Institut für Physik und Astronomie

Arbeitsgruppe Prof. Dr. Anders Levermann

Climate change impacts in an increasingly connected world

Kumulative Dissertation

zur Erlangung des akademischen Grades
„doctor rerum naturalium“ (Dr. rer. nat.)
in der Wissenschaftsdisziplin „Klimaphysik“

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät
der Universität Potsdam

angefertigt am
Potsdam-Institut für Klimafolgenforschung

von

Leonie Wenz

Potsdam, im Mai 2016

Examination Committee

Prof. Dr. Anders Levermann (expert reviewer)
Prof. Dr. Maximilian Auffhammer (expert reviewer)
Dr. Reik Donner (expert reviewer)

Prof. Dr. Frank Spahn (chairman)
Prof. Dr. Matthias Kalkuhl
Prof. Dr. Ricarda Winkelmann
PD Dr. habil. Joerg Koppitz

Disputation

1 December 2016

Abstract

Climate change has strong impacts on natural and societal systems around the globe. Economic performance can be affected by changing climatic conditions and extreme weather events through numerous channels such as agricultural and industrial output, energy demand and labour productivity. In addition to these direct links, economic outcomes can be influenced by climatic events in more complex manners due to highly interconnected production processes and global trade networks. A better understanding of the overall economic implications of climate change is important to avoid social problems and to comprehensively estimate the costs of future warming.

In my thesis, I aim to contribute to this understanding by investigating climate change impacts in the context of an increasingly connected global economy.

To this end, I used numerical, analytical and econometric tools. In particular, I developed a model to study global economic cascade effects. It builds on multi-regional input-output data that provide information on trade relations between various regional sectors thereby describing the static structure of a global network of economic flows.

In the first article of my thesis, I propose an algorithm to increase the level of sectoral and regional detail of these data *(Wenz et al., 2015)*. The algorithm's strength lies in the flexible combination of multiple proxy data sources in different iteration steps along which the accuracy of the refined data improves.

In order to analyse the dynamic response of the network to local weather extremes, I co-developed the model *acclimate* that I present in the second and third articles. It describes the propagation of climate-induced production losses from one regional sector to the next via supply shortages *(Bierkandt, Wenz et al., 2014)* and demand reductions *(Wenz et al., 2014)*. The propagation of losses can be buffered by transport times, the availability of stored input goods, the possibility of production extension and the directing of demand to less affected suppliers.

In the fourth article of my thesis, I apply the model to study the propagation of heat-stress-induced production losses *(Wenz & Levermann, 2016)*. I find that the susceptibility of the global economic network to the propagation of such losses has increased over the first decade of this century and that this increase is mainly due to enhanced economic connectivity. The influence of this structural change dominates over the effect of the comparably weak warming during this period. The results suggest that the intensification of international trade has the potential to amplify climate-related production losses if no adaptation meas-

ures are taken.
In the last two articles of my thesis, I study specific aspects of the climate-economy relationship with a focus on the agriculture and electricity sectors. The fifth article concentrates on the transmission of supply shocks from exporting to importing countries in the food sector *(Bren d'Amour, Wenz et al., 2016)*. The vulnerability of countries to such shocks is analysed by simultaneously accounting for critical caloric import dependencies and teleconnections in the global food system. The results point to similar vulnerability patterns of geographically clustered countries: the Middle East, Western Africa and Central America are most vulnerable to supply shocks in wheat, rice and maize, respectively. Sub-Saharan Africa is most at risk if the exposure of the poor is factored in.
In the sixth article of my thesis, I investigate the impact of temperature increases on electricity demand in Europe *(Wenz et al., 2016)*. I find a universal relation of normalized electricity load to temperature across all examined countries based on which I project future national electricity consumption. The projections show that total electricity consumption and peak load can be expected to increase in Southern and Western European countries and to decrease in the North. This North-South polarization is most pronounced at the end of the projection period (2080-2100) under a scenario of unabated climate change.

Zusammenfassung

Die Folgen des Klimawandels wirken sich auf ökologische und soziale Systeme weltweit aus. In wirtschaftlicher Hinsicht können veränderte klimatische Bedingungen und Extremwetterereignisse etwa die Landwirtschafts- und Industrieproduktion, den Energiebedarf und die Arbeitsproduktivität betreffen. Zusätzlich zu solchen direkten Effekten können aufgrund weltweit vernetzter Produktionsprozesse und globaler Handelssysteme auch komplexere wirtschaftliche Folgen auftreten. Ein besseres Verständnis der globalen ökonomischen Auswirkungen des Klimawandels ist wichtig, um soziale Probleme zu vermeiden und um die Kosten der voranschreitenden Erderwärmung abzuschätzen.
Das Ziel meiner Doktorarbeit ist es, die Folgen des Klimawandels im Kontext einer zunehmend vernetzten Welt zu untersuchen und damit zu diesem Verständnis beizutragen.
Dazu habe ich numerische, analytische und ökonometrische Methoden verwandt und insbesondere ein Modell zur Abbildung globaler ökonomischer Kaskadeneffekte entwickelt. Das Modell beruht auf multi-regionalen Input-Output Daten, welche Informationen über Handelsbeziehungen zwischen verschiedenen Regionalsektoren beinhalten. Diese können als statische Beschreibung eines globalen ökonomischen Netzwerks interpretiert werden.
In dem ersten Artikel meiner Arbeit schlage ich einen Algorithmus vor, der es ermöglicht die regionale und sektorielle Auflösung dieser Daten zu erhöhen *(Wenz et al., 2015)*. Die Stärke des Algorithmus liegt in seiner Flexibilität bezüglich der verwendeten Proxy-Daten, die unterschiedlicher Art sein können und iterativ kombiniert werden. Die Güte der verfeinerten Daten verbessert sich entlang dieser Iterationsschritte.
Um die dynamische Reaktion des durch die Daten beschriebenen Netzwerks auf lokale Wetterextreme zu untersuchen, habe ich das Modell *acclimate* mitentwickelt, das ich in dem zweiten und dritten Artikel vorstelle. Es beschreibt die Ausbreitung von klimabedingten Produktionsverlusten über Lieferengpässe *(Bierkandt, Wenz et al., 2014)* und Nachfrageveränderungen *(Wenz et al., 2014)*. Die Schadensausbreitung kann durch Transportzeiten, das Vorhandensein gelagerter Güter, die Möglichkeit zur Produktionssteigerung sowie durch das Nachfragen bei weniger betroffenen Anbietern abgeschwächt werden.
In dem vierten Artikel meiner Arbeit verwende ich das Modell, um die Ausbreitung der durch Hitzebelastungen verursachten Produktionsverluste zu untersuchen *(Wenz & Levermann, 2016)*. Die Analyse zeigt, dass die Anfälligkeit des globalen Wirtschaftssystems gegenüber der Ausbreitung derartiger Schäden seit Beginn dieses Jahrhunderts zugenommen hat und dass dies im Wesentlichen auf eine stärkere ökonomische Vernetztheit zurückzuführen ist. Diese strukturelle Veränderung hatte einen stärkeren Einfluss als die vergleichs-

weise geringe Erwärmung während dieses Zeitraumes. Die Ergebnisse deuten an, dass zunehmende internationale Handelsverflechtungen klimabedingte Schäden vergrößern könnten, sofern keine Anpassungsmaßnahmen getroffen werden.

In den letzten beiden Artikeln meiner Arbeit widme ich mich zwei spezifischen Aspekten der Beziehung zwischen Klimawandel und Ökonomie. Der fünfte Artikel konzentriert sich auf Versorgungsengpässe bei Grundnahrungsmitteln *(Bren d'Amour, Wenz et al., 2016)*. Die Vulnerabilität von Ländern gegenüber Einbrüchen bei Getreideimporten wird anhand der Wichtigkeit des Getreides für die nationale Ernährung und Verbindungen innerhalb des globalen Versorgungssystems bestimmt. Die Ergebnisse zeigen regional ähnliche Vulnerabilitätsmuster: Länder im Mittleren Osten, Westafrika und Zentralamerika sind jeweils am anfälligsten gegenüber Importeinbrüchen bei Weizen, Reis und Mais. Unter Berücksichtigung der Folgen für die arme Bevölkerung ist Subsahara-Afrika am verwundbarsten.

In dem sechsten Artikel meiner Arbeit untersuche ich den Einfluss steigender Temperaturen auf den Strombedarf in Europa und finde einen universalen Zusammenhang zwischen Stromverbrauch und Temperatur in allen untersuchten Ländern *(Wenz et al., 2016)*. Basierend auf diesem Zusammenhang projiziere ich den zukünftig zu erwartenden Strombedarf der Länder unter verschiedenen Klimawandel-Szenarien. Die Projektionen zeigen, dass in den süd- und westeuropäischen Ländern ein steigender Strombedarf und höhere Tagesspitzenlasten zu erwarten sind, während diese in den nördlicheren Ländern abnehmen werden. Diese Nord-Süd-Polarisierung ist gegen Ende des jetzigen Jahrhunderts und unter der Annahme eines ungebremsten Anstiegs der Treibhausgase am stärksten ausgeprägt.

Contents

1
Introduction

1.1 Climate change impacts in an increasingly connected world

Anthropogenic climate change is one of the major challenges humankind is facing in the 21st century. The warming of the Earth's surface due to an increase in atmospheric greenhouse-gas concentration *(Stocker et al., 2013)* affects natural and societal systems worldwide *(Field et al., 2014; Edenhofer et al., 2014)*. Sea level rise *(Mengel et al., 2016)*, changing climatic conditions in general *(Trenberth, 2011)* and extreme weather events in particular *(Rahmstorf and Coumou, 2011)* put human life *(Vandentorren et al., 2004)* and health *(Patz et al., 2005)*, ecosystems *(Hoegh-Guldberg and Bruno, 2010)* and biodiversity *(Thomas et al., 2004)*, food *(Schmidhuber and Tubiello, 2007)*, water *(Schewe et al., 2014)* and energy supply *(Auffhammer and Mansur, 2014)* as well as societal stability *(Burke et al., 2009; Hsiang et al., 2013)* at risk. Recently, the international community of states agreed upon avoiding dangerous climate change by limiting global warming to well below 2°C until the end of the century (21st Conference of the Parties in December 2015). Yet, even if this ambitious climate change mitigation target is met, large parts of the already emitted greenhouse-gases will remain in the atmosphere for thousands of years *(Solomon et al., 2009)*.

The impact of climate change on the economy has not yet been well understood *(Stern, 2007; Weitzman, 2012; Dell et al., 2014)*. Growing evidence demonstrates that weather fluctuations and extremes influence, for example, agricultural and industrial output *(Lobell et al., 2011; Burke et al., 2015)*, labour productivity *(Hsiang, 2010)*, the export of countries *(Benjamin and Olken, 2010)* and economic growth *(Dell et al., 2012; Felbermayr and Gröschl, 2014)*.
In addition, economic structures have changed considerably in the course of globalization. Goods and commodities are increasingly traded globally and production systems extensively rely on supply and value-added chains spanning multiple countries and sectors *(Rodrik, 2000; Hummels et al., 2001; Costinot et al., 2012)* (Fig. 1.1). While international trade

has been shown to benefit economic development in general (see e.g. *Donaldson (2015)* for a recent review), economic dependencies may also render countries vulnerable to adverse events in other parts of the world *(Newbery and Stiglitz, 1984; Giovanni and Levchenko, 2009)*. Thus, in a globally connected world, climatic shocks are not necessarily locally confined but can have supra-regional repercussions through both supply and demand relations *(Christopher and Peck, 2004; Huppert and Sparks, 2006; Hallegatte et al., 2007; Okuyama and Santos, 2014)*.

For instance, the Japanese tsunami and earthquake in 2011 had wide consequences on industrial production and exports, most notably in the automotive industry *(Hallegatte, 2014)*. A devastating flood in Thailand in the same year strongly impacted the country's high-tech sector which led to a global shortage of hard-disk drives *(Haraguchi and Lall, 2014)*. Also in 2010/11, a series of extreme weather events in major crop producing regions, combined with temporary export restrictions, caused food price spikes, potentially fuelling the Arab Spring *(Trostle et al., 2011; Sternberg, 2012; Fellmann et al., 2014; Lagi et al., 2015)*. In 2005, hurricane Katrina interrupted oil production, import and refining in the Gulf of Mexico with a major effect on energy prices *(Cashell and Labonte, 2005)*.

Particularly in the light of increasingly frequent and intense weather extremes under future warming, a better understanding of the complex network of global economic dependencies is required to comprehensively estimate the costs of climate change, to reduce socio-economic risks and to implement appropriate adaptation measures. My thesis contributes to filling this gap by analysing how climate change might impact our increasingly connected world.

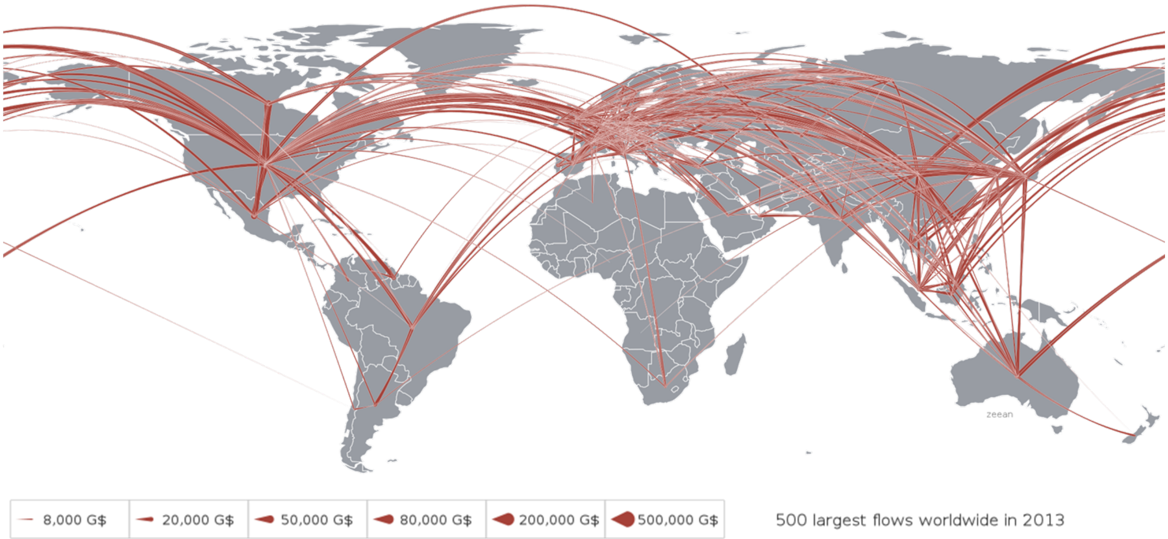

Figure 1.1: Global economic interconnectedness. Shown are the 500 largest trade flows between different regional industry sectors as provided by the Eora multi-regional input-output database for the year 2013 (retrieved from *zeean.net*).

1.2 Scope and contents of the thesis

Local weather extremes and temperature fluctuations can have global economic effects through highly interconnected production processes and international trade networks *(Hummels et al., 2001; Huppert and Sparks, 2006; Werrell and Femia, 2013)*. Following a terminology proposed by *Rose (2004)* and *Veen (2004)*, an extreme event causes damages on stocks by destroying physical and human capital, land and machinery (*direct effects*). These damages can then lead to production and consumption losses (*first-order indirect effects*) that potentially spread to other companies or markets via economic linkages (*higher-order indirect effects*). In order to assess the economy-wide impact of weather extremes including *first-* and *higher-order indirect effects*, suitable data and methodological tools are required to describe this global economic network and to analyse its response to local perturbations.

Input-output (IO) accounts are a useful starting point as they hold detailed information on the economic interactions within a regional economy for a given year[2]. Multi-regional input-output (MRIO) datasets such as Eora *(Lenzen et al., 2012)*, the Global Trade Analysis Project (GTAP; *Narayanan et al. (2012)*) or the World Input Output Database (WIOD, *Timmer*

[2] IO accounts provide information on production activities, the supply and demand of goods and services, intermediate consumption, primary inputs and foreign trade. They consist of supply, use and IO tables *(Hertwich and Peters, 2010)*.

(2012)) describe annual monetary transactions within and between different sectors and countries and can thus be used to identify global supply chains *(Hertwich and Peters, 2010; Wiedmann et al., 2011)*. However, a common shortcoming of these datasets is their lack of regional and sectoral detail as required for disaster impact analyses. Incomplete raw data, computational constraints and other factors impede the compilation of databases that provide concurrently a large number of sectors, regions and years *(Lenzen, 2011; Wiedmann et al., 2011; Lindner et al., 2012; Alexeeva-Talebi et al., 2012)*.

In the first article of this thesis (Sect. 2.1, *Wenz et al. (2015)*), I propose an algorithm to increase the level of detail of MRIO datasets by disaggregating economic flows using available proxy data. This downscaling procedure is complemented by an adjustment rule ensuring the balance of input and output flows in the original MRIO table. The algorithm unfolds its strength through the flexible combination of multiple, possibly incomplete proxy data sources. The accuracy of the refined data improves along different iteration steps. The algorithm has been integrated into the community data platform *zeean* (www.zeean.net) where it is applied to the Eora MRIO tables to obtain highly resolved data on the global economic network.

MRIO tables can be interpreted as a weighted and directed network, where nodes correspond to regional sectors and links describe economic flows *(Maluck and Donner, 2015)*. In the fourth and fifth articles of my thesis (Sects. 2.2 and 2.3, *Bierkandt et al. (2014)* and *Wenz et al. (2014)*), I present a newly-developed model, *acclimate*, that describes the short-term dynamic response of this global economic network to unanticipated extreme events such as heat-waves, floods and storms. *Acclimate* is designed in the spirit of an agent-based model with almost 5000 regional sectors (and final demands) as agents (Fig. 1.2). Their production (or consumption) volumes as well as their interrelations are given by the Eora MRIO database. They dynamically interact with each other with the aim of avoiding individual production (or consumption) losses.
Weather extremes are modelled as external perturbations that reduce the production capacity of one or more regional sectors. The induced production losses (*first-order loss*) can then propagate to other regional sectors via supply shortages and demand reductions (*higher-order loss*). Agents that are either directly or indirectly affected by the external forcing seek to regain their initial productivity as quickly as possible. As a consequence, the model is gradually forced to strive back to its initial state. However, it is not constrained by the assumption of a general equilibrium of prices and quantities in each time step. The dynamics of loss propagation are resolved on the time-scale of the perturbation. This high temporal resolution distinguishes *acclimate* from other modelling frameworks such as static IO analyses or Computational General Equilibrium models (CGEs; overviews of these frameworks can be found in *Veen (2004), Okuyama (2007)* and *Okuyama and Santos (2014)*).

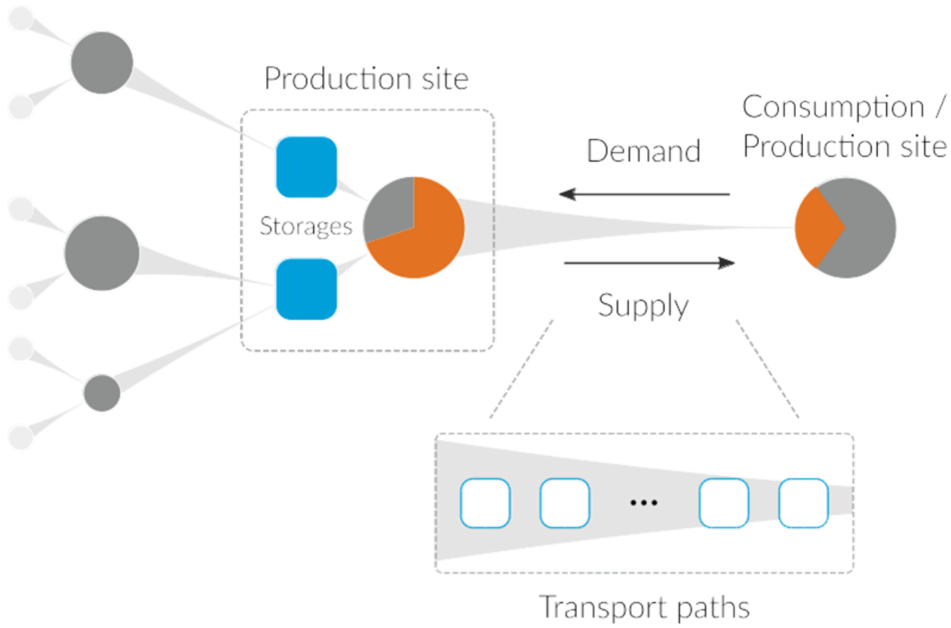

Figure 1.2: Schematic illustration of the model acclimate (adapted from *Otto et al. (2017)*). Regional sectors and final demands (alias production and consumption sites) as given by the MRIO data are interpreted as production and consumption sites. Weather extremes and other external perturbations are modelled as reduction in production capacity (orange shading). The induced losses can propagate to other sites via demand and supply relations. Storage, transport time, idle capacities and the possibility of demand redistribution can buffer the propagation.

The basic set-up of the model *acclimate* is introduced in the second article of my thesis (Sect. 2.2, *Bierkandt et al. (2014)*). It depicts the propagation of production loss through input-supply linkages thereby assuming that a regional sector's production is limited by the minimal relative availability of one input good across all input goods (*perfect complementarity*). The loss propagation can be buffered by the availability of stored inputs and transport times.
In the third article (Sect. 2.3, *Wenz et al. (2014)*), I extend *acclimate* by introducing dynamics that describe the propagation of production loss through demand reductions. Regional sectors with diminished production are assumed to adjust their demand accordingly. With this model extension, further mediating effects can be considered, such as an extension of the initial production capacity (reflecting idle capacities in the economy) and a directing of demand to less affected suppliers.

By means of the extended model *acclimate*, I investigate the effect of unexpected heat-stress on the global economic network in the fourth article of my thesis (Sect. 2.4, *Wenz and Levermann (2016)*). Labour productivity has been shown to decline quasi-linearly with temperature above a threshold of approximately 27°C *(Ramsey, 1995; Pilcher et al., 2002; Dell et al., 2014; Burke et al., 2015)*. Building on a recent econometric study on heat-stress in tropical countries *(Hsiang, 2010)*, I compute first- and higher-order losses from temperature-related reductions in productivity under changing economic and climatic conditions between 1991 and 2011. I find that the susceptibility of the global economic network to the propagation of production losses (higher-order effects) has increased over time. Since the beginning of this century, the structural evolution of the global economic network has been such as to foster the cascading of losses. The application of a newly-developed network measure capturing interregional supply dependencies indicates that the facilitated propagation of production losses is mainly due to an enhanced economic interconnectedness. Particularly under future warming, the intensification of international trade relations has thus the potential to amplify climate-induced production losses if no adaptation measures are taken.

Cascade effects of local weather extremes might also be of relevance with regard to global food security. The agriculture sector is expected to be strongly affected by changing climatic conditions *(Jones and Thornton, 2003; Nelson et al., 2010; Lobell et al., 2011; Asseng et al., 2011; Urban et al., 2012)*. At the same time, exports of major food commodities are increasingly concentrated in a few countries *(FAOSTAT, 2015)*. The 2008-2010 food crisis, where harvest failures and export restrictions due to multiple weather extremes led to price increases around the globe, may hence have been a harbinger of fundamental climate-induced supply shocks with supra-regional implications.
The fifth article of my thesis (Sect. 2.5, *Bren d'Amour et al. (2016)*) analyses the vulnerability of countries to food supply shocks in far-distant producer regions. Vulnerability is thereby measured along two dimensions: the extent to which abrupt shocks on the international grain market translate to the domestic grain market and the number of people living below the international poverty line in that country, i.e. on less than $1.9 a day. Regarding the first dimension, the analysis shows that diets in many countries strongly rely on a single crop imported from few dominant suppliers. These countries are geographically clustered: the Middle East, Western Africa and Central America are most sensitive to supply shocks in wheat, rice and maize, respectively. Considering the second dimension, Sub-Saharan Africa is most vulnerable. Stylized supply shock scenarios indicate that export bans in the major producing regions, Russia, Thailand and the USA, would affect up to 200 million poor people, 90% of which live in Sub-Saharan Africa.

Another sector that will be strongly influenced by future warming is the electricity sector. In addition to its role for the mitigation of greenhouse gases, it can be directly affected by climate change (e.g. unavailability of cooling water) and indirectly due to adaptive responses to a changing environment *(Casillas and Kammen, 2010; Schaeffer et al., 2012; Auffhammer and Mansur, 2014; McFarland et al., 2015)*. Regarding the adaptation aspect, a decreased demand for heating energy can be expected in response to higher temperatures whereas the increased adoption and operation of cooling facilities will lead to higher electricity demand and put pressure on peak loads *(Rosenthal et al., 1995; Isaac and Van Vuuren, 2009; Eskeland and Mideksa, 2010; Barreca et al., 2016)*. Thus, the overall impact of climate change on the electricity sector is ambiguous and location-dependent.

The last article of my thesis (Sect. 2.6, *Wenz et al. (2017)*) examines the relation of electricity consumption to ambient temperature in 35 European countries. Europe is particularly well suited to address this questions because of its climate heterogeneity and an extensive data pool. I investigate the statistical dependence of normalized daily electricity consumption and peak load on daily maximum temperature for the period 2006-2012 and find highly similar characteristics across all countries: load values are smallest for temperatures of about 22°C and increase monotonically in lower and higher temperatures. Building on this universal relation, I extrapolate load profiles beyond a country's currently observed temperature range and estimate future national electricity demand under different scenarios of climate change mitigation. The results show a polarization of future electricity demand with economically significant increases in Southern and Western Europe and drops in the North. This polarization is strongest by the end of the simulation period (2080-2099) and for a scenario of unabated climate change but still applies for earlier periods and a scenario of significant climate change mitigation. The projected shift in consumption from the North to the South will require costly investments in generating capacity and transmission infrastructure.

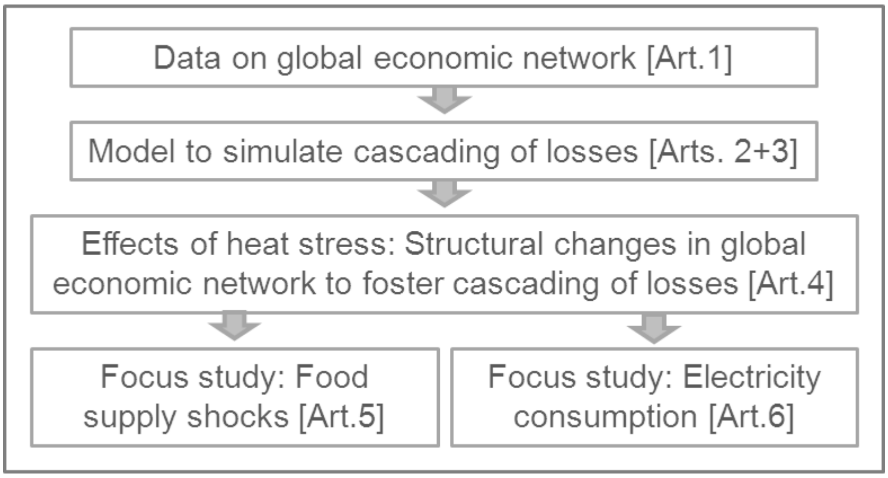

Figure 1.3: Overview of the thesis. Boxes sketch the main contributions of the six articles. The first three articles propose methodological tools to investigate global cascade effects of local climatic impacts. In [Art.1] a refinement algorithm is discussed yielding highly-resolved data on the global economic network. In [Arts. 2+3] a numerical model is introduced to analyse the fundamental response dynamics of this network to climatic events. In the fourth article, the model is applied to study the global economic effects of heat-stress [Art.4]. It is found that the susceptibility of the economic network to the propagation of climate-related losses has increased since the beginning of this century. The last two articles focus on specific aspects of the climate-economy relationship. In the fifth article, the vulnerability of developing countries to food supply shocks in distant producer regions is examined [Art.5]. The last article concentrates on the impact of climate change on the electricity sector [Art.6]. It is shown that altered electricity consumption patterns can be expected throughout Europe under future warming.

1.3 Overview of articles

This thesis is organized around six scientific articles which are either published, accepted for publication or under review (Fig. 1.3). They all provide their own introduction, concluding remarks and references; some also carry supplementary material. Here, I give a brief overview of the titles, contents and author contributions of each article. The original manuscripts are presented in Section 2. Furthermore, I was involved in the work for two other related articles which are included in the Appendix.

Article 1

Regional and sectoral disaggregation of multi-regional input-output tables - a flexible algorithm

Leonie Wenz, Sven Norman Willner, Alexander Radebach, Robert Bierkandt, Jan Christoph Steckel and Anders Levermann

An algorithm is presented to regionally and sectorally disaggregate multi-regional input-output data as required for disaster impact analyses. I developed the algorithm together with Sven Willner. I initiated and coordinated the research, prepared and analysed the exemplary application of the algorithm and led the writing of the paper. All authors contributed to the discussion of the algorithm's performance and to the improvement of the manuscript.

Published in Economic Systems Research (2015)

Article 2

Acclimate - a model for economic damage-propagation: Part 1: basic formulation of damage transfer within a global supply network and damage conserving dynamics

Robert Bierkandt, Leonie Wenz, Sven Norman Willner and Anders Levermann

A numerical model, *acclimate*, to dynamically simulate the response of the global economic network to unexpected climate-related production losses is introduced. The model was jointly developed by all authors. I further contributed to the implementation of the model equations and to the improvement of the manuscript.

Published in Environment Systems and Decision (2014)

Article 3

Acclimate - a model for economic damage-propagation: Part 2: dynamic formulation of the backward effects of disaster-induced production failures in the global supply network

Leonie Wenz, Sven Norman Willner, Robert Bierkandt and Anders Levermann

The model *acclimate* is extended by dynamics capturing demand-side effects of production failures. Two important mediating effects are introduced: production extensions and the possibility to direct demand to unaffected suppliers. I developed the equations, conducted the simulations, analysed the model's response to idealized perturbations and wrote the paper with additional input from all authors. Together with Sven Willner, I integrated the equations into the model *acclimate*.

Published in Environment Systems and Decision (2014)

Article 4

Enhanced economic connectivity to foster heat-stress-related losses

Leonie Wenz and Anders Levermann

This article shows that since the beginning of this century the structural evolution of the global economic network has been such as to foster the propagation of heat-stress-related production losses. I designed the study and analysed the results together with Anders Levermann. I conducted the model simulations, applied the network measure, prepared the figures and led the writing of the manuscript.

Published in Science Advances (2016)

Article 5

Teleconnected food supply shocks

Christopher Bren d'Amour, Leonie Wenz, Matthias Kalkuhl, Jan Christoph Steckel and Felix Creutzig

This study identifies the vulnerability of import dependent countries to food supply shocks that originate in distant producing regions. As a contribution to the analysis, I computed the trade dependencies by linking each country to its three most important suppliers. I helped designing the study, preparing the data, analysing the results and improving the manuscript.

Published in Environmental Research Letters (2016)

Article 6

North-South polarization of European electricity consumption under future warming

Leonie Wenz, Anders Levermann and Maximilian Auffhammer

In this article, the impact of climate change on electricity consumption in Europe is analysed. I designed the study and set up the regression model together with Maximilian Auffhammer. Based on the econometric analysis, I constructed the response functions together with Anders Levermann. I prepared the data and projected future electricity consumption under different climate change mitigation scenarios. The paper was jointly written by all authors.

Published in Proceedings of the National Academy of Sciences (2017)

Appendix

Article A1

Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate

Christian Otto, Sven Norman Willner, Leonie Wenz, Katja Frieler and Anders Levermann

Published in Journal of Economic Dynamics and Control (2017)

Article A2

Abrupt events and the global supply network: a network measure for cascading production losses

Nicole Glanemann, Sven Norman Willner, Leonie Wenz, Robert Bierkandt and Anders Levermann

Under review in Economic Systems Research

2

Original Manuscripts

2.1 Regional and sectoral disaggregation of multi-regional input-output tables - a flexible algorithm

Abstract: A common shortcoming of available multi-regional input–output (MRIO) data sets is their lack of regional and sectoral detail required for many research questions (e.g. in the field of disaster impact analysis). We present a simple algorithm to refine MRIO tables regionally and/or sectorally. By the use of proxy data, each MRIO flow in question is disaggregated into the corresponding sub-flows. This downscaling procedure is complemented by an adjustment rule ensuring that the sub-flows match the superordinate flow in sum. The approximation improves along several iteration steps. The algorithm unfolds its strength through the flexible combination of multiple, possibly incomplete proxy data sources. It is also flexible in a sense that any target sector and region resolution can be chosen. As an exemplary case we apply the algorithm to a regional and sectoral refinement of the Eora MRIO database.

Please find the full manuscript, published in *Economic Systems Research 27 (2015)*, **here.**

2.2 Acclimate - a model for economic damage-propagation: Part 1: basic formulation of damage transfer within a global supply network and damage conserving dynamics

Abstract: Climate extremes are expected to become more frequent and intense under future warming. In a globalized economy, outages of productive capital and infrastructure have the potential to spread around the world. In order to address those repercussions in the framework of a risk analysis or a resilience strategy, a disaster's indirect consequences on the economic supply network need to be understood. We developed a numerical model to simulate these indirect effects along global supply chains for time scales of days to months. This article is the first in a series of four, which describes the damage-propagation model. In this first paper, we describe the pure damage propagation within the network and focus on the fundamental propagation of supply failure between production sites including their input and output storages and transport-related time delay. Idealized examples are presented to illustrate the dynamic damage propagation. Further articles will extend the dynamics to include demand changes due to the perturbation in the supply, the possibility to extend production to compensate for production failure, price responses and adaptive changes in the economic supply network. The underlying global supply network is based on data from multi-regional inputâĂŞoutput tables. Transportation times are derived from geographic distances. In the initial model version presented here, indirect production losses are caused by cascading effects. They are propagated within the network without significant reduction in loss (damage conservation). They can thus be observed within the different storages or they 'leak' out of the system through reduced consumption of the final consumer. As an example, we investigate the cascading behavior of losses for the machinery sector in Japan.

Please find the full manuscript, published in *Environment Systems and Decisions 34 (2014)*, **here.**

2.3 Acclimate - a model for economic damage-propagation: Part 2: dynamic formulation of the backward effects of disaster-induced production failures in the global supply network

Abstract: As global warming accelerates extreme weather events such as floods, droughts and storms are likely to increase in intensity and frequency. With regard to a highly globalized world economy built on complex supply and value-added chains, this trend will challenge societies locally and globally. Regional production disruptions might induce shock waves that propagate through the global supply network and evoke supra-regional shortages. While such cascading effects are promoted by forward linkages in the global economic network, the demand-induced backward dynamics respond in a more complex way. On the one hand, backward linkages may additionally spread economic losses and thus aggravate the disaster aftermath. On the other hand, the readdressing of demand enables a readjustment of production, which may weaken or even dissipate shock waves. Here, we analyze the backward effects of disaster-induced production breakdowns by complementing the numerical damage transfer model Acclimate by a demand side. Based on model simulations, we show that the possibility of production extension and demand readdressing may be crucial for mitigating economic losses in the course of an extreme event.

Please find the full manuscript, published in *Environment Systems and Decisions 34 (2014)*, **here.**

2.4 Enhanced economic connectivity to foster heat-stress-related losses

Abstract: Assessing global impacts of unexpected meteorological events in an increasingly connected world economy is important for estimating the costs of climate change. Here we show that since the beginning of the 21st century the structural evolution of the global supply network has been such as to foster an increase of climate-related production losses. We compute first- and higher-order losses from heat-stress-induced reductions in productivity under changing economic and climatic conditions between 1991 and 2011. Since 2001 the economic connectivity has augmented in such a way as to facilitate the cascading of production loss. The influence of this structural change has dominated over the effect of the comparably weak climate warming during this decade. Particularly under future warming, the intensification of international trade has thus the potential to amplify climate losses if no adaptation measures are taken.

Please find the full manuscript, published in *Science Advances 2 (2016)*, **here.**

2.5 Teleconnected food supply shocks

Abstract: The 2008-2010 food crisis might have been a harbinger of fundamental climate-induced food crises with geopolitical implications. Heat-wave-induced yield losses in Russia and resulting export restrictions led to increases in market prices for wheat across the Middle East, likely contributing to the Arab Spring. With ongoing climate change, temperatures and temperature variability will rise, leading to higher uncertainty in yields for major nutritional crops. Here we investigate which countries are most vulnerable to teleconnected supply-shocks, i.e. where diets strongly rely on the import of wheat, maize, or rice, and where a large share of the population is living in poverty. We find that the Middle East is most sensitive to teleconnected supply shocks in wheat, Central America to supply shocks in maize, and Western Africa to supply shocks in rice. Weighing with poverty levels, Sub-Saharan Africa is most affected. Altogether, a simultaneous 10% reduction in exports of wheat, rice, and maize would reduce caloric intake of 55 million people living in poverty by about 5%. Export bans in major producing regions would put up to 200 million people below the poverty line at risk, 90% of which live in Sub-Saharan Africa. Our results suggest that a region-specific combination of national increases in agricultural productivity and diversification of trade partners and diets can effectively decrease future food security risks.

Please find the full manuscript, published in *Environmental Research Letters 11 (2016)*, **here.**

2.6 North-South polarization of European electricity consumption under future warming

Abstract: There is growing empirical evidence that anthropogenic climate change will substantially affect the electric sector. Impacts will stem both from the supply side – through the mitigation of greenhouse gases – and from the demand side – through adaptive responses to a changing environment. Here we provide evidence of a polarization of both peak load and overall electricity consumption under future warming for the world's third-largest electricity market – the 35 countries of Europe. We statistically estimate country-level dose-response functions between daily peak/total electricity load and ambient temperature for the period 2006-2012. After removing the impact of nontemperature confounders and normalizing the residual load data for each country, we estimate a common dose-response function, which we use to compute national electricity loads for temperatures that lie outside each country's currently observed temperature range. To this end, we impose end-of-century climate on today's European economies following three different greenhouse-gas concentration trajectories, ranging from ambitious climate-change mitigation – in line with the Paris agreement – to unabated climate change. We find significant increases in average daily peak load and overall electricity consumption in southern and western Europe (~3 to ~7% for Portugal and Spain) and significant decreases in northern Europe (~-6 to ~-2% for Sweden and Norway). While the projected effect on European total consumption is nearly zero, the significant polarization and seasonal shifts in peak demand and consumption have important ramifications for the location of costly peak-generating capacity, transmission infrastructure, and the design of energy-efficiency policy and storage capacity.

Please find the full manuscript, published in *Proceedings of the National Academy of Sciences 114 (2017)*, **here.**

3

Discussion & Conclusions

Climate change is expected to have major economic impacts around the globe with considerable implications for nature and society *(Field et al., 2014; Edenhofer et al., 2014)*. While the importance of assessing these effects as comprehensively as possible is uncontested, many aspects of the climate-economy relation have not yet been well understood *(Stern, 2007; Weitzman, 2012; Dell et al., 2014)*.
One of these aspects is the response of the globally connected economy to gradual climate change and abrupt weather extremes. Today's highly interconnected and complex economic network can give rise to cascades of climate losses that have hitherto been unconsidered by large. Such cascade effects are not adequately represented in the reports of the United Nations Intergovernmental Panel of Climate Change (IPCC) and other assessments of climate change impacts *(Levermann, 2014)*. They cannot be captured by Integrated Assessment Models (IAMs), which are predominantly used in the IPCC reports, since these models operate on coarse time scales and are too aggregated to depict a high degree of economic connectedness *(compare e.g. Farmer et al., 2015)*.

My thesis contributes to closing this research gap by introducing a general modelling framework to study global economic cascade effects and by providing three specific case studies to deepen the structural understanding of climate-related damages.
In Sects. 2.2 and 2.3, I introduced the model *acclimate* that is designed to simulate the fundamental response dynamics of the global economic network to unanticipated climatic extremes. Its main strengths, the high temporal resolution and the heterogeneity of the underlying economic system, were detailed in Sects. 2.2-2.4. While the model is already well-suited for qualitative analyses of economic loss propagation, calibration is necessary to allow for quantitative assessments as well.
Such calibration could be achieved by hindcasting the economic effects of past extreme events such as hurricane Sandy (2012) or the flooding in Middle Europe (2013).
Structural improvements of the model include a diversification of the model parameter

across sectors and regions to refine the representation of the global economic system. This step could be complemented by the application of the disaggregation algorithm that was presented in Sect. 2.1. Similarly, the description of transport could be made more explicit by accounting for shipment routes, large ports and other infrastructure.
Furthermore, long-term investment strategies should be attributed to the economic agents. A first step in that direction has been made by introducing price dynamics which permitted to base the agents' decision rationales on clear and simple optimization principles (Art. A1; *Otto et al. (2017)*). With this extension, the agents decide by profit optimization on their optimal production and consumption levels.

The model *acclimate* was applied to investigate the susceptibility of the global economic network to the propagation of heat-stress-induced production losses in Sect. 2.4. Complementary studies on food supply shocks and the effect of climate change on electricity consumption were presented in Sects. 2.5 and 2.6, respectively. In the following, I aim to embed the findings of these studies into a broader context and to discuss potential implications with respect to climate policy, society and adaptation.

Implications for damage estimates and the costs of climate change

There is a growing body of literature that argues that currently used *damage functions* systematically underestimate economic losses from climate change *(Pindyck, 2013; Weitzman, 2013; Burke et al., 2015; Farmer et al., 2015; Moore and Diaz, 2015; Stern, 2016)*. These damage functions play a crucial role in IAMs where they are, for example, used to compute the social costs of carbon and to evaluate abatement policies *(Greenstone et al., 2011; Nordhaus, 2011; Metcalf and Stock, 2015)*. In such analyses, the costs and benefits of climate mitigation actions are weighed to find an optimal environmental policy. While research on the costs of reducing greenhouse gas emissions is rather well established, estimates of the benefits of limiting anthropogenic warming are less complete and subject to large uncertainties *(compare e.g. Weitzman, 2012; Stern, 2013; Nordhaus, 2014)*.

Independent on whether the concept of damage functions is suitable for the representation of climate change in IAMs, the quantification of climate-related damages is complex and has to be based on a structural understanding of potential large-scale impacts and their economic consequences. An increasing amount of analyses is being carried out to improve knowledge about these damages. As an example, econometric studies have analysed how temperature fluctuations influence economic outcomes to assess the effect of future warming on the economy or on specific economic sectors *(e.g. Deschenes and Greenstone, 2007; Schlenker and Roberts, 2009; Auffhammer et al., 2013; Dell et al., 2014; Burke et al., 2015)*.
My thesis adds to this research with three studies.

In Sect. 2.6, I statistically examined the dependence of electricity consumption on temperature for Europe. Electricity consumption is considered to be an important driver of the social costs of carbon since an increased demand for cooling energy can be expected in response to higher temperatures *(Isaac and Van Vuuren, 2009; Mideksa and Kallbekken, 2010; Auffhammer and Mansur, 2014)*. Yet, predicting electricity demand under future warming has proven to be a challenging task. In addition to uncertainties about socio-economic trends and technological progress, adaptive responses to unprecedented temperature variations are difficult to foresee *(Franco and Sanstad, 2008)*. Comparing the relation of electricity load to temperature across European countries with different temperature profiles, I found a similar response pattern throughout the continent. Based on the characteristics of this pattern, I was able to extrapolate national electricity consumption and peak load beyond a country's currently experienced temperature spectrum.
The projections show that electricity consumption and peak load can be expected to decrease in Northern European countries under future warming and to increase in countries of the South and West. As discussed in Sect. 2.6, this shift from the North to the South will have costly implications for transmission infrastructure and generating capacity. The most significant redistribution effects will result from the projected changes in frequency and intensity of peak load across the continent because so-called peaker plants with short ramp-up times have high marginal costs of generation *(Stoft, 2002)*.

Climate change is expected to strongly affect the agriculture sector *(Nelson et al., 2010; Lobell et al., 2011; Field et al., 2014)*. Existing analyses on food security typically focus on the impact of climate change on country-specific average crop yields *(Jones and Thornton, 2003; Lobell and Field, 2007)* and, more recently, on the variability in production *(Asseng et al., 2011; Urban et al., 2012)*. The analysis that I presented in Sect. 2.5 is complementary in the sense that it addresses trade-related aspects of food supply shocks. A supply shock of a globally traded crop could be caused by many factors directly or indirectly related to climate such as harvest failures, production variability and restricting trade policies in exporting countries *(von Braun et al., 2014; Fellmann et al., 2014)*. In the case of maize, exports could also be reduced due to ambitious biofuel policies rendering ethanol production from maize highly profitable *(Abbott, 2013; Serra and Zilberman, 2013)*.
Stylized supply shock scenarios indicate that a simultaneous reduction of global wheat, maize and rice exports by 10% would decrease cereal supply in 58 countries by at least 5%. While this might seem to be small, it could imply price increases in the range of 10%-17% *(compare Haile et al., 2015)*.

In Sect. 2.4, I applied econometric results on heat-stress effects in the modelling framework of *acclimate*. Labour productivity in tropical countries has been found to decline quasi-

linearly with temperatures above a threshold of approximately 27°C *(Hsiang, 2010)*. I used this relationship to assess first- and higher-order production losses from heat-stress for the years 1991-2011 combining observational temperature, population and economic data. The results suggest that the susceptibility of the global economic network to cascade effects has risen over time and that this is mainly due to an enhanced economic connectivity. That is, the dynamic susceptibility is due to the static structure of the economic network.
As a thought experiment, I also computed first- and higher-order losses from heat-stress under a scenario of unabated climate change without economic adaptation. Production losses until 2100 again varied by an order of magnitude for different representations of the economic network (Fig. S6 in Sect. 2.4). While the specific values cannot be considered projections because, for example, a fixed economic network without adaptation is assumed, the sensitivity of the losses to the network structure is a robust feature of the simulations. Qualitatively, I hence found that enhanced economic connectivity, in the context of modern rapid globalization, can exacerbate the economic impacts of temperature fluctuations.

As demonstrated for the case of heat-stress, the model *acclimate* offers a framework in which econometric results as well as climatic and socio-economic scenarios can be incorporated to study the global economic impact of weather extremes and temperature variations. Similarly, the model can be combined with probabilistic estimates of future extreme events as provided by regional and global climate models or by models of smaller-scale events such as hurricanes *(compare Levermann, 2014)*. For instance, future hurricane frequency, intensity and location under climate change have been projected *(e.g. Knutson et al., 2010; Emanuel, 2013)* and translated into economic impacts *(e.g. Nordhaus, 2010; Mendelsohn et al., 2012)*. Such estimates that typically focus on direct damages *(compare Hallegatte, 2012)* could be integrated into the model *acclimate* to analyse potential higher-order losses as well. By this means, climate damages could be understood more comprehensively and a more complete picture of the costs of future warming could be drawn.

Implications for society and adaptation

Cascade effects may render countries vulnerable to adverse weather events in other parts of the world thereby necessitating adaptation measures that address this supra-regional exposure to impacts as well.

There is a broad range of literature on the concept of vulnerability to environmental change and different definitions exist (see *Adger (2006)* for a review). In Sect. 2.5, vulnerability was defined as the confluence of several factors that might facilitate the transmission of food supply shocks in exporting countries to caloric food availability in importing countries. The analysis indicates a regional concentration of countries that concurrently have a high dietary reliance on one crop and a mostly bilateral import dependence. The study focused on developing countries since high incomes and a good fiscal situation are considered to be important factors to reduce vulnerability at an individual and national scale *(Lampietti et al., 2011; Werrell and Femia, 2013)*.

Prior work identified three cornerstones of adaptation: (i) reducing sensitivity, (ii) reducing exposure and (iii) increasing resilience *(compare Adger et al., 2005)*. Besides poverty reduction to enhance societal resilience, several measures that could decrease the sensitivity and exposure of countries to teleconnected supply shocks were discussed in Sect. 2.5. For instance, the reliance on international markets could be reduced by closing regional yield gaps *(compare West et al., 2014)*. Other measures could aim at an increase in regional grain emergency reserves or a diversification of diets and trading partners.

These options were also discussed in the broader context of global heat-stress effects in Sect. 2.4. It was shown that an increase in storage capacities can limit higher-order losses to a certain extent but that they cannot be avoided completely (Fig. 2b in Sect. 2.4).
The diversification of trading partners and goods could reduce vulnerability to specific supply shocks but might enhance overall vulnerability. That is, the risk is spread. In the case of heat-stress effects that can occur simultaneously in different sectors and regions of the world, the total amount of losses was closely linked to the number of network connections. The network measure SPC that was presented in Sect. 2.4 provides a tool to analytically examine supply dependencies at different levels, i.e. for regional sectors, countries and the global economic network as a whole (Fig. 4 in Sect. 2.4). It is a fundamental network measure that is however specific to the issue of production supply because it accounts for the economically motivated assumption of a perfect complementarity of production inputs. Global SPC was found to be a good predictor for global economic losses to unanticipated climatic events if no adaptation measures are taken.
The network measure is discussed in further detail in Art. A2 in the Appendix *(Glanemann et al., under review)* where it is extended to capture supply dependencies of higher-order as well[1] .

While the motivation of my thesis has been to better understand the economic impacts of weather extremes and temperature fluctuations, the application of the presented methods and tools is not limited to that focus. Supply chain disruptions and cascade effects could be caused by numerous other events such as earthquakes, terror attacks and political or economic crises *(Rose and Lim, 2002; Haddad and Okuyama, 2012; Acemoglu et al., 2013)*.

[1] Please note that it is then referred to as Production Shortage Interdependence measure (PSI; Ψ).

Supply shortages of pharmaceuticals, for example, are considered a complex global challenge *(Jensen and Rappaport, 2010; Gray and Manasse Jr, 2012)*.

In addition to anticipatory adaptation options as discussed above, responsive adaptation measures can be seized as well. For instance, first-order effects of heat-stress in indoor sectors could be reduced by an increased adoption of air-conditioning.
In Sect. 2.6, I provided a framework to assess adaptive responses to rising ambient temperatures in terms of electricity demand in Europe. The projected changes in electricity demand indicate that climate change adaptation can again have significant economic implications. Further research is hence required to assess the trade-offs and the effectiveness of specific adaptation measures *(compare Adger et al., 2005)*.

In conclusion, gaining a better understanding of potential climate change impacts is important for building adaptive capacity and for evaluating mitigation policies. While not all impacts of climate change can be predicted, it should be aimed for to obtain and provide the most comprehensive picture to inform society about its future options.

Bibliography

P. Abbott. Biofuels, binding constraints and agricultural commodity price volatility. Working Paper No. w18873, National Bureau of Economic Research, 2013.

D. Acemoglu, A. Ozdaglar, and A. Tahbaz-Salehi. The network origins of large economic downturns. Working Paper No. w19230, National Bureau of Economic Research, 2013.

W. N. Adger. Vulnerability. *Global Environmental Change*, 16(3):268–281, 2006.

W. N. Adger, N. W. Arnell, and E. L. Tompkins. Successful adaptation to climate change across scales. *Global Environmental Change*, 15(2):77–86, 2005.

V. Alexeeva-Talebi, C. Böhringer, A. Löschel, and S. Voigt. The value-added of sectoral disaggregation: Implications on competitive consequences of climate change policies. *Energy Economics*, 34:127–142, 2012.

S. Asseng, I. Foster, and N. C. Turner. The impact of temperature variability on wheat yields. *Global Change Biology*, 17(2):997–1012, 2011.

M. Auffhammer and E. T. Mansur. Measuring climatic impacts on energy consumption: A review of the empirical literature. *Energy Economics*, 46:522–530, 2014.

M. Auffhammer, S. M. Hsiang, W. Schlenker, and A. Sobel. Using weather data and climate model output in economic analyses of climate change. *Review of Environmental Economics and Policy*, 7(2):181–198, 2013.

A. Barreca, K. Clay, O. Deschenes, M. Greenstone, and J. S. Shapiro. Adapting to climate change: The remarkable decline in the us temperature-mortality relationship over the twentieth century. *Journal of Political Economy*, 124(1):105–159, 2016.

F. Benjamin and B. A. Olken. Climate Shocks and Exports. Working Paper No. w15711, National Bureau of Economic Research, 2010.

R. Bierkandt, L. Wenz, S. N. Willner, and A. Levermann. Acclimate - a model for economic damage propagation. part 1: basic formulation of damage transfer within a global supply network and damage conserving dynamics. *Environment Systems and Decisions*, 34(4):507–524, 2014.

C. Bren d'Amour, L. Wenz, M. Kalkuhl, J. C. Steckel, and F. Creutzig. Teleconnected food supply shocks. *Environmental Research Letters*, 11(3):035007, 2016.

M. Burke, S. M. Hsiang, and E. Miguel. Global non-linear effect of temperature on economic production. *Nature*, 527:235–239, 2015.

M. B. Burke, E. Miguel, S. Satyanath, J. a. Dykema, and D. B. Lobell. Warming increases the risk of civil war in Africa. *Proceedings of the National Academy of Sciences of the United States of America*, 106(49):20670–4, 2009.

B. W. Cashell and M. Labonte. The macroeconomic effects of hurricane katrina. Congressional Research Service, Library of Congress, 2005.

C. E. Casillas and D. M. Kammen. The energy-poverty-climate nexus. *Science*, 330(6008): 1181–1182, 2010.

M. Christopher and H. Peck. Building the resilient supply chain. *The International Journal of Logistics Management*, 15(2):1–14, 2004.

A. Costinot, J. Vogel, and S. Wang. An elementary theory of global supply chains. *The Review of Economic Studies*, 80:109–144, 2012.

M. Dell, B. F. Jones, and B. a. Olken. Temperature Shocks and Economic Growth: Evidence from the Last Half Century. *American Economic Journal: Macroeconomics*, 4(3):66–95, 2012.

M. Dell, B. Jones, and B. Olken. What do we learn from the weather? The new climate-economy literature. *Journal of Economic Literature*, 52(3):740–98, 2014.

O. Deschenes and M. Greenstone. The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *The American Economic Review*, 96(1):354–385, 2007.

D. Donaldson. The gains from market integration. *Annual Reviews of Economics*, 7(1):619–647, 2015.

O. Edenhofer, R. Pichs-Madruga, and Y. Sokona, editors. *IPCC, 2014: Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Cambridge, United Kingdom and New York, NY, USA, 2014.

K. A. Emanuel. Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences*, 110(30):12219–12224, 2013.

G. S. Eskeland and T. K. Mideksa. Electricity demand in a changing climate. *Mitigation and Adaptation Strategies for Global Change*, 15(8):877–897, 2010.

FAOSTAT. Food and Agriculture Organization of the United Nations Statistics Division, 2015. URL http://faostat3.fao.org/home/E.

J. D. Farmer, C. Hepburn, P. Mealy, and A. Teytelboym. A third wave in the economics of climate change. *Environmental and Resource Economics*, 62(2):329–357, 2015.

G. Felbermayr and J. Gröschl. Naturally negative: The growth effects of natural disasters. *Journal of Development Economics*, 111:92–106, 2014.

T. Fellmann, S. Hélaine, and O. Nekhay. Harvest failures, temporary export restrictions and global food security: the example of limited grain exports from Russia, Ukraine and Kazakhstan. *Food Security*, 6(5):727–742, 2014.

C. Field, V. Barros, D. Dokken, K. Mach, M. Mastrandrea, T. Bilir, M. Chatterjee, K. Ebi, Y. Estrada, R. Genova, B. Girma, E. Kissel, A. Levy, S. MacCracken, P. Mastrandrea, and L.L.White, editors. *IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Cambridge, United Kingdom and New York, NY, USA, 2014.

G. Franco and A. H. Sanstad. Climate change and electricity demand in california. *Climatic Change*, 87(1):139–151, 2008.

J. d. Giovanni and A. A. Levchenko. Trade openness and volatility. *The Review of Economics and Statistics*, 91(3):558–585, 2009.

N. Glanemann, S. N. Willner, L. Wenz, R. Bierkandt, and A. Levermann. Abrupt events and the global supply network: a network measure for cascading production losses. *Economic Systems Research*, under review.

A. Gray and H. R. Manasse Jr. Shortages of medicines: a complex global challenge. *Bulletin of the World Health Organization*, 90(3):158–158, 2012.

M. Greenstone, E. Kopits, and A. Wolverton. Estimating the social cost of carbon for use in us federal rulemakings: A summary and interpretation. Working Paper No. w16913, National Bureau of Economic Research, 2011.

E. Haddad and Y. Okuyama. Spatial Propagation of the Economic Impacts of Bombing: The Case of the 2006 War in Lebanon. Technical report, University of Sao Paulo (FEA-USP), 2012.

M. G. Haile, M. Kalkuhl, and J. Von Braun. Worldwide acreage and yield response to international price change and volatility: a dynamic panel data analysis for wheat, rice, corn, and soybeans. *American Journal of Agricultural Economics*, 98(1):172–190, 2015.

S. Hallegatte. Economics: The rising costs of hurricanes. *Nature Climate Change*, 2(3):148–149, 2012.

S. Hallegatte. Modeling the Roles of Heterogeneity, Substitution, and Inventories in the Assessment of Natural Disaster Economic Costs. *Risk Analysis*, 34(1):152–167, 2014.

S. Hallegatte, J. C. Hourcade, and P. Dumas. Why economic dynamics matter in assessing climate change damages: Illustration on extreme events. *Ecological Economics*, 62(2):330–340, 2007.

M. Haraguchi and U. Lall. Flood risks and impacts: A case study of Thailand's floods in 2011 and research questions for supply chain decision making. *International Journal of Disaster Risk Reduction*, 14(3):256 – 272, 2014.

E. Hertwich and G. Peters. Multiregional Input-Output Database. OPEN:EU Technical Document, 2010. URL `http://www.oneplaneteconomynetwork.org/resources/programme-documents/WP1_MRIO_Technical_Document.pdf`.

O. Hoegh-Guldberg and J. F. Bruno. The impact of climate change on the world's marine ecosystems. *Science*, 328(5985):1523–8, 2010.

S. M. Hsiang. Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America. *Proceedings of the National Academy of Sciences of the United States of America*, 107(35):15367–72, 2010.

S. M. Hsiang, M. Burke, and E. Miguel. Quantifying the influence of climate on human conflict. *Science*, 341(6151):1235367, 2013.

D. Hummels, J. Ishii, and K.-M. Yi. The nature and growth of vertical specialization in world trade. *Journal of International Economics*, 54(1):75–96, 2001.

H. E. Huppert and R. S. J. Sparks. Extreme natural hazards: population growth, globalization and environmental change. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 364(1845):1875–1888, 2006.

M. Isaac and D. P. Van Vuuren. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, 37(2):507–521, 2009.

V. Jensen and B. A. Rappaport. The reality of drug shortages - the case of the injectable agent propofol. *New England Journal of Medicine*, 363(9):806–807, 2010.

P. G. Jones and P. K. Thornton. The potential impacts of climate change on maize production in africa and latin america in 2055. *Global Environmental Change*, 13(1):51–59, 2003.

T. R. Knutson, J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. Srivastava, and M. Sugi. Tropical cyclones and climate change. *Nature Geoscience*, 3(3):157–163, 2010.

M. Lagi, Y. Bar-Yam, K. Z. Bertrand, and Y. Bar-Yam. Accurate market price formation model with both supply-demand and trend-following for global food prices providing policy recommendations. *Proceedings of the National Academy of Sciences*, 112(45):E6119–E6128, 2015.

J. A. Lampietti, S. Michaels, N. Magnan, A. F. McCalla, M. Saade, and N. Khouri. A strategic framework for improving food security in arab countries. *Food Security*, 3(1):7–22, 2011.

M. Lenzen. Aggregation versus disaggregation in input–output analysis of the environment. *Economic Systems Research*, 23(1):73–89, 2011.

M. Lenzen, K. Kanemot, D. Moran, and A. Geschke. Mapping the structure of the world economy. *Environmental Science & Technology*, 46(15):8374–8381, 2012.

A. Levermann. Make supply chains climate-smart. *Nature*, 504:27 – 29, 2014.

S. Lindner, J. Legault, and D. Guan. Disaggregating input–output models with incomplete information. *Economic Systems Research*, 24(4):329–347, 2012.

D. B. Lobell and C. B. Field. Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, 2(1):014002, 2007.

D. B. Lobell, W. Schlenker, and J. Costa-Roberts. Climate trends and global crop production since 1980. *Science*, 333(6042):616–20, 2011.

J. Maluck and R. V. Donner. A network of networks perspective on global trade. *PloS ONE*, 10(7):e0133310, 2015.

J. McFarland, Y. Zhou, L. Clarke, P. Sullivan, J. Colman, W. S. Jaglom, M. Colley, P. Patel, J. Eom, S. H. Kim, et al. Impacts of rising air temperatures and emissions mitigation on electricity demand and supply in the united states: a multi-model comparison. *Climatic Change*, 131(1):111–125, 2015.

R. Mendelsohn, K. Emanuel, S. Chonabayashi, and L. Bakkensen. The impact of climate change on global tropical cyclone damage. *Nature Climate Change*, 2(3):205–209, 2012.

M. Mengel, A. Levermann, K. Frieler, A. Robinson, B. Marzeion, and R. Winkelmann. Future sea level rise constrained by observations and long-term commitment. *Proceedings of the National Academy of Sciences*, 113(10):2597–2602, 2016.

G. E. Metcalf and J. Stock. The role of integrated assessment models in climate policy: A user's guide and assessment. *The Harvard Project on Climate Agreements Discussion Paper*, pages 15–68, 2015.

T. K. Mideksa and S. Kallbekken. The impact of climate change on the electricity market: A review. *Energy Policy*, 38(7):3579–3585, 2010.

F. C. Moore and D. B. Diaz. Temperature impacts on economic growth warrant stringent mitigation policy. *Nature Climate Change*, 5(2):127–131, 2015.

B. Narayanan, A. Aguiar, and R. McDougalL. Global Trade, Assistance and Production: The GTAP8 Database, 2012. URL http://www.gtap.agecon.purdue.edu/databases/v8/v8_doco.asp.

G. C. Nelson, M. W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T. B. Sulser, C. Ringler, et al. *Food security, farming, and climate change to 2050: Scenarios, results, policy options*, volume 172. International Food Policy Research Institute, 2010.

D. M. Newbery and J. E. Stiglitz. Pareto inferior trade. *The Review of Economic Studies*, 51 (1):1–12, 1984.

W. D. Nordhaus. The economics of hurricanes and implications of global warming. *Climate Change Economics*, 1(01):1–20, 2010.

W. D. Nordhaus. Estimates of the social cost of carbon: background and results from the RICE-2011 model. Working Paper No. w17540, National Bureau of Economic Research, 2011.

W. D. Nordhaus. *A question of balance: Weighing the options on global warming policies*. Yale University Press, 2014.

Y. Okuyama. Economic modeling for disaster impact analysis: past, present, and future. *Economic Systems Research*, 19(2):115–124, 2007.

Y. Okuyama and J. R. Santos. Disaster impact and input-output analysis. *Economic Systems Research*, 26(1):1–12, 2014.

C. Otto, S. N. Willner, L. Wenz, K. Frieler, and A. Levermann. Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate. *Journal of Economic Dynamics and Control*, 83:232–269, 2017.

J. A. Patz, D. Campbell-Lendrum, T. Holloway, and J. A. Foley. Impact of regional climate change on human health. *Nature*, 438(7066):310–317, 2005.

J. J. Pilcher, E. Nadler, and C. Busch. Effects of hot and cold temperature exposure on performance: a meta-analytic review. *Ergonomics*, 45(10):682–698, 2002.

R. S. Pindyck. Climate change policy: What do the models tell us? *Journal of Economic Literature*, 21(3):860–872, 2013.

S. Rahmstorf and D. Coumou. Increase of extreme events in a warming world. *Proceedings of the National Academy of Sciences*, 108(44):4709–4714, 2011.

J. D. Ramsey. Task performance in heat: a review. *Ergonomics*, 38(1):154–165, 1995.

D. Rodrik. How far will international economic integration go? *The Journal of Economic Perspectives*, 14(1):177–186, 2000.

A. Rose. *Modeling Spatial and Economic Impacts of Disasters*. Advances in Spatial Science. Springer, Berlin Heidelberg, 2004.

A. Rose and D. Lim. Business interruption losses from natural hazards: conceptual and methodological issues in the case of the northridge earthquake. *Global Environmental Change Part B: Environmental Hazards*, 4(1):1–14, 2002.

D. H. Rosenthal, H. K. Gruenspecht, and E. A. Moran. Effects of global warming on energy use for space heating and cooling in the united states. *The Energy Journal*, 16(2):77–96, 1995.

R. Schaeffer, A. S. Szklo, A. F. P. de Lucena, B. S. M. C. Borba, L. P. P. Nogueira, F. P. Fleming, A. Troccoli, M. Harrison, and M. S. Boulahya. Energy sector vulnerability to climate change: a review. *Energy*, 38(1):1–12, 2012.

J. Schewe, J. Heinke, D. Gerten, I. Haddeland, N. W. Arnell, D. B. Clark, R. Dankers, S. Eisner, B. M. Fekete, F. J. Colón-González, et al. Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, 111(9):3245–3250, 2014.

W. Schlenker and M. J. Roberts. Nonlinear temperature effects indicate severe damages to us crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106 (37):15594–15598, 2009.

J. Schmidhuber and F. N. Tubiello. Global food security under climate change. *Proceedings of the National Academy of Sciences*, 104(50):19703–19708, 2007.

T. Serra and D. Zilberman. Biofuel-related price transmission literature: A review. *Energy Economics*, 37:141–151, 2013.

S. Solomon, G.-K. Plattner, R. Knutti, and P. Friedlingstein. Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences*, 106(6): 1704–1709, 2009.

N. Stern. *The economics of climate change: the Stern review*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

N. Stern. The structure of economic modeling of the potential impacts of climate change: grafting gross underestimation of risk onto already narrow science models. *Journal of Economic Literature*, 51(3):838–859, 2013.

N. Stern. Economics: Current climate models are grossly misleading. *Nature*, 530(7591): 407–409, 2016.

T. Sternberg. Chinese drought, bread and the arab spring. *Applied Geography*, 34:519–524, 2012.

T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, editors. *IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Cambridge, United Kingdom and New York, NY, USA, 2013.

S. Stoft. Power system economics. *Journal of Energy Literature*, 8:94–99, 2002.

C. D. Thomas, A. Cameron, R. E. Green, M. Bakkenes, L. J. Beaumont, Y. C. Collingham, B. F. N. Erasmus, M. F. De Siqueira, A. Grainger, L. Hannah, L. Hughes, B. Huntley, A. S. Van Jaarsveld, G. F. Midgley, L. Miles, M. a. Ortega-Huerta, a. T. Peterson, O. L. Phillips, and S. E. Williams. Extinction risk from climate change. *Nature*, 427(6970):145–8, 2004.

M. P. Timmer. The World Input-Output Database (WIOD). Contents, Sources and Methods, 2012. URL www.wiod.org.

K. E. Trenberth. Changes in precipitation with climate change. *Climate Research*, 47(1):123, 2011.

R. Trostle, D. Marti, S. Rosen, and P. Westcott. *Why Have Food Commodity Prices Risen Again?* USDA, Washington, DC, USA, 2011.

D. Urban, M. J. Roberts, W. Schlenker, and D. B. Lobell. Projected temperature changes indicate significant increase in interannual variability of us maize yields. *Climatic change*, 112(2):525–533, 2012.

S. Vandentorren, F. Suzan, S. Medina, M. Pascal, A. Maulpoix, J.-C. Cohen, and M. Ledrans. Mortality in 13 French Cities During the August 2003 Heat Wave. *American Journal of Public Health*, 94(9):1518–1520, 2004.

A. V. D. Veen. Disasters and economic damage: macro, meso and micro approaches. *Disaster Prevention and Management*, 13(4):274–279, 2004.

J. von Braun, B. Algieri, and M. Kalkuhl. World food system disruptions in the early 2000s: causes, impacts and cures. *World Food Policy*, 1(1), 2014.

M. L. Weitzman. GHG targets as insurance against catastrophic climate damages. *Journal of Public Economic Theory*, 14(2):221–244, 2012.

M. L. Weitzman. Tail-hedge discounting and the social cost of carbon. *Journal of Economic Literature*, 51(3):873–882, 2013.

L. Wenz and A. Levermann. Enhanced economic connectivity to foster heat stress–related losses. *Science Advances*, 2(6):e1501026, 2016.

L. Wenz, S. N. Willner, R. Bierkandt, and A. Levermann. Acclimate - a model for economic damage propagation. part 2: a dynamic formulation of the backward effects of disaster-induced production failures in the global supply network. *Environment Systems and Decisions*, 34(4):525–539, 2014.

L. Wenz, S. N. Willner, A. Radebach, R. Bierkandt, J. C. Steckel, and A. Levermann. Regional and sectoral disaggregation of multi-regional input–output tables–a flexible algorithm. *Economic Systems Research*, 27(2):194–212, 2015.

L. Wenz, A. Levermann, and M. Auffhammer. North–south polarization of european electricity consumption under future warming. *Proceedings of the National Academy of Sciences*, 114(38):E7910–E7918, 2017.

C. E. Werrell and F. Femia, editors. *The Arab Spring and climate change: a climate and security correlations series*. Center for American Progress, 2013.

P. C. West, J. S. Gerber, P. M. Engstrom, N. D. Mueller, K. A. Brauman, K. M. Carlson, E. S. Cassidy, M. Johnston, G. K. MacDonald, D. K. Ray, et al. Leverage points for improving global food security and the environment. *Science*, 345(6194):325–328, 2014.

T. Wiedmann, H. C. Wilting, M. Lenzen, S. Lutter, and V. Palm. Quo Vadis MRIO? Methodological, data and institutional requirements for multi-region input-output analysis. *Ecological Economics*, 70(11):1937–1945, 2011.

A
Appendix

A.1 Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate

Abstract: World markets are highly interlinked and local economies extensively rely on global supply and value chains. Consequently, local production disruptions, for instance caused by extreme weather events, are likely to induce indirect losses along supply chains with potentially global repercussions. These complex loss dynamics represent a challenge for comprehensive disaster risk assessments. Here, we introduce the numerical agent-based model acclimate designed to analyze the cascading of economic losses in the global supply network. Using national sectors as agents, we apply the model to study the global propagation of losses induced by stylized disasters. We find that indirect losses can become comparable in size to direct ones, but can be efficiently mitigated by warehousing and idle capacities. Consequently, a comprehensive risk assessment cannot focus solely on first-tier suppliers, but has to take the whole supply chain into account. To render the supply network climate-proof, national adaptation policies have to be complemented by international adaptation efforts. In that regard, our model can be employed to assess reasonable leverage points and to identify dynamic bottlenecks inaccessible to static analyses.

Please find the full manuscript, published in *Journal of Economic Dynamics and Control 83 (2017)*, **here.**

A.2 Abrupt events and the global supply network: a network measure for cascading production losses

Abstract: Local production losses caused by unanticipated catastrophic events such as extreme weather, earthquakes and terror attacks entail a high risk of being spread through the globalised supply network thereby affecting many economies. As a contribution to the assessment of the supply network vulnerability to these events, we provide a novel measure for the propagation of production losses. It is in particular developed to identify supply dependencies that can become critical in the short period following extreme events. This measure generalizes the concept of import and export dependencies by taking into account higher-order supply relationships and structural properties of the network. Using information on trade connections and trade volumes as the only input, it tracks the dissemination of the production losses from one supply chain layer to the next in a recursive routine. An extended version of this measure reflects the producers' efforts to compensate the input shortages. Applying the measure to recent input-output data, we demonstrate that the network is structured in a way that some regional sectors' production losses have the potential to affect the global economy significantly. For these cases we identify rapid cascade effects of considerable size. We also find that other network measures do not fully reflect this new measure, as a linear combination of them does not sufficiently reproduce the result on the maximum production loss. The measure introduced in this paper can also be used to gain insights into the production loss dissemination across countries. We find that many countries can be affected substantially through indirect trade relationships with regions that are highly exposed to natural catastrophes.

Please find the full manuscript **here.**

Erklärung

Diese Arbeit ist bisher an keiner anderen Hochschule eingereicht worden. Sie wurde selbständig und ausschließlich mit den angegebenen Mitteln angefertigt.

Potsdam, den 23. Mai 2016

Leonie Wenz