the assumptions made in disciplinary sub-models, and to make explicit what is not included in a particular model and/or analysis; and
- to account for the sociopolitical context in which decisions will be made, and actions will be implemented, including the importance of subjective normative evaluations for decision-making.

There is now a considerable body of literature on the implications of these challenges for 'good' IA. In two landmark papers on integrated assessment modelling of climate change, Morgan and Dowlatabadi (1996) and Schneider (1997) provide checklists of issues and practices IA modellers should keep in mind that are still valid and relevant. For other contributions to this topic, see, e.g., Parson (1996); Risbey et al. (1996); Schellnhuber and Yohe (1997); Rotmans and Dowlatabadi (1998); Morgan et al. (1999); Schröder et al. (2002). Some aspects of the discussion about 'good IA' will be resumed in Chapter 5, when the work presented in this thesis is discussed in the context of other IA efforts.

Finally, it is important to note that not only the challenges of transdisciplinary, policy-oriented IA differ from those of traditional disciplinary scientific endeavours but also the evaluation criteria for 'good' assessments (Funtowicz and Ravetz, 1992; Schröder et al., 2002). A key criterion in IA is the *relevance* of (principally unavoidable) simplifications, which strongly depends on the decision context of the assessment. Since theoretical correctness is often not achievable, the integration of various disciplinary submodules in an IAM should rather strive for *pragmatic compatibility*.

2.2 Impact, vulnerability, and adaptation assessments

The last two decades have witnessed extensive research on potential and observed impacts of climate change on all kinds of natural and social systems, as reviewed in McCarthy et al. (2001). The ultimate

Assessment	Year	WG I	WG II	WG III
First	1990	Science	Impacts	Response Strategies
Second	1995	Science	Impacts, Adaptations, and Mitigation (Scientific-Technical Analyses)	Economic and Social Dimensions
Third	2001	Science	Impacts, Adaptations, and Vulnerability	Mitigation

Table 2.1: Scope of the IPCC working groups in the major IPCC assessments

goal of this research is to support the formulation and implementation of policies that limit adverse impacts of anthropogenic climate change through mitigation of climate change and adaptation to climate change.

Climate impact and adaptation assessments are closely linked. On the one hand, standard impact assessments provide indispensable information for adaptation assessments and adaptation policy about expected (biophysical) impacts of climate change. On the other hand, any comprehensive impact assessment needs to consider the potential for and expected effectiveness of feasible adaptations. In the context of climate change, the term 'vulnerability assessment' is often used to distinguish impact *cum* adaptation assessments from earlier impact assessments that did not consider adaptation. The outcomes of vulnerability assessments inform the specification of short-term needs for adaptation (e.g., by identifying unavoidable climate impacts) and the specification of long-term goals for mitigation (e.g., by identifying 'limits to adaptation' that cannot reasonably be overcome).

This section sketches the evolution of climate change assessments. We start with a brief review of the evolution of the assessment practice, which is followed by a presentation of key concepts and terms in vulnerability assessment. We then present a four-stage conceptual framework for climate change assessments that explains the relationship between key concepts for climate change assessments and reflects the historical evolution of climate change assessments. The discussion in this section provides the background for the development of the ICLIPS impacts module, which is described in Chapter 3.

2.2.1 Evolution of the assessment practice

The term 'climate change vulnerability assessment' is used for a wide range of assessments. However, certain trends can be observed in the assessment practice. The detection of these trends is facilitated by the exceptional circumstance that the complete body of scientific knowledge on climate change, associated impacts, and potential response mechanisms is regularly synthesized by the IPCC. The IPCC has produced three comprehensive assessment reports so far, whereby the three working groups of the IPCC contribute one volume each to these reports. Some important developments in the field of climate change assessments can already be derived from changes in the structure of these working groups (WGs), as shown in Table 2.1.

Since the inception of the IPCC, its WG II has focussed on the impacts of projected climate change. In the First Assessment, climate impacts were exclusively addressed by WG II, with a clear focus on potential biophysical impacts. In the preparation of the Second Assessment, the need for an assessment of the economic and social dimensions of climate change was clearly recognized. The scientific-technical analysis of impacts, adaptation, and mitigation was assigned again to WG II, whereas WG III focussed on the economic and social dimensions. Despite the explicit integration of socioeconomic aspects into the IPCC assessment, WG II and WG III were still partitioned along disciplinary boundaries. For the Third Assessment, the WGs were rearranged in a problem-oriented manner rather than by disciplinary tradition. WG II assessed the environmental, social, and economic dimensions of climate impacts, the vulnerability to climate change across systems, sectors, and regions, as well as potential adaptations to reduce adverse impacts. WG III addressed the technical and economic dimensions of mitigation actions, which can be analyzed largely independent of adaptation.

The preface of the WG II contribution to the IPCC Third Assessment Report highlights various differences compared to earlier WG II assessments (McCarthy et al., 2001, p. ix):

- efforts to address a number of cross-cutting issues, such as sustainable development, equity, and scientific uncertainties;
- the emergence of changes in climate extremes and in climate variability as key determinants of future impacts and vulnerability;
- increasing emphasis on the many interactions of climate change with other stresses on the environment and human populations; and
- the expanded analysis on the value of adaptation measures to diminish the risk of damage from future climate change and from present climate variability alike.

Summarizing the development of vulnerability assessments presented in the IPCC reports, a clear trend is observed towards interdisciplinary assessments of the potential consequences of climate change; towards the integration of impact and adaptation assessments; and towards the integration of climate change with other stresses and concerns.

These trends are in agreement with the development of the political, legal, and financial provisions for vulnerability assessment under the UNFCCC. The role of the UNFCCC for framing vulnerability assessments is two-fold. First, it has established a framework for conducting and financing vulnerability assessments in developing countries. This framework is clearly influenced by the special needs of developing countries, many of which have insufficient capabilities to cope with current climate variability, and whose urgent present needs typically cause decision-makers to adopt a shorter planning horizon than in developed countries. Second, the UNFCCC serves to highlight key issues of the international policy community that are likely to influence the funding practice of other public entities. For a more detailed analysis of the UNFCCC and the decisions of its Conference of the Parties as to their relevance for the conceptualization and practice of vulnerability assessment, see Füssel (2002a).

2.2.2 A generic framework for vulnerability assessment

The climate change community, in large part because of its intensive co-operation within the IPCC, is developing a common terminology, although definitions are still being debated. In this section, we define a number of terms that are important in the context of climate change assessments, noting that some of them are used differently in other scientific communities. For reference, we quote various definitions from the latest IPCC glossary (Houghton et al., 2001; McCarthy et al., 2001) in separate, indented paragraphs.

(Climate) impact assessment: *The practice of identifying and evaluating the detrimental and beneficial consequences of climate change on natural and human systems.*

Adaptation assessment: *The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.*

In the absence of a consensus definition, we use the term *climate change vulnerability assessment* rather broadly for *"any assessment of how projected changes in the Earth's climate could influence natural and social systems and human activities, and/or how human actions could reduce adverse effects of climate change on those systems and activities, with the aim of assisting policy-makers to adequately respond to the challenge of climate change"*. This definition encompasses both impact and adaptation assessments, according to the IPCC definitions above.

Climate change vulnerability assessments, defined in that way, comprise a broad set of activities: from the scientific analysis of the relationship between specific climate variables and certain ecosystem properties to policy-driven assessments how a climate-sensitive economic sector in a country can be made more resilient to all kinds of climate variations, regardless of their attribution. Consequently, climate change vulnerability assessments are conducted in a variety of contexts, and for a diverse group of stakeholders motivated by rather different concerns. It is important to understand from the outset that the determination of *"the consequences of climate change on natural and human systems"* depends on a number of assumptions about future non-climatic developments, some of which (such as the level of adaptation) may even be influenced by the outcomes of the vulnerability assessment.

The classification of vulnerability assessments is helped by the generic framework shown in Figure 2.1 whose development has been motivated by the adaptation frameworks presented in Smithers and Smit (1997) and Smit et al. (2000). This framework, which is applicable beyond the issue of climate change, shows the major determinants of vulnerability assessments. The suitability of a specific assessment approach depends, in particular, on the *system* or sector considered, on the specific climatic and non-climatic *stressors* that this system is exposed to, on the degree of *uncertainty* about future changes in these stressors, on the (natural or anthropogenic) *root causes* of these stressors, on the biophysical and social *effects* potentially caused by these stressors, on the available response *actions* for reducing the vulnerability, on the *time scale* and *spatial scale* of the assessment, and on the *resources* available for the assessment. The thick dotted arrows show the (potential) influence of human actions on all components of the causal chain from root causes to the effects of specific stressors, which is itself denoted by thick solid arrows. The thin arrows with open heads illustrate that the root causes, stressors, systems and effects considered in a specific assessment largely determine the set of relevant response actions.

Table 2.2 applies the conceptual framework from Figure 2.1 to climate change assessments. The right column lists potential choices for each determinant of a vulnerability assessment. Only those items highlighted in boldface are common to *all* assessments whereas the others may vary between assessments. Obviously, a wide range of assessments can be subsumed under the header 'climate change vulnerability assessment', which gives rise to a multiplicity of methodological approaches. In Section 2.2.3, we present a conceptual framework that distinguishes four stages of assessments, based on their analytical purpose, the degree of interdisciplinary integration, the integration of climate change with natural climate variability and non-climatic stressors, and the degree of stakeholder participation.

'Impacts' and 'vulnerability' are central concepts in this section. The latter term is used in many different ways by various research communities, such as those dealing with climate change and global

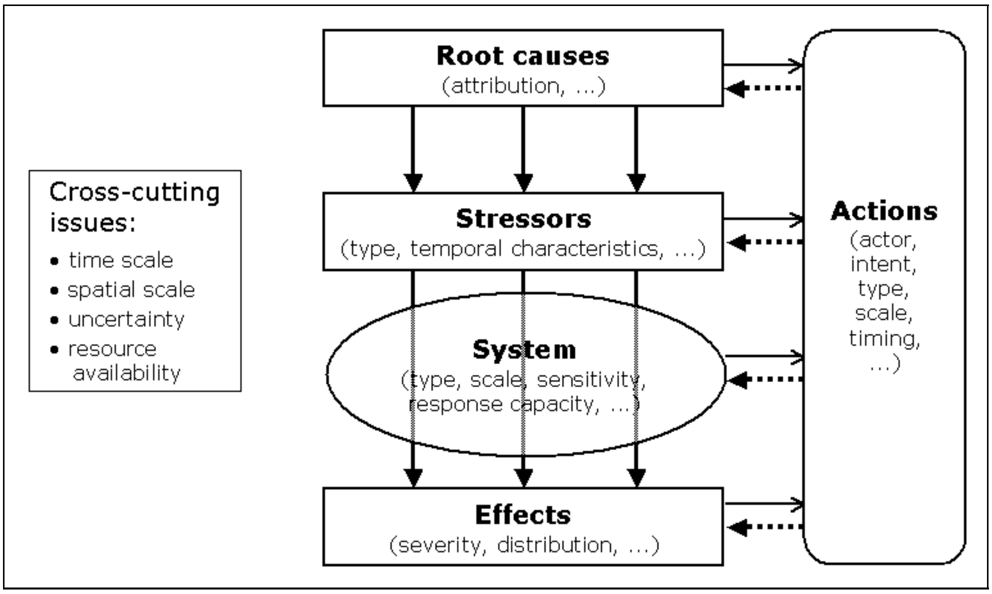


Figure 2.1: Generic framework for vulnerability and its assessment

change, natural hazards and disasters, and secure livelihoods and famine. One school of thought, which prevails in social geography and political ecology, regards (social) vulnerability as the response capacity of a household or a community to external stresses, as determined by socioeconomic and political factors (Blaikie et al., 1994; Bohle et al., 1994). Pertinent studies suggest a causal structure that concentrates on the differential abilities of communities to cope with external stress. Vulnerability according to this view corresponds closely to the *non-climatic factors* in our framework (see Figure 2.3 in Section 2.2.3). A second school, which is characteristic for the risk, hazards, and disasters literature, conceptualizes vulnerability as the dose-response relationship between an exogenous hazard to a system and the associated risk of adverse effects (UNDHA, 1993; Dilley and Boudreau, 2001). This notion of vulnerability corresponds most closely to the *sensitivity* box in Figure 2.3. A third school, which is predominant in global change and climate change research, uses vulnerability as an integrated measure of the expected adverse effects to a system that originate from certain external stressors (Cutter, 1993; Boughton et al., 1999; McCarthy et al., 2001). For a comprehensive review of alternative conceptualizations of vulnerability, the reader is referred to Cutter (1996); Kelly and Adger (2000); Dilley and Boudreau (2001).

> **(Climate) Impacts:** *Consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential and residual impacts. [. . .]*
>
> **Vulnerability:** *The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.*

We employ the IPCC definition cited above, which follows the third school of thought. In that definition, the *vulnerability* of a system to climate change is identified with the level of expected impacts

Dimension	**Question**	**Potential choices**
System	Who or what is vulnerable?	A community, a geographic region, a economic sector, a natural system
Root causes	What causes the vulnerability?	**Greenhouse gas emissions,** other driving forces
Stressors	Vulnerable to what?	**Anthropogenic climate change,** natural climate variability, atmospheric composition, other non-climatic factors
Effects	What is at risk?	Ecosystem viability, food security, human health, economic assets, other valued goods and services
Actions	What can be done?	Mitigation of climate change, adaptation to climate change
Time scale	Which time horizon?	Few decades, many centuries
Spatial scale	Which region?	River catchment, coastal strip, country, continent
Uncertainty	How to treat uncertainties?	Single best guess, multiple scenarios, sensitivity analysis, probabilistic assessment
Resources	What resources are available?	Scoping study, detailed vulnerability assessment

Table 2.2: Application of the framework from Figure 2.1 to climate change vulnerability assessments.

over time for a certain level of global climate change, considering the adaptive capacity of the respective system. Reilly and Schimmelpfennig (1999) actually define vulnerability as the *"probability-weighted mean of damages and benefits"*. The vulnerability of a system includes an external dimension, which is represented by its *exposure* to climate variations, as well as an internal dimension, which comprises its *sensitivity* to them and its *adaptive capacity*. The distinction between an external and an internal dimension of vulnerability is similar to the one between biophysical and social vulnerability, as applied in the 'hazards of place' model of vulnerability developed by Cutter (1996). However, since the inclusion of *'or'* in the first part of the definition seems to indicate a lingering persistence of the view that external shocks and inherent coping ability are alternative definitions of vulnerability rather than co-factors, connecting these factors with *'and'* would be more appropriate (Brooks, 2002).

Vulnerability is a broader concept than impacts, although the two are closely related. Whilst climate impacts can generally be described by changes either in biophysical indicators, such as the primary productivity of an ecosystem, or in socioeconomic indicators, such as the revenues from ski tourists in a region, the same is not true for vulnerability to climate change. No agreed metric exists to measure the vulnerability of an ecosystem or a ski resort.

The main distinctions between impacts and vulnerability, as understood by the IPCC, can be explained using the conceptual framework depicted in Figure 2.1:

Stressors: The concept of vulnerability relies on a realistic representation of the main *stressors* to a system, which often requires to include non-climatic stressors as well, and to explicitly consider the uncertainty in climatic and non-climatic scenarios.

System: The concept of vulnerability explicitly acknowledges the dynamic nature of the vulnerable system or community, including its ability to adapt to gradual changes over time.

Effects: The concept of vulnerability relies on the (partly normative) evaluation of projected impacts according to their desirability and relevance. A system or community is only considered vulnerable if goods and services are adversely affected that are valuable to certain stakeholders. Vulnerability assessments thus link natural with socioeconomic analysis.

Actions: Vulnerability assessments are often framed with a specific set of potential response actions in mind, which would either mitigate external stressors or enhance the response capacity of the vulnerable system or community.

Estimates of future climate impacts are contingent on various assumptions. The most important of these assumptions concerns the level of adaptation, as illustrated in Figure 2.2. This diagram depicts hypothetical trajectories for the level of climate-related impacts over time (due to anthropogenic climate change as well as natural variability) on a climate-sensitive system. The lowest trajectory denotes the (unrealistic) reference case of an undisturbed climate where variations in the level of impacts are solely caused by changes in non-climatic factors such as demographic and economic development. The other trajectories present the impacts associated with a specific climate change scenario for four different assumptions regarding adaptation. They include (in descending order of impacts) the ‘dumb farmer’, who does not react to changing climate conditions at all; the ‘typical farmer’, who adjusts their practice in reaction to persistent climate changes only; the ‘smart farmer’, who uses available information on expected climate conditions to adjust to them proactively; and the ‘clairvoyant (or genius) farmer’, who has perfect foresight of future climate conditions and faces no restrictions in implementing adaptation measures. The metaphorical names used to characterize the different assumptions on adaptive behaviour can be applied to any impacted agent. We employ these names because they are frequently used in the pertinent literature (see, e.g., Rothman and Robinson, 1997; Schneider, 1997). The bars on the right-hand side of Figure 2.2 illustrate the corresponding interpretations of the term ’(climate) impacts’. The different assumptions on adaptation and the associated understanding of ‘impacts’ can be related to specific stages of vulnerability assessments that will be presented in Section 2.2.3.

2.2.3 Evolution of the conceptual framework

In this section, we sketch the evolution of the conceptual framework for climate change vulnerability assessments. We present four prototypical stages of vulnerability assessment, knowing that actual as-

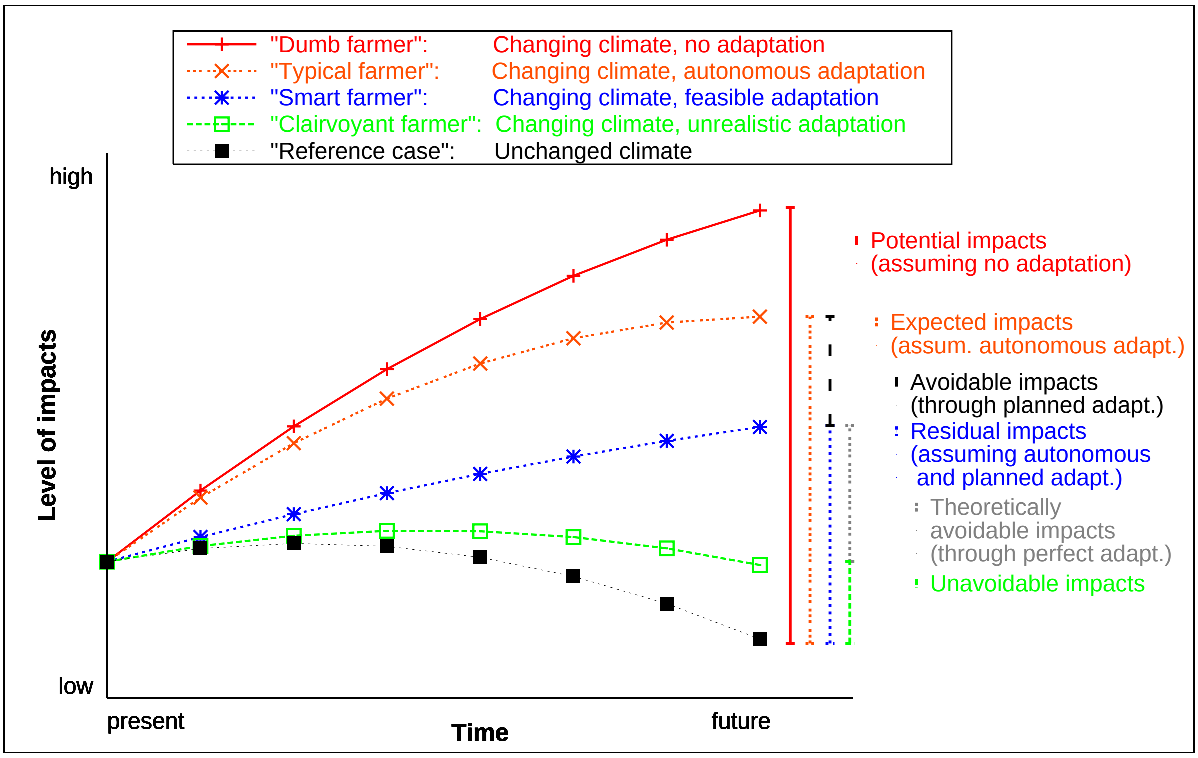


Figure 2.2: Different conceptualizations of climate impacts and adaptation

sessments usually combine features from more than one stage. In any case, the presented classification should not be interpreted to the effect that all but the final stages have become obsolete. Each assessment type provides valuable results, and the most appropriate one in a specific situation depends on a variety of factors, such as the scope of the analysis, the level of knowledge, the urgency of the threat, and the resources available. Obviously, the specification of (global long-term) mitigation policies and of (regional short-term) adaptation policies have rather different information needs with respect to the characteristic spatiotemporal scales of the assessments, the consideration of non-climatic stressors and factors, the treatment of uncertainty, and the importance of normative valuations (see Sections 1.3 and 2.2.2).

Table 2.3 summarizes the different assessment stages distinguished here. The evolution of vulnerability assessments has been motivated by changing stakeholder needs from science-driven (positive) assessments that estimate potential climate impacts to policy-driven (normative) assessments that recommend specific adaptation measures. This shift had important consequences for the degree to which non-climatic factors are included, the consideration of the effects of current climate variability and extremes, the temporal and spatial scales of analysis, the treatment of uncertainty, the integration with other policy goals, and the degree of stakeholder involvement. For a more detailed discussion of these issues the reader is referred to Rothman and Robinson (1997); Smith (1997); Klein and MacIver (1999); Klein and Nicholls (1999); Klein et al. (1999); Smit et al. (1999).

In the sequel of this section a conceptual framework is presented to illustrate the approach towards each of the four stages of vulnerability assessment. The purpose of this conceptual framework is twofold. First, we present the prevailing understanding of the climate change community in general, and as pre-

	Impact assessment	First-generation vulnerability assessment	Second-generation vulnerability assessment	Adaptation policy assessment
Analytical approach	Positive	Positive	Positive	Normative
Main result	Potential impacts	Pre-adaptation vulnerability	Post-adaptation vulnerability	Recommended adaptations
Consideration of adaptation	Little	Partial	Full	Full
Integration of natural and social science	Low	Low – medium	Medium – high	High
Illustrative research question	What are potential biophysical impacts of climate change?	Which socioeconomic and health impacts are likely to result from climate change?	What is the vulnerability to climate change, considering feasible adaptations?	Which adaptations are recommended to reduce the vulnerability to climate change?

Table 2.3: Characteristic properties of different stages of climate vulnerability assessment

sented in the IPCC in particular, on key concepts related to vulnerability and adaptation to climate change, and on the relationships between those concepts. Second, by presenting four stages of vulnerability assessment we sketch the development of the underlying theory and practice over time.

The conceptual framework is illustrated by a staged 'box-and-arrows' diagram, which combines natural and social science views of the issue. These two communities follow rather different approaches in the study of human-nature system interactions. The natural sciences apply a physical flows view that focusses on the flow of matter and energy between system components. The social sciences, in contrast, apply an actor system view that emphasizes the flow of information between different actors that determines social decision-making. Clearly, the consideration of the decision process is central for any attempt to influence the 'physical' part of the human-nature interaction through purposeful policy decisions.

The combination of natural and social sciences approaches for the simulation of human-nature system interactions has attracted considerable attention from both scientific communities. Robinson (1991) presents a conceptual framework for modelling in the Human Dimensions of Global Change Programme (HDGC), and for relating it to the activities of the International Geosphere-Biosphere Programme (IGBP). In a nutshell, this framework distinguishes natural systems (the scope of IGBP) and human systems (the scope of HDGC). The latter are further split up into physical human activities (e.g., demography, production, and consumption) and sociopolitical activities (e.g., decision-making and institutional organization). Different types of system views are then proposed for the modelling of the interaction between the three subcomponents of integrated human-nature systems. This concept was later formalized on a global level by Schellnhuber and Wenzel (1998); Schellnhuber (1999) who represented the “Earth system” by the “ecosphere” and the “human factor”, whereby the latter embraces a ‘physical’ sub-component (the “anthroposphere”) and a ‘metaphysical’ sub-component (the “global subject”).

The discussion of different views of the human-nature system is relevant for the conceptual framework presented here because they have important implications for the visual representation of the considered system. The primary goal of *system-dynamics diagrams*, as applied in the natural sciences, is to clarify the behaviour of complex systems whereas *influence diagrams* (and the social science models based upon them) are developed for helping people to make decisions. These two types of diagrams have been characterized as follows:

> *“Despite their superficial similarities, there are important differences between influence diagrams and the system-dynamics notation [. . .] First, the two notations interpret the nodes and arrows very differently. In system dynamics, nodes represent stocks, sources, and sinks of conserved quantities, such as materials, water, money, or numbers of humans or other species. The arrows represent flows of these quantities [. . .] Influences, on the other hand, do not represent material flows — they represent knowledge and beliefs, about how the value of variables affects the value or probability distributions on other variables, which may reflect knowledge on material flows, or of other evidential relationships. [. . .].”*
>
> (Morgan and Henrion, 1990, Section 10.7)

Clearly, both representations are relevant in the context of climate change. The “integrated assessment framework” diagram developed by the IPCC (Watson and the Core Writing Team, 2001, Fig. SPM-1), for instance, combines the two aspects. The IPCC framework has been criticized by Barker (2001), who argues for using a physically based stock-and-flow approach for the representation of the integrated system instead of the more general cause-effect approach applied in the IPCC diagram. However, this critique appears only valid in the context of physically based integrated assessment models.

Figure 2.3 (top) depicts the conceptual framework developed by the author of this thesis, and Figure 2.3 (bottom) explains the graphical elements that are used in its presentation. This diagram is a hybrid of a system-dynamics diagram and an influence diagram, whose elements include flow variables (e.g., emissions) and state variables (e.g., concentrations), complex probabilistic properties of a system (e.g., climate variability), spatiotemporal events (e.g., exposure), human actions (e.g., adaptation), and dose-response relationships between other elements (e.g., sensitivity). As a result, some of the relationships between elements of the framework represent physical flows, whereas others indicate functional relationships or the flow of information. The different elements and relationships in the framework are distinguished by different graphical representations.

Any mental model highlights some aspects of the considered system at the expense of others. The most important topics that are *not* explicitly addressed in our framework are the temporal dimension of considered processes and dynamical aspects, and the spatial scales of the considered systems and cross-scale relationships, the uncertainty associated with different elements of the framework, and the actual process of policymaking.

In the remainder of this section, we will briefly discuss characteristic features of each stage of vulnerability assessment. For a more extensive discussion, including examples, see Füssel and Klein (2002a,b).

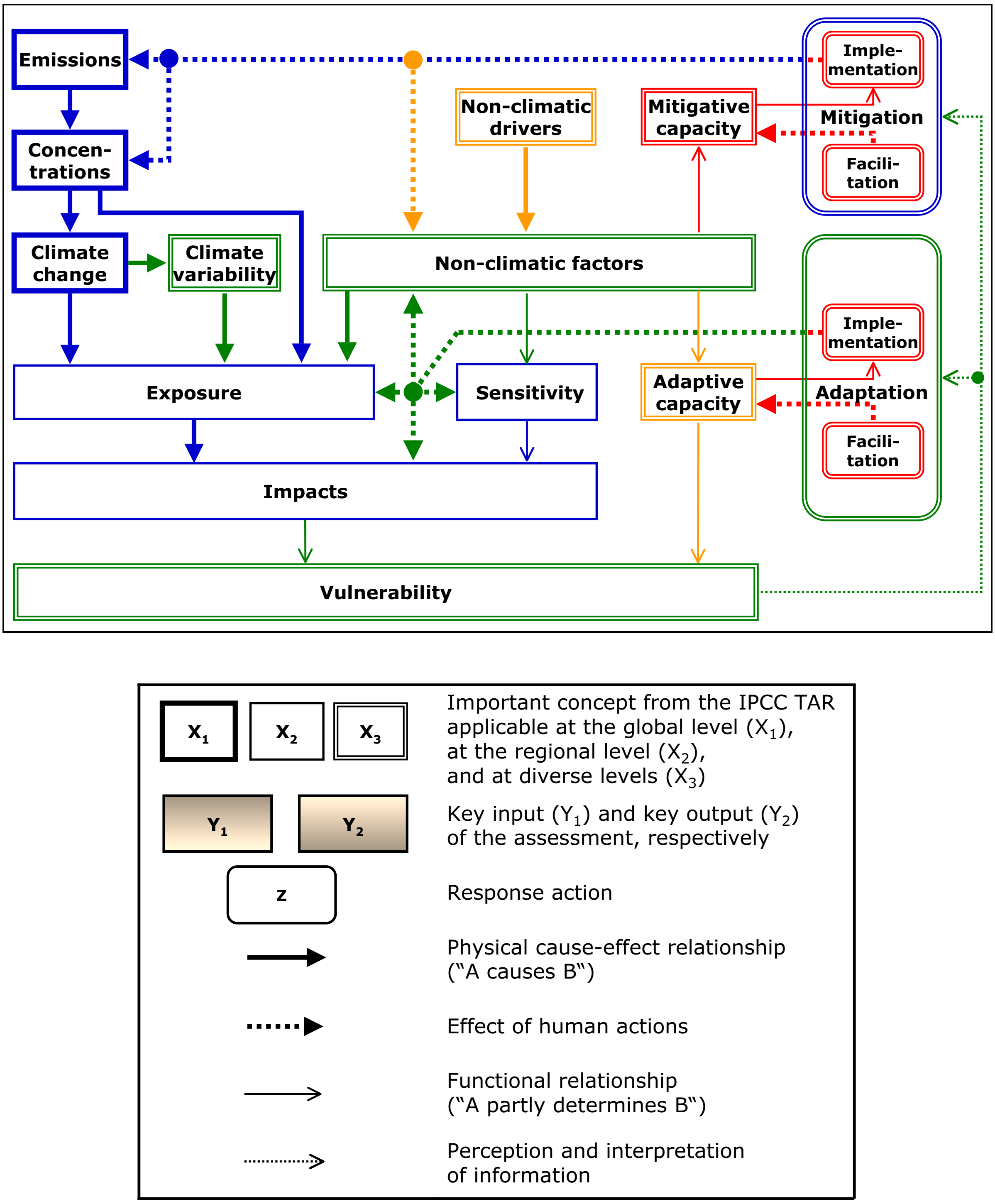


Figure 2.3: *Top:* Evolution of climate vulnerability assessments (blue: climate impact assessment; green: first-generation vulnerability assessment; yellow: second-generation vulnerability assessment; red: adaptation policy assessment). *Bottom:* Legend.

Impact assessment

Impact assessments evaluate the potential effects of several climate change scenarios, including a (hypothetical) constant climate scenario, on one or more impact domains. The main concepts considered in a (climate) impact assessment and their relationships are depicted in blue in Figure 2.3.

The assessment starts from scenarios of *emissions* or atmospheric *concentrations* of greenhouse gases and radiatively active particles, such as the often assumed $2\times CO_2$ case. *Climate change* projections are determined through the application of appropriate climate models. Climate is a multi-dimensional phenomenon that exhibits variations on different spatiotemporal scales. Impact assessments often focus on long-term changes in average climate conditions (such as annual mean temperature, precipitation, and sea-level rise) because these results are most readily available from climate models. The *exposure* of a system (often termed 'exposure unit') to climatic stimuli depends on the global level of *climate change* and on the system's location. The link from *concentrations* to *exposure* in the conceptual framework indicates that some systems are directly affected by changes in atmospheric composition. Well-known examples include the direct effect of carbon dioxide on plant physiology and the combination of local air pollution and high temperatures in causing respiratory diseases in humans. The *sensitivity* of a system denotes the —generally multi-dimensional and dynamic— dose-response relationship between its exposure to climatic stimuli and the resulting effects. Consequently, climate *impacts* are a function of (the change in) the *exposure* of a system to climatic stimuli and its *sensitivity* to these stimuli. The terms *potential impacts* and *residual impacts* are used to distinguish impact estimates between assessments that do *not* consider adaptation (i.e., where *sensitivity* is assumed to be unaffected by climate change) and those that do consider adaptation (see below).

The bold borders around the boxes for *emissions* and *concentrations* of greenhouse gases and for the level of *climate change* indicate that these concepts are applicable at the global level. The *exposure* and the *sensitivity* to climatic stimuli as well as the resulting *impacts* can only be analyzed for specific exposure units, which is indicated by the thin borders.

> **Mitigation:** *An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases.*

The main policy response addressed in impact assessments, as understood here, is *mitigation*, which refers to actions that limit the level and rate of climate change. The two basic mitigation options are the reduction of gross GHG *emissions* (e.g., through fuel switching in the energy sector), and the reduction of their *concentrations* through enhancing the sink capacity of biological and other systems. Since adaptation is not explicitly considered, these assessments are most relevant for policy formulation in the case of severe long-term climate impacts where adaptation is difficult. In addition, they serve to raise awareness of the potential scale and magnitude of climate change impacts. Examples include many ecological studies as well as country studies conducted within, for instance, the United States Country Studies Program (USCSP). Selected references are Monserud et al. (1993); Leemans and van den Born (1994); Kwadijk and Middelkoop (1994); Nicholls and Leatherman (1995); Rosenzweig and Parry (1994); Martens et al. (1995b, 1997). This approach is also typical for integrated assessment models of climate change that present geographically explicit projections for the impacts of different emission scenarios on various impact sectors, mostly in biogeophysical units. Examples include CLIMPACTS (Kenny et al., 1995), IMAGE 2 (Alcamo et al., 1998a), MIASMA (Martens, 1998b), and the ICLIPS model (Füssel and van Minnen, 2001; Toth et al., 2002; Toth, 2003b, see Section 2.4).

First-generation vulnerability assessment

First-generation vulnerability assessments are an extension of impact assessments. The new elements are shown in green in Figure 2.3.

Climate variability constitutes an important component of a system's *exposure* to climatic stimuli. Even though it is generally accepted that global *climate change* will affect regional *climate variability*, consideration of these effects in model-based impact assessments is often hampered by the considerable disagreement between climate models on potential changes in climate variability, including the frequency, intensity, and location of extreme events.

Non-climatic factors denote a wide range of factors that influence the vulnerability of a system or society to climate change. They include ecological, economic, social, demographic, technological and political conditions, some of which may be affected by *mitigation* activities. *Non-climatic factors* can affect the *sensitivity* as well as the *exposure* of a system to climatic stimuli. The latter link is particularly relevant for mobile exposure units. For instance, if a person or a community relocates in response to an external (non-climatic) stress, their *exposure* to climatic variations obviously will change.

Vulnerability is a broader concept than potential *impacts* (see Section 2.2.2), and not all of the differences can be shown in the diagram depicted in Figure 2.3. The double border of the 'vulnerability box' indicates that this concept is applicable at, and differs between, different scales. For instance, even if the overall vulnerability of a country to climate change is low, certain subgroups of the population may still be strongly affected. The thin arrow that points from *impacts* to *vulnerability* denotes that the impact potential (in concert with the *adaptive capacity*, see below) is an important determinant for the vulnerability of a system. However, it does not suggest that impacts cause vulnerability.

Recognition of the *vulnerability* of valued systems to climate change is likely to trigger policy responses at different levels. This potential for human agency is indicated by the thin dashed arrows in the framework diagram from *vulnerability* to *mitigation* and *adaptation*.

> **Adaptation:** *Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation. [. . .]*

Adaptation, as defined by the IPCC, comprises a broad range of activities. Alternative definitions have sometimes restricted the use of this term to adjustments in social systems, to deliberate changes, to major structural changes in a system, to responses that follow observed changes in external conditions, or to a subset of climatic stimuli (Smit et al., 2000). The conceptual framework presented here distinguishes *adaptation* measures between those that are targeted directly at the vulnerable system and those that affect *non-climatic factors* influencing the system.

First-generation vulnerability assessments raise awareness of the (potential) vulnerability of sensitive systems or communities to climate change, often in comparison with various non-climatic stresses. In so doing they help to prioritize further research and determine the need for mitigation and adaptation measures to reduce adverse effects. However, as long as the feasibility of implementing adaptations is not assessed, the assessment does not provide a full picture of the vulnerability of the considered system. Depending on the level of adaptation assumed, assessment results may fall anywhere in the range spanned by the 'dumb farmer' and the 'clairvoyant farmer' trajectories in Figure 2.2. For a more detailed discussion of unrealistic adaptation assumptions and for examples of studies that would be regarded as first-generation vulnerability assessments in our classification, see Smithers and Smit (1997) and Smit and Pilifosova (2001). Most initial national communications to the UNFCCC produced by developing countries are also first-generation vulnerability assessments (Lim, 2001).

Second-generation vulnerability assessment

The step from climate impact assessments to first-generation vulnerability assessments was characterized by the explicit inclusion of non-climatic factors that may influence climate impacts, and by the evaluation of potential impacts in terms of their relevance to goods and services valued by society. The resulting broader view on the potential consequences of climate change also helps to assess adaptation needs. The potential for, and limitations to, adaptation are more thoroughly assessed in *second-generation* vulnerability assessments. The new components of the corresponding conceptual framework are shown in yellow in Figure 2.3.

> **Adaptive capacity (or adaptability):** *The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.*

The *adaptive capacity* of a system or society determines its potential to cope with or to reduce adverse effects of climate change. Under *ceteris paribus* conditions, *adaptive capacity* and *vulnerability* are therefore negatively correlated. It should be noted that the IPCC definitions for 'adaptive capacity' (as well as of 'adaptation' and 'vulnerability') refer to social and natural systems alike. Determinants of adaptive capacity in social systems comprise such *non-climatic factors* as economic resources, technology, information and skills, infrastructure, institutions, and equity (Smit and Pilifosova, 2001; Yohe and Tol, 2002). Since the ability of a system to cope with current climate variability is an important indicator for its capacity to adapt to future climate change, analyses of vulnerability across systems or regions to current climate variability can provide important lessons for adaptation science.

Vulnerability assessments tend to focus on the vulnerable system and the multiple stresses that may threaten it rather than on the multiple effects of a particular stress factor such as climate change (Ribot, 1995). An important element in many second-generation vulnerability assessments is therefore the explicit consideration of *non-climatic drivers* (e.g., demographic, economic, sociopolitical, technological, and biophysical drivers) that affect relevant *non-climatic factors* (e.g., the degree of economic diversification, the level of education, and the strength of social networks).

Second-generation vulnerability assessments are conducted to estimate realistically the vulnerability of certain sectors or regions to climate change, in concert with other stress factors. To this end, they include assessments of the potential of adaptations to reduce adverse impacts. The results correspond most closely to the 'realistic farmer' trajectory in Figure 2.2. If limits to adaptation are identified for valued systems, this provides important information for the determination of critical levels of climate change.

Second-generation vulnerability assessments are not yet commonplace, in absence of a clear methodology. More than first-generation assessments they require the involvement of social scientists in a multidisciplinary research group. In addition, second-generation assessments require a stronger involvement of stakeholders and, focusing more on adaptive capacity, rely more heavily on qualitative data. The *Assessments of Impacts of and Adaptation to Climate Change in Multiple Regions and Sectors* (AIACC) project, which is implemented by the United Nations Environment Programme (UNEP) and supports the development of scientific and technical capacity amongst developing country scientists to address gaps in knowledge about climate change impacts, vulnerability, and adaptation, includes a number of subprojects that could be considered second-generation vulnerability assessments.

Adaptation policy assessment

Owing to major differences in the characteristic temporal and spatial scales of *mitigation* and *adaptation*, mitigation and adaptation policies are formulated largely independent of each other. This separation is also reflected in the structure of the IPCC Third Assessment Report, where mitigation and adaptation are addressed by different working groups (cf. Section 2.2.1). The fourth stage of climate change assessments presented here refers to assessments that directly address the information needs of decision-makers concerned with adaptation to climate change. We prefer the term ‘adaptation policy assessment’ over ‘adaptation assessment’, which is used in the glossary of the IPCC Third Assessment Report, to emphasize that the main purpose is to contribute to policymaking by providing specific recommendations to planners and policymakers on the enhancement of adaptive capacity and the implementation of anticipatory adaptation measures. Employing the language of Figure 2.2, adaptation policy assessments are about preventing ‘avoidable impacts’ by turning ‘typical farmers’ into ‘smart’ ones. Achieving this objective requires a closer look at the available response options, including considerations as to the feasibility of their implementation and to their integration with existing policies and practices on resource management, disaster reduction, economic development, public health, *etc.*

Elements in Figure 2.3 that are new in adaptation policy assessment are shown in red. Two types of *adaptation* measures are distinguished. (For the sake of completeness, mitigation actions are also included.) *Facilitation* refers to activities that enhance *adaptive capacity*, thereby improving the conditions for the *implementation* of adaptation measures. Such activities include awareness raising, capacity building, and the establishment of institutions, information networks, and legal frameworks for action. *Implementation* refers to activities that actually avoid adverse climate *impacts* on a system by reducing its *exposure* or *sensitivity* to climatic hazards, or by moderating *non-climatic factors*. The relationship between *adaptive capacity* and *adaptation* in the conceptual framework is twofold. Adaptive capacity determines the feasibility of adaptation measures of the *implementation* type, and it is itself influenced by adaptation measures of the *facilitation* type. The same structure applies to *mitigation* measures, whereby the concept of *mitigative capacity* has been introduced into the literature only recently (Yohe, 2001).

The development of feasible adaptation strategies requires an intensive dialog with relevant stakeholders throughout the assessment process. Key objectives of such a dialogue are to identify the needs and priorities of stakeholders, to establish trust in the assessment team and methodology, to facilitate mutual learning, and to ensure that suggested policies are compatible with other policy goals such as sustainable development, economic diversification, and biodiversity conservation. Existing uncertainties about future climate change are an important issue for stakeholder dialogues and for the formulation of robust adaptation strategies. This topic is explored further in Pittock and Jones (2000); Willows and Connell (2003).

To date, there is little guidance for full-blown adaptation policy assessments. An important initiative to advance the state of the art is the development of an *Adaptation Policy Framework* for Stage II adaptation under decision 11/CP.1 of the UNFCCC (Lim, 2001). The development of this framework is guided by the United Nations Development Programme (UNDP) and the World Bank’s Global Environment Facility (GEF). One example of an adaptation policy assessment is the project *Climate Change and Adaptation Strategies for Human Health in Europe* (cCASHh), which aims to assess the status and facilitate the enhancement of adaptation possibilities of communities to climate-related impacts on human health in Europe.

2.3 Analytical frameworks for scientific decision support

This section discusses how science can contribute to climate change-related decision-making. We start with an overview of the decision problem, which is followed by a discussion of three categories of decision-analytical frameworks. The choice of a particular framework has strong implications for the design of IAMs in general, and for the modelling of climate impacts in particular. For a more detailed discussion of this topic, see, e.g., Toth and Mwandosya (2001); Toth (2001, 2003a).

2.3.1 Challenges for climate policy

The specification of climate policies poses a variety of challenges for decision-making (adapted from Toth and Mwandosya, 2001):

Global problem: The atmosphere is a global public good in the sense that actions anywhere on the globe can change its composition, and that such changes have global effects. Even though the causes and impacts of climate change have global scope, they are nevertheless heterogeneously distributed. As a result, a multiplicity of decision-makers with heterogeneous interests and without an adequate institutional frame is involved in the decision-making process.

Long-term problem: Global warming results from the cumulative effect of increased atmospheric GHG concentrations, which, in turn, represent the cumulative effect of anthropogenic GHG emissions. Owing to the inertia of the carbon cycle and the climate system, both integrations involved have long time scales (from decades to millennia). Consequently, emissions now may cause damages in the far future, and emission *reductions* now provide little benefits in the near future, except for certain secondary benefits such as reduced air pollution. The beneficiaries of mitigation measures (principally future generations) are thus largely disparate from those who implement (and pay for) these measures.

Pervasive problem: The burning of fossil fuels, which is the main cause of anthropogenic climate change, is the primary source of energy (electricity, heat, mechanical energy) in most societies across the world. In addition, almost any natural or social system is sensitive to, and thus potentially affected by, global climate change. Since both the causes and the impacts of climate change are extremely pervasive, agreement on a coordinated policy is very difficult.

Large consequences: The anticipated consequences of climate change are very large. They include the potential of "nightmare" or "doomsday" scenarios (Schellnhuber and Yohe, 1997) with catastrophic outcomes up to the global scale, which would be irreversible on time scales relevant for human decisions. As a consequence, a wait-and-see approach is unlikely to be consistent with the precautionary principle.

Large uncertainties: There are large uncertainties about many impacts of climate change potentially associated with any given forcing scenario, and about the costs, benefits, and implementation barriers of possible responses now and in the future. The requirement for decision-making under uncertainty calls for sequential decision-making based on a risk-management approach, with an emphasis on policies that are robust across a range of plausible outcomes.

As a result of these challenges, the decision situation is characterized by *"tensions between the limited capacity to predict and the urgent need to act in a situation faced with high stakes of risk"* (Toth and Mwandosya, 2001). Key issues in the climate policy debate are divergent views concerning *scientific uncertainties* about climate change and its impacts; *socioeconomic uncertainties* about the costs and effectiveness of various response measures; the *valuation* of non-market impacts; the *aggregation* of costs and benefits across sectors, regions and time under divergent equity assumptions; and the *integration* with other topics, such as the broader issues of sustainable development and poverty reduction.

Climate policy needs to find answers to five key policy-relevant questions about societal responses to the challenges of climate change (Toth and Mwandosya, 2001):

1. *How* should the response be made (mitigation, adaptation, etc.)?
2. *When* should the response be made?
3. *Where* should the response take place?
4. *Who* should pay for the response?
5. *What objective* should the response be targeted at?

Decision-analytical frameworks (DAFs) for climate policy are defined by Toth and Mwandosya (2001) as "*analytical techniques aimed at synthesizing available information from many [...] segments of the climate problem to help policy-makers assess the consequences of various decision options within their own jurisdictions. DAFs organize climate-relevant information in a suitable framework, apply a decision criterion [...], and identify options that are better than others under the assumptions that characterize the analytical framework and the application at hand.*" They help to answer the above-mentioned questions by determining (a) what the goals of the relevant decision-maker(s) are, and whether these are fully specified at the beginning of the analysis; (b) where the boundaries of the analysis are; (c) how uncertainties are handled; and (d) how the intricate interplay between scientific analysis and decision-makers shall be organized.

Three types of models are generally distinguished in policy analysis: predictive, optimizing, and satisficing models (Morgan and Henrion, 1990). In the context of climate change, they correspond to *policy evaluation models*, *policy optimization models*, and *policy guidance models*, respectively. Whereas predictive and optimizing models have long been applied to the climate change problem, the ICLIPS model presented in Section 2.4 is the first satisficing IAM. In the remainder of this section, we discuss the relative advantages and disadvantages of the three modelling approaches for climate change decision support.

2.3.2 Policy evaluation: scenario analysis

Policy evaluation analyses follow a 'forward' direction from causes to effects. A scenario analysis starts from prescribed scenarios of demographic and socioeconomic development, includes assumptions about the implemented climate policy, determines the associated GHG emissions and climatic changes, and simulates the consequences for various climate-sensitive sectors. Climate impacts are typically determined by geographically explicit process-based or empirical-statistical models and expressed in biophysical units, such as simulated crop yields. The feedback from climate impacts on future socioeconomic development can also be considered in principle. A prominent exemplar of policy evaluation models is the IMAGE family of models (Alcamo, 1994; Alcamo et al., 1998a).

Due to the generally high level of scientific detail, scenario analysis can provide a rather detailed picture of the likely consequences of specific policy scenarios. It is then up to the user of the model to decide whether they can accept the climate impacts projected under a specific socioeconomic scenario. If none of the predefined scenarios turns out to be universally acceptable, an iterative 'trial and error' process needs to be implemented. This process can be time-consuming and ineffective since it is virtually impossible to span the full space of plausible futures.

2.3.3 Policy optimization: cost-benefit and cost-effectiveness analysis

Optimizing frameworks are related to decision analysis, which is a formal quantitative technique to identify the 'best' choice from a range of alternatives. The special cases of decision analysis most widely applied to the climate change problem are cost-benefit analysis and cost-effectiveness analysis.

Cost-benefit analysis

Cost-benefit analysis (CBA) strives for the maximization of general utility over a predefined time period, whereby 'utility' is defined in a normative way from observed or perpetuated social preferences. The consistent appraisal of the merits associated with various options is done by quantifying in monetary terms as many costs and benefits as possible, including items for which the market does not provide a satisfactory measure of value. In the context of climate policy, CBA aims at identifying a single 'optimal' climate policy that minimizes the sum of the net costs (in a broad sense) associated with mitigation of climate change, adaptation to climate change, and residual climate impacts. One of the best known IAMs for global cost-benefit analysis is DICE (Nordhaus, 1994; Nordhaus and Boyer, 2000)

CBA requires a consistent utility valuation of decision outcomes, i.e., the use of a common numeraire that makes all policy strategies comparable to each other. The usual choice is global net present value, expressed in US$ for a certain base year. The need for a common yardstick is the root of a multitude of methodological and practical problems, which severely compromise the validity and significance of the results of global cost-benefit models for the problem of anthropogenic climate change (Morgan et al., 1999). The methodological problems are related to the *valuation* of diverse climate-sensitive commodities at the local or individual level, their *aggregation* across various dimensions, and the treatment of *uncertainty*. Anthropogenic climate change spans the lifetimes of several generations, it will effect societies existing under very different climatic and socioeconomic conditions, and many of its impacts cannot easily (or at all) be expressed in monetary terms (e.g., the loss of human life or ecosystems). Consequently, valuing the outcomes of different climate policies requires fundamentally *normative* decisions, which cannot be made by scientists alone. CBA tends to conceal the difficult choices that decision-makers are facing in seemingly value-neutral mathematical language. Hence, problems may arise when a proposed 'optimal' policy is investigated in detail with respect to its regional, temporal, and sectoral implications. In the following, we mention only the most important methodological problems. For a more detailed discussion, the reader is referred to the “Ten commandments for good policy analysis” proposed in Morgan and Henrion (1990), and to Azar (1998); Bruckner et al. (1999); Helm et al. (1999); Morgan et al. (1999); Rothman (2000); Schneider and Sarukhan (2001); Ahmad and Warrick (2001); Jacoby (2003).

The impacts of climate change may be categorized according to the primary numeraire for describing them into ecosystem impacts (e.g., biodiversity loss), health impacts (e.g., increased mortality during heat waves), social impacts (e.g., forced migration or loss of heritage sites from sea-level rise), and economic market impacts. The latter may be further classified into impacts on the activity of primary sectors (e.g., agriculture), impacts on the activity of other economic sectors (e.g., tourism), and impacts on human-made capital (e.g., property loss during extreme weather). It is generally assumed that non-market impacts of climate change are at least as important as market impacts, even under smooth climate change scenarios (Pearce and Cline, 1996). However, there is no universal method for the valuation of non-market impacts since economic values have meaning only in the context of specific choices, and the characteristics of that choice largely determine the inferred value (Pearce, 1993; Kopp et al., 1997). Hence, economic valuation techniques for non-market impacts remain problematic in many situations.

The establishment of a common numeraire involves not only the comparison of different climate-sensitive commodities at the local or individual level but also their aggregation across individuals, population sub-groups, economic sectors, regions, and time. All these aggregations require the assignment of weights to specific impacts, based on certain political or ethical concepts of intra- and intergenerational equity. Arrow’s Impossibility Theorem proves the inability to aggregate individual preferences in a consistent way, except for imposed and dictatorial aggregation schemes (Arrow, 1950). Hence, interpersonal and intergenerational comparisons cannot be made on an objective basis. Moreover, aggregation of impacts to higher scale levels has to consider that there are values to society outside of individual values, such as goods and services that have a more common character, and values related to issues of equity and security. Finally, important interactions between different social and economic agents are often neglected in the assessment of impacts on the social welfare function.

The last issue may be illustrated by a simple gedankenexperiment from Rothman (2000). Imagine that climate change would cause the complete destruction of US agriculture. Since agriculture comprises only about 1% of US gross domestic product (GDP), this would result in a mere 1% GDP loss in standard measures, which is much less than the average annual growth rate of GDP in the USA. Hence, according to prevailing monetization techniques, next year’s US economy without any agriculture would be ‘richer’, and thus preferable, to this year’s economy with agriculture. If they were asked, most US citizens would probably articulate a different preference. They were likely to assign a higher value to the destruction of agriculture, taking into account issues such as the extreme dependence of other sectors of society on agriculture, the benefits of access to fresh, local produce, likely increases in consumer prices for food, and the cultural importance of rural life-styles.

The aggregation of impacts across time is usually done by applying exponential discounting to future costs and benefits. However, there are severe doubts whether discounting factors derived from the short-term behaviour of economic agents can be applied to intergenerational problems such as climate change (Howarth and Norgaard, 1995). For instance, Layton and Brown (2000) found that respondents to a survey about climate impacts on forests had the same preferences over the two very different time horizons considered (60 years and 150 years). The implications of discounting can be illustrated by another gedankenexperiment. Assume that one cent had been deposited at a bank account in the year 1 AD at an interest rate of 3% per year. This cent would have accumulated to about $5 \cdot 10^{23}$ Dollars (or Euros) after two thousand years, which corresponds to many billion times the global GDP in the year 2001.

Conversely, a loss of $5 \cdot 10^{23}$ Dollars two thousand years from now would be valued just one cent in the present even at the very modest discount rate of 3% per year. Another problematic issue in the monetary valuation of future impacts is the standard assumption that current relative price levels will remain constant in the future. However, there is substantial evidence that relative prices of many non-market goods potentially affected by climate change, such as environmental integrity, would increase with the substantial growth in income generally projected for the future (Tol, 1996).

All methodological issues discussed so far would also be relevant under perfect knowledge about the future. However, the scientific understanding about climate change and its regional impacts is still characterized by large uncertainty and even outright ignorance. The handling of uncertainties poses additional methodological challenges, in particular if the knowledge gaps are unevenly distributed between the cost and damage functions, or if the (subjective) probability distribution of the damage function is right-skewed. In a deterministic framework, quantitative analysis is generally restricted to a ‘best guess’ scenario. Impacts with a low subjective probability such as large-scale singular events (the so-called ‘climate catastrophes’) are generally neglected in the analysis even though they may be highly relevant for policy decisions.

In risk assessment and management, probabilistic (syn. stochastic) CBA is widely applied to deal with uncertain future outcomes. Recently there have been various attempts to apply this technique to account for uncertain ‘climate catastrophes’. These analyses have consistently shown the high sensitivity of model results to the consideration of these events. However, even probabilistic CBA cannot provide unique recommendations for climate policy in the presence of large uncertainties about the likelihood of specific events, different valuations of their impacts, and different risk attitudes. Azar and Lindgren (2003) characterizes the situation as follows: *“The uncertainty about the impacts is so large that basically any optimal outcome can be justified.”* For a recent discussion of the implications of uncertainty about the consequences of future climate change for various decision-analytical frameworks, see Aaheim and Bretteville (2001).

In addition to the various methodological issues, it is also important to be conscious about the context in which the analysis results are applied. Cost-benefit analysis, if done well, identifies the ‘optimal’ policy option in the sense that everybody could *potentially* be better off than for any other option *if* those people who are positively affected under that policy would compensate those who are negatively affected. However, the UNFCCC does not provide a mechanism for ensuring that such a redistribution from the ‘winners’ to the ‘losers’ of climate change would *actually* take place. Whilst some scholars call for establishing a Climate Impact Relief Fund or comparable compensation mechanisms (Müller, 2002; Schellnhuber, 2003), it cannot be said with any certainty whether such a mechanism will eventually be implemented.

In a review of how optimizing IAMs deal with the above mentioned challenges, Rothman (2000) finds that the economic valuation of climate impacts in current IAMs is characterized by the following important limitations: partial coverage of impact categories, little consideration of intersectoral dependencies, emphasis on equilibrium impacts assuming well-behaved climate change; the assumption of fully rational agents with perfect knowledge; use of ‘best guess’ scenarios despite right-skewed distribution of uncertainties, application of willingness-to-pay rather than willingness-to-accept in the contingent valuation of non-market impacts, and the assumption that the redistribution between positively and negatively affected population groups would actually take place. This practice consistently underestimates the economic value of climate impacts, compared to a situation with perfect knowledge and a more realistic representation of the decision situation (Roughgarden and Schneider, 1998; Rothman, 2000).

Cost-effectiveness analysis

Considering the numerous difficulties involved in the monetization of climate impacts, cost-effectiveness analysis (CEA) has been proposed as a valuable complement to CBA. CEA compares the costs associated with alternative ways of achieving a specified objective. Unlike CBA, the level of benefit is treated as an external given that is to be achieved at least cost. In the context of climate policy, the maximum permitted level of climate change would be the result of international negotiations in the framework of the UNFCCC. CEA could then be applied to identify the least-cost policy (involving a mix of mitigation and adaptation) that is consistent with this objective. This approach has been implemented, for instance, in the MINICAM model (Edmonds et al., 1996).

CEA avoids most of the problems associated with the valuation of non-market impacts of climate change that were discussed in the context of CBA. However, the need to express the costs of climate policies in a single numeraire still requires normative choices as to the aggregation of utility across regions and generations. In addition, international redistribution mechanisms would be required for transferring the global least-cost policy into policies that are also optimal for each region. Furthermore, the 'optimal' policy identified by CEA will generally reach the maximum level of climate change specified as an input to the analysis. This would not be a problem if the system behaviour and potential thresholds were known with certainty. However, given the large uncertainties in climate impact projections, such a policy might be associated with a substantial risk of actually missing the target, due to imperfect knowledge. Finally, the application of CEA resides on the implicit assumption that the policy costs are worthwhile for achieving the pre-specified objective. However, it is exactly this assumption that is very much contended in the context of climate change among the different stakeholders involved.

Summarizing the caveats of optimizing approaches to climate change decision-making, Toth and Mwandosya (2001) conclude that *"the lack of an individual decision-maker, utility problems, and incomplete information suggest that decision analysis cannot replace the political process for international climate-change decision-making."*

2.3.4 Policy guidance: the guardrail approach

The 'traditional' IA frameworks described above are associated with various shortcomings. Whilst scenario analysis can provide indispensable information on the expected implications of selected policy strategies, it is not particularly well suited for assisting decision-makers in identifying the whole range of possible options and evaluating them according to specified policy criteria. Whilst the determination of an 'optimal' policy strategy appears attractive from a theoretical point of view, the preceding discussion revealed that this very objective raises a multitude of methodological and practical problems. Any optimizing framework needs to imply value-laden paradigms at the outset, none of which is backed by the UNFCCC. Article 2 of the UNFCCC frames the requirement for long-term climate policy primarily in terms of an environmental objective. This objective calls for an 'inverse' approach to decision support that provides information about possible emission strategies that are consistent with specified environmental targets.

Concept

The *guardrail approach* puts the ultimate objective of the UNFCCC's in the focus of the integrated assessment model's application and the associated science-policy dialog. In a nutshell, the approach can be summarized as follows: Based on a set of pre-defined constraints ('guardrails'), the admissible scope of action is sought by investigating the dynamics between society and environment.

Recognizing that it is unlikely that the different social actors involved in international climate policy formulation will agree on what would constitute an 'optimal' climate policy, the guardrail approach is based on the assumption that it may be easier to specify a set of knock-out criteria, which characterize certain developments that should be avoided by (almost) any means. The question *"What kind of world do we want to live in?"* is raised at the outset of the analysis. A guardrail analysis then explores the leeway (or 'possibility space') that remains for society by determining the *set of all admissible climate protection strategies* that are compatible with the predefined guardrails. Climate development and its subsequent impacts are thus confined to tolerable corridors in multi-dimensional state space spanned by inconvertible key variables. Relevant domains for the specification of guardrails include 'intolerable' impacts of climate change (e.g., food security, water availability, ecosystem degradation, and health effects), 'unacceptable' mitigation efforts (e.g., costs and availability of energy services), and 'unfair' burden sharing schemes. Guardrails can be specified in any suitable metric. The guardrail approach therefore allows a clear-cut separation between the scientific analysis of the relevant sub-systems of the Earth on the one hand, and normative decisions on the valuation of climate impacts, and their acceptability, on the other hand.

It should be noted explicitly that the guardrail approach was primarily designed to exclude *a priori* intolerable climate evolutions. It would thus be a major misinterpretation of this approach to assume that a policy that is compatible with a certain set of guardrails would be completely tolerable. For a more in-depth discussion of this topic, including the application of ternary logic or fuzzy logic to describe the indeterminacy of model users, the reader is referred to Bruckner et al. (1999).

Some aspects of the guardrail approach already appear in the 'backcasting' method for energy policy analysis (Robinson, 1982). In a backcasting analysis, future goals and objectives (for energy policy) are first defined in an explicitly normative way. The analysis works then backwards from this future end-point to the present in order to determine the physical feasibility of that future and the policy measures that would be required to reach it. In the systematic suggested by Morgan and Henrion (1990, Chapter 3), the guardrail approach is a satisficing method. Since the guardrail approach applies a hybrid decision criterion that includes rights-based and utility-based decision criteria, it may be characterized as a 'bounded-risk bounded-cost' strategy. Yet in contrast to the decision-analytical frameworks discussed in Morgan and Henrion (1990), the guardrail approach aims at characterizing the complete set of acceptable policy strategy rather than just determining a single acceptable policy path. The guardrail approach may be considered as a dynamical generalization of the 'critical loads' concept, which proved very successful in the negotiation process of the Second Sulphur Protocol (Batterman, 1990; Alcamo et al., 1990; Hettelingh et al., 1995). In this tradition, Swart and Vellinga (1994) called for "a new approach to climate change research" that starts with defining "critical levels" of ecosystem response on a regional level, and to work backwards to determine "ultimate objective levels of GHG concentration changes". However, the proposed approach was not implemented in any IAM. The guardrail approach enables the implementation of the 'pessimization paradigm' and more complex paradigms for sustainable development (Schellnhuber and Wenzel, 1998; Schellnhuber, 1999). However, a detailed discussion of that topic is beyond the scope of this thesis. From an economic perspective, the guardrail approach borrows features from multi-criteria analysis, cost-benefit analysis, and scenario analysis (cf. Bruckner et al., 2003b), which are combined with elements of the 'bounded rationality' concept (Simon, 1972).

The guardrail approach was initially termed 'tolerable windows approach'. It is also known as *inverse* *approach*, as it takes the form of an inverse control problem. All three terms are used synonymously in this thesis. A preliminary version of the tolerable windows approach was proposed by the German Advisory Council on Global Change (WBGU, 1995), and the mature concept is described in Petschel-Held et al. (1999); Bruckner et al. (1999, 2003b). A conceptually similar but methodologically different approach is the 'safe landing analysis' (Alcamo and Kreileman, 1996, 1997, 1998; Swart et al., 1998). The guardrail approach has been taken up in the concept of 'critical climate change', defined as "the quantitative magnitude of climate change (expressed as changes in temperature and precipitation) above which unacceptable long-term effects on ecosystems may occur, according to current knowledge" (van Minnen et al., 2002).

Specification of impact guardrails

The specification of impact guardrails can, in principle, refer to any of the five "reasons for concern" distinguished by IPCC (cf. Section 1.2). However, the related social decision problem differs between these categories, due to differences in the severity of the associated impacts and in the certainty with which forecasts can be made. The most important distinction is the one between 'singular' and 'regular' impacts of climate change. Singular impacts denote discontinuous changes in the large-scale operation of the climate system, such as a potential switch-off of the thermohaline ocean circulation or a major change in the Asian monsoon system. The primary social decision problem here is whether such a phase change is considered acceptable at all, taking into account its potential irreversibility on time scales relevant for human decision-making. Due to the large uncertainty about levels of GHG concentrations that would trigger such events, respective guardrail analyses would also have to consider the likelihood (in a broad sense) of violating the guardrail. The second category of guardrails refer to the impacts of regular climate change, such as gradual decreases in the agricultural potential of a region. The affected systems can be further distinguished into those dominated by human management (such as agriculture and agroforestry) and those dominated by natural biogeochemical processes (such as natural ecosystems and hydrology). Whereas the vulnerability of the former changes over time as it is closely associated with the level of economic development, institutional capacities, and technological capacities of societies, natural systems have a more or less constant sensitivity to climatic stimuli. The basic question for all regular impacts is what level of climate impacts is considered tolerable, taking into account the potential for non-climatic developments and adaptation.

In the classification of the five reasons for concern, singular impacts are represented by large-scale singular events and the extreme events category. So far, guardrail analyses have focussed on preserving the thermohaline circulation (Toth et al., 1998b; Zickfeld and Bruckner, 2003). However, uncertainty about future impacts is particularly large for singular impacts. The climate impact response functions presented in this thesis focus on 'regular' impacts. They address aggregate impacts, the distribution of impacts, and, to some extent, threats to unique systems.

Consideration of uncertainty

The guardrail approach, as described above and implemented in the ICLIPS model, is a purely deterministic approach. It implicitly assumes that future climate change and its impacts can be described deterministically. Due to the large uncertainties involved in climate change, a formal treatment of uncertainties will be the main issue in the further development of the guardrail approach. Compared to other decision-support frameworks, however, even the deterministic guardrail approach encourages the consideration of uncertain information. Various guardrail analyses undertaken for the German Advisory Council on Global Change (WBGU), for instance, have considered the ‘borders of ignorance’ by not allowing the climate system to significantly transgress the global temperature range experienced during the evolution of human civilizations (WBGU, 1995, 1997). Uncertain impacts can also be accounted for by the specification of probabilistic guardrails, which limit the probability of a certain undesirable outcome. For a more in-depth discussion of the consideration of uncertainties in the guardrail approach, the reader is referred to Bruckner et al. (1999); Toth et al. (2003b); Kleinen et al. (2003).

2.4 The ICLIPS integrated assessment model

The guardrail approach was operationalized in the ICLIPS (Integrated Assessment of Climate Protection Strategies) modelling framework. The ICLIPS model is designed to help social actors in making informed judgements about climate change impact targets, mitigation costs, and implementation mechanisms, and to explore their implications for long-term future emission paths as well as for intermediate emission targets. In the hierarchy of Earth system models suggested in Schellnhuber and Kropp (1998), the ICLIPS model lies between a “conceptual model” and an “analogical model”.

This section explains the mathematical implementation of the guardrail approach in the ICLIPS model, outlines the structure of the model, presents its major application modes, and briefly discusses the handling of uncertainty.

2.4.1 Mathematical foundation

The ICLIPS IAM implements the guardrail approach as a specially formulated dynamic control problem. The transient behavior of the coupled global economy-climate system is described by a (deterministic) dynamical model given by a set of (potentially time-dependent) *differential equations*

$$\dot{\boldsymbol{x}}(t) \quad = \quad \boldsymbol{f}(\boldsymbol{x}, \boldsymbol{u}, t) \tag{2.1}$$

with respective *initial conditions*

$$\boldsymbol{x}(t_0) \quad = \quad \boldsymbol{x}_0 \tag{2.2}$$

that links the evolution of the *state vector* $\boldsymbol{x} \in I\!R^n$ (Euclidian n-space) to a (piecewise continuous) *control vector* $\boldsymbol{u} \in \boldsymbol{U}$. The state vector comprises all variables that are necessary to describe the time evolution of the climate-economy system with sufficient precision, such as the concentrations of all major greenhouse gases and global mean temperature change. It may also include additional aggregated variables for the purpose of guardrail definition. Depending on the particular model and the goal of the analysis, the control vector may include variables such as the emission of greenhouse gases, the level of carbon taxes, and the investment in renewable energy research.

The policy targets to be explored in any given guardrail analysis impose environmental, climatic, economic, and social constraints on the climate-socioeconomic system. In principle, any component of the state or control vectors can be included in the definition of guardrails. The set of all guardrails can be described in vector form by an application-dependent *constraint function*

$$\boldsymbol{h}(\boldsymbol{x}, \boldsymbol{u}, t) \quad \leq \quad \boldsymbol{0}. \tag{2.3}$$

This formulation is general enough to account for simultaneous restrictions on the present value of certain control variables and on the present value, cumulated values, and the rate of change of certain state variables.

A guardrail analysis intends to identify the set of all climate protection strategies that simultaneously satisfy all constraints on the state and control variables. This leads to the problem of dynamic non-uniqueness, which can be treated most suitably by using the theories of differential inclusions and optimal control. Most importantly, the theory of differential inclusions (or multivalued differential equations) provides some powerful theorems on the existence and optimality of solutions, and methods to obtain these solutions (Aubin and Cellina, 1984; Aubin, 1991; Deimling, 1992). The correspondence between control problems and differential inclusions is easily seen by expressing the control system from Equation 2.1 as the equivalent *differential inclusion*

$$\begin{aligned} \dot{\boldsymbol{x}}(t) &\in \boldsymbol{f}(\boldsymbol{x},\boldsymbol{U},t) \\ &\equiv \bigcup_{\boldsymbol{u}\,\in\,\boldsymbol{U}} \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},t). \end{aligned} \tag{2.4}$$

Inserting the constraint function (Equation 2.3) into the dynamical model (Equation 2.1), we obtain the differential inclusion

$$\begin{aligned} \dot{\boldsymbol{x}}(t) &\in \boldsymbol{F}(\boldsymbol{x},t) \\ &\equiv \{\boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},t) \mid \boldsymbol{u} \in \boldsymbol{U} \wedge \boldsymbol{h}(\boldsymbol{x},\boldsymbol{u},t) \leq \boldsymbol{0}\}. \end{aligned} \tag{2.5}$$

In contrast to traditional optimal control problems, we are not interested in a single *optimal* path, but in a family of *admissible* paths. The most comprehensive solution of the differential inclusion

$$\dot{\boldsymbol{x}}(t) \in \boldsymbol{F}(\boldsymbol{x},t), \qquad x \in I\!R^n, \quad t \in T \tag{2.6}$$

for the time period $T = [t_0, t_e]$ with initial conditions $\boldsymbol{x}(t_0) = \boldsymbol{x}_0$ is the *set of admissible trajectories* denoted as

$$\mathcal{S}(\boldsymbol{F},T,\boldsymbol{x}_0) = \{\boldsymbol{x}(\cdot) \in AC(T,I\!R^n) \mid \boldsymbol{x}(t_0) = \boldsymbol{x}_0 \wedge \forall_{t\in T}\, \dot{\boldsymbol{x}}(t) \in \boldsymbol{F}(\boldsymbol{x},t)\} \tag{2.7}$$

whereby $AC(D,R)$ denotes the Banach space of absolutely continuous functions with domain D and range R. Applying Equation 2.7 to the 'ICLIPS differential inclusion' (Equation 2.5), we obtain its solution

$$\begin{aligned} \mathcal{S}(T,\boldsymbol{x}_0) = \{&\boldsymbol{x}(\cdot) \in AC(T,I\!R^n) \mid \boldsymbol{x}(t_0) = \boldsymbol{x}_0 \wedge \\ &\exists_{\boldsymbol{u}(\cdot)\in L_2(T,\boldsymbol{U})}\, \forall_{t\in T}\, \dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},t) \wedge \boldsymbol{h}(\boldsymbol{x},\boldsymbol{u},t) \leq \boldsymbol{0}\} \end{aligned} \tag{2.8}$$

whereby $L_2(D,R)$ denotes the Hilbert space of measurable functions with domain D and range R.

Given the initial conditions, the set of admissible state trajectories (or *set of admissible futures*) is uniquely determined by the *set of admissible control paths*. Even in the case of a highly aggregated IAM, each of these sets (if they are non-empty) will typically consist of an infinite number of time trajectories in a high-dimensional state space. The actual determination of these path bundles, which would require a complete model inversion, goes far beyond what can be achieved either analytically or numerically. Implementations of the guardrail approach must therefore be concerned with the determination of 'partial solutions', which consist of projections of the high-dimensional set of admissible state-control trajectories onto pertinent subspaces related to crucial variables of the model. Fortunately, various interesting partial solutions can be derived without knowing the complete solution. In particular, Leimbach and Bruckner (2001) have developed a generally applicable method to determine the boundaries of the control space portrayed as necessary emission corridors in discrete form by successively solving a multitude of dynamic optimization problems. The remainder of this section discusses policy-relevant partial solutions of guardrail analyses. For a more formal discussion, see Bruckner et al. (1999); Petschel-Held et al. (1999); Bruckner et al. (2003b).

The most important partial solutions that can be determined by the ICLIPS model are necessary (emission) corridors. A *necessary corridor* projects the full solution (i.e., the bundle of all admissible trajectories) onto a plane that is defined by the time axis and the axis of a specific state or control variable, most often global greenhouse gas emissions. It is defined as

$$\mathrm{Cor_i}(T, \boldsymbol{x}_0) \quad = \quad \{(x_i, t) \in I\!R \times T \mid \exists_{\boldsymbol{x}(\cdot) \in \mathcal{S}(T, \boldsymbol{x}_0)}\, \boldsymbol{x}(t)\big|_i = x_i\}, \tag{2.9}$$

whereby $\boldsymbol{x}\big|_i$ denotes the projection of the vector $\boldsymbol{x}$ onto its i-th dimension. For the sake of convenience, we interpret $\mathcal{S}(T, \boldsymbol{x}_0)$ here as the set of admissible *state-control* trajectories during the time period T with initial conditions $\boldsymbol{x}_0$.

It is important to understand that a necessary corridor does not contain information about the dynamics of the system because the projection operates on single points rather than whole emission trajectories. Therefore, every point inside the corridor *can* be reached by an admissible trajectory, and every trajectory that leaves the corridor is clearly *not* admissible. However, an arbitrary trajectory lying inside the emission corridor is not necessarily admissible. In particular, the upper boundary of the necessary emission corridor is generally *not* an admissible emissions path.

To aid the interpretation of model results, the presentation of necessary emission corridors is often complemented by selected admissible emission paths that indicate the ‘inner structure’ of the solution space, such as in Figure 2.4. This diagram shows an illustrative necessary emission corridor (in green), which was determined by the algorithm described in Leimbach and Bruckner (2001) based on certain constraints for future climate development. The horizontal axis represents time, and the vertical axis denotes the level of greenhouse gas emissions. The red line depicts the (unmitigated) reference emission scenario that serves as an upper bound for any emission scenario. Of particular interest are the blue trajectories inside the corridor that define the upper boundary of the corridor for discrete points in time. We observe that emission paths that maximize emissions at a certain point in time lie far inside the corridor before and afterwards. Hence it is not admissible to follow the upper boundary of the corridor for the whole time period. (In contrast to the corridors for emission *rates* presented here, the upper boundary of the corridor of *cumulative* emissions presented in Petschel-Held et al. (1999) *is* a feasible control path.)

The (necessary) emission corridor —representing ‘policy space’— allows some degree of flexibility in choosing the actual emission path. Negotiators can consider policy details that are not explicitly modelled and can set near-term targets within the corridor accordingly. For example, experience from the negotiations about national emission targets for the Kyoto Protocol indicates that the mitigation commitments that are decided upon in international agreements are determined by various domestic considerations (energy, industrial, transport, agriculture, and other policies), which are impossible to represent adequately in a highly aggregated long-term model. However, the emission corridor is helpful because it clearly indicates the range inside which aggregated global emissions need to be in a given year. Depending on the emission target being considered, the model can calculate a new subcorridor within

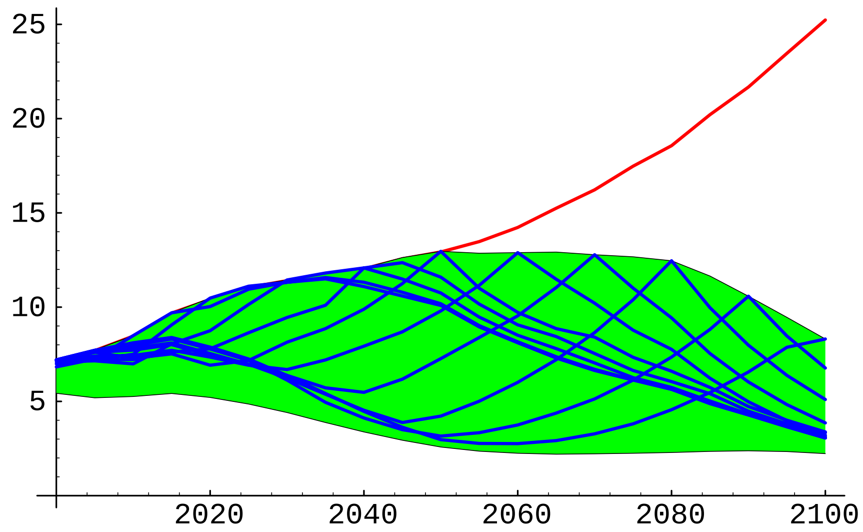


Figure 2.4: Inner structure of an illustrative necessary emission corridor

the original emission corridor for the rest of the time horizon. This flexibility also allows mid-course corrections in light of new information and recalculation of the emission corridor on the basis of revised model parameters or normative targets.

Through a low-dimensional parametrization of control space, it is also possible to determine sufficient conditions for admissible control strategies. For an example with an earlier version of the ICLIPS model, see Petschel-Held et al. (1999). In principle, one can also determine *sufficient emission corridors* in the sense that all parameterized emission trajectories inside the corridor are admissible. However, the additional constraints needed to ensure this kind of 'generalized convexity' are rather strict.

Another interesting result of the ICLIPS model are *reachable domains*, defined as feasible combinations of values of at least two model variables under given constraints. A two-dimensional reachable domain is defined as

$$\mathrm{Reach}_{\mathrm{ij}}(T, \boldsymbol{x}_0) \quad = \quad \{(x_i, x_j) \in I\!R^2 \mid \exists_{\boldsymbol{x}(\cdot)\in\mathcal{S}(T,\boldsymbol{x}_0),t\in T}\ \boldsymbol{x}(t)\big|_i = x_i \wedge \boldsymbol{x}(t)\big|_j = x_j\}. \qquad (2.10)$$

Reachable domains can, in principle, be determined for any combination of model variables. An algorithm for determining reachable climate domains is presented in Section 3.6.5, and selected results are presented in Section 4.1.

2.4.2 Model structure

IAMs addressing the climate change problem deal with a very heterogeneous system. They face a number of challenges in terms of the diversity of spatial and temporal scales as well as the complexity of the processes involved. IAMs need to account for global GHG emissions from all major sources. However, they should also be able to deal with climate change impacts in relevant sectors at a level of regional detail that is relevant for (at least) national-level policymakers. The atmospheric residence times of most

GHGs and the inertia of the atmosphere-ocean-terrestrial biosphere system demands long-term analysis extending over centuries. In contrast, assessments of socioeconomic and technological development patterns, the resulting GHG emissions and mitigation costs are highly uncertain beyond a few decades into the future. Policy attention is also focussed on actions to undertake in the next decade or two. Complexities range from highly non-linear processes in the Earth system to the intricacies involved in instruments and implementation mechanisms of various mitigation options.

IAMs to be used for inverse analysis face additional challenges. The determination of *sets* of admissible emission paths requires the consideration of a very large number of scenarios. Hence, the computational efficiency of each (dynamical) model component is a crucial criterion. In response to these challenges, the ICLIPS IAM is implemented as a tightly interconnected system of submodules that differ in their spatial resolution, temporal characteristics, and application modes.

Figure 2.5 shows the structure of the ICLIPS model and the data-flow for different application modes that will be described in Section 2.4.3. The core of the ICLIPS model system is the ICLIPS climate-economy model (ICEM) that combines a highly aggregated multiregional model of the world economy and a multi-gas reduced-form climate model in an optimizing framework (Toth et al., 2003a). ICEM is linked to a reduced-form impacts module that consists of sector-specific global and regional climate impact response functions (CIRFs).

The ICLIPS aggregated economic model (AEM; Leimbach and Toth, 2003) is a Ramsey-type optimal growth model. It describes the most essential elements of the long-term economic development process, the investment and capital accumulation cycle, in an endogenous way. The global economy is split into eleven regions so that the AEM can cope with the varying starting conditions and development patterns of different regions and depicts essential growth dynamics elements that result from interregional relations. AEM allows for the mobility of capital and intertemporal trade as well as trading of GHG emission rights among regions. Similar to the economic modules of other IAMs, the economic growth path is determined by exogenous population and endogenous investment dynamics. Assumptions about productivity change are elaborated in a technological diffusion model that describes the process of regions that are currently less developed catching up with more developed ones as a result of technology transfer. Baseline emissions throughout the twenty-first century resemble the SRES A1FI emission path (Nakicenovic and Swart, 2000).

The ICLIPS model incorporates dynamic regional carbon-mitigation cost functions (Gritsevskyi and Schrattenholzer, 2003). The procedure combines processes of technological change in energy systems over the long term in the context of macroeconomic models and establishes relatively simple relationships between cumulative mitigation actions, technological changes, and their effects on economic development. A multitude of scenarios is processed statistically to derive dynamic carbon-mitigation cost curves. These cost curves are used to determine the costs of CO_2 emission reductions relative to emissions in the baseline scenario. Since capital stock dynamics in the energy sector are not explicitly modelled in the core model, an upper limit has been set to the rate of emission reduction to prevent unrealistic model behavior.

Greenhouse gas emissions link the AEM to the ICLIPS climate model (ICM; Bruckner et al., 2003a). ICM accounts for all major greenhouse gases —carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, sulfur hexaflouride (SF_6), tropospheric and stratospheric ozone (O_3), and stratospheric water vapor— as well as the (globally averaged) radiative effects of aerosols originating from sulfur dioxide (SO_2) emissions and biomass burning. In contrast to most optimizing integrated assessment models, the ICLIPS dynamic optimization model includes nonlinear carbon-cycle and non-CO_2

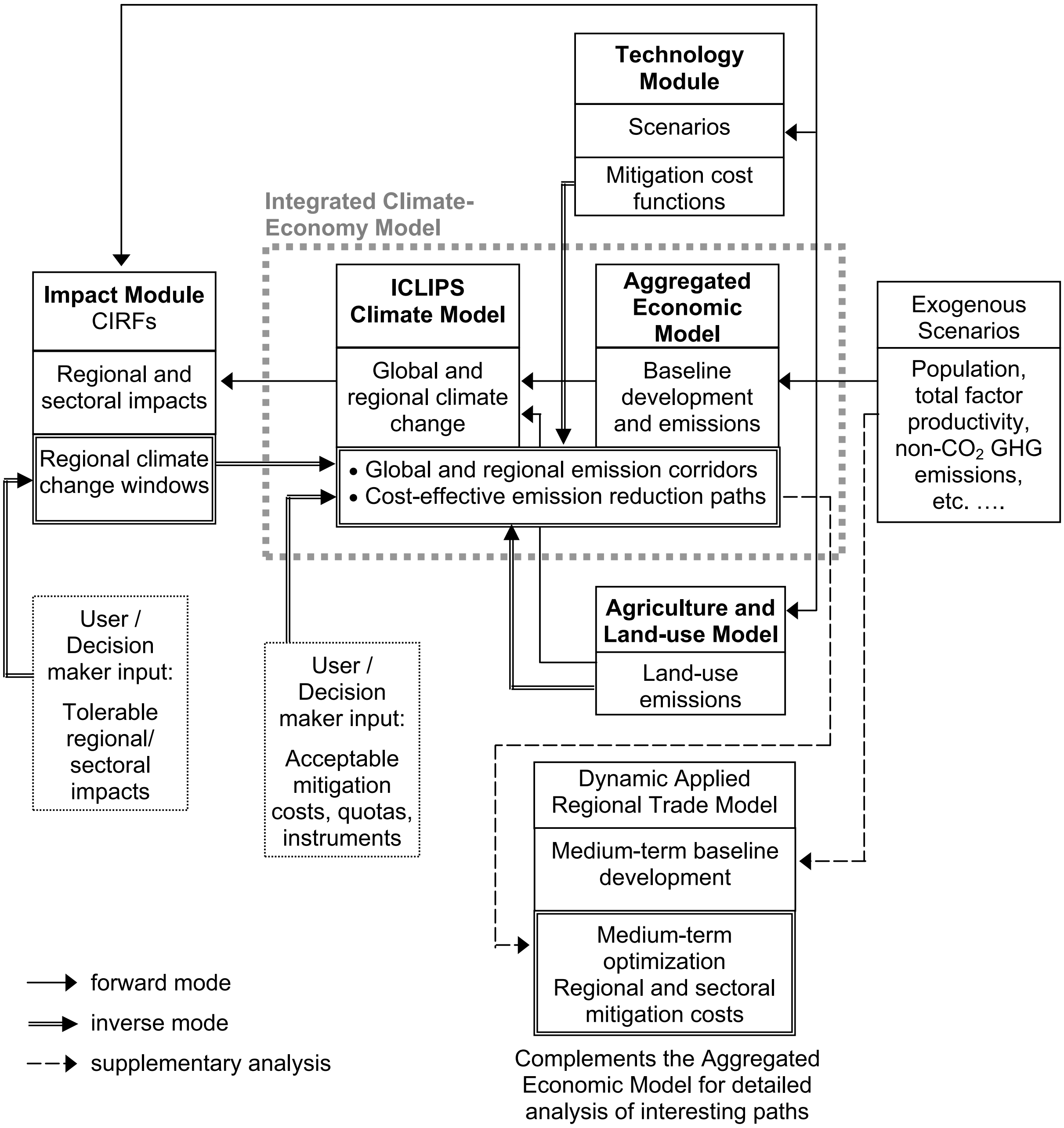


Figure 2.5: Structure and application modes of the ICLIPS integrated assessment model. Source: Toth et al. (2003a).

chemistry as well as climate and sea-level rise modules that reflect state-of-the-art understanding of the dynamic behavior of the systems involved. The biogeochemical modules convert emissions into concentrations, and the climate module translates the corresponding radiative forcing (changes in the radiative energy balance of the Earth) into global mean temperature increases over time. The projected change in global mean temperature is used to scale patterns of regional changes in temperature, precipitation, and cloud cover derived from more complex climate models, the so-called general circulation models. Finally, sea-level rise modules calculate changes from thermal expansion of oceans and ice melting.

ICEM is programmed in GAMS (General Algebraic Modelling System; Brooke et al., 1994). Since GAMS does not provide for a dynamic description of model variables and their relationships, a GAMS model needs to be specified for discrete time steps, whereby differential equations are approximated by appropriate difference equations. The initial dynamic optimization problem is therefore transformed into a high-dimensional static optimization problem, which can be addressed by suitable non-linear solvers. ICEM is computationally very efficient because it distinguishes only a few world regions. Whereas this level of detail is sufficient for reproducing important features of the dynamics of the economic system and the climate system, meaningful assessments of climate change impacts typically require a finer spatial resolution.

ICEM is linked to the ICLIPS impact module, which consists of a comprehensive set of regionalized CIRFs (see Chapter 3) via pathways for CO_2 concentration and global mean temperature change. CIRFs indicate how climate-sensitive sectors and systems react to changes in selected indicators of the global climate system. They have been developed in order to incorporate information from geographically explicit impact models into the integrated ICLIPS model without impairing its computational efficiency. The climatic input to the impact models is constructed by a scaled scenario approach that uses maximum information from GCM experiments in a highly efficient manner. Results are typically presented at the level of single countries or groups thereof.

The integrated ICLIPS model is supplemented by the ICLIPS Impacts Tool, a graphical user interface that provides access to a large set of results from the impact simulations performed in the ICLIPS framework (see Section 3.7).

2.4.3 Application modes

The ICLIPS model can be applied in three different modes:

Forward mode: The model is used for scenario analyses to determine how a given scenario of socioeconomic development and associated GHG emissions affects climate change and its impacts. Illustrative results are presented in Section 4.2.1.

Inverse mode: The model is used for guardrail analyses to demarcate the emission policy space under exogenously specified environmental and social targets. The ICLIPS model steps beyond the span of all other global IAMs by allowing users to establish climate stabilization objectives on the more tangible basis of what they consider unacceptable impacts (such as reduced food production potential or ecosystem change) rather than on the more abstract basis of GHG concentrations of GMT change, and by determining the set of admissible climate protection strategies instead of just one.

An inverse application of the ICLIPS model involves various steps, as shown in Figure 2.6. In the *decision step*, social actors as users of the ICLIPS model can specify their willingness to accept a certain amount of climate change impacts in important sectors in their own jurisdiction by means of appropriate climate change indicators covered by a CIRF from the impacts module. Given the aggregation level of the impacts module, detailed knowledge of the affected impact sector and good understanding of the surrounding socioeconomic conditions are generally required to make an informed judgement about the

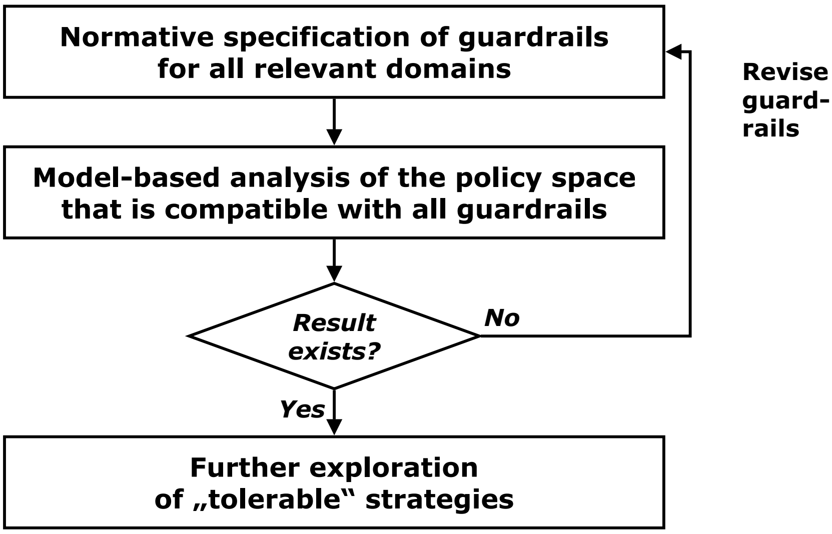


Figure 2.6: Structure of a guardrail analysis with the ICLIPS integrated assessment model

level of climate change induced impacts with which the given sector or region can cope. It is, of course, possible to ignore the CIRFs and to define acceptable changes directly in climatic terms. Second, the same social actors can reveal their perceptions about their society's willingness to pay for climate change mitigation in terms of the acceptable social costs for their nations as well as in terms of acceptable burden sharing principles and implementation schemes internationally. The model user can also specify inter- and intragenerational equity preferences, e.g., in terms of the initial allocation of the total emission budget across regions and possible changes of the allocation rule over time

The decision step is followed by an *analysis step*. If GHG emission paths exist that satisfy the set of constraints specified in the analysis step, the model determines an emission corridor that contains all such permitted paths. It is important to remember that each point within or at the boundary of the corridor can be reached by at least one acceptable emission path whereas not all arbitrary paths within the corridor are necessarily permitted paths. For the given set of constraints, the emission corridor can be perceived as the room to maneuver for global climate policy over the long term. Specific 'interesting' policy paths can then be assessed in detail using both quantitative and qualitative information. If no such path exists, the user-specified guardrails need to be revised because they are not compatible with each other. The loosening of constraining impact guardrails may involve compensations for unavoided impacts or resource transfers to increase the adaptive capacity in the most vulnerable regions and sectors. Alternatively, willingness to pay for emission reductions can be increased or more cost-reducing flexibility instruments can be allowed on the mitigation side. Illustrative results are presented in Section 4.5.

Cost-effectiveness mode: The economic constraints in a guardrail analysis are replaced by the objective to maximize discounted global welfare. In that way, the model determines the least-cost policy path (within the emission corridor determined in an inverse analysis) that is compatible with the given environmental guardrails. Illustrative results are also presented in Section 4.5.

2.4.4 Handling of uncertainty

Future climate change and its impacts are subject to many uncertainties. The accumulation of uncertainty throughout the process of climate change prediction and impact assessment has been variously described as a 'cascade of uncertainty' (Schneider, 1983) or the 'uncertainty explosion' (Henderson-Sellers, 1993). Hence, the treatment of uncertainties is a crucial concern in any climate change assessment.

There are various taxonomies of uncertainty in the context of IA. A broad classification distinguishes between uncertainty due to variability and uncertainty due to limited knowledge. These two categories are closely related to *aleatory* and *epistemic* uncertainties, respectively. For a more detailed discussion of this topic, see Morgan and Henrion (1990); van Asselt and Rotmans (2002).

The major techniques for examining the effects of uncertain inputs within a predictive model are:

Sensitivity analysis computes the effects of changes in inputs on model predictions.

Uncertainty propagation (or stochastic modelling) generalizes sensitivity analysis by calculating the uncertainty in the model outputs induced by the probabilistically described uncertainties in its inputs.

Importance analysis compares the importance of the input uncertainties in terms of their relative contributions to uncertainty in the outputs.

Whilst sensitivity analysis has been extensively applied to the ICLIPS model, there are various practical and methodological obstacles that currently prevent the application of uncertainty propagation and importance analysis in guardrail analyses of global climate change. First, both techniques are targeted at predictive models that determine single-valued outputs which can be described in probabilistic terms. In contrast, the output of models implementing the guardrail approach consists of complex sets that are not amenable to a straightforward description by a probability distribution. It is, for instance, not clear how to define (or compute, or visualize) a stochastic emission corridor. Second, both techniques require a description of uncertain parameters by (objective or subjective) probability distributions. However, this is not possible for many sources of epistemic uncertainty in the context of climate change due to empirical, methodological, institutional, and philosophical problems (Webster, 2003). There are even types of evidential knowledge that cannot be described in terms of probabilities at all (Dempster, 1967). The theory of *imprecise probabilities* provides various mathematical techniques that do not require fully probabilistic descriptions of uncertain inputs (Walley, 1991, 2000). Evidence theory and possibility theory, for instance, generalize the concept of 'probability' by providing lower and/or upper bounds on probabilities rather than exact values. Unfortunately, these techniques are in general more complicated than probability theory. Hence, their application in the context of climate change is currently limited to very simple models. Furthermore, the results are typically characterized by very large output uncertainties (see, e.g., Kriegler and Held, 2003).

The exploration of uncertainties with the ICLIPS model largely follows the practice prevailing in other recent IAMs of similar complexity. The integrated model as well as its main modules have been exposed to systematic sensitivity tests by varying one key model parameter after another across a plausible range and observing how the fundamental output categories change as a result. The results of selected sensitivity analyses are reported in Chapter 4. For additional uncertainty analyses with the integrated ICLIPS model, see Toth et al. (2003a,b), and for analyses with the impacts module, see Füssel and van Minnen (2001); Füssel et al. (2003).

Chapter 3

Impacts modelling in the ICLIPS integrated assessment model

This chapter describes the development of the impacts module of the ICLIPS integrated assessment model. Section 3.1 reviews the representation of climate impacts in 'traditional' integrated assessment models of climate change (IAMs), Section 3.2 describes the requirements and principle options for the consideration of impacts in 'inverse' IAMs, and Section 3.3 presents the pattern scaling approach for projecting future climate change in the ICLIPS model. Based on that work, Section 3.4 introduces the concept of climate impact response functions (CIRFs), which is central to the consideration of climate impacts in the ICLIPS model, and Section 3.5 describes the impact indicators and models applied in the various sector-specific CIRFs. Section 3.6 presents various applications of the CIRFs, including algorithms for the parameterized approximation of 'tolerable' climate windows and for the computation of reachable climate domains. Finally, Section 3.7 introduces the ICLIPS Impacts Tool, a graphical user interface that provides convenient access to the large set of CIRFs developed for the ICLIPS model.

Section 3.1 is a review of the existing literature by the author of this thesis. Sections 3.2 and 3.3 present work of the author, some of which has already been published in Füssel and van Minnen (2001). Section 3.3 is partly based on climate projections that were provided by external partners in the ICLIPS project. Sections 3.4, 3.5, and 3.6 present work of the author, most of which has already been published in Füssel and van Minnen (2001); Füssel (2003b); Füssel et al. (2003); Bruckner et al. (2003a). Section 3.7 presents work of the author that has already been published in Füssel (2002b, 2003b).

3.1 Impacts modelling in traditional decision frameworks

The discussion in the previous chapter revealed that there is no single best approach to the assessment of climate impacts. Differences between existing assessments can, to a large extent, be linked to different purposes, such as whether they were initiated to inform mitigation or adaptation policy. The adequate representation of climate impacts in IAMs is complicated by the wide range of potential climate impacts; by large uncertainties about future climate change, associated biophysical impacts, and the socioeconomic determinants of vulnerability; by the diversity of plausible non-climatic developments; by the difficulty of accounting for autonomous and planned adaptation; and by the importance of subjective valuations and aggregations.

Various approaches have been pursued in order to represent aggregated climate impacts in IAMs. An early review of over 20 IAMs is presented in Tol and Fankhauser (1998). The focus lies on policy optimization models but some policy evaluation models are included as well. (At the time of the review, no policy guidance model had been developed.) The surveyed IAMs differ widely with respect to the damage categories considered, the measurement unit, and the level of spatial detail, whereby the underlying decision framework was the primary distinguishing factor. All optimizing models represented climate impacts by aggregated monetary damage functions. Key issues in the specification of such damage functions are the choice of explanatory variables (level and/or rate of change in global or regional annual mean temperature, and possibly sea-level rise), the prescribed functional form (usually a polynomial or a power function), the discount rate and time horizon, the choice of the welfare criteria for aggregation across regions, and the treatment of uncertainty. The empirical foundation of such damage functions was, however, rather weak. The functional relationship between climate indicators and (market) impacts was typically devised by the authors and fit to a limited number of impact assessments. Despite the impressive number of optimizing IAMs considered in Tol and Fankhauser (1998), monetized impact estimates were found to be *"based on a rather narrow set of studies"* and *"Damage modules are often not more than ad hoc extrapolations around the* $2{\times}CO_2$ *benchmark"*. Most often, the damage function was defined simply as a quadratic function of the change in annual global mean temperature (AGMT). Impact estimates that considered both the rate and the level of change did this on an even more speculative empirical base.

In contrast, policy evaluation models were found to be more science-oriented, geographically explicit and had process-based modules to estimate climate impacts. All of them used grid-based projections of monthly or daily temperature and precipitation, and some of them included also cloudiness, soil moisture, and sea-level rise. Of course, the greater level of detail associated with this more extensive set of climate inputs comes at the price of higher uncertainty than in projections of AGMT only. Interestingly, the evaluation models were also found to be superior to the optimization models with respect to the consideration of non-climatic developments and of adaptation. All except one of them included adaptive responses to biophysical impacts and non-climatic developments, such as changes in land allocation, crop management practices, and producers' and consumers' behaviour. These models also allowed for adaptation capacity to depend on the socioeconomic situation.

Early examples of cost-benefit models include DICE (Nordhaus, 1994), in which the change in AGMT is the only predictor for the impacts of climate change, and FUND (Tol, 1996), which also considers the rate of change. Tol (2002a,b) later estimates a series of monetary climate damage functions based on globally comprehensive studies using GCM-based scenarios. This impact model takes account of the dynamics of both climate change and the impact sectors, and it uses statistical methods to combine and extrapolate results of different studies over different climates and different degrees of vulnerability to climate change. Another attempt to construct so-called 'climate-response functions' with a broader empirical base was the development of the 'global impact model' (GIM; Mendelsohn et al., 2000). Here, empirical studies of the US economy were used to establish a relationship between local temperature and precipitation on the one hand and market impacts for each climate-sensitive sector on the other, which was then applied worldwide.

The response of the climate system to anthropogenic forcing includes the potential for so-called climate 'catastrophes' or (imaginable) 'surprises' (Schneider et al., 1998). These terms are used to denote changes in climate, atmospheric composition, or the geophysical Earth system with (almost) global impacts. So far, there have been only a few attempts to include such events in IAMs. Gjerde et al. (1999) present an optimizing IAM that takes into account both continuous climate-feedback damages as well as the possibility of an (unspecified) catastrophic outcome. The hazard function representing potential catastrophes is represented by a convex Weibull distribution, which is calibrated to represent the aggregate result of a panel of experts who revealed their subjective probabilities for a climate catastrophe contingent on a specific climate scenario. The version of the RICE model presented in Nordhaus and Boyer (2000) comprises a set of regionally and sectorally disaggregated impact assessments based on a willingness to pay approach. The estimation is undertaken for thirteen world regions and seven impact categories, including 'catastrophic impacts' associated with major geophysical calamities. The resulting impact functions indicate the fraction of annual income that a region is willing to pay to avoid the effects of incremental climate change for a given sector. Keller et al. (2000) subject the DICE model (Nordhaus, 1994) to the additional constraint that the thermohaline ocean circulation (THC) must be maintained and estimate the implications for an 'optimal' climate policy. THC collapse is calculated by a polynomial fit to the results of a simplified ocean model. Mastrandrea and Schneider (2001) couple the DICE model to a simple process-based climate model capable of representing abrupt changes in the THC. Azar and Lindgren (2003) developed a stochastic version of the DICE model that includes the initial possibility of an (unspecified) catastrophic outcome to investigate hedging strategies for mid-term climate policy.

Wright and Erickson (2003) review the state of scientific understanding regarding three frequently mentioned geophysical catastrophes with a view toward their implications for integrated assessment modelling, focussing on cost–benefit models. These catastrophes comprise a 'runaway greenhouse' driven by positive climate-methane hydrate feedbacks, rapid sea-level rise caused by a destabilization of the West Antarctic ice sheet, and a THC disruption triggered by fresh-water perturbation. This analysis reveals inadequacies in widespread model assumptions regarding climate change impacts in general, and potential climate catastrophes in particular. Wright and Erickson (2003) find that the widespread reliance on global mean temperature, which is assumed to be well-behaved and smoothly increasing, as a 'sufficient statistic' for the purposes of policy optimization modelling has contributed to an overly simplistic picture of climate change; that the application of 'best guess' scenarios systematically neglects the possibility of low-probability, high-consequence events with the potential to significantly affect climate policy; that inappropriate assumptions about uncertainty and the resolvability of this uncertainty play a key role for the implication of threshold-type climate catastrophes on 'optimal' emissions reductions; and that standard discounting practice in economic models is inadequate for the analysis of climate impacts, given the possibility of greatly postponed yet significant consequences from near- and medium-term actions. As a consequence, they call for a reframing of the source of climate change damages in economic models, placing changes in climate predictability, rather than gradual changes in mean values, at the focus of impact and adaptation assessments.

3.2 Impacts modelling in inverse decision frameworks

The previous section briefly reviewed the representation of climate impacts in IAMs based on 'traditional' decision frameworks. A key finding of this review was that IAMs based on policy optimization and policy evaluation frameworks follow radically different approaches to the representation of climate impacts. This section starts with a discussion of key requirements for the modelling of 'smooth' climate impacts in ‘inverse’ IA frameworks, with specific reference to the ICLIPS model. It is argued that climate impacts need to be represented by reduced-form models that approximate the results of more complex process-based impact models. The relative merits of various approaches to developing such reduced-form impact models are then briefly discussed.

3.2.1 Requirements

The characteristic feature of ‘inverse’ analyses of the climate change problem is that the analysis is not restricted to a small number of predefined scenarios. In fact, (virtually) all feasible climate development paths need to be assessed as to their compatibility with a set of guardrails specified by the model user. Therefore, the modelling of climate impacts in inverse approaches in general, and in the ICLIPS framework in particular, faces the following requirements.

Consideration of geographical heterogeneity: Anthropogenic climate change, and even more its impacts, will manifest itself very heterogeneously across the world. Models for smooth climate impacts applied in an inverse analysis need to be spatially explicit, with implications for the assessment and communication of uncertainty, in order to enable the specification of guardrails for regional climate impacts.

Application efficiency: An inverse analysis involves the assessment of a large number of future trajectories. In order to limit the overall computational costs, an implementation of the inverse approach needs to constrain the computational complexity of a single model run as well as the number of model runs necessary for the determination of the result set.

The former goal calls for the application of efficient reduced-form impact models instead of sophisticated yet overly complex climate impact models. The most important methods to achieve the latter goal are parametrization, optimization, and regression. *Parametrization* denotes the description of future system states or (control) scenarios by a few parameters. If the parameter space is low-dimensional, a representative subset of scenarios can be tested as to their compatibility with the specified guardrails. However, given the complexity of the climate change problem, the explanatory power of a model with a low-dimensional domain is generally limited. *Optimization* exploits certain properties of the mathematical model of the system or of the result set (such as smoothness, monotonicity, connectivity, or convexity) to restrict the simulations to those scenarios that may be relevant for the determination of the result. *Regression* denotes the development of a statistical model that links certain input and output variables, based on the outcome of a large number of simulation runs with the full model.

The ICLIPS model (see Section 2.4) employs parametrization as well as optimization in order to constrain its computational demand. The control space of the ICLIPS climate-economy model (ICEM) is parameterized by formulating the model for discrete time steps, and the computation of emission corridors is actually done by solving many optimization problems. In contrast, the safe landing method, as described in (Alcamo and Kreileman, 1998), applies a regression technique for determining so-called “safe emission corridors”. A low-dimensional parametrization of plausible future climate states has also been applied to specify the domain of definition of the climate impact response functions (see Section 3.4).

Development efficiency: Computational efficiency is a crucial requirement not only for the *application* of a (reduced-form) impact model in an inverse framework; the computational requirements for the *development* of the reduced-form model need to be reasonable as well. This requirement restricts, in particular, the development of spatially explicit empirical-statistical impact models with many independent input parameters where the fitting procedure would require a large number of simulations with the original impact model.

Descriptional conciseness: The amount of memory available for storing the reduced-form model may also be a limiting factor. This constraint is most relevant for table-based reduced-form impact models.

Software compatibility: The reduced-form impact model employed in an inverse analysis needs to be compatible with the other components of the integrated assessment model that it is linked to.

In the ICLIPS model, the impact model effectively serves to constrain the computation of feasible emission paths by ICEM, which is programmed in GAMS. GAMS requires a model to be specified in terms of variables, sets, equations and inequations but it does not allow the call of external subroutines (such as an impact model) that could perform calculations for specific values of model variables. Hence, the only feasible way to represent impact guardrails in the integrated ICLIPS model is to specify them as inequalities that incorporate variables from ICEM, and to include these inequalities as constraints in the GAMS code. The method for translating impact guardrails into a set of inequalities is described in Section 3.6.4.

Scientific validity: Last but not least, the reduced-form model should reproduced the key characteristics of the sophisticated impact model. The scientific validity of the reduced-form model may be impaired by unrealistic restrictions of the input variables, by unrealistic assumptions about the functional form of the relationship between input and output variables, and by unrealistic assumptions about the topography of the result space.

3.2.2 Types of reduced-form impact models

We have argued above that global IAMs to be applied in an inverse framework, such as the ICLIPS model, require the application of efficient (i.e., reduced-form) impact models. We now present several types of (reduced-form) impact models and discuss their suitability for ICLIPS, based on the criteria specified above.

Figure 3.1 shows the major categories of reduced-form impact models, and sketches their development. The first step always consists of the application of a process-based impact model, which performs scenario analyses for a representative set of (parameterized) inputs. In the second step, the resulting look-up table is used to develop a reduced-form model. The following categories of impact models are considered in Figure 3.1:

Process-based impact models explicitly simulate those real-world processes that are most relevant for a specific impact domain. Typical examples include models for sea-level rise that are developed around equations for thermal expansion and ice melting and crop models that start from determining photosynthetic rates to eventually arrive at potential crop yields. Some of these models also allow to assess the effects of various adaptation options in a changing climate. Process-based models are the back-bone of model-based climate impact assessments as they represent the state of the art of impact

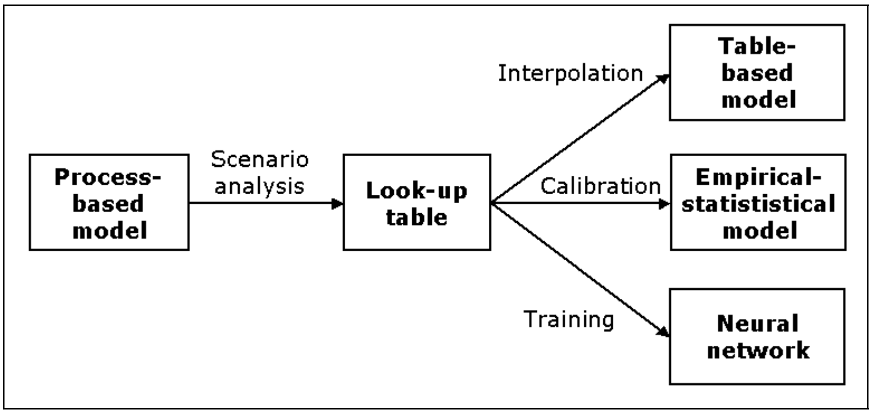


Figure 3.1: Alternatives for developing reduced-form impact models

modelling. However, this advantage generally comes at the price of extensive data requirements and high computational demand.

Look-up tables and table-based models store the results of an impact model for a representative set of combinations of its input variables. They are particularly useful if the original impact model is computationally demanding, and if the IA analysis requires the evaluation of many climate scenarios. A table-based model typically consists of the look-up table and an interpolation routine for determining intermediate function values. The greatest advantages of table-based models are their computational efficiency, and their independence from any *a priori* knowledge about the functional relationship between the input and output variables of the impact model. Their greatest disadvantage is that their size increases exponentially with the number of (independent) input variables. As a result, they become unhandy if more than a few independent input variables are involved.

Empirical-statistical models comprise a broad class of models where a given analytical expression has been calibrated to a set of observed or simulated data. They may either be used as an *alternative* to process-based impact models (if the state of knowledge about a system does not allow for a process-based simulation; not shown in Figure 3.1) or as an efficient *substitute* that approximates their results, which were previously stored in a look-up table. Clear advantages of this category of models are their computational efficiency and their concise description. The most important disadvantage is that they require previous knowledge about the functional relationship between input and output variables (e.g., linearity), and that the calibration procedure may be very time- and data-demanding, depending on the number of spatial units that require independent calibration and on the number of available data points.

Neural networks emulate certain characteristics of biological brains by (often parallel) computers. A neural network consists of several layers of interconnected neurons each of which translates an input vector into a scalar output. The behaviour of a neuron depends on its so-called firing function and the weights associated with its inputs. A neural network first has to be trained by a rather large set of known input-output combinations (e.g., climate vectors and associated impact values derived from observations or process-based impact models). This training works by sequentially adjusting the weights of the neurons through some learning algorithm until the neural network satisfactorily translates input vectors into the corresponding output values. For further information, see, e.g., Haykin (1999). The main advantage of neural networks, compared to simpler empirical-statistical models, is that they do not require an a priori specification of the functional form of the input-output relationship. However, the training of a neural network is more complex because it involves various choices about the learning algorithm.

3.2.3 Conclusions for the ICLIPS model

The main purpose of impacts modelling in ICLIPS is to enable the translation of impact guardrails into constraints for ICEM. Other applications of climate impact response functions (CIRFs), as mentioned in Section 3.6.3, are by-products of that exercise. Table-based CIRFs were chosen as the most appropriate reduced-form representation of climate impacts in the ICLIPS model since there was no compelling reason to develop more sophisticated reduced-form impact models such as empirical-statistical models or neural networks. The choice of this approach provides flexibility for specifying impact guardrails for different geographical units by aggregating the results for individual countries to larger world regions. Depending on the impact indicator, this aggregation is done on the basis of the area, population, or other relevant characteristics of the respective countries.

3.3 Climate scenarios for inverse impact assessments

Most ecological and social systems are sensitive to climatic stimuli and thus potentially vulnerable to anthropogenic climate change. However, the actual climatic drivers and their predictability differ significantly between different systems and impacts. A common classification of climate variables for use in climate impact assessments (Willows and Connell, 2003) distinguishes between *primary variables* (e.g., temperature, precipitation, wind, cloud cover, mean sea level, CO_2 concentration), *compound variables* dependent on combinations of several primary variables (e.g., humidity, evapotranspiration, mist and fog, actual sea level, growing season), *proxy variables* having close and possibly complex dependence on other climate variables (e.g., soil moisture, water run-off), and *synoptic variables* measured over a large spatial domain (e.g., weather types, pressure, pressure gradient, storm tracks, ocean climatology, lightning). Whilst a consideration of all these categories in climate projections for impact assessments is desirable in principle, it is obviously not feasible. This is even more true for global analyses, given the large differences in the availability of historical and simulated climate data (and of suitably calibrated impact models that could appropriately use them) in different regions of the world. Hence, the choice of the type of climate projection to be used in a specific climate impact assessment necessarily reflects a compromise between the knowledge about climate characteristics that are potentially relevant for key systems in a region, the availability of reliable (probabilistic) projections for these variables, and the ability to utilize these projections, either through formal modelling or through other, more qualitative means. Of course, this choice is also influenced by the resources available for the assessment.

The basic idea that motivates inverse analyses of climate impacts, as performed by the ICLIPS model, is to describe that part of the (climate) state space where no ‘intolerable’ impacts would occur, and to identify long-term strategies that would keep the climate system within that ‘tolerable domain’. Of course, the prevention of dangerous climate impacts is not that simple in reality: The cause-effect chain along which greenhouse gas (GHG) emissions affect atmospheric concentrations, radiative forcing, global and regional climate, and climate impacts, is associated with large uncertainties. In addition, non-climate developments play a crucial role in shaping the vulnerability of societies to climate change.

Even in a deterministic inverse analysis, there is the need to limit the dimensionality of the climate state space to a tractable number that allows its effective partitioning according to the externally specified constraints. The main goal for the definition of the climate state space in an inverse IAM is thus to provide maximum 'relevant' information about different trajectories of future climate change with a minimum number of independent variables. Consequently, only such climate impacts can be meaningfully considered in an inverse analysis that can be linked with sufficient confidence to a limited number of climate change indicators. While the application of a probabilistic framework can principally expand the range of impacts suitable for inverse analyses, there is still considerable debate which uncertainties about future climate impacts can be quantified (cf. Section 2.4.4).

Various approaches have been developed to construct climate change scenarios for (global) impact analyses. Two of them are particularly suitable for the low-dimensional parametrization of future climate states. In the *incremental changes approach* (also denoted as 'synthetic scenarios'), arbitrary changes in selected climate variables (typically annual temperature and precipitation) are applied uniformly across the entire region under consideration (see, e.g., van Minnen et al., 2000a). While this approach is useful for sensitivity analyses of the impact model and for a general assessment of *potential* climate change impacts, it does not take advantage of the information available from sophisticate climate models. The *scaled scenario approach* (or 'pattern scaling technique') describes future climate change by using annual global mean temperature (AGMT) as a scaler for spatial patterns of climate anomalies derived from forcing experiments with general circulation models (GCMs). In addition to these methods, temporal and spatial *analogue scenario* are sometimes used, where future climate is equated with a past climate, or with a present climate from a different location. Such analogues may provide important information on the potential and limitations for adaptation to climate change.

The remainder of this section describes the application of pattern scaling to construct the climate scenarios used in the impact assessments of the ICLIPS model. We start this presentation with a general description of the pattern scaling technique, which is followed by more detailed considerations on the determination of climate change patterns, the emulation of multiple GCMs, the combination of historical and simulated climate data, and the options for considering interannual variability.

3.3.1 Pattern scaling

Pattern scaling is a common method for the efficient construction of regionally and seasonally explicit parameterized climate change projections. Elements of this technique were first introduced by Santer et al. (1990), and it was subsequently developed into the form described here (Robock et al., 1993; Viner, 1994; Smith and Pitts, 1997; Mitchell et al., 1999; Huntingford and Cox, 2000). This technique describes future climate change by scaling spatial patterns of climate anomalies, derived from GCM forcing experiments, to the respective change in AGMT, which can be simulated by a simple climate model (SCM). Hence, the technique attempts to combine the advantages of both simple and complex climate models, while overcoming their respective disadvantages in the context of IA.

The pattern scaling technique achieves efficiency and flexibility in approximating the results of transient GCM forcing experiments through a separate description of their dynamical behaviour and their spatial variability. This separation is based on the assumption that transient changes in many pertinent climate variables on a regional scale are approximately linearly dependent on the mean change of a single proxy variable, usually AGMT, across a plausible range of forcing scenarios. Formally, pattern scaling can be described as

$$\Delta V_s(t, z, g) \quad \approx \quad \Delta T_z(t) \cdot V_s^*(g), \tag{3.1}$$

whereby V is a climate variable (such as temperature or precipitation), s denotes a part of the annual cycle (such as the whole year, a season, or a month), t is a future point in time, z is a forcing (or emissions) scenario, g is a grid box (or other spatial unit), and the Δ indicates that we are interested in climate anomalies relative to the unforced climate. On the right side of the equation, $\Delta T_z(\cdot)$ is the simulated change in AGMT used as the *scaler*, and V_s^* is the normalized *response pattern* for the respective climate variable and season.

An application of the scaled scenario approach in an IAM requires three steps (Mitchell, 2001):

1. The (normalized) response pattern for each relevant climate variable and season is extracted from the results of a GCM forcing experiment and is expressed in terms of the scaler, i.e., absolute or normalized change in AGMT. Various options for doing so are briefly described in Section 3.3.2.

2. The selected forcing scenario is simulated by a SCM, giving a time series of the scaler. This is described for the ICLIPS model in Bruckner et al. (2003a).

3. For any future point in time, the climate projection is constructed by multiplying the GCM pattern with the value of the scaler from the SCM and by superimposing the so-determined climate anomaly onto the baseline climate. Details of this step in the ICLIPS model are discussed in Section 3.3.4.

The time-consuming is performed only once for each emulated GCM. The much simpler second and third steps are performed for each climate scenario investigated by the IAM.

As mentioned before, pattern scaling relies on the assumption that transient climate projections for increasing GHG concentrations as simulated by coupled atmosphere-ocean general circulation models (AOGCMs) can be satisfactorily approximated by scaling fixed spatial patterns of climate anomalies to the respective change in AGMT. Pattern scaling was already used with the results of equilibrium GCM experiments (e.g., Santer et al., 1990; Hulme et al., 1995b; Schlesinger et al., 1997). However, the validity of this assumption for different climate indicators (such as annual and seasonal means, and interannual variability, of temperature, precipitation, and other climate variables) and across different GCMs and forcing scenarios could only be thoroughly assessed when the results of long-term transient integrations and ensemble experiments with AOGCMs became available.

The most comprehensive assessment of the accuracy of pattern scaling is described in Mitchell (2001). We cited the key conclusions here even though this review was published after the main work described in this thesis had been completed. It is important to note that the tested 'accuracy' refers exclusively to the *additional* errors introduced by scaling, i.e., to the technique's ability to represent well climate changes simulated by AOGCMs. This does not include an assessment whether the AOGCM projections are good descriptions of future climate change. The main conclusions are as follows:

> *"By using ensemble experiments forced with increasing GHG concentrations from HadCM2 (a fully coupled general circulation model), it is found that the estimates of regional changes in seasonal temperature and precipitation made using pattern scaling techniques are accurate [. . .] in terms of the statistical and practical significance of the errors*

introduced by pattern scaling. It is suggested that pattern scaling is extended from the multi-decadal mean to inter-annual variability, for which the technique is also found to be accurate. [...] Using a sample of six fully-coupled GCMs it is confirmed that pattern scaling may be applied to a wide range of GCMs. Pattern scaling enables an accurate estimate to be made of the regional climate changes that would be simulated by a GCM under different radiative forcing. [...]

A large proportion of the inter-model differences [in normalized climate change patterns] might be attributable to internal variability, and might not be 'disagreements' at all. [...] We conclude that a large proportion of the inter-model differences in estimated regional climate change for a doubling of CO_2 [in the IPCC Second Assessment Report] may be attributable either to differing climate sensitivities or else to internal variability."

(Mitchell, 2001, Chapter 8)

These encouraging conclusions are in contrast to widely held assumptions that pattern scaling is a good approximation for temperature (which is spatially continuous, represented well by GCMs, and has a high signal-to-noise-ratio under radiative forcing) but that it works poorly for precipitation. The main difference between studies that found low accuracy for precipitation (e.g., Mitchell et al., 2000) and (recent) studies that found good accuracy (e.g., Huntingford and Cox, 2000; Dai et al., 2001; Mitchell, 2001) is the use of ensemble experiments in the latter ones, which increased the signal-to-noise-ratio of the projected precipitation changes. For instance, Dai et al. (2001) compared regional patterns of seasonal-mean temperature and precipitation changes from GCM ensemble experiments between a business-as-usual and a greenhouse-gas stabilization scenario. The correlation coefficients between the two scenarios were $r \approx 0.99$ for temperature, and $r \approx 0.93$ for precipitation, respectively. In Section 3.3.2, an alternative method is presented for analyzing the accuracy of pattern scaling that also works for the results of a *single* forcing experiment. This method, which was applied in ICLIPS, is based on an analysis of the variance explained by the first, and subsequent, empirical orthogonal functions, and of the transient behaviour of the respective time coefficients.

Specific results from Mitchell (2001, Chapter 4) with relevance to the application described here are that (a) patterns form high emission scenarios give a better approximation of the response in a low emission scenario than *vice versa*, i.e., there is a superiority of interpolation over extrapolation; (b) in stabilization scenarios, there tends to be a smoothing out of the regional contrasts in temperature response; (c) the hydrological intensification is inversely related to the rate of increase in radiative forcing because a slow increase in radiative forcing increases the warming of the ocean as a proportion of the total warming; and (d) it appears reasonable to scale patterns constructed from single scenarios (in contrast to ensembles). These results suggest to derive response patterns to be applied in the analysis of long-term climate impacts from long-term scenarios where the rate of increase in radiative forcing lies within the upper range of plausible future scenarios. This is exactly what has been done in ICLIPS.

The climate change scenarios applied in the ICLIPS model, and those analyzed in Mitchell (2001), assume that the climate system is forced by spatially uniform increases in the concentrations of radiatively active atmospheric components. This assumption is valid for long-lived well-mixed greenhouse gases, such as CO_2, CH_4, and N_2O, but not for short-lived sulphate aerosols. Mitchell et al. (2000) found that response patterns from GHG-only scenarios differ significantly from those for GHG-plus-aerosol scenarios. However, the SRES emission scenarios recently developed by the IPCC project future emissions of SO_2, the main precursor of sulphate aerosols, which are much lower than in the IS92 scenarios adopted by Mitchell et al. (2000). As a result, the error of not considering the regional climate effects of sulphate aerosols is not nearly so great as previously thought. Forward analyses employing the pattern scaling approach may take advantage of recent enhancements of the pattern scaling technique, where GHG patterns and a number of region-specific sulphate aerosol patterns are individually scaled and linearly recombined (Ramaswamy and Chen, 1997; Schlesinger et al., 1997). This approach has not been followed in the ICLIPS model since appropriate data from a range of GCMs had not been available when the model structure was developed.

It is important to note that none of the GCM scenarios investigated in Mitchell (2001) involves any large-scale singularities. Additional scalers would be required to capture important nonlinear effects such as a regional cooling that may be caused by a weakening of the global ocean circulation (see, e.g., Rahmstorf, 1995). Another improvement to pattern scaling is suggested in Mitchell (2001): *"a superior form of pattern scaling might use two parameters: one parameter might estimate the unstabilized response as a function of the scaler [...], and an additional parameter might estimate the stabilizing component of the response, perhaps as a function of the gradient of the scaler"*.

3.3.2 Determination of climate change patterns by EOF analysis

Three different techniques have been used to extract spatial response patterns from transient GCM integrations:

1. Linear regression
2. Anomalies for a particular time slice
3. Enhanced signal-to-noise ratio

The last technique is not considered here since it has been found to be "suboptimal" (Mitchell et al., 1999, p. 550). Linear regression is the optimal method for capturing the climate change pattern from a transient GCM forcing experiment. The regression may be done on the basis of a pre-defined scaler (e.g., AGMT), or it may include identification of the 'optimal' scaler through statistical techniques such as empirical orthogonal function (EOF) analysis. In ICLIPS, EOF analysis is applied if the transient results of the GCM experiment are available; otherwise, time-slice anomalies are used.

EOF analysis is a statistical technique for sequentially identifying a system of orthogonal base vectors that covers a maximal fraction of the variance exhibited in a collection of high-dimensional vectors (Mardia et al., 1978; von Storch and Navarra, 1995). The first EOF corresponds to that (suitable normalized) base vector that accounts for a maximum proportion of variance; each subsequent EOF is orthogonal to the previous ones and 'explains' a maximum of the residual variance. Any vector from the original collection can then be approximately represented by its coordinates in the new base.

Formally, EOF analysis can be described as

$$\boldsymbol{V_t} = \sum_{k=1}^{K} v_{kt} \cdot \boldsymbol{V_k^*} + \boldsymbol{\eta_t}. \tag{3.2}$$

The $\boldsymbol{V_t}$ are the original high-dimensional vectors (e.g., simulated anomaly patterns for a specific climate variable at a particular time t, whereby the two-dimensional fields are regarded as a one-dimensional vector), v_{kt} is the k-th EOF (or time) coefficient of $\boldsymbol{V_t}$, $\boldsymbol{V_k^*}$ is the k-th EOF (or principal vector), and $\boldsymbol{\eta_t}$

is the residual. The EOFs are defined as that set of K orthogonal vectors which sequentially minimize the variance of the residual in Equation 3.2. The coefficients are given by

$$v_{kt} \quad = \quad \langle \boldsymbol{V_t}, \boldsymbol{V_k^*} \rangle. \tag{3.3}$$

For details on the computation of the EOFs, see, e.g., von Storch and Navarra (1995, Chapter 13).

Hooss et al. (2001) applied EOF analysis to the results of a long-term forcing experiment with the periodically-synchronously coupled GCM ECHAM3-LSG at T21 resolution (Voss et al., 1998; Voss and Mikolajewicz, 2001). In the scenario integration, the CO_2 concentration was increased fourfold from present-day level over a period of 120 years, and remained constant for another 730 years. In this context, the first EOF can be identified with the dominating spatial pattern of differences ('anomalies') in a climate variable between the scenario and the control run. The product of the first EOF (at a particular location) and the first EOF coefficient (at a particular point in time) approximates the amount of regional change in the corresponding climate variable, i.e., $\boldsymbol{V_t} \approx v_{1t} \cdot \boldsymbol{V_1^*}$. In many cases, the first EOF can be identified with a mode of the (physical) system from which the data are sampled. For the second and higher indexed EOFs, however, such an association is possible only under very special circumstances (North, 1984).

Figure 3.2 shows the main results of the EOF analysis. The first EOFs of temperature and sea-level rise have been scaled so that the corresponding time coefficients equal one at the end of the 850 year simulation period. The first EOFs for precipitation, cloud cover, and humidity have been standardized such that the integrals over time of their EOF coefficients correspond to the standardized coefficient for annual mean temperature. Since the trajectories for precipitation and cloud cover exhibit significant fluctuations, the integral was chosen as a robust statistic of these trajectories.

We observe that the fraction of the residual variance in a climate variable that *cannot* be explained by the first EOF is positively correlated to the degree of its natural year-to-year variability. This fact, by itself, is not a surprise. The relevant question in this context is whether the higher EOFs still represent a discernible climate change signal. The first EOF for annual mean temperature already explains 96.7% of the variance. Figures 3.2.a and 3.2.b show the time coefficients of the first to third EOFs for precipitation and cloud cover, respectively. The time coefficients for the first EOFs clearly follow the increase in radiative forcing and can be attributed to it, whereas the time trajectories for the second and third EOFs fluctuate apparently randomly around zero. These results suggest that the inclusion of the second and third EOFs would not significantly improve our ability to describe the climate change signal for these variables. We thus conclude that the respective first EOF covers the overwhelming fraction of the climate change signal simulated by ECHAM3 for all pertinent climate variables. Figure 3.2.c depicts the time coefficients for annual as well as seasonal temperature change. All trajectories match very well. Therefore, although the *spatial patterns* of temperature change vary considerably across the seasons (not shown here), the simulated *time evolution* does not differ significantly. Finally, Figure 3.2.d shows the response of different climate variables. The transient response differs clearly between radiative forcing, sea level rise, and the atmospheric climate variables. However, the time evolution for temperature approximates those of the other atmospheric variables rather well even though there is some variability also within this last group.

Summarizing the results of the EOF analysis we conclude that the climate change signal simulated by ECHAM3 is satisfactorily approximated by scaling appropriately normalized spatial patterns of the dominant climate anomalies for each climate variable (i. e. the respective first EOFs) to the change in

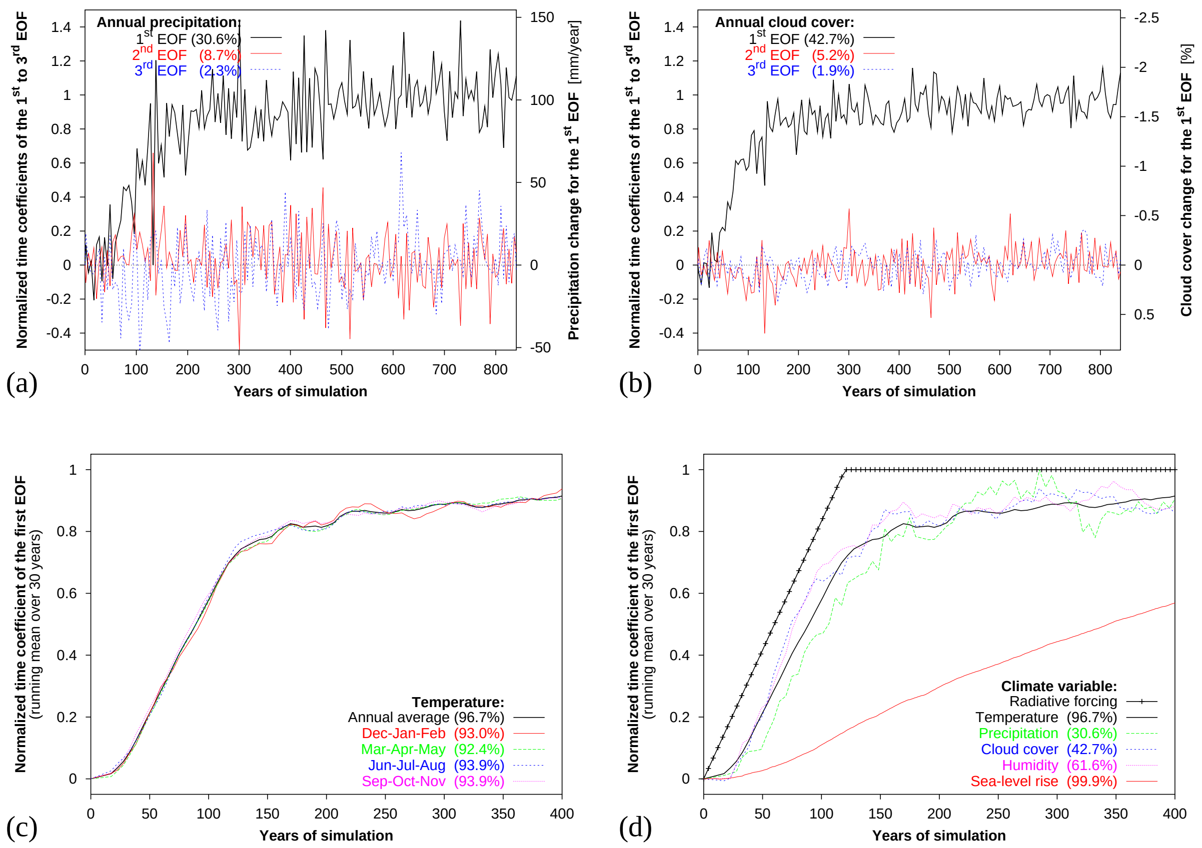


Figure 3.2: Trajectories of the EOF coefficients for various climate variables derived from the ECHAM3 experiment. The percentage of the variance in a climate variable that can be explained by the respective EOF is given in brackets. (a, b) First to third EOF for anomalies in annual precipitation and cloud cover. (c) First EOF for annually averaged temperature and seasonal temperature. (d) First EOF for radiative forcing and annually averaged temperature, precipitation, cloud cover, humidity, and sea-level rise. Source: adapted from Hooss et al. (2001)

global mean temperature (represented by the time coefficient of the first EOF for annually averaged temperature change).

3.3.3 Emulation of multiple GCMs

GCMs differ in their temporal response to changes in external forcing, in their overall sensitivity, and in their regional feedback patterns. A central goal in the development of the ICLIPS model has been to define the climate-impacts interface in such a way that climate impact response functions (CIRFs) based on climate projections from *different* GCMs can use the output from a *single* parametrization of the ICLIPS climate model (ICM). The basic idea is to emulate any GCM by combining the temporal response of a 'default' GCM with the overall sensitivity and the regional pattern of the respective GCM to be emulated. The CIRFs presented here account for differences in the climate sensitivity (see below) and in the climate change patterns of GCMs. They are driven by the *normalized* change in AGMT, i.e., the change in AGMT divided by the climate sensitivity. Interestingly, the idea of standardizing response patterns from GCM experiments on the basis of their climate sensitivities was already present when the first elements of the pattern scaling technique were developed by Santer et al. (1990). By definition, a single parametrization of a dynamic model cannot produce different temporal responses. The normalized change in GMT is computed by the ICM based on the temporal response of the long-term experiment with ECHAM3 (cf. Section 3.3.2). The main reason for the selection of that GCM experiment was its long integration period.

Obviously, the validity of this approach depends on the degree of agreement in the temporal responses of the different GCMs considered. Recent reviews of GCM experiments exhibited a systematic relationship across GCMs between their climate sensitivity and their temporal response (Cubasch et al., 2001; Raper et al., 2002). Models with high climate sensitivity tend to have a large net heat flux into the ocean, which causes a delay in the climate response. Consequently, the transient climate response initially has a smaller spread among the models than the models' climate sensitivities alone would suggest. The idea that the climate sensitivity is a model-specific constant has also been challenged recently. Senior and Mitchell (2000) report that the 'effective' climate sensitivity in a transient integration of HadCM2 increases over time, due to changes in cloud feedbacks. It is thus suggested to determine the climate sensitivity based on the results of very long integrations, whenever these are available. In contrast, Watterson (2000) found very little variation of the effective climate sensitivity over time. Clearly, these findings ask for caution in using a single dynamic model to emulate the temporal response of different GCMs, in particular when their climate sensitivities differ significantly.

The CIRFs presented in this thesis were computed for three GCMs: ECHAM3-LSG, ECHAM4-OPYC, and HadCM2. In addition to the ECHAM3 experiment described above, we use climate change projections from two alternative GCM experiments that are available through the IPCC Data Distribution Centre. We chose the ECHAM4GGA1 experiment, performed with ECHAM4-OPYC3 (Bacher et al., 1998; Roeckner et al., 1996) at T42 resolution (approximately 2.8° by 2.8°) and the HadCM2GGAX ensemble experiment, performed with HadCM2 (Johns et al., 1997) at a resolution of 2.5° latitude by 3.75° longitude. The respective integrations of the latter two GCMs involve a 1% per annum increase in GHG concentrations from 1990 to 2099. Since transient results were only available for the ECHAM3 experiment, and the integrations of the other GCMs used a different forcing scenario we could not compare the temporal response of these GCMs. However, as the climate sensitivities of the three GCMs are very similar, we have no reason to assume that the inaccuracies introduced by using the same temporal response for all GCMs are substantial.

We will now look more closely at various aspects of the hybrid climate model applied in the ICLIPS IAM. The globally averaged temperature response of a GCM to an increasing forcing is described in the ICM by a linear impulse response function (IRF) of the form

$$\Delta T(t) \equiv \int_{t_0}^{t} \Delta\tilde{Q}(u) \cdot R(t-u)\,\mathrm{d}u, \tag{3.4}$$

$$\Delta\tilde{Q}(t) \equiv \log_2 \frac{C(t)}{C(t_0)}. \tag{3.5}$$

$\Delta T(t)$ and $\Delta\tilde{Q}(t)$ are the time paths of the change in AGMT and the normalized change in radiative forcing (both compared to the base year t_0), respectively. $R(t)$ is the Green's function (see below), and

$C(t)$ is the time path of the *equivalent* CO_2 concentration, defined as the CO_2 concentration that gives a radiative forcing equivalent to the sum of the forcings from all well-mixed greenhouse gases.

In the current context, the *Green's function* $R(t)$ can be represented as superposition

$$R(t) \equiv \sum_{i=1}^{n} A_i \cdot \frac{e^{-\frac{t}{\tau_i}}}{\tau_i} \tag{3.6}$$

of a number of exponentials of different amplitudes A_i and (real) relaxation times τ_i (Hasselmann et al., 1993). These parameters are obtained by fitting the IRF to the results of a transient GCM experiment (see below). The relevant time integral from Equation 3.4 is

$$\begin{aligned} \int_{t_0}^{t} R(t-u)\,\mathrm{d}u &= \int_{t_0}^{t} \left(\sum_{i=1}^{n} A_i \cdot \frac{e^{-\frac{t-u}{\tau_i}}}{\tau_i} \right) \mathrm{d}u \\ &= \sum_{i=1}^{n} A_i \cdot \left(\int_{t_0}^{t} \frac{e^{-\frac{t-u}{\tau_i}}}{\tau_i}\,\mathrm{d}u \right) \\ &= \sum_{i=1}^{n} A_i \cdot \left(1 - e^{-\frac{t-t_0}{\tau_i}} \right). \end{aligned} \tag{3.7}$$

Equation 3.4 assumes a linear relationship between radiative forcing and AGMT change in *equilibrium*. This presumption is only approximately correct due to various nonlinear processes, for instance the ice-albedo feedback (Voss and Mikolajewicz, 2001). However, recent investigations of this issue were summarized in Boer and Yu (2003, p. 428) as follows: *"Results from climate change simulations with a variety of GCMs indicate that global mean temperature change is proportional to the global mean radiative forcing, broadly independent of the nature and pattern of the forcing. Simulation results also reveal [that] temperature patterns show a remarkable linearity or additivity whereby the sum of response patterns for different forcings is closely the response pattern for the sum of the forcings."*

The *(equilibrium) climate sensitivity* of the climate system or a climate model, denoted as $\Delta T_{2\times CO_2}$, is defined as the change in AGMT resulting from a doubling of atmospheric CO_2 content after the climate system, or the climate model, has attained a new equilibrium (Cubasch et al., 2001). Because of the long time scales associated with deep ocean equilibration, the direct calculation of the climate sensitivity with a coupled model requires a very long simulation and a considerable commitment of computer resources. For that reason, the climate sensitivity of a GCM is usually approximated with less costly methods. This is most commonly achieved by coupling the atmospheric GCM component to a mixed-layer (or 'slab') ocean model. In that case there is no exchange of heat with the deep ocean, and the model can be integrated to a new equilibrium in a few decades. Alternatively, the climate sensitivity can be estimated based on a transient integration of the fully coupled GCM using the linear response model presented above. Integration of Equation 3.4 for an instantaneous CO_2 doubling, i.e.,

$$\Delta\tilde{Q}(t) \equiv \begin{cases} 0, & t < t_0, \\ 1, & t \geq t_0, \end{cases} \tag{3.8}$$

provides the following characterization of the climate sensitivity:

$$\Delta T_{2\times CO_2} \equiv \lim_{t\to\infty} \Delta T(t)$$

$$\begin{aligned}
&\stackrel{(3.4)}{=} \lim_{t\to\infty}\int_{t_0}^{t}\Delta\tilde{Q}(u)\cdot R(t-u)\,\mathrm{d}u \\
&\stackrel{(3.8)}{=} \lim_{t\to\infty}\int_{t_0}^{t} R(t-u)\,\mathrm{d}u \\
&\stackrel{(3.7)}{=} \lim_{t\to\infty}\sum_{i=1}^{n} A_i\cdot\left(1-e^{-\frac{t-t_0}{\tau_i}}\right) \\
&= \sum_{i=1}^{n} A_i. \qquad (3.9)
\end{aligned}$$

Climate sensitivity is thought, based primarily on models, to lie in the range of 1.5 °C to 4.5 °C (Cubasch et al., 2001). Cloud feedbacks remain the greatest source of uncertainty in model predictions of global mean warming. Uncertainty in indirect aerosol radiative forcing precludes a more accurate, observationally based estimate of climate sensitivity.

In order to separate the *temporal response* of a GCM from its climate sensitivity, Green's function (Equation 3.6) is normalized by defining

$$\tilde{R}(t) \equiv \sum_{i=1}^{n}\tilde{A}_i\cdot\frac{e^{-\frac{t}{\tau_i}}}{\tau_i}, \qquad (3.10)$$

$$\tilde{A}_i \equiv \frac{A_i}{\Delta T_{2\times CO_2}}. \qquad (3.11)$$

The $\tilde{A}_i$, summing up to 1, represent the *fractional* contribution of each exponential to the equilibrium temperature change. Calibration of the normalized IRF to the output of the multi-century CO_2 quadrupling experiment with ECHAM3 described above yields the following results (Hooss et al., 2001):

$$\begin{aligned}
\tilde{A}_1 &= 0.71 \qquad \tau_1 = 14\,\mathrm{a}, \\
\tilde{A}_2 &= 0.29 \qquad \tau_2 = 450\,\mathrm{a}.
\end{aligned}$$

Figure 3.3 provides an illustration of the temporal response based on this calibration. The left plate depicts the normalized Green's function, $\tilde{R}(t)$, and its two addends. The right plate depicts the time integral, $\int_0^t \tilde{R}(t-u)\,\mathrm{d}u$, and its two addends.

We now define the *normalized* change in AGMT over time as

$$\begin{aligned}
\Delta\tilde{T}(t) &\equiv \frac{\Delta T(t)}{\Delta T_{2\times CO_2}} \\
&= \int_{t_0}^{t}\Delta\tilde{Q}(u)\cdot\tilde{R}(t-u)\,\mathrm{d}u. \qquad (3.12)
\end{aligned}$$

It can be shown that the following relationship holds for any greenhouse-gas *stabilization* scenario (i.e., if $\lim_{t\to\infty}\Delta\tilde{Q}(t)$ exists):

$$\begin{aligned}
\lim_{t\to\infty}\Delta\tilde{T}(t) &= \lim_{t\to\infty}\Delta\tilde{Q}(t) \\
&\stackrel{(3.5)}{=} \lim_{t\to\infty}\log_2\frac{C(t)}{C(t_0)}. \qquad (3.13)
\end{aligned}$$

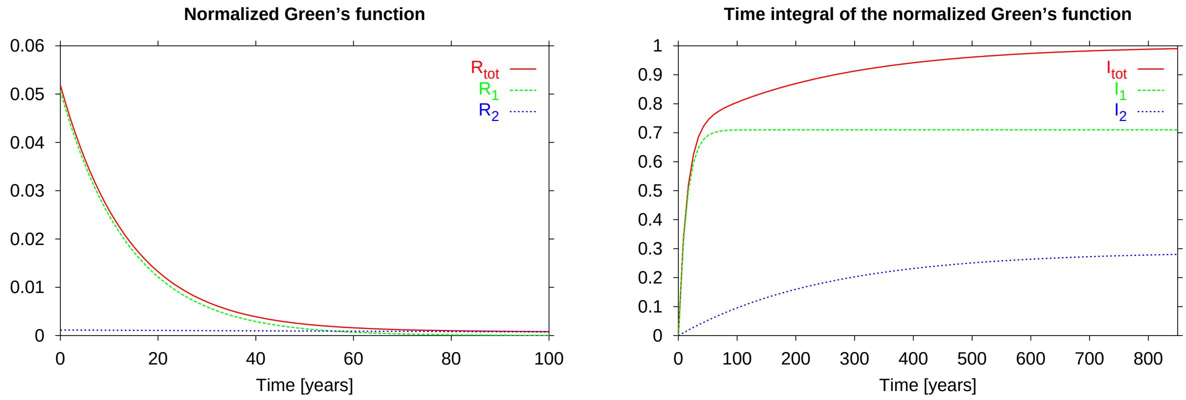


Figure 3.3: The normalized Green's function (left) and its time integral (right) calibrated to the results of the ECHAM3 experiment. Note the different time periods covered by the two diagrams.

The *normalized* change in AGMT is thus closely linked to the concept of "stabilization of greenhouse gas concentrations in the atmosphere" (UNFCCC, Art. 2). Such a GCM-independent correspondence does not exist between *absolute* AGMT change and GHG concentrations.

Climate change patterns state the change in a climate variable at each location for a unit change in normalized AGMT. The ICLIPS model includes monthly anomaly patterns for near-surface temperature, precipitation, and cloud cover that are extracted from the results of transient experiments with three AOGCMs. Even though future climate states are described solely by the change in AGMT, the regional and seasonal variability in the climate change signal simulated by the AOGCM are nevertheless included in the impact analysis. Submonthly climate characteristics and interannual climate variability are not currently considered in ICLIPS.

The climate change patterns for ECHAM3 were determined by EOF analysis (cf. Section 3.3.2). The spatial patterns for the other GCMs had to be calculated from the climate differentials between the final 30-year periods of the scenario integration and the control integration because the transient model output required for an EOF analysis was not available. Figure 3.4 presents the climate change patterns for annual temperature and precipitation from the three GCMs considered here (for details on their construction, see Section 3.3.4). Simulated temperature anomalies are specified in absolute terms whereas changes in precipitation and cloud cover are expressed proportional to the baseline value.

3.3.4 Combination of simulated and observed climate data

So far, we have implicitly assumed that it is possible to meaningfully superimpose simulated climate anomalies onto a historical baseline climatology. In this section, we present the details of the 'climate change function' that defines the climatic input for the regionally explicit impact simulations in ICLIPS. This climate change function combines patterns of climate anomalies derived from GCM simulations with observed climate data to construct plausible projections of future climate change.

Although AOGCMs are the most reliable source for projections of future climate under changed atmospheric forcing, they have not been designed to provide direct input for models used in assessing regional impacts of climate change, e.g., crop models or epidemiological models. Therefore, careful interpretation of the GCM output is required for this purpose (Robock et al., 1993; von Storch, 1995;

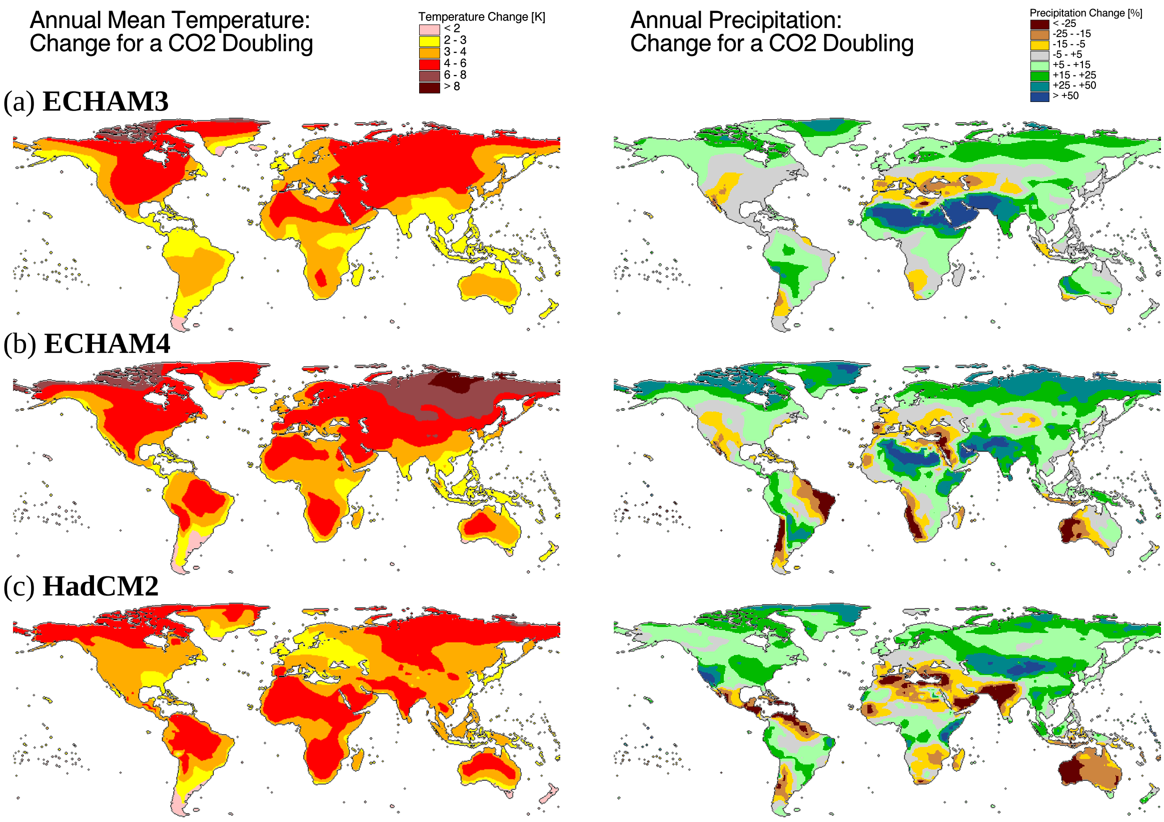


Figure 3.4: Climate change patterns depicting the changes in annual mean temperature and precipitation as simulated by three GCMs for the stabilized climate after a doubling of the equivalent CO_2 concentration. (a) ECHAM3, (b) ECHAM4, and (c) HadCM2.

Henderson-Sellers, 1996; Smith and Pitts, 1997; Claussen, 1998). The main causes for inconsistencies at the interface of climate models and impact models are the use of different spatial and temporal scales, inter- and extrapolating from a restricted number of climate simulations, and the imperfect simulation of current climate by GCMs.

Assessments of climate impacts involve at least the comparison of a system's functioning between the baseline climate and a future climate, possibly allowing for concurrent changes in non-climatic parameters. However, a simple comparison of the system behaviour for the *observed* baseline climate on the one hand and for a *simulated* future climate on the other would also attribute differences due to a poor simulation of present-day climate to the enhanced greenhouse effect. The method presented here aims at minimizing this error.

The climate projections for impact assessments in ICLIPS are derived by a scaled scenario approach that superimposes linearly scaled climate anomaly patterns onto a baseline climatology. In a formal way, the task of defining the climate change function can be formulated as follows. The available information comprises

$\boldsymbol{A} \quad \in \mathcal{C}$ the observed baseline climatology,

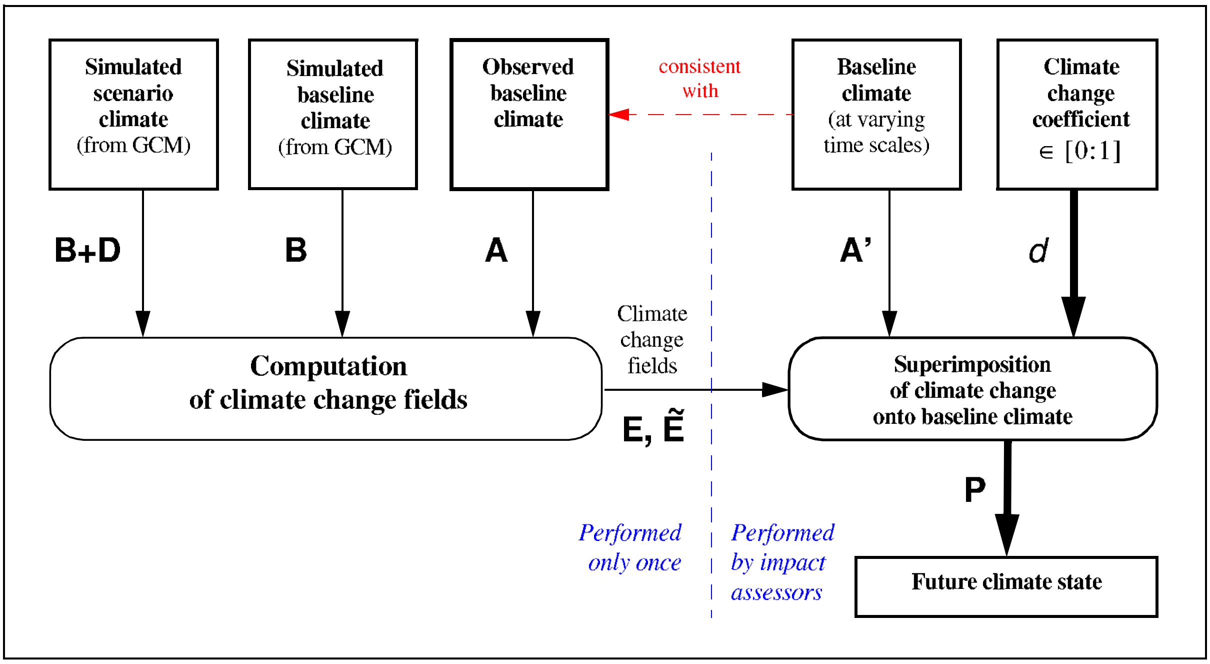


Figure 3.5: Computation of regionalized future climate states

$$\begin{array}{lll} \boldsymbol{B} & \in \mathcal{C} & \text{the simulated baseline climatology, and} \\ (\boldsymbol{B}+\boldsymbol{D}) & \in \mathcal{C} & \text{the simulated future climatology, with} \\ \mathcal{C} & & \text{the (convex) set of valid regionalized climate states.} \end{array}$$

We assume that the (implicitly defined) simulated climate anomaly $\boldsymbol{D}$ represents the maximum level of climate change to be considered in the impact assessment. In other words, we do not extrapolate to levels of climate change beyond those simulated by the GCM. Based on this information, we are seeking to define a *climate change function*

$$\mathbf{P}_{\mathbf{ABD}} : \mathcal{C} \times [0,1] \rightarrow \mathcal{C}$$

such that $\mathbf{P}_{\mathbf{ABD}}(\boldsymbol{A}', d)$ corresponds to the superimposition of a fraction d of the simulated climate anomaly $\boldsymbol{D}$ onto a baseline climate $\boldsymbol{A}'$. $\boldsymbol{A}'$ should be consistent with $\boldsymbol{A}$ but not necessarily identical. For instance, $\boldsymbol{A}'$ might have a finer temporal resolution, or $\boldsymbol{A}'$ might refer to the historical climate of a single year rather than the mean climate (see Section 3.3.5).

The overall concept for the construction of the climate change function is illustrated in Figure 3.5. It is important to note that we define the climate change function independently for each spatial unit (e.g., a grid cell). Hence, the value of $\mathbf{P}_{\mathbf{ABD}}(\boldsymbol{A}', 1)$ in a specific grid cell depends only on the values of $\boldsymbol{A}$, $\boldsymbol{A}'$, $\boldsymbol{B}$, and $\boldsymbol{D}$ in that grid cell. In the remainder of this section, we use boldface letters to denote a vector representing climate patterns and normal letters for its components (i.e., values for specific grid cells). Arithmetic operations on vectors denote operations on each component of a vector.

A climate change function implicitly defines an *absolute climate change field* as follows:

$$\boldsymbol{E}_{\boldsymbol{ABD}} \equiv \mathbf{P}_{\mathbf{ABD}}(\boldsymbol{A}, 1) - \boldsymbol{A}.$$

Applying this notation, the climate change function shall satisfy the following, intuitively sensible conditions.

Validity: $\mathbf{P_{ABD}}$ shall always produce valid results, i.e.,

$$\mathbf{P_{ABD}}(\boldsymbol{A}', d) \in \mathcal{C} \qquad \forall\, \boldsymbol{A}' \in \mathcal{C}, d \in [0, 1].$$

Linearity: The projected deviation from the observed average baseline climate shall be linear in the scaling factor, d, and in the simulated climate anomaly, $\boldsymbol{D}$. This requirement can be expressed as

$$\begin{aligned}\mathbf{P_{ABD}}(\boldsymbol{A}, d) &= \mathbf{P_{A,B,d \cdot D}}(\boldsymbol{A}, 1) \\ &= \boldsymbol{A} + d \cdot \boldsymbol{E_{ABD}} \qquad \forall\, d \in [0, 1].\end{aligned}$$

A linear climate change function is completely described by the corresponding absolute climate change field.

Monotonicity: The sign of the projected climate deviation at any point shall not differ from the sign of the simulated climate deviation:

$$\boldsymbol{E_{ABD}} \cdot \boldsymbol{D} \geq \mathbf{0}.$$

Identity: If the baseline climate is perfectly simulated in the control run (i.e., $\boldsymbol{A} = \boldsymbol{B}$), projected and simulated climate change shall match:

$$\boldsymbol{E_{AAD}} = \boldsymbol{D}.$$

In addition to these 'hard' requirements, the definition of the climate change function is guided by the following goals.

Retaining basic global characteristics: The climate change function shall retain the basic characteristics of the simulated climate anomaly. In particular, the global means of $\boldsymbol{E_{ABD}}$ and of $\boldsymbol{D}$ should not differ significantly.

Avoiding clearly unrealistic climate projections: It is of course impossible to forecast the amount of future climate change at locations where not even the baseline climate is satisfactorily reproduced by a GCM. However, since extreme climate change projections may have significant effects on the results of impact assessments, $\mathbf{P_{ABD}}$ shall not project climate states that are likely to be unrealistic.

Supporting different climate baselines: $\mathbf{P_{ABD}}$ should yield valid and plausible climate projections if applied to a baseline climate $\boldsymbol{A}'$ consistent with, but different from $\boldsymbol{A}$.

There are two straightforward definitions for $\mathbf{P_{ABD}}$, namely to superimpose either the *absolute* change or the *relative* change in a climate variable between the scenario run and the control run onto the observed baseline climate. The corresponding climate change functions are denoted as $\mathbf{P}^{+}_{\mathbf{ABD}}$ and $\mathbf{P}^{*}_{\mathbf{ABD}}$, respectively. We have noted above that any linear climate change function is uniquely determined by the corresponding absolute climate change field, $\boldsymbol{E_{ABD}}$. However, $\mathbf{P}^{*}_{\mathbf{ABD}}$ is more intuitively specified by the *relative climate change field*, $\boldsymbol{\tilde{E}_{ABD}}$. Hence, $\mathbf{P}^{+}_{\mathbf{ABD}}$ and $\mathbf{P}^{*}_{\mathbf{ABD}}$ are defined as follows:

$$\begin{aligned} \mathbf{P}^{+}_{\mathbf{ABD}}(\boldsymbol{A'}, d) &\equiv \boldsymbol{A'} + d \cdot \boldsymbol{E_{ABD}}, \\ \boldsymbol{E_{ABD}} &\equiv \boldsymbol{D} \end{aligned}$$

and

$$\begin{aligned} \mathbf{P}^{*}_{\mathbf{ABD}}(\boldsymbol{A'}, d) &\equiv \boldsymbol{A'} \cdot (1 + d \cdot \boldsymbol{\tilde{E}_{ABD}}), \\ \boldsymbol{\tilde{E}_{ABD}} &\equiv \frac{\boldsymbol{D}}{\boldsymbol{B}}. \end{aligned}$$

A suitable definition of $\mathbf{P_{ABD}}$ needs to adequately handle locations where the observed and simulated baseline climate, $\boldsymbol{B}$ and $\boldsymbol{A}$, differ significantly. For instance, neither $\mathbf{P}^{+}_{\mathbf{ABD}}$ nor $\mathbf{P}^{*}_{\mathbf{ABD}}$ can ensure valid results for bounded climate parameters like cloud cover. In the remainder of this section, we present the specification of the climate change function that is compatible with the above mentioned criteria. Since $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{D}$ are *fixed* patterns, they are usually omitted. The index is used instead to indicate the climate variable considered. Hence, $\mathbf{P_{TMP}}$, $\mathbf{P_{PRE}}$, and $\mathbf{P_{CLD}}$ denote the climate change functions for temperature, precipitation, and cloud cover, respectively.

Temperature

Since the spatiotemporal variability of absolute temperature is comparatively low, both $\mathbf{P}^{+}$ and $\mathbf{P}^{*}$ produce valid (and almost identical) results. In accordance with established procedures (see Carter et al., 1994; Viner and Hulme, 1994; Hulme et al., 1995b), $\mathbf{P}^{+}$ is applied, i.e., the simulated temperature change is simply added to the observed baseline figure. We thus define

$$\boldsymbol{E_{TMP}} \equiv \boldsymbol{D_{TMP}} \tag{3.14}$$

Precipitation

Precipitation is characterized by a high spatial and temporal variability, and GCM simulations of the current climate show substantial errors in some regions. Furthermore, precipitation changes can be caused by two distinct physical mechanisms: *intensity* changes within the same region suggest a multiplicative approach to determine future changes whereas *dynamical* changes bringing precipitation to different regions suggest an additive approach. This situation complicates the development of plausible projections of future precipitation.

Figure 3.6 shows the implications of three different choices of $\mathrm{P_{PRE}}$ for a specific location. In this illustrative example, observed baseline precipitation is always A_{PRE} =0.5 (in arbitrary units) whereas simulated precipitation in the control run, B_{PRE}, and in the scenario run, $B_{PRE} + D_{PRE}$, vary independently from 0 to 1. The figure shows that the application of $\mathbf{P}^{+}$ (in green) to precipitation changes

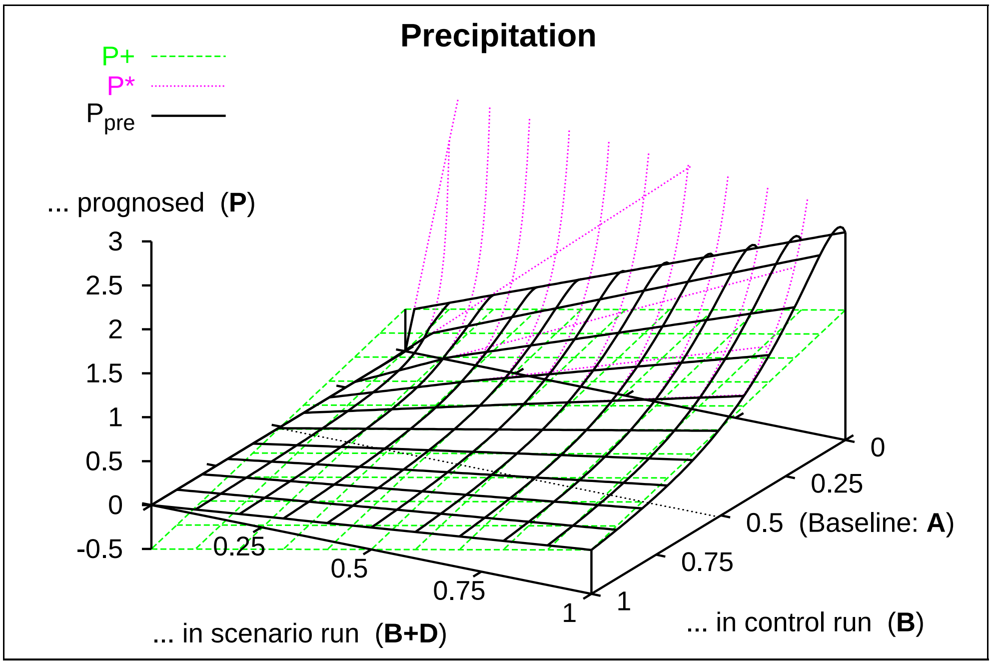


Figure 3.6: Alternative methods for calculating future precipitation

may result in negative precipitation projections. Hence, it is generally suggested to interpret the simulated amount of precipitation change as a fraction of the baseline figure (Carter et al., 1994; Viner and Hulme, 1994; Hulme et al., 1995b), i.e., to apply $\mathbf{P}^*$ (in pink). While this method ensures non-negative precipitation projections, precipitation change may be considerably overestimated if actual precipitation is significantly underestimated in the control run, i.e., if $B_{PRE} \ll A_{PRE}$. In Carter et al. (1994, App. A.1.2), it is vaguely suggested for locations where simulated and observed baseline precipitation differ significantly: "*In such cases, the discretionary use of differences rather than ratios might be appropriate.*" In SCENGEN, the relative amount of precipitation change for a CO_2 doubling is arbitrarily capped at 500% (Hulme et al., 1995b). It should be noted that the use of absolute vs. relative patterns of precipitation change may have noticeable effects on the results of impact assessments (Alcamo et al., 1998a, p. 93).

Our definition is a 'compromise' between the application of the absolute and relative precipitation change. In order to ensure $\mathrm{P}_{\mathrm{PRE}}(A'_{PRE}, d) \geq 0$, we define $\mathrm{P}_{\mathrm{PRE}}$ (in black) using the *relative* climate change field, the elements of which are given by

$$\tilde{E}_{PRE} \equiv \frac{D_{PRE}}{A_{PRE}} \cdot \left(\frac{A_{PRE}}{B_{PRE}}\right)^{\lambda_{AB}}, \tag{3.15}$$

$$\lambda_{AB} \equiv \begin{cases} \sqrt{\dfrac{B_{PRE}}{A_{PRE}}}, & \text{if } B_{PRE} < A_{PRE} \\ 1, & \text{otherwise.} \end{cases} \tag{3.16}$$

This definition represents a middle course between the two extreme cases characterized by $\lambda_{AB} = 0$

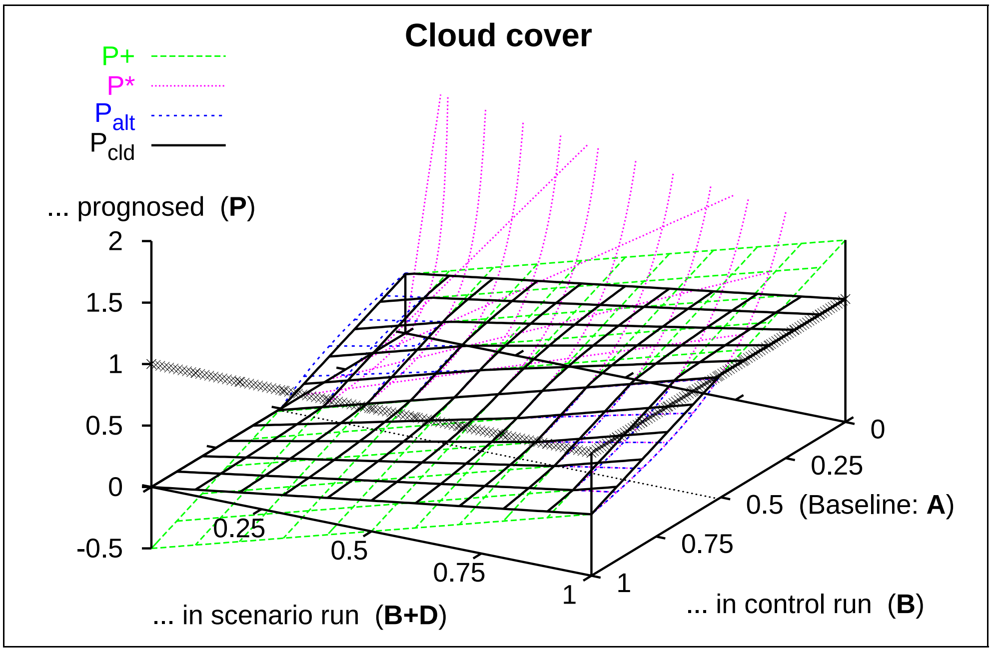


Figure 3.7: Alternative methods for calculating future cloud cover

(corresponding to $\mathbf{P}^+$) and $\lambda_{AB} = 1$ (corresponding to $\mathbf{P}^*$). It is motivated as follows. When present-day precipitation in a grid cell is *not* underestimated by the GCM (i.e., if $B_{PRE} \geq A_{PRE}$), the relative climate anomaly is applied to the observed baseline value (i.e., $\lambda_{AB} = 1$). However, at locations where baseline precipitation is considerably underestimated (i.e., if $B_{PRE} < A_{PRE}$), we also have low confidence in the simulated amount of *relative* precipitation change. In order to avoid a possibly huge overestimation of precipitation change, we thus apply a precipitation change that lies between the relative and the absolute amount of change (i.e., $0 < \lambda_{AB} < 1$). Simply switching between the two extreme cases would imply to always choose the result that has lower absolute value, thereby systematically reducing the simulated amount of global precipitation change The above —admittedly heuristic— definition, which describes a smooth transition between the two extreme cases, conserves the global characteristics of the simulated climate anomalies (from ECHAM3) much better.

Cloud cover

Changes in cloud cover (resp. insolation) have not been considered in many global climate impact assessments. The choice of $\mathrm{P}_{\mathrm{CLD}}$ needs to account for the fact that cloud cover is restricted by lower *and* upper bounds (of 0 and 1, respectively). Figure 3.7 shows four possible definitions of the climate change function for cloud cover. Both $\mathbf{P}^+$ (in green) and $\mathbf{P}^*$ (in pink) may violate the upper bound, which is indicated by lines of crosses. The simplest way to ensure *valid* results is to use any of these two projections, and to cap the results at the lower and upper bounds. However, this method results in a significant number of grid cells where cloud cover is, unrealistically, estimated as 0 or 1. Another evident method is to apply the relative change in *cloud cover* if actual cloud cover is *overestimated* in the GCM control run, and the relative change in the complementary variable *cloudlessness*, defined as 1 – cloud cover, if actual cloud cover is *underestimated* by the model. This method is illustrated by $\mathrm{P}_{\mathrm{alt}}$ in Figure 3.7. However, the simulated cloud cover anomaly is systematically reduced by this method. In our definition of $\mathrm{P}_{\mathrm{CLD}}$ (in black), we thus refine this idea by applying the *relative* change in cloud cover resp. cloudlessness only in those cases where the simulated cloud cover anomaly has a *different* sign than the error in the simulation of baseline cloud cover, i.e., if $\mathrm{sgn}(D_{CLD}) \neq \mathrm{sgn}(B_{CLD} - A_{CLD})$. Otherwise, the *absolute* cloud cover change is applied. Analyses with various patterns for cloud cover anomalies from ECHAM3 have shown that this definition preserves the main characteristics of the climate change signal quite well. The elements of the relative climate change field are thus defined as

$$\tilde{E}_{CLD} \equiv \frac{D_{CLD}}{A_{CLD}} \cdot \begin{cases} \dfrac{A_{CLD}}{B_{CLD}}, & \text{if } B_{CLD} > A_{CLD}, D_{CLD} < 0 \\ \dfrac{1 - A_{CLD}}{1 - B_{CLD}}, & \text{if } B_{CLD} < A_{CLD}, D_{CLD} > 0 \\ 1, & \text{otherwise.} \end{cases} \tag{3.17}$$

This definition ensures valid results if $A'_{CLD} = A_{CLD}$. If $A'_{CLD} \neq A_{CLD}$, explicit capping of $\mathrm{P}_{\mathrm{CLD}}$ at the upper bound of 1 may be necessary. This is reflected in a slightly modified definition of $\mathrm{P}_{\mathrm{CLD}}$, as follows:

$$\mathrm{P}_{\mathrm{CLD}}(A'_{CLD}, d) \equiv \min\{1, A'_{CLD} \cdot (1 + d \cdot \tilde{E}_{CLD})\}. \tag{3.18}$$

Spatial resolution of climate data

The various climate data sets involved in the definition of the climate change function typically have different spatial resolutions. The ICLIPS model uses the 1961–1990 mean climatology constructed by New et al. (1999) as baseline climate, which covers all land areas except Antarctica on a 0.5°-by-0.5° grid. In contrast, the control climate and the forced climate are derived from GCM integrations on a much coarser grid. In accordance with impact assessments in other global IAMs (e.g., Alcamo, 1994; Jonas et al., 1996), we define the climate change function on the finer 0.5°-by-0.5° grid in order to use the available information on the spatial variability of present climate.

In principle, there are various options available to bridge the gap in spatial resolution between the GCM data and the baseline climate. We interpolate the GCM output to the finer grid using inverse-distance interpolation (Smith and Hulme, 1998). Interestingly, the simulated baseline climate (from ECHAM3) agreed significantly better with the observed climatology after interpolation from the coarse GCM grid to the finer grid of the observed data. This may be related to the fact that the baseline climatology has also been derived by interpolation of station data. The application of advanced downscaling techniques like limited area models, analogy approaches, stochastic weather generators, or statistical models is presently not feasible on a global scale due to their huge data requirements (von Storch, 1995; Semenov and Porter, 1995). Since the results of impact assessments are anyhow aggregated to world regions comprising many grid cells, the at best marginal gains of using more sophisticated sub-grid interpolation techniques do not seem to justify the considerable efforts necessary for their application.

A correct interpretation of the equations above requires to identify $\boldsymbol{B}$ and $\boldsymbol{D}$ with the *interpolated* ('downscaled') GCM output. The only equation that needs to be modified is Equation 3.16, which becomes

$$\lambda_{AB} \equiv \begin{cases} \sqrt{\frac{\overline{B}_{PRE}}{\overline{A}_{PRE}}}, & \text{if } \overline{B}_{PRE} < \overline{A}_{PRE}, B_{PRE} < A_{PRE} \\ 1, & \text{otherwise.} \end{cases} \tag{3.19}$$

$\overline{\boldsymbol{B}}$ and $\overline{\boldsymbol{D}}$ denote the *original* GCM patterns whereas $\overline{\boldsymbol{A}}$ denotes the observed baseline climate scaled up to the coarser grid of the GCM.

Seasonally explicit climate change projections

The climate change signal resulting from increasing GHG concentrations varies not only spatially but also seasonally. The climate change function described above can be applied without any changes to seasonal or monthly climate statistics. The scaler, d, still refers to the standardized change in *annual* global mean temperature.

Summary

We have presented a generally applicable method for constructing regionally specific climate change projections based on the results of transient GCM experiments by means of a linear climate change function. This function, $\mathbf{P_{ABD}}$, is described by scalable absolute resp. relative climate change fields. It is constructed by combining information from an observed mean baseline climate, $\boldsymbol{A}$, a simulated baseline climate, $\boldsymbol{B}$, and a simulated climate anomaly, $\boldsymbol{D}$. It produces valid results also if applied to baseline climates $\boldsymbol{A}'$ that differ from $\boldsymbol{A}$.

The climate change function is particularly useful for the production of reduced-form impact models in the form of climate impact response functions (CIRFs). The climate change fields $\boldsymbol{E_{TMP}}$, $\tilde{\boldsymbol{E}}_{\boldsymbol{PRE}}$, and $\tilde{\boldsymbol{E}}_{\boldsymbol{CLD}}$ need to be computed only once. For any baseline climate $\boldsymbol{A}'$ at a temporal resolution suitable for a particular process-based, regionalized impact model, the CIRF can then be produced through assessing the impacts for the set of future climate states described by

$$\mathbf{P}(\boldsymbol{A}', d) = \begin{pmatrix} \mathrm{P_{TMP}}(A'_{TMP}, d) \\ \mathrm{P_{PRE}}(A'_{PRE}, d) \\ \mathrm{P_{CLD}}(A'_{CLD}, d) \end{pmatrix}_g \tag{3.20}$$

$$= \begin{pmatrix} A'_{TMP} + d \cdot E_{TMP} \\ A'_{PRE} \cdot (1 + d \cdot \tilde{E}_{PRE}) \\ \min\{1, A'_{CLD} \cdot (1 + d \cdot \tilde{E}_{CLD})\} \end{pmatrix}_g \tag{3.21}$$

for suitable choices of the scaling factor $d \in [0, 1]$. The index g denotes that the definition inside the brackets is applied to each grid cell.

3.3.5 Consideration of interannual climate variability

Climate is characterized by considerable variability on various temporal scales. However, most model-based climate impact assessments compare the behaviour of a climate-sensitive system between an observed and a perturbed *mean* climate, thus missing important aspects of the problem. The consideration of current climate variability, and potential changes thereof, in climate impact analyses is constrained by the availability of (a) data about current climate variability, (b) reliable projections about future changes in relevant aspects of climate variability, and (c) models that can adequately process this information.

In this section, we briefly discuss opportunities and limitations for the consideration of *interannual* climate variability in impact assessments based on a scaled scenario approach. Examples of systems that are strongly affected by interannual climate variability include agricultural systems where a particularly warm (or cold, or dry, or wet) season may lead to large losses or even a complete failure in certain crops, and many forest ecosystems whose composition and dynamics is strongly affected by the occurrence of wild-fires, which are linked to particularly warm and/or dry periods.

The availability of monthly climate time-series for the 20^{th} century covering the terrestrial surface on a $0.5°$-by-$0.5°$ grid (although with limited reliability in some regions) provides a basis for the consideration of interannual climate variability in global climate impact assessments (New et al., 2000). However, projections about potential changes in interannual climate variability are often very uncertain. As a first approximation, one may assume that anthropogenic climate change affects only the mean but not the shape of the distribution of relevant climate characteristics. Although this assumption has been challenged by a growing body of model experiments, it is still more realistic than not considering interannual climate variability at all.

The method for constructing climate change functions presented above can be applied without change to particular years of a historical time-series instead of the mean climate of a reference period. For instance, $\boldsymbol{A}'$ can be identified with $\boldsymbol{A}_t, t \in \{1901, 1902, \ldots, 2000\}$, or a detrended version of that time series, instead of the mean baseline climate, $\boldsymbol{A}$. Obviously, the use of time series instead of the mean climate substantially increases the computational requirements since impact simulations would have to be performed for each year of the time series.

Various interesting results can be derived from the vector of impact estimates for individual years of the time series. The mean and median provide important estimates of average impacts of the imposed climate anomaly. In addition to the average performance of a system, other percentiles of the impact vector may be relevant in a risk assessment context. For instance, flood defence systems are determined by extreme floods rather than the average flood. Despite these advantages, the CIRFs presented here do not consider interannual climate variability, primarily due to the lack of appropriately designed and calibrated global impact models (see Section 3.5 for details). The model used for simulating climate impacts on natural ecosystems is an equilibrium model that, by definition, computes the long-term vegetation distribution based on average climate definitions. The crop model and the global hydrological model could, in principle, be applied to time series of climate data. However, since they were calibrated using mean climate data, we do not consider their uncritical application to individual years of time-series as appropriate.

3.4 Climate impact response functions: general approach

Process-based impact models require a degree of spatial resolution, and thus computing time, that prohibits their direct integration into the ICLIPS core model (see Section 3.2 for a detailed discussion of this topic). In this section, we present the conceptual basis of the *climate impact response functions* (CIRFs), which constitute the core of the reduced-form impacts module of the ICLIPS model. The sectoral impact models applied in the computation of the CIRFs are described in Section 3.5, and Section 3.6 discusses the application of CIRFs.

3.4.1 Purpose

The overall purpose of CIRFs is to assist in the interpretation and operationalization of UNFCCC Article 2. CIRFs have been developed in the context of the guardrail approach (see Section 2.3.4) to enable the distinction of acceptable and unacceptable climate futures for different normative choices about impact guardrails.

CIRFs describe how a particular climate-sensitive system or sector responds to climatic changes. They are produced by multiple simulation runs of geographically explicit sectoral impact models for a representative sample of future climate scenarios. The resulting CIRF indicates the dose-response relationship between selected climatic variables from the ICLIPS core model and a suitable impact indicator that describes the degree to which the system or sector is affected. The CIRFs described here refer to (predominantly biophysical) climate impacts on natural vegetation, agricultural crop production, and water availability. Other important impact domains, such as human health and coastal zones, are not currently included, primarily due to a lack of reliable models or data with global coverage.

CIRFs are a useful means for the aggregated presentation of results from climate impact simulation and for their inclusion into IAMs. In an inverse application, they allow the translation of thresholds for climate change impacts ('impact guardrails') into constraints for their input variables ('climate windows'). It thus becomes feasible to specify long-term objectives for climate protection in a model-based inverse analysis of the climate problem with respect to the *impacts* of climate change instead of crude proxy variables, like the change in global mean temperature.

The development of CIRFs is related to efforts to develop "ecological response functions" for specific climate change scenarios (Krol et al., 1997; Toth et al., 2000) and agricultural "response-surface diagrams" that link crop yields to incremental changes in annual temperature and precipitation (van Minnen et al., 2000a, 2002). Note that similar terms like 'climate impact response function' have been previously used in different contexts (e.g., Carter et al., 1994; Huntley et al., 1995). The main new aspects in our approach are the use of several non-monetary aggregated climate impact indicators in combination with geographically specific impact models, the concise representation of simulation results independent from a specific emission scenario, and the inclusion of maximum information from GCMs on the spatial and seasonal variability of climate change.

It is important to understand that CIRFs in ICLIPS are defined for scaled scenarios based on the results of *specific* AOGCM experiments. Hence, CIRFs for climate change patterns from new GCM simulations cannot be derived from existing CIRFs. The computation of GCM-independent CIRFs is only warranted for impact domains where the *relevant* differences between different GCMs can be expressed by a few parameters. A prominent example concerns changes in the thermohaline ocean circulation, the stability of which under increasing GHG concentrations is primarily determined by three GCM-specific parameters: the climate sensitivity, the hydrological sensitivity, and the vertical diffusivity in the ocean (Ganopolski et al., 2001).

3.4.2 Calculation procedure

This section presents the calculation procedure for the CIRFs applied in the ICLIPS model. CIRFs are computed by applying a geographically explicit impact model to a representative subset of plausible future climate states. These climate states are defined by the climate change functions described in Section 3.3, whereby climate change patterns for monthly averaged temperature, precipitation and cloudiness are scaled to the simulated change in AGMT and superimposed onto the baseline climate. The raw output of the impact model is further processed to derive various aggregated impact indicators for individual countries or larger regions (cf. Section 3.5).

The main input variable of the CIRFs in ICLIPS is the normalized change in AGMT. The CIRFs for natural vegetation and crop production use the atmospheric CO_2 concentration as a second input factor because it affects the behaviour of crops and natural ecosystems (Jones et al., 1998). Although increasing CO_2 is the principal cause of global climate change, the relationship between CO_2 concentration and the *transient* change in AGMT is not one-to-one. Even for a fixed climate sensitivity, the trajectories of these two variables are partially decoupled due to the influence of non-CO_2 greenhouse gases and aerosols, and to the thermal lag of the climate system (see Section 4.1 for selected results). The CIRFs for water availability do not consider the CO_2 concentration.

The domain of definition of the CIRFs was chosen so that it includes the trajectories of all SRES emission scenarios up to the year 2100. Global mean temperature change and CO_2 concentration range from 0 °Cto $1.6 \cdot \Delta T_{2\times \mathrm{CO}_2}$ and from 325 ppm to 1200 ppm, respectively. The CO_2 concentration in the year 1970 was chosen as the minimum CO_2 concentration in order to be consistent with the reference climate period (1961–1990). For the computation of the CIRFs, the climate and CO_2 ranges are varied independently in 21 and 23 steps, respectively. The impact model is run for each of these combinations, and the suitably aggregated model output is saved in look-up tables for further processing.

We introduce now some concepts that are important for the application of CIRFs in inverse mode, i.e., for guardrail analyses with the ICLIPS model (see Section 3.6.3).

A CIRF in ICLIPS can be denoted as

$$\begin{aligned} \mathrm{f} &: C \times P \to I \\ C &= [0, 1.6] \\ P &= [325 \text{ ppm, } 1200 \text{ ppm}] \\ I &\subset I\!R. \end{aligned}$$

where f is the CIRF, and C and P are the ranges of the normalized global mean temperature change and the atmospheric CO_2 concentration, respectively. As described in Section 3.4.2, the minimum values of C and P refer to the baseline period 1961–1990. I denotes the (scalar) range of the respective impact indicator.

An *impact guardrail* can, in general, be expressed as

$$\mathrm{f}(\Delta\tilde{T}, p_{\mathrm{CO}_2}) \quad \leq \quad i_{max},$$

where $\Delta\tilde{T} \in C$ and $p_{\mathrm{CO}_2} \in P$. Applied backwards, a CIRF uses an impact guardrail to partition its domain into two subsets. (The term ‘domain’ as used here and in the following is a shorthand for ‘domain of definition’ interpreted in its mathematical sense.) We term that subset of the domain where a specific guardrail is not violated the associated admissible (or, for historical reasons: tolerable) *climate window*, which is defined as

$$\mathrm{f}^{-1}([-\infty : i_{max}]) \quad \equiv \quad \left\{ (\Delta\tilde{T}, p_{\mathrm{CO}_2}) \in C \times P \,\middle|\, \mathrm{f}(\Delta\tilde{T}, p_{\mathrm{CO}_2}) \leq i_{max} \right\}.$$

If the CIRF is continuous, the tolerable climate window is fully determined by the *impact isoline*

$$\mathrm{f}^{-1}(i_{max}) \quad \equiv \quad \Big\{(\Delta\tilde{T}, p_{\mathrm{CO_2}}) \in C \times P \,\Big|\, \mathrm{f}(\Delta\tilde{T}, p_{\mathrm{CO_2}}) = i_{max}\Big\}, \tag{3.22}$$

which contains all points for which the simulated impacts equal the impact guardrail, and separates the tolerable climate window from the intolerable part of the domain.

3.4.3 Limitations

Limitations of the present CIRFs and their application in the ICLIPS model are as follows.

First, all climate impacts are determined in equilibrium with a changed mean climate. The effects of higher statistical moments, such as interannual climate variability, on future impacts are currently not considered.

Second, the ICLIPS climate model, like other reduced-form climate models that mimic GCM results in a deterministic manner, produces smooth climate change projections without any ‘surprises’. This is related to the limited ability of GCMs to simulate changes in climate variability, including extreme events, and potentially abrupt transitions between multiple equilibria of the climate system. In addition, the applied variant of the pattern scaling technique does not consider the regional climate effects of aerosols.

Third, the response of most systems to climatic changes is contingent upon various non-climatic factors. Since the approach to CIRFs presented here considers only climate and atmospheric composition as input variables, its validity is highest for those sectors, indicators, and regions where changes in these variables are the main driving forces of the changes ahead.

Finally, it is widely recognized that the vulnerability of a system or sector to climate change is a function of the *exposure* of the system to climate variations, its *sensitivity* to these variations, and its *ability to adapt* to changing climate conditions over time (McCarthy et al., 2001). The potential of adaptation to reduce adverse impacts of climate change as well as the capacity of a system to actually perform adaptations are thus important factors in a comprehensive vulnerability analysis (cf. Section 2.2). However, adaptation to climate change is specific for each vulnerable system, and it often depends on the full set of stressors that a system is exposed to. These features make it very difficult to appropriately address adaptation in an IAM with global scope such as the ICLIPS model.

Another obstacle to the consideration of adaptation in the ICLIPS model is related to the underlying decision-analytical framework. Human adaptation to long-term climate change may strongly affect the cultural and social foundation of societies by involving, for instance, changes in food patterns, in the seasonal and daily timing of activities, in land use, and in town planning. Hence, even if a specific adaptation option is *feasible* from a biophysical point of view, this does not necessarily mean that it is also regarded as *desirable*. Simply assuming that societies will implement certain wide-ranging adaptation measures would thus be inconsistent with the aim of the guardrail approach to separate the scientific and normative aspects of the climate problem. In a guardrail analysis, the main responsibility for evaluating the simulated climate impacts, and for assessing the ability and willingness of communities to implement certain adaptation measures, lies with the model users.

The specification of impact indicators for CIRFs in Section 3.5 takes into account that the specified limitations are less severe if climate and atmospheric composition change are the prime driving forces affecting a system, and if the potential for adaptation is limited.

3.5 Climate impact response functions: sector-specific approaches

This section presents sector-specific approaches to the definition and computation of CIRFs. We start with an overview of the impact indicators used in the ICLIPS impacts module, which is followed by a description of the sectoral impact models applied in the computation of the CIRFs. The focus lies on those aspects that are relevant in the ICLIPS framework, and the reader is referred to the references for details.

3.5.1 Impact indicators

In the development of aggregated impact indicators, the following criteria were considered:

Clarity and relevance: The indicator shall represent information on the anticipated impacts of climate change that is comprehensible and relevant for the target users of the model.

Scientific validity: There must be a strong causal relationship between the input variables of the CIRF and the impact indicator that can be represented by a scientifically credible impact model.

Specificity: It should be possible to distinguish the impacts of changes in climate (and atmospheric composition) from those caused by other factors.

Universality: The indicator should be applicable in all, or at least most, regions covered by the model.

Table 3.1 presents the impact indicators applied in the current version of the ICLIPS model. Some of them are based on climate impact indicators defined earlier for the IMAGE 2.0 model Krol et al. (1997). Climate impacts on natural vegetation, crop production, and water availability are assessed by applying adapted versions of BIOME 1, the FAO crop suitability model, and WaterGAP 1.1, respectively. A common characteristic of these models is that they use soil information and daily climate data as inputs. Quasi-daily climate time series are derived from monthly averages by linear interpolation (for temperature) and by spline interpolation (for precipitation and cloudiness). The results of BIOME 1 and the FAO crop model are also affected by atmospheric CO_2. All models include a hydrological submodel, although its implementation differs somewhat between the models. The models are globally applicable, a spatial resolution of $0.5°$-by-$0.5°$ being used for the computations, and they are computationally efficient.

Spatial coverage of the impact indicator

Some impacts are more relevant in certain areas than in others. For instance, ecosystem changes are likely to be valued particularly high in protected areas, and changes in crop potential are most relevant in the current cultivated area. Therefore, certain impact indicators are not only determined for the total land area but also for protected areas, for the current cultivated area, and for the non-agricultural area (see Table 3.1 for details). This is achieved by weighting the simulation results for each grid cell with the percentage of the respective area.

Data on the extent of protected areas is taken from the most recent version of the *UN List of Protected Areas* (see Figure 3.8). Criteria for the inclusion of a protected area in this list are its size (at least $10\,km^2$), its management objective (IUCN Categories I to V), and the authority of the management agency (country or federal state level). The data on agricultural areas is from Ramankutty and Foley (1998). Figure 3.8 shows the spatial patterns of protected areas and cultivated areas.

Indicator	Explanation
Change of present biome [% of area]	Percentage of the area where the present biome becomes inviable under altered climate conditions.[1]
Stable biome area [% of current area]	Percentage of the present range of a specific biome that remains climatically suitable. Newly suitable areas are not taken into account.[2]
Total biome area [% of current area]	Total potential area of a specific biome. Newly suitable areas can compensate for losses within the present range.[2]
Stable forest area [% of current area]	Percentage of the present forest area that remains suitable for forest growth. A change from one forest biome to another one is permitted by this indicator.
Total forest area [% of current area]	Total potential forest area (including newly suitable areas).
Maximum food energy [Gcal/km^2]	Potential food energy production, using caloric yield as the criterion for crop allocation in each grid cell.[3]
Maximum crop performance [% of max. yield]	Performance of the 'best' crop, using the actual performance of a crop (expressed as a percentage of the maximum attainable yield) as the criterion for crop allocation.[3]
Weighted crop performance [% of max. yield]	Overall performance of the presently cultivated crops. The relative performance of each crop averaged across the cultivated area of a country is weighted with its present share in the cultivated area of the country.
Crop yield [t/km^2]	Rainfed yield of a specific crop.[4,5]
Suitable area [% of area]	Area where a specific crop can grow (assuming 10% of the maximum attainable yield as the minimum threshold for suitability).[4,5]
Runoff [mm/yr]	Sum of surface runoff and groundwater recharge.

[1]This indicator is available (a) for the total land area, (b) for the land area excluding areas used for agriculture, and (c) for protected areas.
[2]This indicator is comprised of various biome-specific sub-indicators.
[3]This indicator is available (a) for the total land area and (b) for the cultivated area.
[4]This indicator is available (a) for the total land area, (b) for the cultivated area, and (c) for the cultivated area whereby in regional aggregations each country is weighted with the crop-specific acreage.
[5]This indicator is comprised of various crop-specific sub-indicators.

Table 3.1: Climate impact indicators in the ICLIPS model for natural vegetation (top), crop production (centre), and water availability (bottom)

Spatial aggregation of the impact indicator

The grid-based simulation of climate impacts in ICLIPS allows the presentation of CIRFs for individual countries as well as for virtually any world region. The default regionalization at which results are presented depends on the chosen impact indicator.

Ecosystem impacts are often presented at the level of biogeographic regions. While biomes are

(a)

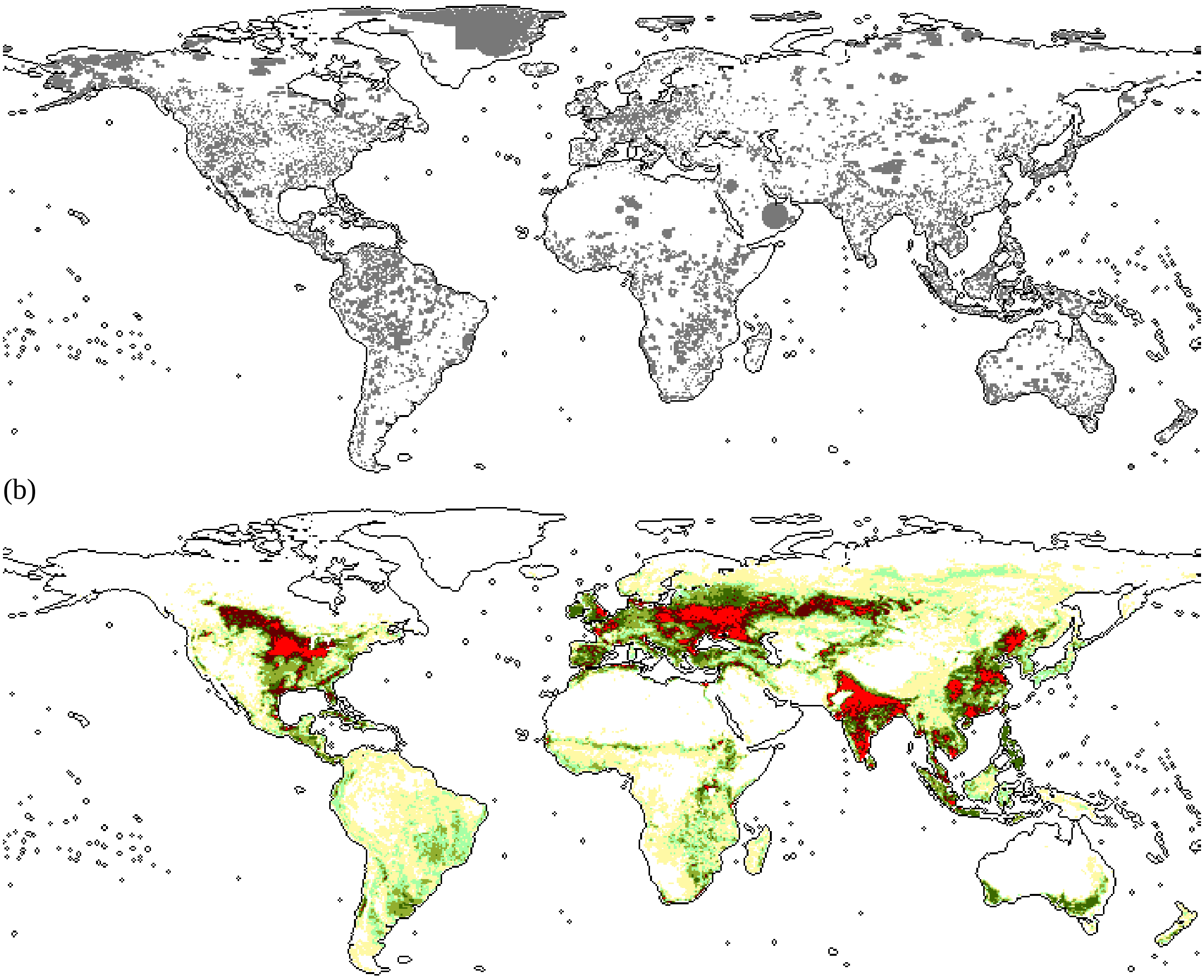


Figure 3.8: Global distribution of (a) protected areas and (b) agricultural areas.

defined with respect to the *functional* properties of the vegetation, for instance a similar guild structure, biogeographic regions represent clusters with respect to their *taxonomic* characteristics. Since most concepts of biodiversity are based on taxonomic entities (i.e., species, genera, etc.), it is worthwhile to analyze climate impacts in each of these clusters of taxonomic entities separately.

Figure 3.9 depicts the biogeographic regions (syn. floral kingdoms) of the world. Although Capensis covers only parts of the Republic of South Africa, this region is consistently distinguished from Aethiopis due to the high degree of endemism in its flora. Its small size, however, makes Capensis particularly sensitive to the effects of arbitrary local fluctuations in GCM integrations. This scale mismatch lets us abstain from a separate assessment of vegetation impacts in Capensis. Greenland and Antarctis are precluded from the analysis since they are predominantly covered by ice.

Impacts on agricultural crop production are generally reported for single countries, trade 'blocs', or

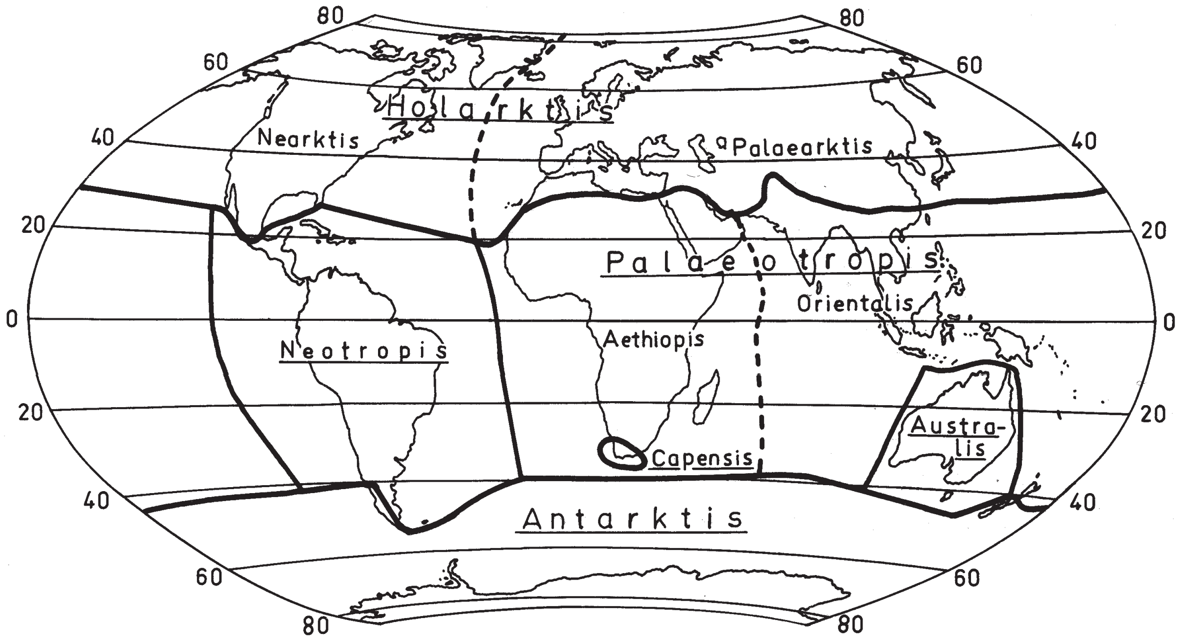


Figure 3.9: Biogeographic regions of the world. Source: Bick (1989)

other economically defined regions. Figure 3.10 shows the 11 world regions distinguished in the ICLIPS aggregated economic model (AEM) that define the 'default' regionalization for agricultural impacts.

A catchment area or a whole country is a suitable reference for reporting impacts on water availability. Aggregation of results from different catchment areas is problematic since water in general cannot be easily transferred between basins.

3.5.2 Natural vegetation

Climate, weather and atmospheric composition are, among other factors such as land use, nutrient availability, and ultraviolet radiation, important determinants for the distribution of life on Earth. Each climate zone is characterized by their typical ecosystems. Major and abrupt climatic changes have often had devastating effects on biodiversity in prehistorical times. About 200 million years ago, the end-Triassic mass extinction event resulted in a turnover of more than 95 percent of megafloral species. A three- to fourfold increase in CO_2 (due to extensive basaltic volcanicity), associated with a rise in global mean temperature of 3 to 4 °C, has been suggested as the main cause of this mass extinction (McElwain et al., 1999). A rapidly growing body of evidence shows that recent climatic changes have already affected the phenology and physiology of organisms, the range and distribution of species, and the composition and dynamics of ecological communities, and that they probably have already caused the extinction of species (see, e.g., Pounds et al., 1999; Hughes, 2000; Gitay et al., 2001; Walther et al., 2002).

The impacts of anticipated climate change on natural vegetation have been extensively studied over the last years. Major themes of interest were the equilibrium vegetation distribution in a changed climate (see, e.g., Martin, 1996; Haxeltine and Prentice, 1996; Halpin, 1996; Villers-Ruíz and Trejo-Vázquez, 1998), the transient response of ecosystems to climate change (see, e.g., Steffen et al., 1996; Kirilenko

Figure 3.10: World regions distinguished in the ICLIPS aggregated economic model

and Solomon, 1998; van Minnen et al., 2000b), and the feedback of vegetation change on the global biogeochemical cycles (see, e.g., Smith et al., 1992; Smith and Shugart, 1993; Neilson, 1993; Klein Goldewijk et al., 1994; Cao and Woodward, 1998; Cox et al., 2000). The computer models that are used in these assessments can be distinguished into equilibrium and dynamic models, by their level of geographical and functional detail, and by their inclusion of non-climatic factors.

The global scope of the analysis presented here and the need for easily conceivable, aggregated indicators of climate impacts on natural ecosystems motivated the use of a biogeographical vegetation model. We apply the BIOME 1 model (Prentice et al., 1992), adapted for IMAGE 2.1 (Alcamo et al., 1994, 1998a), to simulate the potential vegetation distribution for current and future climate states. This model determines, for each 0.5°-by-0.5° grid cell of land surface, which one of the 14 distinguished biomes occurs in equilibrium with given local climate and soil conditions and the concentration of atmospheric CO_2. Biomes, such as tundra, savanna, and tropical evergreen forest, are coarse categories of vegetation assemblages. Other factors that threaten biodiversity are not considered by the model. For a semi-quantitative assessment of the importance of five major threats to biodiversity (climate, atmospheric CO_2, nitrogen deposition, land use, and biotic exchange), see Sala et al. (2000).

BIOME 1 proceeds in three steps. In the first step, the model derives a set of bioclimatic indices from the monthly climate statistics, for instance the effective temperature sum above certain temperature thresholds and a moisture index. BIOME 1 defines climatic envelopes based on these indices for 16 plant functional types (PFTs). PFTs are classes of plant species, grouped by morphological (e.g., broadleaved vs. coniferous) and phenological characteristics (e.g., evergreen vs. summergreen). The climate envelopes are applied in the second step to determine which PFTs can principally occur in a grid cell, based on the non-violation of any of the constraints. In a final step, BIOME 1 applies a dominance hierarchy as a proxy for competition between different PFTs. 14 biomes are defined as combinations of one or more PFTs at the same hierarchy level. For a list of all biomes, see Figure 4.5.

BIOME 1 has been extensively used for assessing the response of natural vegetation to anticipated climatic changes (see, e.g., Leemans et al., 1996; Yates et al., 2000). Improvements in IMAGE 2.1 compared to the original model include a CO_2 dependency of the moisture threshold (Alcamo et al., 1998a). Enhanced levels of CO_2 increase the water use efficiency of plants which allows them to grow under more arid conditions. Indirect impacts of climate change on vegetation due to altered disturbance regimes (e.g., forest fires, insect pests, and wind storms) and transient processes such as migration are not considered in the model. In addition, the model does not account for possibility of multiple stable states, which have been observed for various aquatic and terrestrial ecosystems (Scheffer et al., 2001).

Progress has been achieved recently in developing dynamic vegetation models (see, e.g., Cramer et al., 2001). Such models include a higher level of physiological detail that enables them to simulate transient vegetation changes and the carbon dynamics of ecosystems. Kirilenko and Solomon (1998) compared the vegetation response to long-term climate change simulated by BIOME 1 and by MOVE, a global biome model that explicitly includes vegetation migration and succession. They found that the equilibrium biome changes simulated by the two models were quite similar, with the overall Kappa statistic (a coefficient for pairwise agreement between two classification ratings) lying between 0.94 and 0.99. These results imply that dynamic aspects are of minor importance for the impact indicators applied in ICLIPS because they are solely based on the long-term distribution of biomes. Equilibrium vegetation models have, however, only limited value for determining the timing of vegetation changes. Consequently, statements on the unsuitability of a future climate for the current biome (e.g., in Table 4.1) do not aim to pretend that the actual vegetation change will occur exactly at the specified date. Depending on the migration abilities of competing species and the occurrence of weather-related disturbances such as fire, wind-throw, pests, and disease outbreaks, these changes may lag several decades behind the changes in climatic conditions (Gitay et al., 2001). Also, the transition from one biome to another will not be a smooth and uniform process. Since the vast majority of emission scenarios lead to continued increases in AGMT and CO_2 levels far into the 22^{nd} century, however, the changes simulated for a transient climate state in the 21^{st} century will eventually be realized.

A recent review of the applicability of bioclimate envelope models for predicting the impacts of climate change on unmanaged ecosystems emphasizes the importance of considering a hierarchy of factors operating at different spatial (and functional) scales (Pearson and Dawson, 2003). Climate is found to be the dominant factor for the large-scale distribution of species whereas factors such as topography, land use, soil type, and biotic interaction dominate at smaller scales. It is thus concluded *"that when applied at an appropriate scale bioclimate envelopes have the potential to describe changes in species' distributions"*. The applicability of bioclimate envelope models appears even more appropriate in ICLIPS if we consider that the impact indicators applied here refer to the distribution of biomes rather than individual species. In summary, the application of BIOME 1 is regarded as duely justified here given the choice of impact indicators and the large spatial scales at which results are presented.

Similar to previous studies of this subject (e.g., Leemans and Halpin, 1992; Martin, 1996; Krol et al., 1997; Villers-Ruíz and Trejo-Vázquez, 1998; Leemans and Hootsmans, 1998), the impact indicators for natural ecosystems applied here are based on the extent of shifts in biomes. We use the percentage of an area where the current biome becomes inviable as the *main* indicator to quantify the impacts of climate change on natural vegetation. This indicator values all simulated biome changes equal. From an ecological point of view, it might appear desirable to assign higher weights to impacts in species-rich areas and centers of endemism than elsewhere (Groombridge, 1994; Olson and Dinerstein, 1998), or to apply a more elaborated distance measures between biomes, like the "dissimilarity index" defined in Sykes et al. (1999). An alternative way, applied in IMAGE 2.1, distinguishes four types of biome changes (Leemans and Eickhout, 2003): improvement, neutral change, degradation, and extinction. This classification emphasizes ecosystem productivity, carbon storage, and opportunities for human use. However, it is also acknowledged that *"Although some of the changes are definitely positive from the perspective of human use, they are not positive from all perspectives."* In protected areas, for instance, *any* major change in ecosystems is generally considered undesirable. In addition, the valuation of changes looks at an equilibrium vegetation, not at the actual transient dynamics, which may paint a quite different picture. In particular, *"potentially positive effects will not materialize during the first century"* (Leemans and Eickhout, 2003). In the CIRFs presented here, we refrain from implementing either of these approaches since these attempts to increase the 'scientific power' of the aggregated impact indicators are likely to reduce their comprehensibility for the non-expert users of the ICLIPS model.

Biomes are rather coarse categories of vegetation assemblages. Significant ecosystem impacts may thus occur even if no biome change is simulated. In areas with high biodiversity, for instance in most tropical forests, species generally have a small niche volume and are thus particularly sensitive to climatic change (Bazzaz, 1998; Körner, 1998). The results presented in Section 4.2 are therefore regarded as low estimates of climate impacts on ecosystems.

Article 2 of the UNFCCC calls for the limitation of climate change in such a way as *"to allow ecosystems to adapt naturally to climate change"*. Ecosystems adapt by acclimatization, migration, and evolution. Evolution typically occurs at time scales much longer than those associated with anthropogenic climate change, except for short-lived species. For that reason, it can be neglected in the impact assessment presented here. The potential for acclimatization is already considered in the specification of the BIOME 1 model. Migration is the most important adaptation mechanism for ecosystems beyond their limits of physiological acclimatization. It represents, however, only an inferior adaptation since ecosystems will not move wholesale in response to climate change. For that reason, optimistic as well as pessimistic assumptions regarding migration were considered in the specification of the impact indicators.

The indicator "change of present biome" (see Table 3.1) is defined for the total land area, non-agricultural areas, and protected areas (such as nature reserves, national parks, and wildlife sanctuaries). We regard the last variant, which may alternatively be termed "percentage of endangered nature reserves", as particularly policy-relevant for various reasons. First, the legal protection of an area is a clear statement on the societal appreciation of its *present* ecological features. Any fundamental vegetation change is thus likely to be valued negatively. Second, non-climatic human-induced stresses, for instance land reclamation, are generally less important in protected areas than elsewhere.

As additional impact indicators, we use the stable area and the total area of individual biomes and of forest biomes (see Figure 3.11). The stable area corresponds to a pessimistic view of adaptation that does not account for the establishment of biomes at locations that become climatically suitable in the future. The total area represents a rather optimistic view where biomes suddenly pop up as soon as the climatic conditions become suitable, regardless of restrictions related to dispersion potentials and the availability of migration corridors. While the stable area never exceeds the baseline area, the total area can be either

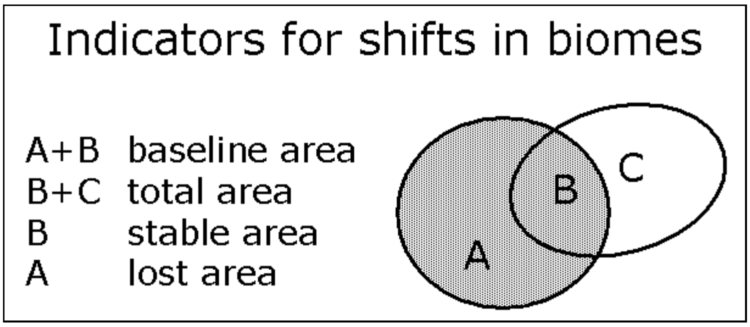


Figure 3.11: Indicators for shifts in biomes

smaller or larger In general, biome shifts are expressed as percentage of the baseline area. Employing the notation of Figure 3.11, the indicator "stable biome area", for instance, refers to $\frac{B}{A+B}$.

3.5.3 Agricultural crop production

The FAO crop suitability model, as adapted for the Terrestrial Environment System (TES) of IMAGE 2.1 (Alcamo et al., 1998a), has been applied to assess the risks of climate change for agricultural production and food security. This model computes the rainfed yield (defined as the harvestable part of dry weight production) of the 19 most important annual crops for given climatic and non-climatic conditions. The focus lies on annual crops that are used as staple food. Other crops with regional importance (e.g., grape-vine in parts of Europe) are therefore not considered.

The FAO model proceeds in two steps. In the first step, which is similar to BIOME 1, the model computes the potential distribution of the 19 crops under rainfed conditions worldwide on a 0.5°-by-0.5° grid, based on monthly climate data, CO_2 concentration, and soil data. The grid cells where the environmental conditions are adequate for growing specific crops are determined by applying crop-specific constraints to a set of agroclimatic indices for temperature and moisture availability defined in FAO (1981). In the second step, the model computes the potential rainfed production for all suitable crops, based on the growth functions of de Wit (1978). The production is determined by the net biomass production, defined as gross photosynthesis minus plant respiration (van Minnen et al., 2000a). Photosynthesis is governed by temperature, moisture availability, soil conditions, and the atmospheric CO_2 concentration. Soil reduction factors that are taken into consideration are fertility, salinity, acidity, rooting depth, and drainage conditions according to FAO (1988). Plant respiration depends on total biomass and temperature (Leemans and van den Born, 1994). Atmospheric CO_2 affects the distribution and production of crops in two ways. First, increased levels of CO_2 reduce transpiration rates and thus increase the water use efficiency of plants (Alcamo et al., 1998a). Second, the so-called CO_2 fertilization effect describes the direct stimulation of photosynthesis under enhanced CO_2 levels (Klein Goldewijk et al., 1994).

Multi-cropping and irrigated agriculture are not included in this version of the crop model. Consideration of adaptation to changing climate conditions is rather limited. However, seasonal adjustments of cropping activities in response to climate change are taken into account since the model design assumes an optimal planting date. More detailed adaptation assessments of the agricultural sector require a rather different class of models that include the effects of demographic, socioeconomic, and technological developments on the demand and supply of food as well as the interdependencies between different

Model input		
$\boldsymbol{c}$	$= (c_g)_{g \in G}$	gridded climate and CO_2 data[1]
Primary model output		
$\mathrm{y}_{ig}(c_g)$	[t/km^2]	simulated yield of crop i in grid cell g for given climatic and non-climatic conditions[2]
Baseline data		
$\boldsymbol{c}^*$	$= (c^*_g)_{g \in G}$	gridded baseline climatology
$\hat{y}_i$	[t/km^2]	maximal yield of crop i (under optimal conditions)
q_i	[Gcal/t]	energy density (specific calorie value) of crop i
p_i	[US$/t]	average export price of crop i
A_g	[km^2]	total land area of grid cell g
C_g	[km^2]	cultivated area of grid cell g
F_{iN}	[1]	fraction of the cultivated land in country N covered by crop i
Index sets		
I		all crops
G		all land grid cells
$\mathcal{N}$		all countries

[1]Even though the atmospheric CO_2 concentration is spatially homogeneous, it is included into the gridded climate vector for the sake of notational convenience.
[2]Non-climatic data, in particular soil conditions, are not explicitly included in the function definition because it remains constant throughout the simulation.

Table 3.2: Inputs to the computation of aggregated crop indicators

regions.

Based on the simulated yields for specific crops, various aggregated indicators were defined (see Table 3.1). The aggregated indicators express potential impacts on the agricultural sector, whereby simple decision rules are applied to allow for switching to more suitable crops. Depending on the specific indicator, the crop allocation in a grid cell is based on the relative performance of a crop (i.e., that fraction of the crop-specific maximum yield attainable under optimal climate and soil conditions which is realized under given conditions), on its caloric yield, or on its market price. All crop indicators except the 'weighted crop performance' were computed for the total land area of a region (e.g., a country) as well as for the current cultivated area. We consider the latter case to be particularly relevant because significant shifting of the areas used for agriculture will often be difficult due, for instance, to the unavailability of the required infrastructure or conflicts with other land uses.

In the remainder of this section, we describe more formally the aggregated crop indicators applied in the ICLIPS model. The relevant variables and parameters of the crop model are described in Table 3.2.

Two groups of aggregated crop indicators can be distinguished. The first group of indicators applies simple decision rules to optimize crop allocation under changing climatic conditions. These indicators can be aggregated to any world region $R (R \subseteq G)$. The definitions below refer to the current cultivated area of a region yet it is straightforward to extend them to the total land area.

Maximum food energy [Gcal/km^2]:

$$\mathrm{Q_R}(\boldsymbol{c}) = \frac{\sum_{g \in R} C_g \cdot \max_{i \in I}\{\mathrm{y}_{ig}(c_g) \cdot q_i\}}{\sum_{g \in R} C_g}$$

In each grid cell, food energy production is maximized. The energy content of a crop represents a crude proxy for its nutritional value, admittedly neglecting other important qualities. Since price levels of particular crops or other incentives that are important for farmers producing cash crops are not considered, this indicator is mainly relevant for regions with a high share of subsistence agriculture.

Maximum crop price [US$/km^2]:

$$\mathrm{P_R}(\boldsymbol{c}) = \frac{\sum_{g \in R} C_g \cdot \max_{i \in I}\{\mathrm{y}_{ig}(c_g) \cdot p_i\}}{\sum_{g \in R} C_g}$$

In each grid cell, the monetary crop value is maximized. This indicator assumes that (a) *relative* price levels of different crops will remain essentially constant in the future, and (b) input requirements for different crops do not differ substantially. Due to the problems associated with these assumptions, this indicator does not belong to the standard set shown in Table 3.1.

Maximum crop performance [%]:

$$\mathrm{S_R}(\boldsymbol{c}) = \frac{\sum_{g \in R} C_g \cdot \max_{i \in I}\left\{\frac{\mathrm{y}_{ig}(c_g)}{\hat{y}_i}\right\}}{\sum_{g \in R} C_g}$$

In each grid cell, that crop is cultivated which maximizes the *relative* performance. The indicator thus measures whether *any* of the 19 crops can grow reasonably well in a specific climate.

The second group of aggregated crop indicators is based on the current distribution of crops. These indicators describe the sensitivity of the agricultural sector to climatic changes under the assumption that crop switching is *not* a feasible or desirable adaptation option, e.g., due to opposing diet preferences. Simulation results are stated as production changes relative to the baseline. The availability of information on the harvested area of each crop determines the spatial resolution at which these indicators can be computed. Since respective data is not generally available at sub-national levels, we define these indicators at the country level. Only those countries can be considered where at least one crop grows successfully in the current cultivated area under the baseline climate, i.e., where $\sum_{i \in I, g \in N} C_g \cdot \mathrm{y}_{ig}(c_g^*) > 0$.

Weighted crop performance [%]:

$$\mathrm{W_N}(\boldsymbol{c}) = \frac{\sum_{i \in I, g \in N} F_{iN} \cdot C_g \cdot \mathrm{y}_{ig}(c_g)}{\sum_{i \in I, g \in N} F_{iN} \cdot C_g \cdot \mathrm{y}_{ig}(c_g^*)}$$

This indicator measures the overall performance of the *current* cropping pattern in a changed climate by weighting the performance of each crop with its share in the cultivated area of a country. Owing to data limitations, the so-defined indicator assumes that all crops are *uniformly* distributed across the cultivated area of a country. Heterogeneous cropping patterns in countries that cover different climatic zones and/or soil types, e.g., the United States, Russia, and China, are therefore not adequately represented. This indicator can be easily aggregated to groups of countries by weighting the country-specific results with the (cultivated) area of each country.

Crop production with constant output shares [%]:

$$\mathrm{O_N}(\boldsymbol{c}) = \frac{1}{\sum_{i \in I : F_{iN} > 0} \left[F_{iN} \cdot \frac{\sum_{g \in N} C_g \cdot \mathrm{y}_{ig}(c_g^*)}{\sum_{g \in N} C_g \cdot \mathrm{y}_{ig}(c_g)} \right]}$$

If a division by zero occurs in the right hand side of the equation, we define $\mathrm{O_N}(\cdot) = 0$. The reciprocal of this indicator, $\frac{1}{\mathrm{O_N}(\boldsymbol{c})}$, describes the change in the extent of the cultivated area of a country that is required to retain baseline production levels of *all* crops under changed climatic conditions. Therefore, the indicator becomes zero if *any* of the current crops completely fails in the changed climate. This indicator is not included in the standard set of impact indicators because it cannot be easily aggregated to larger world regions and it is very sensitive to small variations in the model output.

Obviously, none of the indicators described above is capable of describing the *actual* future of a country's agricultural sector. Instead, they purposely span the possible range of adaptation to a changing climate (by means of crop switching) from the 'ahistoric' case of simply maximizing calorie production without taking into account any other restrictions than climate to the 'history-dominated' case of not changing the crop distribution at all. Consequently, these indicators provide a coarse indication of the sensitivity of a region's agricultural sector to climatic changes.

3.5.4 Fresh-water availability

The global hydrological model WaterGAP 1.1 (Döll et al., 1999) has been used to simulate global and regional water availability. Water availability is computed at the level of river basins as the total runoff (i.e., surface runoff and groundwater recharge) of all grid cells therein.

Routing between grid cells is not included in this model version. The daily water balance of each grid cell is therefore computed as

$$\frac{\partial S}{\partial t} = P_{eff} - E_a - R \qquad (3.23)$$

where S is the actual water content in the effective rooting zone, P_{eff} the effective precipitation (rainfall plus meltwater), E_a the actual evapotranspiration, and R the surface runoff. Both E_a and R are functions of S, which itself is calculated from these variables, based on the previous time step. E_a is calculated from the potential evapotranspiration, E_p, and the total available soil water content, S, as

$$E_a = \min\left(E_p; E_{p,max} \cdot \frac{S}{S_{max}}\right) \qquad (3.24)$$

whereby $E_{p,max} = 10\,\mathrm{mm/d}$, and S_{max} is the product of the vegetation-specific rooting depth and the available water capacity in the uppermost metre of the soil (Batjes, 1996). Runoff R is calculated according to Bergström (1995) as

$$R = P_{eff} \cdot \left(\frac{S}{S_{max}}\right)^{\gamma}, \quad (3.25)$$

with P_{eff} as defined above, and γ being the regional runoff coefficient. S, P_{eff}, E_a, E_p, and R are time-dependent. Hence, the water balance is fully described by the ordinary differential equation

$$\dot{S}(t) = P_{eff}(t) - \min\left(E_p(t); E_{p,max} \cdot \frac{S(t)}{S_{max}}\right) - P_{eff}(t) \cdot \left(\frac{S(t)}{S_{max}}\right)^{\gamma}. \quad (3.26)$$

WaterGAP is a reduced-form model with only one calibration parameter, the runoff coefficient γ, that was adjusted to time series of annual discharges of 41 large watersheds (Grabs et al., 1996). A regionalization algorithm was then used to assign values to the other river basins. The applied version of WaterGAP does not consider the CO_2 concentration. Increasing CO_2 levels reduce the evapotranspiration rates of plants and thus partly compensate the additional water loss due to increasing temperatures. This effect is particularly relevant in dry areas. The simulated decreases in runoff may therefore be slightly overestimated. Nevertheless, precipitation will be the dominant factor in determining the water availability in all watersheds around the world.

3.6 Climate impact response functions: presentation and application

This section discusses potential applications of the CIRFs developed in ICLIPS. We start with a description of the impact result space in ICLIPS, which is followed by a presentation of various types of impact diagrams that visualize selected aspects of this result space, and of the different application modes of CIRFs. Later, we present algorithms for the parameterized approximation of 'tolerable' climate windows and for the computation of reachable climate domains, which facilitate the application of CIRFs in guardrail analyses with the integrated ICLIPS model.

3.6.1 Dimensionality of the impact result space

The impact models applied in ICLIPS and the impact indicators derived from their results are based on a number of simplifying assumptions. The result space is nevertheless high-dimensional, being spanned by the following dimensions:

Impact indicator: One of several indicators for climate impacts (see Table 3.1 for a complete list).

Sub-indicator: Some impact indicators require a sub-category to be specified (see Table 3.1 for details). The indicator "crop yield", for example, is available for 19 different crops.

Area coverage: Some impacts have been simulated for the total land surface as well as for spatial subsets that mask out, or focus on, agricultural and protected areas (see Table 3.1 for details). The indicator "crop yield", for example, is available for the total land area as well as for the current cultivated area in a region.

Regional grouping and region: The grid-based simulation results from the impact models are first aggregated to the country level. However, results for individual countries are only reported if they are sufficiently robust. For many impact indicators, results are presented for larger regions only. Default regional groupings include biogeographic regions and geopolitical regions (cf. Section 3.5.1).

Climate model: The scaled scenario approach links a CIRF to the climate change patterns from a specific GCM. The present version of the ICLIPS model uses climate change patterns from ECHAM3-LSG, ECHAM4-OPYC and HadCM2 (cf. Section 3.3.3).

Level of climate and CO_2 change: CIRFs represent the dose-response relationship between the level of global climate change and the CO_2 concentration as independent variables and an impact indicator for a specific region and climate projection as the dependent variable. A CIRF is uniquely selected by specifying each of the dimensions listed above. The value of the impact indicator for a *specific* CIRF is then determined by the independent variables, i.e., by the level of climate and CO_2 change (cf. Section 3.4.2).

3.6.2 Types of impact diagrams

Impact diagrams are used to present selected results of the impact simulations by combining data points from CIRFs along various dimensions of the impact result space. Different types of impact diagrams are used to provide different perspectives on the result space. The impact diagrams related to vegetation impacts shown below serve mainly an illustrative purpose. A detailed discussion of the simulation results follows in Chapter 4.

Response surface diagrams are 3-dimensional diagrams that display the response of a regional impact indicator (the vertical dimension) across the whole domain of definition of the CIRF (the two horizontal dimensions) by interpolating across the points at the intersection of the selected increments. These diagrams give an overview of the sensitivity of the impact indicator to individual and combined changes in its driving variables. Impact isolines connect points on the response surface where the impact indicator equals some pre-defined values. Response surface diagrams provide an easily understandable visualization of a CIRF. Their 3-dimensional nature, however, makes them less suitable for inverse applications and for sensitivity analyses.

In the case of CIRFs with only one input variable (e.g., for water availability), response-surface diagrams are represented by two-dimensional dose-response curves, and isolines turn into single points on these curves.

Figures 3.12.a and 3.12.b show the fraction of protected areas worldwide and in Western Europe, respectively, where the climate becomes unsuitable for the current biome based on climate change patterns from ECHAM4. A comparison of the two diagrams reveals that the sensitivity of ecosystems to climate change is greater in Western Europe than in the rest of the world whereas the sensitivity to CO_2 is below the average in Western Europe.

Impact isoline diagrams show the projection of impact isolines from a response surface diagram onto the 2-dimensional domain of the CIRF. An isoline separates those climate regimes where the simulated

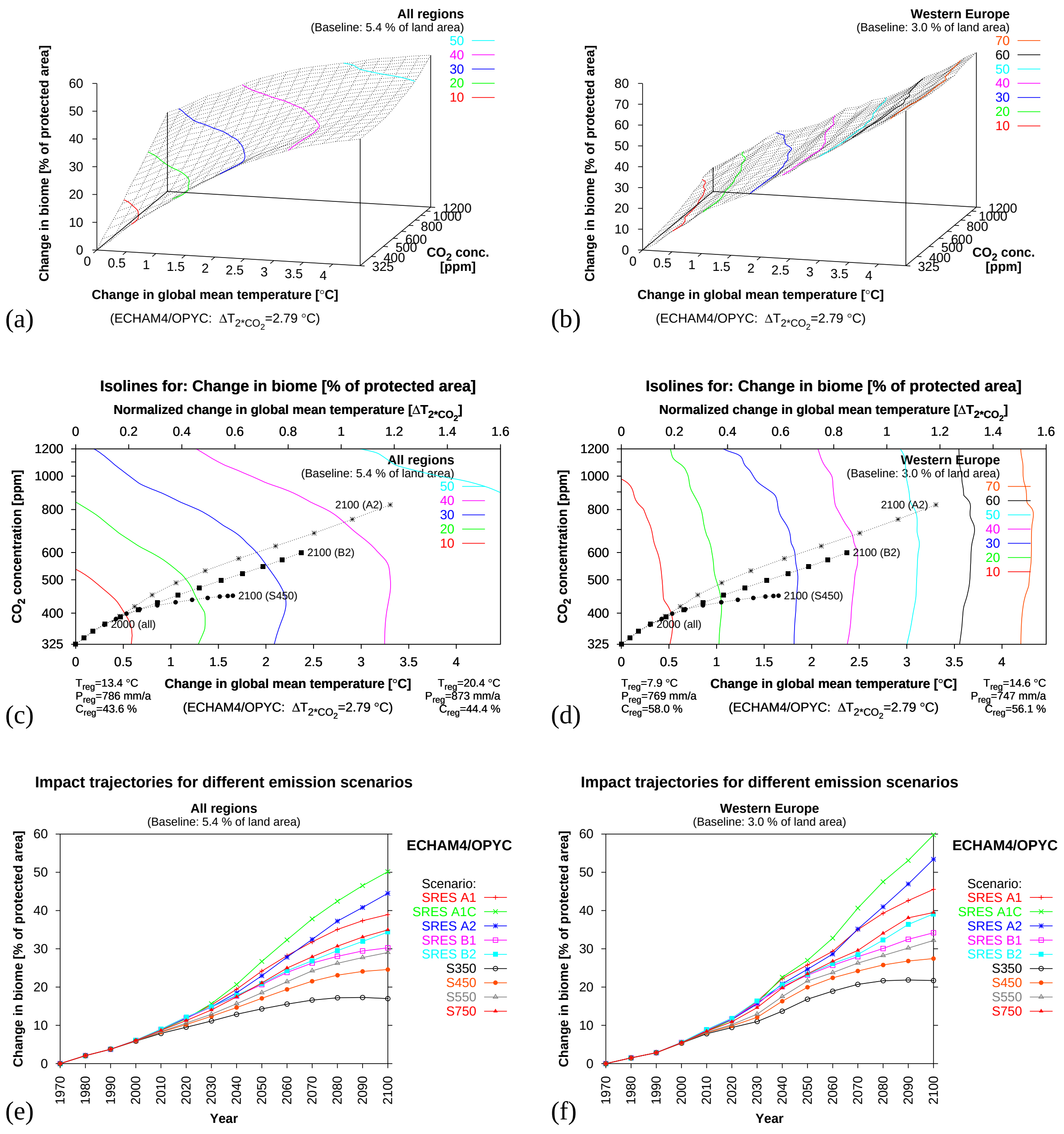


Figure 3.12: Different types of impact diagrams. (a), (b): response surface diagrams; (c), (d): impact isoline diagrams; (e), (f): multi-scenario trajectories.

impacts lie below the associated impact level from those regimes where they lie above. This feature is essential for guardrail analyses with the ICLIPS model because observing an impact guardrail becomes equivalent to constraining the evolution of the climate-CO_2 trajectory to the 'tolerable' climate window delimited by the respective impact isoline. The climate evolution simulated for selected emission scenarios can be shown by projecting the associated time trajectories onto the isoline diagram. In an effort to determine 'critical climate change, CIRFs for uniform changes in regional temperature and precipitation and corresponding isoline diagrams have been determined in van Minnen et al. (2002).

Figures 3.12.c and 3.12.d show the impact isoline diagrams corresponding to the response surface diagrams depicted in Figures 3.12.a and 3.12.b, respectively. (Owing to size restrictions for the impact diagrams and to limitations of the software used to produce them, the legend of isoline diagrams is usually shown inside the diagram, even though this is not the most appealing option.) The three pointed lines originating in the bottom left corner depict the time trajectories simulated for three IPCC emission scenarios in decadal time steps from 1970 (bottom left corner) to 2100. A comparison of their endpoints in Figure 3.12.c shows that the SRES A2 emission scenario causes higher global impacts in the year 2100 (between 40 and 50%) than the SRES B2 scenario (between 30 and 40%) and the S450 scenario (between 20 and 30%). When interpreting these numbers, it should be considered that they were determined by an equilibrium biome model. The realization of the simulated changes may therefore be delayed (cf. Section 3.5.2).

Multi-scenario trajectories depict the time path of an impact indicator in *one* region for *different* emission scenarios. Only those data points of the CIRF are shown that correspond to climate-CO_2 combinations actually reached by one of the emission scenarios. The temporal evolution of potential impacts can be clearly seen whereas information on the differential importance of each of the two driving variables is lost. These results are analogous to results derived from other impact models in forward mode (e.g., Krol et al., 1997; Toth et al., 2000; Arnell et al., 2002).

Figures 3.12.e and 3.12.f show multi-scenario trajectories for the same indicators as in Figures 3.12.c and 3.12.d, respectively.

Multi-regional trajectories show the time path of an impact indicator in *different* regions for *one* emission scenario. If the baseline value of the impact indicator differs between different regions, the trajectories can refer either to the absolute value of the indicator or to relative changes compared to the baseline value.

The trajectories shown in Figures 3.13.a and 3.13.b depict the fraction of protected area in 11 world regions (see Figure 3.10) that would experience a biome change under the SRES A2 emission scenario based on climate change patterns from ECHAM4 and HadCM2, respectively. The simulated impacts vary widely across regions whereby the lowest impacts are consistently simulated for Middle East and North Africa and the highest impacts for Central and Eastern Europe.

Multi-regional isoline diagrams show the projection of impact isolines onto the domain of the CIRF. In contrast to the impact isoline diagrams described above, the isolines refer to the *same* impact guardrail for *different* regions rather than to *different* impact guardrails for *one* region. This diagram type as well as the multi-regional trajectories facilitate cross-regional sensitivity analyses of an impact indicator.

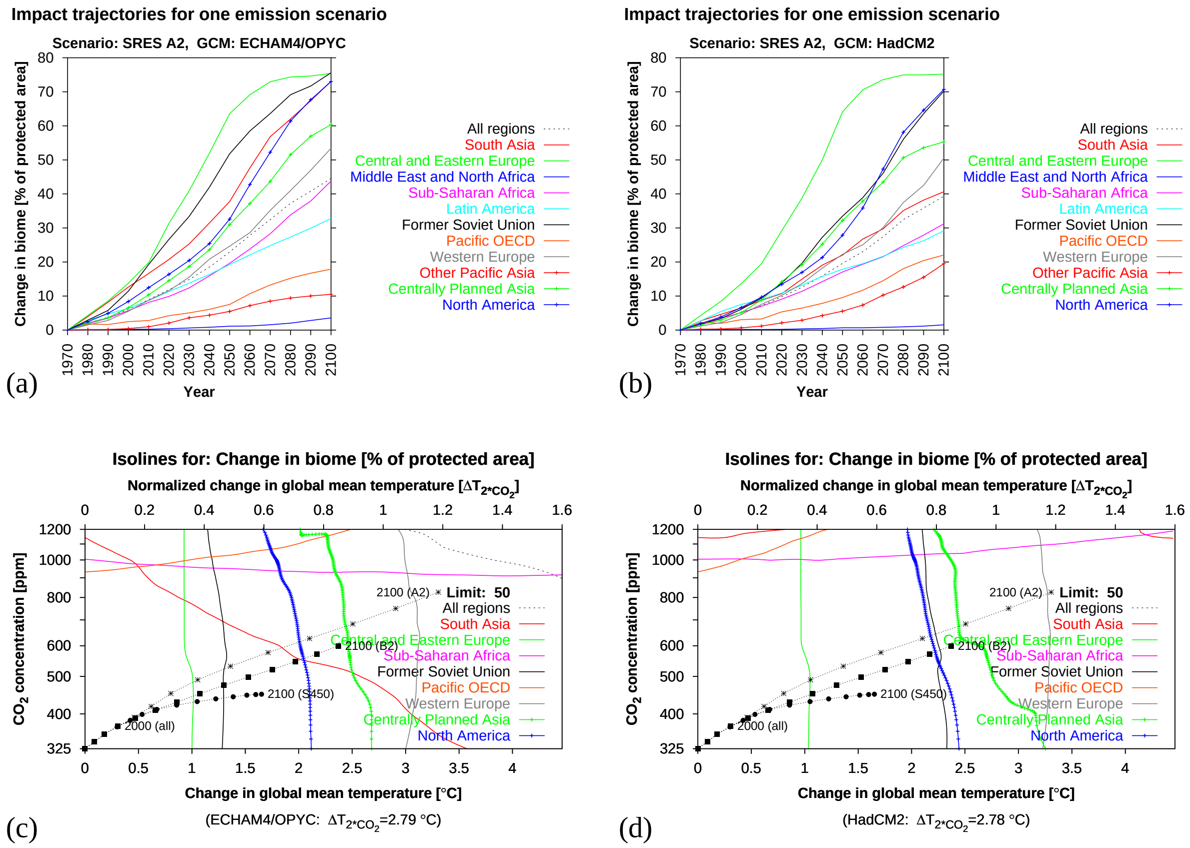


Figure 3.13: Different types of impact diagrams (ctd.). (a), (b): multi-regional trajectories; (c), (d): multi-regional isoline diagrams.

Figures 3.13.c and 3.13.d show isolines that refer to a simulated change of the current biome in 50% of the protected area in several regions based on climate change patterns from ECHAM4 and HadCM2, respectively. In the year 2100, the 50% guardrail is exceeded in 5 to 6 (out of 11) regions under the SRES A2 scenario, in 3 to 4 regions under the SRES B2 scenario and in 1 to 2 regions under the S450 scenario. The largest difference between the ECHAM4 and HadCM2 climate change patterns is simulated for South Asia (primarily due to a large difference in the projected precipitation changes for that region).

Multi-category isoline diagrams show isolines for *different* sub-indicators in *one* region. They facilitate cross-category analyses of impact indicators in a region.

The isolines shown in Figure 3.14.a/b correspond to those climate–CO_2 states where specific biomes are no longer viable in 50% of their current area in Central and Eastern Europe, which turned out to be particularly sensitive in Figures 3.13.a/b. The diagrams reveal the differential sensitivity of biomes in this region, with cool conifer forest being most and temperate deciduous forest being least sensitive.

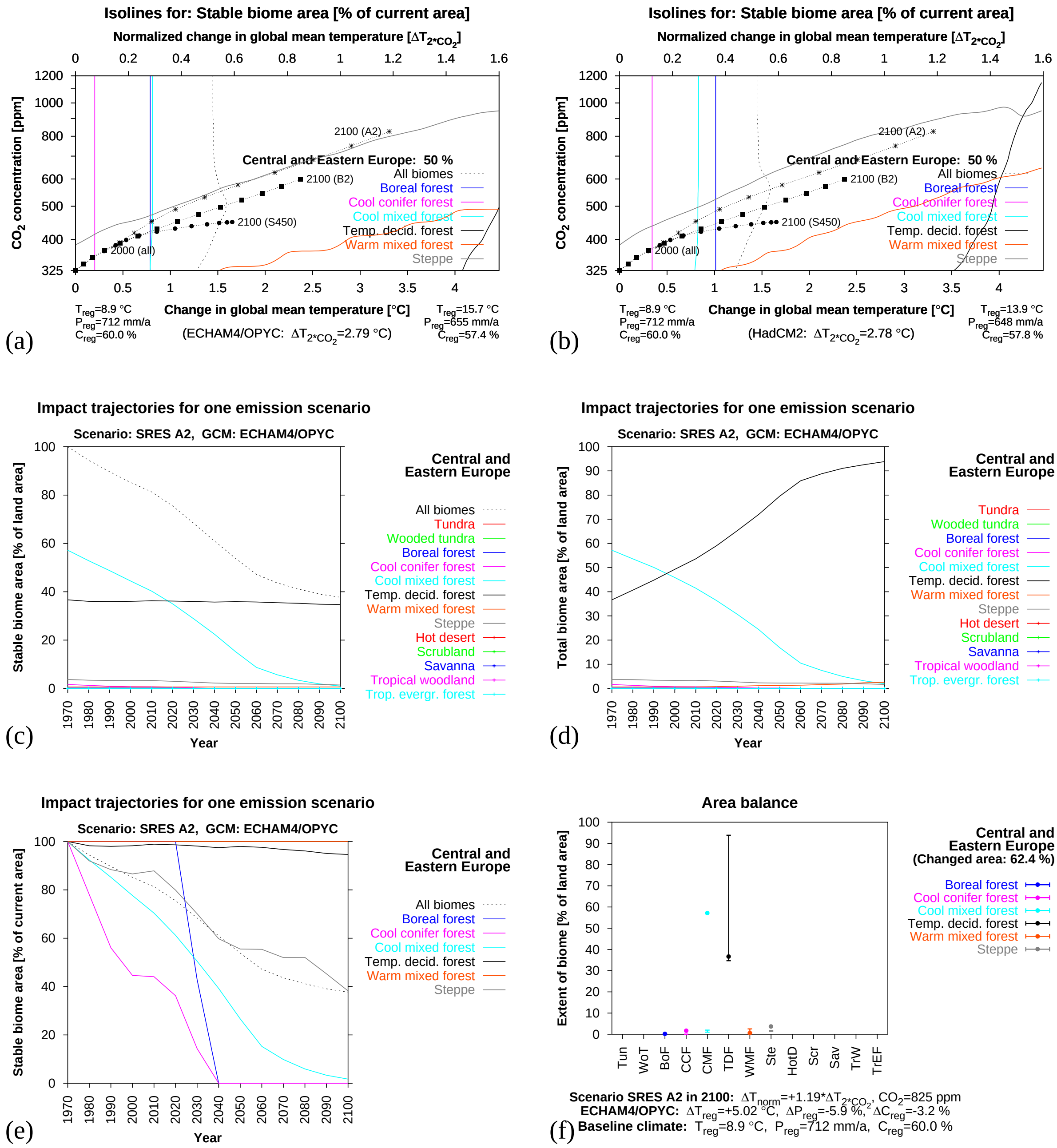


Figure 3.14: Different types of impact diagrams (ctd.). (a), (b): multi-category isoline diagrams; (c), (d): multi-category trajectories (absolute); (e): multi-category trajectories (normalized); (f): area balance diagram.

Multi-category trajectories show the time path of *different* sub-indicators within a region for *one* emission scenario.

Figures 3.14.c and 3.14.d depict the time trajectories for the stable and total potential area, respectively, of each biome in Central and Eastern Europe under the SRES A2 scenario as a fraction of the total land area. The area suitable for cool mixed forest is simulated to decrease from about 60% to almost nothing whereas the potential area for temperate deciduous forest increases from less than 40% to more than 90%. Figure 3.14.e shows the normalized version of Figure 3.14.c, which focusses on the relative changes in the extent of different biomes rather than the absolute changes.

Area balance diagrams differ from the diagram types presented above insofar as they combine results for *two* area-related impact indicators for *two* climate states only. An area balance diagram depicts the gain-loss balance of an area-related indicator across different sub-categories or regions *for a specific future climate state* in comparison with the baseline climate.

Figure 3.14.f shows the simulated share of each biome in the total area of Central and Eastern Europe for baseline climate conditions as well as for the climate simulated by ECHAM4 for the year 2100 of the SRES A2 scenario. The extent of each biome under baseline climate conditions ($A + B$ in Figure 3.11) is indicated by points whereas the stable area (B) and the total area ($B + C$) in the changed climate state are denoted by lower and upper bars, respectively. The data points shown in this diagram correspond to the values of the trajectories at the right-hand side of the diagrams depicted in Figure 3.14.c/d.

3.6.3 Applications of climate impact response functions

There are three principal applications for CIRFs:

Overview mode: A CIRF allows to assess the sensitivity of a system to changes in each of the forcing variables, including the detection of possible non-linearities. The joint effect of the driving variables and possible trade-offs can also be easily identified. Response surface diagrams are particularly suitable for this application.

Forward mode: CIRFs are used to determine the likely impacts of a specific climate state or scenario, analogous to standard applications of process-based climate impact models. The results of this type of application are depicted by multi-scenario and multi-regional trajectory diagrams.

Inverse mode: A CIRF can be used to partition its domain in two parts, according to the compliance with a previously defined impact guardrail. The integrated ICLIPS model can then determine the bundle of permitted emission paths by constraining the values of the respective model variables to the admissible partition. The information for this type of application is provided by impact isoline diagrams.

Examples for all application modes of CIRFs and results of the integrated ICLIPS model will be presented in Chapter 4.

3.6.4 Parametrization of climate windows

In this section we present two parameterized approximations of ‘tolerable’ climate windows from the two-dimensional domain of CIRFs for natural vegetation and crop production. Both of them approximate a tolerable climate window by up to two constraints. Their main difference is in the number of scalar parameters required to specify these constraints.

The parameterized approximations are used to translate impact guardrails into constraints that can be directly applied in guardrail analyses with the ICLIPS climate-economy model (ICEM). Each constraint is represented by a linear tolerance function defined over the suitably normalized domain of the CIRF. The first approximation, which is the standard method for the consideration of impact guardrails in inverse analyses with the ICLIPS model, uses up to four scalar parameters to describe the constraints. The second approximation, which is slightly less accurate, uses only two scalar parameters. This simplification makes it possible to perform guardrail analyses for a representative subset of impact-related constraints, together with various choices for socioeconomic guardrails. The result consist of a set of emission corridors for a representative selection of all conceivable impact and socioeconomic guardrails. This set can be used offline to estimate the size and shape of emission corridors for arbitrary impact constraints. Owing to the considerable computational demand of a guardrail analysis with the ICLIPS model, such a scanning of all potential impact guardrails is not possible for the four-dimensional approximation.

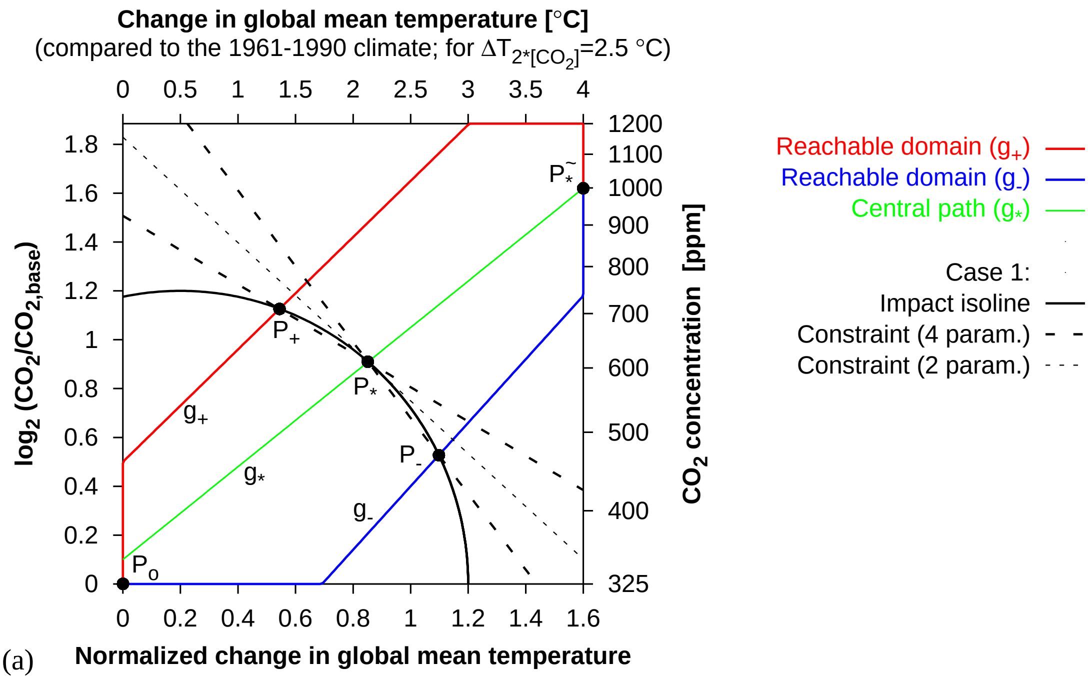
The parametrizations of tolerable climate windows take advantage of the fact that only a subset of the domain of a CIRF, termed *reachable climate domain*, can actually be reached by 'reasonable' emission scenarios. For practical purposes, the description of a tolerable climate window can therefore be restricted to its intersection with the reachable climate domain. Each of the two parametrizations distinguishes eight cases, depending on the 'shape' of the intersection between the climate window and the reachable domain. Figure 3.15 illustrates the main elements of the parametrization for two of these cases. Each diagram shows the domain of a CIRF, spanned by the normalized change in AGMT and the logarithmically scaled CO_2 concentration. The logarithmic scaling of the latter variable reflects the approximately logarithmic relationship between CO_2 concentration and equilibrium AGMT change (see Equations 3.4 and 3.5 in Section 3.3.3).

Various straight lines are depicted in Figure 3.15. The so-called *central path*, g_* (in green), approximates a trajectory corresponding to the average of the four SRES marker emission scenarios. g_+ (in red) and g_- (in blue) approximate the upper and lower *boundaries of the reachable climate domain*, respectively. Reachable climate domains are understood here as subsets of the domain of definition of a CIRF that can be reached by plausible emission scenarios. The algorithm for determining them is explained in Section 3.6.5, and selected results based on the ICLIPS climate model are presented in Section 4.1. Based on the reachable climate domain depicted in Figure 4.1.b, the lines in Figure 3.15 are specified as follows:

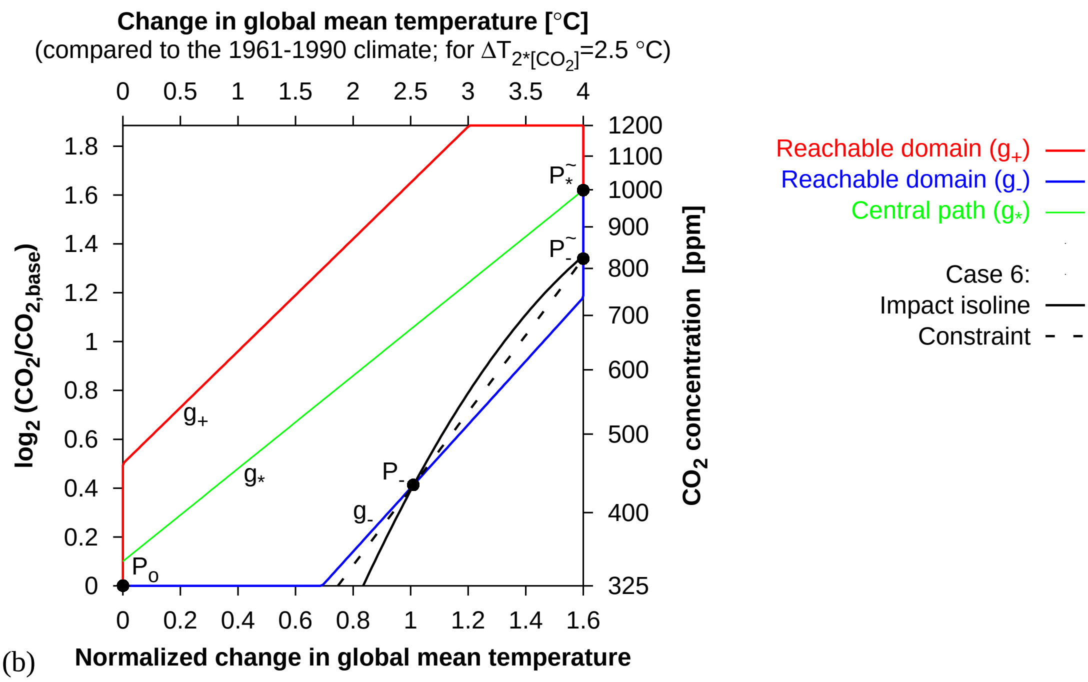
$$\begin{aligned} g_+ : \quad [\mathrm{CO_2}]_{norm} &= 1.15 \cdot \Delta T_{norm} + 0.50 \\ g_- : \quad [\mathrm{CO_2}]_{norm} &= 1.30 \cdot \Delta T_{norm} - 0.90 \\ g_* : \quad [\mathrm{CO_2}]_{norm} &= 0.95 \cdot \Delta T_{norm} + 0.10 \end{aligned}$$

For each of these straight lines, we are only interested in the segment that lies inside the domain of definition of the CIRF. This segment is extended by parts of the boundary of the CIRF's domain so that the resulting *directional* traverse connects P_0 (the baseline climate) with $\tilde{P}_*$ (the maximum level of climate change on the central path). For details, see Figure 3.15. Since the baseline climate is assumed to be tolerable, P_0 always lies inside the (tolerable) climate window.

The two parametrizations of tolerable climate windows presented here are based on the existence of specific points at the intersections of the impact isoline (in black) with the upper and lower boundary of the reachable domain, and with the central path. These points are defined as follows:



(a)



(b)

Figure 3.15: Parameterized approximation of tolerable climate windows for two (out of eight) cases. Impact isoline diagrams for (a) case 1, and (b) case 6.

Case	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
P_+	$+$	$-$	$+$	$-$	$+$	$-$	$+$	$-$
P_-	$+$	$+$	$-$	$-$	$+$	$+$	$-$	$-$
P_*	$+$	$+$	$+$	$+$	$-$	$-$	$-$	$-$
Constraints (4 parameters)	(P_+, P_*) (P_*, P_-)	(P_*, P_-)	(P_+, P_*)	$(P_*, -\frac{\pi}{4})$	$(P_+, \tilde{P}_+)$ $(\tilde{P}_-, P_-)$	$(\tilde{P}_-, P_-)$	$(P_+, \tilde{P}_+)$	
Constraints (2 parameters)	(P_*, α_*)	(P_*, P_-)	(P_+, P_*)	$(P_*, -\frac{\pi}{4})$	$(P_+, \tilde{P}_*)$ $(\tilde{P}_*, P_-)$	$(\tilde{P}_-, P_-)$	$(P_+, \tilde{P}_+)$	

Table 3.3: Cases distinguished in the specification of constraints for parameterized climate windows. $+$: the respective point exists; $-$: the respective point does not exist. (α_* is defined in the text.)

P_+ / $\tilde{P}_+$: the first / last intolerable point on the traverse defined by g_+
P_- / $\tilde{P}_-$: the first / last intolerable point on the traverse defined by g_-
P_*: the first intolerable point on the traverse defined by g_*
$\tilde{P}_*$: the last point on the traverse defined by g_*

Constraints related to 'tolerable' climate windows are represented in the ICLIPS model by one or more linear 'tolerance functions' defined over the normalized domain of the CIRF. Positive values of the tolerance function indicate admissible climate states (i.e., states inside the tolerable climate window), and negative values indicate non-admissible climate states. We specify the constraints either in the two-points form or in the point-angle form.

Two points: (P_1, P_2) denotes the constraint that excludes all points to the *left* of the directional line that connects $P_1 = (x_1, y_1)$ with $P_2 = (x_2, y_2)$. This constraint is represented by the tolerance function

$$\mathrm{Tol}(P_1, P_2) : (x, y) \to (y_2 - y_1) \cdot (x - x_1) - (x_2 - x_1) \cdot (y - y_1). \quad (3.27)$$

Point and angle (or slope): (P_1, α) denotes the constraint that excludes all points to the *left* of the directional line that goes through $P_1 = (x_1, y_1)$ and has the slope $\tan(\alpha)$. This constraint is represented by the tolerance function

$$\mathrm{Tol}(P_1, \alpha) : (x, y) \to \sin(\alpha) \cdot (x - x_1) - \cos(\alpha) \cdot (y - y_1). \quad (3.28)$$

Table 3.3 shows how the constraints are defined depending on the existence of P_+, P_-, and P_*. The following cases are distinguished in the four-dimensional parametrization:

Cases 1–3: P_* exists, and P_+ or P_- (or both) exist.

If P_+ (or P_-) exists, a constraint is defined by the line that connects P_+ with P_* (or P_* with P_-). If both points exist, two constraints are defined.

Case 4: P_* is defined but neither P_+ nor P_- exist.

This reflects the rare case that a segment of the central path is intolerable even though the boundary of the reachable climate domain is completely tolerable. The constraint passes through P_*. In the absence of specific information, the sensitivity to both drivers (i.e., normalized temperature and CO_2 change) is assumed to be equal, as expressed by $\alpha = -\pi/4$.

Cases 5–7: P_* does not exist but P_+ or P_- (or both) exist.

If P_+ (or P_-) exists, a constraints is defined by the line that connects P_+ with $\tilde{P}_+$ (or $\tilde{P}_-$ with P_-). Since P_* does not exist, the complete central path, including $\tilde{P}_*$, is tolerable. The existence of P_+ (or P_-) thus implies the existence of $\tilde{P}_+$ (or $\tilde{P}_-$). If both points exist, two constraints are defined.

Case 8: Neither P_+ nor P_- nor P_* exists.

If neither the boundary of the reachable domain nor the central path contain intolerable segments, no constraint is defined.

The parametrization described above approximates well all but rather 'degenerate' climate windows. In general, the climate window is represented by two linear constraints on the normalized input variables of the CIRF. Since these constraints are defined by up to four independent points on pre-defined traverses, four scalar parameters are generally required for their specification.

We now present a variation of this parametrization that needs only two parameters. The only cases that required more than two parameters for their description are the cases 1 and 5, i.e., where both P_+ and P_- exist. For the two-dimensional parametrization, the specification of the constraints is modified as follows:

Case 1': If P_* exists, the two original constraints are replaced by a single one (see Figure 3.15.a). The line that defines the new constraint goes through P_*. Its slope is determined by the slope of the line that connects $P_+ = (x_+, y_+)$ with $P_- = (x_-, y_-)$, as represented by $\alpha_* = \arctan\left(\frac{y_+ - y_-}{x_+ - x_-}\right)$.

Case 5': If P_* does not exist, the two original constraints are modified by substituting the fixed point $\tilde{P}_*$ for the variable points $\tilde{P}_+$ and $\tilde{P}_-$. As a result, each constraint can be described by a single parameter.

The two diagrams in Figure 3.15 illustrate the cases 1 and 6. 'Case 1 isolines' are typical for impacts on natural ecosystems (see Section 4.2). Since changes in the mean climate as well as increases in CO_2 concentration can trigger ecosystem transformations, tolerable climate windows typically involve constraints for both variables. 'Case 6 isolines' are often associated with crop impacts (see Section 4.3). Anticipated climate change alone is often simulated to decrease crop yields but this effect tends to be (partly) compensated by the stimulation of plant growth under elevated CO_2 concentration. Hence, the intolerable part of the domain is restricted to combinations of high levels of climate change with low CO_2 concentrations (i.e., the lower right part of the impact isoline diagram).

3.6.5 Computation of reachable climate domains

The implementation of the ICLIPS climate-economy model in the optimization calculus GAMS offers the novel possibility to establish *reachable domains*, defined as feasible combinations of values of at least two model variables under given restrictions (cf. Section 2.4.1). In this section, we describe an algorithm for determining reachable *climate* domains, understood as those subsets of the two-dimensional domain of the CIRFs that can be reached by 'plausible' emission scenarios.

If previous knowledge ascertains that a reachable domain is connected along all but one of its dimensions, it can be determined straightforwardly by successively maximizing and minimizing one dimension while prescribing the values for the other ones. However, such an algorithm fails for certain convoluted reachable domains, including many of the reachable climate domains considered here.

For the sake of brevity, we employ a notation for reachable climate domains that is slightly different from the one introduced in Section 2.4.1. Based on Equation 2.10 on p. 53, we define the reachable climate domain for a time period $[t_1, t_2]$ as

$$\mathrm{RD}(t_1, t_2) \quad \equiv \quad \mathrm{Reach}_{\mathrm{ij}}([t_1, t_2], \boldsymbol{x}_0) \quad \subseteq C \times P,$$

whereby C and P denote the ranges of AGMT change and CO_2 concentration, respectively. The reachable climate domain for a point in time t is denoted as $\mathrm{RD}(t) \equiv \mathrm{RD}(t, t)$.

The algorithm for determining $\mathrm{RD}(t_1, t_2)$ presented here requires two preconditions to be true. First, $\mathrm{RD}(t_1, t_2)$ needs to be simply connected so that it can be approximated by a single polygon. Second, all $\mathrm{RD}(t)$ need to be connected along one optimization dimension. The hypothetical reachable domain depicted in Figure 3.16.a, for instance, is connected along the p dimension but *not* along the c dimension where the intersection at $p = p_1$ consists of two separate intervals. We note without formal proof that the reachable climate domains considered here fulfill these two conditions. In fact, the $\mathrm{RD}(t)$ are connected along both optimization dimensions. The $\mathrm{RD}(t_1, t_2)$, even though being simply connected, are often disconnected along both dimensions, which prevents the application of the straightforward algorithm sketched above.

The basic idea of our algorithm is illustrated in Figure 3.16.b. First, reachable climate domains are determined for discrete time slices. Second, the algorithm successively constructs the union of these reachable climate domains, which approximates the reachable domain for the whole time period. We note that the first step is similar to an algorithm for computing higher-dimensional emission corridors that was developed independently by Kriegler and Bruckner (2003).

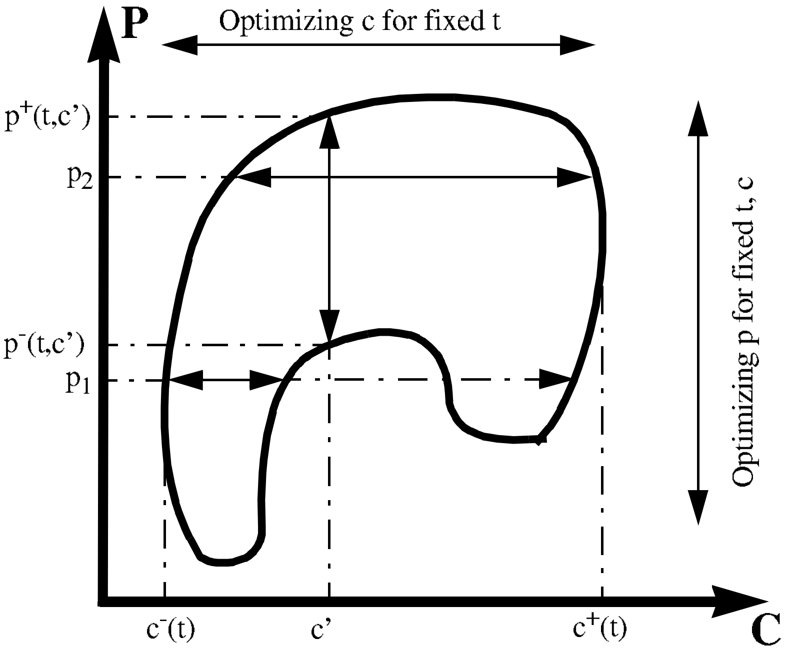
Through suitable modifications of the objective ('goal function') to be maximized or minimized, the ICLIPS climate model (ICM) can be used to determine, i.a., the maximum and minimum temperature at time t (denoted as $c^+(t)$ and $c^-(t)$, respectively, in Figure 3.16.a), and the maximum and minimum CO_2 concentration at time t for a given temperature change c' (denoted as $p^+(t, c')$ and $p^-(t, c')$, respectively). All these optimizations refer to a given set of plausible emission scenarios implemented as constraints on admissible control strategies.

The algorithm for determining $\mathrm{RD}(t_1, t_2)$ proceeds as follows:

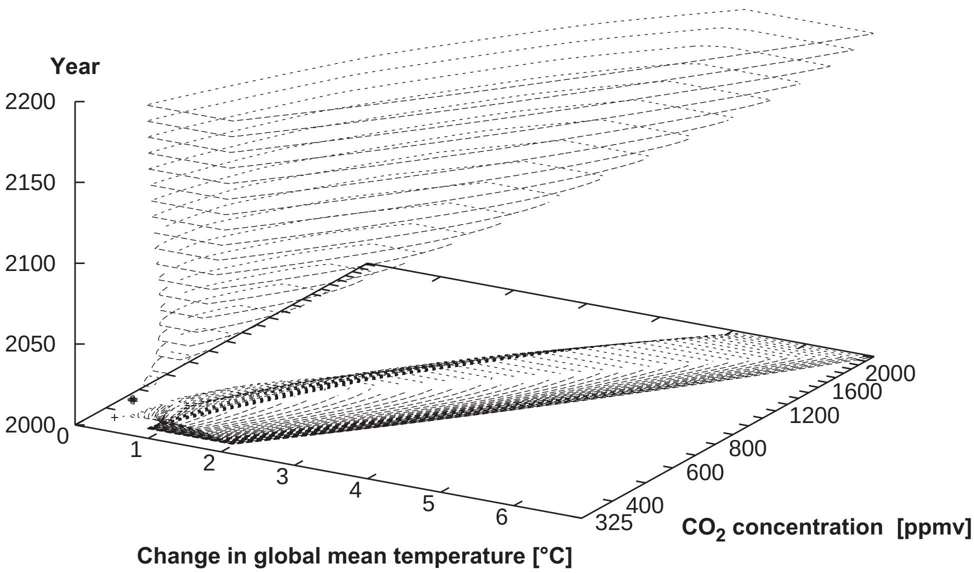
1. Discretize the time period $[t_1, t_2]$ into a finite set of time slices, which is denoted as T. (In the present example, the discretization is determined by the temporal resolution of the ICM.)

2. Determine the maximum and minimum temperature reachable at *any* of these time slices as follows:

$$c^+ \quad \equiv \quad \max_{t \in T} c^+(t),$$
$$c^- \quad \equiv \quad \min_{t \in T} c^-(t).$$



(a)



(b)

Figure 3.16: Two reachable climate domains. (a) Hypothetical reachable domain with a convolution. (b) Time evolution of a reachable climate domain determined by the ICLIPS Climate Model. Depicted are the boundaries of the reachable domains for each point in time by dashed and dotted lines as well as their projections onto the temperature-CO_2 concentration surface. (For a description of the underlying assumptions, see Section 4.1.)

Discretize the reachable temperature interval $[c^-, c^+]$ into an ordered set of values $\{c_1, c_2, \ldots, c_k\}$ such that $c_1 = c^-$ and $c_k = c^+$.

3. For each time slice $t \in T$, define a traverse (i.e., the boundary of a polygon) by a sequence of points, as follows:

$$\begin{aligned}\mathcal{P}_t \equiv\ & (c_1, p^-(t, c_1)), (c_2, p^-(t, c_2)), \ldots, (c_k, p^-(t, c_k)),\\ & (c_k, p^+(t, c_k)), (c_{k-1}, p^+(t, c_{k-1})), \ldots, (c_1, p^+(t, c_1)).\end{aligned}$$

   If the algorithm finds no feasible solution for a specific combination of t and c, the respective point is omitted from the traverse.

   $\mathcal{P}_t$ is a closed line of up to $2k$ segments. Since $\mathrm{RD}(t)$ was required to be connected along the optimization dimension, its boundary is approximated by $\mathcal{P}_t$. (Actually, the choice of the optimization dimension does not matter here because $\mathrm{RD}(t)$ is connected along both dimensions.) In the graphical representation of Figure 3.16.a, the first (up to k) segments of $\mathcal{P}_t$ approximate the 'lower part' of the boundary of $\mathrm{RD}(t)$, and the last (up to k) segments approximate the 'upper part'.

4. For a smoothly changing climate system and a sufficiently fine discretization of the time axis, the union of all time-specific reachable domains, $\bigcup_{t\in T} \mathrm{RD}(t)$, approximates the reachable climate domain for the whole time period, $\mathrm{RD}(t_1, t_2)$. This final step determines sequentially, based on the $\mathcal{P}_t, t \in T$, a traverse $\mathcal{P}$ that approximates the boundary of that union:

   Select any time-specific traverse, which is denoted as $\mathcal{P}_{t'}$. Find another traverse $\mathcal{P}_{t''}$ such that the intersection of the two polygons enclosed by $\mathcal{P}_{t'}$ and $\mathcal{P}_{t''}$ is non-empty. Since we required $\mathrm{RD}(t_1, t_2)$ to be simply connected, such a $\mathcal{P}_{t''}$ must exist. Determine the boundary of the union of these two polygons, and substitute it for $\mathcal{P}_{t'}$. Repeat this step for each remaining traverse until the boundary of the union of all polygons has been determined, which is denoted as $\mathcal{P}$.

   The determination whether two polygons have a non-empty intersection is done by checking whether any pair of segments from their boundaries intersect, whereby the case that one polygon is a subset of the other one needs to be treated separately. A similar method is used to determine the boundary of the union of two polygons, which consists of all those segments from each boundary that do not lie inside the other polygon.

This algorithm has been used to determine the boundary of reachable climate domains under various constraints for emission scenarios. A specific reachable domain (with rather weak constraints) was used in the parametrization of 'tolerable' climate windows in Section 3.6.4. Other results are presented in Section 4.1.

3.7 ICLIPS Impacts Tool

This section presents the ICLIPS Impacts Tool, a graphical user interface that provides access to a large set of climate impact response functions (CIRFs) from the ICLIPS model.

3.7.1 Purpose of the software

The reduced-form impacts module of the ICLIPS integrated assessment model is comprised of CIRFs that depict the regional sensitivity of selected impact sectors to changes in important climatic and atmospheric drivers. These CIRFs result from a large set of simulations with sector-specific impact models. The CIRFs were initially developed to enable the incorporation of thresholds for climate impacts in guardrail analyses with the ICLIPS model. However, they are also a valuable source of information in their own right.

The ICLIPS Impacts Tool makes the comprehensive set of CIRFs developed for the ICLIPS model available to a wider community. The graphical user interface provides convenient access to a large number (ca. 100,000) of climate and impact diagrams for a wide range of impact indicators, geographical regions, and climate projections. The ICLIPS Impacts Tool may be used to obtain an overview about potential climate impacts as simulated by several biophysical impact models, and to derive 'tolerable' climate windows corresponding to a certain level of climate impacts. It also supports sensitivity analyses across impact indicators, geographical regions, emission scenarios, and climate projections from different GCMs.

The main limitations of the ICLIPS Impacts Tool are two-fold. First, the climate and impact models applied to determine the CIRFs ignore some important factors, for instance the possibility of large-scale singularities in the climate system, socioeconomic factors affecting the vulnerable system, and the potential of planned adaptation (cf. Section 3.4.3). Second, the computer tool covers only the impacts part of the ICLIPS integrated assessment model. Whilst the inclusion of additional features into the ICLIPS Impacts Tool appears desirable at first sight, they would certainly increase its complexity. Potential users might no longer be able to manage the program and understand all assumptions that exert influence on the model results. The ICLIPS Impacts Tool thus represents a compromise between flexibility in its use, realism in the representation of the relevant system components, and comprehensibility of its results.

Further developments of the ICLIPS Impacts Tool may either extend the database of CIRFs or the functionality of the software. The most important functionality not yet implemented in the ICLIPS Impacts Tool is the export of the numerical simulation results represented in the impact diagrams, preferably by using parameterized approximations of impact isolines (cf. Section 3.6.4) or of the response surface diagrams (see, e.g., Downing et al., 1985; Webster and Sokolov, 2000).

3.7.2 Use of the software

Figure 3.17 shows the main screen of the ICLIPS Impacts Tool. The central task of the software is the step-by-step selection of an impact diagram from the large accompanying database.

Most dimensions of the impact result space (cf. Section 3.6.1) are represented by a menu in the top panel. The five menus to the left always comprise the dimensions "Impact indicator", "Area coverage", "Regional grouping", and "Climate model" as well as the selection of the "Diagram type". The choices that are *actually* available in a specific menu depend on the selections made in the menus to its left. For instance, the selected impact indicator determines which area coverage and regional grouping can be chosen. The dimensions represented in the last two menus to the right depend on the selected diagram type (cf. Table 3.4). Response surface diagrams, for instance, require the selection of a region and, potentially, a sub-indicator. In Figure 3.17, the menu on the far left is disabled because the impact indicator "Change of biome" does not comprise sub-indicators (cf. Section 3.5.1).

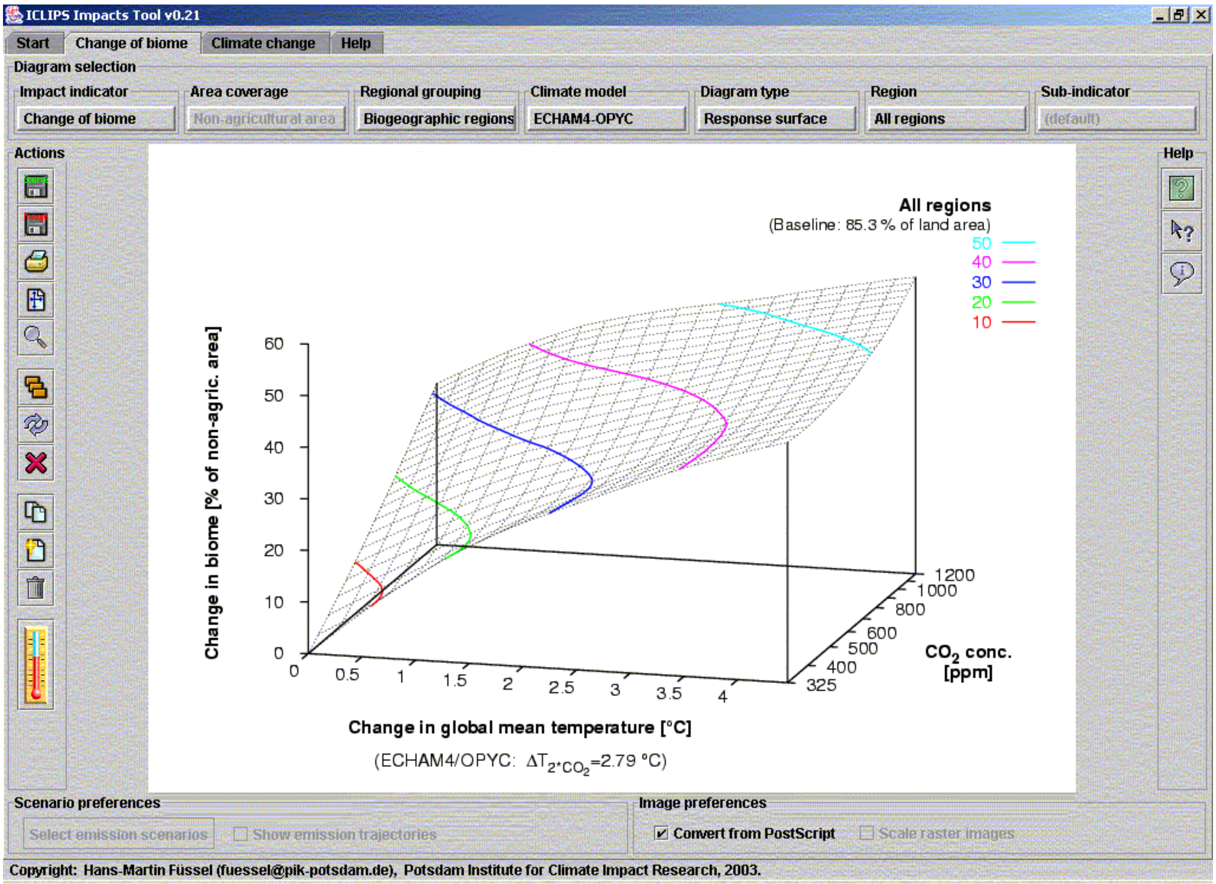


Figure 3.17: Screen shot of the ICLIPS Impacts Tool showing a response surface diagram

Diagram type	First dimension	Second dimension
Response surface, impact isolines, scenario trajectories	Region	Sub-indicator[1]
Multi-regional isolines	Sub-indicator[1]	Impact guardrail
Multi-regional trajectories	Sub-indicator[1]	Emission scenario
Multi-category isolines	Region	Impact guardrail
Multi-category trajectories, area balance	Region	Emission scenario

[1]This dimension is only relevant if the impact indicator requires the selection of a sub-category.

Table 3.4: Dimensions of the two far right-hand menus in Figure 3.17 for each diagram type

After a choice has been made from all menus, the selected impact diagram is displayed in the central part of the screen. The bottom panel allows the user to specify one or more emission scenarios, the time trajectories of which can be displayed in isoline diagrams (see Figure 3.12 for examples). Various graphical properties for the display of impact diagrams can also be specified. The toolbar to the left allows the user, i.a., to export impact diagrams in different file formats, to print them, and to simultaneously display multiple diagrams. The toolbar to the right gives access to the user help system of the ICLIPS Impacts Tool.

3.7.3 Technical aspects

The ICLIPS Impacts Tool is written in Java 2 (including Swing and Java Advanced Imaging). It is distributed on a CD-ROM that runs without installation on all platforms for which the Java Runtime Environment (JRE) is available, including Microsoft Windows, Mac OS X, Linux, Solaris, and AIX.

Owing to the high dimensionality of the impact result space, the set of impact diagrams is rather large (about 100,000). These diagrams are available as Encapsulated PostScript (EPS), Graphics Interchange Format (GIF), and Portable Network Graphics (PNG) files. The EPS format combines a small file size with an excellent output quality, including the possibility to scale the diagram without quality loss. However, the Java Virtual Machine only supports the display of raster graphics like GIF and PNG (whereby the latter requires JRE version 1.3 or higher). The ICLIPS Impacts Tool is thus equipped with two different display modes. In basic mode, the raster graphics are displayed directly. In advanced mode, the external image handling tool ImageMagick is called to perform an on-the-fly conversion of the EPS files into a raster format. ImageMagick is freely available for many operating systems, including Microsoft Windows. It is already contained in standard Linux distributions. The program documentation, which is in HTML format, is displayed by a standard browser.

The ICLIPS Impacts Tool is distributed on a CD-ROM that comprises

- the platform-independent Java code,
- all impact diagrams (in compressed EPS and PNG files),
- the program documentation,
- JRE 1.4 for Windows and Linux, and
- ImageMagick for Windows.

The CD-ROM allows the ICLIPS Impacts Tool to be run in advanced mode on 32-bit Windows and Linux platforms. On Mac OS X (which already comprises the JRE), it runs in basic mode only unless ImageMagick and Ghostscript is installed. On other platforms, such as Solaris and AIX, the JRE needs to be installed for running the ICLIPS Impacts Tool. (All third-party software mentioned before is available for free from the respective developers.) A web browser is required to view the documentation.

The ICLIPS Impacts Tool applies object-oriented programming techniques in order to facilitate the inclusion of new results as they become available. However, the extension of the database would require the use of DVDs as distribution media since the storage capacity of CD-ROMs is already fully utilized.

Chapter 4

Results of the ICLIPS integrated assessment model

This chapter presents simulation results of the ICLIPS model. Section 4.1 shows reachable climate domains determined with the ICLIPS climate model. Sections 4.2, 4.3 and 4.4 present selected climate impact response functions for natural ecosystems, agricultural crop production, and water availability. Finally, Section 4.5 describes a guardrail analysis with the integrated ICLIPS model that applies climate impact response functions for natural vegetation.

Section 4.1 is based on the contribution of the author of this thesis to Bruckner et al. (2003a). Sections 4.2 and 4.3 present work of the author that has been published in Füssel and van Minnen (2001); Füssel et al. (2003); Toth et al. (2002). Section 4.4 is based on a contribution to Füssel et al. (2003) from one of the co-authors of that publication. Section 4.5 presents work of the ICLIPS group published in Toth et al. (2002) with major contributions from the author.

4.1 Results of the ICLIPS climate model

The ICLIPS climate model (ICM) simulates the global carbon cycle, the chemistry of non-CO_2 greenhouse gases, radiative forcing, and the climate system on a global scale. ICM is typically applied as a component of the ICLIPS climate-economy model (ICEM) where it provides dynamic restrictions for the computation of admissible emission corridors in guardrail analyses. We present here two stand-alone applications of the ICM that also yield useful results.

Climate trajectories

Like any other climate model, ICM may be used to compute climate trajectories for specific emission scenarios in 'forward mode'. Illustrative results for three emission scenarios specified by the IPCC SRES team (Nakicenovic and Swart, 2000) are included in Figure 4.1.b. Climate trajectories are also used in impact isoline diagrams that partition the climate–CO_2 state space into 'tolerable' and 'intolerable' regions for specific choices of impact guardrails (cf. Section 3.6.2).

Reachable climate domains

Reachable domains are defined as feasible combinations of values of at least two model variables under given restrictions for plausible emissions scenarios (cf. Section 2.4.1). We present here results for reachable climate domains defined over the domain of the climate impact response functions (CIRFs) that were determined by the algorithm described in Section 3.6.5. This algorithm involves multiple applications of ICM with appropriately modified goal functions and constraints.

Figure 4.1 depicts all feasible combinations of the atmospheric CO_2 concentration and the change in annual global mean temperature (AGMT) for a given climate sensitivity of 2.5 °C under the following set of assumptions and restrictions for future greenhouse gas emissions.

- Two time horizons are considered: 2100 and 2200.
- As long as the remaining restrictions hold, energy-related CO_2 emissions and total anthropogenic CH_4 and N_2O emissions can be altered freely and independently.
- The rate of change for energy-related CO_2 emissions and for total anthropogenic CH_4 and N_2O emissions is restricted to ±3% per year before the year 2100, and to ±1% per year afterwards.
- Energy-related CO_2 emissions are bounded by the fossil-fuel intensive SRES A1C-AIM scenario during the 21st century. After 2100, the upper bound increases by 1% per year.
- During the 21st century, the SRES A2 marker emission scenario —yielding the highest CH_4 and N_2O emissions out of all fully harmonized SRES scenarios— is used as an upper bound for total anthropogenic CH_4 and N_2O emissions. The upper bound remains constant thereafter.
- CO_2 emissions due to land-use change and total SF_6 emissions are prescribed according to the SRES A2 marker emission scenario until the year 2100, and remain constant thereafter.
- Future halocarbon emissions are prescribed according to the Montreal protocol and its amendments.
- SO_2 emissions are coupled to energy-related CO_2 emissions assuming a globally averaged desulphurization rate that may vary between 0.5% and 2% per year.

Although these assumptions are guided by the SRES emission scenarios, they are obviously debatable. Their primary purpose here is to provide reasonable restrictions for the representative computation of a reachable climate domain.

As Figure 4.1 clearly shows, a specific change in global mean temperature may come along with rather different CO_2 concentration levels and vice versa. The temperature spectrum associated with a given CO_2 concentration level can be explained by diverse preceding CO_2 emission paths and by different past or present concentration levels of the other greenhouse gases and aerosols. Furthermore, in Figure 4.1.b, identical CO_2 concentration levels may be realized at different points in time. Contrary to popular perception, the related ambiguity can be tremendous even for a fixed climate sensitivity. Up until 2200, a CO_2 concentration level of 550 ppm, for example, may be accompanied by a change in global mean temperature between less than 1 °C or even more than 3 °C (compared to the period 1961–1990). If an uncertainty interval for the climate sensitivity were used instead of a fixed climate sensitivity

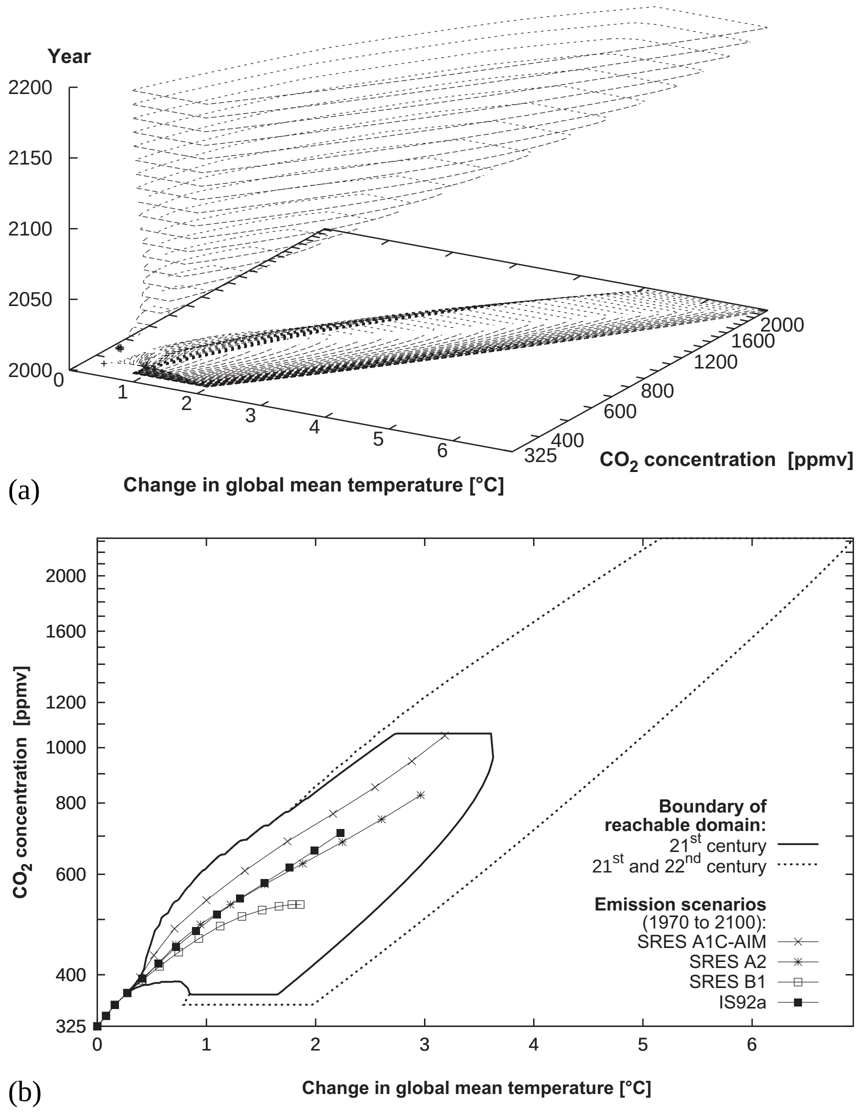


Figure 4.1: Reachable climate domains up to 2200. (a) Time evolution of the reachable climate domain. Depicted are the boundaries of the reachable domains for each point in time by dashed and dotted lines as well as their projections onto the temperature-CO_2 concentration surface. The dashed (dotted) lines show the maximum (minimum) temperatures compatible with the investigated CO_2 concentration levels for specific points in time. Temperature change is specified with respect to the average climate of the period 1961–1990 for a climate sensitivity of 2.5 °C. (b) Envelope of all time-dependent boundaries of the reachable climate domain until 2100 (solid lines) and 2200 (dashed lines). The results of a forward calculation for three SRES scenarios and one IS92 scenario are presented for comparison. The trajectories depict the CO_2 concentration and the change in global mean temperature in decadal steps from 1970 (lower left corner) until 2100. Further assumptions and restrictions are discussed in the text.

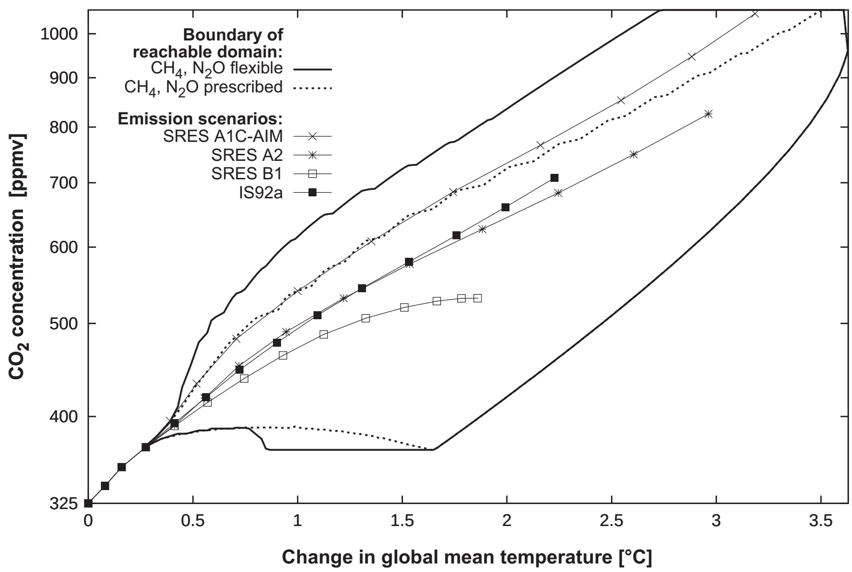


Figure 4.2: Reachable climate domains for the 21st century for variable and prescribed CH_4 and N_2O emissions depicted by bold lines and dotted lines, respectively.

value of 2.5 °C, the resulting reachable domains would become even wider. Due to the lagged response of the climate system and to the additional CH_4 and N_2O accumulating between 2100 and 2200, the temperature range associated with a given CO_2 concentration level extends considerably towards higher temperature levels if 2200 instead of 2100 is used as the time horizon considered.

Figure 4.1 also shows that the inertia of the CO_2-emitting economic system (operationalized by the restrictions for the emission scenarios) and the slow removal of carbon from the atmosphere unavoidably lead to CO_2 concentrations above present-day levels throughout the 21st century. CO_2 concentrations slightly below the 2000 level sometimes in the 22nd century are compatible with the restrictions for emission scenarios but they would still be accompanied by considerably higher global mean temperatures due to the inertia of the climate system.

Careful analysis of Figure 4.1.a reveals that the lowest concentration values of the year 2100 and 2200 simultaneously define the lowest concentration values of the overall envelope depicted in the lower diagram for the time horizons 2100 and 2200, respectively. In other words, the lowest concentration levels reachable in the next 100 years (200 years) can only be realized in 2100 (2200) after the concentration profile associated with the emission profile that minimizes concentrations in 2100 (2200) has already culminated. The respective emission profile is unique as are the emission profiles that maximize concentration levels in 2100 (2200). This explains the existence of horizontal parts of the envelopes depicted in Figure 4.1. The ambiguity of the temperature levels associated with the lowest and highest concentration levels originates from different radiative forcing contributions from CH_4, N_2O, and SO_2 emissions.

The influence of various assumptions concerning CH_4 and N_2O on the shape of reachable climate domains is further investigated in Figure 4.2. The (wider) corridor labelled “CH_4 , N_2O flexible” corresponds to the narrower corridor in Figure 4.1. Another corridor is shown inside where CH_4 and N_2O concentrations are prescribed according to the SRES A2 scenario that previously defined the upper bound of their flexibility ranges. For a given CO_2 concentration level, *maximum* values for temperature change are therefore identical in both cases. Thus the related part of the reachable climate domain envelope is not altered. Prescribing high CH_4 and N_2O emissions, however, considerably increases the *minimum* temperatures associated with given CO_2 concentrations. Note that CH_4 and N_2O emissions in the SRES A1C-AIM scenario are lower than the prescribed ones. SRES A1C-AIM is therefore able to realize smaller minimum temperature changes for given CO_2 concentrations and consequently transgresses the boundary of the reachable climate domain in the prescribed emission case.

For maximum CO_2 concentration levels (represented by the top right 'corner' of the reachable domain), the temperature range is considerably smaller for fiexed than for variable CH_4 and N_2O emissions. The remaining ambiguity is due to different SO_2 scenarios. For low CO_2 concentration levels, the temperature ambiguity diminishes even more, and the horizontal line at the bottom of the reachable climate domain envelope almost vanishes. This is a consequence of the last constraint that (loosely) links SO_2 emissions to CO_2 emissions. Hence, the variability of SO_2 emissions (and the associated temperature effect) is proportional to the level of CO_2 emissions. The lower right 'corner' of the reachable domain can be reached in 2100 by the most stringent CO_2 emission reductions permitted by the predefined constraints. The minimum temperature change in 2100 (compared to 1961–1990) is about 0.85 °C for variable CH_4 and N_2O emissions, yet about twice that amount for prescribed (high) emissions. This result clearly emphasizes the importance of non-CO_2 emissions for long-term climate protection.

The approach to reachable climate domains presented here should not be confused with complementary efforts to display the climate-concentration combinations accessible via *specific* SRES scenarios (Smith et al., 2001, Figure 19-1). This latter line of investigation delivers isolated results similar to the results for the different scenarios depicted in Figure 4.1.b. These results therefore do not reveal those parts of the climate-concentration state space which are only accessible by purposeful but still constrained emissions mitigation policies.

4.2 Climate impact response functions for natural vegetation

In this section, we present CIRFs for natural vegetation. Simulation results for agricultural crop production and water availability are presented in Sections 4.3 and 4.4, respectively. Due to the large number of impact indicators, considered regions, and climate projections considered in the CIRFs, only selected findings can be shown here. The extensive set of simulation results is accessible via the ICLIPS Impacts Tool (see Section 3.7).

The BIOME 1 equilibrium vegetation model as adapted for IMAGE 2 has been applied in the ICLIPS framework to determine the dominating biome based on seasonal climate data, CO_2 concentration, and soil conditions (see Section 3.5.2). Various impact indicators were defined that reflect the sensitivity of potential natural vegetation to global climate change (see Section 3.5.1).

This section starts with simulation results for specific emission scenarios that represent applications of CIRFs in 'forward mode'. Subsequently we show scenario-independent simulation results that enable the application of CIRFs in 'inverse mode'. Finally, we discuss the results of various sensitivity tests for the simulated vegetation impacts. *Quantitative* simulation results are presented by means of various impact diagrams (cf. Section 3.6.2) whereas the text generally deals with their *qualitative* aspects. Occasionally, less important results are mentioned in the text without the support of an impact diagram.

4.2.1 Results for specific climate scenarios

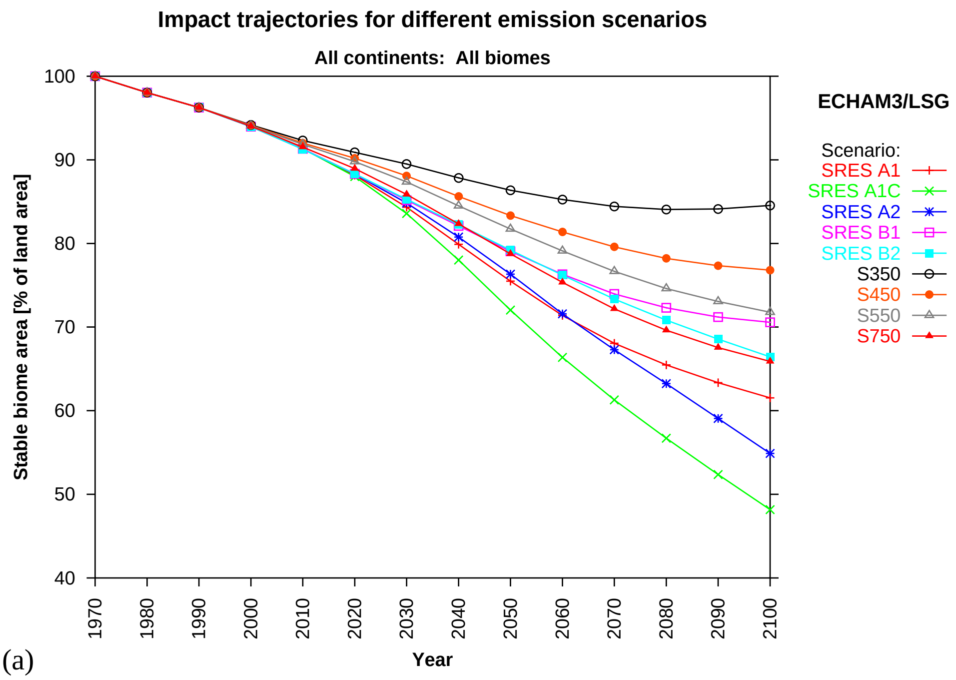
We report here selected simulation results for the impacts of climate and CO_2 change on ecosystem transformation for a number of 'no-policy' and 'stabilization' emission scenarios defined by IPCC. We use the aggregated indicators "stable biome area" and "total biome area" (expressed as a percentage of the baseline area in the reference period 1961–1990) to represent climate impacts on ecosystems. It is important to stress again that vegetation changes were simulated by an equilibrium vegetation model. Since there may be a significant time lag between climate change and the vegetation change caused by it, the results stated below indicate the long-term effects of a certain climate scenario but not necessarily its transient impacts.

Figure 4.3 shows simulation results based on climate change patterns from the ECHAM3 model that resemble the 'ecological response functions' presented in Toth et al. (2000). The *multi-scenario trajectories* in Figure 4.3.a depict globally aggregated ecosystem impacts for various emission scenarios defined by the IPCC. The wide range of plausible future GHG emissions in the absence of specific climate protection measures is covered by the four so-called SRES marker scenarios (A1, A2, B1, and B2) and by a coal-intensive scenario (SRES A1C). We also investigate four scenarios with stabilizing concentrations (S350, S450, S550, and S750) defined in Houghton et al. (1994). Simulated global biome shifts in 2100 range from 15% to more than 50%, which underlines the wide range of possible future developments despite the inertia of the climate system. The *multi-regional trajectories* in Figure 4.3.b show results for one of these emission scenarios (SRES A1) broken down by biogeographical regions (cf. Figure 3.9 on p. 91). This diagram provides a first hint on the regional heterogeneity of vegetation impacts, which will be explored in more detail later.

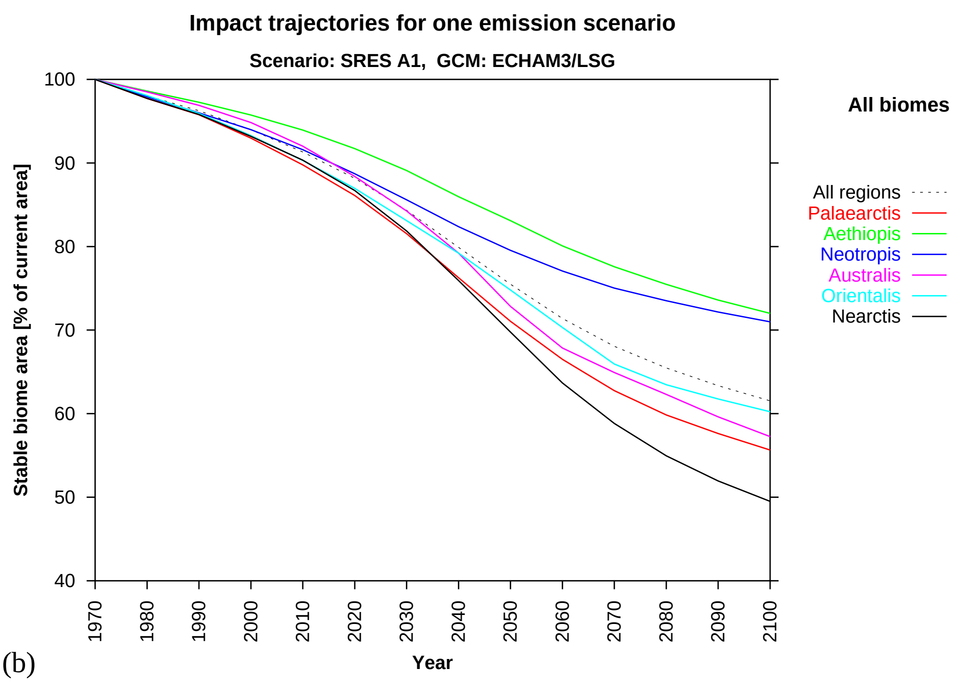
Figure 4.4 provides information on the sensitivity of specific biomes on the global level. The *multi-category trajectories* in Figures 4.4.a and 4.4.b show the stable area and the total area, respectively, of each biome (except for "ice"). Due to their varying climatic requirements, biomes show very different responses to the simulated climate change. Tropical woodland, for instance, is not expected to lose a large fraction of its current extent, and it may even expand considerably into areas that are currently unsuitable. Prospects are much worse for some high-latitude biomes. Figure 4.4.a shows that climatic conditions would become unsuitable for wooded tundra and cool coniferous forest throughout their present range by the end of the 21st century. According to Figure 4.4.b, the total potential area of wooded tundra (and even more of tundra) is also drastically reduced.

Figure 4.5 presents a summary of biome-specific simulation results based on climate change projections from three GCMs. This *area balance diagram* compares the stable and total area of each biome in a future climate (after equilibration) to its baseline extent. For the year 2100 of the SRES A1 scenario (that was also chosen in Figure 4.4), ICM simulates a CO_2 concentration of 690 ppm and a (transient) increase in AGMT that equals the climate sensitivity of the respective GCM (see Table 4.1). The bold long bars depict the baseline area of each biome whereas the (thinner) lower and upper bars show the stable area and the total area in the future, respectively. The difference between the latter two values denotes the area that may become newly suitable.

The simulations for the ECHAM4 and HadCM2 climate change patterns yield more cool mixed forest and hot desert but less steppe and tropical evergreen forest than those for the ECHAM3 patterns. On the global level considered here, the differences are generally moderate. With the exception of tropical evergreen forest, there is an agreement on the sign of the projected changes in the total area of each biome across all GCMs.

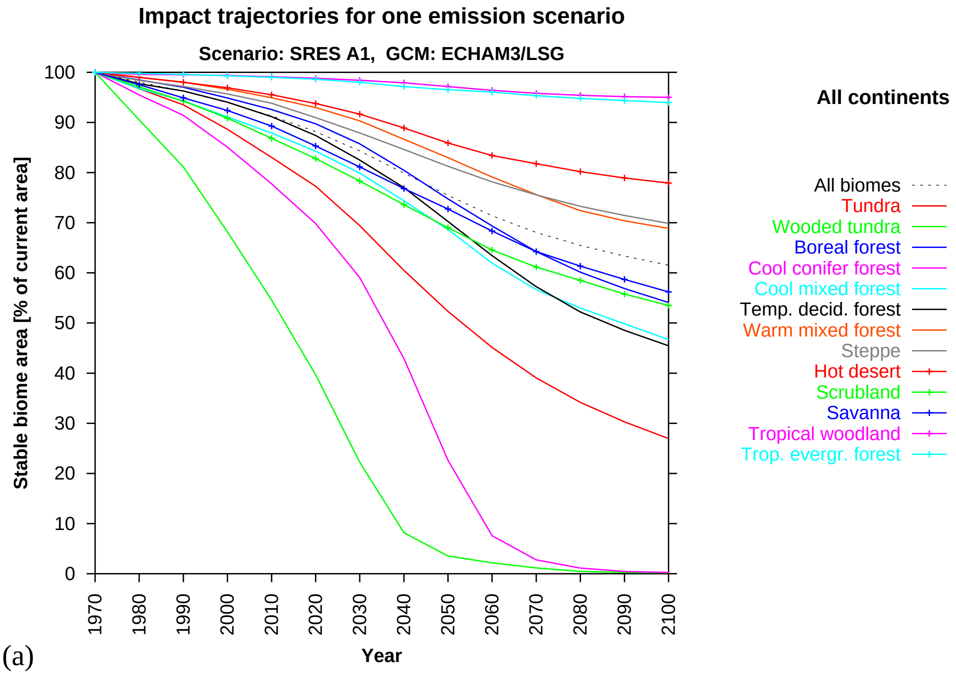


(a)

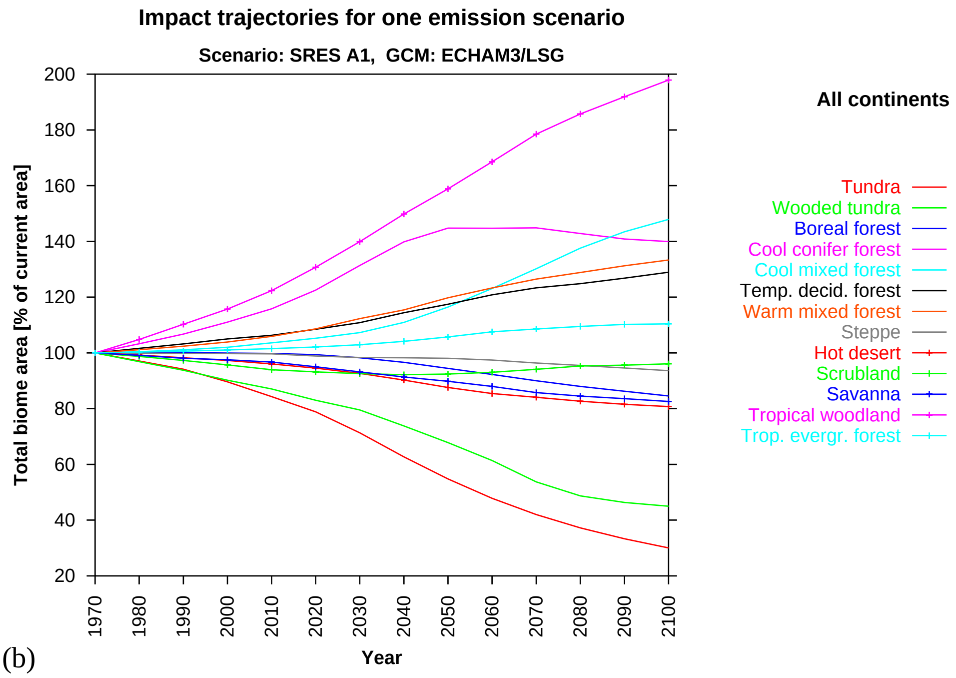


(b)

Figure 4.3: Trajectories depicting simulated vegetation changes. (a) Globally aggregated stable biome area for various emissions scenarios. (b) Stable biome area in various biogeographic regions for the SRES A1 emissions scenario.



(a)



(b)

Figure 4.4: Trajectories depicting globally aggregated changes in specific biomes for the SRES A1 emissions scenario. (a) Stable biome area. (b) Total biome area.

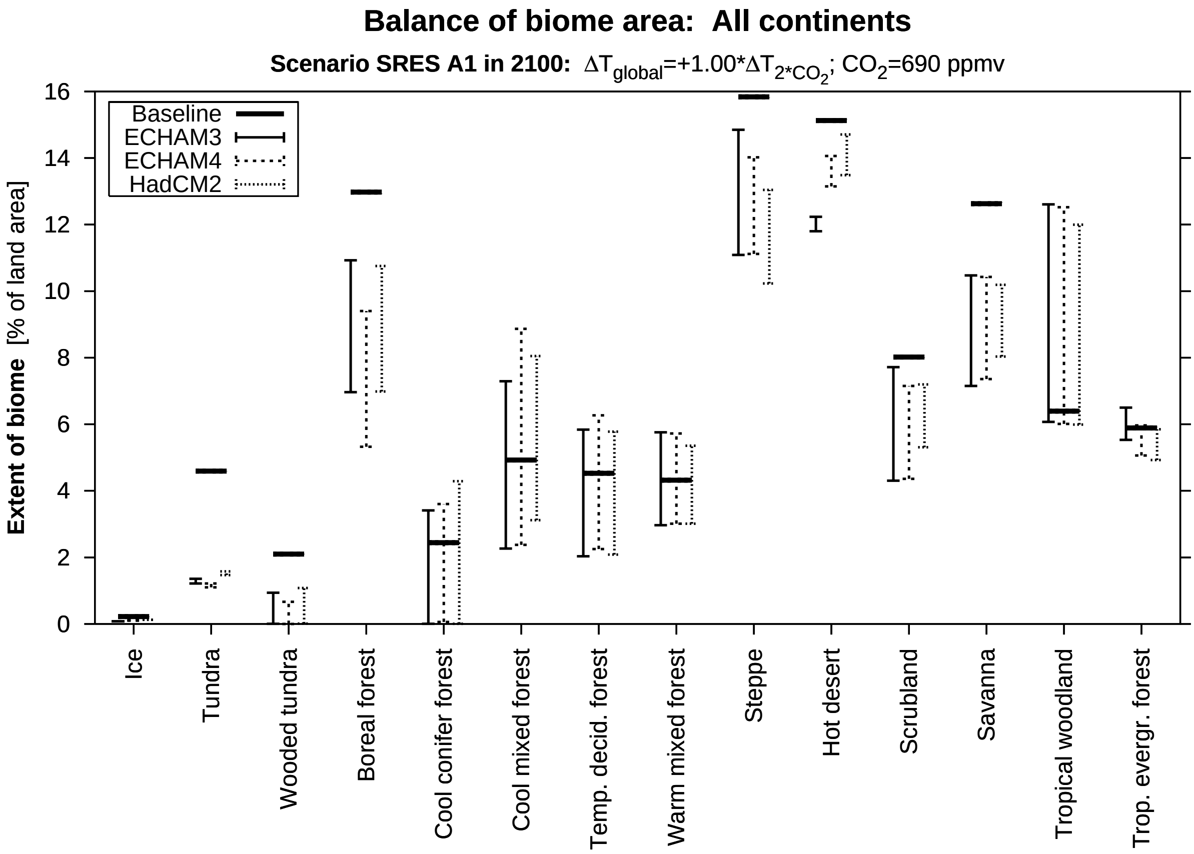


Figure 4.5: Area balance diagram, depicting the potential extent of all biomes for the baseline climate (1961–1990) and for the climate state simulated by three GCMs for the year 2100 of the SRES A1 marker scenario. ▬: potential area of each biome in the *baseline* climate; $\perp$: stable area and $\top$: total area of each biome in equilibrium with the *changed* climate. $\Delta T_{2\times \mathrm{CO}_2}$ is the GCM-specific climate sensitivity.

The presentation of scenario-dependent simulation results is concluded with Table 4.1, which summarizes vegetation impacts for the total land area and for protected areas based on climate projections from three GCMs. The results for the *global* extent of biome change between the baseline climate and the climate of the year 2100 are robust across GCMs, and they correspond well for the total land area and for protected areas. Another robust feature in all simulations is that high-latitude regions (i.e., Nearctis and Palaearctis) are more sensitive to global climate change than low-latitude regions (i.e., Aethiopis, Australis, and Neotropis). Interestingly, the regional variability in the vegetation sensitivity is consistently larger for protected areas than for the total land area. In particular, in regions where vegetation is generally highly sensitive to global climate change, vegetation in protected areas is even more sensitive.

4.2.2 Scenario-independent results

The scenario-dependent results discussed above provide important information on the impacts associated with a pre-defined set of emission scenarios. However, they cannot be directly used for the specification

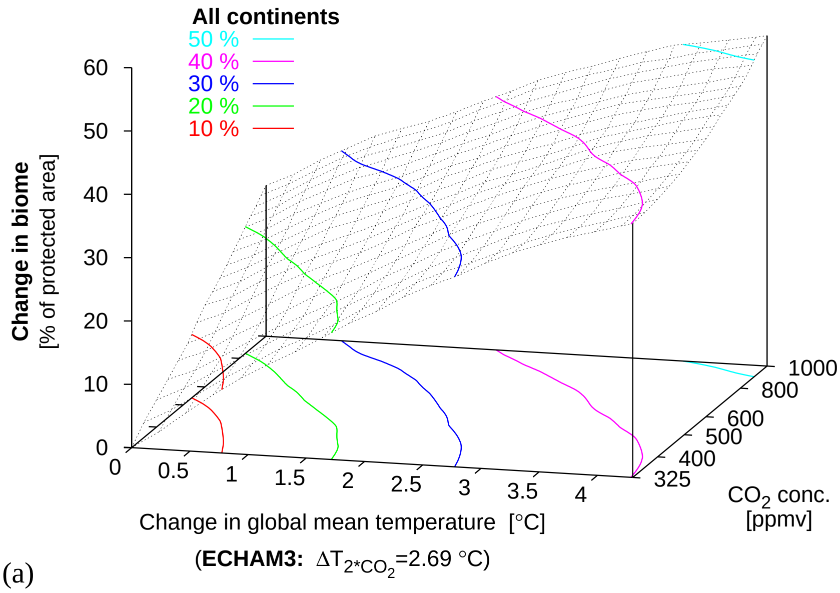
GCM	**ECHAM3**		**ECHAM4**		**HadCM2**	
Equilibrium climate change for a doubling of the equivalent $\mathbf{CO_2}$ concentration						
$\Delta T_{2\times \mathrm{CO_2}}$ (global)	2.7 °C		2.8 °C		2.8 °C	
Δ*TMP* (land area)	3.7 °C		4.4 °C		3.9 °C	
Δ*PRC* (land area)	+8%		+6%		+4%	
Δ*CLD* (land area)	−2%		+1%		−1%	
Biome change simulated for the climate of the year 2100[†] (left: total land area; *right: protected areas)*						
Global average	**38%**	***37%***	**39%**	***39%***	**35%**	***34%***
Maximum change in a region	51% Nearctis	*57% Palaearctis*	52% Nearctis	*65% Nearctis*	54% Nearctis	*62% Nearctis*
Minimum change in a region	28% Aethiopis	*23% Neotropis*	21% Australis	*13% Australis*	19% Aethiopis	*15% Aethiopis*
Decade when *global* guardrail for biome change is exceeded						
10% change	2010s	*2010s*	2010s	*2010s*	2010s	*2020s*
20% change	2030s	*2040s*	2030s	*2040s*	2040s	*2040s*
30% change	2060s	*2060s*	2060s	*2060s*	2070s	*2070s*
Decade when *regional* guardrail for biome change is exceeded						
20% change	2030 Palaearctis	*2020 Palaearctis*	2020 Palaearctis	*2020 Palaearctis*	2030 Nearctis	*2030 Palaearctis*
50% change	2090 Nearctis	*2070 Palaearctis*	2090 Nearctis	*2060 Palaearctis*	2080 Nearctis	*2070 Nearctis*

[†]For the SRES A1 marker scenario, we calculated $\Delta\tilde{T}(2100) = 1.00$ and $p_{\mathrm{CO_2}}$(2100) = 690 ppm. The amount of climate change in the year 2100 thus corresponds to the figures stated in the uppermost part of the table for a doubling of the equivalent CO_2 concentration.

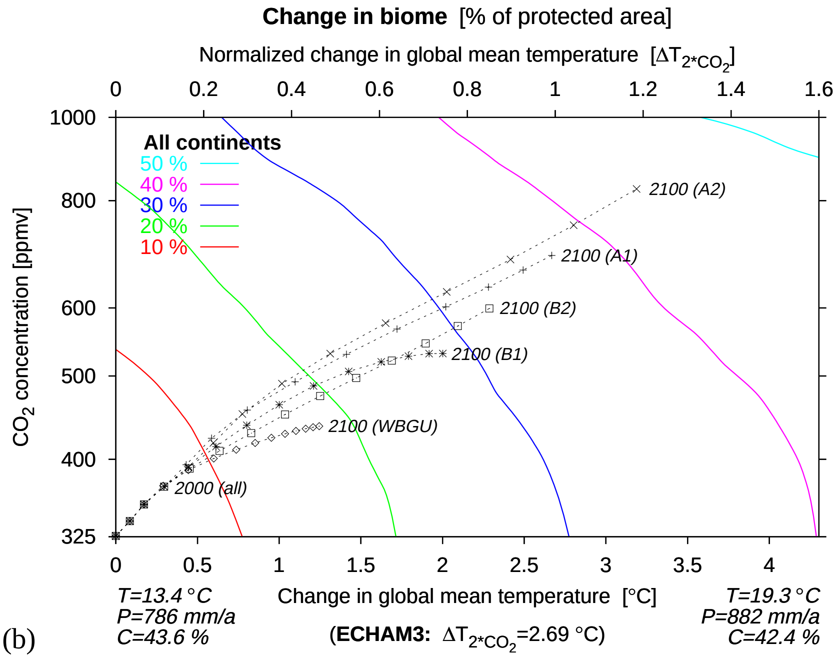
Table 4.1: Simulated climate impacts on natural vegetation relative to the baseline period (1961–1990) for the SRES A1 marker scenario. The climate data refers to changes in annual global mean temperature (Δ*TMP*), precipitation (Δ*PRC*), and cloud cover (Δ*CLD*).

of impact constraints in guardrail analyses. The scenario-independent results presented here have been determined with the explicit goal to be used in inverse mode, i.e., for guardrail analyses.

Figure 4.6 shows the globally averaged sensitivity of vegetation in protected areas to changes in AGMT and atmospheric CO_2. The *response surface diagram* in Figure 4.6.a depicts the dose-effect relationship between the two input variables of the CIRF (on the horizontal axes) and the chosen impact indicator (on the vertical axis). We observe that the relationship between each input factor and the impact indicator is monotonously increasing and rather smooth. The combined effect of changes in both forcing variables is generally larger than the effect of each individual input factor but less than their sum. The coloured isolines connect points on the response surface for which the simulated impacts are equal. In the present example, they correspond to exemplary impact guardrails that limit biome changes to



(a)



(b)

Figure 4.6: Impact diagrams depicting the percentage of the world's protected areas where the current biome becomes inviable across a range of changes in several regional climate variables (scaled by the change in global mean temperature) and CO_2 concentration. (a) Response surface diagram. (b) Impact isoline diagram. The climate trajectories corresponding to the four SRES marker scenarios and an additional climate stabilization scenario defined by the WBGU are depicted in decadal steps from 1970 (bottom left corner) to 2100. T, P, and C refer to annual temperature, precipitation, and cloud cover in the considered region (i.e., all continents).

10%, . . . , 50% of protected areas worldwide. In Figure 4.6.a, the isolines drawn on the response surface are also projected on the base surface.

The *impact isoline diagram* in Figure 4.6.b shows the projection of the isolines from Figure 4.6.a onto the domain of the CIRF. The diagram is annotated with information about the climate projection that drives the simulated vegetation changes. The level of climate change is indicated above and below the diagram by the normalized and absolute change in AGMT, respectively. The annual mean values of all considered climate variables within the respective region for the baseline climate and for the endpoint of the climate domain (i.e., for an AGMT change of $1.6 \cdot \Delta T_{2\times \mathrm{CO}_2}$) are also provided. This reminds the reader that pattern scaling considers changes in all pertinent climate variables. We also depict the climate trajectories computed for the four SRES marker scenarios and for an additional climate stabilization scenario proposed by the German Advisory Council on Global Change (WBGU, 1997). The trajectories start in the bottom left corner of the diagram, which represents the climate of the baseline period 1961–1990. Their time evolution is denoted in decadal steps until 2100. The ‘30% guardrail’ (shown in blue), for instance, is violated by the SRES A1 scenario around 2070.

Since the genetic pools of different biogeographic regions are quite distinct, imposing constraints on globally averaged vegetation impacts only is unlikely to be sufficient for the preservation of terrestrial biodiversity. Hence, we present in Figure 4.7 selected simulation results for regional vegetation change. The *multi-regional isoline diagram* depicted in Figure 4.7.a refers to an illustrative ‘20% guardrail’ for each biogeographic region (coloured isolines) and on the global level (dashed isoline). The almost vertical gradient of the impact isolines for high-latitude regions (e.g., Nearctis; see also Figure 4.7.b) reflects the well-known fact that vegetation in these regions is most sensitive to temperature changes. In contrast, the more horizontal isolines in water-limited regions (e.g., Australis; see also Figure 4.7.c) indicate that CO_2 increase is an important driver for vegetation change there. Owing to the considerable variability in the sensitivity of ecosystems to climate and CO_2 change across regions, climate windows become much more restrictive if an impact constraint refers to each region instead of the global average (see also Table 4.1).

4.2.3 Sensitivity analysis

The sensitivity of CIRFs was analyzed, i.a., for variations in the source and the temporal resolution of the climate projection, and in the spatial coverage and the aggregation level of the impact indicator. Furthermore, the definition of different impact indicators accounts, in a very crude manner, for different assumptions about the adaptation potential of climate-sensitive systems. This section presents selected results of the sensitivity analysis for simulated vegetation impacts.

Sensitivity to the source of the climate change projection

Vegetation impacts were determined based on climate change patterns from three different GCMs. Figure 4.5 indicated a good agreement of the projected vegetation changes at the global level. Figure 4.8 provides additional information by presenting selected impact isoline diagrams based on climate change patterns from ECHAM4 and HadCM2 that correspond to results for ECHAM3 shown in Section 4.2.2. In general, the simulated vegetation impacts differ less between ECHAM4 and HadCM2 than between ECHAM3 and either of the other GCMs.

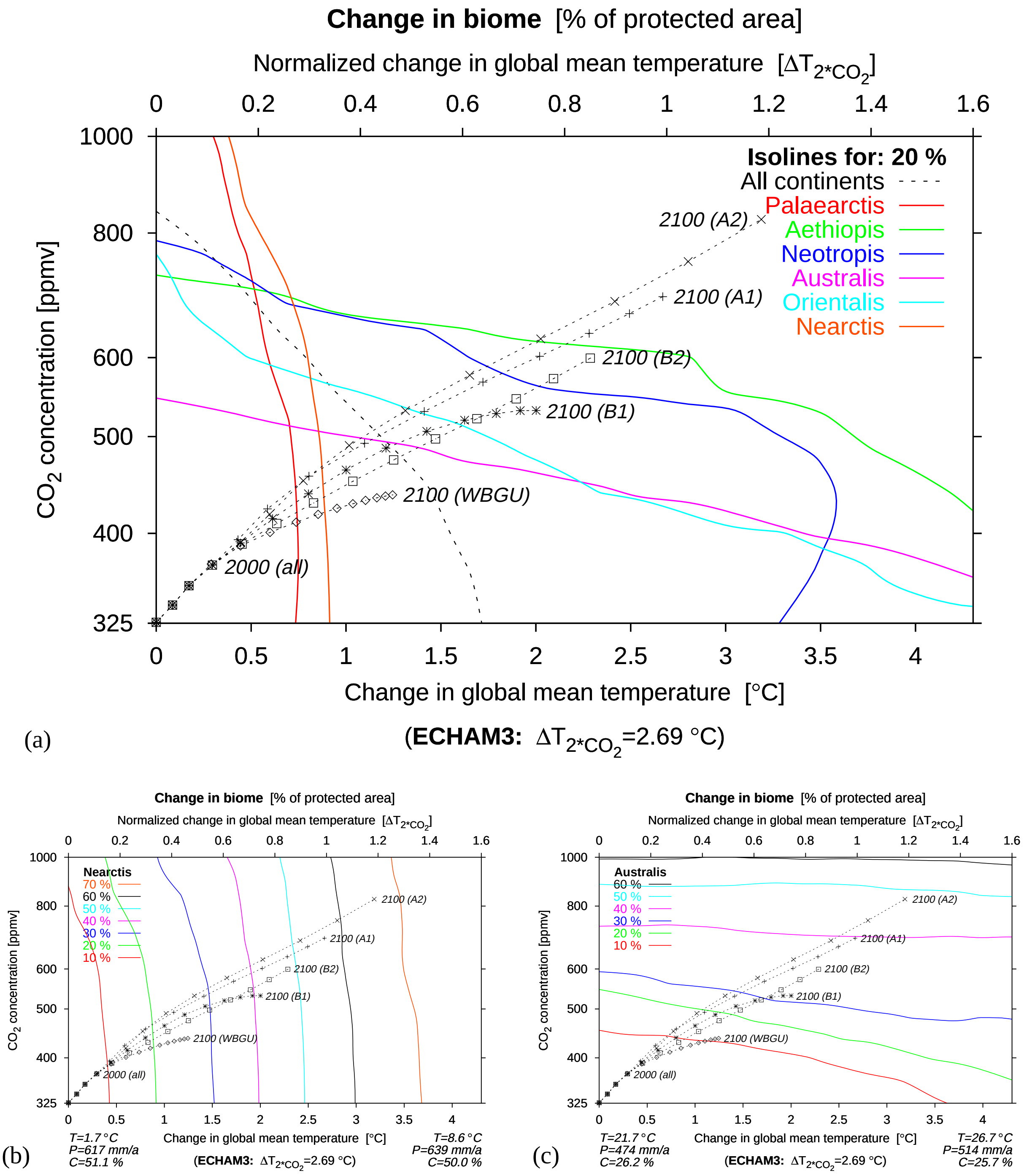


Figure 4.7: Isoline diagrams for global and regional biome change in protected areas. (a) Multi-regional isoline diagram for biome change in each biogeographic region and globally averaged. The guardrail refers to a vegetation change of 20% in the respective region. (b,c) Impact isoline diagrams for biome change in (b) Nearctis and (c) Australis.

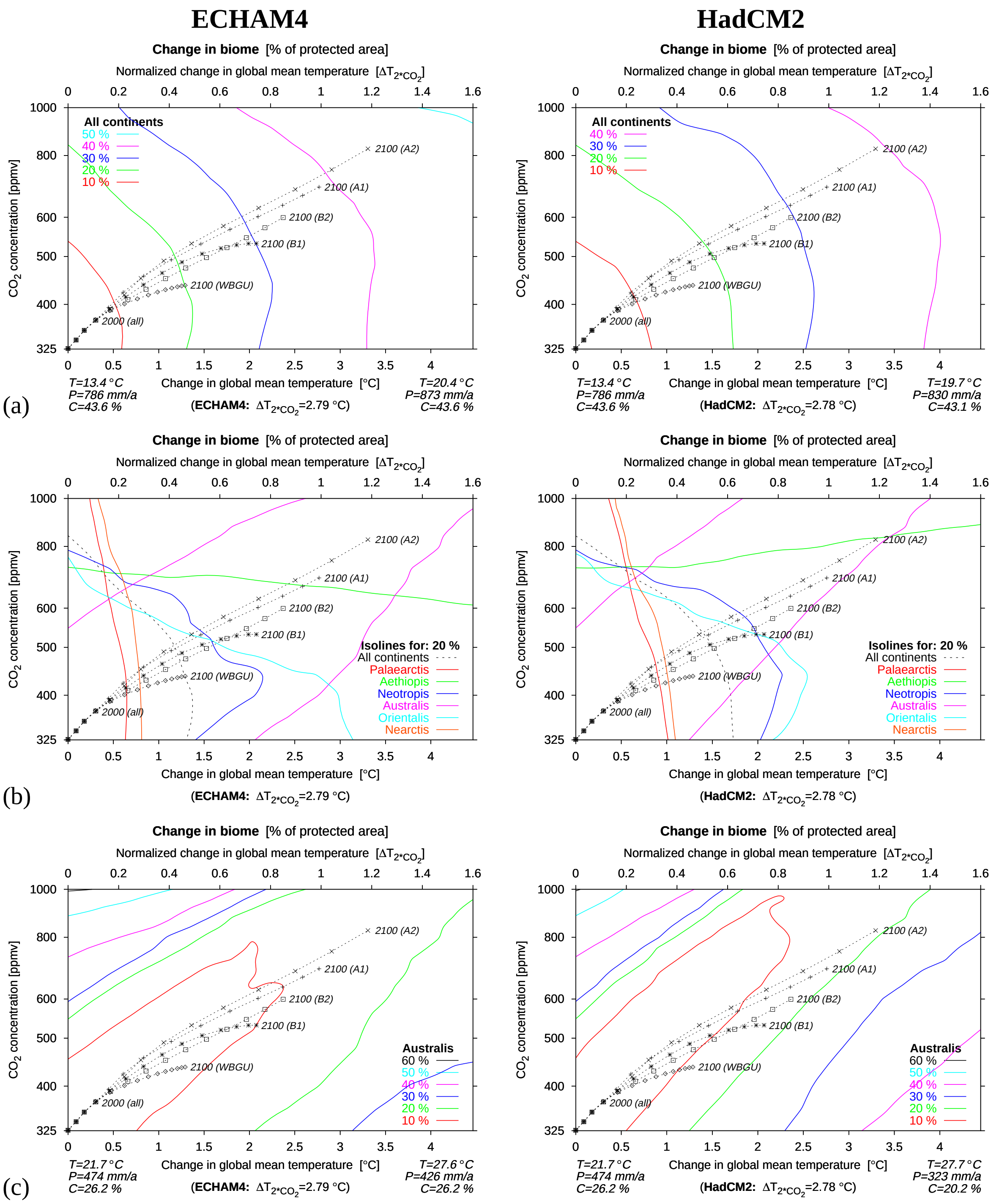


Figure 4.8: Different impact diagrams for climate change patterns from ECHAM4 (left) and HadCM2 (right). For a legend and comparable results based on ECHAM3 patterns, see (a) Figure 4.6.b, (b) Figure 4.7.a, and (c) Figure 4.7.c.

Figure 4.8.a shows that global vegetation responds significantly stronger to the climate change patterns from ECHAM4 and HadCM2 than to the ECHAM3 patterns (cf. Figure 4.6.b) for *constant* CO_2 concentrations. This observation can be partly explained by the slightly lower continental warming simulated by the latter GCM. For more plausible scenarios, comprising changes in both climate and CO_2 concentration, the differences are rather small.

Figure 4.8.b depicts impact isolines for all biogeographic regions. Compared to ECHAM3 (cf. Figure 4.7.a), vegetation responds more sensitive to climate anomalies from ECHAM4 and HadCM2 in Neotropis and Orientalis, and less sensitive in Australis and Aethiopis. In Palaearctis and Nearctis, vegetation impacts based on climate patterns from ECHAM3 and ECHAM4 agree well, whereas the sensitivity to the HadCM2 patterns is lower.

Australis shows the largest disagreement in simulated vegetation impacts for different GCM patterns. The main reason are the large uncertainties in precipitation projections for this region. Figure 4.8.c shows that vegetation impacts for *combined* changes in climate and CO_2 (based on the ECHAM4 and HadCM2 patterns) are smaller than those of changes in climate or CO_2 *alone*. Obviously, the higher water-use efficiency of plants associated with enhanced CO_2 levels partly compensates for the effects of decreasing precipitation simulated by these GCMs. Such a compensation effect does not occur for ECHAM3, which projects increasing precipitation for Australis (cf. Figure 4.7.c).

Sensitivity to the temporal resolution of the climate change patterns

Vegetation impacts were simulated for monthly as well as annually averaged climate change patterns. In most regions, simulated vegetation impacts for monthly and for annual patterns from ECHAM3 are broadly comparable. The most noticeable exception concerns Australis where less vegetation change is simulated for seasonally explicit climate anomalies than for annually averaged ones. The major climatic stress for vegetation in most parts of Australis is low water availability in summer. Since the simulated warming is lowest and the precipitation increase is strongest in that season, scrubland remains suitable after the imposition of seasonally explicit climate anomalies in some regions in which it is replaced by the more drought-tolerant steppe according to the annually averaged climate anomalies.

A similar seasonal signal of climate change, essentially characterized by a stronger warming in winter, causes opposite results in Palaearctis. Because vegetation productivity in Palaearctis is predominantly limited by low winter temperatures, seasonally explicit climate anomalies induce more widespread vegetation changes than annually averaged ones.

Sensitivity to the spatial coverage of the impact assessment

Vegetation impacts were simulated for the protected area, the non-agricultural land area, and the total land area of a region. At the global level, the results agree well across the three GCM projections used here (see Table 4.1). The picture changes at the regional level. Protected areas in the low-latitude regions Orientalis and Neotropis are simulated to be less sensitive to changes in climate and CO_2 concentration than the total land area for three respectively two out of three GCM projections. In contrast, the high-latitude regions Nearctis and Palaearctis show more pronounced vegetation changes in protected areas than in other areas across all GCM patterns. This observation can be explained by the inhomogeneous distribution of protected areas within biogeographic regions (see Figure 3.8 on p. 90).

	Land surface[1]	Brazil	China	Germany	India	Russia	SACU[2]	USA
				ECHAM4				
ΔTMP [°C]	$+4.4$	$+4.1$	$+4.7$	$+4.2$	$+3.4$	$+6.4$	$+4.0$	$+4.4$
ΔPRE [%]	$+6.9$	-3.9	$+12.0$	-0.8	$+27.2$	$+16.9$	-6.5	$+3.5$
ΔCLD [%]	$+1.2$	-0.5	$+0.1$	-2.7	$+7.9$	$+2.1$	$+1.1$	-0.9
				HadCM2				
ΔTMP [°C]	$+3.9$	$+4.1$	$+3.6$	$+2.9$	$+4.5$	$+4.3$	$+4.5$	$+3.5$
ΔPRE [%]	$+3.4$	-0.4	$+13.1$	-1.8	-16.3	$+12.3$	-6.2	$+16.5$
ΔCLD [%]	-0.7	-5.4	0.0	-1.4	-5.0	$+1.4$	$+8.6$	$+5.8$

[1]Antarctica and Greenland are excluded.
[2]South African Customs Union; comprises the Republic of South Africa, Namibia, Botswana, Lesotho, and Swaziland.

Table 4.2: Climate change projections for selected countries and regions. The data refers to the simulated changes in annual surface temperature (*TMP*), precipitation (*PRE*), and cloud cover (*CLD*) in response to a doubling of the equivalent CO_2 concentration.

4.3 Climate impact response functions for agricultural crop production

In this section, we present simulation results for agricultural crop production. In contrast to the previous section, the assessment focusses on a limited number of countries and regions that cover a broad range of climate regimes and socioeconomic conditions. Table 4.2 shows the selection of countries considered here together with the simulated change in regional temperature, precipitation, and cloud cover, based on climate change patterns from ECHAM4 and HadCM2.

The FAO crop suitability model as adapted for IMAGE 2 has been applied in the ICLIPS framework to determine the suitable area and the potential rain-fed production of the 19 most important crops worldwide (see Section 3.5.3). Various aggregated indicators express the sensitivity of agricultural production to climate change under different assumptions for crop switching (see Section 3.5.1). We focus on the indicator "weighted crop performance", which describes the response of the currently important crops within the cultivated area of a country. This indicator does *not* allow for crop switching. Hence, it characterizes the sensitivity of the present cropping pattern to altered climate conditions under rather pessimistic assumptions. Later, we present results on the "suitable area" for all crops that provide a more detailed picture of the simulated impacts.

Figure 4.9 shows the globally aggregated simulation results for the chosen indicator, based on climate projections from ECHAM4. The simulated changes in temperature, precipitation and cloudiness *alone* lead to slightly decreasing production levels of the currently important crops. If changes in the CO_2 concentration are also considered, production gains between 5% and 15% compared to the baseline are simulated for the year 2100 under all scenarios. In other words, the beneficial effects of enhanced CO_2 levels more than compensate the climate-induced losses. As a result, reasonable impact guardrails at the global level would not effectively constrain the computation of emission corridors in an inverse analysis with the ICLIPS model.

Figure 4.10 shows the impact isolines for all countries considered here for one illustrative impact

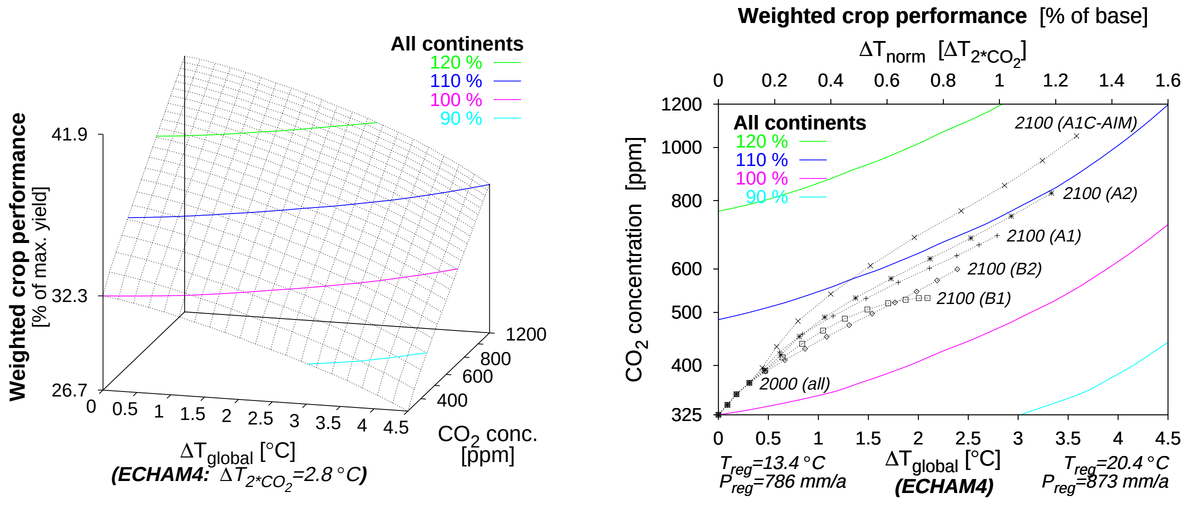


Figure 4.9: Impact diagrams for global crop production. *Left:* Response surface diagram. *Right:* Impact isoline diagram with time trajectories for various SRES emissions scenarios.

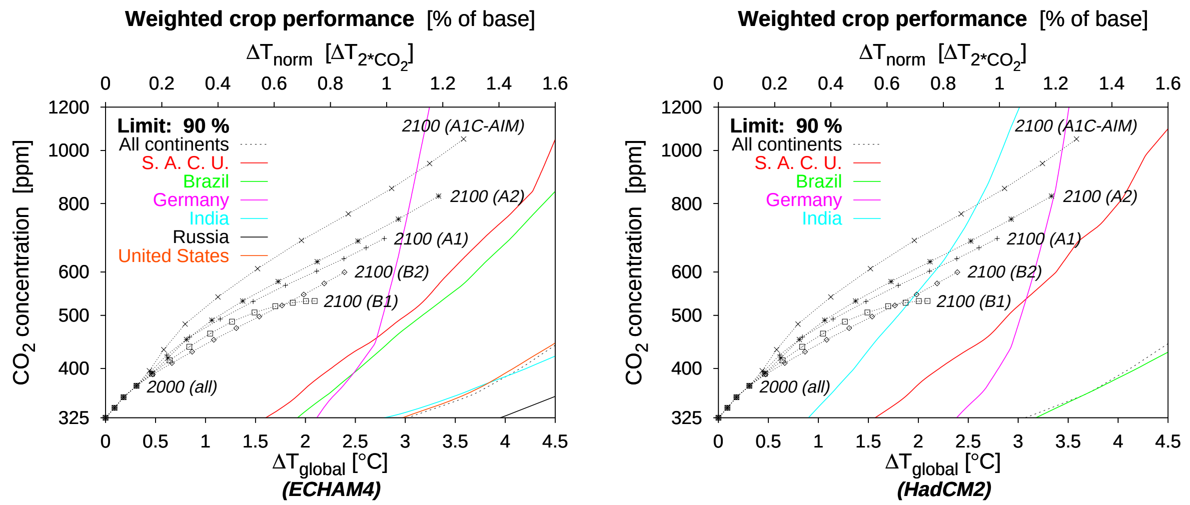


Figure 4.10: Impact isoline diagrams for an illustrative impact constraint that limits weighted losses of current crops to 10% *in each country/region*, based on climate projections from ECHAM4 (*left*) and HadCM2 (*right*).

guardrail. This guardrail corresponds to 90% of the baseline figure, i.e., it limits losses of the production potential to 10%. The left-hand diagram refers to the ECHAM4 climate projection, and the right-hand plate is based on the results of HadCM2. According to the model results, Germany and India are the only countries from our selection where significant reductions of the production potential of currently important crops must be expected. The illustrative impact constraint is violated in Germany in one or two of the high-emission SRES scenarios, depending on the applied GCM pattern. Crop-specific results

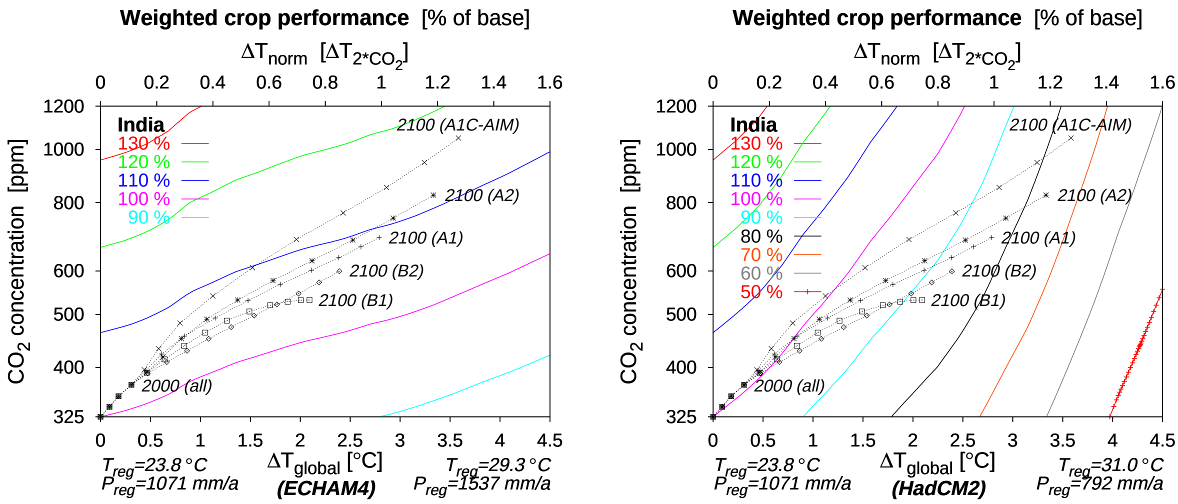


Figure 4.11: Impact isoline diagrams for crop production in India, based on climate scenarios from ECHAM4 (*left*) and HadCM2 (*right*).

(not presented here) show that it will become difficult to grow certain presently important crops (e.g., winter wheat) because the projected temperature increase leads to a disappearance of the required chilling period.

Crop responses between the two GCM projections differ most significantly for India, which is denoted by blue isolines in Figure 4.10. Figure 4.11 shows the impact isoline diagrams for India based on the climate change patterns from ECHAM4 (left) and HadCM2 (right). The illustrative guardrail is not crossed in any of the SRES scenarios for the ECHAM4 projection whereas it is violated in all of them for the HadCM2 results. This difference can be explained by the large discrepancies in the simulated precipitation changes between the two GCMs. In fact, improved projections of future changes in the Asian monsoon (which determines precipitation in India) due to global climate change and to the regional climate effects of aerosol emissions are a key concern of current climate modelling efforts.

We now take a closer look at crop-specific results for various regions. Figure 4.12 (top left-hand diagram) supplements the global simulation results conveyed by the aggregated indicators in Figure 4.9. The diagram shows the global balance of the suitable area for each crop within the current cultivated land based on simulations of the two GCMs considered here for the year 2100 of the SRES A1 scenario. Whereas the area suitable for tropical crops (e.g., tropical maize, cassava) increases on a global scale, a significant fraction of the current area for temperate crops (e.g., wheat, temperate maize) is projected to become unsuitable.

The crop-specific results for India depicted in Figure 4.12 (top right-hand diagram) show that the area suitable for the rain-fed production of rice, the most important staple crop of the country, remains largely unaffected based on the ECHAM4 patterns yet it decreases about half by the year 2100 based on the HadCM2 patterns. It is very likely that irrigated rice production, which currently accounts for about 45% of the cultivated area, would suffer as well, given the large decreases in water availability associated with this climate scenario. For (spring) wheat, the second most important staple crop, we get a different picture. The simulations for both GCM projections project the suitable area to decrease from about 40%

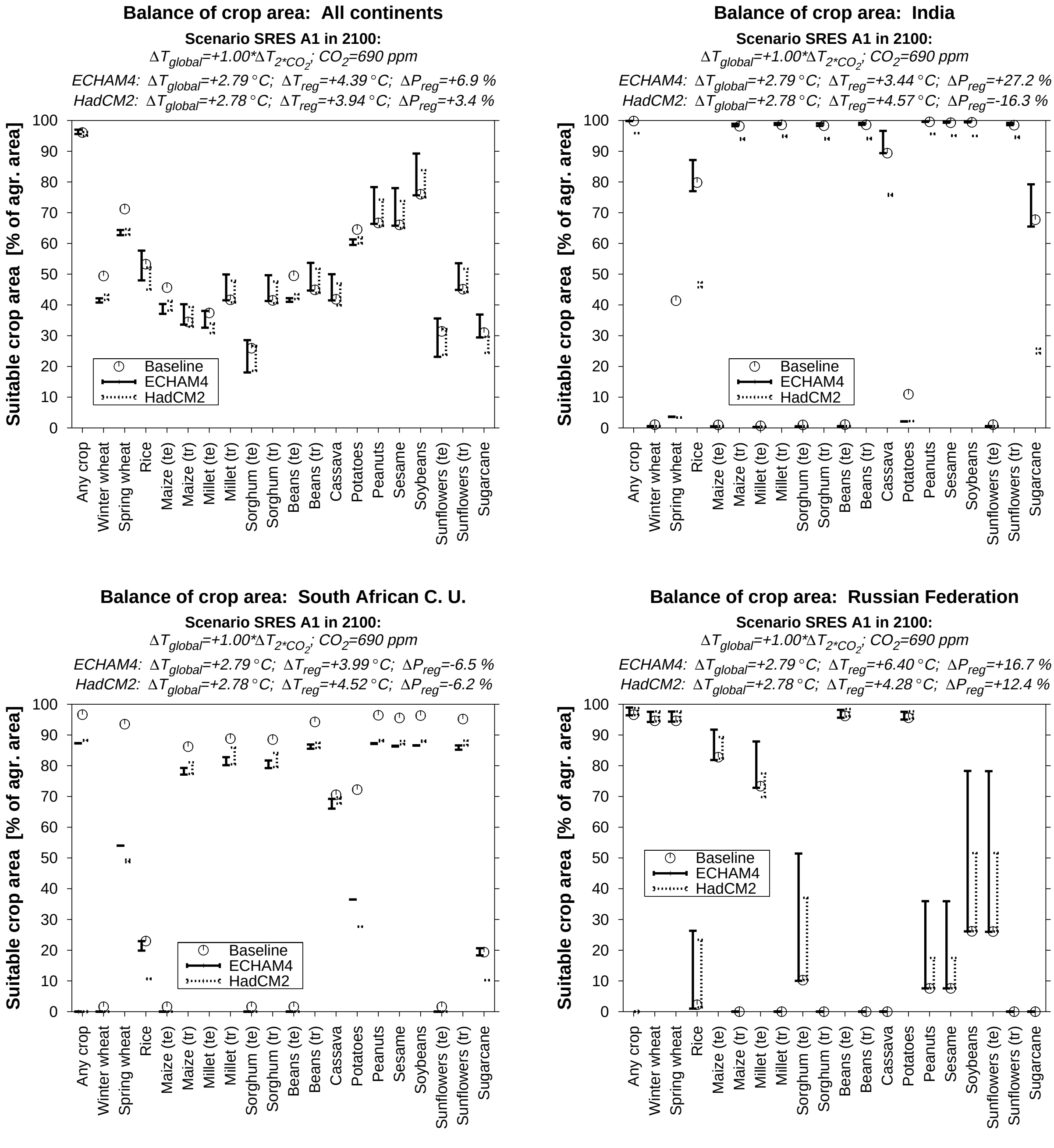


Figure 4.12: Area balance diagrams, depicting the suitable area of all crops considered (te: temperate, tr: tropical) for the baseline climate and for the climate state simulated by ECHAM4 and HadCM2 for the year 2100 of the SRES A1 marker scenario. *Top left:* All continents. *Top right:* India. *Bottom left:* South African Customs Union. *Bottom right:* Russia. (The suitable area for “Any crop” may be less than 100% of the cultivated area because the former is determined by the crop model based on rainfed conditions whereas the latter information includes irrigated areas.)

to less than 5% by the year 2100. These results are not challenged by the fact that about 80% of the cultivated area is irrigated because high temperature rather than water scarcity is the limiting factor here.

Figure 4.12 (bottom left-hand diagram) shows results for the South African Customs Union. The suitable area of all crops is simulated to decrease there. In contrast, Figure 4.12 (bottom right-hand diagram) indicates that the prospects for Russia's agriculture may be rather positive. The simulation results show a significant potential to diversify agricultural production as the current cultivated area becomes suitable for a wider range of crops. Additional results not presented here exhibit that large areas may become newly suitable for agriculture, and yields are expected to increase.

In summary, strong positive and negative responses of currently important crops to climate and CO_2 change have been simulated for different regions. The responses were robust across the two considered GCMs at the global level as well as for many countries. Dramatic decreases in the production of staple crops were simulated for India for one of the two GCM projections. Germany must expect severe constraints to the production of currently important crops but there is considerable potential for crop switching. Russian agriculture is likely to be a 'winner' of climate change. For the other countries from our selection, slight increases in the agricultural potential are simulated for the SRES scenarios, mainly due to the positive effects of enhanced CO_2 levels. In any case, interpretations of the simulation results presented here need to take into account that interannual climate variability, which is much more important for the annual crops addressed here than for most natural ecosystems, has not been considered in this analysis.

4.4 Climate impacts on water availability

The WaterGAP 1.1 model has been applied in the ICLIPS framework to assess the effects of a changing climate on water availability (see Section 3.5.4). The evaluation of simulated future changes in water availability as to their socioeconomic consequences requires considerable knowledge about the affected region. Not even the 'sign' of the evaluation is clear from the outset since both decreasing and increasing runoff may cause adverse impacts on societies. Decreasing runoff may result in insufficient water available for agriculture, industrial, and domestic use whereas increasing runoff may cause higher flood frequencies. Of course, the same ambiguity applies to beneficial impacts. In any case, a serious evaluation of flooding risks would require the application of models with a much higher spatiotemporal resolution than the one used here.

WaterGAP calculations are based on water basins. As water cannot be easily transferred over basin boundaries, this is the spatial unit which is most appropriate for water-related analyses. For each country, a representative basin has been identified, which covers a significant part of the area and the population.

Table 4.3 presents aggregated simulation results of WaterGAP for the same group of countries as in Section 4.3. The figures reported for each GCM refer to the climate state when AGMT has increased by $1.6 \cdot \Delta T_{2\times\mathrm{CO}_2}$ compared to the baseline climate, which corresponds to the maximum level of climate change considered in the CIRFs presented in previous sections. We refrain from the presentation of impact diagrams because the simulated relationship between the (normalized) change in AGMT, the only input variable to the CIRFs for water availability, and the impact indicator is almost linear.

Precipitation change is the most important factor for changes in water availability. In dry regions, a significant percentage of precipitation is evapotranspirated. This percentage is lower under wet conditions where the dependence of evapotranspiration on precipitation levels off. Consequently, with water

Country	**Brazil**	**China**	**Germany**	**India**	**Russia**	**SACU**[1]	**USA**
Basin	Amazon	Yangtze	Rhine	Ganges	Volga	Oranje	Mississippi
			Current climate				
TMP [°C]	24.7	11.7	8.2	21.4	3.7	17.8	10.4
PRE [mm/a]	2096	1030	936	1088	576	359	777
WA [mm/a]	1047	538	563	360	175	4.9	140
			ECHAM4				
Δ*TMP* [°C]	$+7.0$	$+6.2$	$+7.4$	$+5.9$	$+8.4$	$+6.3$	$+7.4$
Δ*PRE* [%]	$+10.2$	$+18.0$	-5.9	$+52.8$	$+11.0$	-13.0	$+7.1$
Δ*WA* [%]	$+18.4$	$+22.9$	-12.6	$+107.2$	$+37.7$	$+41.9$	± 0
WA [mm/a]	1240	661	492	746	241	7.0	140
			HadCM2				
Δ*TMP* [°C]	$+7.3$	$+5.5$	$+5.1$	$+7.9$	$+5.3$	$+7.1$	$+5.3$
Δ*PRE* [%]	$+1.4$	$+21.6$	-3.9	-47.1	$+24.9$	$+1.3$	$+26.2$
Δ*WA* [%]	$+0.4$	$+31.6$	-8.7	-83.9	$+53.1$	-7.1	$+72.1$
WA [mm/a]	1051	708	514	58	268	4.6	241

[1] South African Customs Union

Table 4.3: Simulated water availability in the current climate and in a future climate state characterized by a global mean temperature increase of $1.6 \cdot \Delta T_{2\times CO_2}$, based on two GCM projections. *TMP*, *PRE*, and *WA* denote annual temperature, precipitation, and water availability. The Δ sign indicates a change relative to the current climate.

availability being defined as that part of precipitation which is not evapotranspirated, a percentage change in precipitation typically leads to an even stronger change in water availability. This effect is obvious in the results for most countries considered here.

Increasing temperatures lead to higher evapotranspiration rates and, consequently, to a decrease in water availability. This effect is typically second in importance to precipitation changes. It is clearly visible in scenarios with minor changes in precipitation, e.g., the ECHAM4 scenario for the Mississippi basin in the USA. The only region which does not fit into this picture is the South African Customs Union. For the ECHAM4 climate scenario, WaterGAP simulates a slight (in absolute terms) increase in annual runoff despite decreasing precipitation and increasing temperature. This result can only be explained by the seasonal characteristics of the ECHAM4 climate change projection. The region is highly sensitive to changes in the seasonality of precipitation because it has a very low water availability.

WaterGAP simulates increasing water availability in most countries investigated here. India is the only country from our selection that is threatened with a very large decrease in water availability. Once again, the results for India are highly sensitive to the choice of the climate scenario. Whereas ECHAM4 simulates a precipitation increase in the Ganges basin of 53%, HadCM2 projects a decrease of 47% for the same change in AGMT. The corresponding changes in water availability are even more pronounced (+107% and −84%, respectively). Since the Ganges basin is densely populated and has large irrigated areas, a strong decrease in water availability (such as projected for the HadCM2 scenario) constitutes a serious threat to the people in that region.

4.5 Results of guardrail analyses with the integrated ICLIPS model

This section presents an illustrative guardrail analysis of the integrated ICLIPS model. We show necessary emission corridors based on externally specified constraints referring to climate impacts on terrestrial ecosystems, the regional costs of mitigation measures, and the timing of emissions reductions that also incorporate considerations about intra- and intergenerational equity. Climate impact response functions based on climate projections derived from ECHAM4 are applied in inverse mode to translate limits on vegetation change into simultaneous constraints for climate and CO_2 concentration (for details, see Sections 3.5.2 and 3.6.4).

Natural ecosystems are one of the impact domains explicitly named in Article 2 of the UNFCCC. The chosen impact indicator denotes the global share of the ice-free land surface in non-agricultural areas where the current biome becomes unsuitable under changed climate and atmospheric conditions. (Current agricultural areas were masked out because their land cover is fully controlled by human activities.) Although this indicator covers only one feature of potential climate impacts on ecosystems, we regard the fraction of the land area where ecosystems that have existed for millennia will no longer be feasible as a useful indicator for considering "dangerous anthropogenic interference with the climate system" and its implications. Since climate change is but one of the many factors that threaten biodiversity, this indicator should be regarded as a low estimate of long-term changes in terrestrial ecosystems.

Three main decision variables shape the emission corridor in this analysis. We present here their setting in the 'default case'. First, the *impact constraint* assumes that fundamentally transforming more than 35% of the Earth's ecosystems would constitute an intolerable climate change impact. This is a globally averaged figure, and as such it ignores the differences in the current areas and the relative ecological and social importance of different ecosystems yet it is suitable for our illustrative example. Second, the *mitigation cost constraint* assumes that mitigation costs exceeding 2% of the per-capita consumption (relative to the unmitigated reference scenario) of any present or future generation in any region would be socially unacceptable. The model allows the user to specify different cost limits for different regions, but for the sake of simplicity, we assume a uniform limit here. It should be noted that there are many unresolved issues in the field of emission mitigation costs. Income effects of climate change impacts are not considered explicitly in the ICLIPS model, which does not attempt to define monetary damage functions. Third, the *timing constraint* may specify a start year before which no effective emissions reductions take place. This constraint is not effective in the default case. In a sensitivity analysis, deviations from this default case are investigated by variations of the three constraints.

Besides the specification of the three normative constraints ('guardrails') outlined above, some additional assumptions have to be made in a guardrail analysis. The costs of emissions reduction are expressed with respect to a reference emissions scenario. The ICLIPS aggregated economic model (AEM) has been calibrated to replicate the IIASA-WEC A2 scenario, which resembles the fossil-fuel-intensive SRES A1FI scenario. We permit unrestricted trading of emission rights between different regions. For the purpose of this analysis, a compromise-based allocation of emission rights is assumed to begin with the status quo (emission rights allocated according to current emissions levels) and to gradually transform into an equal per-capita entitlement by 2050 (based on the region's population in the base year 1990).

Whilst energy-related CO_2 emissions are modelled endogenously based on the dynamic cost mitigation functions contained in AEM, emissions of other gases have to be described or linked to CO_2 emissions. Emissions of non-CO_2 greenhouse gases are prescribed until 2100 according to the average of the four SRES marker scenarios and are kept constant thereafter. SO_2 emissions are coupled with

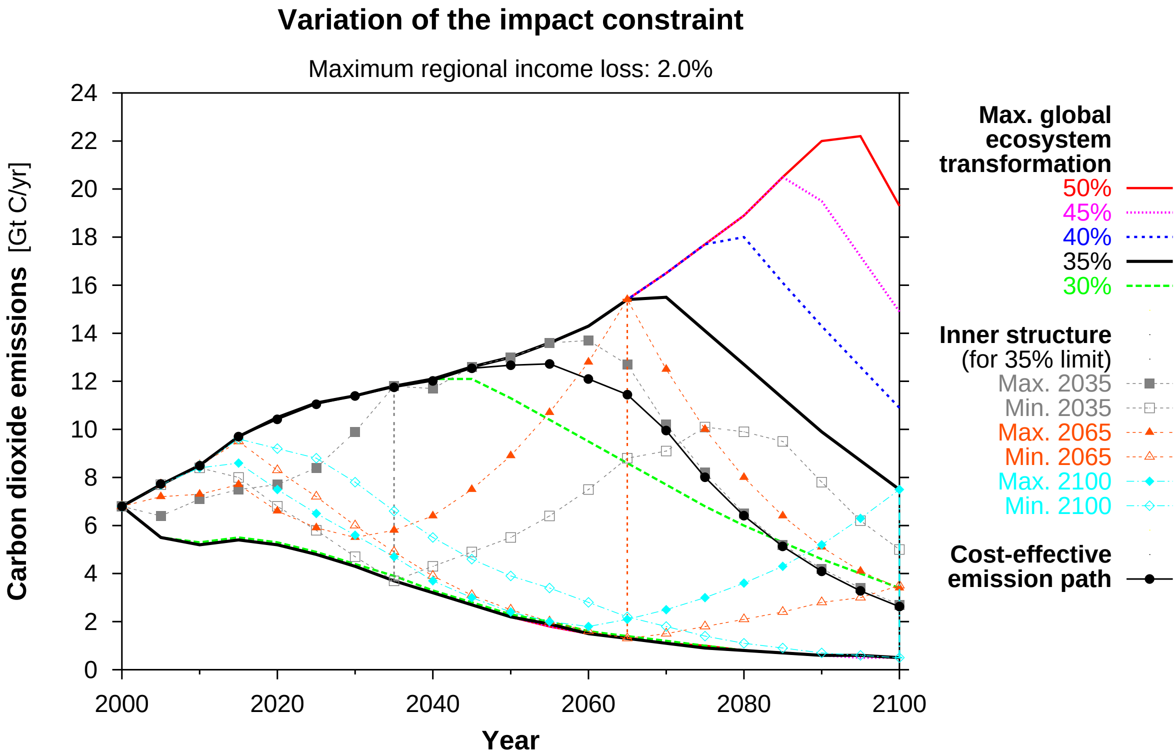


Figure 4.13: Corridors for energy-related CO_2 emissions for the default case and for variations of the impact constraint. The internal structure is illustrated by emission paths that hit the upper and lower boundaries of the corridor (the area inside the black borderlines) in selected years.

energy-related CO_2 emissions, assuming a globally averaged desulphurization rate of 1.5% per year. We note that some of these assumptions may strongly affect the climate change (or impact) target that can be reached for a given mitigation cost limit.

Figure 4.13 displays (necessary) global carbon emission corridors that result from variations of the impact constraint. The area bounded by the thick black borderline shows the emission corridor for the default case. Its internal structure is illustrated by various thin dashed paths (marked with symbols) that maximize or minimize emissions in a given year. It follows from the conceptual foundations of the guardrail approach (see Section 2.4.1) that any point within the corridor can be reached by at least one permitted emission path but an arbitrary path inside the corridor is not necessarily a permitted path. For example, the upper boundary of the corridor can be reached in 2065 only (by the path marked with full red triangles) if emissions remain substantially below baseline emissions for several decades in the first half of the twenty-first century. The cost-effective path (shown by the thin black line with circles), in contrast, follows the baseline up to about 2040 and then switches to a path of accelerating reduction. This shift occurs as both autonomous and learning-by-doing types of technological development make mitigation less expensive. It also reflects the discounting of future mitigation costs.

In order to illustrate the trade-offs between impacts and mitigation costs, the sensitivity of the emission corridor to variation in the three normative constraints is explored. Figure 4.13 shows emission corridors for a range of ecosystem transformation limits from 30% to 50%, thus indicating their sensitivity to variations in the impact constraint. The 30% limit results in a drastically narrower emission corridor (the green line inside the 35% corridor). No corridor exists for the 25% limit. This suggests that, given the amount of greenhouse gases already in the atmosphere and the inertia of the climate system, it is not possible to limit ecosystem transformation to 25% of nonagricultural areas globally by controlling CO_2 emissions alone, with the given willingness to pay. Conversely, if the global society were willing to allow half of the world's ecosystems to undergo biome changes, the corridor of acceptable carbon emission paths (red line) would be much wider, permitting higher annual and cumulative emissions. Further model experiments not reported here revealed that the 25% target could be reached if emissions of all other greenhouse gases were reduced in line with energy-related CO_2. This implies that it is important to improve our understanding of the mitigation options of non-CO_2 gases. There is also a non-trivial trade-off between acidification-related stresses due to SO_2 emissions and high rates of (regional) climate change due to the fast reduction of such emissions.

In Figure 4.14.a, another set of corridors indicates the sensitivity of the emission policy space to societies' willingness to pay for climate change mitigation. The limit to acceptable consumption loss is varied between 0.3% and 3% for the default case of a 35% maximum ecosystem transformation. These variations mainly affect the lower boundary of the corridors.

The timing of mitigation action has been the subject of fierce debates in climate policy in recent years. The effects of delaying emission reductions are also investigated in Figure 4.14.a. If emissions proceed along the baseline path until 2015, 2025, and 2035 (the gray, brown, and light blue lines, respectively), while the impact and cost constraints remain those specified for the default case, the implications of delaying emission reductions are rather modest for the corridor.

Figure 4.14.b shows that setting the limit of ecosystem transformation to 30% leads to much narrower corridors that are also much more sensitive to variations in the socioeconomic constraints. At least about 1% consumption loss is required to have an open corridor. If emission reductions are postponed until 2015, 2025, and 2035, the resulting corridors (the areas between the equally coloured dashed lines) become increasingly narrower compared with a situation in which emission reductions are implemented without delay. The 2035 corridor (delineated by the light blue lines) is a very tight lane of sustained emission reduction that approaches the maximum rate permitted by the declining-cost technologies and the emission reduction rate constraint.

In summary, the model results presented here reveal the strong nonlinearity and sensitivity of the climate policy space to impact constraints such as the transformation of ecosystems. The emission corridors were found to be much more sensitive to variations in the impact constraint than in the mitigation cost constraint. The results also disclose the intricate relationships among the numerous decision factors as they determine how near-term choices foreclose or preserve options for long-term climate policy. The timing of emission reductions and the mitigation of non-CO_2 greenhouse gases turned out to be important factors that determine whether 'ambitious' impact targets can be achieved at reasonable cost.

We conclude by noting that the guardrail analysis presented in this section proved the applicability of the CIRFs developed in this thesis for inverse analyses of the climate change problem. Further guardrail analyses with the ICLIPS model that apply CIRFs for natural vegetation and agricultural crop yield are presented in Toth et al. (2003a,b).

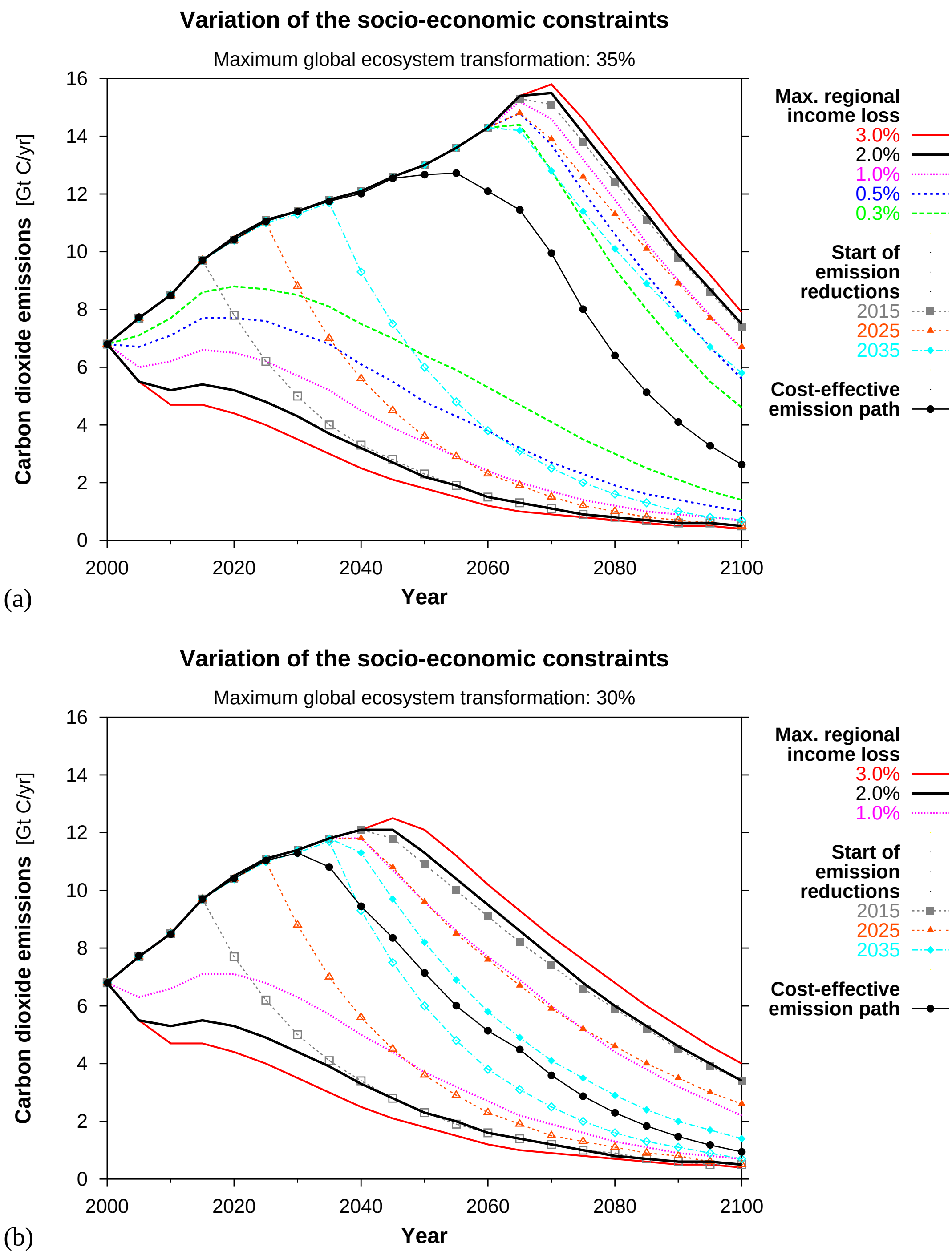


Figure 4.14: Corridor for energy-related CO_2 emissions for the default case and for variations of the socioeconomic constraints for a (a) 35% and (b) 30% limit of global ecosystem transformation, respectively.

Chapter 5

Summary and conclusions

This thesis has covered a broad range of issues related to the assessment of climate impacts and their representation in an integrated assessment model that implements the guardrail approach to climate change decision support. Section 5.1 of this concluding chapter summarizes key aspects of the work presented in the previous chapters. Section 5.2 discusses this work in the context of proposed criteria for good integrated assessment and gives an outlook into possible future developments.

5.1 Summary

Chapter 1 provided an introduction into the climate change problem. It started with a brief review of the physics of climate change. The still considerable uncertainty about many aspects of future climate change has strong implications for climate impact and adaptation assessments and for climate change policy-making. The uncertainties in global warming projections for the end of the 21st century due to human choice (in the form of different plausible emission scenarios) and to imperfect scientific understanding are estimated to have similar magnitude. Scientific uncertainties are larger at finer spatial levels, for climate variables other than temperature, and for higher-order statistics.

The brief review of expected climate impacts largely followed the structure of the five "reasons for concern" proposed in the IPCC Third Assessment Report. This classification is based, i.a., on the spatial characteristics of the considered impacts, on their substitutability, and on their regularity and predictability.

The discussion on societal response options stressed that the principle options, mitigation of climate change and adaptation to climate change, differ significantly in their characteristic spatiotemporal scales, in their comprehensiveness, in the diversity of measures, in the actors involved, and in several other factors that are important for decision-making. As a result, scientific assessments for mitigation and adaptation typically occur largely independent from each other. The "ultimate objective" of the UNFCCC was mentioned as an important focal point for science-policy dialogues and for scientific analysis, including the work presented in this thesis.

Chapter 2 introduced integrated assessment (IA) as a set of activities that combine knowledge from different scientific disciplines, and possibly from other sources, to arrive at new insights that stakeholders perceive as useful for their decision-making. Owing to the complexity of the issue, mathematical models are the principal tools for the integrated assessment of climate change.

The information needs of climate policy decision-makers have initiated a broad range of climate impact, vulnerability, and adaptation assessments. Key concepts were defined and a hierarchical conceptual framework was presented for structuring these assessments, and for describing the evolution of the assessment practice and of the underlying theory. Early impact assessments were primarily used to inform decisions about long-term targets for the mitigation of climate change. The increasing awareness of the importance of adaptation as a complementary policy strategy to mitigation has been accompanied by efforts to provide information about future climate impacts that is relevant for adaptation policy. In particular, climate impact projections, and estimates of the uncertainty in these projections, are required at spatiotemporal scales that are appropriate for the planning and implementation of adaptation measures.

The main challenges for climate policy decision-making were briefly discussed. Major decision-analytical frameworks applied in this context were evaluated as to their suitability for guiding policy decisions about targets and measures for international climate policy in the context of the UNFCCC. The guardrail approach was identified as particularly useful due to its clear-cut separation of scientific analysis from normative value judgements and to its openness to non-quantifiable knowledge.

The ICLIPS model was presented as the first integrated assessment model of climate change (IAM) based on the guardrail approach. Guardrail analyses lead to the problem of dynamic non-uniqueness, which is treated in the ICLIPS model by using the theories of differential inclusions and optimal control. Whilst the computation of the full solution of a guardrail analysis is not possible for any realistic representation of the coupled climate-society system, interesting partial solutions such as emission corridors can be determined by solving a number of suitably defined dynamical control problems. Various options for the consideration of uncertainties in the ICLIPS model were discussed. In the deterministic version of the guardrail approach implemented in the ICLIPS model, the main options for doing so are sensitivity analysis and the specification of guardrails that purposefully consider current knowledge limits. The application of more sophisticated techniques such as uncertainty propagation is complicated by the set-valued nature of typical solutions of a guardrail analysis.

Chapter 3 started with a review of the representation of climate impacts in existing IAMs that revealed fundamentally different approaches between predictive and optimizing models. The former apply geographically explicit impact models to determine climate impacts in biophysical units whereas the latter use highly aggregated monetized damage functions, typically with a prescribed functional form.

The representation of climate impacts in the ICLIPS model faces the challenge of simultaneously achieving a level of detail that is analogous to predictive models and a level of computational efficiency that is comparable to the simple damage functions from optimizing models. Climate impact response functions (CIRFs) were identified as the most appropriate reduced-form representation of climate impacts in the ICLIPS model. They are derived from a suitably chosen set of simulations with geographically explicit impact models. The change in global mean temperature, normalized by the equilibrium climate sensitivity of the emulated GCM, and the CO_2 concentration link the CIRFs to the ICLIPS climate-economy model.

Spatially and seasonally explicit climate change scenarios for the impact simulations were constructed by scaling climate change patterns derived from forcing experiments with three different general circulation models (GCMs). The accuracy of the linear approximation applied in the pattern scaling technique was shown by applying empirical orthogonal function analysis. A method for superimposing (scaled) climate change patterns on a historical baseline climatology was further developed that ensures valid results for bounded climate variables, preserves key characteristics of the climate change signal simulated by the GCM, and avoids clearly unrealistic climate change projections despite weaknesses in the simulation of the current climate by GCMs.

Various aggregated indicators were defined for describing climate impacts on natural vegetation, crop production potential, and water availability with the aim of providing policy-relevant information at an aggregation level where climate projections from GCMs can provide useful information. These indicators were computed by geographically explicit impact models that had already been applied in (predictive) climate change assessments with the IMAGE model. Impacts are initially determined at the country level and then aggregated to larger world regions.

CIRFs can be applied to assess climate impacts for specific emission scenarios, to seek for possible thresholds in the simulated response of a climate-sensitive system, to identify particularly sensitive regions and indicators, and to explore uncertainties from different sources. These analyses are facilitated by the availability of the ICLIPS Impacts Tool, a graphical user interface that provides convenient access to more than 100,000 impact diagrams. Various types of impact diagrams give different perspectives on the high-dimensional result space of the impact simulations performed in ICLIPS. The most important application of CIRFs in ICLIPS, however, is in inverse mode where they translate impact guardrails specified in biophysical units into sets of constraints for variables from the ICLIPS climate-economy model. This translation was made possible by the development of algorithms for the computation of (generally non-convex) reachable climate domains through solving a number of suitably defined dynamic optimization problems, and for the translation of admissible climate windows derived from CIRFs into sets of parameterized constraints.

Chapter 4 presented selected simulation results of the ICLIPS model. Reachable climate domains in the two-dimensional space spanned by global mean temperature change and CO_2 concentration were determined for different assumptions on future emissions scenarios. The results showed that even for a fixed climate sensitivity, a particular level of CO_2 concentration may be accompanied by a wide range of global mean temperature change, and vice versa. This ambiguity is caused by the variable levels of non-CO_2 greenhouse gases and of aerosols, and by the inertia of the climate system. Further analyses revealed the importance of constraining the emissions of non-CO_2 greenhouse gases (particularly CH_4 and N_2O) for reaching low levels of global climate change.

Regional and global CIRFs for natural vegetation indicate that ecosystems throughout the world are highly sensitive to the projected changes in climate and atmospheric CO_2. Natural vegetation was modelled to be most sensitive in high-latitude regions where low (winter) temperature is the prime limiting factor for vegetation growth. At the global scale, wooded tundra and cool conifer forests were simulated to disappear from (almost) all of their present locations by the end of the 21^{st} century under business-as-usual emission scenarios. Other biomes, e.g., tropical woodlands, have the potential to considerably expand into currently unsuitable regions. In general, impacts agreed well for the climate change patterns provided by three different GCMs. Considerable discrepancies were found in some regions with a significant spread across precipitation projections. The agreement would have been lower if GCMs with very different climate sensitivities had been used as well.

The CIRFs for agricultural crop production show that the projected climate changes generally have an adverse impact on the weighted average of the currently important crops. However, for most countries and climate scenarios considered, these climate-induced losses were compensated by the beneficial effects of enhanced CO_2 levels. Potentially dangerous results were simulated for certain regions in Asia. Increasing temperatures, in association with major changes to the monsoon that may be brought about by the global emissions of greenhouse gases (and/or by the regional emissions of aerosol precursors) could lead to drastic decreases of the potential to grow current staple crops. One particular analysis investigated the suitable area for the cultivation of different crops in India under a 'business-as-usual' emission scenario. The temperature increases simulated by all GCMs would make wheat production impossible almost everywhere by 2100, and the area suitable for rice cultivation could be halved by that time if the massive precipitation decreases simulated by one of the GCMs actually manifested.

The guardrail approach and its implementation in the ICLIPS model allow long-term emission strategies to be explored under a wide variety of normative concerns that shape the global climate policy debate. CIRFs enable the ICLIPS model to include guardrails for global and regional impacts of climate change. An analysis was presented that determined global carbon emission corridors subject to constraints for global vegetation change, regional mitigation costs, and the timing of emission reductions. The model results revealed the strong nonlinearity and sensitivity of the climate policy space to the chosen impact constraint. The existence and the shape of the emission corridor turned out to be much more sensitive to variations in the impact constraint than to the limits on mitigation costs or the timing of emission reductions.

5.2 Conclusions

A large variety of approaches have been used over the last decade to estimate impacts of climate change in IAMs, each of which with its own merits and shortcomings. We introduced CIRFs as a convenient method for summarizing and visualizing the (biophysical) impacts of changes in fundamental indicators of global climate change on selected climate-sensitive sectors. CIRFs are the most suitable reduced-from representation of climate impacts in the ICLIPS model, given the requirements posed by the particular decision-analytical framework applied and by the global scope of the model. In contrast to point estimates or functional relationships interpolated from a few points, the CIRFs discussed in this thesis specify the responses of climate-sensitive sectors across a wide span of plausible patterns of climate change derived from GCMs and, where relevant, CO_2 concentrations. As a result, they can be used directly by social actors to assess the risks of climate change, and to impose impact constraints in a guardrail analysis with the ICLIPS model.

CIRFs cannot resolve the still vast uncertainties that characterize climate impact assessments. Nevertheless, the CIRF approach provides a framework for considering the information available from GCMs for use with impact models to derive regional assessments. The suitability of CIRFs for inverse analyses is due to their independence from specific emissions scenarios, their reliance on physically consistent climate scenarios, and their biophysical foundation. The concise presentation of extensive model results provided by CIRFs also facilitates comparisons of different sources of uncertainty, such as those associated with the GCMs, the impact models, etc. Finally, CIRFs can serve as input to other impact assessment tools for further processing. The availability of the fulls set of CIRFs in the ICLIPS Impacts Tool makes it also possible to use them independently from the ICLIPS model.

Major limitations of the impacts analysis presented in this thesis are as follows. First, none of the impact models considers the effect of transient climate changes on the investigated system. However, the implications of this simplification were limited by choosing impact indicators that focus on the long-term effects of a certain climate state. Second, the climate scenarios and the impact simulations consider only the mean climate despite the well-known importance of higher statistical moments for many impact sectors. However, it was shown that the pattern scaling technique and the computation of CIRFs can easily be extended to consider (at least) interannual climate variability. This path was not explored in the ICLIPS project due to the (then) prohibitive computational costs of working with time series of annual climate statistics rather than with climate means only. Changes in higher moments of climate variables can be included in the CIRFs if these changes are detectable and significant in GCM forcing experiments. Third, none of the climate scenarios considered includes the possibility of singular climate change. However, rather than being a limitation of the CIRFs themselves, this is a feature of the ICLIPS climate model (and indeed of any deterministic simple climate model). Fourth, the impact indicators focus on biophysical changes, which are not necessarily the primary concern of policymakers. However, CIRFs that integrate the biophysical sensitivity with models of socioeconomic vulnerability and adaptation would typically need to consider detailed climatic, environmental, and socioeconomic information that is unlikely to be universally available at a global scale. In any case, the development of such integrated CIRFs could only be reasonably attempted by analyses with a much higher level of complexity than the one presented here. In addition, the implementation of potentially wide-ranging adaptation measures should not be silently assumed in guardrail analyses.

Various scholars have suggested that integrated assessment of climate change (IA) needs to address certain topics, or needs to meet certain criteria. How does the ICLIPS model rate according to these criteria?

Schneider (1997) presents a hierarchy of five generations of IAMs. According to that hierarchy, the ICLIPS model combines many aspects from the second generation, a few from the third generation, and (arguably) one from the fourth generation. From that perspective, it appears not much different from other existing IAMs. However, it may be argued that the proposed hierarchy, which dates before the development of the guardrail approach, does not account for the possibility that some of the difficult tasks 'reserved' for higher-generation models may actually be taken over by the model user in a guardrail analysis. For instance, the explicit consideration of changing value systems which was only mentioned for the fifth-generation models could, in principle, be explored by the users of the ICLIPS model, based on their individual perceptions. The checklist of good practices for IA provided in Schneider (1997) includes, i.a., the clear specification of the limited context of a particular IA exercise, the discussion how uncertainty and value-laden judgements are treated, and the ability to include culturally-dependent components. Recalling the extensive discussion about the guardrail approach and its explicit objective to separate scientific analysis and value judgements, it may suffice to note here that the ICLIPS model appears to be a step into the right direction with respect to each of these points.

Morgan et al. (1999) discuss several basic assumptions of conventional policy tools and their validity with a view to the special features of global change problems. Their list includes the assumptions

- of a single decision-maker (the 'single commoner') facing a single problem;
- of manageable impacts that can be valued at the margin;
- that values are known, static, and exogenously determined;
- that decisions should be made on the basis of maximizing expected utility;
- that exponential discounting provides an adequate representation of future costs and benefits; and
- that uncertainty is modest and manageable.

These assumptions are (often implicitly) made in conventional tools for policy analysis because they seem to decrease the complexity of the decision problem by enabling the identification of a unique 'best' policy based on assumedly objective grounds. However, none of these assumptions is *per se* true in the context of global climate change, and their inappropriate use may cause very misleading results.

The guardrail approach implemented in the ICLIPS model is rather modest in its assumptions. Even though uncertainty and the diverse perspectives of different decision-makers are important issues in guardrail analyses, neither of the assumptions mentioned above are actually required. However, the other side of this coin is a greater 'burden' for the designated decision-makers. In the presence of scientific uncertainty or value dependence, the decision must be made by the decision-maker (*sic!*) not the analyst in a guardrail analysis. Stakeholders who prefer to simply follow the seemingly objective advice of policy assessments may find this difficult. However, the task of IA cannot be to create certainty out of uncertainty or objectivity out of subjectivity. Rather, IA should combine and structure the available knowledge (but not more!) in a way that makes it accessible to decision-makers and enables them to draw conclusions that are consistent with the available information.

Which steps are conceivable to improve the concept and the application of CIRFs?

First, it was already discussed that CIRFs could be defined to consider the effects of interannual variability, if this was deemed relevant for the respective impact sector, and if the impact model was actually calibrated to time series of annual data. Guardrails could then be defined, for instance, with respect to the return period of certain hazardous events.

Second, if a probabilistic impact model was available for a certain sector (based on either objective or subjective probability distributions), probabilistic CIRFs could be determined and probabilistic guardrails be defined analogous to the previous case.

Third, guardrail analyses might focus on certain regions. The CIRFs in ICLIPS were designed to have global coverage, which required the use of globally applicable impact models. Regionally focussed CIRFs could use information that is available for specific regions only. The potential for the consideration of adaptation options in CIRFs is also greater for regionally specific than for global analyses.

Finally, the development of CIRFs in ICLIPS may be regarded as a small step towards a more modular approach to the integrated assessment of climate change. Current IAMs are usually monolithic blocs that aim to provide information which meets the perceived needs of a restricted group of stakeholders. Recognizing the difficulties of building comprehensive IAMs that can be flexibly applied to different policy questions, it has been suggested that "third-generation" IAMs should be developed in a modular way (Hulme, 2001). The basic idea of this approach is to flexibly build custom-made integrated assessment 'models' in response to specific demands from the policy community by taking suitable model components 'from the shelf', and by linking them appropriately. Jaeger et al. (2002) describe how recent developments in object-oriented software design facilitate the development of modular IAMs. The overall concept of this "co-productive approach" to IA is explained in Schellnhuber et al. (2003). The respective community integrated assessment system (CIAS) comprises, on the one hand, a set of relevant sub-modules with well-defined interfaces developed by different institutions and, on the other hand, various participants in the science-policy dialogue with well-defined roles denoted as demander, surveyor, composer, responder, and CIAS operator. In fact, the ICLIPS Impacts Tool is already a part of the initial CIAS framework, which has been established by the Tyndall Centre for Climate Change Research together with the the Potsdam Institute for Climate Impact Research.

The ball is in the game. May someone pick it up and take it further!

Bibliography

Aaheim, H. A. and Bretteville, C. (2001). Decision-making frameworks for climate policy under uncertainty. CICERO Working Paper 2001:2, CICERO, Oslo University, Oslo, Norway.

Ahmad, Q. and Warrick, R. A. (2001). Methods and tools. In McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., editors, *Climate Change 2001: Impacts, Adaptation and Vulnerability,* chapter 2. Cambridge University Press, Cambridge.

Albritton, D. L. and Meira Filho, L. G. (2001). Technical summary. In *Climate Change 2001. The Scientific Basis*, pages 21–83. Cambridge University Press, Cambridge.

Alcamo, J., editor (1994). *IMAGE 2.0: Integrated Modeling of Global Climate Change*. Kluwer, Dordrecht.

Alcamo, J. and Kreileman, E. (1996). Emission scenarios and global climate projection. *Global Environmental Change*, 6:305–334.

Alcamo, J. and Kreileman, E. (1997). The global climate system: Near term action for long term protection. Report 481508001, RIVM, Bilthoven, The Netherlands.

Alcamo, J. and Kreileman, E. (1998). Emission scenarios and global climate protection. In Alcamo, J., Leemans, R., and Kreileman, E., editors, *Global Change Scenarios of the* 21^{st} *Century. Results from the IMAGE 2.1 Model*, pages 163–192. Pergamon, Oxford.

Alcamo, J., Kreileman, E., Krol, M., Leemans, R., Bollen, J., van Minnen, J., Schaeffer, M., Toet, S., and de Vries, B. (1998a). Global modelling of environmental change: an overview of IMAGE 2.1. In Alcamo, J., Leemans, R., and Kreileman, E., editors, *Global Change Scenarios of the* 21^{st} *Century. Results from the IMAGE 2.1 Model*, pages 3–94. Pergamon, Oxford.

Alcamo, J., Kreileman, G. J. J., Krol, M. S., and Zuidema, G. (1994). Modeling the global society–biosphere–climate system. Part 1: Model description and testing. *Water, Air, and Soil Pollution*, 76:1–35.

Alcamo, J., Shaw, R., and Hordijk, L., editors (1990). *The RAINS Model of Acidification: Science and Strategies in Europe*. Kluwer, Dordrecht.

Arnell, N. W., Cannell, M. G. R., Hulme, M., Kovats, R. S., Mitchell, J. F. C., Nicholls, R. J., Parry, M. L., Livermore, M. T. J., and White, A. (2002). The consequences of CO_2 stabilisation for the impacts of climate change. *Climatic Change*, 53:413–446.

Arrow, K. J. (1950). A difficulty in the concept of social welfare. *The Journal of Political Economy*, 58:328–346.

Aubin, J., editor (1991). *Viability Theory*. Birkhäuser, Basel.

Aubin, J. and Cellina, A., editors (1984). *Differential Inclusions*. Springer, Berlin.

Azar, C. (1998). Are optimal CO_2 emissions really optimal? — four critical issues for economists in the greenhouse. *Environmental and Resouce Economics*, 11:1–15.

Azar, C. and Lindgren, K. (2003). Catastrophic events and stochastic cost–benefit analysis of climate change. *Climatic Change*, 56:245–255.

Bacher, A., Oberhuber, J. M., and Roeckner, E. (1998). ENSO dynamics and seasonal cycle in the tropical Pacific as simulated by the ECHAM4/OPYC3 coupled general circulation model. *Climate Dynamics*, 14:431–450.

Baede, A. P. M., Ahlonsou, E., Ding, Y., and Schimel, D. (2001). The climate system: an overview. In *Climate Change 2001. The Scientific Basis*, chapter 1. Cambridge University Press, Cambridge.

Barker, T. (2001). Representing the integrated assessment of climate change, adaptation and mitigation. Working Paper 11, Tyndall Centre for Climate Change Research, Norwich, UK.

Batjes, N. H. (1996). Development of a world data set of soil water retention properties using pedotransfer rules. *Geoderma*, 71:31–52.

Batterman, S. (1990). Optimized abatement strategies using critical loads: Suggested deposition criteria and results. IIASA Working Paper WP-90-067, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Bazzaz, B. A. (1998). Tropical forests in a future climate: Changes in biological diversity and impact on the global carbon cycle. *Climatic Change*, 39:317–336.

Bergström, S. (1995). The HBV model. In Singh, V. P., editor, *Computer models of watershed hydrology*, pages 443–476. Water Resources Publications, Highlands Ranch, CO.

Bick, H., editor (1989). *Ökologie*. Gustav Fischer, Stuttgart.

Blaikie, P., Cannon, T., Davis, I., and Wisner, B. (1994). *At Risk: Natural Hazards, People's Vulnerability and Disasters*. Routledge, London.

Boer, G. J. and Yu, B. (2003). Climate sensitivity and response. *Climate Dynamics*, 20:415–429.

Bohle, H.-G., Downing, T. E., and Watts, M. J. (1994). Climate change and social vulnerability: Toward a sociology and geography of food insecurity. *Global Environmental Change*, 4:37–48.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Sirnet, S., Tedesco, K., Klas, M., Bonani, G., and Ivy, S. (1992). Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. *Nature*, 360:245–249.

Boughton, D. A., Smitz, E. R., and O'Neill, R. V. (1999). Regional vulnerability: A conceptual framework. *Ecosystem Health*, 5:312–322.

Brooke, A., Kendrick, D., and Meeraus, A. (1994). *GAMS, A User's Guide, Release 2.25*. The Scientific Press, San Francisco, CA.

Brooks, S. (2002). *Climate change, vulnerability and conservation in Costa Rica: An investigation of impacts, adaptive environmental management and national adaptation networks*. PhD thesis, School of Geography and the Environment, University of Oxford, Oxford, UK.

Bruckner, T., Hooss, G., Füssel, H.-M., and Hasselmann, K. (2003a). Climate system modeling in the framework of the tolerable windows approach: The ICLIPS climate model. *Climatic Change*, 56:119–137.

Bruckner, T., Petschel-Held, G., Leimbach, M., and Toth, F. L. (2003b). Methodological aspects of the tolerable windows approach. *Climatic Change*, 56:73–89.

Bruckner, T., Petschel-Held, G., Toth, F. L., Füssel, H.-M., Helm, C., Leimbach, M., and Schellnhuber, H.-J. (1999). Climate change decision–support and the tolerable windows approach. *Environmental Modeling and Assessment*, 4:217–234.

Cao, M. and Woodward, F. I. (1998). Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature*, 393:249–252.

Carter, T. R., Parry, M. L., Harasawa, H., and Nishioka, S. (1994). IPCC technical guidelines for assessing climate change impacts and adaptations. Part of the IPCC Special Report to the First Session of the Conference of the Parties to the UN Framework Convention on Climate Change, Department of Geography, University College London, London, UK.

Claussen, M. (1998). On the inconsistency at the interface of climate impact studies and global climate simulations. In Schellnhuber, H.-J. and Wenzel, V., editors, *Earth System Analysis. Integrating Science for Sustainability*, pages 273–276. Springer, Berlin.

Claussen, M., Kubatzki, C., Brovkin, V., Ganopolski, A., Hoelzmann, P., and Pachur, H.-J. (1999). Simulation of an abrupt change in Saharan vegetation in the mid-Holocene. *Geophysical Research Letters*, 26:2037–2040.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., and Totterdell, I. J. (2000). Acceleration of global warming due to carbon–cycle feedbacks in a coupled climate model. *Nature*, 408:184–187.

Cramer, W., Bondeau, A., Woodward, F. I., Prentice, I. C., Betts, R. A., Brovkin, V., Cox, P. M., Fisher, V., Foley, J. A., Friend, A. D., Cucharik, C., Lomas, M. R., Ramankutty, N., Sitch, S., Smith, B., White, A., and Young-Molling, C. (2001). Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. *Global Change Biology*, 7:357–373.

Cubasch, U., Meehl, G. A., Boer, G. J., Stouffer, R. J., Dix, M., Noda, A., Senior, C. A., Raper, S., and Yap, K. S. (2001). Projections of future climate change. In *Climate Change 2001. The Scientific Basis*, chapter 9. Cambridge University Press, Cambridge.

Cutter, S. L. (1993). *Living with Risk*. Edgar Arnold, London.

Cutter, S. L. (1996). Vulnerability in environmental hazards. *Progress in Human Geography*, 20:529–539.

Dai, A., Meehl, G. A., Washington, W. M., Wigley, T. L., and Arblaster, J. M. (2001). Ensemble simulation of twenty-first century climate changes: Business-as-usual versus CO_2 stabilization. *Bulletin of the American Meteorological Society*, 82:2377–2388.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdottir, A. E., Jouzel, J., and Bond, G. (1993). Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, 264:218–220.

de Wit, C. T. (1978). *Simulation of assimilation, respiration and transpiration of crops*. Simulation Monographs. PUDOC, Wageningen, The Netherlands.

Deimling, K., editor (1992). *Multivalued Differential Equations*. de Gruyter, Berlin, Germany.

Dempster, A. P. (1967). Upper and lower probabilities induced by a multivalued mapping. *Annals of Mathematical Statistics*, 38:325–339.

Dilley, M. and Boudreau, T. E. (2001). Coming to terms with vulnerability: a critique of the food security definition. *Food Policy*, 26:229–247.

Döll, P., Kaspar, F., and Alcamo, J. (1999). Computation of global water availability and water use at the scale of large drainage basins. *Mathematische Geologie*, 4:111–118.

Downing, D. J., Gardner, R. H., and Hoffmann, F. O. (1985). An examination of response-surface methodologies for uncertainty analysis in assessment models. *Technometrics*, 27:151–163.

Edmonds, J., Wise, M., Pitcher, H., Richels, P., Wigley, T., and MacCracken, C. (1996). An integrated assessment of climate change and the accelerated introduction of advanced energy technologies: An application of MiniCAM 1.0. *Mitigation and Adaptation Strategies for Global Change*, 1:311–319.

FAO (1981). Report on the agro–ecological zones project. Vol. 3: Methodology and results for South and Central America. World Soil Resources Report 48, Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO (1988). FAO/UNESCO Soil Map of the World. Revised Legend. World Soil Resources Report 60, Food and Agriculture Organization of the United Nations, Rome, Italy.

Folland, C. K., Karl, T. R., Christy, J. R., Clarke, R. A., Gruza, G. V., Jouzel, J., Mann, M. E., Oerlemans, J., Salinger, M. J., and Wang, S.-W. (2001). Observed climate variability and change. In *Climate Change 2001. The Scientific Basis*, chapter 2. Cambridge University Press, Cambridge.

Funtowicz, S. O. and Ravetz, J. R. (1990). *Uncertainty and Quality in Science for Policy*. Kluwer, Dordrecht.

Funtowicz, S. O. and Ravetz, J. R. (1992). Three types of risk assessment and the emergence of post-normal science. In *Social Theories of Risk*, pages 251–273. Greenwood, Westport, CT.

Füssel, H.-M. (2002a). Coevolution of the political and conceptual frameworks for climate change vulnerability assessments. Paper presented at the 2002 Berlin Conference on the Human Dimensions of Global Environmental Change — "Knowledge for the Sustainability Transition", Berlin, Germany.

Füssel, H.-M. (2002b). The ICLIPS Impacts Tool: Presenting climate impact response functions for integrated assessments of climate change. In *Integrated Assessment and Decision Support — Proceedings of the First Biannual Meeting of the Environmental Modelling and Software Society (iEMSs 2002)*, volume 3, pages 115–120. Lugano, Switzerland.

Füssel, H.-M. (2003b). The ICLIPS Impacts Tool: A graphical user interface to climate impact response functions for integrated assessments of climate change. *Integrated Assessment*, 4:116–125.

Füssel, H.-M. and Klein, R. J. T. (2002a). Climate change vulnerability assessments: An evolution of conceptual thinking. Accepted by Climatic Change.

Füssel, H.-M. and Klein, R. J. T. (2002b). Vulnerability and adaptation assessments to climate change: An evolution of conceptual thinking. In *UNDP Expert Group Meeting "Integrating Disaster Reduction and Adaptation to Climate Change"*, Havana, Cuba.

Füssel, H.-M., Toth, F. L., van Minnen, J. G., and Kaspar, F. (2003). Climate impact response functions as impact tools in the tolerable windows approach. *Climatic Change*, 56:91–117.

Füssel, H.-M. and van Minnen, J. G. (2001). Climate impact response functions for terrestrial ecosystems. *Integrated Assessment*, 2:183–197.

Ganopolski, A., Petoukhov, V., Rahmstorf, S., Brovkin, V., Claussen, M., Eliseev, A., and Kubatzki, C. (2001). CLIMBER–2: a climate system model of intermediate complexity. Part II: model sensitivity. *Climate Dynamics*, 17:735–751.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., von Storch, H., Whetton, P., Jones, R., Mearns, L., and Fu, C. (2001). Regional climate information — evaluation and projections. In *Climate Change 2001. The Scientific Basis*, chapter 1. Cambridge University Press, Cambridge.

Gitay, H., Brown, S., Easterling, W., and Jallow, B. (2001). Ecosystems and their goods and services. In *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, chapter 5. Cambridge University Press, Cambridge.

Gjerde, J., Grepperud, S., and Kverndokk, S. (1999). Optimal climate policy under the possibility of a catastrophe. *Resource and Energy Economics*, 21:289–317.

Grabs, W., de Couet, T., and Pauler, J. (1996). Freshwater fluxes from continents into the world oceans based on data of the global runoff data base. GRDC Report 10, Global Runoff Data Centre, Federal Institute of Hydrology, Koblenz, Germany.

Gritsevskyi, A. and Schrattenholzer, L. (2003). Costs of reducing carbon emissions: An integrated modeling framework approach. *Climatic Change*, 56:167–184.

Groombridge, B., editor (1994). *Biodiversity Data Sourcebook*. WCMC Biodiversity Series No. 1. World Conservation Press, Cambridge.

Halpin, P. N. (1996). Global climate change and natural-area protection: management responses and research directions. *Ecological Applications*, 7:828–843.

Hasselmann, K., Sausen, R., Maier-Reimer, E., and Voss, R. (1993). On the cold start problem in transient simulations with coupled atmosphere–ocean models. *Climate Dynamics*, 9:53–61.

Haxeltine, A. and Prentice, C. I. (1996). BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles*, 10:693–709.

Haykin, S. (1999). *Neural Networks. A Comprehensive Foundation*. Prentice Hall, New Jersey, 2nd edition.

Helm, C., Bruckner, T., and Toth, F. L. (1999). Value judgements and the choice of climate protection strategies. *International Journal of Social Economics*, 26:974–998.

Henderson-Sellers, A. (1993). An antipodean climate of uncertainty. *Climatic Change*, 25:203–224.

Henderson-Sellers, A. (1996). Can we integrate climatic modelling and assessment? *Environmental Modeling and Assessment*, 1:59–70.

Hettelingh, J. P., Posch, M., de Smet, P. A. M., and Downing, R. J. (1995). The use of critical loads in emission reduction agreements in Europe. *Water, Air, and Soil Pollution*, 85:2381–2388.

Hooss, G., Voss, R., Hasselmann, K., Maier-Reimer, E., and Joos, F. (2001). A nonlinear impulse response model of the coupled carbon cycle–climate system (NICCS). *Climate Dynamics*, 18:189–202.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., and Xiaosu, D., editors (2001). *Climate Change 2001: The Scientific Basis*. Cambridge University Press, Cambridge.

Houghton, J. T., Meira Filho, L., Bruce, J., Lee, H., Callander, B. A., Haites, E., Harris, N., and Maskell, K., editors (1994). *Climate Change 1994. Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emissions Scenarios*. Cambridge University Press, Cambridge.

Howarth, R. B. and Norgaard, R. B. (1995). Intergenerational choices under global climate change. In Bromley, D. W., editor, *Handbook of Environmental Economics*, chapter 6. Basil Blackwell, Oxford.

Hughes, L. (2000). Biological consequences of global warming: Is the signal already apparent? *Trends in Ecology & Evolution*, 15:56–61.

Hulme, M. (2001). Integrated assessment models. Tyndall Centre Working Paper 2, Tyndall Centre for Climate Change Research, Norwich, UK.

Hulme, M., Jiang, T., and Wigley, T. (1995b). *SCENGEN: A Climate Change Scenario Generator. Software User Manual, Version 1.0*. Climate Research Unit, University of East Anglia, Norwich, UK.

Huntingford, C. and Cox, P. M. (2000). An analogue model to derive additional climate change scenarios from existing GCM simulations. *Climate Dynamics*, 16:575–586.

Huntley, B., Berry, P. M., Cramer, W., and McDonald, A. P. (1995). Modelling present and potential future ranges of some European higher plants using climate response surfaces. *Journal of Biogeography*, 22:967–1001.

Jacoby, H. D. (2003). Informing climate policy given incommensurable benefits estimates. ENV/EPOC/GSP(2003)2/FINAL, Organization for Economic Cooperation and Development, Paris, France.

Jaeger, C. C., Leimbach, M., Carraro, C., Hasselmann, K., Hourcade, J. C., Keeler, A., and Klein, R. (2002). Integrated assessment modelling: Modules for cooperation. Nota di Lavoro 53.2002, Fondazione Eni Enrico Mattei, Milano, Italy.

Johns, T. C., Carnell, R. E., Crossley, J. F., Gregory, J. M., Mitchell, J. F. B., Senior, C. A., Tett, S. F. B., and Wood, R. A. (1997). The second Hadley Centre coupled ocean–atmosphere GCM: model description, spinup and validation. *Climate Dynamics*, 13:103–134.

Jonas, M., Fleischmann, K., Ganopolski, A. V., Krabec, J., Sauer, U., Olendrzynski, K., Petoukhov, V. K., and Shaw, R. W. (1996). Grid point surface air temperature calculations with a fast turnaround: Combining the results of IMAGE and a GCM. *Climatic Change*, 34:479–512.

Jones, T. H., Thompson, L. J., Lawton, J. H., Bezemer, T. M., Bardgett, R. D., Blackburn, T. M., Bruce, K. D., Cannon, P. F., Hall, G. S., Hartley, S. E., Howson, G., Jones, C. G., Kampichler, C., Kandeler, E., and Ritchie, D. A. (1998). Impacts of rising atmospheric carbon dioxide on model terrestrial ecosystems. *Science*, 280:441–443.

Keller, K., Tan, K., Morel, F. M. M., and Bradford, D. F. (2000). Preserving the ocean circulation: Implications for climate policy. *Climatic Change*, 47:17–43.

Kelly, P. M. and Adger, W. N. (2000). Theory and practice in assessing vulnerability to climate change and facilitating adaptation. *Climatic Change*, 47:325–352.

Kenny, G. J., Warrick, R., Mitchell, N., Mullan, A., and Salinger, M. (1995). CLIMPACTS: An integrated model for assessment of the effects of climate change on the New Zealand environment. *Journal of Biogeography*, 22:883–895.

Kharin, V. V. and Zwiers, F. W. (2000). Changes in the extremes in an ensemble of transient climate simulations with a coupled atmosphere-ocean GCM. *Journal of Climate*, 13:3760–3788.

Kirilenko, A. P. and Solomon, A. M. (1998). Modeling dynamic vegetation response to rapid climate change using bioclimatic classification. *Climatic Change*, 38:15–49.

Klein, R. J. T. and MacIver, D. C. (1999). Adaptation to climate change and variability: Methodological issues. *Mitigation and Adaptation Strategies for Global Change*, 4:189–198.

Klein, R. J. T. and Nicholls, R. J. (1999). Assessment of coastal vulnerability to climate change. *Ambio*, 28:182–187.

Klein, R. J. T., Nicholls, R. J., and Mimura, N. (1999). Coastal adaptation to climate change: Can the IPCC guidelines be applied? *Mitigation and Adaptation Strategies for Global Change*, 4:239–252.

Klein Goldewijk, K., van Minnen, J. G., Kreileman, G. J. J., Vloedbeld, M., and Leemans, R. (1994). Simulating the carbon flux between the terrestrial environment and the atmosphere. *Water, Air, and Soil Pollution*, 76:199–230.

Kleinen, T., Füssel, H.-M., and Bruckner, T. (2003). Vorsorgeprinzip und Klimawandel: Der Leitplankenansatz. In Böschen, S., Lerf, A., and Schneider, M., editors, *Über die Anerkennung von und den Umgang mit Nichtwissen*. edition sigma, Berlin. (in press).

Kopp, R. J., Krupnick, A. J., and Toman, M. (1997). Cost-benefit analysis and regulatory reform. *Human and Ecological Risk Assessment*, 3:787–852.

Körner, C. (1998). Tropical forests in a CO_2-rich world. *Climatic Change*, 39:297–315.

Kriegler, E. and Bruckner, T. (2003). Joint emissions corridors for industrial and developing countries. Accepted by Integrated Assessment.

Kriegler, E. and Held, H. (2003). Climate projections for the 21^{st} century using random sets. In *Proceedings of ISIPTA '03: 3^{rd} International Symposium on Imprecise Probabilities and Their Applications*. University of Lugano, Lugano, Switzerland.

Krol, M., Alcamo, J., and Leemans, R. (1997). Global and regional impacts of stabilizing atmospheric CO_2. *Mitigation and Adaptation Strategies for Global Change*, 1:341–361.

Kwadijk, J. and Middelkoop, H. (1994). Estimation of the impact of climate change on the peak discharge probability of the river Rhine. *Climatic Change*, 27:199–224.

Layton, D. F. and Brown, G. (2000). Heterogeneous preferences regarding global climate change. *Review of Economics and Statistics*, 82:616–624.

Leemans, R., Cramer, W., and van Minnen, J. G. (1996). Prediction of global biome distribution using bioclimatic equilibrium models. In Melillo, J. M. and Breymeyer, A., editors, *Effects of Global Change on Coniferous Forests and Grassland*, pages 413–450. Wiley, New York.

Leemans, R. and Eickhout, B. (2003). Analysing change in ecosystems for different levels of climate change. ENV/EPOC/GSP(2003)5/FINAL, Organization for Economic Cooperation and Development, Paris, France.

Leemans, R. and Halpin, P. N. (1992). Global change and biodiversity. In Groombridge, B., editor, *Biodiversity 1992: Status of the Earth's Living Resources*, pages 254–255. Chapman and Hall, London.

Leemans, R. and Hootsmans, R. (1998). Ecosystem vulnerability and climate protection goals. Report 481508004, RIVM, Bilthoven, The Netherlands.

Leemans, R. and van den Born, G. (1994). Determining the potential global distribution of natural vegetation, crops and agricultural productivity. *Water, Air, and Soil Pollution*, 76:133–162.

Leimbach, M. and Bruckner, T. (2001). Influence of economic constraints on the shape of emission corridors. *Computational Economics*, 18:173–191.

Leimbach, M. and Toth, F. L. (2003). Economic development and emission control over the long term: The ICLIPS Aggregated Economic Model. *Climatic Change*, 56:139–165.

Lim, B., editor (2001). *UNDP–GEF Workshop for Developing an Adaptation Policy Framework for Climate Change. Preliminary Report*, St. Adele, Canada.

Mardia, K. V., Kent, J. T., and Bibby, J. M. (1978). *Multivariate Analysis*. Academic Press, London.

Martens, P. (1998b). *Health & Climate Change. Modelling the Impacts of Global Warming and Ozone Depletion*. Earthscan, London.

Martens, W. J. M., Jetten, T. H., and Focks, D. A. (1997). Sensitivity of malaria, schistosomiasis and dengue to global warming. *Climatic Change*, 35:145–156.

Martens, W. J. M., Niessen, L. W., Rotmans, J., Jetten, T. H., and McMichael, A. J. (1995b). Potential impact of global climate change on malaria risk. *Environmental Health Perspectives*, 103:458–464.

Martin, P. H. (1996). Will forest preserves protect temperate and boreal biodiversity from climate change? *Forest Ecology and Management*, 85:335–341.

Mastrandrea, M. D. and Schneider, S. H. (2001). Integrated assessment of abrupt climatic changes. *Climate Policy*, 1:433–449.

McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., editors (2001). *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Cambridge University Press, Cambridge.

McElwain, J. C., Beerling, D. J., and Woodward, F. I. (1999). Fossil plants and global warming at the Triassic–Jurassic boundary. *Science*, 285:1386–1390.

Mearns, L. O., Hulme, M., Carter, T. R., Leemans, R., Lal, M., and Whetton, P. (2001). Climate scenario development. In *Climate Change 2001. The Scientific Basis*, chapter 13. Cambridge University Press, Cambridge.

Mendelsohn, R., Schlesinger, M., and Williams, L. (2000). Comparing impacts across climate models. *Integrated Assessment*, 1:37–48.

Milly, P. C. D., Wetherald, R. T., Dunne, K. A., and Delworth, T. L. (2002). Increasing risk of great floods in a changing climate. *Nature*, 415:515–518.

Mitchell, J. F. B., Johns, T. C., Eagles, M., Ingram, W. J., and Davis, R. A. (1999). Towards the construction of climate change scenarios. *Climatic Change*, 41:547–581.

Mitchell, J. F. B., Johns, T. C., Ingram, W. J., and Lowe, J. A. (2000). The effect of stabilising atmospheric carbon dioxide concentrations on global and regional climate change. *Geophysical Research Letters*, 27:2977–2980.

Mitchell, J. F. B., Karoly, D. J., Hegerl, G. C., Zwiers, F. W., Allen, M. R., and Marengo, J. (2001). Detection of climate change and attribution of causes. In *Climate Change 2001. The Scientific Basis*, chapter 1. Cambridge University Press, Cambridge.

Mitchell, T. D. (2001). *An investigation of the pattern scaling technique for describing future climates*. PhD thesis, University of East Anglia, Norwich, UK.

Monserud, R. A., Tchebakova, N. M., and Leemans, R. (1993). Global vegetation change predicted by the modified Budyko model. *Climatic Change*, 25:59–83.

Morgan, M. G. and Dowlatabadi, H. (1996). Learning from integrated assessment of climate change. *Climatic Change*, 34:337–368.

Morgan, M. G. and Henrion, M. (1990). *Uncertainty: A guide to dealing with uncertainty in risk and policy analysis*. Cambridge University Press, Cambridge.

Morgan, M. G., Kandlikar, M., Risbey, J., and Dowlatabadi, H. (1999). Why conventional tools for policy analysis are often inadequate for problems of global change. *Climatic Change*, 41:271–281.

Müller, B. (2002). A new Delhi mandate? *Climate Policy*, 2:241–242.

Nakicenovic, N. and Swart, R., editors (2000). *Emissions Scenarios*. Cambridge University Press, Cambridge.

Neilson, R. P. (1993). Vegetation redistribution: a possible biosphere source of CO_2 during climatic change. *Water, Air, and Soil Pollution*, 70:659–673.

New, M., Hulme, M., and Jones, P. (1999). Representing twentieth-century space-time climate variability. Part I: Development of a 1961–1990 mean monthly terrestrial climatology. *Journal of Climate*, 12:829–856.

New, M., Hulme, M., and Jones, P. (2000). Representing twentieth-century space-time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. *Journal of Climate*, 13:2217–2238.

Nicholls, R. J. and Leatherman, S. P. (1995). Potential impacts of accelerated sea–level rise on developing countries. *Journal of Coastal Research*, Special Issue No. 14.

Nordhaus, W. D. (1994). *Managing the Global Commons. The Economics of Climate Change*. MIT Press, Cambridge, MA.

Nordhaus, W. D. and Boyer, J. (2000). *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA.

North, G. R. (1984). Empirical orthogonal functions and normal modes. *Journal of Atmospheric Sciences*, 41:879–887.

Olson, D. M. and Dinerstein, E. (1998). The global 200: a representation approach to conserving the Earth's most biologically valuable ecoregions. *Conservation Biology*, 12:502–515.

Parry, M., Arnell, N., McMichael, T., Nicholls, R., Martens, P., Kovats, S., Livermore, M., Rosenzweig, C., Iglesias, A., and Fischer, G. (2001). Millions at risk: defining critical climate change threats and targets. *Global Environmental Change*, 11:181–183.

Parson, E. A. (1996). Three dilemmas in the integrated assessment of climate change. *Climatic Change*, 34:315–326.

Pearce, D. W. (1993). *Economic Values and the Natural World*. Earthscan, London.

Pearce, D. W. and Cline, W. R. (1996). The social costs of climate change: Greenhouse damage and the benefits of control. In Bruce, J. P., Lee, H., and Haites, E. F., editors, *Climate Change 1995. Economic and Social Dimensions of Climate Change*, chapter 18. Cambridge University Press, Cambridge.

Pearson, R. G. and Dawson, T. P. (2003). Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful. *Global Ecology & Biogegography*, 12:361–371.

Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., and Rahmstorf, S. (2000). CLIMBER-2: A climate system model of intermediate complexity, Part I: Model description and performance for the present climate. *Climate Dynamics*, 16:1–17.

Petschel-Held, G., Schellnhuber, H.-J., Bruckner, T., Toth, F. L., and Hasselmann, K. (1999). The tolerable windows approach: Theoretical and methodological foundations. *Climatic Change*, 41:303–331.

Pittock, A. B. and Jones, R. N. (2000). Adaptation to what and why? *Environmental Monitoring and Assessment*, 61:9–35.

Pounds, J. A., Fogden, M. P. L., and Campbell, J. H. (1999). Biological response to climate change on a tropical mountain. *Nature*, 398:611–615.

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., and Solomon, A. M. (1992). A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography*, 19:117–134.

Rahmstorf, S. (1995). Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. *Nature*, 378:145–149.

Räisänen, J. and Palmer, T. N. (2001). A probability and decision-model analysis of a multimodel ensemble of climate change simulations. *Journal of Climate*, 14:3212–3226.

Ramankutty, N. and Foley, J. (1998). Characterizing patterns of global land use: an analysis of global croplands data. *Global Biogeochemical Cycles*, 12:667–685.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G. Y., and Solomon, S. (2001). Radiative forcing of climate change. In *Climate Change 2001. The Scientific Basis*, chapter 6. Cambridge University Press, Cambridge.

Ramaswamy, V. and Chen, C.-T. (1997). Linear additivity of climate response for combined albedo and greenhouse perturbations. *Geophysical Research Letters*, 24:567–570.

Raper, S. C. B., Gregory, J. M., and Stouffer, R. J. (2002). The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response. *Journal of Climate*, 15:124–130.

Reilly, J. M. and Schimmelpfennig, D. (1999). Agricultural impact assessment, vulnerability, and the scope for adaptation. *Climatic Change*, 43:745–788.

Ribot, J. C. (1995). The causal structure of vulnerability: Its application to climate impact analysis. *GeoJournal*, 35:119–122.

Risbey, J., Kandlikar, M., and Patwardhan, A. (1996). Assessing integrated assessments. *Climatic Change*, 34:369–395.

Robinson, J. B. (1982). Energy backcasting: A proposed method of policy analysis. *Energy Policy*, 10:337–344.

Robinson, J. B. (1991). Modelling the interactions between human and natural systems. *International Social Sciences Journal*, 130:629–647.

Robock, A., Turco, R. P., Harwell, M. A., Ackerman, T. P., Andressen, R., Chang, H.-S., and Sivakumar, M. V. K. (1993). Use of GCM output for impact analysis. *Climatic Change*, 23:293–335.

Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giorgetta, M., Schlese, U., and Schulzweida, U. (1996). The atmospheric general circulation model ECHAM-4: Model description and simulation of present day climate. Report No. 218, Max Planck Institute for Meteorology, Hamburg, Germany.

Rosenzweig, C. and Parry, M. L. (1994). Potential impact of climate change on world food supply. *Nature*, 367:133–138.

Rothman, D. S. (2000). Measuring environmental values and environmental impacts: Going from the local to the global. *Climatic Change*, 44:351–376.

Rothman, D. S., Amelung, B., and Polomé, P. (2003). Estimating non-market impacts of climate change and climate policy. ENV/EPOC/GSP(2003)12/FINAL, Organization for Economic Cooperation and Development, Paris, France.

Rothman, D. S. and Robinson, J. B. (1997). Growing pains: a conceptual framework for considering integrated assessments. *Environmental Monitoring and Assessment*, 46:23–43.

Rotmans, J. and Dowlatabadi, H. (1998). Integrated assessment modeling. In Rayner, S. and Malone, E. L., editors, *Tools for Policy Analysis*, volume 3 of *Human Choice and Climate Change*, chapter 5. Battelle Press, Columbus, OH.

Roughgarden, T. and Schneider, S. H. (1998). Climate change policy: quantifying uncertainties for damages and optimal carbon taxes. *Energy Policy*, 27:415–429.

Sala, O. E., Chapin III, F. S., Armesto, J. J., Berlow, R., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson, R. B., Kinzig, A., Leemans, R., Lodge, D., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M., and Wall, D. H. (2000). Global biodiversity scenarios for the year 2100. *Science*, 287:1770–1774.

Saloranta, T. M. (2001). Post-normal science and the global climate change issue. *Climatic Change*, 50:395–404.

Santer, B. D., Wigley, T. M. L., Schlesinger, M. E., and Mitchell, J. F. B. (1990). Developing climate scenarios from equilibrium GCM results. Report No. 47, Max Planck Institute for Meteorology, Hamburg, Germany.

Scheffer, M., Carpenter, S., Foley, J. A., Folke, C., and Walker, B. (2001). Catastrophic shifts in ecosystems. *Nature*, 413:591–596.

Schellnhuber, H.-J. (1999). Earth system analysis and the second Copernican revolution. *Nature*, 402(SUPP):C19–C23.

Schellnhuber, H.-J. (2003). Integrated assessment of adaptation and mitigation options. Paper presented at the 3rd World Climate Change Conference (WCCC 2003), Moscow, Russian Federation.

Schellnhuber, H.-J. and Kropp, J. (1998). Geocybernetics: Controlling a complex dynamical system under uncertainty. *Naturwissenschaften*, 85:411–425.

Schellnhuber, H.-J., Warren, R., Haxeltine, A., and Naylor, L. (2003). Developments in integrated assessment: the co-productive approach. ENV/EPOC/GSP(2003)6/FINAL, Organization for Economic Cooperation and Development, Paris, France.

Schellnhuber, H.-J. and Wenzel, V., editors (1998). *Earth System Analysis. Integrating Science for Sustainability*. Springer, Berlin.

Schellnhuber, H.-J. and Yohe, G. W. (1997). Comprehending the economic and social dimensions of climate change by integrated assessment. In *Proceedings of the WCRP Conference: Achievements, Benefits and Challenges*. World Meteorological Organization, Geneva, Switzerland.

Schlesinger, M. E., Andronova, N., Ghanem, A., Malishev, S., Reichler, T., Rozanov, E., Wang, W., and Yang, F. (1997). Geographical scenarios of greenhouse-gas and anthropogenic-sulfate-aerosol induced climate changes. Technical report, Climate Research Group, University of Illinois at Urbana-Champaign, Urbana, IL.

Schneider, S. and Sarukhan, J. (2001). Overview of impacts, adaptation, and vulnerability to climate change. In McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., editors, *Climate Change 2001: Impacts, Adaptation and Vulnerability*, chapter 1. Cambridge University Press, Cambridge.

Schneider, S. H. (1983). CO_2, climate and society: A brief overview. In Chen, R. S., Boulding, E., and Schneider, S. H., editors, *Social Science Research and Climate Change: An Interdisciplinary Appraisal*, pages 9–15. D. Reidel, Boston.

Schneider, S. H. (1997). Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions. *Environmental Modeling and Assessment*, 2:229–249.

Schneider, S. H., Kuntz-Duriseti, K., and Azar, C. (2000). Costing non–linearities, surprises,and irreversible events. *Pacific and Asian Journal of Energy*, 10:81–106.

Schneider, S. H., Turner II, B. L., and Morehouse Garriga, H. (1998). Imaginable surprise in global change science. *Journal of Risk Research*, 1:165–185.

Schröder, M., Claussen, M., Grunwald, A., Hense, A., Klepper, G., Lingner, S., Ott, K., Schmitt, D., and Sprinz, D. (2002). *Klimavorhersage und Klimavorsorge*. Springer, Berlin.

Semenov, M. A. and Porter, J. R. (1995). Climatic variability and the modelling of crop yields. *Agricultural and Forest Meteorology*, 73:265–283.

Senior, C. A. and Mitchell, J. F. B. (2000). The time-dependence of climate sensitivity. *Geophysical Research Letters*, 27:2685–2688.

Simon, H. A. (1972). Theories of decision-making in economics and behavioral science. *American Economic Review*, 49:253–283.

Smit, B., Burton, I., Klein, R. J. T., and Street, R. (1999). The science of adaptation: a framework for assessment. *Mitigation and Adaptation Strategies for Global Change*, 4:199–213.

Smit, B., Burton, I., Klein, R. J. T., and Wandel, J. (2000). An anatomy of adaptation to climate change and variability. *Climatic Change*, 45:223–251.

Smit, B. and Pilifosova, O. (2001). Adaptation to climate change in the context of sustainable development and equity. In McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., editors, *Climate Change 2001: Impacts, Adaptation and Vulnerability*, chapter 18. Cambridge University Press, Cambridge.

Smith, J. B. (1997). Setting priorities for adapting to climate change. *Global Environmental Change*, 7:251–264.

Smith, J. B. and Hulme, M. (1998). Climate change scenarios. In Feenstra, J. F., Burton, I., Smith, J. B., and Tol, R. S. J., editors, *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. Version 2.0*, chapter 3. United Nations Environmental Programme, Nairobi, Kenya.

Smith, J. B. and Pitts, G. J. (1997). Regional climate change scenarios for vulnerability and adaptation assessments. *Climatic Change*, 36:3–21.

Smith, J. B., Schellnhuber, H.-J., and Mirza, M. M. Q. (2001). Vulnerability to climate change and reasons for concern: A synthesis. In McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., and White, K. S., editors, *Climate Change 2001: Impacts, Adaptation and Vulnerability*, chapter 19. Cambridge University Press, Cambridge.

Smith, T. M., Leemans, R., and Shugart, H. H. (1992). Sensitivity of terrestrial carbon storage to CO_2-induced climate change: Comparison of four scenarios based on general circulation models. *Climatic Change*, 21:367–384.

Smith, T. M. and Shugart, H. H. (1993). The transient response of terrestrial carbon storage to a perturbed climate. *Nature*, 361:523–526.

Smithers, J. and Smit, B. (1997). Human adaptation to climatic variability and change. *Global Environmental Change*, 7:129–146.

Steffen, W. L., Cramer, W., Ploechl, M., and Bugmann, H. (1996). Global vegetation models: incorporating transient changes to structure and composition. *Journal of Vegetation Science*, 7:321–328.

Swart, R., Berk, M., Janssen, M., Kreileman, E., and Leemans, R. (1998). The safe landing approach: riks and trade-offs in climate change. In Alcamo, J., Leemans, R., and Kreileman, E., editors, *Global Change Scenarios of the* 21^{st} *Century. Results from the IMAGE 2.1 Model*, pages 193–218. Pergamon, Oxford.

Swart, R. J. and Vellinga, P. (1994). The 'ultimate objective' of the Framework Convention on Climate Change requires a new approach to climate change research. *Climatic Change*, 26:343–349.

Sykes, M. T., Prentice, I. C., and Laarif, F. (1999). Quantifying the impact of global climate change on potential natural vegetation. *Climatic Change*, 41:37–52.

Tol, R. S. J. (1996). The damage costs of climate change towards a dynamic representation. *Ecological Economics*, 19:67–90.

Tol, R. S. J. (2002a). Estimates of the damage costs of climate change. Part I: Benchmark estimates. *Environmental and Resouce Economics*, 21:47–73.

Tol, R. S. J. (2002b). Estimates of the damage costs of climate change. Part II: Dynamic estimates. *Environmental and Resouce Economics*, 21:135–160.

Tol, R. S. J. and Fankhauser, S. (1998). On the representation of impact in integrated assessment models of climate change. *Environmental Modeling and Assessment*, 3:63–74.

Toth, F. L. (2001). Decision analysis for climate change: development, equity and sustainability concerns. *International Journal of Global Environmental Issues*, 1:223–240.

Toth, F. L. (2003a). Climate policy in light of science: The ICLIPS project. *Climatic Change*, 56:7–36.

Toth, F. L. (2003b). ICLIPS: Integrated Assessment of Climate Protection Strategies. *Climatic Change*, Special issue 56(1–2).

Toth, F. L., Bruckner, T., Füssel, H.-M., Leimbach, M., and Petschel-Held, G. (2003a). Integrated assessment of long–term climate policies: Part 1 — Model presentation. *Climatic Change*, 56:37–56.

Toth, F. L., Bruckner, T., Füssel, H.-M., Leimbach, M., and Petschel-Held, G. (2003b). Integrated assessment of long–term climate policies: Part 2 — Model results and uncertainty analysis. *Climatic Change*, 56:57–72.

Toth, F. L., Bruckner, T., Füssel, H.-M., Leimbach, M., Petschel-Held, G., and Schellnhuber, H.-J. (1997). The tolerable windows approach to integrated assessments. In *Climate Change and Integrated Assessment Models — Bridging the Gaps. Proceedings of the IPCC Asia–Pacific Workshop on Integrated Assessment Models*, CGER–Report CGER–I029–'97, pages 403–430. Center for Global Environmental Research, Ibaraki, Japan.

Toth, F. L., Bruckner, T., Füssel, H.-M., Leimbach, M., Petschel-Held, G., and Schellnhuber, H.-J. (2002). Exploring options for global climate policy: A new analytical framework. *Environment*, 44(5):22–34.

Toth, F. L., Cramer, W., and Hizsnyik, E. (2000). Climate impact response functions: an introduction. *Climatic Change*, 46:225–246.

Toth, F. L. and Mwandosya, M. (2001). Decision-making frameworks. In Metz, B., Davidson, O., Swart, R., and Pan, J., editors, *Climate Change 2001: Mitigation*, chapter 19. Cambridge University Press, Cambridge.

Toth, F. L., Petschel-Held, G., and Bruckner, T. (1998b). Kyoto and the long-term climate stabilization. In *OECD Workshop Report on "Economic Modelling of Climate Change"*, pages 307–328. Organization for Economic Cooperation and Development, Paris, France.

UNDHA (1993). Internationally agreed glossary of basic terms related to disaster management. DNA/93/36, United Nations Department of Humanitarian Affairs, Geneva, Switzerland.

United Nations General Assembly (1992). United Nations Framework Convention on Climate Change. United Nations, New York.

van Asselt, M. B. A. and Rotmans, J. (2002). Uncertainty in integrated assessment modelling. *Climatic Change*, 54:75–105.

van der Sluijs, J. P., Potting, J., Risbey, J., van Vuuren, D., de Vries, B., Beusen, A., Heuberger, P., Corral Quintana, S., Funtowicz, S., Kloprogge, P., Nuijten, D., Petersen, A., and Ravetz, J. (2002). Uncertainty assessment of the IMAGE/TIMER B1 CO_2 emissions scenario, using the NUSAP method. Report 410200104, Dutch National Research Programme on Global Air Pollution and Climate Change.

van Minnen, J. G., Alcamo, J., and Haupt, W. (2000a). Deriving and applying response surface diagrams for evaluating climate change impacts on crop production. *Climatic Change*, 46:317–338.

van Minnen, J. G., Leemans, R., and Ihle, F. (2000b). Defining the importance of including transient ecosystem responses to simulate C–cycle dynamics in a global change model. *Global Change Biology*, 6:595–612.

van Minnen, J. G., Onigkeit, J., and Alcamo, J. (2002). Critical climate change as an approach to assess climate change impacts in Europe: development and application. *Environmental Science & Policy*, 5:335–347.

Villers-Ruíz, L. and Trejo-Vázquez, I. (1998). Climate change on Mexican forests and natural protected areas. *Global Environmental Change*, 8:141–157.

Viner, D. (1994). Climate change scenarios for impacts assessment. *Aspects of Applied Biology*, 38:13–27.

Viner, D. and Hulme, M. (1994). The climate impacts LINK project. Providing climate change scenarios for impacts assessment in the UK. A report prepared for the UK Department of the Environment, Climate Research Unit, University of East Anglia, Norwich, UK.

von Storch, H. (1995). Inconsistencies at the interface of climate impact studies and global climate research. *Meteorologische Zeitschrift*, 4:72–80.

von Storch, H. and Navarra, A., editors (1995). *Analysis of Climate Variability. Applications of Statistical Techniques*. Springer, Berlin.

Voss, R. and Mikolajewicz, U. (2001). Long–term climate changes due to increased CO_2 concentration in the coupled atmosphere–ocean general circulation model ECHAM3/LSG. *Climate Dynamics*, 17:45–60.

Voss, R., Sausen, R., and Cubasch, U. (1998). Periodically synchronously coupled integrations with the atmosphere–ocean general circulation model ECHAM3/LSG. *Climate Dynamics*, 14:249–266.

Walley, P. (1991). *Statistical Reasoning with Imprecise Probabilities*. Chapman and Hall, London.

Walley, P. (2000). Towards a unified theory of imprecise probabilities. *International Journal of Approximate Reasoning*, 24:125–148.

Walther, G. R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T. J. C., Fromentin, J.-M., Hoegh-Guldberg, O., and Bairlein, F. (2002). Ecological responses to recent climate change. *Nature*, 416:389–395.

Watson, R. and the Core Writing Team, editors (2001). *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Watterson, I. G. (2000). Interpretation of simulated global warming using a simple model. *Journal of Climate*, 13:202–215.

WBGU (1995). Scenario for the derivation of global CO_2 reduction targets and implementation strategies. German Advisory Council on Global Change (WBGU), Bremerhaven, Germany.

WBGU (1997). Targets for climate protection 1997. German Advisory Council on Global Change (WBGU), Bremerhaven, Germany.

Webster, M. (2003). Communicating climate change uncertainty to policy-makers and the public. *Climatic Change*, 61:1–8.

Webster, M. and Sokolov, A. P. (2000). A methodology for quantifying uncertainty in climate projections. *Climatic Change*, 46:417–446.

Weyant, J., Davidson, O., Dowlatabadi, H., Edmonds, J., Grubb, M., Parson, E., Richels, R., Rotmans, J., Shukla, P., Tol, R., Cline, W., and Fankhauser, S. (1996). Integrated assessment of climate change: An overview and comparison of approaches and results. In Bruce, J. P., Lee, H., and Haites, E. F., editors, *Climate Change 1995. Economic and Social Dimensions of Climate Change*, chapter 10. Cambridge University Press, Cambridge.

Willows, R. and Connell, R. (2003). Climate adaptation: Risk, uncertainty and decision-making. UKCIP Technical Report, United Kingdom Climate Impacts Programme, Oxford, UK.

Wright, E. L. and Erickson, J. D. (2003). Incorporating catastrophes into integrated assessment: science, impacts, and adaptation. *Climatic Change*, 57:265–286.

Yates, D. N., Kittel, T. G. F., and Cannon, R. F. (2000). Comparing the correlative Holdridge model to mechanistic biogeographical models for assessing vegetation distribution response to climatic change. *Climatic Change*, 44:59–87.

Yohe, G. (2001). Mitigative capacity — the mirror image of adaptive capacity on the emissions side. *Climatic Change*, 49:247–262.

Yohe, G. and Tol, R. S. J. (2002). Indicators for social and economic coping capacity — moving toward a working definition of adaptive capacity. *Global Environmental Change*, 12:25–40.

Zickfeld, K. and Bruckner, T. (2003). Reducing the risk of abrupt climate change: Emissions corridors preserving the Atlantic thermohaline circulation. *Integrated Assessment*, 4:106–115.