Chapter 8
Extreme Weather Events and the German Economy: The Potential for Climate Change Adaptation

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Abstract Although climate change is a global challenge, its effects occur locally and differ by region. A feasible adaptation strategy needs to assess regional damages and their socio-economic effects. For Germany, the largest threat comes from extreme weather events, which will impact residential and commercial buildings, infrastructure and in the case of heat waves will limit labor productivity. This paper presents findings from a study of economic effects of climate change adaptation until the year 2050 in Germany on different scales. In particular, the authors have applied an input–output-based macroeconometric model, adjusting it to cope with the challenges of damages from heat waves, and river flood events, by integrating suitable adaptation measures to such events into the model. Infrastructure damages, shifts from domestic production to imports, and low levels of productivity due to heat waves, are some of the topics the paper deals with. Comparing scenarios with (a) integrated extreme weather events and (b) adaptation measures with a reference scenario without extreme weather or adaptation, the simulation results reveal slightly negative effects on economic sectors and Germany's economy as a whole. These effects intensify over time and hurt the economy. Adaptation measures reduce the damages and pay off, but the economy is still worse off with climate change.

Keywords Extreme weather events • Heat wave • River flood • Adaptation

Introduction

In the last 15 years, Germany experienced severe extreme weather events, particularly river floods and heat waves. The flood events of the rivers Elbe, Danube and Oder in the Eastern part of Germany caused massive damages in the years 2002,

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2006, 2010 and 2013 amounting to several bn. Euros (Muenchner Rueck 2003; Chorynski et al. 2012). The most severe heat wave in Germany occurred in the year 2003, followed by above average hot summers in 2006 and 2010 (UNEP 2004; Muenchner Rueck 2004).

Germany's industry contributes 30.8 % to the country's Gross Domestic Product (GDP); a high contribution in comparison with other European countries (France with 19.4 %, UK with 20.6 % or the US with 20.7 %).[1] The industry is situated close to waterways and suffers losses from floods, which in turn affect further upstream and downstream industries. Moreover, Germany is the fifth densely populated country in Europe (after Malta, Belgium, Netherlands and UK) and the damages from floods in densely populated areas are high. In addition, potential inundation areas are cultivated and populated. As the frequency of occurrence and the severity of extreme weather events likely increase in the future (IPCC 2013), adaptation measures will be taken. Estimates of the likely benefits from adaptation measures based on estimates of the prevented damages are relevant to support decision makers to take the appropriate steps. Our results contribute to this decision base.

Latest since the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in the year 1992 economists developed different approaches to quantify economic effects of climate change. Integrated Assessment Models (IAM) extend economic general equilibrium models with damage functions driven by physical impacts, mostly focus on the increase of global average surface temperature. FUND (Climate Framework for Uncertainty, Negotiation and Distribution) (Tol 1997; Tol et al. 2014), Dynamic Integrated Climate-Economy Model (DICE) (Nordhaus 1992; Nordhaus and Sztorc 2013), The Policy Analysis for the Greenhouse Effect (PAGE) (Hope 2011) and MERGE (Model for Evaluating Regional and Global Effects of GHG reductions) (Manne et al. 1995) are the most prominent IAM models. Patt et al. (2010) find that IAM rarely are applied to extreme weather events, though examples can be found in the FUND 3.17 model (Anthoff and Tol 2013). Disaster Impact Models (DIM) focus on the latter, e.g., on floods, hurricanes or earthquakes on a regional level (Hallegatte et al. 2011; Rose and Liao 2005), but lack the overall economic perspective. Although the first reference to adaptation in scientific analyses can already be found in the First Assessment Report of the IPCC in 1991, only the Cancún summit in 2010 has brought this topic back on the UNFCCC framework agenda (Agrawala et al. 2011). In the last 15 years, adaptation to climate change has increasingly entered the literature on climate change policies. Agrawala et al. (2011) give a comprehensive overview on methodologies and adaptation costs at the sectoral, regional and global level. The focus is on adaptation to consequences of gradual temperature changes (e.g., sea-level rise, changes in the tourism sector or in agricultural production). Adaptation to extreme weather events (heat waves, floods, storms) is as well considered, albeit only in the context of their effects on human health. In creating

[1] All data for 2014 from Central Intelligence Agency (2015).

AD-DICE, as an extension of the DICE model, de Bruin et al. 2009 integrate adaptation and mitigation in one model.

Mitigation policy decisions have been supported by the results of a further modelling approach, called macroeconometric simulation models. Examples are E3E by Cambridge Econometrics (Barker et al. 2015; Pollitt et al. 2014; Barker et al. 2011) or the model described in this contribution, PANTA RHEI (Lutz et al. 2005; Lehr et al. 2008; Meyer et al. 2012). The basic idea behind this approach is that the economy is characterized by several non-equilibrium states, such as unemployment, inefficient use of resources etc. and therefore an alternative approach to equilibrium modelling was sought. The research question which will be answered in the remainder of this contribution is: Can this type of model be extended to simulate the effects of climate change and climate change adaptation?

The remainder of this paper is organized as follows: The next section describes the changes needed in the modelling framework and defines the scenarios for (a) frequently recurring extreme weather events (river floods and heat waves) and (b) adaptation measures. In the following section, results are presented in terms of effects on the German economy as a whole and on individual economic sectors until 2050. The last section concludes and gives an outlook.

The Modelling Challenge

This section introduces the model. However, since the model comprises several thousand equations, a closed analytical representation cannot be given and the reader is referred to the available model descriptions in the literature (Lehr et al. 2011; Grossmann et al. 2012).

The Model PANTA RHEI

PANTA RHEI (Lutz et al. 2005; Lehr et al. 2008; Meyer et al. 2012) is an environmentally extended version of the econometric simulation and forecasting model INFORGE (Ahlert et al. 2009; Meyer et al. 2007). A detailed description of the economic part of the model is presented in Maier et al. (2015). Among others, it has been used for economic evaluation of different energy scenarios that have been the basis for the German energy concept in 2010 (Lindenberger et al. 2010; Nagl et al. 2011).

The behavioral equations reflect bounded rationality rather than optimizing behavior of agents. All parameters are estimated econometrically from time series data (1991–2012). Producer prices are the result of mark-up calculations of firms. Output decisions follow observable historic developments, including observed inefficiencies rather than optimal choices. The use of econometrically estimated equations means that agents have only myopic expectations. They follow routines developed in the past. This implies in contrast to equilibrium models that markets will not necessarily be in an optimum and non-market (energy) policy interventions can have positive economic impacts.

Structural equations are usually modeled on the 59 sector level (according to the European 2 digit NACE classification of economic activities) of the input–output accounting framework of the official system of national accounts (SNA) and the corresponding macro variables are then endogenously calculated by explicit aggregation. In that sense the model has a bottom-up structure. The input–output part is consistently integrated into the SNA accounts, which fully reflect the circular flow of generation, distribution, redistribution and use of income.

The core of PANTA RHEI is the economic module, which calculates final demand (consumption, investment, exports) and intermediate demand (domestic and imported) for goods, capital stocks, and employment, wages, unit costs and producer as well as consumer prices in deep disaggregation of 59 industries. The disaggregated system also calculates taxes on goods and taxes on production. The corresponding equations are integrated into the balance equations of the input–output system.

Value added of the different branches is aggregated and gives the base for the SNA that calculates distribution and redistribution of income, use of disposable income, capital account and financial account for financial enterprises, non-financial enterprises, private households, the government and the rest of the world. Macro variables like disposable income of private households and disposable income of the government as well as demographic variables represent important determinants of sectoral final demand for goods. Another important outcome of the macro SNA system are net savings and governmental debt as its stock. Both are important indicators for the evaluation of policies. The demand side of the labor market is modeled in deep sectoral disaggregation. Wages per head are explained using Philips curve specifications. The aggregate labor supply is driven by demographic developments.

The model is empirically evaluated: The parameters of the structural equations are econometrically estimated. On the time consuming model-specification stage various sets of competing theoretical hypotheses are empirically tested. As the resulting structure is characterized by highly nonlinear and interdependent dynamics the economic core of the model has furthermore been tested in dynamic ex-post simulations. The model is solved by an iterative procedure year by year.

The energy module captures the dependence between economic development, energy input and CO_2 emissions. It contains the full energy balance with primary energy input, transformation and final energy consumption for 20 energy consumption sectors, 27 fossil energy carriers and the satellite balance for renewable energy (AGEB 2011). The energy module is fully integrated into the economic part of the model.

Input–output tables provide detailed insights into the flows of goods and services between all sectors of the economy and the interdependence of the economy of a country and with the rest of the world. They are closed accounting schemes where the identity of the sum of inputs and the sum of outputs has to hold in each sector.

PANTA RHEI covers effects for the German economy in total and for 59 economic sectors. Regional disaggregation exists, but it has not been part of the simulations described here.

Integration of Damages

In a first step, PANTA RHEI is extended to allow modelling damages resulting from extreme weather events, the second step is the simulation of adaptation. To effectively integrate extreme events and adaptation measures into the model, it is essential to firstly identify economic sectors most severely affected by extreme events in the past. Since no time series exist concerning extreme weather events in Germany, cost and damages of river flood events and heat waves are primarily derived from the impacts of the Oder/Elbe flood in 2002 and the heat wave in 2003, functioning as reference events or benchmark. Table 8.1 gives an overview of the observed physical impact, its translation into model variables and economic quantities and the literature used.

For instance: A flood event on the Rhine, where numerous production sites of the machinery industry are located, leads to damages on buildings and production sites in the machinery sector. Companies decrease output, because the capital stock is damaged, i.e., the production machinery is damaged, wet, spoiled etc. The industry will rebuild and claim reimbursement from insurances. The economy as a whole experiences a slowdown from the lacking output and growth from the repair measures. There is a time lag between the damage and the full recovery, which depends on the industry analyzed. Intermediate input production slows and is replaced by imports. Transport infrastructure damages impede the transport of intermediate goods. All this leads to an increase of imports in PANTA RHEI. Similar proceeding holds for heat waves. More detailed information on the approach of including extreme weather events in PANTA RHEI can be found in Nieters et al. (2015).

Scenarios: Exploring Consistent Future Developments

The next step involves the definition of future scenarios. The comparison of results from simulation runs under different scenario assumptions gives estimates of relative economic effects. The reference case is based on the reference projection for the German energy system (cf. GWS, Prognos, EWI 2013).

In scenario 1, extreme weather enters the model as shocks and economic interdependences are temporarily overridden. The "shocks" reflecting flood events were modeled in the form of 10-year events, which means that the processes described above take place every 10 years until 2050. The decade between 2041 and 2050 is an exception, since two flood events occur. The "shocks" reflecting heat

Table 8.1 Integration of extreme events in PANTA RHEI

Damages	Target variables	Expected main effects	Sources
Damages of a river flood on. . .			
. . .production sites	– Capital stock of: *Machinery*	Increase in buildings investment and investment in plant and equipment, loss in production	Muenchner Rueck (2003) Braeuer et al. (2009)
	– Other current transfers		
. . .dwellings	– Capital stock of: *Real estate*	Increase in buildings investment and investment in plant and equipment, decrease in consumption	Muenchner Rueck (2003) Braeuer et al. (2009)
	– Other current transfers		
	– Disposable income		
. . .transport infrastructure	– Capital stock of: *Public administration*	Increase in buildings investment, unit costs and depreciation, loss in production	Muenchner Rueck (2003)
	– Other current transfers		
	– Production output		
. . .production	– Imported intermediate goods: *Chemicals* *Machinery* *Metals and semi-finished products* *Basic metals* *Automobiles and parts* *Agriculture*	Increase in imports and prices	Ludwig and Brautzsch (2002) BMI (2013)
. . .disaster management	– Government spending: *Defense* *Public order and safety*	Lower government spending in fields other than defense and public order and safety (e.g., for education), lower disposable income for private households	BMI (2013)
	– Tax increases for private households		
Damages of a heat wave on. . .			
. . .agriculture	– Imported intermediate goods: *Agriculture*	Increase in imports and prices and decrease in production value	Braeuer et al. (2009) Fischer and Schaer (2010)
. . .energy sector	– Electricity imports	Increase in imports and prices and decrease in production value	Rademaekers et al. (2011)
. . .labor productivity	– Labor productivity	Decrease in average wages per hour, increase in employment	Huebler et al. (2008) PIK (2014)
. . .ship traffic	– Input coefficients of land and ship transport services	Increase in imports and prices	Jonkeren et al. (2011)
	– Imported intermediate goods: *All*		

waves are modeled in the form of 4-year events. It has to be stressed that we do not make a point regarding the likelihood of occurrence of flood events or heat waves. The occurrence in 10 or 4-year intervals is merely an assumption in accordance with estimations of climate experts concerning an increase in frequency and intensity of extreme weather events in Europe (IPCC 2014; Braeuer et al. 2009).

Scenario 2 includes adaptation measures. Investing in adaptation measures leads to lesser future damages. Adequate adaptation to prevent damages from river floods events is the creation of additional retention areas, which are located next to running waters and used in case of flood discharge as flood-plain areas and the reinforcement of dikes, paid from public funds. Adaptation to heat waves in electric power generation requires cooling towers. The costs are borne by the utility companies. Companies prevent heat-related reductions in labor productivity by greening roofs and installing air conditioning and have to bear the costs for these investments. Air conditioning is regarded an adaptation strategy as long as environmentally friendly air conditioners are installed and energy from renewable sources is used. Table 8.2 shows the adaptation measures, the translation into model variables and the literature used, similar to Table 8.1.

Scenario comparison shows differences in a large set of economic quantities. Results are given as changes in the following indicators:

- Differences in overall GDP stand for differences in economic performance.
- Differences in employment reflects the social aspects of a future development.
- Private consumption reflects individual well-being.
- Production indicates the opportunities and activities of a country's industry.
- Sector specific production gives an indication of winners and losers.

Table 8.2 Modeling adaptation

Adaptation measures			
Creation of additional retention areas	– Increase in buildings investments – Compensation for farmers increases other current transfers	Assumption: All flood damages are avoided Described expected main effects (s. above) are reduced	Gruenig et al. (2013)
Reinforcement of dikes	– Increase in buildings investments		Gruenig et al. (2013)
Installation of cooling towers	– Increase in buildings investments	Increase in energy imports is avoided	Van Ierland et al. (2007) Weisz et al. (2013)
Roof greening	– Increase in buildings investments	Assumption: Reduction of labor productivity is avoided	Gruenig et al. (2013) Altvater et al. (2012)
Installation of air conditioning	– Increase in buildings investments		ZIA (2014), BKI (2013)

As has been pointed out above, the systems boundary is Germany. Note that the frequency of the extreme weather event cannot be a forecast and therefore the development over time of the economic results strongly hinges on the assumed frequency.

Results I: Extreme Weather Events Compared to Reference Scenario

Simulation results indicate that overall economic effects of recurring heat waves and river floods are moderate in Germany until 2050. Figure 8.1 shows the development of the four indicators described above. All results are produced as follows: the model is run under different scenarios and produces time series of the respective indicator. Subtraction of GDP under the reference scenario from GDP under the extreme weather scenario gives the GDP effect from extreme weather events. Figure 8.1 shows these differences for all for indicators. Negative values mean the indicator is smaller in the extreme weather event scenario compared to the reference.

Overall, the data show a negative effect of weather extremes on the economy, Private consumption is annually between 1 and 3 bn., production between 3.5 and 30 bn. and GDP between 1.8 and 19.5 bn. Euros lower than in the reference. Only employment is higher under extreme events. The positive development can be attributed to two effects: firstly, production shifts from capital-intensive sectors to labor-intensive sectors, as capital is destroyed by the flood and production goes down in some capital-intensive sectors, whereas employment in the labor intensive construction sector grows. Secondly, the increase is due to falling productivity, which is compensated by the model with businesses hiring more personnel, whose wage incomes have become smaller.

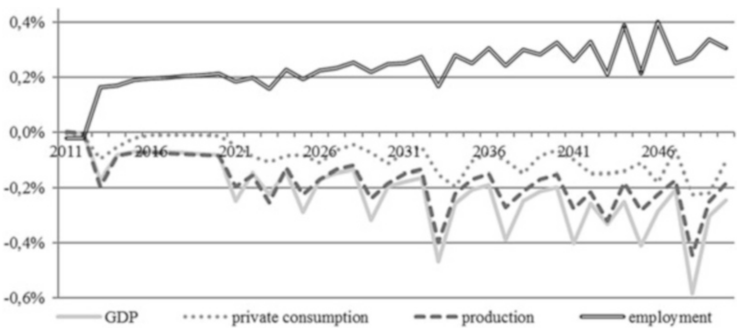

Fig. 8.1 Economic development, difference (in %) extreme weather versus reference scenario, price adjusted

The effect is intensifying over time: In the decade from 2031 to 2040, average effects are higher than in the following decade, even if less events occur, hence effects seem to be lasting, and the predicted increase in the number and intensity of extreme weather events in Germany may challenge its economic development in the future.

Results II: Adaptation to Extreme Weather Events Compared to (a) Extreme Weather and (b) Reference Scenario

Economic effects from adaptation are twofold in the model: they prevent or reduce extreme weather damages and they induce economic activity in the construction sector, in transportation, and in the production of adaptation goods. Figure 8.2 shows the simulation results as differences between two simulation runs. The economic impacts of adaptation are positive in comparison to the extreme weather scenario. The effect is increasing over time, which is due to the fact that firstly, the impacts of extreme weather events are as well rising. Secondly, adaptation measures are cumulative over the years. Hence, the more adaptation measures are undertaken, the more damages are avoided. However, the positive deviation is diminishing in the last decade. This development results from rising costs accompanying some of the adaptation measures.

Figure 8.3 shows the development of GDP in the extreme weather and the adaptation scenario until 2050 in comparison to the reference scenario. It can be seen that the selected adaptation measures reduce the negative effects of extreme weather events, however, in both scenarios the German economy is worse off in comparison to a scenario without extreme weather events.

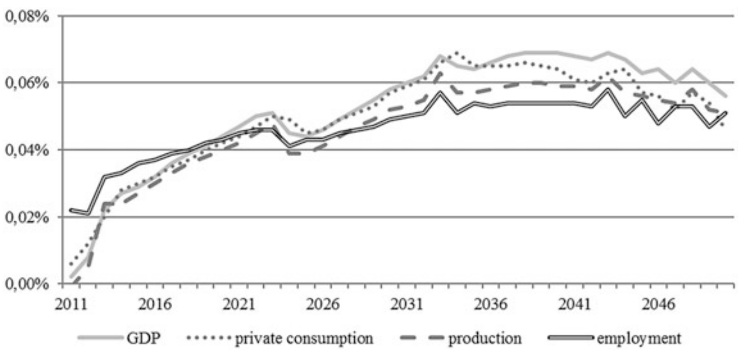

Fig. 8.2 Economic development, difference (in %) extreme weather versus adaptation scenario, price adjusted

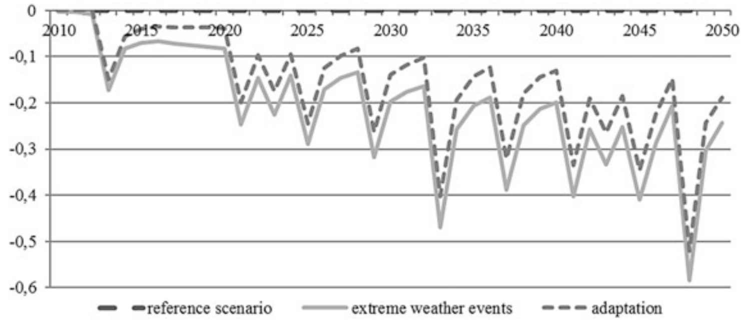

Fig. 8.3 GDP, differences reference versus extreme weather and adaptation scenario, price adjusted

A More Detailed Picture: Extreme Weather and Economic Sectors

How are individual sectors affected by extreme weather? Are there winners and losers in the economy? The contribution of sectors to the aggregate changes can differ markedly. Since the analysis of effects on the total economy may underestimate the effects on individual economic sectors, sector-specific effects have been included in the analysis. Instead of a detailed description of single effects of extreme weather events and adaptation measures on the economic sectors, an overview of the most and least affected industries is given.

For the sector specific analysis, we need one further indicator: Gross Value Added (GVA). Gross Value Added by sector is defined as the difference between turnover and costs by industry. Wages and profits are paid from Gross Value Added. It serves as a measure of sector specific success. In 2014, GVA in Germany amounted to roughly 2.5 tr. Euros. As presented in Table 8.3, the most important sectors with respect to economic performance are "other services" (administrative and support service activities, public administration and defense, education, social activities and health and other) recording GVA of 1.25 tr. Euros. The next largest sector is manufacturing (535 bn. Euros), as well as the trade sector (250 bn. Euros).

Comparing the reference and the extreme weather scenario (see Table 8.4) we find small deviations from the reference scenario. An exception is the transport sector with percentage changes between 0.4 and 0.5 per decade.

Transport and communication services show the largest effects with an average increase in GVA of 0.5 % in the period between 2021 and 2030 and 0.4 % in the other decades. The construction sector follows with deviations amounting to values between 0.1 and 0.3 %. Striking are the simulation results for the agricultural sector, indicating a slightly positive effect—as far as average deviations per decade are considered. Figure 8.4 presents annual deviations from the reference scenario in the sectors agriculture and trade (in percent) and reveals that the total effect on these sectors, positive in both cases, does not reflect the vulnerability of the sectors.

Table 8.3 Gross value added on the sectoral level in 2014, in bn. Euros

Economic sectors	GVA in 2014 in bn. Euros
Agriculture, forestry and fishery	20
Mining and quarrying	7
Manufacturing	535
Energy and water supply	71
Construction	114
Trade; maintenance and repair of motor vehicles	250
Hotel and restaurant industry	45
Transport and communication services	150
Financial intermediation	92
Other services	1252

Table 8.4 GVA, average deviations per decade, extreme weather versus reference scenario, in percent

Economic sectors	2011–2020 (%)	2021–2030 (%)	2031–2040 (%)	2041–2050 (%)
Agriculture, forestry and fishery	0.07	0.01	0.11	0.09
Mining and quarrying	−0.17	−0.31	−0.27	−0.28
Manufacturing	−0.07	−0.22	−0.19	−0.28
Energy and water supply	−0.04	−0.09	−0.13	−0.16
Construction	0.14	0.21	0.28	0.29
Trade; maintenance and repair of motor vehicles	0.08	0.12	0.18	0.20
Hotel and restaurant industry	−0.04	−0.14	−0.14	−0.17
Transport and communication services	0.43	0.48	0.43	0.38
Financial intermediation	0.06	0.07	0.10	0.09
Other services	−0.02	−0.08	−0.09	−0.11

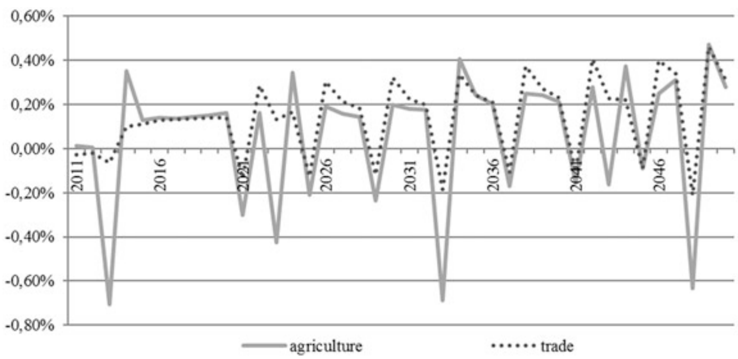

Fig. 8.4 GVA, deviations from the reference scenario of the sectors trade and agriculture, in percent

Simulation results indicate both years with negative and years with positive effects. Even if the negative effect on GVA in the agricultural sector is rather strong on an annual basis in comparison to the other sectors (−0.71 %), the overall effect on the sector is positive, meaning that negative impacts in the years in which extreme events occur are overcompensated by positive effects in the years in between. The same is true for the trade sector: negative effects are observable but positive effects predominate. This means, the stronger the impact, the stronger the counter-reaction in the years following extreme weather events. An increasing number of extreme events may pose a challenge particularly for the agricultural sector. The relatively strong counter-reactions can be attributed to price increases after an extreme weather event due to a likely considerable crop loss. Higher prices in years following an extreme event may compensate farmers for the losses in the previous one, thus leading to an increase in GVA.

Effects of Adaptation to Extreme Weather Events on Economic Sectors

In the adaptation scenario, governments and companies undertake investments to adapt to river floods by extending retention areas and reinforcing dikes. Impacts of heat waves on labor productivity and on power plants are mitigated by investments in green roofing, air conditioning and cooling towers. Table 8.5 shows the average deviations per decade of GVA on the sectoral basis, comparing the reference and the adaptation scenario. Simulation results of the latter reflect a combination of both, impacts of extreme weather events, and adaptation measures. This is because, firstly, undertaking adaptation measures does not mean that all impacts of extreme weathers are avoided at once. This is happening incrementally. Secondly, not all of

Table 8.5 GVA, average deviations per decade, adaptation versus reference scenario, in percent

Economic sectors	2011–2020 (%)	2021–2030 (%)	2031–2040 (%)	2041–2050 (%)
Agriculture, forestry and fishery	0.12	0.05	0.15	0.16
Mining and quarrying	−0.03	−0.17	−0.13	−0.16
Manufacturing	0.00	−0.15	−0.11	−0.19
Energy and water supply	0.00	−0.02	−0.03	−0.05
Construction	0.28	0.47	0.68	0.81
Trade; maintenance and repair of motor vehicles	0.11	0.16	0.23	0.24
Hotel and restaurant industry	0.01	−0.06	−0.05	−0.10
Transport and communication services	0.05	0.12	0.10	0.10
Financial intermediation	0.09	0.11	0.15	0.13
Other services	0.00	−0.04	−0.04	−0.06

the modeled impacts can be reduced by the selected adaptation measures: whereas it is assumed that all effects of river floods can be avoided by the end of the simulation period, the selected measures are for example not suitable to adapt to low river water levels during a massive heat wave. Also in the adaptation scenario ship transport companies have to shift to other means of transportation to deliver (intermediate) goods and raw materials.

The differences in GVA between the reference and the adaptation scenario are similar to the results obtained by comparing the extreme weather and the reference scenario. As discussed by the following examples, effects are small and some of the sectors may benefit from adaptation measures, whereas others may suffer reductions in GVA. In all sectors (an exception is the sector transport and communication services) the positive effect is intensifying in the adaptation scenario, whereas negative effects are diminishing (see, for comparison Table 8.4). In most of the sectors, the development can be attributed to avoided damages. The manufacturing sector, for example, faces lower damages on buildings and properties, since communities gradually invest in additional retention areas and dike reinforcement. Average deviations per decade from the reference scenario amount to between −0.11 and 0.19 %. Hence, the sector mining and quarrying records lower deviations as well. An increasing number of utility companies does not need to reduce or even cease energy production in case of heat waves due to the installation of cooling towers. Therefore, reductions in GVA decrease and amount to between −0.02 and −0.05.

The sectors already "benefitting" from extreme weather events (decade averages), show even higher values in terms of GVA in the adaptation scenario. This is because there is a combination of extreme events and adaptation measures in this scenario. While, for example, the agricultural sector is less affected by river flood events, simultaneously it benefits from compensation payments for the creation of retention areas. Average deviations of GVA in the adaptation scenario are up to 0.16 % higher than in the reference. Investments in dike reinforcement, green roofing or air conditioning lead to a rise in GVA in the construction sector in comparison to the reference (up to 0.81 %) and as well to the extreme weather scenario. The transport sector, in turn, benefits from the positive development in the trade and construction sector. However, in comparison to the extreme weather scenario, where the deviation from the reference amounts to up to 0.17 % in the last decade, the deviation of the adaptation scenario from the reference run is up to 0.10 % and thus decreasing. This is because only the demand for construction material increases in comparison to the extreme weather scenario and the reference, implicating an increased need for transport services. The demand for disposal of rubble, and for machinery and other equipment in affected regions is lower than in the extreme weather scenario, since damages are lower.

Overall, all sectors benefit from adaptation measures, even if this involves financial burdens for companies and the government. Some sectors (agriculture, construction, trade and others) benefit from extreme weather events when focusing on GVA and decade averages, however investments in adaptation measures intensify the positive development. At the same time adaptation to extreme events diminishes negative effects resulting from these events. The sector transport and communication services is the only sector not following a similar pattern. It benefits from adaptation measures in comparison to the reference scenario but compared to the development in the extreme weather scenario it performs worse.

Conclusions

The analysis has shown that extreme weather events have a small effect on the German economy. However, the analysis shows an intensification of the impacts on economic sectors and the economy as a whole in the future. Thus, recurring extreme weather events have the potential to weaken Germany's future economic performance. Adaptation measures not only reduce negative effects on the German economy, but also stimulate economic activity and might also lead to the development of innovations demanded on international markets. However, it has to be emphasized that the results do not take climate change effects on other countries into account. The decline or loss of production sites along the value chain in countries producing raw materials or intermediate goods for German production incurs losses in Germany. Further research into these effects is required.

On a sector-specific level, manufacturing as well as mining and quarrying are the most heavily affected industries with respect to GVA when comparing the extreme weather and the adaptation scenario with the reference scenario. The transport sector benefits the most from extreme events. However, its economic performance diminishes in the adaptation scenario. The construction sector responds above average positively to adaptation measures. For future research, this detailed sector specific analysis needs a detailed regional analysis, too. Not only industries differ in their vulnerability to extreme weather events, but also the individual regions in Germany. Reductions in agricultural production, for example, will have stronger impacts on the economy of Schleswig-Holstein than on North Rhine-Westphalia, since agricultural production in Schleswig-Holstein plays a more important role for the value added in that region than in North Rhine-Westphalia. Regarding this issue, further research is necessary to gain a more comprehensive insight into the impacts of extreme weather events and, thus, adaptation measures in Germany. Detailed knowledge about a region's vulnerability to extreme events is decisive with respect to adaptation strategies. Within a regional approach, the burden sharing process will gain more relevance. Although the effects spread over the whole economy, the local or regional effects on individual households might be much larger. These aspects escape a macro-modeling exercise. Moreover, some responses of the economic sectors to extreme events and adaptation measures reveal weaknesses underlying input–output-based macroeconometric models when analyzing effects of extreme weather events. Further adjustments are needed to capture modified economic relationships resulting from extreme events unhinging preliminary relationships and their interdependencies.

The access to more comprehensive and more detailed data on damages and costs resulting from extreme weather events and costs associated with concrete adaptation measures in Germany will improve simulation results. The program for further research therefore has to meet the threefold challenge of a wider regional focus, including trade and international value chains, a narrower regional focus within Germany and the need for more accurate, sector (and region) specific data on damages from all kinds of extreme weather and temperature increases.

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