Understanding the effect of climate change on human migration

the contribution of mathematical and conceptual models

Eidgenössische Technische Hochschule Zürich
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Environmental Physics

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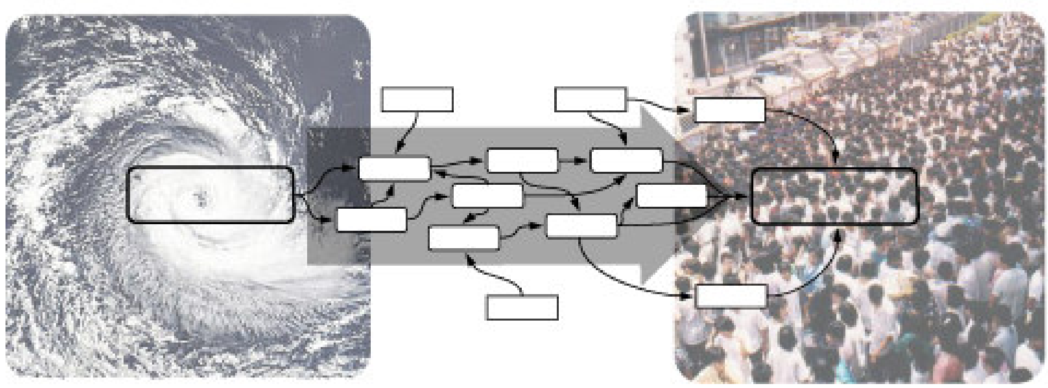

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Summary

In the last two decades, several researchers have predicted mass migrations as a consequence of climate change. They pictured millions of people fleeing from rising sea levels and drought, leading to serious consequences for both migrants and receiving societies. These images have fuelled recent research on climate change as a push factor for migration. This diploma thesis contributes to the understanding of this topic by (i) investigating the possibilities of connecting existing *mathematical* models of climate and migration; (ii) developing four *conceptual* models of the most important mechanisms linking climate change to migration; and (iii) assessing the contribution of both approaches.

In a first stage, the possibility of linking existing mathematical models of climate and migration was investigated. An overview of models showed that the types of models used in climate and migration research are very different. *Climate models* are mostly complex three-dimensional and dynamic mathematical models, based on physical and chemical laws. In contrast, *migration models*, if mathematical at all, are of empirical nature and independent of time and space. In addition, migration studies are characterized by the fact each theory and model focuses on one specific type of migration. Significantly, the type of interest for this diploma thesis, i.e. migration pushed climatic hazards, has not been integrated into migration models. Therefore, exisiting climate and migration models cannot be simply linked. First, climate-related migration has to be studied in order to determine whether it is *similar* to other types of migration from which models could be adopted, or whether *new migration models* have to be created. Given a suitable migration model, the task of connecting such different components of natural and social system lies in the domain of Integrated Assessment Modelling. In this context, one model was found that mathematically connected climate change and migration. However, due to limitations of the sub-models and an accumulation of uncertainties through integration, such integrated models *cannot fulfil the predictive function* often expected from mathematical models. Thus, the value added in comparison to conceptual models was assumed moderate.

Therefore, in a second stage, the emphasis was shifted to conceptual models as an alternative approach. An overview of previous research on this topic revealed that the most urgent need was to *explicitly* demonstrate the linkages between climate change and migration. As a result, conceptual models addressing these linkages were developed for four climatic hazards that are likely to be increased or intensified by climate change (sea level rise, floods, tropical cyclones and droughts). These models were termed "*connection models*" and proved successful in demonstrating the major (direct and indirect) impacts of the respective climatic hazard on the affected community. However, migration could not be explicitely linked to *specific* impacts but could only

be connected to the climatic hazard in a very general way. This is due to a *large knowledge gap* regarding the extent and specific causes of migration in this context. Owing to this knowledge gap, it is presently not possible to make an overall assessment of the potential effect of climate change on migration. With regard to *tropical cyclones and floods,* the results suggest that these hazards cause only little permanent migration and that accordingly, climate change is not likely to trigger mass migrations. *Drought*, in contrast, can lead to considerable migration in some cases and to none in others. What factors determine the extent of migration is presently not known. Concerning *sea level rise* there is no knowledge base of migration on which to base an assessment. In the light of the large amount of people *potentially* at risk of loosing their land and thus of migrating, high priority should be given to further research in this area. An important insight gained during the development of the connection models was the *significance of vulnerability* for the topic studied. While there are indications that climatic hazards *can* be a trigger for migration, it depends largely on the vulnerability of the community affected, whether such an indirect effect as migration in fact takes place. How vulnerable people are to climatic hazards is determined by a complex interaction of social, economic, and political processes.

The connection models proposed in this diploma thesis proved an appropriate tool to give an *overview* of the relevant processes and to offer a *framework to structure knowledge*, facilitating the identification of knowledge gaps, the search for solutions and the communication between researchers from different disciplines. For *future improvement*, the models have to be developed in an *interdisciplinary* team and should adequately *include vulnerability*. The central and indispensable contribution of *mathematical* models in the entire climate-migration chain is seen to lie in the *analysis* of the underlying subjects and connections, particularly *climate change*, its effects on the *climatic hazards*, and the *direct effects* of these hazards.

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My thanks go to Martin Wild for generously sharing his knowledge on climate models and reviewing the corresponding chapter. Thanks, also, to Professor Maarten Krol for permitting me to see excerpts of the as yet unpublished book "Global Environmental Change and Migration".

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Last but not by no means least I want to thank my parents for enabling my studies, for their constant encouragement and support and for all they have taught me along the way.

Abbreviations

AGCM	Atmosphere General Circulation Model
AOGCM	Atmosphere-Ocean General Circulation Model
GCM	General Circulation Model
EBM	Energy Balance Model
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
IAM	Integrated Assessment Model
OGCM	Ocean General Circulation Model
RC models	radiative-convective models
SD models	two-dimensional statistical dynamical models
SLR	sea level rise

1 Introduction

"The gravest effects of climate change may be those on human migration as millions are displaced by shoreline erosion, coastal flooding and severe drought."

(IPCC, 1990, p. 20)

In one of their first reports in 1990, the newly founded Intergovernmental Panel on Climate Change (IPCC)[1] predicted that *climate change would cause millions to migrate*. As rising sea levels flooded the coasts and droughts made subsistence impossible, people would have to flee. Insufficient services in refugee camps would result in epidemics affecting not only refugees but also the surrounding communities (IPCC, 1990).

1.1. Background

In the last two decades, images similar or even more tragic than the gloomy prognosis above were stirred up by *several researchers that predicted mass migrations* as a consequence of climate change. In some accounts, the images included – between the lines – the idea of a *flood of refugees* descending on more *developed nations*. Such portrayals fuelled a new discussion and led to further research on the connection between climate change and human migration.

The interest in this issue is understandable. For one, the initially very controversial discussion on the existence of climate change and the contribution of human activity has subsided in recent years. Scientist agree that the *climate is changing* and that *human activities*[2] *will contribute to an increase* of the globally averaged surface *temperature* by 1.4 to 5.8°C over the period 1990 to 2100 (IPCC, 2001a).

On the other side stands migration that in some contexts is considered a positive and necessary process in a society. As one of the founders of migration studies puts it: "Migration means life and progress; a sedentary population stagnation." (Ravenstein,

[1] The IPCC assesses and summarises peer reviewed and published scientific/technical literature on climate change and is recognized as the leading authoritative scientific voice on climate change. For instance, approx. 1000 lead authors, contributing authors and reviewers worked on the first 2001 report during more than 2 years (IPCC, 2001a).

[2] Especially the use of coal, oil and natural gas for industrial production, heating and transportation.

1889, p. 288). However, the migrations that climate change is predicted to trigger have been assumed to be of an extent and nature very detrimental to human systems.

These migrations are expected to be *forced,* meaning that individuals have no choice, are uprooted from their homes and experience much *suffering and strain*. Moreover, many less developed countries would not be able to cope with the increasing *pressure on the infrastructure* and services that a large number of migrants entails. Local natural resources would be over-exploited and epidemics could break out (El-Hinnawi, 1985). Another reason for the interest in human migration suggests itself: it is the developed countries' fear of torrents of migrants arriving unexpectedly at their borders. This fear originates from the political tension and the social problems often related to immigration (McFalls, 2003; Öberg, 1994). Yet another worry that has spurred research is that large amounts of displaced people could cause conflict and destabilize *international security* (Kavanagh & Lonergan, 1992; Myers, 1993).

These views – put forward largely by early contributions to the debate – are by no means shared by all researchers. While some tone down the predicted extent and impacts of migration (MacKellar, Lutz, McMichael, & Suhrke, 1998), others denounce the concept of such gloomy mass migration as a myth (R. Black, 2001). Remarkably, also the most recent IPCC report (IPCC, 2001b) no longer contains such strong statements as quoted above.

To summarize the reasons for interest in the topic of climate change and migration: the changing climate could trigger large scale migrations, which in turn could (i) cause untold suffering among the migrants; as well as (ii) exert great pressures on the receiving societies and environments; and (iii) finally even induce conflicts.

The *knowledge* of the complex relationship between climate change and migration is *still very limited* (Hugo, 1996). One reason for this is that intensified relevant data is hardly available (Hugo, 1996). In addition, climate change and migration are very different topics – their connection does not fit into the traditional scientific disciplines but requires interdisciplinary research. The IPCC (Scott et al., 2001) rates the filling of this knowledge gap as one of the *highest priority needs* regarding climate change impacts on human settlements.

1.2. Research Objectives

The knowledge gap presented above guides the *superordinate goal* of this diploma thesis: to make a contribution to *improving the understanding of the effects of climate change on human migration*. The idea behind this goal is that by improving the understanding, *a first step* can be made estimating how grave the effects might be; and ultimately knowing how to influence the processes studied.

There are *many possible approaches* to investigating climate change's influence on migration, especially in the light of the multitude of scientific disciplines concerned with both climate change and migration. In order to look into complex relationships, *scientists often use models* because they focus attention and simplify the underlying system. Thus, from the natural science perspective it suggests itself to *combine these* *two topics using mathematical models*. The initial research objectives of this diploma thesis were to:

- *give an overview of existing climate and migration models;*
- *determine the requirements for their mathematical linkage; and*
- *if possible link two selected models.*

In the course of research it was recognized that the connection of existing mathematical models was not wholly suitable to combine the natural with the social sciences and to deepen the understanding that climate change may have on human migration. Therefore, in a second stage, the focus of the diploma thesis was shifted to using *conceptual models* that are more frequently used in the *social sciences*. The newly defined set of research objectives is to:

- *give an overview of existing climate and migration models;*
- *determine the requirements for their mathematical linkage of existing;*
- *develop conceptual models* of the most important mechanisms in which climate change can be connected to migration; and
- discuss the *potential contribution* of both the *mathematical as well as the conceptual approach* to improving the understanding of climate change-influenced migration.

1.3. Research Methods

This diploma thesis is primarily based on literature research. In search for relevant sources, experts from the different scientific fields were contacted. The fields include geography, atmospheric sciences, global environmental change, refugee studies, migration studies, studies of internal displacement and natural hazards research.

1.4. Outline

In Chapter 2, an overview of existing climate and migration models, their common features and differences is given. The output data of climate models are juxtaposed to the required input data for migration models in Chapter 3 in order to determine the requirements for a connection. The approach commonly used to connect far apart processes, Integrated Assessment Modelling, is first presented in general terms and by means of an example and then assessed by discussing its advantages and limitations. From the mathematical approach the thesis goes on to an alternative conceptual approach. A review of research on this conceptual approach in Chapter 4 is followed by the presentation of the concept of connection models applied in this diploma thesis. Four main mechanisms by which climate change can potentially influence migration are identified: sea level rise, floods, tropical cyclones and droughts. Each is described and analysed by means of a connection model, with special emphasis on the link to migration. The results are first discussed separately for each connection model and also in general terms. Finally, in Chapter 6, an overall discussion and conclusions regarding the goals of this thesis are presented.

2 Climate and Migration Models: an Overview

The mathematical connection of climate and migration models requires an *overview and understanding* of both types of models. This includes knowing what types of models are predominantly used, what their inputs and outputs are, and what functions they fulfil. The two fields need not necessarily be very similar, especially as the field of climate is treated by *natural* scientists, whereas migration lies in the hands of *social* scientists. In view of the different approaches and "cultures" within these two camps, this chapter starts out with presenting the *functions and different types of models* in general. This lays the basis for a common language, preventing misunderstandings and enabling a comparison. Subsequently, climate and migration models are each presented in detail. The thoroughness of the analysis has the purpose to convey an *impression* of, or *even a sense* for these two very different fields and the way they think and work. This mutual understanding is considered a prerequisite to connect the topics successfully. After the overview of both model types, their common features and differences are discussed.

2.1. Models

> *"… models vary widely in concept, design and purpose. Nevertheless everybody seems to believe that his or her use of the term is the genuine one, supposedly understood by everyone else. […] In interdisciplinary cooperation, then, severe misunderstandings emerge and hinder the flow of ideas and knowledge between the different traditional branches of science."*
>
> *(von Storch, 2001, p. 32)*

2.1.1 Definition and Functions

That Minshull (1975) distinguishes 36 different uses of a "model" within geography illustrates just how multifarious the term is used. All scientific disciplines use "models" in some way or another, but what is exactly meant by the term varies widely. In an attempt to define models on a general level Imboden and Koch (2003) consider models "a *simplified description* of a real system". They emphasize that a model is not a copy of a system but rather compare it to a pair of glasses with which a system is looked at and studied. Stehr (2001, p. 3) similarly defines models as "*simplified representations* of what is thought to be an underlying more complex reality". These models are constituted of elements and relationships between these elements.

One of the *main functions* of models is to *reduce complexity*. This is achieved by choosing the constitutive elements which means leaving other possible features out. This choice of elements directs attention to certain aspects and away from others that are considered less important by the modeller. Thus, the model acts as a "*focusing device*" (Stehr, 2001). While models generally have common functions, their *purposes* are diverse: they include *description* of the underlying system, *understanding* the mechanisms and behaviour, *simulation* and last, but by all means not least the *prediction* of the future development (Rapoport, 1980; von Storch, 2001).

It is also the purpose of the model that determines the choice of elements. An example from the environmental sciences – the modelling of a forest – illustrates this point. A forest model could serve quite different purposes: to understand the forest as a natural habitat for young deer, for instance, or to predict the forest's capacity to absorb CO_2 from the atmosphere. The elements chosen in each of these cases are likely to be quite different.

2.1.2 Classification

Models can be classified by many traits, e.g. their function, the technique used to construct the model or the degree of knowledge that the model represents. The classification of models can deliver a *framework* within which it becomes possible to understand climate and migration models as well as discuss and compare them in a common language. On a general level, Seppelt (2003) distinguishes *three types of models: conceptual, physical and mathematical*:

- *Conceptual models* focus on the "concept" of the reality it represents. This means that the goal is not to describe the system in a quasi-realistic way but in contrast to focus on the essential characteristics and/or dynamics of the system. The *notion* or the *idea* is described which enables to *grasp an understanding*. Often this type of conceptual models are represented graphically (see Figure 2.1).
- *Physical models* are characterised by the fact that they are *physical objects*. Mostly, these models are *scaled* reproductions of a real system, as for instance model houses used in architecture or model bridges in civil engineering.
- *Mathematical models* are models that use mathematical functions to describe the system in question. This type of models was originally used in physics and chemistry to develop consistent theories but later expanded into many other disciplines also in the social sciences (Imboden & Koch, 2003). The broad application and diversity of mathematical models today requires further classification (see below).

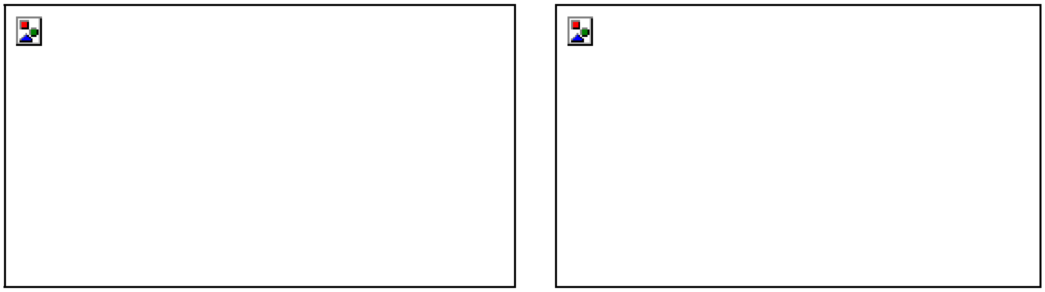


Figure 2.1: Examples of conceptual models in the field of migration and climate (E. S. Lee, 1966; Stocker et al., 2001).

These three types of models are *not isolated* constructs but can be used *complimentarily* in research. An example from early climate research may illustrate this point: Starr (1956) and his group compared the classical theory of the general circulation of the atmosphere with newly available empirical data. On discovering that the data did not fit to the classical theory, they formed a hypothesis founded on the empirical data. They tested this new hypothesis with a mathematical model as well as a simple physical model. In the physical model the circulation of air in the atmosphere was represented by the movement of heated water in a rotating vessel. The argument in favour of their new hypothesis was strong, as *both* the mathematical and the physical model confirmed their findings. Seppelt (2003) also reports that in the development of environmental models, the *starting point* is often a *conceptual model* which can *then* be described in a *mathematical way* and then be formulated in numerical codes for a computer program.

Mathematical models have reached a wide range of applications and can be further classified as shown in Table 2.1. It has to be added that mathematical models cannot always be assigned unambiguously to one model type. For instance, most climate models incorporate mechanistic as well as empirical elements – thus they are considered neither white box nor black box models but rather "grey box models".

Table 2.1: Classification of mathematical models. (Environmental Protection Agency, 2004; Seppelt, 2003)

model trait	model types	commentary and description
foundation of model	*mechanistic vs.*	Mechanistic (also theoretical or white box) models are based on fundamental scientific and engineering knowledge about the phenomena of the system (for instance physical, chemical or biological). This means that they are suited for extrapolating from outside of the domain that the initial data was collected.
	empirical	Empirical (also black box) models are based on relationships between variables derived by looking at the experimental observations. From this it follows that these models often lack generality and are not so suited for extrapolating.
time dependency	*static vs.*	Static (also "steady state") models assume that the system observed does not vary with time.
	dynamic	Dynamic models include the time as a dimension and thus describe the behaviour of the system over time.

spatial scale	*lumped vs.*	Lumped models show no spatial dependence.
	distributed	Distributed models include space as a dimension and describe the system in one, two or three dimensions.
inclusion of variability	*deterministic vs.*	In deterministic models the outcome is directly determined by the inputs and there is a fixed number of definite answers.
	probabilistic	Probabilistic (also stochastic) models include variability. This means that the output is not only determined by the model components but also to a certain extent by random variability.

M. Black (1962) emphasises that the mere fact of mathematical treatment cannot *explain* the underlying observations. For instance, an observed growth of a bacteria population can be fitted to a mathematical function. This description however, does not provide an explanation *why* the population grows in this manner – this step requires further interpretation. In this way, mathematical models "do not provide immediate knowledge, the *knowledge is hidden in the numbers*" (von Storch, 2001, p. 31).

It has become apparent that there are many different types of models that can serve diverse purposes. Climate scientists and migration researchers also have dissimilar notions of what a model is. In the following, climate models are presented in the language and structure used by the climate research community. Readers familiar with climate respective migrations models may skip to page 22 for a discussion and comparison of both model types.

2.2. Climate Models

Climate is often defined as "*average weather*", meaning the mean and variability of relevant quantities such as temperature, precipitation, and wind over a certain timespan ranging from months to thousands or millions of years (the classical period is 30 years). However, in the field of climate modellers, the term climate is commonly understood in a wider sense: Climate is the *state*, including a statistical description, *of the climate system* (IPCC, 2001a).

The Climate System

The climate system is divided into five major *components*, namely the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere. Within as well as between these components, countless processes take place on very different spatial and time scales. This makes the climate system very complex. Further complication is added by so-called *feedback mechanisms*. An example is the water vapour feedback: As the atmosphere warms due to climate change, it can absorb more water and the concentration of the water vapour may increase. This mechanism in turn leads to an intensification of the warming, as water vapour is a strong greenhouse gas (IPCC, 2001a).

By a "climate model" the relevant fields of research most commonly understand a mathematical representation of the Earth's climate system. This means that climate models are always *mathematical* models according to the general classification delineated in Chapter 2.1.2. Climate models simulate the physical, geophysical, chemical and biological processes that go on *within* the climate *components* as well as *between* them. The main functions of these models are to gain *insight* into climate processes and variability and to *project* the response of the climate to human impact (IPCC, 2001a).

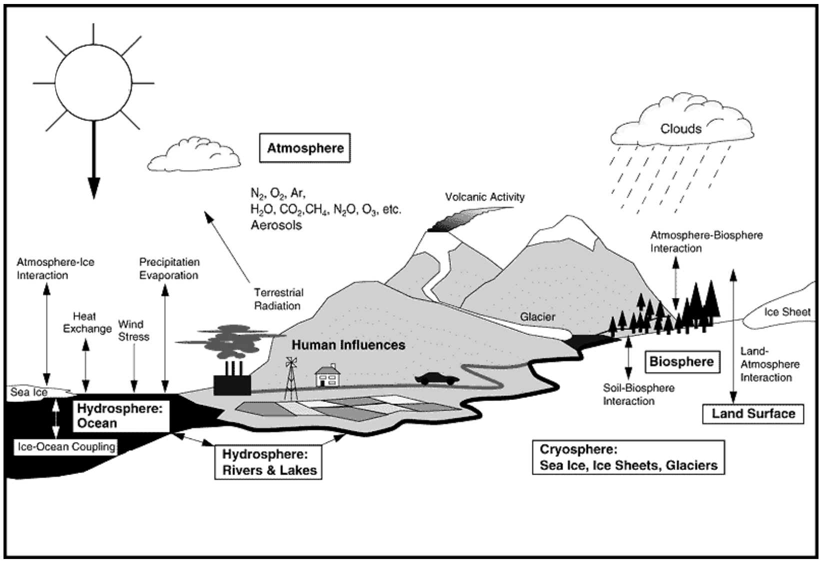


Figure 2.2: Schematic view of the climate system and its components (adapted from Baede, Ahlonsou, Ding, & Schimel, 2001).

2.2.1 The Origin of Climate Models

The origin of climate models lies in the interest in *forecasting the weather*. For many decades the weather was forecasted with qualitative methods. In the year *1920* the English scientist Richardson was the first to develop a technique for *computing* the weather. To carry out the enormous number of necessary calculations he outlined a *vision* of a myriad of workers in a great hall each working only on equations of one geographical position. When he tested his technique to compute the weather in two geographical positions, it took him *six weeks* to calculate the advance of the weather in *six hours*. The results were *horribly in error* (Nebeker, 1995). Significant progress towards the first numerical weather predictions was not made until 25 years later. Mathematician von Neumann wanted to demonstrate the revolutionary potential of the recently developed electronic *computer* by applying it to meteorology. His choice of meteorology as an application example was based on the importance of weather forecasts for the military. He believed that if weather could be simulated it could maybe be controlled and thus used for military purposes (Cox, 2002; Nebeker, 1995). Four years after initiation of the project in *1946*, the first realistic 24-hour forecasts were calculated (Nebeker, 1995). Starting from such regional meteorological models, the first models simulating the *global circulation* of the atmosphere (see Figure 2.3) were developed in the *1960s* (McGuffie & Henderson-Sellers, 1997). The progress in climate modelling was probably spurred by the growing interest in possible human induced climate change and the revival of the old hypothesis stating that the climate is strongly affected by the concentration of CO_2 (Pales & Keeling, 1965).

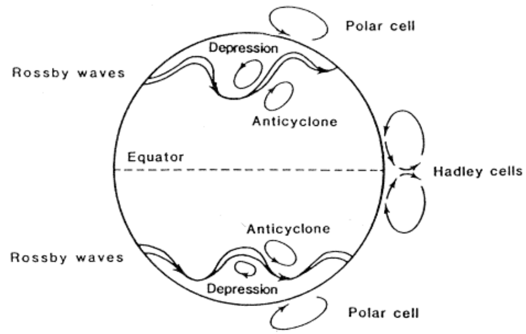


Figure 2.3: Important elements of the general circulation of the atmosphere (McGuffie & Henderson-Sellers, 1997).

In the present day, climate models are divided into four categories (McAvaney et al., 2001). A short overview of this classification is given below before each model type is examined in more detail. It has to be added that the boundaries between these model types are not very clearly cut and the transitions from one to the next category are often quite smooth.

- *General circulation models* are comprehensive global three-dimensional models that are run on supercomputers. They represent as much as possible of the entire climate system in order to project the climate response to a range of human influences such as greenhouse gas emissions or land use changes.
- "*Simple models*", by contrast, are less comprehensive and focus on specific aspects of interest to the researcher. They can be used to understand and gain insight into specific processes or to study a large number of alternatives.
- *Intermediate Complexity Models* bridge the gap between both model types mentioned above: They describe most processes of global circulation models, though in a more reduced form.
- *Regional climate models* are restricted to one geographic area of interest. Within this area they are very comprehensive models with a higher resolution than GCMs.

(At this point, hurried readers might want to skip to the migration models on page 16.)

2.2.2 General Circulation Models (GCMs)

On the part of scientists, but also on the part of policy makers and the public, there is a strong interest in understanding and quantifying *human influence on the climate*. One of the main questions is how the climate system will respond to further emissions of greenhouse gases (GHG). In order to project this response, the complex climate system has to be modelled very *comprehensively*. For this purpose, models of each component of the climate system have been developed, improved and coupled together (see Figure 2.4).

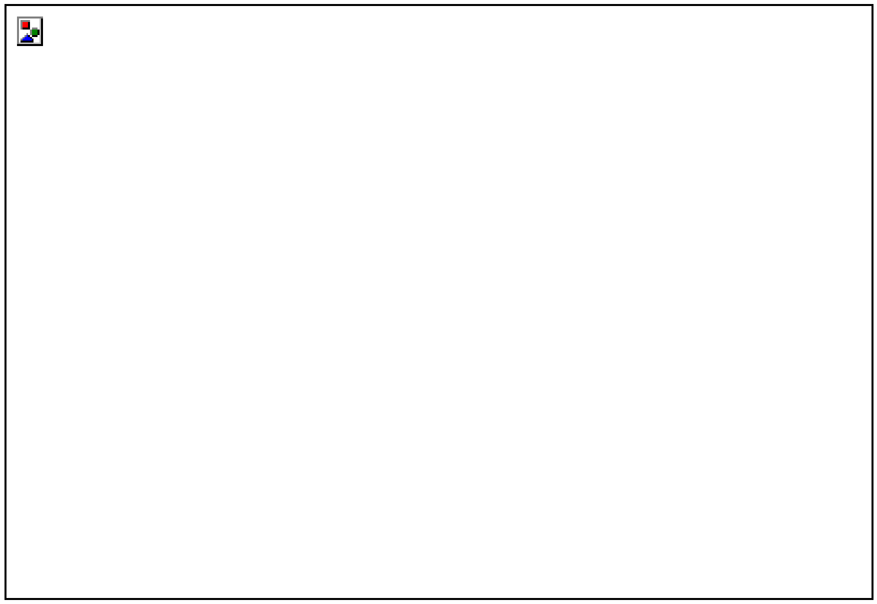


Figure 2.4: The development of general circulation models: models of each component of the climate system were developed and coupled together (IPCC, 2001a).

The component to be modelled earliest on a global level was the atmosphere. *Atmospheric General Circulation Models* (AGCMs) are complex three-dimensional models of the physics and dynamics of the atmosphere. They are very similar to the models used for weather forecasting. A three-dimensional grid is placed over the Earth surface (see Figure 2.5). Within each one of the resulting "boxes", the state of the climate is described.

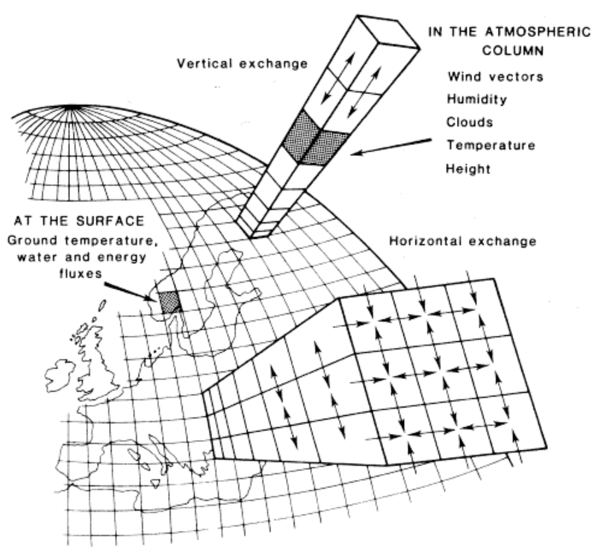


Figure 2.5: Three-dimensional grid placed over the Earth surface to model the atmosphere (McGuffie & Henderson-Sellers, 1997).

At the lowest atmospheric layer, the atmosphere borders on the *oceans*. This system boundary needs to be fed with data about of the ocean surface temperature. In the early stages of AGCMs the temperature of the ocean was assumed to be *permanent*, based on observed averages on a seasonal or monthly basis. Later on, in the 1980s, it was common to add a "*slab ocean*" to the AGCM. This means that the ocean is treated as if it were a well mixed body of constant depth (usually 70 to 100 metres) in order to simulate certain interactions. This approach is most appropriate for short time-scales (under 30 years), where the slow-moving deep sea currents show little effect (McGuffie & Henderson-Sellers, 1997).

In the 1990s, AGCMs were coupled to the so-called *Ocean General Circulation Models* (OGCMs). These models describe the physics and dynamics of the oceans and the sea ice and had been developed independently. The temporal and spatial resolution of current GCMs (see Table 2.2) is primarily limited by the time it takes for the calculations, i.e. by computational restrictions.

Table 2.2: Temporal and spatial resolution of General Circulation Models (Baede et al., 2001; personal communication Wild, 2004).

aspect	resolution
atmosphere	
time steps	approx. 30 min
horizontal resolution	approx. 250 km
number of vertical levels	10 to 30
ocean	
time steps	approx. 1 day
horizontal resolution	125 km to 250 km
vertical resolution	200m to 400m

In both the circulation models processes take place that are on a smaller scale than model "boxes" (termed "sub-gridscale"), as for instance the formation of clouds or ocean convection. This means that the process cannot be modelled explicitly, however important it may be. In such cases climate modellers turn to a technique called "*parameterisation*". This technique allows to include the *average* effects of the sub-gridscale process (IPCC, 2001a). Clouds can serve as an example: as the dynamics of cloud formation cannot be modelled with current horizontal resolutions of 250km, a parameterisation scheme calculates the amount of cloud and rain in a box from known parameters such as temperature, humidity and aerosol concentration.

The result of the coupling of both model types are *Atmosphere-Ocean General Circulation Models* (AOGCMs) that describe not only both components but also the interactions between them. The integration of these interactions is very difficult due to their different time scales. AOGCMs are now being expanded with models of land surface processes, the sulphur and the carbon cycle to yield a more and more detailed representation of the climate system. This results in highly complex models that consume vast computational resources. There are only approximately twenty centres worldwide that have developed fully coupled AOGCMs (McAvaney et al., 2001).

With their comprehensive approach, coupled models have achieved to "provide *credible simulations of climate*, at least down to *sub-continental* scales and over temporal scales from seasonal to decadal." Thus, they are "considered to be suitable tools to provide useful projections of future climates" (IPCC, 2001a, p. 54). However, GCMs also have *disadvantages*: their complexity and high demand for computational resources make it impossible or impractical to study many different alternatives or to investigate the sensitivity of the system to small changes. Such functions can be provided by simpler models.

2.2.3 Simple Models

The only characteristic that simple models have in common is – as the term suggests – that they are simpler than GCMs. However, there are large differences in which way they are "simpler": Some have a very low resolution, while others focus exclusively on one climate system component or process. Others again operate with less spatial dimensions. As stated above, simple models meet complementary demands to GCMs. One of their great advantages is their *computational efficiency* that allows many runs in short time. The functions of simple models include (Baede et al., 2001; McAvaney et al., 2001):

- to study and gain insight into a *specific process* of the climate system;
- to investigate the *sensitivity* of the climate to a particular process over a wide range of parameters;
- to run the system over many decades as necessary for *simulating past climates* as for instance the last glacial maximum; or
- to be used within larger Integrated Assessment Models to analyse the costs of emission reduction and impacts of climate change.

McGuffie and Henderson-Sellers (1997) describe three types of models that can be considered simple:

Energy Balance Models

Energy balance models (EBMs) *predict the surface temperature* of the Earth by studying its energy balance. The most simple EBMs are zero-dimensional: the Earth is considered a single point in space with a mean temperature that is governed by the long term *balance between radiation input and radiation output*. More frequent are *one-dimensional* models in which the predicted surface temperature varies with *latitude*. These models simulate the meridional heat transport by integrating diffusion of heat from one latitude zone to the next with simplified relationships. EBMs are used as simple instructional tools and for investigating the sensitivity of the climate system to external changes.

Radiative-Convective Models

Radiative-convective (RC) climate models also *predict* the variation of *temperature* with one dimension, but in contrast to the EBMs the dimension in question is *altitude*. Convection is not explicitly simulated and is thus parameterised. RC models are used to study the effects of changing atmospheric composition on surface temperature and to investigate the different external and internal forcings.

Two-dimensional Statistical Dynamical Models

Two-dimensional statistical dynamical (SD) models most commonly combine the two dimensions of EBMs and RC models: *altitude and latitude*. In these models, dynamics are explicitly dealt with and the general circulation is represented by cellular flow between latitudes. Zonally averaged energy transport between latitudes is modelled in a both "statistical and dynamical" way. This means that empirical observations – *statistics* – summarize the wind speed and directions, whereas on the *dynamical* side theoretical formulations such as the eddy diffusion coefficient govern energy transport. Specialized two-dimensional SD models include many chemical species and reactions and have been used to make simulations of the chemistry of the stratosphere and mesosphere.

Each one of theses types of models can be more and more refined. For instance some RC models include cloud prediction schemes and SD models integrate reaction chemistry. Moreover, there are many more models that are considered simple models, as shown by work by the IPCC (1997), where simple models have been widely used to project sea level rise for a number of emission scenarios. The sea level rise is calculated in four steps: GHG emissions ➔ GHG concentrations ➔ mean radiative forcing ➔ mean global temperature ➔ sea level rise. For instance in the first step a *carbon cycle model* (simple model) determines the GHG concentrations on the basis of scenarios for GHG emissions. For each step, only the relevant and necessary calculations are made – information on spatial dimensions, precipitation, changes in variability and climate extremes, etc. is omitted.

2.2.4 Intermediate Complexity Models

Intermediate Complexity Models are models positioned between the comprehensive GCMs and simple models. Their principle trait is that they "include most of the processes described in comprehensive models, albeit in a more reduced, i.e., *more parameterised* form"(Claussen et al., 2002, p. 580). This means that on the one hand they simulate the interactions among several components of the climate system while on the other hand they are more computationally efficient than comprehensive models. This last characteristic, similarly to the simple models, allows for long-term climate simulations or a broad range of sensitivity experiments. McAvaney et al. (2001) see their main range of application as tools to explore and understand significant processes of the climate system together with their *interactions* and *feedbacks*.

2.2.5 Regionalisation

The average horizontal resolution of AOGCMs is approximately 250km and accordingly too coarse to deliver results appropriate to predict local and regional climate change. Nonetheless, interest in specific regional projections is great. The IPCC (2001a) gives an overview of different techniques used for achieving better results on a regional level:

- AOGCMs with an *overall* higher resolution;
- AOGCMs with average resolution worldwide and a higher resolution with regard to the region of interest (called "zooming grid");

- regional climate models that only model the region of interest, but this area in a high resolution (typically 50km). At their system boundaries they require input data for which they use results from AOGCMs; and
- empirical/statistical and statistical/dynamical downscaling methods (see chapter 10.6 in IPCC (2001a) for an introduction).

Recent progress in this field has produced interesting outcomes. Results from models operating with high resolution traditionally differed substantially in magnitude or sign in their results (IPCC, 2001a). There is, however, recent evidence that high resolution models improve in their consistency with respect to regional scale projections (personal communication, Wild, 2004).

2.2.6 Predictability

The predictability of the climate depends on two factors: the predictability of the *climate system itself* (including its reaction to a given external forcing) and the predictability of the *external forcing*, as for instance solar radiation or the human-induced emission of greenhouse gases.

Being a complex, non-linear system, the climate may display what is called *chaotic behaviour*. This means that the deterministic behaviour of the system is critically dependent on very small changes of the initial conditions. Thus, predictions are not only degraded by the limited ability to represent the significant climate processes accurately, but also by inevitable errors and uncertainties in the initial conditions, particularly in the ocean (Baede et al., 2001). To deal with these uncertainties and to increase the accuracy of forecasts, climate modellers repeat their prediction many different times – using different initial conditions as well as different global models. Such collections of runs are called "*ensembles*" and are the basis of probabilistic forecasts (IPCC, 2001a).

The authors of the IPCC formulate their opinion on the predictability of the climate system very cautiously: "There is *evidence to suggest* that climate variations on a global scale resulting from variations in external forcing are *partly predictable*. […] *global* or continental scale climate change and variability *may be more predictable than regional* or local scale change, because the climate on very large spatial scales is less influenced by internal dynamics, whereas regional and local climate is much more variable under the influence of the internal chaotic dynamics of the system." (Baede et al., 2001, p. 95-96, my italics).

Thus it seems that the climate system is "partly" predictable, *given* the variation in external forcing. However, the external forcing produced by humans is also difficult to predict, as it depends on population change, technological as well as societal development, and many other factors. Therefore, instead of predicting one most likely future, IPCC researchers construct different *possible scenarios of human behaviour* and determine *climate projections* on their basis (Baede et al., 2001).

2.3. Migration Models

> *"Social scientists do not approach the study of immigration from a shared paradigm, but from a variety of competing theoretical viewpoints fragmented across disciplines, regions and ideologies."*
>
> *(Massey et al., 1994, p. 700)*

This is the starting point for an overview of migration models. What researchers in the field of migration understand under the term "migration model" is not as clearly defined as in the field of climate for the reason cited above. Moreover, "*theories*" are the preferred unit of research rather than "models". The meaning of these two terms in science is somewhat inconsistent. Following the very broad definition of model as a *simplified description* of a real system (see Chapter 2.1.1), both terms model and theory will be used interchangeably in this thesis. To get an overview of the wide variety of migration models, theoretical viewpoints as well as applied modelling will be looked at.

.

2.3.1 Introduction

In general terms, migration is defined as "the geographic *movement* of people *across a* specified *boundary* for the purpose of establishing a new permanent or semipermanent residence" (Haupt & Kane, 1998, p. 35). This broad definition allows for many different forms of migration. Some examples are

- large-scale migration from the countryside to the urban centres;
- refugees from trouble spots seeking asylum in industrialised countries;
- young families moving to another city following new job opportunities; or
- so-called "brain drain": highly educated and skilled people from developing countries leaving their home for better opportunities.

On a systematic level, a distinction is made between *international* migration which refers to moves between countries and *internal* migration which stands for movement between areas within a country. These two types of migration differ in various aspects. Internal migration is far more frequent and is often related to housing adjustments or life-cycle changes. In contrast, international moves are not very common and are primarily for economic reasons (McFalls Jr., 2003). Whereas in most countries residents are free to chose where to migrate to *within* the national boundaries, international migration flows are strongly influenced by immigration regulations in the destination countries.

All types of migration are influenced simultaneously by countless factors of diverse nature (see Table 2.3). This diversity of influences may contribute to the fact that the phenomenon of migration is studied from so *many different perspectives* (following Öberg, 1994): *Economists* have found economic reasons both on the micro and the macro level, while sociologists try to explain some migration flows with the distribution of power and prestige. *Geographers* are interested in phenomena like urbanization and approach the migration topic from this perspective. *Demographers* study many of these aspects but focus primarily on the number of migrants, their age and sex distribution. Finally, *political scientists* and *jurists* analyse immigration regulations and policies and their consequences. After finding many convincing reasons and incentives for people to migrate, some researchers turn to the question why then most people choose not to migrate (Faist, 2000).

Table 2.3: Factors influencing historic and contemporary international migration (compiled from Öberg, 1994).

Factor	Examples
economic	wage differences, different access to economic wealth and material standard of living
social	proximity to relatives and friends
cultural	lifestyles, ethnicity, social organizations, religion, values
geopolitical	tension, conflict, political instability, threats to life
environmental	carrying capacity of land for inhabitants with limited resources

2.3.2 Common Migration Framework

The way in which each discipline has separately approached migration might contribute to the fact that to date a consistent, common theoretical base has not been developed. This might seem surprising in the light of the fact that migration studies have a long history. As early as 1885, Ravenstein searched for underlying principles of migratory processes and concluded his analysis of migration in England with seven "laws"[3]. Approximately 80 years later, Lee (1966) posited that since the starting point set by Ravenstein, despite the fact that many studies had been carried out in the field, the number of *generalizations* had hardly grown. Another 30 years later, Massey et al. (1993) still lament the same problem, namely that the theoretical base for understanding the forces that drive migration remains weak.

Nevertheless, theoretical work of course has been done, as presented in the next Chapter 2.3.3. These theories and models differ largely in their level of analysis, their focus and their assumptions. The small core that *most of them can agree upon* is described by the *migration situation* framework, and conceptualising migration as a *push-pull process*.

Lee (1966) laid a foundation to migration theory by providing a simple framework in which to study migration (see Figure 2.6). Migration is based on many individual decisions. Common to each and every migration situation is a *place of origin* and a *place of destination*, both with attracting, repelling and neutral factors (designated with +, - and 0). The sign of these factors is *individual for each person*: for instance a neighbourhood with many children can be an attracting factor for one person, but repelling to another. In-between the two places there are *intervening obstacles* that can be of physical nature or also political (immigration laws).

[3] As an illustration, the 6th law on migration is his finding "that each main current produced a counter current of feebler strength." (Ravenstein, 1885, p. 287)

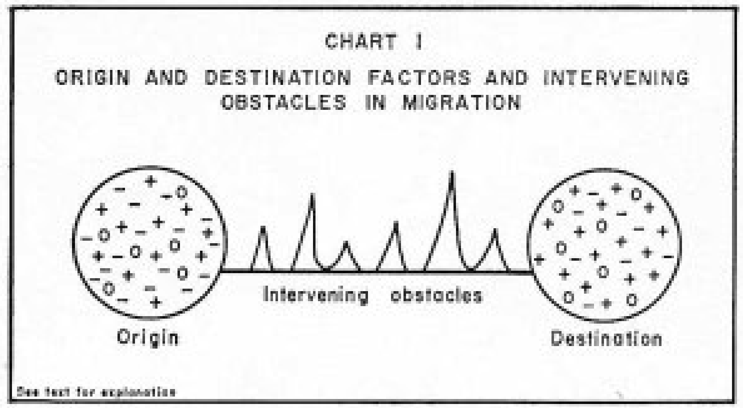


Figure 2.6: Conceptualisation of the migration situation as a common framework to study migratory processes. Source: (E. S. Lee, 1966, p. 50)

This framework also illustrates migration as a *push-pull process*: Migrants are "pushed" by the repelling factors of their homeland and "pulled" by (what appear to be) attracting factors of a new place. However, this approach is not without its difficulties, as the distinction between push and pull factors is sometimes difficult from a scientific standpoint. For instance, wage differentials can be considered in both ways: low wages as a push factor, high wages as a pull factor.

2.3.3 Theoretical Viewpoints on Migration

Many different migration models have developed over the last decades. The information presented in the following has been gathered from various overviews on migration theories (Faist, 2000; Goetz, 1999; Massey et al., 1993), structured and complemented with data from more specific publications.

Gravity Model

In early migration models, migration was viewed in a very mechanistic manner: The *gravity model* postulates migration to be proportional to the population masses in the areas of origin and destination, and inverse to the distance between these two areas. This approach is easily questioned by the fact that empirical data does not corroborate the thus postulated large migration flows between India, China and Russia. However, it is considered a useful starting point as empirical rule of thumb and is still frequently used as basis for building more complex models (Faist, 2000).

In- and Out-Migration Models

In-migration models are only concerned with the in-flow of migrants into a certain region irrespective of their place of origin. The opposite is the case for out-migration models that only study migrants leaving a certain area. These models try to relate *properties of the place of origin* (as for instance income, unemployment rate changes, population size, average temperature in January, in-migration rates, education attainment) to out-migration rates (Goetz, 1999).

Neoclassical Economics

Already in the 19th century Ravenstein claimed that of the many factors causing migration such as oppressive laws, heavy taxation, an unattractive climate, etc. none is as strong as "the desire inherent in most men to "better" themselves in material respects" (Ravenstein, 1889, p. 286). The *micro theory* of neoclassical economics sees migration as a phenomenon composed of many *individual decisions of rational actors*. Each actor makes a *cost-benefit calculation* and migrates in the case that he expects a positive net return (Massey et al., 1993). Critics point out that according to this theory the world should experience prodigious flows of migrants from low-wage to high-wage countries, particularly from the very poor to the most rich. Empirical evidence, however, does not corroborate this prediction.

A further developed branch of such micro theory includes more factors than only monetary ones. The goal of rational individuals or families is no longer to maximize income, but rather to *maximize utility*. The concept of utility can include such aspects as employment, land and housing markets, state and local taxes, availability of public goods, topological, climatological, and environmental amenities (Greenwood, 1985).

According to the *macro theory*, migration is a result of a *disequilibrium* in the demand for labour. In a region with a high demand for labour, wages will be high, whereas in a region for less demand for labour, wages will be low. This disequilibrium results in migration of workers from the low-wage region to the high-wage region. The supply of workers in the high-wage region thus increases, wages fall and over time this leads to a narrowing of the differential and finally to equilibrated wages (Massey et al., 1993). Often-cited exponents of this theory are Harris and Todaro (1970, cited in Massey et al. (1993)) who applied it empirically to developing countries.

Contrary to this theory, people were found to be migrating to areas with low income or high-unemployment (Knapp & Graves, 1989). In the thus triggered search for an explanation, focus was placed on location-specific amenities. People are willing to earn less in return for a lake view, a warmer climate or close vicinity to good schools. For instance, when a individual's income increases, a new demand for non-traded goods arises that can only be satisfied by relocation. This implies that wages are not in disequilibrium but in *equilibrium* – high wages are to be found close to location-specific amenities (Greenwood, 1985).

New Economics of Migration

This theory framework was developed in the context of *developing* countries. From the perspective of the new economics of migration, it is not the *individual* who decides on migration to maximize his or her utility. In this theory it is a family or a household that decides and maximizes the *collective* utility. Besides income, the *control of economic risks* is seen as a main factor of utility. Migration is perceived as a strategy for a household to *diversify their sources of income*. A family will allocate its resource "family labour" in a way to control risks and send one family member to earn money to urban centres or abroad. If another family member becomes redundant or the season's harvest is very low, this migrant's remittances can fill the gap. This phenomenon is not so relevant in developed countries, where insurance systems such as the crop insurance market or unemployment insurance have been created for the purpose of risk minimization (Massey et al., 1993).

Dual Labour Market Theory

According to the dual labour market theory, migrants are not *pushed* across international borders by the conditions in their home countries but are *pulled* by a constant demand for foreign labour in developed countries. This demand is *intrinsic* to advanced industrial nations: Employers have difficulties in finding workers for unskilled as well as seasonal jobs, because these are associated with low social status. To solve this problem by raising the wages of these jobs is a very expensive measure because it requires to raise the wages on all higher levels of the occupational hierarchy as well. In the past, such jobs were often occupied by women and teenagers, but in the last decades, these two sources have decreased. The resulting *gap for unskilled workers* is then filled with immigrants. For these, the wages are still high in comparison to their home countries and the income is seen as means to the end – while the status aspect recedes into the background (Massey et al., 1993).

World Systems Theory

The sociological theorists behind the World Systems Theory claim that "the penetration of capitalist economic relations into peripheral, noncapitalist societies creates a mobile population that is prone to migrate abroad" (Massey et al., 1993, p. 444) In the process of capitalist development changes occur in the local societal structures, livelihood systems and community values that in their combination lead to international migration. In the following, some mechanisms that drive such changes are described for illustration:

- Capitalist farmers mechanize their production, thus destroying traditional land-use systems, decreasing the need for manual labour and rendering people redundant and mobile.
- Following the investment and setting up of businesses, transportation and communication links are automatically set up and expanded. Such links serve as bridges and also promote the movement of people.
- Hand in hand with economical penetration goes the creation of cultural links between the capitalist and the developing country. Some examples for such linked countries like Senegal-France and India-England have a colonial past, others such as Mexico-USA are more recent. These are reinforced by mass media and advertisement and channel international migration.

Perpetuation or "Migration leads to migration"

Many of the above theories deal with reasons and motives of people to move from one area to another. All these theories do not take into account the *dynamics* that migration develops once the first migrants to move serve as bridges between their countries of origin and destination. This important phenomenon has many names – "chain migration" (McFalls Jr., 2003), "beaten path effect" (Goetz, 1999) and "friends and relatives effect" (Hatton & Williamson, 2002) amongst others. The basis for this phenomenon are so-called migrant networks that are defined as "sets of interpersonal ties that connect migrants, former migrants, and non-migrants in origin and destination areas through ties of kinship, friendship and shared community origin."(Massey et al., 1993, p. 448) These networks serve as "migration systems" or channels for further migration. Prospective migrants gain direct access to a wide variety of *information* on the place of destination (transportation, jobs, housing, immigration rules etc.). Additionally, they can reckon with *support* if they choose to migrate to the same destination: initial accommodation, assistance in finding a job and access to a social network is often provided by friends and relatives who have migrated ahead. Thus, by reducing the movement costs such networks *increase the likelihood of migration between two specific places*. A natural scientist would speak of a positive feedback loop.

In addition to the "beaten path effect" there are other *positive* socio-economic *feedback loops* within migration. In migration literature this phenomenon is titled "*cumulative causation*". An example is the effect on the distribution of income: In the sending countries, families that receive remittances from migrants abroad experience an increase their income. Thus, the relative income level of other households in the community decreases and creates an incentive for others to also send family members to work in near cities or abroad. Another effect can be observed when skilled people move to commercial centres, increasing human capital which leads to economic growth while in the sending countries the gap created aggravates the economic situation. Further migration of labour is thus encouraged (Massey et al., 1993).

2.3.4 Application

The body of theories and models summarized above is very diverse: while the gravity model is already a mathematical equation, other theories such as the world systems theory are a verbal description of globally connected processes far off from any mathematical formulation. Much of this theory has not (yet) found its way to practitioners. In practice, migration is mostly sought to be predicted quantitatively in the context of population projections. Principally, there are two types of migration forecasts: national and international migration projections and more detailed forecasts dealing with a specific topic of interest.

National and International Migration Projections

Mostly, international migration projections are *not based on mathematical models*. The US National Research Council (2000) assessed past world migration projections and found that "agencies estimate current and sometimes previous levels of recent migration, and project levels into the future as *constant* for arbitrary periods, as declining toward zero, or as *zero* from the start." The same general approach is to be found on the national level: of 31 developed countries surveyed by Keilman (1991), eight *omitted* external migration *completely* and projected a *value of zero*.

Migration Forecasts for Specific Purposes

For specific interests, studies are commissioned with more sophisticated forecasting techniques and are sometimes carried out in cooperation with researchers. In the following three cases are presented to give an impression of the types of models actually used in practice.

- Champion, Fotheringham and Rees (2002) developed a model to predict migration within 100 regions of England with the aim of "investigating the impacts of alternative economic and policy scenarios on population flows". A *weighted least square regression* was carried out between past migration rates and a large set of potential variables. Those with the most explanatory power as well as policy relevance were chosen for the prediction model.
- Brücker, Alvarez-Plata and Siliverstovs (2003) reviewed methodologies that had been used for estimating the flow of migrants associated with the Eastern Enlargement of the European Union. These were representative *public opinion polls*, *extrapolation of similar past migration* situation and *econometric models using regression techniques*.
- Pedersen, Pytlikova and Smith (2004) analysed determinants of the migration flows into 27 OECD countries in the period from 1990 to 2000. They assumed individuals with utility-maximizing behaviour and determined the explanatory power of many variables on gross migration flows with *"ordinary least square" regression*. Examples of explanatory variables are: linguistic distance, gross domestic product, stock of immigrants from source country, distance in km, trade volume, unemployment rates, an index for degree of freedom, political rights etc.

2.3.5 Predictability

The quality of world migration projections has been assessed by comparing past projections on a national level to actual migration rates. The results of the evaluation reveal a poor quality: in *40 per cent* of the cases *even the direction* of net migration was not correct and in the remaining cases the predicted figure was often too high or too low. Moreover, migration streams as for instance to oil-rich countries and away from regions of conflict were not anticipated (National Research Council, 2000).

In the light of these facts the question arises where these errors come from. There are two factors in particular that render the predictability of migration very low: A large part of the error is due to the *inability to forecast crisis migration*, i.e. migration resulting from conflicts, natural disasters and other large-scale transformations (National Research Council, 2000). The second factor (important on the international level) is the fact that migration to a large part depends on *national migration policies* which in turn are almost impossible to foresee. These findings suggest that "the procedures currently used to project migration, while they produce substantial errors, *may be hard to improve on*." (National Research Council, 2000)

2.4. Model Types: Climate versus Migration Models

In this subchapter climate and migration models are discussed separately in general terms and with a focus on how they include each other into their theory. Subsequently, common features and fundamental differences are investigated and the mathematical models are compared on the basis of the traits set out in Chapter 2.1.2.

2.4.1 Climate Models

Unlike in the field of migration, climate modellers do not approach the climate from a variety of competing theoretical viewpoints, but, in general, have a *common approach*. There exist very comprehensive mathematical models that represent as much as possible of the *entire climate system*. A range of further mathematical models is used for specific purposes (such as understanding and exploring a particular process, testing model sensitivity or simulating the climate over long time periods). Very direct consequences of climate change, such as sea level rise, are simulated in separate additional models. Furthermore, GCM *outputs are used* in a number of impact models (for instance vegetation, crop production and water availability). Socio-economic impacts, amongst these also migration, have hardly been modelled.

2.4.2 Migration Models

As stated in Chapter 2.1.1, models act as focussing devices, drawing attention to certain aspects and away from others. The long list of different approaches to migration theory seems to exemplify this point. *Each theory focuses on specific elements and processes within migration*. While neoclassical economics concentrate only on *economic* elements, world system theory is more concerned about *sociological* aspects. While equilibrium models focussing on local amenities are mostly applicable to *internal* migration in developed countries, dual market theory specifically addresses *international* migration from developing to more developed countries. This focussing necessarily implicates that some aspects are always omitted. The specific perspective of the different models makes each of them suitable for different specific migration situations. However, *none integrates* or is able to explain *all types* of migration and some migration situations are not covered at all. Sudden migration flows resulting from *conflicts, natural disasters* and other large-scale transformation are not well integrated into migration theory in spite of the severe impact this "crisis migration" can have. The explanation given is that this type of migration is obviously the most difficult, if not (in some cases) impossible, to predict (National Research Council, 2000). However, research could focus on understanding migration behaviour, once the trigger event has occurred.

With regard to climate change, this is of particular interest. *Natural hazards*, which are one way in which climate change could influence migration, are *not integrated into migration theory* and are considered very *difficult to impossible to predict*. Also the potential factor "loss of land" caused sea level rise has not found its way into migration theory. Another conceivable mechanism, migration driven by drought, is also not specifically addressed. *Whether or not this migration is similar to other types of migration covered by current migration theory, is not known*.

The only way climate has been integrated into migration theory is in a specific branch of research trying to explain *internal* migration in developed countries by means of *environmental preferences*. Such preferences (for instance a lake view or a warmer climate that act as pull factors) explain why people migrate to areas with low income or high unemployment against the predictions of the theory on neoclassical economics (see wage equilibrium theory in the subchapter on neoclassical economics). Regarding climate, it was found that people prefer winter sunshine, warm and dry summers and infrequent but moderate precipitation (Svart, 1976). Studies in this field have established a relationship between such preferred climates and migration by means of surveys on individual attitudes as well as empirical research. The latter mostly employed regression techniques to correlate migration with variables such as annual temperature, annual percent sunshine, the ratio of average maximum temperature in January over the average daily minimum in July, etc. (Svart, 1976). In his literature review Svart (1976) concludes that regional environmental preferences are a significant cause of migration. If the zones of preferable climate in developed countries shift due to climate change and this change is perceived by the people, it can thus be expected that regional migration preferences will change as well.

To summarize how climate has been included in migration theory:

- Climate has been investigated as a causal *pull factor* for migration and has been found to have an influence on *internal migration in developed countries*.
- The *way* climate has been treated is predominantly as a *independent variable* in (multivariate) *regression techniques* and not in the mechanistic and dynamic way typical for the natural sciences.
- Migration treating climate as a push factor, resulting from natural disasters or from loss of land has not been treated in migration theory.

2.4.3 Common Features and Differences

Climate and migration have a number of aspects in common. Both the climate and migration can be described as *very complex* systems or processes that are influenced by numerous *feedbacks*. Examples for such feedbacks are the "beaten path effect" (see page 20) in migration or the water vapour feedback (see page 8) in the climate system. The climate as well as migration are topics that require research to be of an *interdisciplinary* nature in order to gain a thorough understanding.

Besides these common features, however, the nature of climate and migration as well as the research concerned with it are fundamentally different. Some differences are presented in Table 2.4.

Table 2.4: General differences between climate and migration models.

trait	climate	migration
model types	mathematical	many conceptual, mathematical
theoretical basis	Generally, there is a common theory on how the climate works.	There are many different migration theories, each focussing on specific migration situations. None integrates *all* types of migration and some migration situations are not covered at all.
predictability	The climate system is "partly" predictable, *given* the variation in external forcing. The models provide *credible simulations* at least down to sub-continental scales.	The predictability of migration is rather low and is not expected to be improved on significantly.

Also, when limiting the comparison to only the *mathematical models,* dissimilarities become apparent (see Table 2.5): While most climate models are spatially distributed and dynamic, migration models are usually independent of space and time.

Table 2.5: Classification of mathematical climate and migration models according to the traits set out in Chapter 2.1.2.

trait	**climate models**	**migration models**
foundation of model	*mechanistic basis & empirical*	*empirical*
time dependency	*dynamic*	*mostly static, very few dynamic*
spatial scale	*mostly distributed*	*mostly lumped*
inclusion of variability	*deterministic/probabilistic (ensemble)*	*deterministic*

More importantly, climate models build on fundamental scientific and engineering knowledge about the phenomena of the system. The rigid chemical and physical laws underlying the climate system allow a certain predictability. In contrast, there are no rigid laws describing human behaviour that could be used for migration. Instead, for migration prediction, past trends are extrapolated or empirical correlations are used. This is the essential difference that scholars of both subjects readily agree on:

> *"Climate system models are fundamentally different from statistical models used in some of the social sciences, which are based purely on empirical correlations and are unrelated to an underlying body of physical law."*
>
> *(IPCC, 1997, p. 3)*

> *"Of course I am perfectly aware that our laws of population, and economic laws generally, have not the rigidity of physical laws."*
>
> *(Ravenstein, 1885, p. 241)*

3 The Mathematical Approach: Climate, Migration and their Connection

This chapter concentrates on the *mathematical interface* between climate and migration models: The outputs of climate models are put side by side with the inputs necessary for migration models. By this means, the *requirements* for a mathematical *linkage* of existing models are determined. Then, the actual mathematical connection of these two sides is illustrated by means of an example. Thereafter, the limitations and functions of this mathematical approach are discussed.

3.1. The Connection of Climate Outputs and Migration Inputs

3.1.1 Output Data from Climate Models

For many simple models the *mean temperature* is the main output variable which is given for different altitudes or latitudes. In contrast, general circulation models produce tens and hundreds of output variables (see Box 3.1 below).

Box 3.1: Examples for Outputs of General Circulation Models

Temperature, humidity, wind, and cloud water all at various levels within the atmosphere, total precipitation as well as its convective and advective fraction, solar and thermal radiative fluxes at the surface and at the top of the atmosphere both under cloudy and cloud free conditions, various surface fields such as soil moisture, evaporation, runoff, snow depth and surface albedo (personal communication Wild, 2004).

Figure 3.1 gives a schematic overview of how the outputs of climate models are created. Some of the output variables are the *same as input variables* (as for instance temperature, wind and humidity). An example: at t_0 the measured value of the variable "relative humidity" is fed into the climate model. The model then calculates the first time step and delivers the new value for the relative humidity at t_1. Other variables are calculated by parameterisations within the climate model. For instance the "cloud cover" at t_0 is not required as an input but is calculated from other input values such as relative humidity, the temperature and other factors.

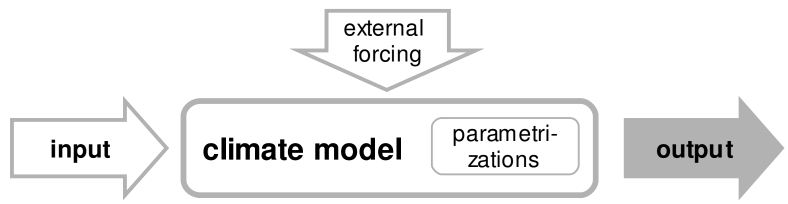


Figure 3.1: Schematic overview of the factors governing the output variables of climate models. Examples for the external forcing are the sun activity and the concentration of CO_2 in the atmosphere.

The climate model provides a set of outputs at certain time steps. These sets are further utilized in different ways: averaging them over the time span of interest is relatively simple and yields a *mean average* temperature. More complicated are the calculations necessary to determine the *variability* of climatic features, as for instance heavy rainfalls. Many climate modellers put their GCM results online at the disposal of the international climate research community.

3.1.2 Input Data for Migration Models

As seen in Chapter 2.3, the approaches to explaining and modelling migration are multifarious. Each model or theory sees different determinants causing and affecting migration. Therefore, the required *input is very diverse*, as illustrated in Table 3.1. It ranges from size of population, over average regional income to foreign investment and agricultural mechanization levels. For some models, climate is taken into account – for a discussion of the inclusion of climate see Chapter 2.4.2.

Table 3.1: *Exemplary* input data of selected migration models.

Model/Theory	**Examples for Input Data**
gravity model	population in place of origin and destination, distance between both areas
in-migration model	income, unemployment rate changes, population size, ***average temperature in January***, education attainment
neoclassical economy	earnings at place of origin, average earnings at place of destination, probability of finding a job (the unemployment rate is often used as an indicator), the costs of transportation.
new economics of migration	an indicator for the economic risk of families and/or households in a region
dual labour market theory	demand for immigrant labour, which depends on strength of structural inflation, how strong social status is dependent on job hierarchy, etc.
world systems theory	foreign investment, index for mechanization and/or commercialisation of agriculture, presence of a "global city", etc.

3.1.3 Connecting Climate Model Outputs and Migration Model Inputs

In order to determine the requirements for connecting existing models, it suggests itself to juxtapose climate model outputs with migration model inputs (see Figure 3.2).

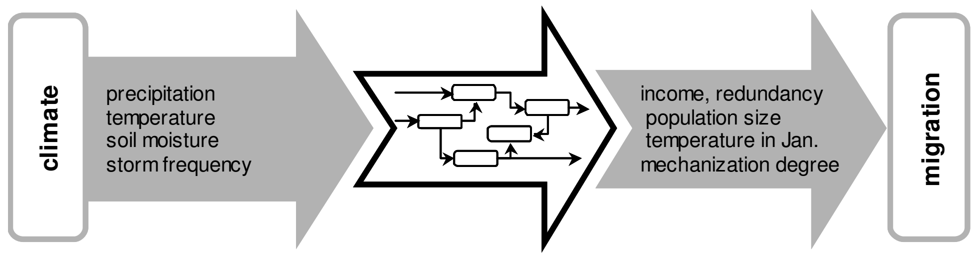


Figure 3.2: Selected examples for climate model outputs and migration model inputs.

This approach shows that in very *specific cases* a direct or short linkage is possible: as discussed in Chapter 2.4.2, pleasant climates are considered a causal *pull factor* for *internal migration in developed countries*. In these cases, a mathematical connection of existing models would be relatively *simple*: mean temperatures projected by climate models could be inserted into these migration regression models as *independent variables*. A requirement for this procedure to be of use is that climate models provide credible simulations of climate down to at least national scale (e.g. for Europe) or even regional scale, especially within large countries (as for instance the USA and Australia). As yet, projections are credible to a sub-continental level and are expected to be improved due to an intense research effort in regional climate modelling.

For other connections of the existing models, mathematical functions would have to be found that correlate natural variables such as precipitation, temperature and wind speed to mostly economic factors such as income and redundancy. How can wind speed influence redundancy or soil moisture influence income? Such connections only seem possible *over long causal chains* or "causal nets". The most obvious chain might be that less precipitation could lead to less crop yield which could lead to less income in a primarily agrarian society and thus to more out-migration. The requirements for such a connection would be the abil*ity to represent all these processes in between* in an adequate model.

However, before further developing these aspects, the applied approach of juxtaposing outputs with inputs has to be critically assessed. In the discussion of migration models (see Chapter 2.4), it becomes apparent that no migration model integrates *all* types of migration. Each model focuses on a specific type of migration. This *focus obviously remains the same* when it is successfully connected to a climate model. In the specific cases cited above, for instance, it becomes possible to estimate the influence that a change in temperature has on the choice of place of residence within a developed nation. However, this diploma thesis is interested in *climate-related migration* (predominantly in and from developing countries). This means that simply establishing a connection between *any* two models is *not functional*, the migration model in question would have to deal with climate-related migration. However, as seen above, this type of migration situation is among those that have not been covered by any models or theories. This means that climate-related migration would first have to be studied in order to determine whether *new models* have to be created, or whether this type of migration is *similar to other types* already covered by models. It is important to note that such a similarity cannot be a priori assumed, based on the fact that many different migration models have been made necessary by many migration types.

Consequently, a mathematical model of climate-influenced migration is possible only if, besides successfully modelling all the processes in between, also a *specific migration model is developed* (or a well-founded reasons for adapting others is given). The question that remains is if, given a suitable migration model, the mathematical modelling of such long and complex in between chains is a *feasible – and meaningful – undertaking at all*. An affirmative answer to this question is given by Integrated Assessment modellers.

3.2. Mathematical Connection of Climate with Migration: Integrated Assessment Modelling

The distinctive feature of modelling the climate-migration connection is the long chain of processes that covers many different disciplines. This very feature makes it difficult to search for existing models of the connection: they are not to be found in any of the scientific disciplines that "only" model one specific part of a possible causal net. The Intergovernmental Panel on Climate Change presents a *very comprehensive* overview of scientific knowledge on the impacts of climate change (IPCC, 2001b). The overview given makes apparent that climate change impacts are not approached as long process chains. Rather, specific sectors (hydrology, ecosystems, human health, etc.) are investigated, within which dynamic models are commonly used as tools. Examples are basin watershed models, crop models for potential agricultural productivity, and potential vegetation models. Models over long process chains and/or including migration *are not found*. However, in the chapter on methods and tools (Ahmad et al., 2001), reference is made to "*Integrated Assessment*" that aims at giving a coherent *synthesis of all aspects* of climate change – predominantly for policy-makers. This relatively new approach is described as an "interdisciplinary *process of structuring knowledge elements* from various scientific disciplines in such a manner that all relevant *aspects of a societal problem* are considered in their mutual coherence" (Rotmans & van Asselt, 2001, p. 101). One of the approaches within Integrated Assessment is the use of mathematical models that "attempt to integrate information *by linking mathematical representations of different components* of natural and social systems" (Risbey, Kandlikar, & Patwardhan, 1996, p. 69). The ambitious aim is to integrate very dissimilar information units, ranging from financial to biogeochemical, into one common structure. This *corresponds precisely to the task* to connect climate and migration. This means that Integrated Assessment Modelling is the very method (and the only one found) with which such a connection can be approached.

A look at existing models reveals that migration has hardly been integrated up to the present date. Integrated Assessment Models (IAMs) may include processes and activities determining *GHG concentrations*, the climate *system responses* and subsequent economic and environmental *impacts*. The treatment of the impacts is generally the weakest part (Ahmad et al., 2001). Indeed, not many models take demographic elements, let alone migration, into account. Rotmans and Dowlatabadi (1998) investigated IAMs and found only four that included demography. A closer look reveals that in all these cases "inclusion" means that the demographic variables are simply fed into the model as input and no interaction is modelled. However, there are *exceptions* and *one* model specifically studying the climate-migration relationship was found. It is described in the following with the purpose of giving an example in which way climate and migration can be mathematically connected.

3.2.1 Example

An IAM explicitly dealing with climate and migration was constructed for two States of Northeast Brazil (Krol, Fuhr, & Döring, in press). In order to *analyse* possible *climate change impacts*, Krol et al. chose a *very vulnerable region*, for which climate change potentially poses a serious threat. The two States of Ceará and Piauí lie in a semi-arid region that relies greatly on agricultural production and has unfavourable soil conditions. The model "dynamically describes the relationships between the climate forcing, water availability, agriculture and selected societal processes" (Krol et al., in press, p. 123). It models these processes for the 332 municipalities of the two Brazilian States in time steps of one year. As basis for the model serve five already existing models. In the new integrated model, these disciplinary models represent "*modules*" that are interconnected (see Figure 3.3).

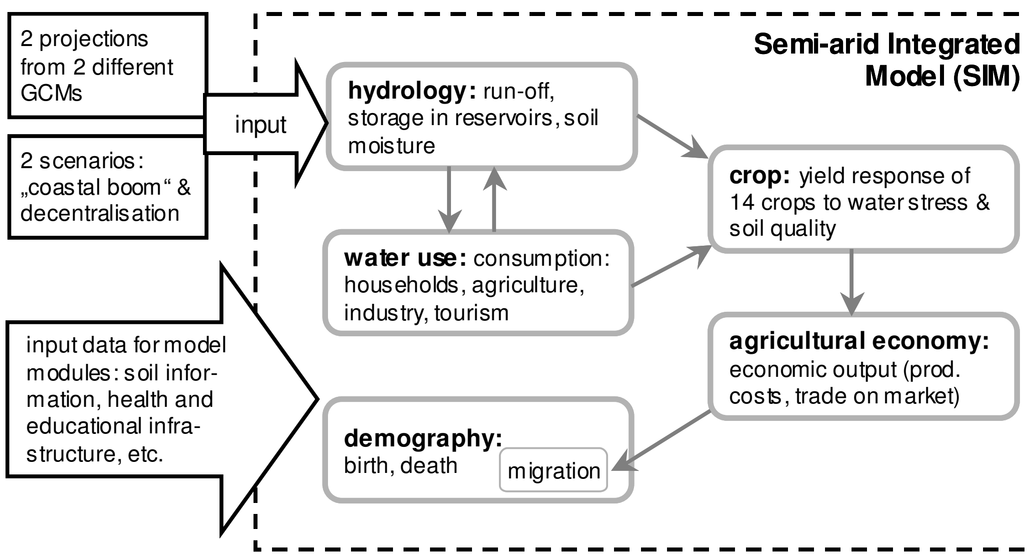


Figure 3.3: Conceptualisation of the Semi-arid Integrated Model used to connect climate change with migration. Based on the description by Krol et al. (in press). For the purpose of clarity, only connections *explicitly* mentioned in the article were included with arrows.

Climate change itself is not modelled[4] but provided as *input* to the model. The climate data were taken from two different GCMs based on a continuing increase of GHG at present rates. For Northeast Brazil, there is a yawning gap in the GCM prediction of precipitation changes (2070-2099 compared to 1961-1990). Where one model forecasts an *increase of 20 per cent*, the other predicts a *decline of 50 per cent*. With these

[4] This is rather unusual for IAMs and shows how impact-focussed this model has been designed.

two climate projections, a total of *three input scenarios* was created by combining them with reference scenarios of regional development. Both climate projections – the increase as well as decrease in precipitation – were combined with a reference scenario labelled "coastal boom and cash crops"[5]. In addition, the decrease in precipitation was combined with an alternative scenario termed "decentralisation"[6]. With these three input scenarios, three model runs were carried out.

Of specific interest for this diploma thesis is the *migration model* used within the demography module that is based on the approach of neoclassical economics (see page 19). Studies carried out in the region had shown a strong connection between migration and *unemployment* in the rural area. In the model, migration is viewed as a phenomenon composed of many individual decisions of households or families. Migration is chosen as the option when the *valued gain* in the *quality of life exceed migration costs*. *Quality of life* is modelled as an indicator composed of *family income* as the dominant factor and educational as well as health infrastructure, whereas *migration costs* are calculated on the basis of the linear *distance* between the municipalities.

The results of 50 year-runs show that the *effect of climate change on mean migration is modest*. The difference in migration rates between the two very different climate projections is small. The model predicts that economic development of the rural areas is a much more important determinant for migration than the climate, in particular when agricultural production becomes less important to the regional economy in relative terms.

3.2.2 Limitations and Advantages of the Mathematical Approach

The above example illustrates that it is *possible to mathematically model the climate-migration connection*. However, the quality and function of such models has to be discussed, as Integrated Assessment Modelling *lacks credibility* in the scientific communities of the individual disciplines (Rotmans & Dowlatabadi, 1998). Therefore, the limitations as well as advantages of the mathematical approach are presented in general and by means of the Brazilian example. These then serve as basis for the discussion.

Limitations

Many *limitations of IAM* that may contribute to the lack of credibility are presented by both IAM scholars and critics:

- Even the disciplinary *sub-models* used as basis for integration the studied processes *are not indisputable*. An integration of such already deficient sub-models inevitably leads to further simplification and cannot yield an ideal representation of all processes (Rotmans & van Asselt, 2001).
- The very purpose of analysing an *entire set of cause-effect* leads to a large number of modules and with it an *accumulation of their uncertainties* (Rotmans & van Asselt, 2001).

[5] In this scenario the production activities are concentrated in the coastal areas and agriculture is oriented on cash cropping.

[6] In this scenario development and the production activities are more evenly distributed geographically and more participation of the population is aimed at.

- There is no common approach or set of rules how to link the different knowledge "units". This means that the linkage is at present carried out in different ways. This is especially problematic as the linking is carried out "in a heuristic and almost *intuitive manner*" (Rotmans & van Asselt, 2001, p. 102).
- There exists a tendency towards adopting elements from early work within IAM *uncritically*. This lack of assessment is particularly serious when these elements have been developed by disciplinary experts (Risbey et al., 1996).
- The *assumptions* underlying the sub-models that serve as basis for integration are not necessarily valid in the much broader context of integrated assessment. The danger of such erroneous adoptions is particularly high when modelling teams do not have the expertise of all the disciplinary fields that they are integrating into one model (Risbey et al., 1996).

These limitations are not all unique to IAMs and some may also be found in other fields such as climate modelling. However, Integrated Assessment Models have received criticism for not treating these sources of uncertainty adequately. In most disciplines, the *validation* of a *model* is a necessary and integrated part of model development. In climate research, for instance, a newly developed model is first tested against the present climate. Thereafter it is tested against past climates before being used to gain insight into possible future climates (McGuffie & Henderson-Sellers, 1997). No validation of IAMs seems to have taken place by running them over historical time periods (Risbey et al., 1996).

Next to model validation another tool that enables the critical assessment of scientific work is the *review process*. However, the *common approach* with *individual* peers reviewing the work seems *inappropriate* for research that integrates knowledge from so numerous disciplines (Risbey et al., 1996). Which scientist can be expected to assess the quality of not only the model as a whole but also of each single module? For a meaningful assessment of IAM, *several* reviewers of different scientific disciplines would have to participate in the review process.

The IAM community has acknowledged many of the above mentioned limitations and problems. IAM scholars themselves point out that "the most significant pitfalls are that policymakers and researchers may treat integrated assessment models as 'truth machines'"(Rotmans & Dowlatabadi, 1998, p. 302). Some state that the *predictive capability* – as it is *rather limited* – is much less important than other functions of IAMs (Rotmans & van Asselt, 2001). These are described in the following paragraph.

Advantages and Functions

The functions of Integrated Assessment Models are to (Risbey et al., 1996; Rotmans & Dowlatabadi, 1998; Rotmans & van Asselt, 2001):

- offer an *overall picture* of those processes that are causally relevant for understanding a complex environmental and/or societal problem, which enables to gain insight and put the processes in a broader perspective;
- help to explore of *interactions and feedbacks*, leading to (counterintuitive) results that would not be available from a disciplinary approach;

- make qualitative judgments (termed *"insights"*) about impacts and dynamics of the system;
- provide a *framework in which to structure* current scientific knowledge and in this way help to set priorities for new research; and
- serve as tools for *communication* among disciplinary scientists and also policy makers.

This list presents functions compiled from three overview papers. No common and clear core functions of IAMs crystallize from the reading. Rather, some of the functions mentioned remain vague: IAMs can "provide a *useful guide* to complex issues", "have *interpretative and instructive* value"(Rotmans & van Asselt, 2001, p. 107 & 110) and "*help* to identify and evaluate potential strategies"(Rotmans & Dowlatabadi, 1998, p. 369). The multitude of functions and the vagueness do not mean that IAMs cannot successfully fulfil certain functions. Rather, as this young approach has not yet found its established range of application, it underlines the utmost importance of explicitly stating the function that the IAM should fulfil in the specific case.

Limitations and Advantages: the Brazilian Example

The specific IAM on the semi-arid region in Brazil (see Chapter 3.2) stated its goals as *understanding the relationships involved*. A simple intuitive causal chain resulting from the model description is depicted in Figure 3.4: If global climate change results in less rain for Northeast Brazil, agricultural production will decline and because the region is heavily dependent on agriculture, so will the income. As the income is one of the main determinants for migration, migration will increase.

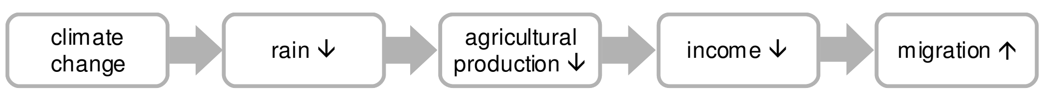


Figure 3.4: Intuitive causal chain connecting climate change with migration according to the Integrated Assessment Model presented in Chapter 3.2.

The results of the model indeed showed a sensitive reaction of the region's agricultural production to precipitation projections (predominantly the rain-fed systems). However, regarding migration the results do not coincide with intuition: the decline in agricultural production does not seem to have a significant impact on migration. The explanation offered is that as rain-fed productivity decreases and irrigated production does not grow substantially, the agricultural sector plays a declining role in relative terms in regional economy. At first sight this reasoning is plausible: if the population becomes less dependant on agriculture which in turn depends on climate, the population becomes less vulnerable to climate change. However, this only seems a reasonable deduction if the population finds *alternative means* of income. Where these could come from is not mentioned in the paper.

In this example the authors quite clearly do not present their model as a "truth machine": the explicit goal of the paper is the *understanding* of relationships and in the conclusion the work's primary utility is declared as in composing *internally consistent projections*. Moreover, the results are not presented quantitatively (which would insinuate precision); rather, the wording is qualitative and chosen carefully. They state that the results of the model (i) "*indicate* that mean migration rates *may remain* high in future, albeit lower or even significantly lower than at present" and (ii) that "the effect of climate change on mean migration *appears to be* modest" (Krol et al., in press, p. 140, emphasis added).

In spite of such carefulness, the results are all the same contestable. As Risbey et al. (1996, p. 372) emphasize, "qualitative judgments are inextricably tied to quantitative model outputs and hence to underlying model assumptions, and may have similar shortcomings". In the present case, the migration model alone might have serious shortcomings. There is no information if and in which way the suitability of the chosen model for this type of migration was assessed and whether the model was validated. So the migration alone might lead to a high uncertainty. If the *accumulated* uncertainty of the integrated model is unacceptably high, i.e. if the predictability tends towards zero, even qualitative judgments are of little value. The point here is not to assess whether or not the uncertainty of this specific model is too high, but to underline that as long as uncertainty is not addressed or quantified, little can be said of the results – be they quantitative or qualitative.

3.2.3 Discussion: Integrated Assessment Models

To summarize, Integrated Assessment modellers have distanced themselves from IAMs as *predictive* tools and have defined a range of other functions including qualitative judgments. However, although qualitative results might be more robust, they still rely on the same quantitative model results that are intentionally placed in the background due to their limited predictive capability. In this context, Risbey et al. (1996, p. 388, emphasis added) advocate that "a first step might be to *define the insight*[7] *as concisely* as possible, and *identify the most important processes and assumptions* that come into play in forming that insight."

The mathematical connection of climate with migration is possible with the Integrated Assessment Modelling approach. The functions this models can successfully fulfil are:

- providing a framework in which to structure knowledge;
- presenting mechanisms and assumptions that lead to qualitative judgments; which partially overlaps with the function of
- exploring interactions and feedbacks.

In the light of these results, the question arises if the time-consuming mathematical modelling is the adequate tool to fulfil these functions, especially as the mere existence of quantitative results holds the danger of feigning false exactness and may tempt researchers and policymakers alike to overlook its limitations. An alternative approach might be sought very close by. As mentioned in Chapter 2.1.1, the *starting point* of a mathematical model is very often a *conceptual model*. Might not this level – the *conceptual* connection of climate and migration– fulfil similar functions without the dangers that arise from quantification? An answer to this question is sought by first reviewing past conceptual work in Chapter 4, employing the conceptual approach

[7] Risbey et al. use the term "insights" for qualitative judgements.

by developing such models in Chapter 5, and discussing its potential contribution in Chapter 6.

4 The Conceptual Approach: a Review

The comparison of models for climate and migration has shown the large *differences* in science *approaches* between topics and disciplines. Next to the mathematical methods, conceptual models (for a definition see page 6) also offer a framework within which to study the influence of climate change on migration. In contrast to the mathematical approach, on the conceptual level there is a sizeable body of *literature available*. It is the goal of this chapter to draw from this basis the lessons past research can teach for a conceptual connection of climate change and migration. For this purpose, first an overview of research efforts is given, followed by the lessons learnt.

Research carried out in the conceptual field can be divided into chiefly three categories:

1. current and recent case studies investigating the influence of climate variability on migration in a specific region;
2. historic and prehistoric case studies; and
3. a general discussion on the topic coined by the term "environmental refugees".

4.1. Current Case Studies

Current and recent case studies have a large advantage in comparison to case studies from the past: There is more information available and the causal linkages are thus easier to explore. However, it is difficult to find current examples of migration as the climate at present is changing only slowly and unusually large climate variability is not commonly found. In general, there are *not many studied analogues* of climate and society, as the social sciences during the 20th century did not deal with this interaction (Meyer et al., 1998). However, there *are* examples that will be presented later on to create the conceptual models in Chapter **5**.

But what is the *function* of using case studies in general? Case studies are often used as analogues. The assumption underlying this use is that cases from the *past or present* can deliver information about what will happen in the future (Glantz, 1988): Investigating how society reacts to present climate variability (or past climate changes) can improve the understanding of how society will react to future climate change. Meyer et al. (1998) point out that valuable lessons may be learnt with this approach but also call attention to the fact that there are *always* differences between analogues and that "it can always be argued that those differences invalidate the analogy advanced". Jamieson (1988) investigates for which reasons analogies of *human response* to climate change may fail. He finds that there are possible differences in (i) the technological possibilities; (ii) the political and social organization in responding to climate change; and (iii) the information position regarding the forthcoming change. This means that differences in these important aspects limit the value of the analogue. To say it in other words the more similar the two cases are regarding these features, the more valid the analogue will be.

An additional aspect that has to be kept in mind is that a literature review regarding the climate-migration relationship will likely over-represent cases in which climate has a striking influence because researchers lay a focus on precisely such cases (Meyer et al., 1998). For for instance in the example in Chapter **3.2.1**, Krol et al. (in press) chose a *region that was specifically very vulnerable to* climate change. Therefore, the availability heuristic[8] has to be taken into account when making an *overall judgment based only on case studies*/analogues.

4.2. Historical and Prehistoric Case Studies

Some 13'000 years ago great amounts of the Earth's water was bound in ice shields. Sea levels were low and the Bering Strait opened up. Human beings from Siberia crossed the land bridge to Alaska and are considered by most archaeologists to have been the first to populate the Americas (Marshall, 2001). This famous crossing is just one of the examples where climate change has been brought into connection with migration. The task that researchers face in these case studies is threefold: they have to *present evidence for (i) migration; (ii) concurrent climate change; and (iii) the causal linkage between the two*. In the following two examples from different time periods and regions are presented.

Migration of Nomad People in Eastern Asia

The migrations of nomads in Eastern Asia was correlated with climate change for the period of 190 B.C. to A.D. 1880 (Fang & Liu, 1992). The researchers examined direct records of *migrations* from ancient Chinese chronicles. Regarding *climate change* they adopted prior work regarding three indicators: air temperature derived from phenological phenomena, the frequency of winter thunderstorms and dust falls that were both well recorded in ancient China. They compared the migrations to the three climate indicators and found correlation coefficients ranging from 0.527 to 0.770. The main interpretation of this relationships, supported by chronicle descriptions, regards the *climate as a push factor*: "cold and dry climatic conditions caused economic failure of the nomads and so triggered them to migrate" (Fang & Liu, 1992, p. 163).

[8] According to this heuristic, the approximate likelihood of an event is judged by the share of cases in which it appears *that can be readily recalled*.

Polynesian Migrations

The peopling of Polynesia between 300 and 1400 AD was linked to climatic change by Bridgman (1983). For the data on *climate*, he relies on available knowledge based on a variety of methods. For the Polynesian *migrations* he also falls back on information established over many years by means of archaeology, the degree of similarity in languages, cultural practices, plants, etc. He hypothesizes that the change from optimal to inhospitable climate influenced the migrations "through physical perception and decision making by the Polynesians, rather than having a direct impact". The little Climatic Optimum (750 to 1250 AD) featured persistent trade winds, clear skies and limited storminess and may thus have constituted ideal conditions for voyaging. By contrast, in the Little Ice Age (1400 to 1850 AD), the storminess as well the variability in trade winds increased which might have helped prevent migration.

Overview

In the case of the Bering Strait the climate enabled a crossing between two continents by binding large quantities of water in the form of ice. However, the environment as a *push factor* for migration is the most dominant hypothesis presented[9]. Researchers can often support their hypotheses with the evidence found, but *verification* proves to be a difficult, if not impossible task. Climatic factors are usually easier to detect in archaeological records than information on socio-economic problems that might also have influenced migration, but is less accessible (Meyer et al., 1998). This is especially the case for prehistoric case studies where only the *concomitance* of migration and climate change (steps (i) and (ii)) can be established but *no causal linkage* between the two can be proven. This makes the danger of attributing change too simplistically to climate greater than for case studies from the past than for current situations (Meyer et al., 1998). However, researchers treating examples from the past are very explicit in mentioning that there is no proof and that climate is one of many factors.

4.3. Research on "Environmental Refugees"

Since the mid 1980s, a growing body of literature on "environmental refugees" has dealt with *environmental deterioration as a push factor for migration*. Although the factor "environment" encompasses phenomena not influenced by climate change, such as earthquakes and environmental accidents (Bhopal, Chernobyl), most of the environmental push factors studied (floods, cyclones, droughts, sea level, etc.) are closely related to climate. Indeed, climate change is often named as (one of) the most relevant environmental factors. Therefore, many of the issues and conclusions of this scientific discussion directly *apply to climate-influenced migration*.

"Environmental refugees" was the term first used to describe the theme that has since been treated from many sides. Research has focussed on defining and quantifying the term, describing environmental deterioration on a global scale, classifying different

[9] Readers interested in historical and prehistoric examples are referred to further literature (J. N. Gregory, 1989; Huang et al., 2003; Tyson, Lee-Thorp, Holmgren, & Thackeray, 2002; van Andel, 1989; van Geel, Buurman, & Waterbolk, 1996; Verschuren, Laird, & Cumming, 2000; Zaitseva, Mikliaev, & Mazurkevich, 1995).

types of environment-induced migration and exemplifying the phenomenon with case studies. Even though the term "environmental refugees" has been criticized time and again, it has persistently clung to the debate.

4.3.1 Definition

The term "environmental refugees" was coined by a publication in the mid 1980s that was one of the first to call attention to a new category of refugees (El-Hinnawi, 1985). The widely quoted definition reads as follows:

> *"environmental refugees are defined as those people who have been forced to leave their traditional habitat, temporarily or permanently, because of a marked environmental disruption (natural and/or triggered by people) that jeopardized their existence and/or seriously affected the quality of their life. By 'environmental disruption' is meant any physical, chemical and/or biological changes in the ecosystem (or the resource base) that render it temporarily or permanently, unsuitable to support human life."*
>
> *(El-Hinnawi, 1985, p. 4)*

The term "environmental refugees" has been subject to criticism with respect to both the word "refugee" as well as its prefix "environmental". *Refugees* are legally defined as people persecuted for *political reasons* by the UN[10]. This refugee status determines the degree of support the people receive (Gallagher & Martin-Forbes, 1992) and thus bears an enormous significance for both asylum seekers and hosting nations. Environmental reasons – like economic reasons – are not included in this definition.

The reason why the term "environmental" has been criticized for other reasons. Researchers agree that population movement is not generated by one single cause, but by a *dynamic interaction of a variety of causal agents*[11]. However, while some researchers consider the environmental component clearly the *most relevant* in certain cases (El-Hinnawi, 1985; Jacobsen, 1988; Myers, 2002), others consider environmental degradation as *one amongst many* influencing factors (Desanker et al., 2001; Kavanagh & Lonergan, 1992). For instance Myers (2002) considers the roots of Haitian mass migration to be of environmental nature, while Schwartz and Notini (1995, cited in Black) establish that it is "evident" that most Haitians have fled their country for political and economic reasons. Castles (2002, p. 4) specifically addresses the issue of causality and asks "On what basis are environmental factors assigned primacy in complex situations?".

With a net of numerous interwoven factors, it is very difficult to distinguish or even isolate individual causal agents (Kavanagh & Lonergan, 1992). McGregor (1993, p. 158) argues that by using the term "environmental" there is a "misleading implication that environmental change as a cause of flight can be meaningfully separated from

[10] According to the United Nations Convention relating to the Status of Refugees from 1951, refugees are persons persecuted "for reasons of race, religion, nationality, membership of a particular social group or political opinion".

[11] A myriad of causal agents is presented by the literature, such as population pressure, lack of access to services, rapid urbanization, poverty, unemployment, inadequate food supplies, pandemic diseases, government shortcomings, violation of human rights and conflicts.

political and economic changes". However, Lee (1997) convincingly replies that in that case, the same must be said of the conventional term "political refugee".

It should be added that even though also critics in this discussion acknowledge environment as one of many possible push factors for migration, *the environment has not by any means become established as such in migration literature*. In traditional migration literature the environment as a push factor is still *largely ignored* (Lonergan, 1998, see also Chapter 2.4.2).

4.3.2 Development of the Research Focus

The first publications on the topic of environmental refugees (El-Hinnawi, 1985; Jacobsen, 1988) focus strongly on the *state of the environment* and its deterioration without going into the linkage between environmental decline and migration in detail. The number of environmental refugees worldwide is estimated at approx. 10 million[12] (Jacobsen, 1988, p. 6), rivalling the number of officially recognized refugees. For the future, estimates have been set at 150 million (Myers, 1993), as presented in Table 4.1) and one billion (IOM & RPG, 1992, p. 9).

Table 4.1: Estimated number of environmental refugees in a greenhouse-affected world, resulting primarily from flooding, sea-level rise and famine (Myers, 1993, p. 191)[13].

Country or region	Total of Refugees Foreseen (millions)
Bangladesh	15
Egypt	15
deltas and other coastal zones	70
agriculturally dislocated areas	50
Total	**150**

Myers emphasizes that these numbers are only exploratory but warns of a dire future: "environmental refugees totalling anywhere between 100 and 200 million would prove a deeply destabilizing factor in international relations. […] Governments would try to shuffle off responsibility, and *cries of blame* would echo back and forth among the global community. […] And the sheer tragedy in human terms would *surpass anything we have known in the history of humankind*." (Myers, 1993, p. 202-203, emphasis added).

Sharp criticism is raised against this type of approach and such strong claims: Black (2001) examines the examples of environmental refugees presented as evidence and concludes that they represent a *weak academic case*. He studies selected examples in

[12] The derivation of this number is not further explained by the author nor is the estimate based on a explicit definition of the term "environmental refugees".
[13] The numbers are based on following definitions: "people who can no longer gain a secure livelihood in their homelands because of drought, soil erosion, desertification, or other environmental problems" (Myers, 1993, p. 190). In 2002, Myers still predicts the same number, but slightly modifies his definition by adding: "together with the associated problems of population pressures and profound poverty" (Myers, 2002, p. 609).

detail and demonstrates that they do not stand up to closer scrutiny. Mainly, his reservations are directed towards the *linkage* between environmental deterioration and migration (as are Wood's (2001)). He criticizes that the examples *fail to demonstrate the linkage* between environment and migration they postulate.

4.3.3 Discussion

Indeed, several examples of general statements of linkage without further explicit demonstration can be found in the literature:

- "The effects of desertification on man appear most dramatically in the mass exodus that accompanies a drought crisis." (El-Hinnawi, 1985, p. 26)
- "Land degradation […] is another example of environmental decline that contributes to population displacement." (Kavanagh & Lonergan, 1992, p. 18)
- In Egypt, it is "realistic to anticipate that the sea level rise could eventually displace as many as 15 million people. This prognosis, moreover, is cautious and conservative." (Myers, 1993, p. 194). The explanation given is that there are already ten million people living three feet above high tide and that population is projected to grow.

The line of reasoning behind these statements seems to be "*common sense*", as Castles (2002) terms it: If desertification occurs, land is degraded or sea levels rise, people will undoubtedly be forced to migrate (see Figure 4.1). He points out that the lack of demonstrating the linkage occurs not only on the general level, but also in the case studies presented as evidence for environmentally-induced migration. Instead, the concomitant occurrence of environmental change is mistaken for proof of causality (see for instance, the example of Haiti above).[14]

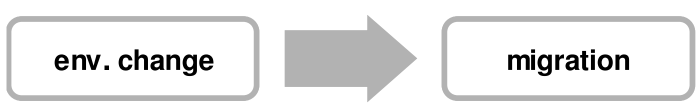


Figure 4.1: "If the environment deteriorates, it is obvious that people will have to migrate.": Schematic illustration of the "common sense" line of reasoning followed by some proponents of the concept of environmental refugees.

Critics (such as R. Black, 2001) discard conclusions derived from the general macro level and build their case on the micro level of field work and case studies. From these they deduct that what "common sense" fails to take into account is *human reaction and adaptation* to environmental change (Lonergan, 1998). The existence of not only "vicious", but also "virtuous" adjustment paths is pointed out (O'Neill, MacKellar, & Lutz, 2001) and the importance of the *role of the state* in choosing and following such paths is emphasized. An effective state can tackle prevention, long-term adaptation or interim relief much better than weakened states (Castles, 2002). This argument receives support from one of the prehistoric examples: "A typical case is that, while relief was provided efficiently and quickly, the migrations might be halted. The best

[14] In this respect, the mathematical approach has a clear advantage. It forces researchers to explicitly model the linkage, laying a foundation for verification and directed discussion.

example is from The Yuan History. When the Mongols suffered from severe droughts year after year around the 1320s, the emperor of the Yuan dynasty gave them a great deal of food, money, and cloth, but banned them from migrating. Violators would be killed." (Fang & Liu, 1992, p. 166)

4.3.4 Summary

If one wanted to reduce the discussion to a common denominator it would be along the following lines: *Scientists agree that migration has multiple interacting causes including environmental ones and that in some cases environmental change plays an important role.* In addition, many scholars agree that migration caused to a substantial part by environmental change is a current reality and constitutes a growing problem (Döös, 1997; El-Hinnawi, 1985; Gallagher & Martin-Forbes, 1992; Jacobsen, 1988; Kavanagh & Lonergan, 1992; Myers, 1993; Ramlogan, 1996; Westing, 1994). However, they have not been able to disarm two strong points of criticism:

- What are the *concrete linkages* between environment and migration?
- On what grounds is the environment judged a *separable* and the *dominant* factor in the light of complex situations with multiple factors?

However, even if the environment were only one among many factors and mainly exacerbated socio-economic factors, the important question, *whether further environmental change will significantly increase the number of migrants in the future*, would still remain. This question requires and legitimises further research into the effect of the environment on migration. In addition, if environment is a relevant factor – as most researchers readily agree – then it *should be integrated into traditional migration research*.

4.4. Lessons Learnt

Historical and especially *prehistoric examples* are a difficult approach to studying present and future climate-influenced migration for two main reasons:

- In comparison to current or recent examples it is more difficult to gain an insight into the dynamics and interactions of migration situations. This is attributed to the fact that there is less and poorer data available than in present case studies.
- The impact of climate change depends heavily on the reaction of society (knowledge basis, social structures, technology, etc.). Societies have changed so strongly in the last centuries that it would be very questionable to draw conclusions from such analogies.

There are not many *current or recent case studies* available, but they overcome the limitations mentioned above. As lies in their nature, they can make a statement about one specific case – as for instance a village or a country. The *advantage* of this approach is that within this one case a *well-founded* statement is possible. The case studies allows researchers to go into depth on the micro scale and specifically address the multi-causality. However, it is obviously not possible to draw general conclusions on the global phenomenon from a single case study. For this purpose a compilation and comparison is necessary.

In the *discussion of environmental refugees* many scholars agree that migration caused to a substantial part by environmental change is happening. What generally stands out is the *key concept of multi-causality* of migration. The climate *cannot be seen as the sole cause* of migration, there are always many other factors interacting dynamically that play an important role. Nevertheless, the question how climate change might influence migration in the future still remains of interest. At the very heart of the controversy in this field lies the *lack of explicit demonstration of* the postulated *linkages.* Linkages that are based purely on *common sense* are justly criticized: the *concomitance* of climate change and migration is an indicator for but should not be mistaken as evidence for a causal linkage.

To summarize, while prehistoric and to some extent historical examples have serious limitations, current and recent case studies are valuable tools to gain insight into the specific dynamics of climate-influenced migration. On this specific as well as the more general scale, explicit linkages that go beyond common sense and concomitance are required.

5 An Application of the Conceptual Approach: Connection Models

The discussion in Chapter 3 shows that mathematical models, for the task in question, cannot deliver the predictive and/or quantitative results often expected from the mathematical approach. Some of the functions they *can* provide may well also be covered with a conceptual approach. Previous research along this conceptual line has approached climate-induced migration either with case studies or on a very general level. The core criticism and weakest point is the fact that the *explicit linkage between the environment and migration has not been demonstrated.*

Based on these insights, in this chapter a deepened understanding is sought by means of developing conceptual models with a focus precisely on the linkages between climate and migration. For this purpose, first the approach of "*connection models*" is presented, that is then applied separately to the four main climatic hazards by which migration is said to be influenced. Finally, the results of these different models are summarized and generalisations about the climate-migration relationship are extracted.

5.1. Connection Models

5.1.1 The Concept of Connection Models

During the analysis of climate-influenced migration, it rapidly becomes apparent that there is not one single way in which this influence is exerted. The influence of increased floods and sea level rise on migration is of different nature and varies in magnitude. Therefore, in a first step, the literature of the conceptual approach serves as a starting point to *identify these different mechanisms*. The same literature has postulated cursory linkages on the basis of "common sense" within each mechanism. These *postulated linkages are made explicit* (see Figure 5.1.a) before creating a conceptual model with a "*higher resolution*" (see Figure 5.1.b). This is achieved by looking with detail into all processes involved and reviewing general literature as well as case studies.

These models are termed "*connection models*" as it is their goal to identify and briefly describe the possible connection between climate change and migration. In this context it is important to note that *connection* is not to be put on a par with *causation*. The previous chapter shows the universal agreement that migration is always caused by the interaction of a *variety* of agents. Climate change can accordingly not be the *sole* cause leading to migration. Connection models depict *influences* and show along which process chains and nets climate can *contribute* to migration.

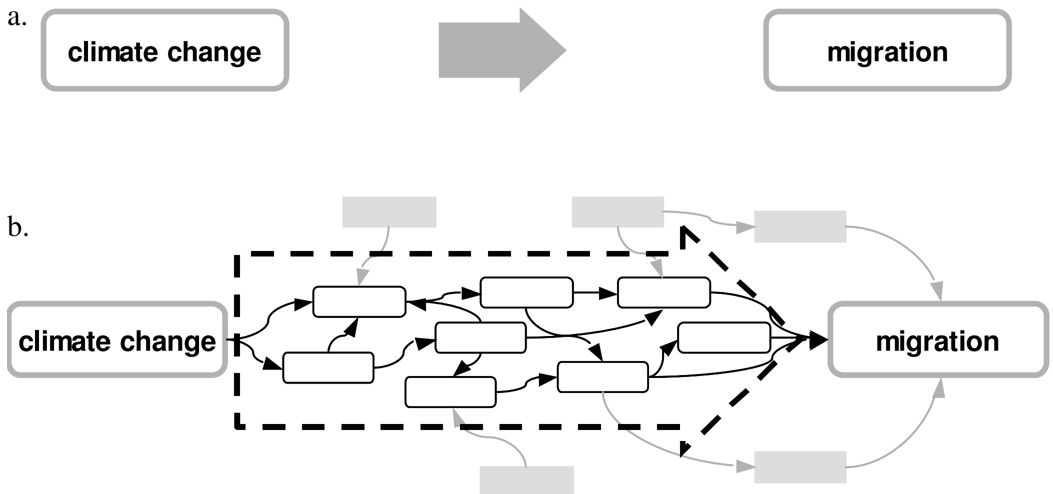


Figure 5.1: **a.** Schematic illustration of the "common sense" line of reasoning. **b.** Proposed approach of increasing the resolution of the linkage.

Needless to say, natural and socio-economic systems across the world are very diverse and react in different ways. It is the goal of the models to isolate the most important elements and relationships that are not site specific and give a general overview of a typical situation. A special focus is laid on the final link to migration, as it is the most debated of all.

The advantage of such a framework is that it is possible to discuss which linkages are generally agreed upon in the scientific community and which are the ones that are contentious. Moreover, the framework also enables to classify specific case studies with their valuable knowledge. The case studies can be used to contribute knowledge on one or more specific linkages.

5.1.2 Identification of Mechanisms

As a *starting point* to identify relevant mechanisms serve *predictions* about the ways in which climate will change. On the other side are the environmental factors that have been postulated *push factors* for migration within the literature of "environmental refugees". On these two bases it is possible to *single out* those environmental push factors that are *related to climate change*.

Climate Change Forecasts

The *main changes* predicted to occur within the next century are presented in the following boxes.

Box 5.2: Climate Change Projections: Global Averages

- *increase* in globally averaged surface *temperature* by 1.4 to 5.8°C (1990 to 2100)
- *increase* in globally averaged *precipitation*
- *rise* of global mean *sea level* by 0.09 to 0.88 metres (1990 to 2100)

(IPCC, 2001a, p. 13-16)

Box 5.1: Climate Change Projections: Extreme Events

The following changes are likely or very likely[1] to occur over some areas:

- *higher maximum temperatures* and more hot days;
- more *intense precipitation* events;
- increased summer continental drying and associated *risk of drought;*
- increase in tropical *cyclone peak wind intensities as well as mean and peak precipitation intensities*;
- *increase in the risk of droughts and floods* that occur with El Niño events.

(IPCC, 2001a, p. 13-16)

Environmentally Influenced Migration

Throughout the literature concerned with "environmental refugees", researchers have attempted to meaningfully subdivide this broad category of people (see, for instance, Bates, 2002; El-Hinnawi, 1985; Gallagher & Martin-Forbes, 1992; Jacobsen, 1988; Lonergan, 1998). The resulting categories of "mechanisms" are similar in some points but quite different in others, depending on the classification criteria (as for instance the degree of voluntariness, duration of movement, velocity of onset). Therefore, the mechanisms are presented without classification (see Box 5.3 below).

Box 5.3: Postulated Mechanisms of Environmentally Influenced Migrations

Vulcanic eruptions, earthquakes, avalanches, floods, tropical cyclones, drought, deforestation, land degradation, desertification, famine, sea level rise, environmental accidents, development projects (dam construction), environmental warfare.

Postulated Climate-Influenced Migration

To qualify for "climate-influenced migration", the mechanisms has to fulfil two criteria. It has to

- be *repeatedly mentioned* as an environmental factor influencing migration in the literature (Box 5.3); and
- be *influenced by projected climate change* according to the lists of climate change forecasts (Boxes 5.1 and 5.2).

The resulting mechanisms are described in Table 5.1.

Table 5.1: Mechanisms of postulated climate-influenced migration.

Mechanism	Commentary
floods and tropical cyclones	Another category that is widely considered to influence migration are natural disasters (alternatively called elemental disruptions or natural hazards). However, not all of these are influenced by climate (for instance earthquakes). *Floods* are one natural hazard expected to increase with climate change and thus meets the criteria. So do severe storms in general. However, *tropical cyclones* are chosen as a specific mechanism, as they cause most damage and often affect developing countries.
sea level rise	One mechanism that fulfils these criteria is *sea level rise*: it is specifically mentioned by most authors (from Jacobsen (1988) to Bates (2002)) and is postulated to cause the majority of future migrants by Myers (1993).
drought	*Drought* is also influenced by climate change, and occupies a special position among the natural hazards because of its slow onset. It is said to cause migration in combination to land degradation and by leading to famine.

In the following chapters, the four mechanisms identified are analysed by means of the presented connection model approach. Following a short introduction, model modules are presented successively, taking a starting point with climate change.

5.2. Floods and Tropical Cyclones

Climate-related natural hazards have *always affected societies* and would continue to do so without climate change. However, climate change is expected to change the *location, frequency and/or intensity* of the natural hazards. That is to say that climate change is obviously not the cause for floods in general, but can be the cause for *more floods*[15]. This additional or intensified natural hazard, then, is assumed to cause migration in a simple manner (see Figure 5.2): "A natural hazard displaces people by destroying their land, houses and other tangible goods and assets" (Haque, 1997, p. 48). As derived above, those hazards that are expected to be affected by climate change according to the IPCC and are relevant for the goal of this diploma thesis are floods and tropical cyclones.

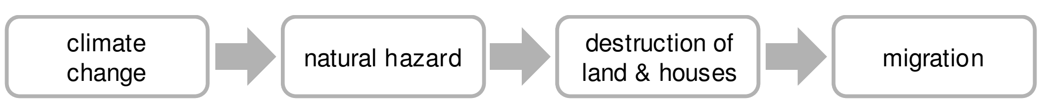


Figure 5.2: Schematic illustration of the postulated connection between climate change, natural hazards and migration.

Although natural hazard research is still in a formative stage (Haque, 1997), most scholars seem to agree that natural hazards are *not a major* cause of migration. People are usually *displaced only temporarily* and return to re-build their homes (El-Hinnawi, 1985; IOM & RPG, 1992; O'Neill et al., 2001). However, Haque (1997, p. 44) for instance dissents and states that there is an "unanimous agreement" that natural

[15] For the purpose of simplicity, the model depicts a direct connection between climate change and the natural hazard. This should be read as the *additional or intensified* natural hazard generated.

hazards are one of the "*primary sets of causes* of forced population migration" and that the vast *majority* of the five million people made homeless annually *remain permanently displaced*.

In this chapter, floods and tropical cyclones are treated in separate connection models in Chapters 5.2.1 and 5.2.2. As the link from natural hazards in general to migration has hardly been treated, migration is discussed jointly for both floods and tropical cyclones in Chapter 5.2.3 and related to other responses in Chapter 5.2.4.

5.2.1 Floods

In Bangladesh there are different terms for the word "flood" to distinguish between *beneficent and destructive* floods (Blaikie, Cannon, Davis, & Wisner, 1994). This reflects the very *ambivalent nature* of floods that throughout history have brought humankind wealth and prosperity but also destruction and suffering (UN Department of Economic and Social Affairs, 2002). For millennia, people have sought to protect themselves against the *negative* impacts of high-magnitude floods: City walls against flooding are reported to have been built as early as 4'000 years ago in China (Wu, 1989). Today, the need for response remains: in 2002, flood disasters affecting a total of *167 million people* were reported (IFRC, 2003). Despite the vast amount of people affected annually, there are only *few surveys of the direct impacts* of floods on people (Blaikie et al., 1994).

A Climate Change ➔ Flooding

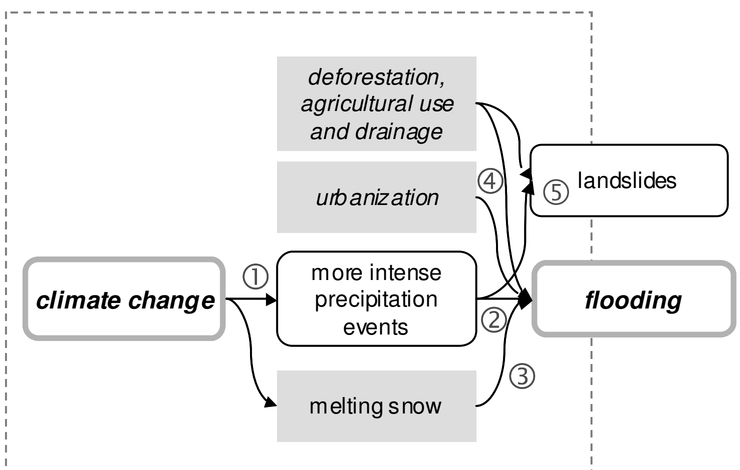


Figure 5.3: Connection model of the influence of climate change on flooding. For the entire connection model, see the Annex. (Boxes with a thick border and bold text represent the main elements of the postulated mechanism. Grey boxes are processes that influence the chain externally. Italics indicate that the process is or can be influenced by humans.)

① *Climate Change ➔ More Intense Precipitation Events*

Climate change is expected to increase globally averaged *precipitation*, as well as the frequency of *intense* precipitation *events* (IPCC, 2001a). This insight is the result of simulations of complex climate models and can thus only exhaustively be explained by the myriad of processes represented in the models. A rough outline of an explanation can still be given: The warming of the atmosphere increases the *evaporation* of surface moisture. As globally a surface moisture *balance* is necessary, the annual *precipitation must increase*. And as there is an increased evaporation and the warmer atmosphere can contain more vapour, there is also more moisture in each rain-producing weather system (McGuire, Mason, & Kilburn, 2002).

② *More Intense Precipitation Events ➔ Flooding*

Flooding is a natural process that occurs when a river flows over its bank onto lands not usually submerged. The most important cause for extraordinary discharges of water that cause over-flowing are *excessive rainfalls* (K. Smith, 2001). When rain falls in the catchment basin, some of it is *intercepted* by vegetation and *evaporates* back into the atmosphere. Of the water that reaches the ground, a part is taken up by vegetation and *transpired*, while another infiltrates the soil and gradually reaches the stream. When the absorption capacity of the vegetation and soil is exhausted by intense rains, surface water *runoff* is created that reaches the stream quickly. This convergence of runoff can lead to a river flowing over its banks (UN Department of Economic and Social Affairs, 2002).

③ *Melting Snow*

Surcharges of water can also be caused by the melting of snow. In both North America and Asia such melting is an important factor of flooding in spring and summer (K. Smith, 2001). Snow cover and melting are also influenced by climate change through changes in temperature as well as annual distribution and intensity of precipitation.

④ *Deforestation, Agricultural Use and Drainage, and Urbanization*

The slopes, soils and vegetation of a catchment basin are important factors influencing water flow and flood risk. As stated, vegetation and especially soils have an absorption capacity that largely reduces surface water runoff. This means that when *forests* and other vegetation are *removed*, infiltration rates are reduced. Similarly, *agricultural use* reduces natural water storage due to the associated gradual loss of organic material and soil erosion (and in some cases the drainage of wetlands and marshes). The reduced water storage causes runoff rates to increase which leads to higher flood peaks (K. Smith, 2001; UN Department of Economic and Social Affairs, 2002).

Urbanization is one of the most important land-use changes that affects water flow. The sealing of vast surface areas by paving and buildings reduces infiltration very effectively, leading to fast runoff (K. Smith, 2001; UN Department of Economic and Social Affairs, 2002).

⑤ *Landslides*

Many of the processes leading to flooding also increase the risk of landslides: Heavy rainfalls *saturate the soil* and thus reduce the shear resistance of the earth material. Deforestation reduces soil binding by roots causing the material to become looser. Also, it makes the slope more exposed to the effects of water (K. Smith, 2001).

B Direct Effects

① Sewage Spread and Stagnant Water

The vast water masses of flooding can spread sewage by filling sewerage systems and washing out pit latrines. This can lead to the contamination of drinking water. Also, long after the acute event has passed, water may remain stagnant in pools and puddles and become breeding sites for insect vectors (Blaikie et al., 1994).

② Injuries and Fatalities

The physical force of the water masses themselves as well as the sediments and debris carried along can cause human injury and fatalities. Loss of life can also be caused by drowning (Blaikie et al., 1994; K. Smith, 2001).

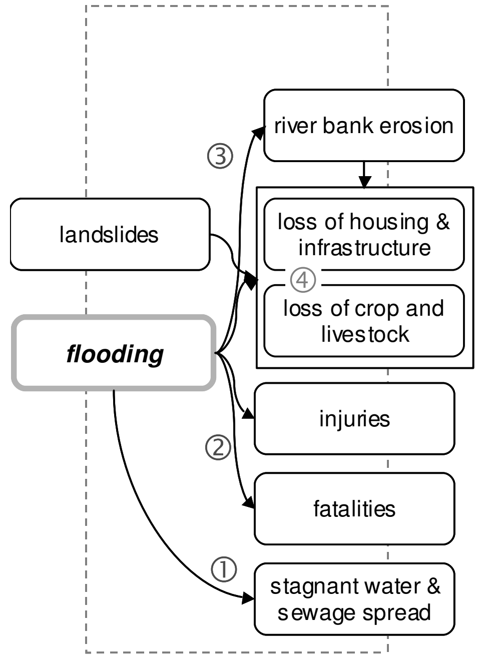


Figure 5.4: Connection model of the direct effects of flooding.

③ River Bank Erosion

Flooding causes river banks to erode and accrete. While erosion shears away segments of bank line, new land emerges in other places. Large deltas are especially vulnerable, as for instance Bangladesh, where the tributaries and distributaries of three major rivers make more than 150,000 kilometres of bank line (Haque & Zaman, 1989).

④ Loss of houses, livestock and crops

Houses and infrastructure can be damaged and destroyed by either the debris-carrying water masses, accompanying landslides or river bank erosion. In urban areas this physical damage is often the main cause of tangible loss (K. Smith, 2001). In rural areas, *standing crops, livestock and the agricultural infrastructure* can be damaged by the same processes (Kayastha & Yadava, 1985; K. Smith, 2001).

C Indirect Effects

① Diseases

Besides *directly* affecting human health through injuries, flooding can *indirectly* take a heavy toll on human health by bringing about a sharp increase in *diseases*. Drinking water contaminated with sewage spread can lead to cholera and dysentery; malaria and yellow fever might break out due to the multiplication of insect vectors in stagnant water (Blaikie et al., 1994). Such diseases often increase the overall number of fatalities (Blaikie et al., 1994; K. Smith, 2001).

② *Less Work Opportunities*

Injuries and diseases can render people unable to work long after the floods have subsided. In addition, large landowners whose crops have been damaged no longer need labourer in their fields, which can result in wide-spread redundancy (Blaikie et al., 1994; Kayastha & Yadava, 1985).

③ *Reduced Income*

For a family dependent on agricultural products, the loss of standing crops means a serious decline in family income. The inability to work (be it due to injury or redundancy) has the same for families that rely on employment (Blaikie et al., 1994).

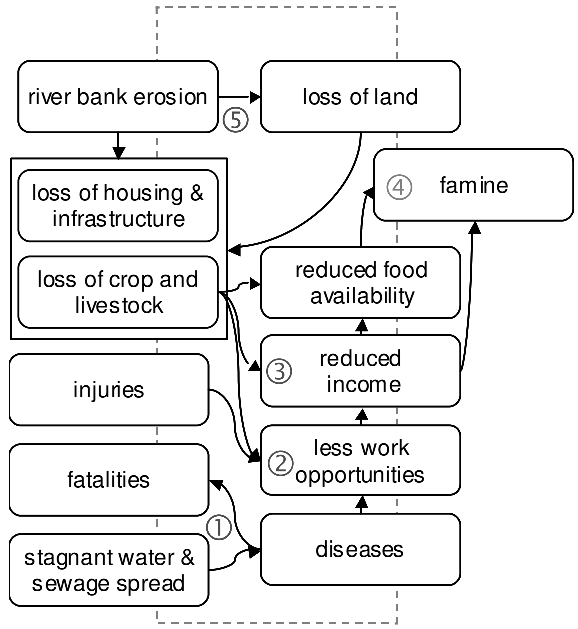


Figure 5.5: Connection model of the indirect effects of flooding.

④ *Famine*

Drought can act as a trigger for famine by reducing the own production and reducing their income to buy food. However, the question of how large the contribution of drought in fact is, is addressed in the Chapter 5.4.6 on drought.

⑤ *Loss of Land*

River bank erosion carries away agricultural land and settlements (Haque & Zaman, 1989). This, in turn, leads to the loss of whatever was on this land – housing, infrastructure, crop or livestock.

The link to migration is discussed in Chapter 5.2.3 and related to other responses to natural disasters in Chapter 5.2.4.

5.2.2 Tropical Cyclones

In contrast to floods, tropical cyclones are not of ambivalent nature. Be they called hurricanes in the Atlantic or typhoons most of the North Pacific Ocean, tropical cyclones cause damage, destruction and death along many coasts[16].

[16] As a matter of form one beneficial effect must be named. Tropical cyclones may bring much-needed precipitation to otherwise dry regions.

A Climate Change ➔ Tropical Cyclone

Tropical cyclones are a specific type of storm originating over warm tropical waters. If and how climate change will affect their *location* and *frequency* is uncertain (IPCC, 2001b). Some projections are available for changes in *peak intensities* (increase by 5 to 10 per cent) and *precipitation rates* (increase by 20 to 30 per cent), but the IPCC calls to caution of projections due to remaining uncertainty.

A possible *explanation* for the increase in precipitation rates of tropical cyclones is similar to the one given above for floods; it may be due to the *increased amount of water vapour* held in a warmer atmosphere (Giorgi et al., 2001). However, in general, the connections between climate change and tropical cyclones still constitute a *knowledge gap*. At this moment it does not seem possible to determine the ways in which climate change influences tropical cyclones.

B Direct Effects

The hazards associated with tropical cyclone are heavy rainfalls, strong winds, tornadoes and storm surge (Moran & Morgan, 1997).

① Heavy Rainfalls and Strong Winds

Heavy rainfalls and strong winds are a direct consequence of the structure of a tropical cyclone. The formation of these storms is a complex process still being investigated by atmospheric scientists. In the following, a rough sketch is given (Bader, 2004; McGuire et al., 2002): A low pressure system makes air converge and rise – a sustained convection develops. Over warm surface waters the converging air contains great amounts of water vapour. As the air rises and cools, this water vapour condenses, releasing heat. The lightened air rises even more, *accelerating the incoming air* near the surface. The constant supply of water vapour from warm oceans intensifies this upward motion and under certain circumstances a tropical cyclone is formed. The condensing water vapour causes the *rainfalls* and the air that is being sucked into the centre creates the *strong winds*. After landfall, these winds subside rapidly owing to the great friction over land as well as the decline of the cyclone. Because as soon as the eye of the cyclone moves over land, it lacks its main energy source, the ocean moisture, and weakens. Heavy rains, in contrast, can persist after the storm has moved well inland (Moran & Morgan, 1997).

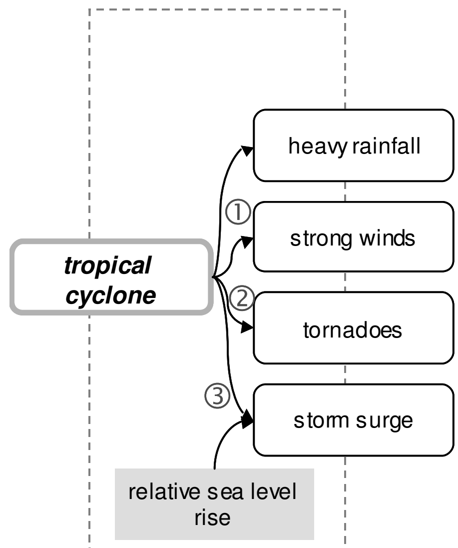


Figure 5.6: Connection model of the direct effects of tropical cyclones. For the entire model, see the Annex.

② *Tornadoes*

A tornado is a "violently rotating and narrow column of air, averaging about 100 m in diameter, which extends to the ground" (K. Smith, 2001, p. 222). When tropical cyclones make landfall their rotating air can produce tornadoes. The processes of formation have not yet been determined precisely. However, studies have shown that they are most common to the northeast of the eye and are frequently created outside the region of the strong cyclone winds (Moran & Morgan, 1997)[17].

③ *Storm Surge*

The strong onshore *winds* of the tropical cyclones approaching land *pile up water* against the coast creating a storm surge that can flood coastal communities. This rise is increased by a *direct rise* of water level due to the cyclone's *low* atmospheric *pressure*. Intensifying factors are low ocean depth near the coast and coincidence with high tide (McGuire et al., 2002).

C Indirect Effects

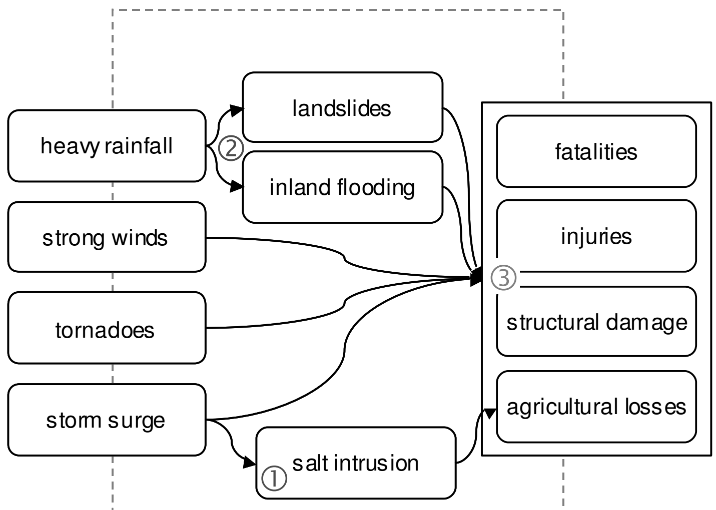


Figure 5.7: Connection model of the indirect effects of tropical cyclones.

① *Salt Intrusion*

The storm surge spreads sea water across vast coastal areas. The salt water infiltrates soils causing salt to be deposited. This can cause long-lasting damage to the soils and agricultural production (K. Smith, 2001).

② *Inland Flooding and Landslides*

Heavy inland rainfall can create freshwater flooding and landslides (K. Smith, 2001). Their impacts are described in the context of floods (starting from page 51).

[17] Readers interested in current research on cyclone-induced tornado formation are referred to a technical paper by McCaul (1991).

③ *Agricultural Losses, Structural Damage, Injuries and Fatalities*

Storm surges, strong winds, tornadoes, flooding and landslides can all cause agricultural losses, structural damage, injuries and fatalities, but usually do so to a different extent. Storm *surges* cause the *most deaths* by drowning (Burton, Kates, & White, 1993; K. Smith, 2001), although in countries well prepared for tropical cyclones like the USA, freshwater flooding has surpassed storm surges as main death cause. S*trong winds* with speeds from 120 to over 250 km/h produce the largest part of the *structural damage* either directly or by the debris carried along (K. Smith, 2001). Since the winds weaken after landfall, the damage caused is confined to within about 200 km of the coastline (Moran & Morgan, 1997).

Besides the damage and destruction of private and public buildings, "structural damage" can also involve infrastructure facilities. Damage to these may cause disruption of important functions such as *transport, communication, water and electricity supply*, etc. that complicates the other effects (Blaikie et al., 1994; K. Smith, 2001).

5.2.3 The Migration Link

The social sciences have investigated many effects of and responses to natural disasters. Subjects ranging from the effects of disasters on income, crime and divorce rates to individual emotional and behavioural response and recovery and restoration have been treated (for references, see S. K. Smith & McCarty, 1996). However, the *effect* of natural disasters on *migration has hardly been examined*. In the following, first the extent of migration following natural hazards is treated before examining the migration destinations and reasons.

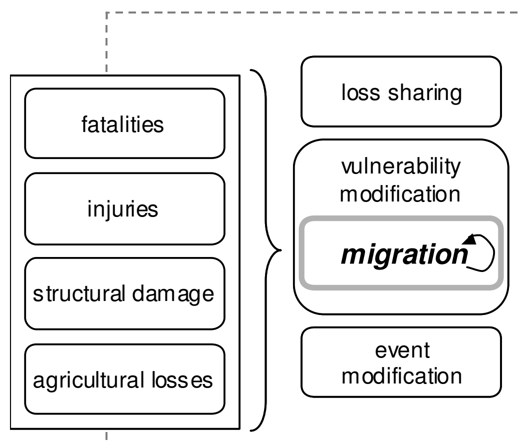


Figure 5.8: Connection model of the migration link.

The Extent of Migration

There is a consensus that before or after the onset of a natural disasters, the displacement of large amounts of people is very common. In these instances, most people go to relatives and friends (Belcher & Bates, 1983; Quarantelli, 1982). However, this *displacement is usually only temporary* and *most of the people return* to re-create their lives and rebuild their pre-disaster homes (Gold, 1980; Haque, 1997; Morrow-Jones & Morrow-Jones, 1991; Quarantelli, 1982). It might seem astounding that most people chose to return to damaged and destroyed houses in an obviously hazardous area. Researchers attribute this behaviour to a strong force termed "(emotional) *attachment to place*" that is inherent to people in more as well as less developed societies (Gold, 1980; Haque, 1997). Burton et al. (1993) hypothesize that in contrast slow-onset impacts, intensive events (as floods and tropical are) can be more easily "forgotten", especially if they occur at long intervals.

Despite the agreement on the small extent of migration, *references* for these statements are seldom given and often evidence is presented anecdotally, as for instance the account of Bangladeshi farmers that "were observed resettling offshore islands that two months before had been swept bare of any trace of human habitation" (Burton et al., 1993, p. 81). However, thorough search has yielded some empirical cases that are presented in the following.

Studies investigating the *intended* response of people to a natural disaster generally support the assumption that migration is not contemplated an option for most people from across very different cultural areas. In a study conducted in Florida (USA), for instance, *90 per cent* of the contestants indicated that they would *rebuild* their homes if they were ever destroyed by a hurricane (Cross, 1985, cited in K. Smith, 2001). The results are similar in the less developed Dominican Republic. Two weeks after being hit by hurricane David in 1979, *86 per cent* of study contestants thought they would continue living in their community and only 8 per cent wanted to leave (Belcher & Bates, 1983). The impression emerging from these two cases is supported by cross-cultural studies that were carried out in 18 different hazard sites (in 12 countries) (Burton et al., 1993). In *two thirds* of the sites, a change of location was *not mentioned as a response at all* and only in three sites was there a significant percentage (between *10 and 31 per cent*) of people considering migration. Notably, the hazard prevalent in all of these three sites was drought.

However, people's intentions are often not identical with their actual behaviour. The approach of examining *intentions* reflects the difficulty in generating relevant data. One of the largest problems in this task is that once the disaster event is over, it is very difficult to trace the movement of those who have left permanently. Only in one study found did the researchers concretely examine the *behaviour of disaster-affected people*. S. K. Smith and McCarty (1996) examined the demographic effects of hurricane Andrew (1992) on Dade County in Florida (USA) and found out that approx. *30 per cent of those initially displaced* left their homes permanently and 11 per cent left the county. In order to obtain information about those who had left the researchers surveyed 6'000 households and questioned them about their *neighbours' behaviour*.

Two major earthquakes in Central America were also examined with regard to the responses. The earthquake that devastated the Nicaraguan capital Managua in December 1972 and initially displaced about half of the population was examined by Burton et al. (1993). A population count two years after the event showed that the population of Managua had grown from 420'000 in 1972 to more than 650'000 in 1974. This was interpreted as an indication that presumably the *majority had returned* to their homes. Investigations on the earthquake that affected Guatemala in 1976 went a step further and interviewed people from damaged areas (Belcher & Bates, 1983). Two years after the event, slightly more than *90 per cent* were still *living in the same village* or town as before. However, a control group of people from *undamaged areas* was interviewed and surprisingly displayed the same results. So slightly more than 90 per cent of both the people from damaged *and* undamaged areas (92.2% and 93.0%

respectively) were still living in the same village or town as before (Belcher & Bates, 1983). This could indicate that the migration rate experienced after the earthquake is not higher than average population movement and may thus not necessarily be caused by the natural hazard.

To summarize, this sample of cases strongly supports the general assumption that most people do not contemplate migration as a response to natural disaster and also act according to these intentions. A share of virtually none up to about 30 per cent of the people initially displaced, do migrate permanently.

Migration Destinations

Very little of the natural disaster research has focused on the people that do not return to their homes (Morrow-Jones & Morrow-Jones, 1991). A study in the Ghaghara floodplain in India found that permanent migration was usually *within the floodplain* and only sometimes beyond it, and then to higher land fringing the flood plain (Kayastha & Yadava, 1985). A study of displacement induced by river bank erosion in Bangladesh also concluded that people do not move very far (Haque & Zaman, 1989): Interviews in one of the worst affected sub-districts showed that 60 per cent of the contestants had been displaced at least once in their lifetime and that of these, *97.8 per cent had moved less than five miles*[18]. However, these results must be interpreted with caution. By only interviewing people *in* the hazardous area about *previous displacement* the sample only contains people that are still vulnerable to the hazard but not people that might have fled the hazard for instance by migrating to far-away cities. The supposition of an upward bias in this study is supported by surveys in Bangladeshi urban slums (reported by Mahmood, 1995): up to 50 per cent of the squatter dwellers state that they had come to the cities due to river bank erosion.

Being extraordinarily prone to natural disasters (riverine flooding, drought as well as tropical cyclones) Bangladesh seems a suitable country to investigate the extent and the destinations of disaster-induced migration. Mahmood (1995) investigated migration in Bangladesh over the last decades. He found that next to prospects for better economic, social and educational opportunities at the destination, flooding, riverbank erosion, drought and tropical cyclones indeed *played a role* in internal migration. With regard to *international migration* however, the most important reason was "excess *demand for labour* in different parts of the world, whether explicit to labour import or implicit by allowing illegal migration" (Mahmood, 1995, p. 716).

The above already mentioned study on the effects of hurricane Andrew in Dade County revealed that two years after approximately 350'000 people had been displaced, 69 per cent had returned to their homes, 20 per cent had moved within the county, 7 per cent within the state and only 4 per cent moved out of the state of Florida (author's calculations based on the figures by S. K. Smith & McCarty, 1996).

The examples from India, Bangladesh and the USA suggest that of those who do migrate, the *majority moves very short distances* and that only *some move medium*

[18] Reasons offered were the high expenses for greater moves and a strong belief of the displaced that their land would re-emerge soon. The single most important factor for the choice of destination was the presence of friends and patrilineal relatives.

distances (in the cases presented: to higher lands in India, the cities in Bangladesh and outside Dade County in the USA). With regard to international migration, Burton et al. (1993) point out that the choice of destinations is often constrained by political barriers. The fact that international migration in Bangladesh was driven by demand is a clear indication that it is the immigration rules that are relevant and limit the realization of existing migration pressure.

Migration Reasons

Having established that certain migration occurs after natural disasters, the interest turns to the *reasons* and direct *causes* for the migration. By determining the main reasons for migrating, the link "backwards" to the indirect effects of the natural hazards can be made.

The link might seem relatively *simple*, as for instance presented by the study on hurricane Andrew: 90 per cent of the participants selected "structural *damages*" and "*loss of utilities*" (such as electricity, telephone and water services) as the primary reason for *initially* moving from their houses (S. K. Smith & McCarty, 1996)[19]. However, this does not directly answer the question what makes some of these people decide to migrate permanently. Results of the survey in the Guatemala show that *permanent migration did not depend* on the *extent* of *damaged* suffered: about 50 per cent of *both* migrants *and* non-migrants[20] had suffered heavy housing damage or destruction. These results were confirmed by the study in the Dominican Republic: the people's intention to continue living in their community did *not* depend on the extent of *damage* suffered to housing (Belcher & Bates, 1983). The researchers found that many of those intending to move permanently came from villages dependent on coffee production and that the hurricane winds had destroyed 80 per cent of the annual harvest. The thus triggered prospects of a *bleak economic future* were interpreted as being a strong reason to move[21]. This might indicate that it is the impact on the entire livelihood (i.e. not only housing, but also work and other aspects) of people that influences migration. Examples for such "other factors" can be extracted from the mentioned cases and other literature. For one, *people who have invested are less likely to migrate*. In this way, house-owners are less likely to migrate than renters (Belcher & Bates, 1983; Quarantelli, 1982). The same is valid for those companies or people involved in intensive resource uses, with high capital and/or labour investment (Burton et al., 1993). Another livelihood factor is that the *wealthier* and more *powerful* people are also *less likely to move* as they have the means to reconstruct their homes (Morrow-Jones & Morrow-Jones, 1991).

The above chapter on migration destinations also provides some ideas on migration reasons. The only example where migration took place to a very large extent is the case of river bank erosion in Bangladesh. Of those still living in the heavily affected sub-district 60 per cent had been displaced at least once and at the same time many city squatters attribute their migration to the cities to river bank erosion (Haque &

[19] Notably, 10 per cent quoted other reasons (unfortunately not specified in the paper).
[20] To be exact, 51.4% of the migrants and 51.9% of the non-migrants.
[21] In contrast, the other villages surveyed relied on other agricultural products that were not in the month of harvest or can be planted as many as three or four times a year.

Zaman, 1989; Mahmood, 1995). This suggests that it is the loss of land brought about by river bank erosion that is the crucial element in triggering sizeable migrations.

A new type of migrants related to a natural disaster was identified in the Guatemalan case (Belcher & Bates, 1983). Poor and landless people from *unaffected* rural areas moved to the cities, searching for potential disaster aid, housing[22] and/or employment in the reconstruction building boom. For these people, the motivation to migrate was not a push factor but clearly the economic opportunity presenting itself.

To summarize, the primary reasons for initially moving are the structural damage and the loss of utilities. However, it is not clear what factors determine the decision to migrate permanently. Surprisingly, the extent of damage does not appear to be very relevant. Factors that are assumed to influence the decision are (i) the extent to which opportunities to generate income have been affected; as well as (ii) the initial situation of the individual or household (wealth, power, prior investment into the home etc.).

5.2.4 Responses

The model presented focuses on establishing the possible connection between climate change, climatic natural hazards and migration. However, in determining whether *migration will take place or not*, alternatives to migration and general response options play an important role. There exists a wide range of responses – be it as immediate reaction or as long term preparation for the next hazard onset. People will usually rely on a *combination* of adjustments and within the same community, households will adopt different mixes (Burton et al., 1993). The range of adjustments can be divided into three types of strategies involving the modification of (i) the loss burden; (ii) the hazard event; and (iii) human vulnerability (K. Smith, 2001). Table 5.2 summarizes responses within these three categories for flooding as well as tropical cyclones (Remarkably, migration is only treated marginally, if at all). Among the responses presented, over the last decades the focus has shifted from engineering works towards a mix of the above strategies (Burton et al., 1993).

Table 5.2: Overview of responses to flooding and tropical cyclones (mainly based on the descriptions by K. Smith, 2001; complemented by information from Blaikie et al., 1994; Burton et al., 1993).

<table>
<tr><th></th><th>flooding</th><th>tropical cyclones</th></tr>
<tr><td rowspan="2">Loss-Sharing</td><td colspan="2">Disaster Aid: National relief and rehabilitation assistance and international disaster aid. Apart from cash donations, specialist external help is often important (for instance for electricity supplies and telephone systems).</td></tr>
<tr><td colspan="2">Insurances: Insurances of different types (flood insurance, crop insurance, etc.) are key loss-sharing strategies. As a reaction to major natural disasters, for instance Sri Lanka established a national crop insurance system and the USA subsidised flood insurances.</td></tr>
</table>

[22] For instance, squatters settlements were built, where no rent was paid and the residents de facto owned their houses.

Event Modification	***Weather Modification:*** At the present time there are no technologies to suppress storms or floods.	
	Flood Abatement: Watersheds can be modified, e.g. by reforestation or terracing.	
	Flood Diversion: Rivers can be redirected away from risk areas by engineering structures, such as levees, channels and detention basins.	***Storm Protection:*** Some protection is achieved by shore works, cross dams, protective plantings of trees along embankments, etc.
	Hazard Resistant Design: The flood-proofing of buildings includes raising living spaces above the likely flood level and installing watertight walls and doors. Temporary responses include blocking-up entrances, sealing doors and windows and removing damageable goods to higher levels. Sand bags are used to keep flood waters away from structures.	***Hazard Resistant Design***: Measures include better waterproofing of the roof, the use of hurricane clips for fastening roof cladding and sheathing or tying down house roofs and the fitting of storm shutters. In certain areas, the flood-proofing measures (see on the left) also apply.
Vulnerability Modification	***Forecasting and Warning:*** Systems of forecasting the natural hazard and warning the population have become widely applied and have proven effective in many countries.	
	Community Preparedness: This means knowing what specific actions to take upon warning (evacuation, emergency health, water and food supply, etc.). Such preparedness can be general (routine civil emergency arrangements) or specialised (flood or cyclone programmes).	
	Land Use Planning: Land use planning has been used to limit further floodplain development. In combination with such planning, building codes are increasingly being implemented.	***Land Use Planning:*** This important tool has proven difficult to implement because of the large desirability of waterfront locations.
	Vulnerability Modification on a Household Level: Households may build up stores of food and saleable assets, diversify their production strategy as well as their income sources and invest in social support networks.	
	Migration: This is a long-term strategy that can be adopted by individuals or governments that plan voluntary or forced[23] resettlements.	

5.2.5 Discussion: Floods and Tropical Cyclones

Within all linkages, knowledge gaps can be found, once they are examined in detail. In this context, it is especially the influence of climate change on tropical cyclones that stands out as an important knowledge gap. However, the influence was sure and direct enough to warrant a connection. All in all, the *connection* of climate change to migration via floods and tropical cyclones has proven *only partly possible*. The we*ak link* in the chain is the linkage to *migration*. As illustrated by the brace, the link is of a *very general nature*: the presented case studies link migration to the *occurrence* of hazard events and not to the *processes positioned directly in front* of migration in the connection model. This shows that it is not clear what factors really determine the

[23] Interested readers are referred to Blaikie et al. (1994) for an example of large-scale voluntary resettlement in Mozambique and Haque (1997) for references of forced resettlement in Peru and Belize.

decision to migrate permanently once a person has become displaced. Also, it is not known whether differences exist between migration behaviour after floods in comparison to tropical cyclones. The current information basis hardly just allows to draw conclusions for natural hazards in general. Thus, the *link to migration* is undoubtedly one of the greatest *knowledge gaps* in understanding the overall connection.

While mass displacements after a natural hazard is a phenomenon often reported, mass migration of the permanent type is seldom heard of. The case studies confirm this impression and suggest that a small share of *almost none up to about 30 per cent* of people affected by a natural hazard migrate. When assessing in which way climate change might influence migration, it must not be forgotten that climate change does not cause but only *increases or intensifies* natural hazards. Thus, in the light of projected changes regarding tropical cyclones (increase in peak intensities by 5 to 10%, increase in precipitation rates by 20 to 30%), it is not likely that climate change will trigger new mass migrations by means of tropical cyclones. A similar conclusion can probably be drawn with regard to floods, although more quantitative information on the increase of intense precipitation events would first have to be assessed.

Of great relevance in understanding the connection between climate change and migration is also the wide range of responses possible to floods and tropical cyclones. Comparing these responses to the actual connection model shows that once implemented, these response options can intercept many of the arrows (equalling connections) drawn. The flood connection model offers many examples for illustration:

- "heavy rainfall ➔ flooding" is also determined by watershed management and engineering;
- "flooding ➔ loss of crop" can be influenced by a diversification of crops as well as of the timing of sowing;
- "loss of crop ➔ less income" can be weakened by crop insurance systems;
- whether the connection "diseases ➔ fatalities" is realized depends heavily on the medical system; and
- "loss of housing ➔ migration" is dependent on many factors not (yet) determined.

Evidently, the outcome of the natural hazard not only depends on the hazard itself, but *also on the community* it affects. The way in which this community is structured, has knowledge and financial resources to its disposal and has prepared for such hazard events substantially influences the actual impact of the natural hazard. This is roughly the content of the *concept of vulnerability*. It is defined as the "characteristics of a person or group in terms of the capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard. It involves a combination of factors that determine the degree to which someone's life and livelihood is put at risk by a discrete and identifiable event in nature or in society." (Blaikie et al., 1994, p. 9).

The tropical cyclone that hit Bangladesh in 1970 can serve as another example to illustrate the concept. The cyclone was one of the most devastating of the century with a loss of at least 225'000 lives. The cause for such a disaster is not seen as simply lying in the atmospheric processes. Responsibility for the disaster was sought in many places (Burton et al., 1993):

– the government that encouraged people to populate very risky areas by reclaiming land from the sea with sophisticated technologies;
– those who contribute to population pressure;
– the uneven land relations resulting in large numbers of landless labourer that search for land and work near the coast;
– the public works "requested in Karachi, designed in Holland, and financed in Washington" that were built to stabilize shifting islands and keep out high tide and destructive salt; this encouraged settlement on these islands, that are very exposed and neither had storm protection nor evacuation plans;
– the poor warning system that failed to reach many Bangladeshi because officials failed to pass on the warning of the meteorologists and it was not broadcast on the radio.

If land relations had been less uneven, if land had not be reclaimed and islands had not been made habitable, and if the warning system had worked, the disaster would not have assumed the horrifying dimensions it did.

It is the local situation and the vulnerability of the population in question that *strongly influences whether the depicted connections are realized or not*. This is represented by the grey vertical bars in the connection models. Integrating this aspect yields the complete connection model (see Annex).

5.3. Sea Level Rise

While natural hazards have severely affected societies in the last centuries, sea level rise in its projected rate is a relatively new phenomenon for most world regions and largely attributable to climate change. Along the coasts of the world, there are more than *100 million* people that live within one meter of mean sea level (Zhang, Douglas, & Leatherman, 2004). In addition, coastal populations are growing twice as fast as the global population (Nicholls & Mimura, 1998). The number of people that are at risk of being of being affected by sea level rise (SLR) is *very large and growing*. The way in which the mechanism of SLR is considered to work is straightforward. For instance Leatherman (2001) states that "as land is lost because of SLR, there will be an increase of out-migration". The mechanisms is depicted in Figure 5.9: Climate change-induced sea level rise causes land loss which forces people to migrate. In a first approximation, many researchers estimate the number of displaced people by estimating the land area inundated by a certain projected SLR and determining how many people (will) live on this land (Jacobsen, 1988; Milliman, Broadus, & Gable, 1989; Myers, 1993).

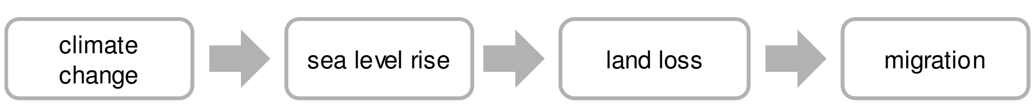


Figure 5.9: Schematic illustration of the postulated mechanism of sea level rise.

Black (2001) questions this plausible chain. He criticizes that there is no evidence of displaced populations due to recent SLR and points out that there is a variety of *adaptive responses* of which migration is only one. He emphasizes that "in general, calculating the population 'at risk' from SLR is a long way from predicting mass flight" (R. Black, 2001, p. 8).

5.3.1 Climate Change ➔ Eustatic Sea Level Rise

In the 20th century, the eustatic sea level[24] has risen 1 to 2 mm per year, a rate significantly higher than the average rate of the last millennia. The IPCC projects it to further rise by 0.09 to 0.88 metres between 1990 and 2100 with a central value of 0.48 metres (Church et al., 2001; IPCC, 2001a). The way in which climate change influences eustatic sea level is depicted in Figure 5.10 and further described below.

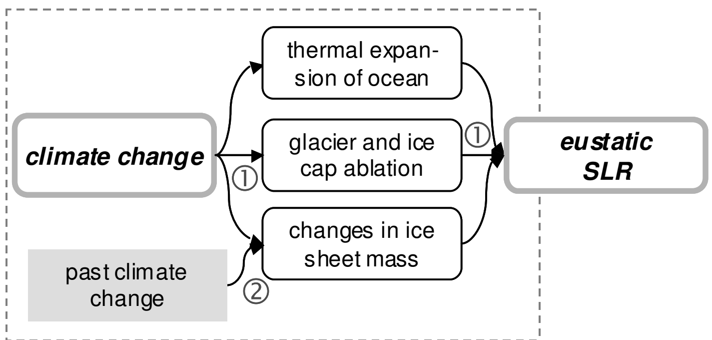


Figure 5.10: Connection model of the influence of climate change on eustatic sea level rise. The entire model is to be found in the Annex.

① *Linkage*

Climate change affects the sea level by changing the volume of water in the oceans, i.e. it affects the *eustatic* sea level. It does this in three main ways (Church et al., 2001):

– The warming of the atmosphere leads to a warming of the oceans through heat transfer which makes the *oceans expand* (given the same mass, warm water has a larger volume than cold water) and thus the sea level rises.
– A second factor is the exchange of water between oceans and *glaciers or ice caps*. The ablation of these ice masses increases the volume of total water in the oceans.
– Finally, there is also an exchange of water between the oceans and the large *ice sheets* (Greenland, Antarctica). Processes affecting the volume of ocean water include ablation, ice discharge, precipitation over the ice sheets and run-off. Whereas Greenland is expected to contribute to SLR, Antarctica is predicted to counteract this effect by growing due to increased precipitation.

[24] "Eustatic" sea level change is that which is caused by an alteration to the volume of water in the world ocean or the volume of the ocean basins.

② *Long-term Effects*

Current and future changes in the mass of ice-sheets are not only caused by recent or current climate change. Significant changes are still taking place and will continue to do so as long-term adjustments to past climate changes – specifically to the glacial-interglacial transition that has been taking place in the last 20'000 years (Church et al., 2001).

5.3.2 Eustatic ➔ Relative Sea Level Rise

If eustatic mean sea level were to rise 50 cm over the next century, this would *not* result in *coastal lines* worldwide lying 50 cm above their current levels by 2100. For instance, in the course of the 100 years, in some regions the land itself can be uplifted which also affects the coastal line. The *relative* sea level (i.e. the level of the sea relative to the land) is affected by mean sea level rise as well as the vertical movement of land. With regard to the *impacts* of sea level changes on natural and socio-economic coastal systems, it is the *relative* sea level that is *relevant* (Klein & Nicholls, 1998; Milliman et al., 1989). The different factors and processes that influence relative SLR (also named observed or local SLR) in addition to eustatic SLR are presented in Figure 5.11. How large an effect such factors can have is illustrated by the fact that of the 20 coastal megacities[25] projected by 2010, eight have already experienced a relative rise in sea level which exceeds likely eustatic sea level rises, for instance Tianjin with an average subsidence of *five cm per year* in the late 1980s, primarily due to water extraction (Nicholls, 1995)[26]. These factors are relevant on a worldwide basis – see Figure 5.12 for coasts that have subsided significantly during the last century.

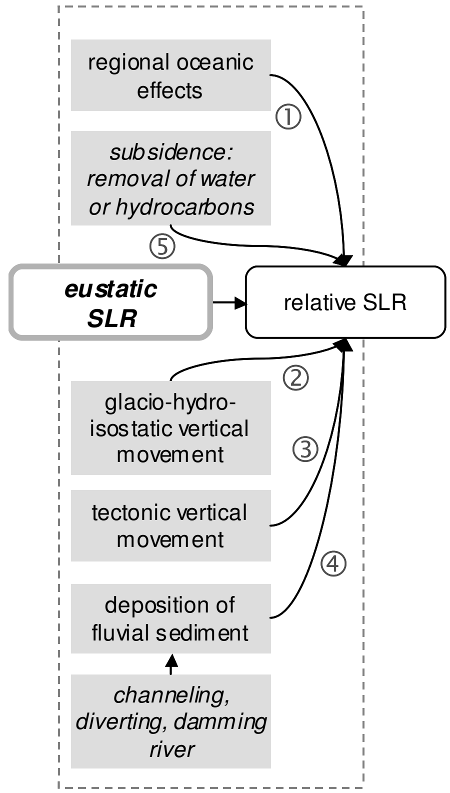


Figure 5.11: Connection model of the connection between eustatic and relative sea level rise.

① *Regional Oceanic Effects*

The mean eustatic SLR does not distribute itself evenly across the globe. While some regions are confronted with a rise that is substantially higher than average, other regions are predicted to experience lower rises (Church et al., 2001).

[25] Megacities are considered cities with a population exceeding 8 million people.

[26] Tianjin (and Shanghai) now have city areas lying beneath high tides and have constructed extensive dike systems. Also, they have aimed at controlling water withdrawal (Nicholls & Leatherman, 1995).

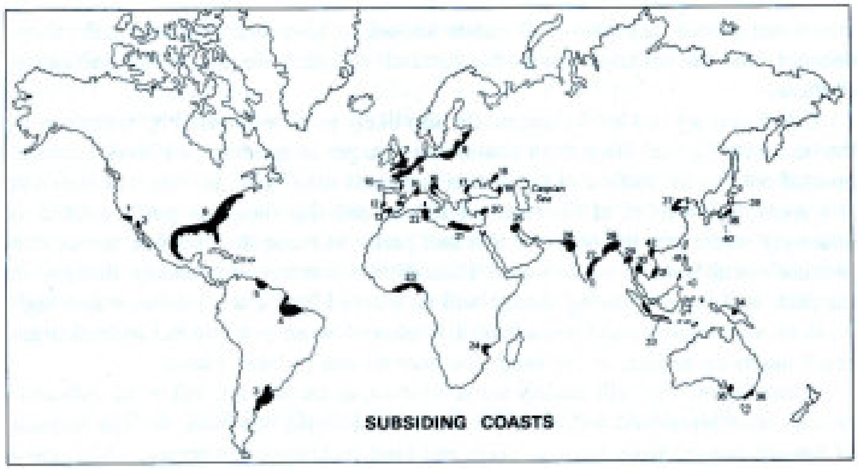


Figure 5.12: An overview of subsiding coasts worldwide. Those coasts are denominated that exhibit a subsidence of more than 2 mm per year over the last century and evidence for continuation of this subsidence (Bird, 1995).

② *Glacio-Hydro-Isostatic Vertical Movement*

On time-scales of tens of thousands of years, glacio-hydro-isostatic effects are very important processes for the sea level. The *varying loads of ice* and water on the continents cause vertical land movements (Church et al., 2001). Today, such movements influence the relative sea level, as for instance in Scandinavia where the land masses are being uplifted as a result of deglaciation and the associated loss of weight ("isostatic rebound").

③ *Tectonic Vertical Movement*

On large time scales, the tectonic plates of the lithosphere are in motion and can lead to uplift or subsidence of land masses.

④ *Deposition of Fluvial Sediment*

On medium time scales, when fluvial sediment reaches the coast it is *deposited* and can lead to an *accumulation* at the shore front. This causes a change in the coastal line and relative sea level (Milliman et al., 1989). Large deltas have been formed at large estuaries where the rate of sedimentation is higher than the subsidence typical for deltas (as for instance the Nile delta in Egypt, or Bangladesh that for great parts lies on a delta of three major rivers). This effect, however, is *counteracted* in some regions by the channelling, diverting or damming of the river, which prevents the fluvial sediment from reaching the coast (Milliman et al., 1989).

⑤ *Subsidence through Removal of Water or Hydrocarbons*

Human activities can also influence the local sea level. The extraction of *water or hydrocarbons* from underneath coastal areas can lead to subsidence. Another human activity that causes subsidence is the draining of peat deltas for agriculture because the contact of the organic soils with the air trigger their oxidation.

These influences open the range of possible future sea level changes considerably. Where an isostatic uplift is combined with low regional effects eustatic SLR may be *compensated*. In contrast, in delta areas where the river has been dammed and with high regional effects and groundwater extraction, the observed SLR will lie well *beyond* the global mean.

5.3.3 The Direct Effects of Relative Sea Level Rise

Regarding the impacts of relative SLR, it is possible to fall back on recent and current case studies, because local subsidence has occurred in many places. From a societal perspective, the six most important biogeophysical effects of relative SLR, irrespective of its causes, are increasing flood-frequencies, erosion, inundation, rising water tables; saltwater intrusion and biological effects (Klein & Nicholls, 1998; Nicholls & Leatherman, 1995).

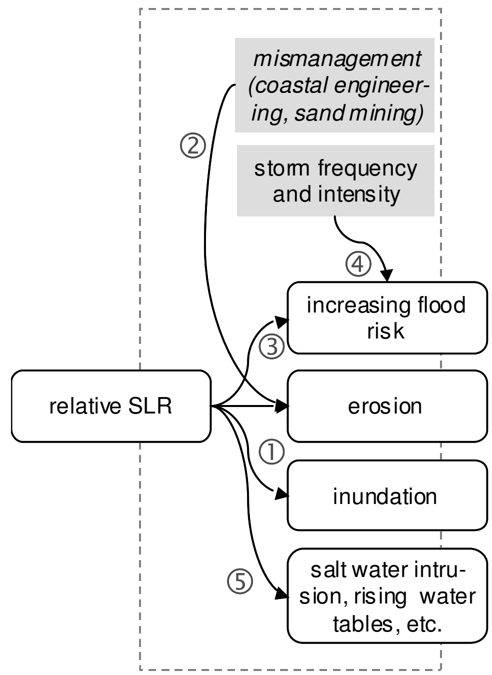


Figure 5.13: Connection model of the biogeophysical effects of relative sea level rise.

① *Inundation and Erosion*

Inundation is the permanent submergence of low-lying land and follows as a direct consequence of relative SLR. *Erosion* in this context is the physical removal of sediment by waves and currents (Klein & Nicholls, 1998). Erosion and inundation are closely related and often confused in the literature, although there are important differences between the two. In contrast to inundation, erosion necessarily involves a *movement of sedimentary material*. The main erosion effects happen in discrete time steps in the form of *storms* (Pilkey & Cooper, 2004). In a detailed study, Zhang, Douglas and Leatherman (2004) confirmed that *SLR indeed induces beach erosion* and also substantiated the general assumption that, on average, the erosion rate is about two orders of magnitude greater than the rate of SLR[27]. Relative SLR causes beach erosion by *enabling* waves to break closer to shore and *to act farther up the beach profile* (Leatherman, 2001).

② *Mismanagement*

Beach erosion has been found to be substantially caused by *human activities*. On Fiji, coastal inhabitants cleared mangroves for fuel wood and land reclamation and used beach sands intensively for construction material (Mimura, 1999). Schnack (1993) similarly found that beach erosion on the east coast of South America was often

[27] This means that if sea level were to rise 10 cm this would lead to a retreat in sandy coastal line of approx. 10 metres, all else constant.

caused by mismanagement, as for instance the mining of beach sand for construction purposes. Also, engineering structures that *successfully* protected the *targeted* beaches were found to be causing *erosion* in *adjacent* beaches.

③ *Flood Risk*

The height of storm surges is influenced by the local sea level, the normal astronomical tides and the storm itself (Flather & Khandker, 1993). Thus, relative SLR causes increasing flood levels which leads to increased flood risk (for references, see Nicholls, Hoozemans, & Marchand, 1999). Figure 5.14 shows the areas most vulnerable to coastal flooding for the 2080s with the number of average annual people flooded (Nicholls et al., 1999). The underlying assumptions are that the atmospheric CO_2 concentration is 731 ppm, that there is a rise of *eustatic sea level of 38 cm* from 1990 to 2085 and that *protection evolves concomitantly* to the rising sea level (Nicholls et al., 1999). According to these calculations, the average *annual people flooded* by the 2080s would amount to *93 million*, more than five times more than the 13 million in the reference scenario without SLR.

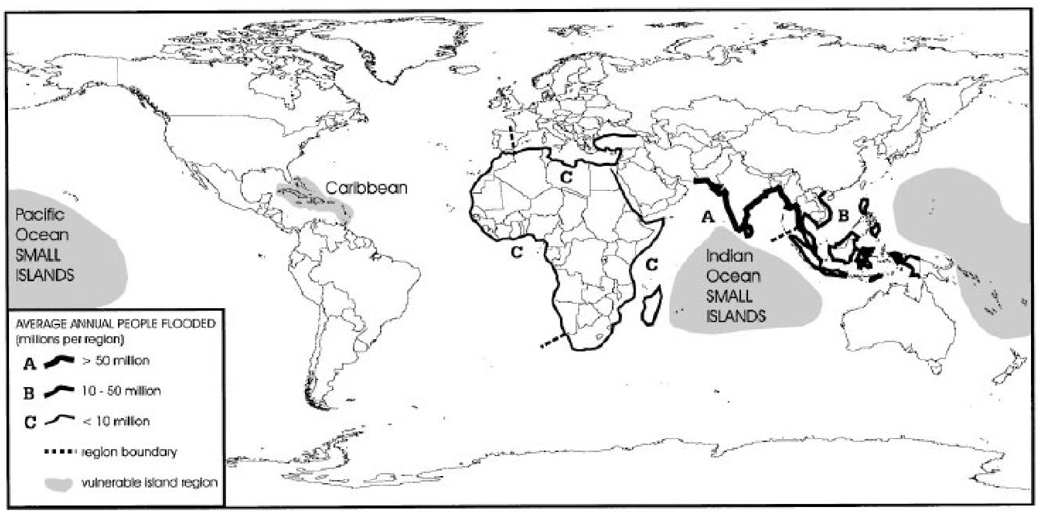


Figure 5.14: Areas vulnerable to coastal flooding for 2080s assuming an eustatic sea level rise of 38 cm and an evolving protection (Nicholls et al., 1999).

④ *Storm Frequency and Intensity*

As mentioned above, the height of storm surges also depend on the storms themselves. Should they become more frequent or more intense, this will also influence the flood risk. As stated in Chapter 5.1.2, the IPCC does not forecast tropical cyclones to occur more frequently but does predict an increase in tropical *cyclone peak wind intensities as well as mean and peak precipitation intensities* in some regions of the world.

⑤ *Other Effects*

SLR also has other important effects, such as biological effects, rising water tables and salt water intrusion. These are not considered primarily relevant for migration, even though they could influence it indirectly. For instance if groundwater and surface water is displaced with saline sea water, drinking water supplies are threatened and agricultural use of the water is restricted (Klein & Nicholls, 1998).

5.3.4 Indirect Effects

① *Land loss*

Both inundation and erosion lead to land loss. Erosion involves complex physical reorganization of materials (Pilkey & Cooper, 2004) that ultimately leads to an offshore transport of the sand. It is the dominant process in causing land loss for *open-ocean* beaches. In contrast, *inundation* is the main cause for land loss of *sheltered coasts*, for instance for coastal marshes or lagoons (Leatherman, 2001). On steep, rocky coasts, sea level often does not cause significant land loss at all.

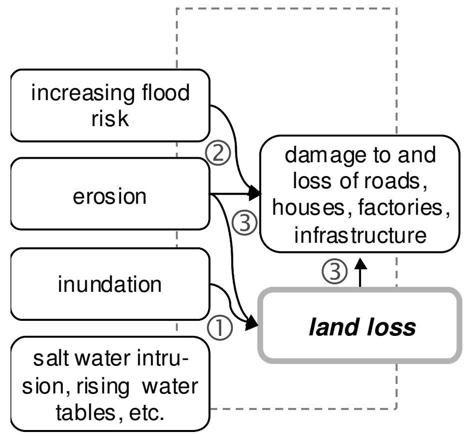


Figure 5.15: Connection model of the further reaching effects.

Nicholls and Leatherman (1995) investigated the effect of eustatic SLR (by the year 2100) on the coastal systems of developing countries. They calculated the land at risk of being lost by inundation and erosion. Subsequently, they calculated how many people lived on this land and termed these as "population at risk". Table 5.3 illustrates their results: Four vulnerable countries alone, Bangladesh, China, Egypt and Nigeria have an estimated population of *over 90 million at risk*. Taking expected population growth into account would lead to an ever higher figure. However, actual projected SLR by 2100 is below 1 metre (see page 63). Furthermore, *100 years* give a lot of time for *human response*, and as the authors point out, "protection is both feasible and likely in many cases".

Table 5.3: Land at risk of being lost from a 1 metre sea level rise, and population living on this land that are thus at risk of being displaced (adapted from Nicholls & Leatherman, 1995).[28]

Country	land at risk	population at risk	
	in %	in millions	in %
Bangladesh	17.5	**13**	11
China[29]	1.3	**72.0**	6.5
Egypt	12 to 15	**6.0**	10.7
Nigeria	2.0	**3.2**	3.6
Senegal	3.1	0.1 to 0.2	1.4 to 2.3
Uruguay	<0.1	0.01	0.4
Venezuela	0.6	0.06	0.3
Total		**94.4 to 94.5**	

[28] The numbers are for present population, i.e. population growth in the future is not accounted for.
[29] For China, land and population at risk includes increased flooding due to sea level rise.

② *Effects of Flood Risk*

An "increased flood risk" will affect the population in different ways. Some people will become located in the new enlarged coastal flood plain, i.e. they are at risk of being flooded every 1000 years. For others, their risk of being flooded *increases* from every 20 to every 15 years while those located even nearer to the coastal line might face the new situation of experiencing a flood three times a year. And in the most extreme case, "some would drown" (Klein & Nicholls, 1998, p. 18). Equally diverse as the increases of frequency are the effects that a flood can have: they can range from virtually no damage (a temporarily lightly flooded road) to serious damages and even loss of houses, factories and infrastructure.

③ *Damage to and Loss of Roads, Houses, Factories, Infrastructure*

In the area of impacts the causal connections become difficult to pursue in a detailed manner. Many authors list socio-economic impacts of SLR but they are seldom directly brought into relationship with the underlying biogeophysical effects. Impacts mentioned are the *capital loss* of houses, roads, factories and infrastructure and with it the *lost productive capacity*, be it agricultural, residential, tourism, recreation or industrial (McLean, Tsyban, Burkett, Codignotto, Forbes, Mimura, Beamisch et al., 2001; Titus, 1993). Next to the loss of economic values through loss of land, the loss of *ecological, cultural and subsistence values* is also mentioned (Klein & Nicholls, 1998).

The degree of damage can vary considerably and can be caused by storm winds, the floods accompanying the storm, the loss of land or direct erosion. But can they be clearly distinguished? If storms are the mechanism with which erosion act, to which is the damage to be attributed? Erosion causes loss of land. But does it also cause damage without the loss of land? There are many open questions to which answers are not readily found in the SLR literature.

5.3.5 Migration

In the literature, this last link to migration is hardly ever *specifically examined* but rather just touched upon. Some take the connection for granted and give no further explanation (as for instance Myers, 2002; Nurse et al., 2001). Nicholls et al. (1999) is slightly more specific in assuming that if people are flooded by a storm surge more than once per year, the damages would be above the "nuisance level" and *some type of response*, as for instance migration, is required and expected.

Only two (and rather meagre) specific cases were found in this context:

- In the first decades of the 20th century, large areas of the Chesapeake Bay islands (USA) were inundated what led to widespread abandonment of settlements (Leatherman, 2001).
- In Ghana, coastal erosion is reported to have destroyed houses in the small town of Keta in 1995. This forced "about 20 families to be temporarily accommodated in tents on the beach" (Hens & Kwesi Boon, 1999, p. 342). Unfortunately, no reference is given and so it is impossible to find out if after

their "temporary accommodation", these families rebuilt their houses or migrated (and if so where to).

The migration *destination* is an aspect raised in some articles. Moore and Smith (1995) see the developed countries as the destination in the specific case of small island nations in the south-west Pacific ocean. They conclude that while migration *pressures* would further grow (partly as a result of climate change) significant out-migration would probably only occur if *developed countries* relaxed their *immigration regulations* for Pacific islanders. Myers (1993, p. 201) sees the developed countries as a destination not only for islands but in general and argues that "the refugees would feel justified in seeking sanctuary in developed nations on the grounds that it would be the developed nations that would have largely set up the problem of global warming." Döös (1997) argues on the contrary and predicts what could be called a *domino migration*: people that experience permanent flooding would have no choice but to move further inland, thereby increasing the population density and causing migration from there.

5.3.6 Responses

> *"Unless the rate of inundation is very gradual, it is ridiculous to imagine that people would passively accept such losses."*
>
> *(Broadus, 1993, p. 272)*

The message in Broadus' blunt words is clear: response options play an important role in determining the effects of SLR. And with it, whether migration will take place or not. Regarding SLR, response strategies can be divided into three categories (Klein & Nicholls, 1998, p. 25):

- *Managed Retreat* emphasizes "progressive abandonment of land and structures in highly vulnerable areas and *resettlement* of inhabitants".
- *Accommodation* emphasizes "conservation of ecosystems harmonised with the continued occupancy and use of vulnerable areas and *adaptive* management responses".
- *Protection* emphasizes "*defence* of vulnerable areas, population centres, economic activities, and natural resources".

The variety of strategies possible within these three categories are listed in Table 5.4. The choice of response depends strongly on the specific situation. Retreat would be a viable option for sparsely developed coasts, but hardly for urbanized or other areas with a very high concentration of values (Leatherman, 2001). In this context, Titus (1993) points out that in general, developing countries are more flexible in their response, because unlike more developed countries, high-investment development and concentration of values hast not (yet) occurred.

In the past, such protection measures were in the focus of attention. However, protection is not the universal remedy for SLR and holds certain dangers:

- Hard protection structures might encourage the construction of houses and infrastructure too near to the coast (Leatherman, 2001).

– As pointed out in the above chapter on mismanagement, engineering structures might have negative side effects on adjacent beaches.
– Very importantly, while the sea level continues to rise over the next centuries, such protection measures are temporary as they need reconstruction and reinforcement after a few decades (Leatherman, 2001).

Table 5.4: Response strategies available to relative sea level rise (adapted from Klein & Nicholls, 1998).

Response strategy	Type of adaptation		Timing of adaptation	
	Autonomous	Planned	Reactive	Pro-active
Managed Retreat				
– no development in susceptible areas	✓	✓		✓
– conditional phased-out development		✓	✓	✓
– withdrawal of government subsidies		✓	✓	✓
Accommodation				
– advanced planning to avoid worst impacts	✓	✓		✓
– modification of land use	✓	✓	✓	✓
– modification of building styles and codes	✓	✓		✓
– protect threatened ecosystems		✓		✓
– strict regulation of hazard zones		✓	✓?	✓
Protection				
hard structural options				
– dikes, levees, and flood walls	✓	✓	✓	✓
– seawalls, revetments and bulkheads	✓	✓	✓	✓
– groynes	✓	✓	✓	✓
– detached breakwaters		✓	✓	✓
– floodgates and tidal barriers		✓	✓	✓
– saltwater intrusion barriers		✓	✓	✓
soft structural options				
– beach nourishment (see Figure 5.16)		✓	✓	✓
– dune restoration and creation		✓	✓	✓
– wetland restoration and creation		✓	✓	✓
– afforestation	✓	✓		✓

5.3.7 Discussion: Sea Level Rise

What becomes apparent by means of the connection model is that it is *not as simple* as sometimes postulated. First of all, the SLR that is *relevant* for the impacts is not the eustatic, but the *relative* one, which is *influenced by many other factors*. In many cases, relative SLR is projected to be higher than the eustatic one. In general, the connection between climate change and migration via SLR has been only achieved to a certain extent. Eustatic sea level has already risen and is projected to *rise further*. The eustatic rise *significantly influences* the locally relevant *relative* SLR. This will lead to an increasing flood risk, erosion and inundation along many coasts of the world. Moreover, many of the external factors exacerbate these impacts rather than cushion them – be it the damming of a river, subsidence due to water removal or sand mining. However, the last link to migration – though exceedingly plausible – has not been able to be based on a reliable source or case studies. In this context, human *response strategies* play a *great role* and can certainly also prevent migration. Although relative sea level has risen significantly in some regions affecting coastal communities independent of climate change, *migration hardly seems to have been studied*. The knowledge gap that has become apparent in this case is even larger than that concerning natural hazards. In order to obtain even only the dimension of migration to be expected from projected sea level rise, *numerous case studies in coastal regions affected by relative sea level rise in the past have to be carried out*.

The knowledge gap in SLR is larger not only concerning migration, but also with regard to the *socio-economic impacts* in general, as can also be seen in the structure of the connection model (see Annex). This finding is confirmed by the IPCC (McLean, Tsyban, Burkett, Codignotto, Forbes, Mimura, Beamisch et al., 2001) that states that progress on *socio-economic* impacts of SLR has neither been very substantial nor especially comprehensive. Depicting these impacts proves difficult due to the different time scales on which SLR acts. For instance a flood is an event limited in time with very unmistakable direct effects. In contrast, sea level rise is a process that has very slow and constant direct influences (as inundation), but also acts in discrete time steps via storms and consequent flooding. This makes is difficult to depict SLR effects in the connection model. However, the model could be improved by searching for more information within literature on coastal erosion and coastal storms.

Table 5.5: Three scenarios of sea level rise and related erosion rates for sandy beaches projected from 1990 to 2100.[30] The erosion rates are by no means exact figures but serve the sole purpose of giving the reader a sense for the order of magnitude.

Scenario	**sea level rise**		**erosion rate for sandy beach**	
	total	*average per 5 years*	*total*	*average per 5 years*
low	9 cm	0.4 cm	10 m	0.4 m
medium	48 cm	2.2 cm	50 m	2.2 m
high	88 cm	4.0 cm	90 m	4.0 m

The long time scales mentioned are made more palpable when examining Table 5.5 that shows an overview of projected SLR and related erosion rates from 1990 to 2100. Averaging the medium scenario total SLR (the central value of the IPCC (2001a) projections) over the 110 years renders roughly *two centimetres every five years*. Translating these figures into erosion rates is very dependent on the coast. For instance in a detailed study of Gambia, coastal retreat as a result of a one metre SLR was estimated to lie between 60 and 840 metres (Jallow, Barrow, & Leatherman, 1996). As a rule of thumb for a *first approximation*, the rule of two orders of magnitude was applied in Table 5.5. This results in an erosion rate of approx. *2 metres*

[30] Calculation: In order to create the scenarios, the lower and upper boundary as well as the central value of the projected sea level rise for 1990 to 2100 (IPCC, 2001) were used. A very coarse estimate of possible erosion was simply calculated by applying the rule that erosion is two orders of magnitudes higher than the sea level rise, as set out above in the chapter on erosion.

every five years for the medium scenario (or 4 metres for the high scenario). Whether SLR changes occur gradually along sheltered coasts or in the form of storms along open coasts, a rise of one metre (a measure often applied in studies) will *not take place from one day to the next*.

Given (i) the available scientific *knowledge* that serves as early warning and (ii) considerable *time* spans in which to react, it can be assumed that the population and the governments *will react* with a variety of the responses presented above. As in the case of floods and tropical cyclones, also the responses to SLR might interrupt some of the connections. For instance, the arrow between relative SLR and inundation or erosion is not realized if seawalls are built. Also, even if land is lost, this does not inevitably lead to migration. Instead, land might be reclaimed with beach nourishment (see Figure 5.16). However, the choice of response as well as prevention strategies does not only depend on the specific coastal features and the population density, but also on a country's human, technological and financial resources (Klein & Nicholls, 1998). Again, the importance of the concept of vulnerability becomes apparent.

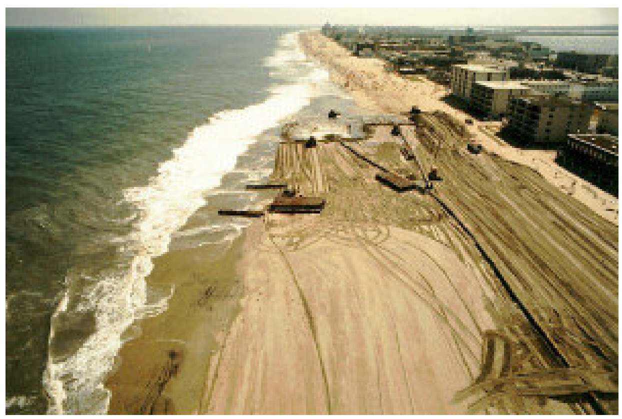


Figure 5.16: Example of a protection option: beach nourishment in Ocean City, USA (Rutgers Institute of Marine & Coastal Sciences, 2001).

Especially but no only in the developed countries, response options preventing migration is possible and probable – however, it has to be noted that sea level will continue rising for hundreds of years and, once built, protection measures will have to be not only maintained but also reconstructed and reinforced periodically – with the related costs. Migration might thus become more probable in the long run in view of increasing costs and efforts required for the protection options.

5.4. Droughts

Droughts, like floods and tropical cyclones, are considered *natural hazards* influenced. However, they differ in important ways and are regarded as among the most *complex* natural hazards (Wilhite, 2000). A drought is a "creeping" phenomenon and develops *slowly* which makes it difficult to determine its onset and end. Drought impacts *accumulate* and magnify the longer the conditions are sustained. In addition, the area affected is usually much greater than for other natural hazards.

The fact that no universal definition of "drought" exists – because each discipline has developed its own – leads to a great deal of confusion (Wilhite, 2000). Generally, three different drought types are recognized: meteorological, hydrological, and agricultural drought (K. Smith, 2001; Wilhite, 2000). What they have in common is that they are all initially caused by a *relative shortage of water*.

– *Meteorological drought* is solely related to precipitation and defined by the deficiency of *precipitation* from the average amount received over a period of time.
– In contrast, *hydrological drought* depends on local *water supplies* and is defined by a reduction in stream flow and ground water levels (or the levels of lakes and reservoirs). It can continue for a long time after a meteorological drought has terminated, as the refilling of reservoirs is a slow process.
– The definition of *agricultural drought* is based on an altogether different approach. It occurs when average *crop growth* and yields cannot be maintained due to water deficiency. Agricultural drought is mostly defined by *soil moisture* (and not precipitation), as this is the most important factor in determining crop yield potential. The soil moisture required is crop-specific and also depends on the growth-stage of the crop grown[31].

Even though these three types of drought are widely agreed upon, many statements on drought can be found that do not specify which drought they mean. It is not uncommon to find texts first explaining the differences between the three types of droughts only to continue the passage with assertions about droughts of an unspecified type.

The way in which drought (of an unspecified type) is assumed to cause migration is not as straightforward as in the other connection models. Some refer to the events in Africa in the 1970s and 1980s as evidence for drought-induced migration, and simply postulate that "droughts forced millions of people to migrate" without making the mechanism explicit (El-Hinnawi, 1985; Hugo, 1996; Jacobsen, 1988). Magadza (2000) is more specific by stating that in sub-Saharan Africa droughts often translate to famine that leads to migration. Döös (1997, p. 56) goes a step further by declaring that "in case extensive droughts occur, the question is not so much if, but rather when, famines will occur". The chain implicit in these two statements is that when droughts occur, crops fail, people go hungry, and migrate in search for food. These views are illustrated and brought into connection with climate change in Figure 5.17.

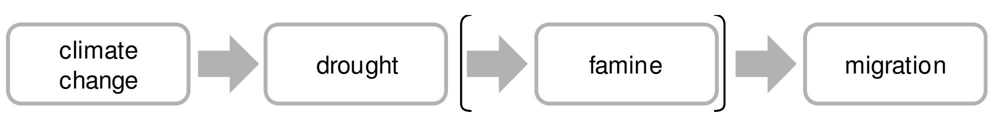


Figure 5.17: Schematic illustration of the most simple postulated connection between climate change, drought and migration.

However, this simplistic view is not universally shared. In the context of migration from semi-arid regions and famine, *land degradation* is very often also mentioned as

[31] For instance, when soil moisture deficiency occurs specifically at a vulnerable crop growth stage, this may constitute an agricultural, but neither a hydrological nor a meteorological drought.

important causal agent. However, there are many different opinions as to the causes and impacts of land degradation as well as its connection to drought. For instance, some state that human-induced land degradation contributes to drought (IOM & RPG, 1992), while others assert that drought contributes to land degradation (Ramlogan, 1996). While Ramlogan (1996) sees *desertification* and deforestation as *reasons for land degradation*, for others *desertification is the consequence* and most severe form *of land degradation* (Jacobsen, 1988; Westing, 1994). It becomes apparent that not only drought, but also the terms "land degradation" and "desertification" have different meanings and definitions, and are in some cases presumably used carelessly as catchwords.

5.4.1 Climate Change ➔ Drought

① *Climate Change ➔ Hydrological and Agricultural Drought*

Climate change is expected to increase summer continental drying and the associated *risk of drought* in most mid-latitude continental interiors (IPCC, 2001b). In this context, drought is defined as general summer drying and a *reduction in soil moisture*. As in the case of the other natural hazards, this insight is the result of simulations of the latest generation of AOGCMs and can thus only exhaustively be explained by the myriad of processes represented in the models. However, in general, the drying is attributed to a "combination of increased temperature and potential evaporation not being balanced by precipitation" (Cubasch et al., 2001, p. 573). A study investigating this topic found that the probability for long dry spells (one of the drought indicators), increased due to a reduction of rainfall *events* and not *mean* precipitation (J. M. Gregory, Mitchell, & Brady, 1997).

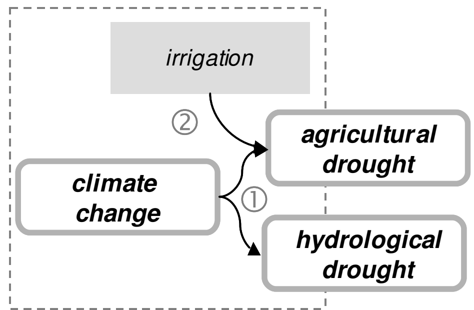


Figure 5.18: Connection model of the influenceof climate change on drought. For the entire connection model, see the Annex.

① *Irrigation ➔ Agricultural Drought*

As agricultural drought depends on soil moisture and not precipitation, irrigation can prevent agricultural drought in the case that enough water is available. However, poor irrigation practices can also lead to land degradation (see next chapter).

5.4.2 Direct Effects

① *Crop and Range Plant Decline*

Water is the most important factor for plant growth. The water is necessary to *replenish* the water lost by transpiration and also to transport nutrients into the plant. If the plant absorbs less water than it looses by transpiration, *wilting* will occur and eventually the plant will die. Plants react to water stress by *reducing growth*, for instance by decreasing the size of leaves. In this way, drought leads to a general *decrease in dry matter and seed yield* relevant for both the productivity of crops and range land (Salinger et al., 1997). In addition, the crop yield is decreased because under water stress, plants are more susceptible to pests and diseases (Wilhite & Vanyarkho, 2000).

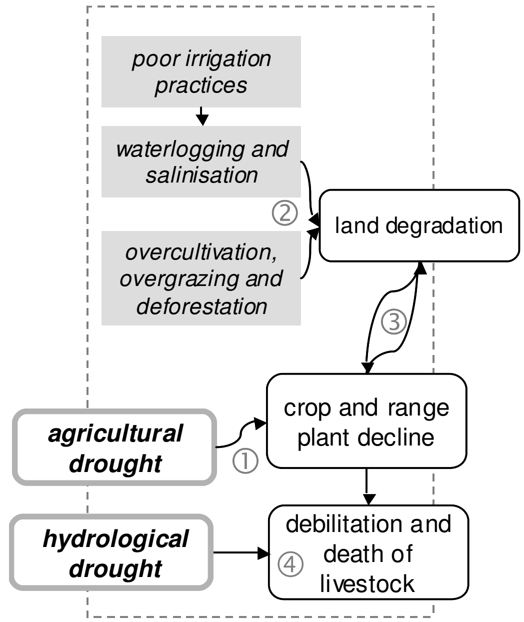


Figure 5.19: Connection model of the direct effects of drought.

Plant growth is also influenced by other climate change effects. In general, increased CO_2 concentrations can stimulate growth, but the effect depends not only on the species but also the interaction of the CO_2 effect with temperature, water availability, etc. (Arnell et al., 2001).

③ *Land Degradation*

Land degradation is defined as the reduction or loss of the biological and economic *productivity* and complexity of land[32]. It refers to both the degradation of the *soil* as well as the *vegetation* and caused by *drought* as well as *human activities*. The latter are considered the main cause as they impedes the natural restoration process that enabled drylands to recover from droughts in the past (Dregne, 2000). These human activities include poor irrigation practices, overcultivation, overgrazing and deforestation that are described briefly in the following:

Poor irrigation practices might lead to waterlogging and/or the salinization of soils. In the case of *waterlogging*, water accumulates in poorly drained soils due to excessive irrigation, making the water level rise. When it reaches the root zone, the air spaces in the soil are filled and prevent plants from obtaining oxygen. *Salinization* occurs when salt accumulates in the soil. When soil water evaporates and is not transported downwards, e.g. in poorly drained soils, the salts present in the water accumulate in the upper soil horizons. High salt concentrations limit the availability of water for plants.

[32] As defined by the United Nation Convention to Combat Desertification.

Overgrazing occurs when plants are grazed to the point where their energy reserves are depleted and cannot persist, exposing soils. Overgrazing can be caused by allowing animals to graze during fast growth periods of the plants or by not allowing the plants to fully recover in between two grazings. Similarly, o*vercultivation* occurs when land is used more intensively than permitted by its natural fertility. It can be prevented by fallowing the land (natural fertility regeneration) or by compensating by means of fertilizers. In dry areas trees and open woodlands play a vital role in stabilizing soil and water. *Deforestation* removes this protection, exposing the soil to water, wind and rain.

② *Crop and Range Plant Decline ➔ Land Degradation*

By decreasing crop cover, droughts increase the erosion susceptibility of the soil and lead to and increase in wind and water erosion (Dregne, 2000). In a vicious circle, land degradation, i.e. the reduced productivity of the land, leads to a low crop and range cover.

④ *Debilitation and Death of Livestock*

The most important affect of drought on livestock is usually indirect through its effect on crop and range plant decline. The quality and quantity of fodder is influenced and can lead to a debilitation and malnutrition of the livestock, as does low availability of water. Such debilitation makes the animals more susceptible to pests and diseases (Kay, 1997; Salinger et al., 1997).

5.4.3 Indirect Effects

① *Less Work, Reduced Income and Reduced Food Availability*

The effect of the reduction of crop yields due to drought can be compared to the effects depicted in the case of flooding. Farmers laying off workers may lead to the loss of a job which contributes to a reduction of income which can also be directly be induced by the low yields in crop and livestock production. Low income and a decreased crop yield can cause reduced food availability (Wilhite & Vanyarkho, 2000).

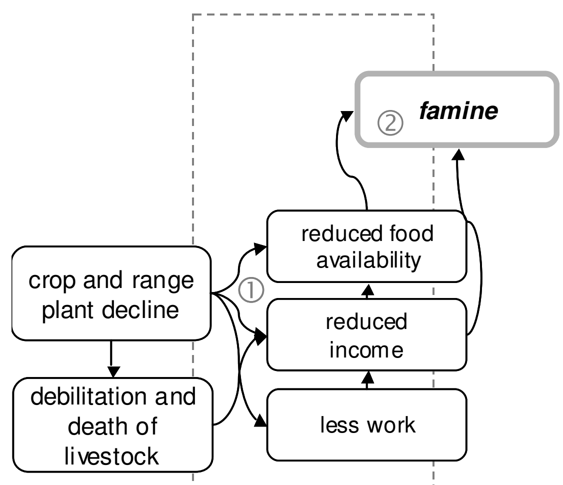


Figure 5.20: Connection model of the indirect effects of drought.

② *Famine*

Drought can act as a trigger for famine by reducing the own production and reducing their income to buy food. However, the question of how large the contribution of drought in fact is, is addressed in the discussion.

5.4.4 The Link to Migration

Migration Extent

Drought is readily associated with migration in the minds of many. This general assumption is presumably based on a number of cases in which drought coincided with migration. Cited examples are:

- the great drought in the Sahel from 1969-1974, where millions migrated and the population shifted southward and to the cities (Findley, 1994);
- the mass rural-urban migration of men in search of work in north-east Brazil after a severe drought in 1985 (K. Smith, 2001);
- mass migration of up to 75 per cent of the population in drought-stricken regions of the American Great Plains in the 1890s, 1910s and 1930s (Warrick, 1980); and
- the displacement of nearly 2.7 million people by drought in the Sudan in 1988 (see Table 5.6) (Mahran, 1995).

Table 5.6: Number of displaced people by war and by drought in the Sudan in 1988 (in millions) (Mahran, 1995).

Region of Destination	Total	Reason of Displacement	
		Security	Drought
Northern	0.16	0.08	0.08
Khartoum	1.80	1.80	n.a.
Central	0.52	0.32	0.20
Eastern	0.60	n.a.	0.60
Darfur	0.86	0.06	0.80
Kordofan	1.07	0.07	1.00
Bahr Elghazal	0.41	0.41	n.a.
Equatoria	0.80	0.80	n.a.
Upper Nile	0.56	0.56	n.a.
Total	**6.78**	**4.10**	**2.68**

These cases suggest that migration is a *common* and very *likely* response to drought. However, results of other studies leads to the *contrary* conclusion, i.e. that drought hardly influences migration:

- The relative importance of different factors on migration in Burkina Faso was quantified on the basis of migration statistics between provinces in the 1980s (Henry, Boyle, & Lambin, 2003). A basic gravity model developed by the researchers had an explanatory power of 52 per cent. To this percentage, socio-demographic variables added 12 per cent and environmental variables[33] including drought another 5 per cent. On its own, the variable *"drought fre-*

[33] Socio-demographic variables of the provinces include number of men, economic activity rate, literacy rate, etc. while the environmental variables comprise drought frequency, rainfall variability, soil degradation, cotton yields, cultivated land area and others.

quency" only contributed 0.8 per cent to the total explanatory power of 73 per cent.

– In the Senegal River valley in Mali the levels of *migration did no rise during the drought* (1983 to 1985) in comparison to the other years, even though migration patterns changed (result of a longitudinal household survey by Findley, 1994).

All in all, the *results are ambivalent: in times of drought, some areas have witnessed mass migration while in others migration has remained roughly constant*.

Migration Destinations and Reasons

In order to understand migration in drought-prone regions, it is important to consider that *different types of migration* also take place under normal circumstances. For instance in many parts of Africa migration has played an important part in society over decades (Autier et al., 1989; Prothero, 1968). In this context two common types of migration are listed below (Findley, 1994). Both types are labour migration that involves moving in search of labour and income, usually to support their families financially:

– *Seasonal labour migration*. These seasonal migrants are usually young men (and sometimes women) that work in their rural homes in the rainy season, i.e. during times of high agricultural activity. After the harvest time, they migrate to nearby urban areas in search of labour and incomes until the rainy season begins again (Autier et al., 1989; Findley, 1994; Prothero, 1968).
– *Long-cycle labour migration.* These moves involve longer durations and further distances. Today, these destinations include Europe. An example are Sahelians that migrate to France and return home definitely after an average of 7.7 years (Conde & Diagne, 1986, cited in Findley, 1994).

Findley (1994) provides insights into changes of such existing migration patterns during drought with a longitudinal household survey in Malian villages. As stated above, the aggregate levels of *migration did not rise* during drought, but the pattern noticeably shifted from long-cycle to seasonal migration. While before the drought *75 per cent* of the migrants had been *out-migrants* (defined as being away for more than 6 months, many of which are assumed to be long-cycle labour migrants), their share *dropped to 36 per cent* during the drought. The total number of migrants staying *inside Mali* nearly *doubled* from 22 to 42 per cent while the share of those going to France (the prime foreign destination for Malians) went down from 47 to 27 per cent.

These results contradict the notion that as droughts persist, mass migrations occur and the developed countries are increasingly chosen as destinations (as for instance propagated by Döös, 1994; and Myers, 1993). The reason for the decline of out-migrations (or long-cycle migrations) is that they are "impractical as spontaneous responses to a drought-induced crop failure" (Findley, 1994, p. 541). Out-migration of a family member is considered an *investment* that not only requires long-term planning, but also the means to finance the air fare and initial living expenses looking for work. In a drought situation, the household's means that would have gone into financing migration are diverted to *more urgent needs*.

So in Mali, out-migration decreased and seasonal labour migration increased. While few others have investigated out-migration or long-cycle migration, the increased of seasonal labour migration as a response strategy is confirmed in many other African cases (see Burton et al., 1993 for the case of Tanzania; and Corbett, 1988 for an overview of cases in Nigeria, Sudan and Ethiopia). However, results from studies in Asia do not confirm this pattern:

- Households in Bangladesh responded with a number of adjustments to a severe drought in 1994-1995. While 55 per cent of respondents sold livestock and over 70 per cent either sold or mortgaged land, *migration* of family members had *only occurred in 1 of 265 households* (Paul, 1995, cited in Smith, 2001);
- Similarly, after two dry years in rural villages in Karnataka, India in 1983, migration of family members had been a response strategy in *only 2 per cent* of the households (Caldwell, Reddy, & Caldwell, 1986). However, the majority of households were receiving money or other help from family members working elsewhere. This could be an indication that migration already took place substantially in years before the drought and – through remittances – made it unnecessary to send more household members on labour migration.

Such a theory is to a certain extent supported by Findley (1994) who sees a possible explanation of an overall constant migration in the fact that there already were many out-migrants from the region surveyed. A new negative migration loop is thus postulated as a hypothesis to be investigated. On the whole, seasonal labour migration in many African countries seems to differ from labour migration in India and Bangladesh. However, it is not clear whether the countries are simply situated at different stages of a similar development path or whether the differences are to be attributed to other reasons.

With insights into labour migration alone, not all of the observed migrations in the Sudan and the Sahel can be explained. For this purpose, also so-called "*distress migration*" has to be considered. As described in the chapter on responses below, there are many coping strategies under famine conditions, one of which is labour migration. However, when insurance mechanisms have been exhausted and nearly all productive assets have been sold, the very last step (in many Asian as well as African countries) is migration *in search of food* and relief (Corbett, 1988). A study in Mali investigating malnutrition in rural villages came to the conclusion that the few families that had left the villages were indeed those with the most malnourished children (Autier et al., 1989). In the severest of cases, these "distress migrations" can take place on a large scale and are "typically accompanied by *abject misery*, large-scale beggary and greatly increased mortality" (Adhana, 1991, p. 187). These migrations are said to be usually of temporary nature (Adhana, 1991).

In addition to *labour* migration of individual households members and *distress* migration of entire households in the case of severe famine, there also seems to be migration of entire households for other reasons. In cross-cultural studies in 18 different hazard sites households were questioned about the intended response to the hazard present in the location (Burton et al., 1993). The only three sites where there was a significant percentage (between *10 and 31 per cent*) of people considering migration were all sites prone to drought. The countries were Tanzania, Brazil and Australia. It seems very unlikely that near-starvation was the of all these migration intentions. Another hint to this type of migration is given in a study by Caldwell et al. investigating an Indian drought in 1983, where the stage of destitution typical for distress migration was not reached. They state that they were not able to interview all households due to the "dislocations and movements arising from the crises" (Caldwell et al., 1986, p. 681). Although the evidence is somewhat meagre, it justifies further research into a "normal" type of migration out of drought-prone regions

In summary, the studies reviewed suggest that in times of drought, *changes in labour migration patterns* may occur. In Mali, *long-cycle migration decreases* in times of drought because the investment required cannot be afforded. *Seasonal labour migration,* in contrast, *increases* in many *African* countries as *income* can be generated and additionally *household size* and with it consumption goes down. However, as samples from India and Bangladesh show, seasonal labour migration is *not a significant response (anymore?) in all countries*. In addition, distress migration of entire households in search of food may occur in severe cases of hunger and there are indications for an increase in an as yet undefined type of household migration.

5.4.5 Responses to Drought

As in the two previous cases, alternatives to migration and general response options contribute to understanding whether migration will take place or not. Agricultural drought elicits direct responses to cope with the actual event as well as long-term responses to influence the impact of future droughts (see Table 5.7). However, in contrast to the sudden-onset hazards, the period in which responses are developed is prolonged. As a drought worsens, strategies might be changed and further reaching responses might be chosen.

Table 5.7: Overview of responses to drought (mainly based on K. Smith, 2001; complemented by Blaikie et al., 1994).

	Response
Loss-Sharing	***Disaster Aid**:* This includes national relief and rehabilitation assistance and international disaster aid including the shipment of food and relief goods. In some countries food-for-work or cash-for-work schemes were implemented (e.g. Zambia, north-east Brazil).
	***Insurances**:* Crop insurances are an important mechanism to share losses associated with droughts.
Event Modification	***Weather Modification**:* At the present time there are no technologies to artificially stimulate rainfall.
	***Hazard Resistant Design**:* In order to make drought-prone regions less dependent on rainfall, dams and pipelines for the artificial storage and transfer of water supplies can be constructed.

Vulnerability Modification	***Forecasting and Warning**:* In order to be effective, drought forecasts need to be available many months ahead in order to aid seasonal decisions on crop planting and water management. Early warning systems are based on remote sensing of vegetative growth, field workers' observations, rising grain prices, combined with falling livestock prices and wages, etc. Problems have arisen by pitching the scale of analysis at the national level, as droughts and food shortages can occur on a regional scale.
	***Community Preparedness**:* Sahel nomads practice herd diversification, increase herds and food storage in rainy years to eat or sell them in drought times, have developed informal systems of gifts or loans of any spare animals available for those in greatest distress, and have various fall-back activities, such as gazelle hunting or caravan trading. Farmers can replace their crops, gap fill their fields and resow or irrigate their crops. Simple grain storage systems can prevent a farmer having to sell grain at a low price to a trader at harvest time and purchase grain at a higher price later on. Other general responses are eating less, eating wild famine foods, selling livestock and valuables, such as jewellery, or other capital assets, such as radios, bicycles or firearms, which can be sold to buy grain.
	Collective Self-Reliance: Southern African countries have joined together for the purpose of food availability by enabling the exchange of food rains among the members.
	***Land Use Planning**:* Drought increases the pressure on land resources. Land use planning can be used to limit human activities that amplify drought-related disaster, such as overgrazing, poor cropping methods, deforestation and improper soil conservation techniques.
	***Migration**:* Migration is not mentioned as a response. For more information, see chapter on migration above.

The roles of labour and distress migration in African countries is better understood in the context of different response strategies. Corbett (1988) found that responses to famine follow a general pattern (see Table 5.8.). In the first stage, consumption is reduced, agricultural practices are adjusted and additional income is secured by sales, *labour migration* and loans. Thus, these strategies depend on the wealth, social relations and education attained prior to the drought. All these activities do not undermine the direct subsistence ability of the household. This occurs in the second stage, where people put their *future* livelihood at risk by selling livestock or agricultural tools to be able to buy food and secure minimal *current* nutrition. In the third stage, households are destitute, have nothing left to sell and may be too weakened by hunger and related diseases to work. At this stage, *distress migration* of entire households in search of relief seems the only option left.

Table 5.8: Household coping strategies in the face of famine (based on a review of several empirical studies in Ethiopia, Sudan and Nigeria by Corbett, 1988).

First Stage: Insurance mechanisms	**Second Stage: Disposal of productive assets**	**Third Stage: Destitution**
– changes in cropping and planting practices – reduction of consumption levels – collection of wild foods – use of inter-household transfers and loans – increased petty commodity production – **employment migration** – sale of small stock – sale of possessions (e.g. jewellery)	– sale of livestock (e.g., oxen) – sale of agricultural tools – sale or mortgaging of land – credit from merchants and moneylenders – further reduction of consumption levels	– **distress migration**

5.4.6 Discussion: Drought

The review of the connections between drought and migration confirms the observation that droughts are among the most complex natural hazards (Wilhite, 2000). For one, the lack of a universal definition of drought, together with the variety of existing migration types, might easily confuse discussions on "drought-related migration". Also, while most sudden-onset natural hazards have comparable effects on migration, agricultural droughts seem to have very different impacts on human mobility. Wilhite (2000) states that the character of drought impacts will differ profoundly depending on the level of development of the country. In this connection, the concept of vulnerability presented earlier on suggests itself for discussing the societal impacts of drought.

An Example of Vulnerability

A case study on droughts in the American Great Plains serves as a good illustration example. Warrick (1980) investigated the effect of meteorological drought on crop yield and social aspects during four different drought periods. The results summarized in Table 5.9 show that the impacts of the droughts do not directly correlate with their severity. For instance, although the meteorological drought in the 1910s was the least severe, the crop yield decline was the second highest. Even more striking is the difference between the droughts in the 1890s and 1950s. The impacts of drought in the 1890s was disastrous; it led to serious malnutrition and starvation and caused mass migration of up to 75 per cent of the population. In the *1950s, the severity* of the drought and also crop yield decline were similar, even slightly *higher,* than in the 1890s. Nevertheless, there were no adverse health effects and also no discernible change in migration.

Table 5.9: Overview of the four main drought periods in the American Great Plains (compiled on the basis of the description by Warrick, 1980).

	1890s	**1910s**	**1930s**	**1950s**
severity of meteorological drought (rank)	3	4	1	2
percentage decline in wheat yield *	16%	24%	29%	19%
migration	50 – 75% in many areas	25 – 50% in many areas	18 – 50%	according to trend decline
health effects	malnutrition, starvation	no starvation	some malnutrition	none
farm transfers			increase from 6 to 10%	stable or slight decline from 5%
government relief	none	none	yes	yes

*decline of the 2 worst years in relation to the long-term trend

These results show how two *droughts*, that in meteorological as well as agricultural terms were of very *similar severity*, had *utterly different effects* on migration and society. The lessening of impacts over the years can be attributed to *technological* mechanisms (e.g. fallowing, crop varieties, tillage practices, stubble mulching, etc.) and *socio-economic* mechanisms (maintenance of financial reserves, availability of loans, stabilized prices, crop insurance schemes, federal farm policies, etc). Warrick postulates that the main share of impact reduction was not achieved by the technological mechanisms that reduce the effect of drought on crop yield but rather by the socio-economic mechanisms that "protect societal well-being from the effects of yield declines" (Warrick, 1980, p. 114). He also emphasizes the importance of the *government's attitude* to relief that changed from complete rejection (1890s and 1910s, the farmers themselves were to be blamed) to the willingness to bring relief and spread costs in severe cases.

Evidently, the impacts of drought, like those of floods and tropical cyclones, are a result of the *interaction of a physical impact and human vulnerability*. What made the difference between the migration from the Great Plains droughts of the 1890s and the 1950s was the vulnerability of the farmers that had its *root causes in social, economic, and political processes*.

Vulnerability and Famine

The "distress migration" described for Africa above and also observed in the American Great Plains, is not one of the first coping strategies to drought. Rather it is a *last resort* when people start hungering and become malnourished, i.e. when drought has translated to famine. Whether or not famine ensues from drought, is also determined by vulnerability. This has been an insight from the development of famine theories. Early theories explained famine simply as a result of "food availability decline". An event like drought leads to crop failure, the amount of food declines and with time, people begin to hunger. However, these theories failed to explain why food is not bought or food aid is not delivered. New theories added people's *access to food* as an important component besides the amount of food available: "Food entitlement decline" occurs when the different entitlements to food (for instance by producing it, buying it with money or goods, buying it with own labour, receiving it as gift or aid and stealing it) are reduced (Blaikie et al., 1994). For instance, a drought in Maharashtra, India, lasting from 1970 to 1973 was "effectively prevented from triggering a famine by an employment guarantee scheme" (Blaikie et al., 1994, p. 81). In this way, the population was given one type of entitlement to food (buying it with labour) and famine was averted. It is human vulnerability that largely influences people's entitlements to food.

As Devereux (1993, p. 183) puts it: "Drought causes crop failure, but *vulnerability* to drought causes famine." Some factors contributing to this vulnerability are listed below. To illustrate how these factors may influence famine, the ways in which war causes famines are described: "Government or rebel forces appropriate men, food and animals; burn crops and destroy granaries; plan mines in fields which disable farmers; and create food blockades by disrupting trade and preventing food aid from getting through." (Devereux, 1993, p. 189). In this light the number of people displaced by drought (in contrast to war) in the Sudan in 1989 (see Table 5.6) should be questioned. Considering the above mechanisms by which wars cause famine, it seems unfeasible to identify people solely displaced by drought. For the future, Devereux (1993, p. 189) concludes that it is *not drought, but war* that "will probably remain as the last major proximate cause of famine in Africa".

Factors Cited that Contribute to Famine

Drought, unsuitable technologies for providing water for humans and livestock, population pressure and a fragile ecosystem, deforestation and a fuel crisis, chronic uncertainties over land tenure, lack of credit, monopolistic power of merchants in rural areas, low income, poor import capacity, war disruption, overcultivation of fragile soils, loss of access to land through expropriation, widespread reliance on unreliable waged employment (compiled from different sources by Blaikie et al., 1994, p. 79).

5.5. Discussion: Climate-Influenced Migration

It is the goal of this Chapter 5 to deepen the *understanding* of the connection between climate change and migration by means of conceptual models. In this subchapter, first the use of connection models for this task is discussed. Subsequently, the concrete results of the four climatic hazards are summarised and discussed. Then, the concept of vulnerability is reviewed, followed by questions for possible future research.

5.5.1 Connection Models

In all the four cases, the linking two topics so far apart *involves a variety of different disciplines* as well as *sources*. The example of drought may illustrate the variety of *disciplines* involved: atmospheric sciences are important for meteorological drought; hydrology, plant biology and agronomy are involved in determining crop yield; economics look at the change in food prices; sociology investigates the social systems that determine access to food; and epidemiology examines the spread of diseases among the malnourished. At the very end of the chain, migration is investigated by no discipline in particular. The multitude of disciplines involved calls for an interdisciplinary approach, at best an *interdisciplinary team* in investigating such an issue.

During literature research, different types of *sources* proved typical for certain stages within the chain:

- To determine how *climate change will influence* the respective climatic hazard, knowledge is reliably found in the *IPCC report* on the scientific basis of climate change (IPCC, 2001a). A well structured overview of the relevant information is presented and further specific reference to *recent journal articles* is made.
- Information on the *direct effects* of the climatic hazards is often to be found in *books, textbooks* and sometimes reviews. As these climatic hazards have been studied for decades independently of climate change, a lot of knowledge has been generated and summarised. Examples are how drought effects crops or how strong winds cause structural damage.
- Information on the *indirect effects* is more *difficult* to find, as it varies strongly depending on the vulnerability of the population affected. The sources most used are *books, reviews and case studies*.
- There are no textbooks explaining the link between the indirect effects and *migration*. Information is hardly available even from reviews and is therefore gathered mostly from *individual case studies* described in journal articles.

The transition of source types reflects the relative state of knowledge in the stages and point towards the largest knowledge gap which is the linkage to migration. The state of knowledge about the extent, destinations of and reasons for migration in such cases is extremely low. *Being beyond doubt the "weakest link in the chain", it is migration research that has to be advanced in order to improve the overall understanding*.

5.5.2 The Influence of Climate Change on Migration

Gathering information from different types of sources from a variety of disciplines, though time-consuming, has made it possible to draw a net of effects originating from the climatic hazards. Most of the arrows in the four connection models, representing influences, are plausible and are mostly based on reliable references. However, the final linkage to migration is based on occasional case studies gathered from various sources and is only of a very general nature. The link is made to the *occurrence* of the hazard event, but not to the processes positioned directly in front of migration in the connection model.

Concerning migration, *most* case studies were found with regard to *drought*, many based on the mass exodus witnessed from the drought-stricken Sahel in recent decades. Sudden-onset natural hazards like tropical cyclones and floods have received less attention, as substantial permanent migration does not seem to occur despite initial mass displacement. On the topic of sea level rise, the least information is to be found. Although a lot of research has recently dealt with SLR, the indirect effects such as migration have hardly been treated empirically at all. In the following, the results regarding the migration linkage are presented:

- ***Sudden-onset natural hazards (Tropical Cyclones and Floods)***: The cases viewed display similar patterns and suggest that a small share of *almost none up to about 30 per cent* of people affected by a natural hazard migrate. An exception to this rule is river bank erosion that causes migration by literally cutting the ground under the feet of the occupants. In general, the crucial factors in the decision to migrate *permanently* does not seem to be related to the structural damage (that usually causes the initial displacement), but rather to the *extent to which opportunities to generate income have been affected*; as well as the *initial situation* of the individual or household (wealth, power, prior investment into the home etc.). The majority of migrants moves *very short distances* and some *medium distances*. With regard to international migration from developed countries, *immigration rules* limit the realization of existent migration pressure.
- ***Sea level rise***: Although relative sea level has risen significantly in some regions and has affected coastal communities independent of climate change, migration hardly seems to have been studied at all. Some very general hypotheses have been presented but lack arguments and references. The link between loss of land and migration seems exceedingly plausible, and is supported by the review on natural hazards, where seemingly river bank erosion causes most migration due to the loss of land. However, protection responses have proven quite capable of preventing migration. Research is needed on the choice of responses and the extent of migration in the past in order to estimate the dimension of migration to be expected from projected sea level rise.
- ***Drought***: The overall picture that emerges from the cases is *ambivalent*. The extent of migration seems to depend largely on the vulnerability to drought as well as the social, political and cultural situation. *Seasonal labour migration increases* in many *African* countries but is not changed in other countries. These moves are undertaken to generate income and usually take place over short distances. Whether the *decrease of out-migration to Europe in Mali* constitutes a common pattern or an isolated phenomenon remains unclear. In cases of destitution and severe hunger, *distress migration* of entire households over short distances *in search of food* may occur. However, in such cases drought is a trigger at most and causes must be sought in the exceptionally *high vulnerability* of the population. Furthermore, there are indications that general out-migration increases in times of drought.

5.5.3 Vulnerability

As set out from the beginning, the models aimed at establishing only *connections* in awareness of the fact that migration is always caused by the interaction of a *variety* of agents and can accordingly not be *solely* caused by climate change. In the connection models presented, the significance of the connections differ largely, varying from causation to a small contribution: While intense precipitation events can be safely said to *cause* floods, the reduction of produced food and work *may well contribute* to famine, but is *neither a necessary nor a sufficient cause* (As discussed in Chapter 5.4.6, government policies or international aid, to name just two measures, could avert famine that mostly occurs as a consequence of war or civil strife.). The significance of the *connections made* also follows a typical pattern across the different stages. The effect of climate change on the climatic hazard – with the important exception of sea level rise – is not a causation but a contribution to the frequency and/or intensity of the event. On the other hand, the connections between the climatic hazards and the direct effects are often usually much stronger. From there on to the more indirect effects, the significance of the connections decreases continually. These connections can become mere influences in a much wider net of connections.

In all four connection models it has become apparent that whether the depicted connections are realized or not, depends on the responses chosen, and on the local situation and resources. In short, it depends on the vulnerability of the population in question. The *actual* impacts of the climatic hazard are the results of its *interaction* with a social system. For the proponents of the concept of vulnerability the physical impact is *neutral* and it is the "people who transform the environment into resources and hazards, by using natural features for economic, social, and aesthetic purposes" (Burton et al., 1993, p. 32). For a general illustration of the concept see Figure 5.21. Its importance is shown most impressively by the case of the American Great Plains, where two agricultural droughts of very similar dimensions in one case (1890s) led to serious malnutrition, *mass migration and even starvation* and in the other (1950s) had *no effects* on health or migration (Warrick, 1980). In the light of the great importance vulnerability has in determining in which way a population will be affected, the *production of vulnerability in a society has to be investigated and considered* in assessing the impacts of climatic hazards.

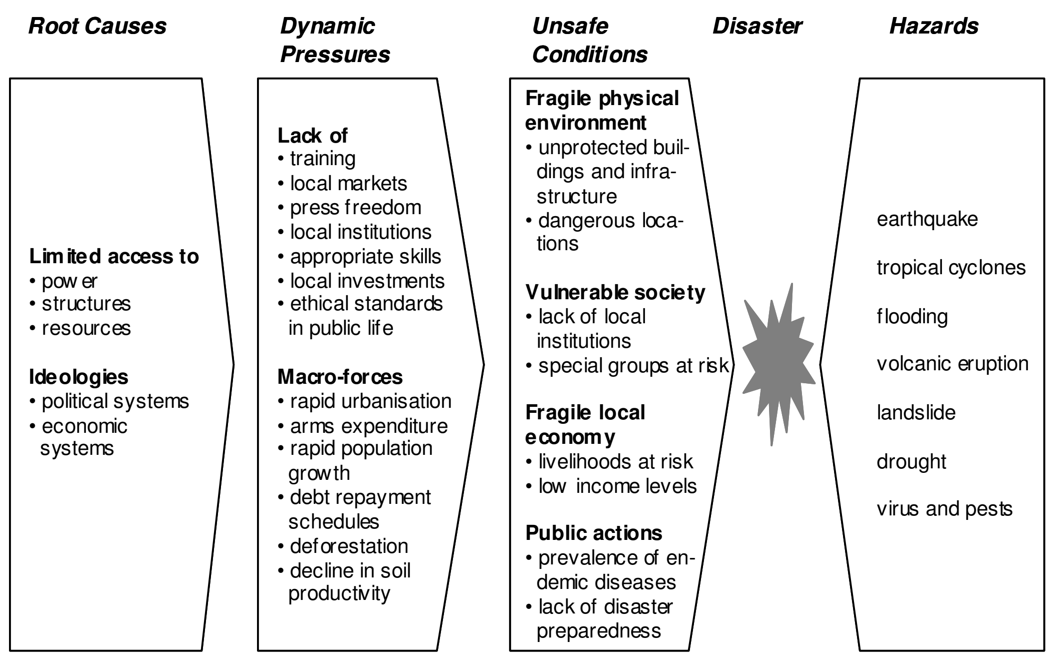


Figure 5.21: The progression of vulnerability from root causes through dynamical pressures to unsafe conditions, that, together with the hazard as trigger, leads to disaster (adapted from Blaikie et al., 1994).

That climate change will increase or intensify the climatic hazards as described in the corresponding chapters is *likely* (for tropical cyclone intensity, risk of drought) *to very likely* (for intense precipitation events) (IPCC, 2001a). The direct effects of the climatic hazards are likely in many cases, but are not deterministic and are already influenced by the vulnerability of the community affected. The more indirect the effects become, the more their realization depends predominantly on the vulnerability – and with it on the level of development – of each and every country.

5.5.4 Future Research

As discussed above, the weakest link in the overall understanding of the connection between climate change and migration lies in migration research. The state of knowledge about migration in such cases is extremely low. Numerous case studies are required to advance knowledge in this field and attain more well-founded conclusions. These case studies would ideally investigate different types of climatic hazards in diverse societal settings. Central questions to be addressed include:

- To what extent does permanent migration occur (in comparison to average migration)?
- What are the reasons for this migration?
- Which destinations are chosen?
- Which destinations would be chosen if there were no immigration rules?

In addition to these general questions, specific questions are of interest for the different climatic hazards.

Sudden-Onset Natural Hazards

- What are the differences in migration extent, destinations and reasons between (i) different natural hazards and (ii) different vulnerability? Based on the results of this thesis, the hypothesis would be that the differences in vulnerability are more relevant than those of hazard type in determining migration.
    - To which extent does migration from river bank erosion occur and is it really much more frequent than migration ensuing from other types of hazards?
- Given initial mass displacement:
    - What factors make people return and rebuild their homes?
    - Which reasons make people migrate permanently? (In which way do they differ from those who return to their homes?)

Drought

- What are the extent, destinations and reasons for the indicated drought migration that is neither labour migration nor distress migration?
- What factors determine the difference in drought migration behaviour in different countries?
- How does labour migration change in times of drought?

- Is the observed decrease in long-cycle migration during drought in Mali confirmed in other settings?
- Does a negative feedback loop exist within long-cycle migration, i.e. is the extent of labour migration increase during drought dependent on the number of household members who have already left? Might this contribute to explaining the differences between labour migration in Africa and Asia?

Sea Level Rise

The results from sudden-onset natural disasters suggest that migration occurs substantially when there is a loss of land. Therefore, migration from SLR should be given special emphasis. Before it is possible to determine *specific* questions regarding sea level rise, the basic questions set out above have to be addressed.

A possible reason for the lack of case studies is that migration has not occurred in those regions affected by relative SRL in the past. If this is the case, migration was presumably prevented by the choice of response options.

– Which responses have been chosen along the coasts where relative sea level has already risen?

As seen in Table 5.3, the size of population at risk varies a lot from one country to the next. To obtain a worldwide overview of potential migration in a most efficient manner, it would seem worthwhile to single out the especially vulnerable countries with a preliminary scan and then investigate those cases specifically. The regions most vulnerable to SLR are coral reef nations and river deltas (Leatherman, 2001; McLean, Tsyban, Burkett, Codignotto, Forbes, Mimura, Beamish et al., 2001; Titus, 1993).

Immigration into Developed Countries

In case the *principal* interest in climate-induced migration regards *future fluxes* of migrants into developed countries, studies investigating the extent, origins, types and reasons of current immigration should be striven for in a first step.

Connection Model

Besides filling the most important knowledge gap of migration, the connection model could be improved by discussing it with experts from the respective disciplines. The thickness of the connection arrows could be chosen according to the degree of influence it represents. Another idea would be to create similar connection models focussing less on the individual and more on the institutional or economic level.

Vulnerability

The connection models in this diploma thesis have set the natural phenomenon as the starting point and trace the connection to migration from there. Such an approach does not facilitate the inclusion of vulnerability that has proven to be of utmost importance in determining the impacts in general and migration in specific. The connection models could be adapted and enlarged by the aspects of human vulnerability (see Figure 5.22).

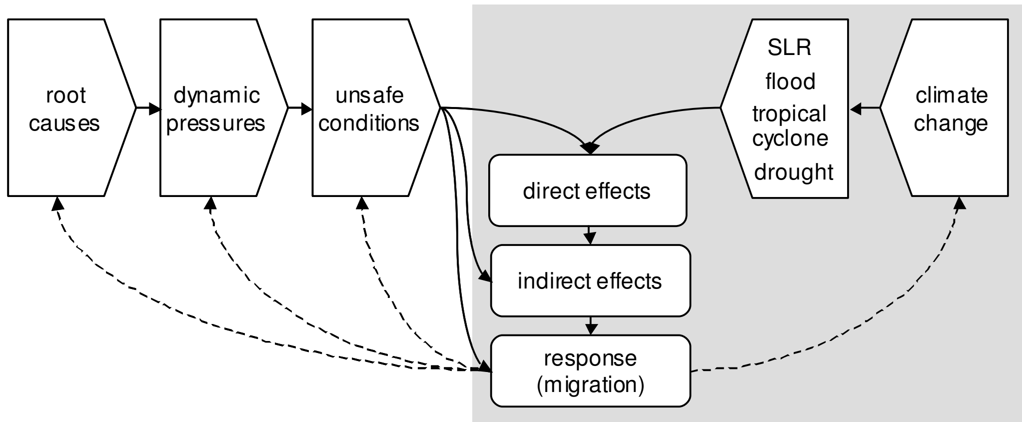


Figure 5.22: The enlargement of the connection model approach (in grey) by the concept of vulnerability.

6 Discussion and Conclusion

As a starting point for this chapter, the entire set of research objectives set out in the introduction are taken up again. They are to:

- *give an overview of existing* climate and migration *models*;
- determine the *requirements for their mathematical linkage*;
- *develop conceptual models* of the most important mechanisms in which climate change can be connected to migration; and
- discuss the *potential contribution* of both the *mathematical as well as the conceptual approach* to improving the understanding of climate change-influenced migration.

Due to the modular structure of this diploma thesis, the three first objectives have already been discussed individually in the respective chapters. Therefore, in this chapter, the *conclusions* regarding these objectives are presented in turn. The last research objective is then discussed and concluded upon.

Overview of Existing Climate and Migration Models

In general, climate models are *mathematical* models that simulate the physical, geophysical, chemical and biological processes that go on within the climate system. In Figure 6.1, this climate system is represented by the large box with the broken line. Climate modellers build on a *common viewpoint* and agree on the nature of the important climate processes. They have developed comprehensive models that represent a *large part of the climate system* and can take weeks to run on a supercomputer (illustrated by the large box nearly filling the climate system). For specific purposes (such as exploring a particular process or testing model sensitivity), a range of simpler models is used.

Migration models are not as clearly defined as climate models. While some of the models are of *mathematical* nature, many are *conceptual* and often termed "theories". Migration is approached from a variety of competing theoretical viewpoints. Each theory or model concentrates on a specific type of migration. For instance, focus can be laid on *economic or sociological* aspects, *internal* or international destinations, etc. As depicted in Figure 6.1, no model integrates *all* types of migration (there is no large box nearly filling migration) and some migration situations are not covered at all. Mathematical migration models are usually independent of space and time, in contrast to climate models, that are often spatially distributed and dynamic.

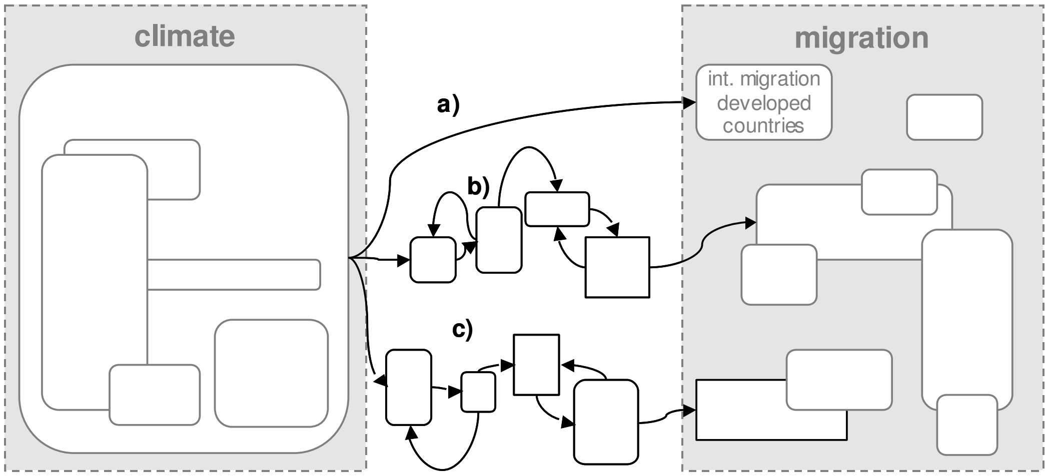


Figure 6.1: Conceptualisation of the extent to which climate and migration models cover their field (boxes with the broken line). Possible connections can be direct (a), involve substantial in between modelling (b), or even require the development of new models in the field of migration (c). Explanation of symbols: Boxes with rounded corners represent existing models; and squares represent new models.

At the heart of the contrast between climate and migration models lies the subject they treat. While climate models can build on the rigid chemical and physical laws underlying the climate system, migration modellers are faced with human behaviour that does not underlie any rigid laws.

Requirements for a Mathematical Linkage of Existing Models

The mathematical linkage of existing models is possible. One type of migration model was found that focuses on how climatic preferences (for instance winter sunshine, warm and dry summers) influence migration within developed countries. In this case, the connection can be a direct one (see a) in Figure 6.1). In other cases, a connection would require the modelling of a long chain of processes between rather unrelated phenomena, as for instance from the climate model output "storm frequency" to the migration model input "national income" (see b) in Figure 6.1). However, such a connection is only of use if the migration model chosen focuses on the type of migration of interest in this thesis, i.e. migration pushed by climate change, primarily in developing countries. Since no migration model focusing on this type of migration exists, climate-related migration would first have to be studied in order to determine whether new models have to be created, or whether climate-related migration is similar to other, already modelled, types from which the model could be adopted. The case in which a new model would have to be developed is illustrated in c) in Figure 6.1.

A requirement for all types of connections is that climate projections are credible on a national, if not sub-national level, as migration models are limited geographically.

Creation of Conceptual Models of the Most Important Mechanisms

Four climatic hazards were identified as the most important mechanisms: *sea level rise, floods*, *tropical cyclones* and *droughts*. A conceptual model was developed for each, connecting climate change to migration via the respective climatic hazard. These models are termed "*connection* models" in order set them apart from the more common causal chains.

In each case it was possible to establish the connections to the major (direct and indirect) impacts of the respective climatic hazard on the affected community. However, migration could not be *explicitly* linked to specific impacts but could only be connected to the climatic hazard in a very general way. This is due to a large knowledge gap identified in migration, including its extent, destinations and direct causes. Although there case studies that confirm migration resulting from the floods, tropical cyclones and droughts, the *direct and concrete reasons for moving* remain unknown. For instance, the decision to migrate after being affected by a tropical cyclone does not seem to be related to the extent of house damage suffered. The specific results are listed in the following: here

- Tropical cyclones and floods often lead to initial mass displacement but only to a small share permanent migration (a review of cast studies suggest of *almost none up to about 30 per cent).* Taking into consideration that climate change is projected to "only" increase the frequency or intensity of already *existing* cyclones and floods, climate change does *not seem likely to trigger mass migrations* by these mechanisms.
- What effects sea level rise has on migration is not known, as there have hardly been any cases studied. While migration is a very plausible response to the loss of land, protection responses are capable of preventing migration. Since sea levels are projected to rise slowly, (approx. 0.5 cm to 4 cm every 5 years, according to IPCC, 2001a), response options are to be expected. The meagre knowledge base does *not allow any assessment* about the influence on migration at this moment in time. In the light of large amount of people potentially at risk, sea level rise-induced migration is one of the highest research priorities in this field.
- Also with regard to drought, *an assessment cannot be made* at present. The case studies available convey *very different* pictures of the impacts of drought on societies and migration. Due to the slow onset of droughts, there are always many other factors acting concomitantly over a long period of time that also determine the local development.

An important insight gained is the importance of vulnerability in assessing the impacts of climatic hazards. The *climatic hazard* (caused or intensified by climate change) *is a trigger that can lead to the depicted effects*. However, the *realization* of the connections established (i.e. the *actual* impacts) depend on the vulnerability of the society affected. The more indirect the effects are, as for instance the socio-economic impacts including migration, the more do they depend on the social, economic, and political processes that determine how *vulnerable* people are.

Contribution of Mathematical and Conceptual Approach

In this discussion an attempt is made to determine the *ideal ranges of application* of both types of models. In general, conceptual models are simpler and require less effort to create. Accordingly, for those functions that can be fulfilled equally well by both types of models, it suggests itself to use *conceptual models*. These include:

- to structure information from many different disciplines in a common framework
  - in which to identify knowledge gaps and relative needs for research;
  - in which to search for solutions (in the connection models presented in this thesis, for instance, measures can be looked for by determining how each connection depicted could be prevented); and
  - by which researchers from different disciplines are enabled to communicate and "talk about the same thing".
- to offer an overall picture of the relevant processes; and
- make qualitative judgments about impacts.

Conceptual models have the *additional advantage* of preventing to get lost in details, which for instance in this diploma thesis allowed recognizing the importance of vulnerability. They also provide a starting point to assess where mathematical models can be meaningfully implemented.

In general, a much-valued advantage of *mathematical models* is their ability to predict the future development of a system. However, it has been shown (see Chapter **3.2.2**on Integrated Assessment Modelling) that models of long process chains that connect numerous sub-models from the *natural and social* sciences are *not able to successfully predict future development*. One of the reasons is that *uncertainties* of all sub-models are *accumulated* due to integration. Another important factor is that disciplinary sub-models are not indisputable and the integrated model can *only be as strong as its weakest link*.

In the case of climate-related migration, the weakest link is undoubtedly migration. As shown in Chapter **2.3.5**, migration models have a low predictability that is not expected to be improved considerably. For natural scientists, this might seem a remarkable statement. However, very unlike many processes studied in the natural sciences, the migration process is not based on rigid physical and chemical laws, but on *human behaviour* that depends on countless factors. To give an *impression* of what this means, the migration behaviour of a person during drought may be considered: for instance, this behaviour might depend on personality, income, the behaviour of the neighbours, previous experiences with drought, the access to buying food, the political security of the country, the availability of government relief, immigration rules and many more. This limitation to predict human behaviour becomes especially visible over *long time scales*. For instance sea level is projected to rise roughly between 10 and 90 cm between 1990 and 2100 (IPCC, 2001a). Whether migration is induced depends to a large extent on whether coastal protection measures are implemented. However, it is impossible to predict which countries will chose what types of response during the *next hundred years*, simply since human systems are subject to enormous changes in such a period (for instance in the last century, unpredictable events like the

Great Depression and the two world wars shaped human development to a great extent).

If thus the low predictability of migration lies *in its nature*, integrated models will *remain unable* to *predict* climate-related migration. The question arises of what added value such models thus are, when the fact that they produce quantitative results may tempt researchers and policymakers alike to overlook its limitations. However, if their limitation as prediction machines is recognized, integrated models can make a contribution to understanding climate-related migration in the form of *exploration tools*. In this context, the fact that the mathematical description *forces* researchers to make the linkages *explicit* is very advantageous. Integrated models might help to understand interactions and lead to counter-intuitive results that can then be investigated in depth with other methods. However, the *central and indispensable contribution* of mathematical models is seen to lie in the *analysis of individual elements and connections*, which, in the context of such a long chain as is climate-related migration, can constitute fields of vast size and complexity. For instance, invaluable contributions have already been made in the field of climate change. The main range of application proposed lies with the *processes subject to* more or less *rigid laws*. In the connection models presented in this diploma thesis, this would cover *climate change*, its effects on the *climatic hazards* and the *direct effects* of these hazards. Regarding the socio-economic impacts, mathematical models may also be of use in single aspects. For instance, a mathematical model relating migration in Burkina Faso to a number of potential explanatory variables, while not explaining dynamics, gave valuable indications as to which factors are important for migration and should thus be further investigated (Henry et al., 2003).

The connections between climate change and migration have been previously approached in many different ways. In its entirety they have been treated in a very general descriptive manner, while chains concerning specific climatic hazards have been investigated in isolated case studies. In this diploma thesis, connection models have been proposed as a method to approach the topic in a *systematic way* and the make the diverse *linkages explicit*. They have proven an appropriate tool to give an *overview* of the relevant processes and to offer a *framework to structure knowledge*, facilitating the identification of knowledge gaps, the search for solutions and the communication between researchers from different disciplines. They revealed migration behaviour in the face of climatic hazard (especially regarding sea level rise) as the weakest link chain requiring high priority research. Two main weaknesses of the connection models in this diploma thesis are (i) that they have been developed by only one author and not an interdisciplinary team and (ii) that they have not treated vulnerability adequately enough. Besides filling the most important knowledge gap of migration, these are limitations to be addressed by further research on this concept.

7 References

Adhana, A. H. (1991). Peasant response to famine in Ethiopia, 1975-1985. *Ambio, 20*(5), 186-188.

Ahmad, Q. K., Warrick, R. A., Downing, T. E., Nishioka, S., Parikh, K. S., Parmesan, C., et al. (2001). Methods and tools. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 105-143). Cambridge: Cambridge University Press.

Arnell, N., Liu, C., Compagnucci, R., da Cunha, L., Hanaki, K., Howe, C., et al. (2001). Hydrology and water resources. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 191-233). Cambridge: Cambridge University Press.

Autier, P., d'Altilia, J.-P., Callewaert, B., Tamboura, B., Delamalle, J.-P., & Vercruysse, V. (1989). Migrations and nutritional status in the Sahel. *Disasters, 13*(3), 245-254.

Bader, S. (2004). *Tropische Wirbelstürme: Hurricanes - Typhoons - Cyclones*. Zürich: MeteoSchweiz.

Baede, A. P. M., Ahlonsou, E., Ding, Y., & Schimel, D. (2001). The climate system: an overview. In J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson (Eds.), *Climate change 2001: the scientific basis. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 85-98). Cambridge: Cambridge University Press.

Bates, D. C. (2002). Environmental refugees? Classifying human migrations caused by environmental change. *Population and Environment, 23*(5), 465-477.

Belcher, J. C., & Bates, F. L. (1983). Aftermath of natural disasters: coping through residential mobility. *Demography, 7*(2), 118-128.

Bird, E. C. F. (1995). Present and future sea level: the effects of predicted global changes. In D. Eisma (Ed.), *Climate change: impact on coastal habitation* (pp. 260). Boca Raton: Lewis Publishers.

Black, M. (1962). *Models and metaphors: studies in language and philosophy* (2nd print ed.). Ithaca: Cornell University Press.

Black, R. (2001). *Environmental refugees: myth or reality?* (New Issues in Refugee Research Working Paper No. 34). Geneva: United Nations High Commissioner for Refugees.

Blaikie, P., Cannon, T., Davis, I., & Wisner, B. (1994). *At risk: natural hazards, people's vulnerability, and disasters*. New York: Routledge.

Bridgman, H. A. (1983). Could climatic change have had an influence on the Polynesian migrations? *Palaeogeography, Palaeoclimatology, Palaeoecology, 41*(3-4), 193-206.

Broadus, J. M. (1993). Possible impacts of, and adjustments to, sea level rise: the cases of Bangladesh and Egypt. In R. A. Warrick, E. M. Barrow & T. M. L. Wigley (Eds.), *Climate and sea level: change observations, projections and implications* (pp. 263-275). Cambridge: Cambridge University Press.

Brücker, H., Alvarez-Plata, P., & Siliverstovs, B. (2003). *Potential migration from Central and Eastern Europe into the EU-15 - an update. Report for the European Commission, DG Employment and Social Affairs.* Berlin: Deutsches Institut für Wirtschaftsforschung.

Burton, I., Kates, R. W., & White, G. F. (1993). *The environment as hazard* (second ed.). New York: Guilford Press.

Caldwell, J. C., Reddy, P. H., & Caldwell, P. (1986). Periodic high risk as a cause of fertility decline in a changing rural environment: survival strategies in the 1980-1983 South Indian drought. *Economic Development and Cultural Change, 34*(4), 677-701.

Castles, S. (2002). *Environmental change and forced migration: making sense of the debate* (New Issues in Refugee Research Working Paper No. 70). Geneva: United Nations High Commissioner for Refugees.

Champion, A., Fotheringham, A. S., & Rees, P. (Eds.). (2002). *Development of a migration model: final report*. London: Office of the Deputy Prime Minister.

Church, J. A., Gregory, J. N., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., et al. (2001). Changes in sea level. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 639-693).

Claussen, M., Mysak, L. A., Weaver, A., Crucifix, M., Fichefet, T., Loutre, M.-F., et al. (2002). Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models. *Climate Dynamics, 18*, 579-586.

Conde, J., & Diagne, P. S. (1986). *South-north international migrations: a case study of Malian, Mauritanian and Senegalese Migrants from Senegal River Valley to France.* (Development Centre Papers). Paris: OECD.

Corbett, J. (1988). Famine and household strategies. *World Development, 16*(9), 1099-1112.

Cox, J. D. (2002). *Storm watchers: the turbulent history of weather prediction from Franklin's Kite to El Niño*. Hoboken, New Jersey: John Wiley & Sons.

Cross, J. A. (1985). *Residents' Acceptance of Hurricane Hazard Mitigation Measures* (Final report summary): University of Washington-Oshkosh.

Cubasch, U., Meehl, G. A., Boer, G. J., Stouffer, R. J., Dix, M., Noda, A., et al. (2001). Projections of future climate change. In J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson (Eds.), *Climate change 2001: the scientific basis. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 525-582). Cambridge: Cambridge University Press.

Desanker, P., Magadza, C. H. D., Allali, A., Basalirwa, C., Boko, M., Dieudonne, G., et al. (2001). Africa. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 487-532). Cambridge: Cambridge University Press.

Devereux, S. (1993). *Theories of famine*. New York: Harvester Wehatsheaf.

Döös, B. R. (1994). Environmental degradation, global food production, and risk for large-scale migrations. *Ambio, 23*(2), 124-130.

Döös, B. R. (1997). Can large-scale environmental migrations be predicted? *Global Environmental Change, 7*(1), 41-61.

Dregne, H. E. (2000). Drought and desertification: exploring the linkages. In D. A. Wilhite (Ed.), *Drought: a global assessment* (Vol. 2, pp. 231-240). London: Routledge.

El-Hinnawi, E. (1985). *Environmental refugees*. Nairobi: United Nations Environment Programme.

Environmental Protection Agency. (2004). *Glossary of frequently used modeling terms*. Retrieved May 13, 2004, from http://www.epa.gov/osp/crem/library/CREM%20Modeling%20Glossary%2012_03.pdf

Faist, T. (2000). *The volume and dynamics of international migration and transnational social spaces*. Oxford: Clarendon Press.

Fang, J.-Q., & Liu, G. (1992). Relationship between climatic change and the nomadic southward migrations in Eastern Asia during historical times. *Climatic Change, 22*, 151-169.

Findley, S. E. (1994). Does drought increase migration? A study of migration from rural Mali during the 1983-1985 drought. *International Migration Review, 28*(3), 539-553.

Flather, R. A., & Khandker, H. (1993). The storm surge problem and possible effects of sea level changes on coastal flooding in the Bay of Bengal. In R. A. Warrick, E. M. Barrow & T. M. L. Wigley (Eds.), *Climate and sea level: change observations, projections and implications* (pp. 229-262). Cambridge: Cambridge University Press.

Gallagher, D., & Martin-Forbes, S. (1992). *Migration and the environment*. Geneva: RPG Refugee Policy Group.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., von Storch, H., Whetton, P., et al. (2001). Regional climate information - evaluation and projections. In J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson (Eds.), *Climate change 2001: the scientific basis. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 583-638). Cambridge: Cambridge University Press.

Glantz, M. H. (1988). *Societal responses to regional climatic change: forecasting by analogy*. Boulder and London: Westview Press.

Goetz, S. J. (1999). Migration and local labor markets. In S. Loveridge (Ed.), *The Web Book of Regional Science (www.rri.wvu.edu/regscwebm.htm)*. Morgantown: Regional Research Institute, West Virginia University.

Gold, J. R. (1980). *An introduction to behavioural geography*. Oxford: Oxford University Press.

Greenwood, M. J. (1985). Human migration: theory, models and empirical studies. *Journal of Regional Science, 25*(4), 521-544.

Gregory, J. M., Mitchell, J. F. B., & Brady, A. J. (1997). Summer drought in Northern midlatitudes in a time-dependent CO2 climate experiment. *Journal of Climate, 10*(4), 662-686.

Gregory, J. N. (1989). *American exodus: the Dust Bowl migration and Okie culture in California*. New York: Oxford University Press.

Haque, C. E. (1997). *Hazards in a fickle environment: Bangladesh*. Dordrecht: Kluwer Academic Publishers.

Haque, C. E., & Zaman, M. Q. (1989). Coping with riverbank erosion hazard and displacement in Bangladesh: survival strategies and adjustment. *Disasters, 13*(4), 300-314.

Harris, J. R., & Todaro, M. P. (1970). Migration, unemployment, and development: a twosector analysis. *American Economic Review, 60*, 126-142.

Hatton, T. J., & Williamson, J. G. (2002). *What fundamentals drive world migration?*

Haupt, A., & Kane, T. T. (1998). *Population Handbook* (4th International ed.). Washington, D.C.: Population Reference Bureau.

Henry, S., Boyle, P., & Lambin, E. F. (2003). Modelling inter-provincial migration in Burkina Faso, West Africa: the role of socio-demographic and environmental factors. *Applied Geography, 23*(2-3), 115-136.

Hens, L., & Kwesi Boon, E. (1999). Institutional, legal, and economic instruments in Ghana's environmental policy. *Environmental Management, 24*(3), 337-351.

Huang, C. C., Zhao, S., Pang, J., Zhou, Q., Chen, S., Li, P., et al. (2003). Climatic aridity and the relocations of the Zhou culture in the southern Loess Plateau of China. *Climatic Change, 61*(3), 361-378.

Hugo, G. (1996). Environmental concerns and international migration. *International Migration Review, 30*(1), 105-131.

IFRC. (2003). *World disasters report 2003: focus on ethics in aid*. Geneva: International Federation of Red Cross and Red Crescent Societies,.

Imboden, D. M., & Koch, S. (2003). *Systemanalyse: Einführung in die mathematische Modellierung natürlicher Systeme*. Berlin: Springer.

IOM, & RPG. (1992). *Migration and the environment*. Geneva and Washington, DC: International Organization for Migration and Refugee Policy Group.

IPCC. (1990). *Policymakers' summary of the potential impacts of climate change. Report from Working Group II to IPCC, Intergovernmental Panel on Climate Change.* S.l.: Commonwealth of Australia.

IPCC. (1997). *An introduction to simple climate models used in the IPCC Second Assessment Report* (IPCC Technical Paper II). Geneva.

IPCC. (2001a). *Climate change 2001: the scientific basis. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC (Ed.). (2001b). *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Jacobsen, J. L. (1988). *Environmental refugees: a yardstick of habitability* (Worldwatch Paper 86). Washington DC: Worldwatch Institute.

Jallow, B. P., Barrow, K. A., & Leatherman, S. P. (1996). Vulnerability of the coastal zone of The Gambia to sea level rise and development of response strategies and adaptation options. *Climate Research, 6*, 165-177.

Jamieson, D. (1988). Grappling for a glimpse of the future. In M. H. Glantz (Ed.), *Societal responses to regional climatic change: forecasting by analogy* (pp. 428). Boulder and London: Westview Press.

Kavanagh, B., & Lonergan, S. (1992). *Environmental degradation, population displacement and global security*. Ottawa: Canadian Global Change Program.

Kay, R. N. B. (1997). Responses of African livestock and wild herbivores to drought. *Journal of Arid Environments, 37*(4), 683-694.

Kayastha, S. L., & Yadava, R. P. (1985). Flood induced population migration in India: a case study of Ghaghara Zone. In K. M. Elahi & L. A. Kosinski (Eds.), *Population, redistribution and development in South Asia* (pp. 79-88).

Keilman, N. (1991). National population projection methods in developed countries. In W. Lutz (Ed.), *Future demographic trends in Europe and North America: what can we assume today?* (pp. 465-486). London: Academic Press.

Klein, R. J. T., & Nicholls, R. J. (1998). Coastal zones. In J. F. Feenstra, I. Burton, J. B. Smith & R. S. J. Tol (Eds.), *Handbook on methods for climate change impact assessment and adaptation strategies. Version 2.0.* Nairobi and Amsterdam: United Nations Environment Programme and Institute for Environmental studies, Vrije Universiteit.

Knapp, T. A., & Graves, P. E. (1989). On the role of amenities in models of migration and regional development. *Journal of Regional Science, 29*(1), 71-87.

Krol, M. S., Fuhr, D., & Döring, A. (in press). Semi-arid Northeast Brazil: integrated modelling of regional development and global change impacts. In J. D. Unruh, M. S. Krol & N. Kliot (Eds.), *Global environmental change and migration* (pp. 119-144). Dordrecht, Netherlands: Kluwer Academic Publishers.

Leatherman, S. P. (2001). Social and economic costs of sea level rise. In B. C. Douglas, M. S. Kearney & S. P. Leatherman (Eds.), *Sea level rise: history and consequences* (pp. 181-223). San Diego: Academic Press.

Lee, E. S. (1966). A theory of migration. *Demography, 3*(1), 47-57.

Lee, S.-w. (1997). In limbo: environmental refugees in the Third World. In N.-P. Gleditsch, L. Brock, T. Homer-Dixon, R. Perelet & E. Vlachos (Eds.), *Conflict and the environment* (pp. 273-292). Dordrecht: Kluwer Academic Publishers.

Lonergan, S. (1998). The role of environmental degradation in population displacement. In *Environmental Change Security Project Report* (Vol. 4, pp. 5-15).

MacKellar, F. L., Lutz, W., McMichael, A. J., & Suhrke, A. (1998). Population and climate change. In S. Rayner & E. L. M. Malone (Eds.), *Human choice and climate change* (Vol. 1 The societal framework, pp. 491). Columbus, Ohio: Battelle.

Magadza, C. H. D. (2000). Climate change impacts and human settlements in Africa: prospects for adaptation. *Environmental Monitoring and Assessment, 61*, 193-205.

Mahmood, R. A. (1995). Emigration dynamics in Bangladesh. *International Migration, 33*(3-4), 699-726.

Mahran, H. A. (1995). The displaced, food production and food aid. In E. E. Eltigani (Ed.), *War and drought in Sudan essays on population displacement* (pp. 63-74). Gainesville: University Press of Florida.

Marshall, E. (2001). Pre-Clovis Sites Fight for Acceptance *Science, 291*(5509), 1730-1732.

Massey, D. S., Arango, J., Hugo, G., Kouacouci, A., Pellegrino, A., & Taylor, J. E. (1993). Theories of international migration: a review and appraisal. *Population and Development Review, 19*(3), 431-466.

Massey, D. S., Arango, J., Hugo, G., Kouacouci, A., Pellegrino, A., & Taylor, J. E. (1994). An evaluation of international migration theory: the North American case. *Population and Development Review, 20*(4), 699-751.

McAvaney, B. J., Covey, C., Joussaume, S., Kattsov, V., Kitoh, A., Ogana, W., et al. (2001). Model evaluation. In J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson (Eds.), *Climate change 2001: the scientific basis. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 471-524). Cambridge: Cambridge University Press.

McFalls, J. A., Jr. (2003). Population: a lively introduction. *Population Bulletin, 58*(4), 1-40.

McFalls Jr., J. A. (2003). Population: a lively introduction. *Population Bulletin, 58*(4), 1-40.

McGregor, J. (1993). Refugees and the environment. In R. Black & V. Robinson (Eds.), *Geography and refugees: Patterns and processes of change* (pp. 157-170). London: Belhaven.

McGuffie, K., & Henderson-Sellers, A. (1997). *A climate modelling primer* (Second ed.). Chichester: Wiley.

McGuire, B., Mason, I., & Kilburn, C. (2002). *Natural hazards and environmental change*. London: Arnold.

McLean, R. F., Tsyban, A., Burkett, V., Codignotto, J. O., Forbes, D. L., Mimura, N., et al. (2001). Coastal zones and marine ecosystems. In *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment*

Report of the Intergovernmental Panel on Climate Change (pp. 343-379). Cambridge: Cambridge University Press.

McLean, R. F., Tsyban, A., Burkett, V., Codignotto, J. O., Forbes, D. L., Mimura, N., et al. (2001). Coastal zones and marine ecosystems. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 343-379). Cambridge: Cambridge University Press.

Meyer, W. B., Butzer, K. W., Downing, T. E., Turner, B. L., Wenzel, G. W., & Wescoat, J. L. (1998). Reasoning by analogy. In S. Rayner & E. L. M. Malone (Eds.), *Human choice and climate change* (Vol. 3 Tools for policy analysis, pp. 491). Columbus, Ohio: Battelle.

Milliman, J. D., Broadus, J. M., & Gable, F. (1989). Environmental and economic implications of rising sea level and subsiding deltas: the Nile and Bengal examples. *Ambio, 18*(6), 340-345.

Mimura, N. (1999). Vulnerability of island countries in the South Pacific to sea level rise and climate change. *Climate Research, 12*, 137-143.

Minshull, R. (1975). *An introduction to models in geography*. London and New York: Longman.

Moore, E. J., & Smith, J. W. (1995). Climatic change and migration from Oceania: implications for Australia, New Zealand and the United States of America. *Population and Environment, 17*(2), 105-122.

Moran, J. M., & Morgan, M. D. (1997). *Meteorology: the atmosphere and the science of weather* (fifth ed.). Upper Saddle River, NJ: Prentice Hall.

Morrow-Jones, H. A., & Morrow-Jones, C. R. (1991). Mobility due to natural disaster: theoretical considerations and preliminary analyses. *Disasters, 15*(2), 126-132.

Myers, N. (1993). *Ultimate security: the environmental basis of political stability*. New York: Norton.

Myers, N. (2002). Environmental refugees: a growing phenomenon of the 21st century. *Philosophical Transactions of The Royal Society: Biological Sciences, 357*, 609-613.

National Research Council. (2000). *Beyond six billion: forecasting the world's population*. Washington, D.C.: National Academy Press.

Nebeker, F. (1995). *Calculating the weather: meteorology in the 20th century*. San Diego: Academic Press.

Nicholls, R. J. (1995). Coastal megacities and climate change. *GeoJournal, 37*(3), 369-379.

Nicholls, R. J., Hoozemans, F. M. J., & Marchand, M. (1999). Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. *Global Environmental Change, 9*, S69-S87.

Nicholls, R. J., & Leatherman, S. P. (1995). Global sea-level rise. In K. M. Strzepek & J. B. Smith (Eds.), *As climate changes: international impacts and implications* (pp. 92-123). Cambridge: Cambridge University Press.

Nicholls, R. J., & Mimura, N. (1998). Regional issues raised by sea-level rise and their policy implications. *Climate Research, 11*, 5-18.

Nurse, L. A., Sem, G., Hay, J. E., Suarez, A. G., Wong, P. P., Briguglio, L., et al. (2001). Small island states. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 843-875). Cambridge: Cambridge University Press.

Öberg, S. (1994). Spatial and economic factors in future south-north migration. In W. Lutz (Ed.), *The future population of the world: What can we assume today?* (pp. 361-385). London: Earthscan.

O'Neill, B. C., MacKellar, F. L., & Lutz, W. (2001). *Population and climate change*. Cambridge: Cambridge University Press.

Pales, J. C., & Keeling, C. D. (1965). The concentration of atmospheric carbon dioxide in Hawaii. *Journal of Geophysical Research, 24*, 6053-6076.

Paul, B. K. (1995). *Farmers' and public responses to the 1994-95 drought in Bangladesh: a case study.* (Quick response report no. 76). Boulder, CO: Natural Hazards Research and Applications Information Center.

Pedersen, P. J., Pytlikova, M., & Smith, N. (2004). *Selection or network effects? Migration flows into 27 OECD countries, 1990-2000* (IZA Discussion Paper No. 1104).

Pilkey, O. H., & Cooper, A. G. (2004). Society and sea level rise. *Science, 303*, 1781-1782.

Prothero, R. M. (1968). Migration in tropical Africa. In J. C. Caldwell & C. Okonjo (Eds.), *The population of tropical Africa* (pp. 250-260). London: Longman.

Quarantelli, E. L. (1982). General and particular observations on sheltering and housing in American disasters. *Disasters, 6*(4), 277-281.

Ramlogan, R. (1996). Environmental refugees: a review. *Environmental Conservation, 23*(1), 81-88.

Rapoport, A. (1980). *Mathematische Methoden in den Sozialwissenschaften*. Würzburg: Physica-Verlag.

Ravenstein, E. G. (1885). The laws of migration. *Journal of the Statistical Society, 48*, 167-219.

Ravenstein, E. G. (1889). The laws of migration. Second Paper. *Journal of the Royal Statistical Society, 52*, 241-289.

Risbey, J., Kandlikar, M., & Patwardhan, A. (1996). Assessing integrated assessments. *Climatic Change, 34*, 369-395.

Rotmans, J., & Dowlatabadi, H. (1998). Integrated Assessment Modeling. In S. Rayner & E. L. M. Malone (Eds.), *Human choice and climate change* (Vol. 3 Tools for policy analysis, pp. 291-377). Columbus, Ohio: Battelle.

Rotmans, J., & van Asselt, M. B. A. (2001). Uncertainty management in integrated assessment modeling: towards a pluralistic approach. *Environmental Monitoring and Assessment, 69*, 101-130.

Rutgers Institute of Marine & Coastal Sciences. (2001). Retrieved August 27, 2004, from http://marine.rutgers.edu/geomorph/oceancityfill.jpg

Salinger, M. J., Desjardins, R., Jones, M. B., Sivakumar, M. V. K., Strommen, N. D., Veerasamy, S., et al. (1997). *Climate variability, agriculture and forestry an update* (Technical Note No. 199). Geneva: World Meteorological Organization.

Schnack, E. J. (1993). The vulnerability of the east coast of South America to sea level rise and possible adjustment strategies. In R. A. Warrick, E. M. Barrow & T. M. L. Wigley (Eds.), *Climate and sea level: change observations, projections and implications* (pp. 336-348). Cambridge: Cambridge University Press.

Schwartz, M. L., & Notini, J. (1995). Preliminary report on desertification and migration: case studies and evaluation. In J. Puigdefábrigas & T. Mendizábal (Eds.), *Desertification and Migrations* (pp. 69-113). Logroño, Spain: Geoforma Ediciones.

Scott, M., Gupta, S., Jáuregui, E., Mwafor, J., Satterthwaite, D., Wanasinghe, Y. A. D. S., et al. (2001). Human settlements, energy, and industry. In J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of working group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 381-416). Cambridge: Cambridge University Press.

Seppelt, R. (2003). *Computer-based environmental management*. Weinheim: Wiley-VCH.

Smith, K. (2001). *Environmental hazards: assessing risk and reducing disaster* (third ed.). London and New York: Routledge.

Smith, S. K., & McCarty, C. (1996). Demographic effects of natural disasters: a case study of hurricane Andrew. *Demography, 33*(2), 265-275.

Starr, V. P. (1956). The general circulation of the atmosphere. *Scientific American, 195*, 40-45.

Stehr, N. (2001). Models as focusing tools: linking nature and the social world. In H. von Storch & G. Flöser (Eds.), *Models in environmental research* (pp. 1-16). Berlin: Springer.

Stocker, T. F., Clarke, G. K. C., Le Treut, H., Lindzen, R. S., Meleshko, V. P., Mugara, R. K., et al. (2001). Physical climate processes and feedbacks. In J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson (Eds.), *Climate change 2001: the scientific basis. Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 417-470). Cambridge: Cambridge University Press.

Svart, L. M. (1976). Environmental preference migration: a review. *Geographical Review, 66*(3), 314-330.

Titus, J. G. (1993). Regional effects of sea level rise. In R. A. Warrick, E. M. Barrow & T. M. L. Wigley (Eds.), *Climate and sea level: change observations, projections and implications* (pp. 395-400). Cambridge: Cambridge University Press.

Tyson, P. D., Lee-Thorp, J., Holmgren, K., & Thackeray, J. F. (2002). Changing gradients of climate change in Southern Africa during the past millennium: implications for population movements. *Climatic Change, 52*, 129-135.

UN Department of Economic and Social Affairs. (2002). *Guidelines for reducing flood losses*.

van Andel, T. H. (1989). Late Pleistocene sea levels and the human exploitation of the shore and shelf of southern South Africa. *Journal of Field Archaeology, 16*(2), 133-155.

van Geel, B., Buurman, J., & Waterbolk, H. T. (1996). Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. *Journal of Quaternary Science, 11*(6), 451-460.

Verschuren, D., Laird, K. R., & Cumming, B. F. (2000). Rainfall and drought in equatorial east Africa during the past 1100 years. *Nature, 403*, 410-414.

von Storch, H. (2001). Models between academia and applications. In H. von Storch & G. Flöser (Eds.), *Models in environmental research* (pp. 17-33). Berlin: Springer.

Warrick, R. A. (1980). Drought in the Great Plains: a case study of research on climate and society in the USA. In J. Ausubel & A. K. Biswas (Eds.), *Climatic constraints and human activities* (pp. 93-123). Oxford: Pergamon Press.

Westing, A. H. (1994). Population, desertification, and migration. *Environmental Conservation, 21*(2).

Wild, M. (2004). Personal communication, September 10. Zurich.

Wilhite, D. A. (2000). Drought as a natural hazard: concepts and definitions. In D. A. Wilhite (Ed.), *Drought: a global assessment* (Vol. 2, pp. 3-18). London: Routledge.

Wilhite, D. A., & Vanyarkho, O. (2000). Drought: pervasive impacts of a creeping phenomenon. In D. A. Wilhite (Ed.), *Drought: a global assessment* (Vol. 2, pp. 245-255). London: Routledge.

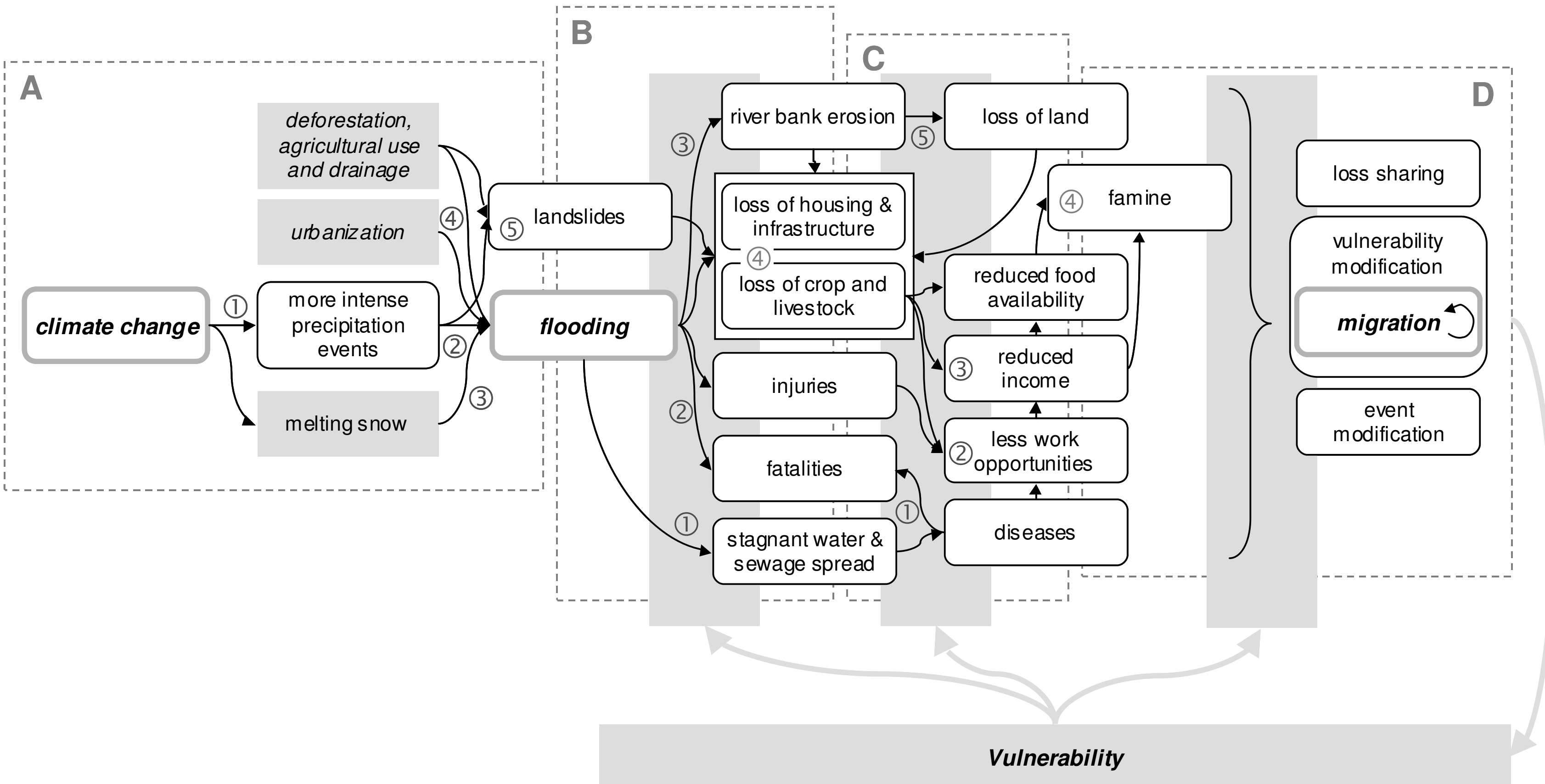
Wood, W. B. (2001). Ecomigration: linkages between environmental change and migration. In A. R. Zolberg & P. M. Benda (Eds.), *Global Migrants, Global Refugees* (pp. 42-61). New York and Oxford: Berghahn.

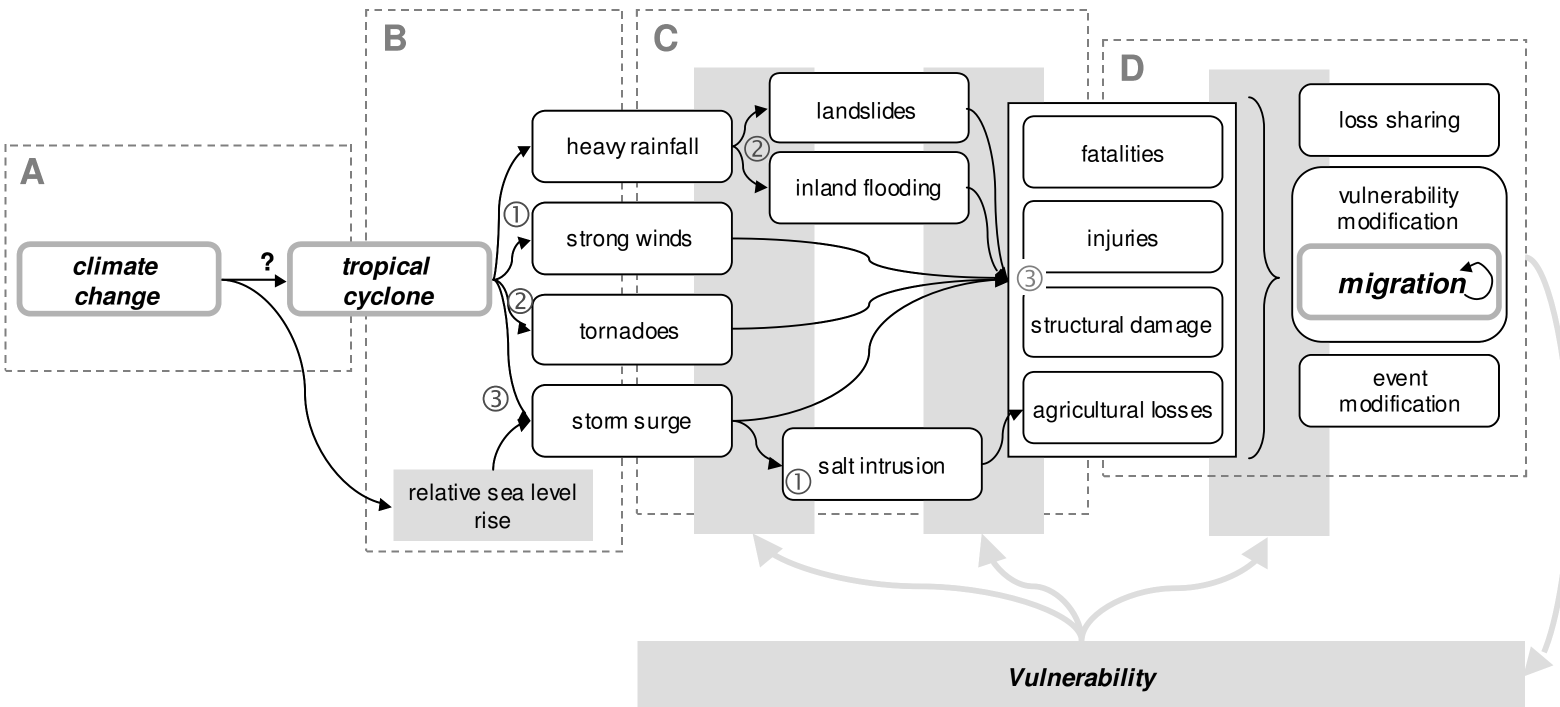
Wu, Q. (1989). The protection of China's ancient cities from flood damage. *Disasters, 13*, 193-227.

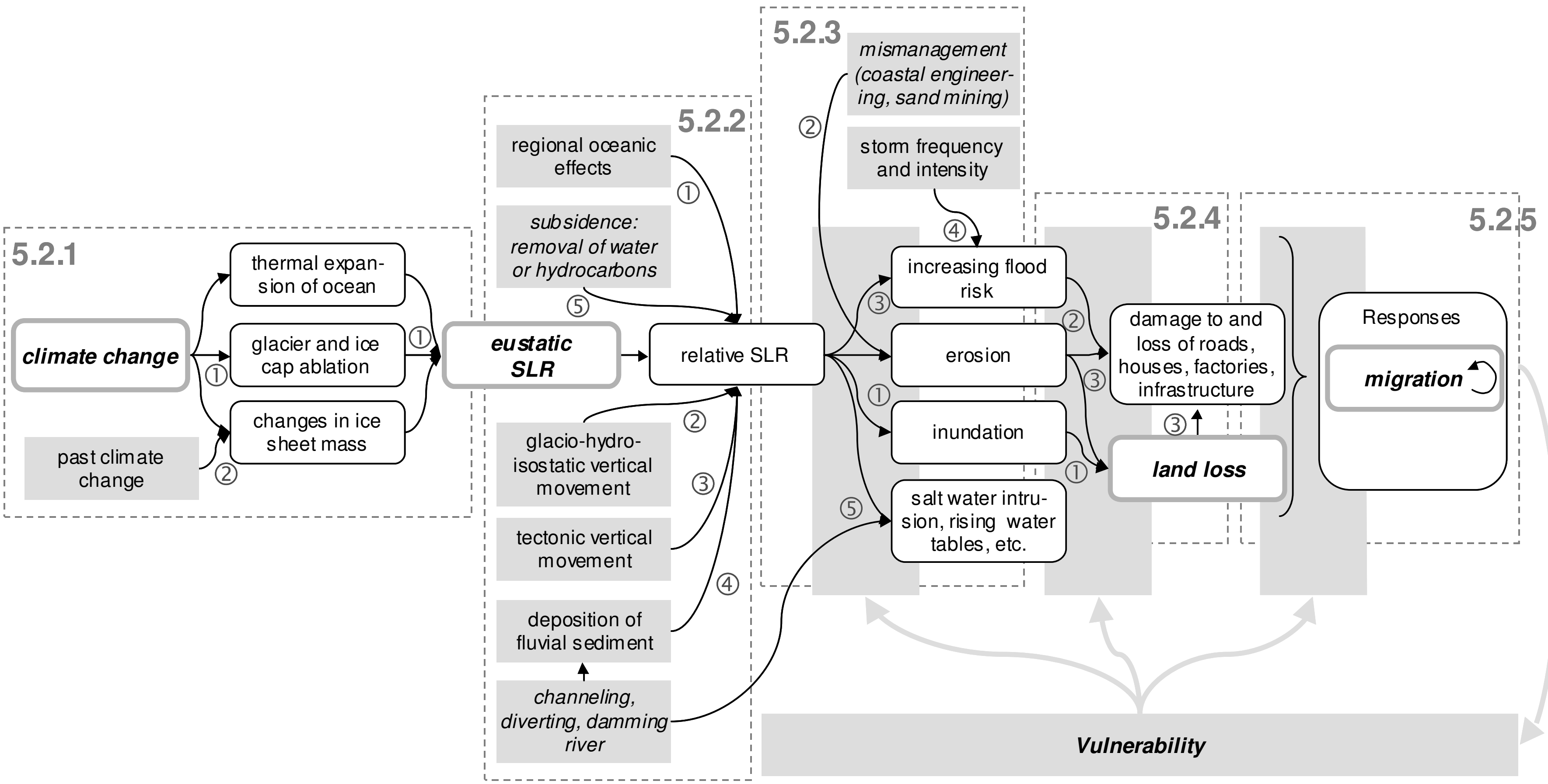
Zaitseva, G. I., Mikliaev, A. M., & Mazurkevich, A. N. (1995). The occupation history of the region between the Dvina and Lovat Rivers in relation to the dynamics of environmental change. *Radiocarbon, 37*(2), 251-257.

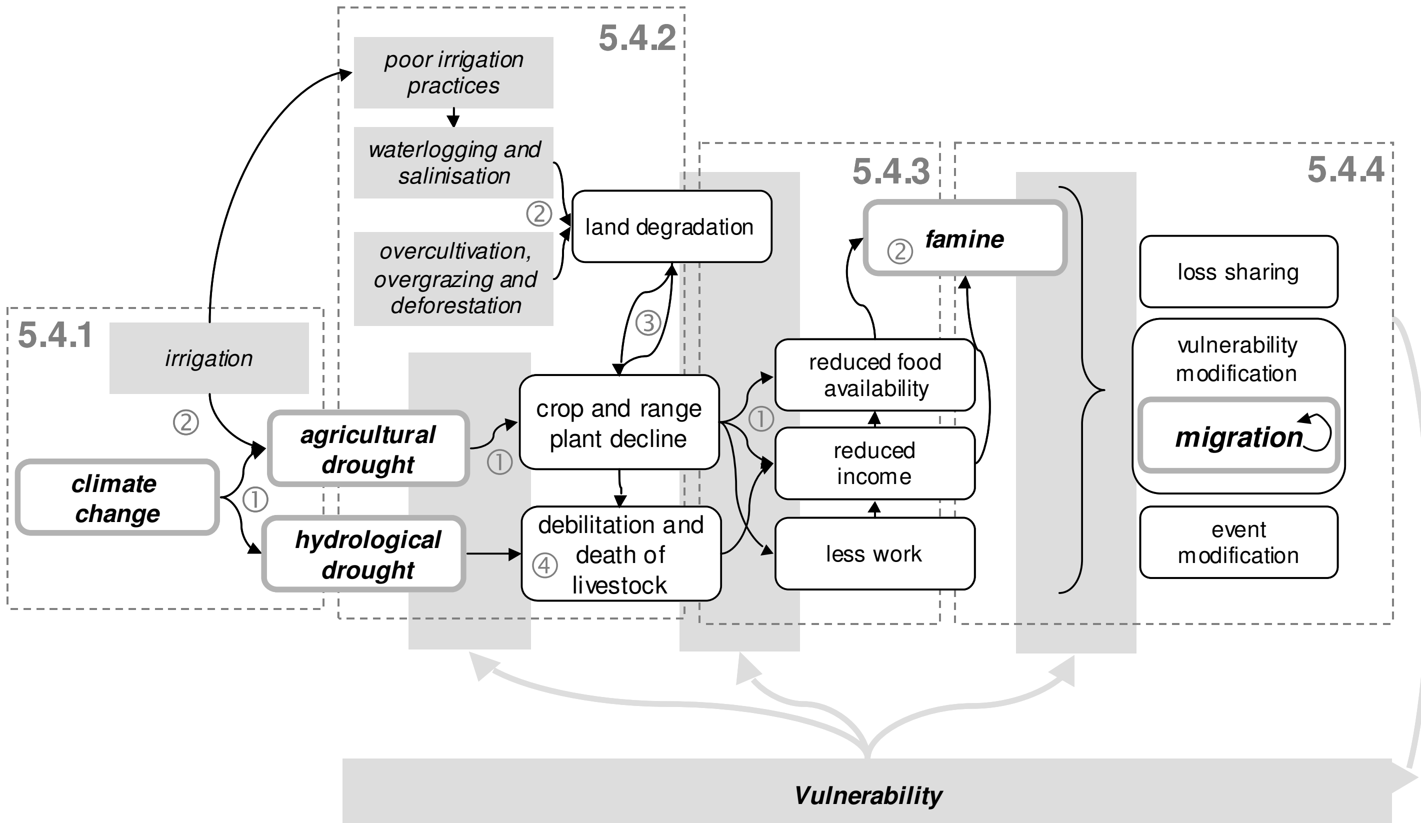
Zhang, K., Douglas, B. C., & Leatherman, S. P. (2004). Global warming and coastal erosion. *Climatic Change, 64*, 41-58.

8 Annex


A
B
C
D
climate change
more intense precipitation events
melting snow
deforestation, agricultural use and drainage
urbanization
landslides
flooding
river bank erosion
loss of housing & infrastructure
loss of crop and livestock
injuries
fatalities
stagnant water & sewage spread
loss of land
reduced food availability
reduced income
less work opportunities
diseases
famine
loss sharing
vulnerability modification
migration
event modification
Vulnerability
①
②
③
④
⑤


A
climate change
?
B
tropical cyclone
heavy rainfall
strong winds
tornadoes
storm surge
relative sea level rise
C
landslides
inland flooding
salt intrusion
fatalities
injuries
structural damage
agricultural losses
D
loss sharing
vulnerability modification
migration
event modification
Vulnerability


5.2.1
climate change
thermal expansion of ocean
glacier and ice cap ablation
changes in ice sheet mass
past climate change
5.2.2
eustatic SLR
regional oceanic effects
subsidence: removal of water or hydrocarbons
relative SLR
glacio-hydro-isostatic vertical movement
tectonic vertical movement
deposition of fluvial sediment
channeling, diverting, damming river
5.2.3
mismanagement (coastal engineering, sand mining)
storm frequency and intensity
increasing flood risk
erosion
inundation
salt water intrusion, rising water tables, etc.
5.2.4
damage to and loss of roads, houses, factories, infrastructure
land loss
5.2.5
Responses
migration
Vulnerability


5.4.1
5.4.2
5.4.3
5.4.4
irrigation
climate change
agricultural drought
hydrological drought
poor irrigation practices
waterlogging and salinisation
overcultivation, overgrazing and deforestation
land degradation
crop and range plant decline
debilitation and death of livestock
reduced food availability
reduced income
less work
famine
loss sharing
vulnerability modification
migration
event modification
Vulnerability