23. CLIMATE CHANGE IMPACTS AT THE NATIONAL LEVEL: KNOWN TRENDS, UNKNOWN TAILS, AND UNKNOWABLES*

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ABSTRACT

Economists attempting to evaluate the impacts of climate change are often caught between hard theory and exceedingly rocky empirics. Impact assessment models are necessarily based on highly aggregated – and sometimes highly simplified – damage functions. This study takes an alternative approach: a bottom-up, physical impact assessment and respective monetization, attempting to cover *a much broader set of* impact fields, feeding directly into a macroeconomic and welfare analysis at the national level. To ensure consistency, our approach applies impact assessment at the sectoral impact chain level using shared socioeconomic pathways, consistent climate scenarios, computable general equilibrium evaluation, and non-market impact evaluation. The approach is applied to assess a broad scope of climate impacts in Austria. Results indicate significant impacts around 'known knowns' (such as changes in agricultural yield from climatic shifts), with uncertainty increased by 'known unknowns' (e.g. changes in water availability for irrigation, changes in pest and diseases) but also raises the question of unknowns and unknowables, which may possibly dominate future impacts (such as exceedance of critical ecosystem function

for supporting agriculture). Climate change, ultimately, is a risk management problem, where insurance thinking warrants significant mitigation (and adaptation) action today.

Analysis of the study result indicate that the current welfare damage of climate and weather induced extreme events in Austria is an annual average of € 1 billion (large events only). This has the potential to rise to € 4 to 5 billion by mid-century (annual average, known knowns of impact chains only), with an uncertainty range of € 4 to 9 billion. When extreme events and the tails of their distribution are included, even for a partial analysis focused on extremes, damages are seen to rise significantly, e.g. with an estimated increase to € 40 billion due to riverine flooding events alone by the end of the century. These highlight the need to consider the distribution of impacts, as well as the central values.

1. Introduction

What we know about climate change confirms it to be one of the major challenges facing humanity in the 21st century. However, what we don't (yet) know—and possibly won't know before it is too late to act—could drive up potential costs higher still. The Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report confirms the bottom line reported in the peer-reviewed literature for decades: climate change is taking place with global mean temperature increase of almost one degree Celsius since 1880 and that it is predominantly caused by human activities (IPCC, 2013). The IPCC also reports that left unabated, future emissions will lead to a temperature increase by the end of the century of 3.2 to 5.4 degrees Celsius. The impacts of such a change are profound. Polar Regions would warm by at least twice as much. Sea levels will rise for centuries (due to the slow process of heat uptake by the deep ocean and arising very long term (thermal expansion) commitment to sea level rise). Furthermore, given that surface air temperature above oceans will warm by less than the global average, many regions, particular land-bound mountainous and continental climate zones, will face more substantial increases; e.g. a 4.5 to 6.6 degree Celsius increase by 2100 is projected for the Alpine region and thus for a country such as Austria (Jacob et al., 2013)[1].

Even the most ambitious mitigation scenarios could potentially lead to dangerous climate change; i.e. even if global average warming is limited to two degrees Celsius relative to pre-industrial levels (the current international goal agreed (UNFCCC, 2010)), noting that this is unlikely to be met). Higher emissions pathways lead to increasingly costly impacts. The IPCC 5th Assessment Report (2014a: 11-14) identifies which risks of climate change are

[1] This range for Alpine regions refers to the „likely" range, i.e. the 17 to 83 percentile. To be fully comparable with the global temperature range given by IPCC, which refers tot he 5 to 95 percentile, the range for the Alpine region would be larger.

"considerable at 1 or 2°C above preindustrial levels" and all global risks to be "high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all of the reasons for concern" (the latter being unique and threatened systems, extreme weather events, distribution of impacts, global aggregate impacts, large-scale singular events).

All of this points to the need to avoid high emission and warming scenarios with mitigation. It also indicates that adaptation to climate change will be needed, to the warming already observed and locked into the climate system over the next few decades (from past and near-term emissions), as well as to future emissions. This is likely to require complementary mixes of mitigation and adaptation (Watkiss et al, 2015), noting that the two address different risks, operate at different aggregation and temporal scales, and that there are limits to adaptation (IPCC, 2014c). Nevertheless, both adaptation and mitigation require well informed decision making and thus knowledge and information on the type and magnitude of climate change impacts expected.

Over the last few years, a wide range of methodologies have emerged for assessing the costs of climate change. Global economic integrated assessment models assess the economic costs of climate change, combining the scientific and economic aspects of climate change within a single, iterative analytical framework. However, they use highly aggregated economic damage functions (usually based on global temperature increase as the sole aggregated climate parameter). They are applied to provide economic costs over time and thus for a specified rise in global mean temperature or for a specific future year, the net present values for future damages over time, and to estimate the marginal social costs of carbon (the damage cost of an extra tonne of GHG emissions). While these provide valuable insights, these costs are extremely difficult to estimate and vary considerably, and are heavily influenced by the choice of discount rate and inclusion of equity weights as well as the coverage of impacts (Watkiss, 2011a): their coverage is therefore recognised as partial and incomplete (IPCC, 2014). Their use has therefore been questioned. Pindyck (2013) emphasizes the arbitrary choice of damage function (especially for higher rates of warming) and neglect of many catastrophic outcomes; Weitzman (2009, 2012) and Wagner and Weitzman (2015) emphasize the deep-seated uncertainty around climate sensitivity that is not fully reflected in the models.[2]

[2] The three most often applied Integrated Assessment Models (IAMs) to date are DICE (Dynamic Integrated Climate and Economy), PAGE (Policy Analysis of the Greenhouse Effect), and FUND (Climate Framework for Uncertainty, Distribution, and Negotiation), with model descriptions given by Nordhaus (1991, 2011); Hope (2006) – on which the Stern review is based (Stern, 2007) –; and Tol 2002a,b, Anthoff and Tol, 2010, respectively. The modelling aspects questioned most – for derivation of social costs of carbon by such means –

There are two main approaches that differentiate impacts specifically. While these do not address all of the challenges above, they provide improved damage functions and reduce aggregation errors. Their focus is primarily the regional, national, and/or sub-national scale. These approaches, as briefly presented in Chapter 3 (Europe) of the present volume, and discussed in more detail in Watkiss and Hunt (2010) are:

- *Scenario-Based Impact-Assessments* combine climate model outputs with sector impact models (or functional relationships) in order to estimate physical impacts, which are then valued so as to estimate welfare costs. However, these assessments are not able to capture cross-sectoral, economy-wide effects. There are a number of variations, including risk assessments, which focus on extreme (probabilistic) events such as flooding (using historical analogues or damage-loss relationships), and econometric assessments, which use historical relationships between economic production and climate and then apply these to future climate scenarios.
- *Computable General Equilibrium (CGE) models* provide multi-sectoral and macro-economic analysis of the economic costs of climate change. They have the advantage of capturing cross-sectoral linkages and economy-wide effects (and metrics), and they can also look at price and trade effects. However, they use aggregated representations of impacts and omit non-market impacts.

These approaches use different metrics, modelling approaches and assumptions. No one method is in principle right or wrong – their use depends on the given objectives. More recently, some studies have begun to combine these approaches in a single framework, to produce more complementary information. An example of such an analysis at the European level is presented in Chapter 3 (Europe), which summarizes results from the EU ClimateCost Project. There is also a clear demand for cost evaluations at the national level, as this is where climate change materializes and where the administration and governance of adaptation takes place.

The objective of this book was to provide a comprehensive impact assessment for a single country, spanning *as broad a* field of impact as possible. Methodologically, it draws from and combines the following:

- Scenario-Based Sector Impact-Assessment: to capture national impacts at the most detailed level available;
- Computable General Equilibrium (CGE) analysis: to capture cross-sectoral linkages and economy-wide effects;

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include arbitrary parameter choice in social welfare functions, climate sensitivity (the temperature increase a GHG doubling implies), arbitrary and non-empirical based climate damage functions (usually a functional relationship between temperature increase and (regional) GDP loss, for FUND also distinguishing individual sectors), and neglect of consideration of possible catastrophic outcomes. For detailed discussions see Watkiss (2011), Pindyck (2013), Stern (2013),and Wagner and Weitzman (2015).

- Qualitative analysis: to capture additional non-market effects.

To our knowledge this is one of only a small number of studies that have applied such a comprehensive approach at the national level (i.e. across many relevant impact fields). To date, national level studies have primarily focused on a few selected sectors (and impacts) covering for example agriculture, water, energy, human health, together with assessments of coastal impacts for non-landlocked countries (e.g. Ruth et al. 2007 for the US; Ciscar et al. 2011 for European countries; Ackerman and Stanton 2011 for an overview).

Increasing the sectoral comprehensiveness does, however, reveal more areas where we have insufficient knowledge. For some issues, incomplete knowledge is inherent in the nature of the problem. For others, it points to a to-do list for future work. Thus, our approach does not result in a 'final' figure with respect to total damages. In fact, the research lets us see that we remain some way from achieving such a figure. However, it does provide a more transparent picture of what we know, what we know we don't know, and to raise the potential to think more broadly and consider new aspects (current unknowns), which itself has profound implications for optimal policy.

Sectoral impacts, their economic costs and their macroeconomic feedback effects (taken in isolation for each impact field) are reported in Chapters 9 (Agriculture) to 20 (Tourism). The economic implications when all of these impacts are considered simultaneously are reported in Chapter 22 (Macroeconomic Evaluation). However, when testing for their aggregated effect, all such impacts are, first, assessed in terms of a single climate and socioeconomic scenario (considered to be a "medium" development) and, second, they do not focus on total weather and climate induced costs, but only on those costs triggered by additional climate change. The present chapter seeks to put these earlier aggregate results into perspective and to thus consider a more comprehensive evaluation.

To do this we move beyond simple aggregated results in three ways: First, total – and not only additional – weather and climate induced costs are considered. Second, we reconsider "known unknowns", such as biodiversity loss due to climate change. Third, we move beyond the expected value of damage alone, recognising this to be inadequate for risk management as it neglects analysis of the tails of the distribution of possible events and impacts. We thus take a closer look at more extreme or catastrophic events – the "fat tails" of climate impacts. By considering these three extensions, more adequate policy conclusions become possible.

Finally, we sketch the implications of potential "unknown unknowns" and "unknowables" in climate change – and the potential societal response.

The structure of this chapter is as follows. Section 2 covers the impacts that we know of, the "known knowns". Section 3 presents the picture of what we already know that we don´t know, including an evaluation of ranges of developments. It also discusses fat tails in the context of tipping elements at a continental scale and illustrates the relevance of tail risks at the national level by considering three types of extreme events and their damage ranges. The final section concludes.

2. KNOWN KNOWNS

a. WEATHER AND CLIMATE INDUCED EXTREME EVENT DAMAGE: TAKING STOCK OF THE PAST

The first area of analysis is to estimate the current welfare damage of climate and weather induced extreme events in Austria.[3] MunichRe (2014) supplies the most comprehensive database on weather and climate related damage for Austria. The data covers all large damage events and most medium ones[4], and has comprehensive coverage since 2002. In 2002 – an extreme year - the weather and climate related large damages in Austria amounted to $€_{2010}$ 3.67 billion (1.5% of GDP)[5], mainly driven by flooding damage. Across the past decade (2001-2010), the annual average damage related to large and medium events in Austria was $€_{2010}$ 705 million (m), equivalent to slightly above 0.25 % of GDP. There is some (less detailed) data over a longer time-period that provides some basis for comparison. This indicates that damages have increased considerably over the last few decades, starting from an annual $€_{2010}$ 97 m in the 1980s, and rising to $€_{2010}$ 129 m in the 1990s (data coverage in the earlier decades is not complete, however, even on large events; König et al. (2014): 665), though this is most likely due to socio-economic change.

According to MunichRe NatCatService data, the climate and weather related premature death toll in Austria over the last decade (2001-2010) was 411, of which 334 were due to heat (330 alone in 2003) and the remaining 77 primarily due to avalanches (38), floods and storms.

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[3] In the literature this is also known as ´adpatation deficit´.

[4] Damage events covered by MunichRe (2014) concern catastrophes of UN classification level 3-6. With medium catastrophes (levels 3 and 4) characterized by damages larger than US$ 25m (40m/50m/60m) when occurring in the 1980s (1990s/200s/2010s) and large and significant catastrophes (levels 5 and 6) characterized by damages beyond US$ 275m (400m/500m/650m) or respective death tolls (more than 100 and more than 500, respectively).

[5] This number relates to total damages (i.e. beyond those insured) of large and significant catastrophes (of levels 5 and 6), but covers direct damages only, i.e. it does not include indirect damages, macroeconomic consequences or non-market damages.

The aggregated 2001-2010 total damages recorded in the database for Austria, totally $€_{2010}$ 7 billion, are attributed to the following types of events: 61% are related to precipitation-triggered events (primarily large and small scale floods including flash floods and landslides/mudflows) while 23% are storm-related. 7% of the damage is related to cold spells and winter damage, 6% to heat waves, droughts and forest fires and the remaining 3% to hail damages.

However, these monetary estimates only include direct damage observed. Thus, neither the indirect disruption or follow-up costs, nor the non-market impacts (such as biodiversity losses, health inconveniences, morbidity and mortality, etc.) are included.

In Table 23.1 we provide monetary estimates for one of the non-market impacts, premature heat related deaths, annual average 2003-2012, using death tolls for this period from Table 12.6 (Chapter 12) and two different monetary evaluation methods as described in Watkiss (2011b). Adding these, we identify a stock of climate and weather induced damages in Austria (the ´adaptation deficit´) at an annual average of $€_{2010}$ 1 billion for the first decade in the 21st century. Including the additional effects from indirect and non-monetary areas, as well as macro-economic costs, would increase these estimates further, possibly by 25-100% (e.g. see Hallegatte et al, 2007).

It is highlighted that this captures the effects of extremes only: the current climate – and the variability between years - also affects many other areas, affecting crop productivity, winter heating and summer cooling, water flows and availability, etc.

b. Future Additional Weather and Climate Change Induced Damages

Considering a reference level of socioeconomic development and a mid-range climate change scenario, the additional economic net damage that climate change causes (i.e. relative to a baseline scenario of equivalent socioeconomic change, but no further climate change), measured in welfare terms amounts to € 1 billion (annual average) for the period 2016-2045 and almost € 2 billion for the period 2036-2065. These numbers are based on sectoral impact models and the integration of their results in a national CGE model. Only those impact chain subsets are covered for which robust results can be derived. Chapter 22 (Macroeconomic Evaluation) is devoted to analysing and interpreting the above welfare results in detail.

Nations, however, are not only confronted with climate and weather damage triggered by *climatic change* (i.e. by a climate change signal beyond the state of climate we observe today). They also have to deal with the total climate and weather induced damage. This includes two further elements: the climate and weather induced damage already observed under the current state of climate (as covered in section *2.a* above); and the climate and weather induced damage due to factors other than climatic change (e.g. population or infrastructure growth, but also changed lifestyle such as increase in living space by person) which are due to "socioeconomic development". In the present study we undertook a closer analysis of the latter in three core areas of climate and weather induced cost, i.e. electricity supply, road transport infrastructure, and riverine flooding. In each of these categories the change in socioeconomic factors alone (i.e. without any further climate change) tends to increase weather and climate induced costs: electricity supply has to react by additional investment to a (peak load) demand that increases with a higher share of air conditioning, an expanded road infrastructure network drives up weather induced damage costs, and the expansion in real values (e.g. of houses) increases riverine flooding damages. The estimated figures (yearly average, period 2036-2065) for additional costs occurring in each of these sectors are as follows:

- energy supply: annual additional investment € 298 m (see Chapter 15 (Electricity) section 4e.ii) to match rising electricity demand (including a rising share of air conditioning)
- road infrastructure: annual additional investment for road damage reconstruction € 20 m (see Chapter 17 (Transport) section 4e.ii) due to a larger road network
- riverine flooding: annual additional riverine flooding cost of € 507 m (see chapter 19 (Catastrophe), Climate Cost approach, baseline damage as given in section 4.e.i. (€ 820 m) subtracting damages observed to date already (Table 19.2; € 313 m)) due to increased real values in flood prone areas.

For the period 2016-2045 the respective damage figures are € 99 m (energy), € 8 m (roads) and € 165m (floods) (sources as above).

Finally, one of the most significant non-market effects, future premature heat related deaths (as reported in Chapter 12 (Human Health)), can be monetised. Based on Watkiss (2011) we employ both the value of a statistical life (VSL) and the value of life years lost (VLY), see Table 23.1 for rates used.

c. Weather and Climate related Damage: Known Totals

The structure of climate and weather induced damage is reported in monetary terms in Table 23.1. This comprises a sum of the components as described in sections *a* and *b* above. The structure of components may be different than in other studies. Note that CGE models are calibrated on historic data that already incorporate (and do not isolate) the the current stock of damages. We identify the current stock of weather and climate induced damages separately (section *a* above). Our CGE analysis identifies additional (net) damages, which will be triggered by future climate change, while the sectoral analysis allows us to isolate additional climate and weather induced costs that will be triggered by just the future change in socioeconomic factors (both as covered in section *b* above). For a reference socioeconomic scenario and mid-range climate change we find climate and weather induced damage in Austria increases from a current annual average of approximately € 1 billion, to between € 2.2 − € 2.6 billion in the 2030s, and to between € 4.2 − € 5.2 billion in the 2050s (all in 2010 €, undiscounted, to allow for direct evaluation for each of the future periods and comparison across them). These numbers don't include any of the "known unknowns" yet, i.e. unquantified impacts identified in Chapters 9 (Agriculture) to 20 (Tourism), such as increased irrigation or increased pest control costs in agriculture, increased soil erosion, increased impact of storm events in forestry, biodiversity losses etc. For a list of most relevant non-quantified impact chains see Table 23.3, for a full account of non-quantified impact chains see the Tables "Impact chains" in each of the Chapters 9 (Agriculture) to 20 (Tourism) and Table 22.1.

Table 23.1: Climate and weather induced damage, across sectors, quantified "known knowns" impact chains only, average annual totals for Austria (for periods 2016-2045 and 2036-2065)

Damage in €m p.a. **(2010 prices, undiscounted)**	**2016-2045**	**2036-2065**
A) Stock of current damages (extremes)		
Damage observed to date (market & non-market)	**850** to **1090**	**850** to **1090**
Annual average of extreme weather event damage (MunichRe, only larger damage, Ø for period 2001 to 2010)	705	705
Non-market damage:		
Heat induced premature deaths (monetary value)	145 to 385	145 to 385
Evaluation using Value of Statistical Life	385	385
Evaluation using Value of Life Years Lost	145	145
B) Additional Future damages		
Damage induced by future climate change	**995**	**1,955**
Welfare loss (reference socioeconomic development, mid-range climate change, see Chapter 22, Table 22.2)		
Additional damage induced by future socioeconomic change	**270**	**825**
Energy additional investment	99	299
Road infrastructure additional investment	8	20
Riverine flooding additional damage	163	506
Non-market damage:		
Heat induced premature deaths (monetary value)	**95** to **255**	**570** to **1,300**
Evaluation using Value of Statistical Life (€ 1.6m per SL)	255	1,300
Evaluation using Value of Life Years Lost (€ 63000 per LYL)	95	570
C) Total annual average (comprising current level plus future additional damages)	**2,210** to **2,610**	**4,201** to **5,170**

Note: Values for VSL and LYL from Watkiss (2011b), toll of heat induced premature deaths under reference socioeconomic scenario and mid-range climate scenario as given in Table 12.6 (first period 400, second 730), equivalent for LYL.

3. What we know we don't know: known Unknowns

a. Which Climate Change And Socioeconomic Scenario Will Materialize?

The climate change impacts quantified in monetary terms in Table 23.1 refer to one scenario, which we call "intermediate". More specifically, it's intermediate in two senses of that word: we use the "reference" socioeconomic scenario and the "mid-range" climate scenario to derive one intermediate cost estimate of climate and weather induced net costs. It's consistent across sectors, and thus also allows for a macroeconomic evaluation of impacts across sectors simultaneously.

However, focusing on intermediate scenarios also misses an important dimension of this book's overall analysis, which also covers climate model and socioeconomic uncertainty: what if parameter combinations are such that they lead to lower (higher) damages? How low (high) might the figures (which were reported in Table 23.1 for the intermediate case) for weather and climate induced damage become?

For each category of impact, Chapters 9 (Agriculture) to 20 (Tourism) identify the respective dimensions that determine the damage most significantly (e.g. for heat induced premature deaths one central parameter is technical adaptation, i.e. what percentage of the (old) population can reduce their risk by air conditioning, that is in addition to which climate scenario materialises). Each chapter's analysis, where the data basis allows to do so, varies these central parameters (if possible in both domains, socioeconomic and climate) in order to stress-test the intermediate values presented. This results in an additional low range and high range damage value for each category of impact.

There's a word of caution in order for the aggregated consideration of these, however. We cannot simply add low (high) range values across all impact fields, as there are also impacts that (at least partly) counterbalance across impact fields. For example, a warmer climate scenario tends to *in*crease premature deaths (and thus to increase damage), but at the same time tends to decrease (winter) heating expenses, creating an additional benefit that is *de*creasing overall damage. Acknowledging these interactions across impact fields gives a narrower range for damage, than just simply adding low (high) impact values across all sectors and impacts. Damage values for consistent low and high damage scenarios are presented in Table 23.2. These values do *not* cover the lowest and highest possible (for a further discussion on these see the section on fat tails below), they simply represent damage values originating from consistently varying central damage relevant parameters within a plausible range. Table 23.2 thus gives lower (higher) range damage values.

Table 23.2: Climate and weather induced damage, across sectors, quantified “known knowns” impact chains only, lower and higher range for average annual totals for Austria (for periods 2016-2045 and 2036-2065)

Damage in €m p.a. (2010 prices)	**2016-2045**	**2036-2065**
A) Stock of damages		
Damage observed to date (market & non-market)	**850** to **1090**	**850** to **1090**
Annual average of extreme weather event damage (MunichRe, only larger damage, Ø for period 2001 to 2010)	705	705
Non-market damage:		
Heat induced premature deaths	145 to 385	145 to 385
Evaluation using Value of Statistical Life	385	385
Evaluation using Value of Life Years Lost	145	145
B) Additional Future damages		
Damage induced by future climate change	**[890** to **1,211]**	**[1,825** to **2,280]**
Welfare loss (resulting from consistent low and high climate change impact scenarios across impact fields)		
Additional damage induced by future socioeconomic change	**[268** to **314]**	**[800** to **1,080]**
Non-market damage:		
Heat induced premature deaths	**82** to **1,535**	**285** to **4,350**
Evaluation using Value of Statistical Life (€ 1.6m per SL)	[210 to 1,535]	[640 to 4,350]
Evaluation using Value of Life Years Lost (€ 63000 per LYL)	[82 to 580]	[285 to 1,840]
C) Total annual average (comprising current level plus future additional damages)	**2,090** to **4,150**	**3,760** to **8,800**

Note: Values for VSL and LYL from Watkiss (2011b), toll of heat induced premature deaths and life years lost across socioeconomic and climate scenarios from Table 12.6 in Chapter 12.

We find that, considering also lower and higher ranges of damages, figures for estimated damage in Austria range € 2.1 to € 4.2 billion per year on average in the period 2016-2045, and € 3.8 to € 8.8 billion in the period 2036-2065.

A significant share of damage is accounted for by heat induced premature deaths. While the damage number here also depends on which monetary unit is chosen for the valuation (VSL or LYL, see Table 23.2), we find that a far larger fraction of the range is determined by climate uncertainty, and the largest fraction by which socioeconomic scenario we choose. The latter is varied from "10% of the population aged 65+ reduce their risk by 50% due to air conditioning" (the "intermediate" case), to "20% to do so" (the low damage case) and to "no additional air conditioning" (the high damage case) (Chapter 12, Table 12.6).

For future socio-economic uncertainty governing market damages, the variation in the damage value is most strongly driven by the share of future construction within/without flooding prone zones, and the thus flooding damage variability. The lower of the damage values is connected to all future buildings being only located in areas associated with a flooding recurrence period of more than 100 years, while the higher value is connected with new buildings being built in equal shares across flooding zones as they have been to date. Additional relevant driving factors arise in "heating and cooling of buildings", due to the thermal quality of buildings, the energy efficiency of heating and cooling systems and their energy characteristics in summer (all of these governed by building codes), and also required comfort levels and behaviour, technology, energy carrier mix, and energy price levels.

Overall, the results show, that the effect of climate change model and socioeconomic uncertainty (low or high damage scenarios) that we could quantify has most impact on flooding damages and building cooling expenses.

b. Climate Change Impacts not Quantified

The determination of the costs of climate change impacts requires detailed and substantial research effort with respect to each of the fields and impact chains identified. The present project depended on substantial input from earlier research projects and sectoral impact models that had been developed and that could be employed within a consistent overall framework. Much of the available data remains, however, incomplete. This meant that a number of impact chains, of high potential relevance, could not be quantified here. The most important are named in Table 23.3. This clearly points to a need for future research.

Table 23.3 lists the most important climate change impact chains *not* quantified within the present project. These are thus *not* covered within the figures for damage given in this and previous chapters and thus likely to further extend the range of costs given here (for a fully detailed list of impact chains *not* quantified see Chapter 22, Table 22.1 and the Tables "Impact Chains" in each of the Chapters 9 (Agriculture) to 20 (Tourism)).

Tab. 23.3: Most relevant climate change impact chains not quantified within the analysis that gives damage figures of Tables 23.1 and 23.2

Field of Impact	Impact chains not quantified
Agriculture	costs of irrigation infestation pressure of pest, diseases, and weeds heat induced labour productivity changes heavy precipitation and hail events flood damage
Forestry	storm events tree species change due to temperature rise heat induced labour productivity changes
Ecosystem Services	no impact in this field has been monetised, thus none of the impacts (loss of pest control and pollination, loss of fertilisation, loss of species, erosion control, water purification, soil functions….) has been considered in the cost of damage here
Human Health	temperature-related morbidity health impacts of extreme precipitation events air-pollution related mortality and morbidity water- and food-borne diseases vector-borne and rodent-borne diseases effects of population displacement
Water Supply and Sanitation	restoration cost due to increases in flood events droughts and resulting investment profiles increased need for water treatment due to lower surface water recharge increased pollution due to increased floods lower oxygen solubility in surface waters
Buildings	lower comfort due to higher summer temperatures increased storm frequency
Electricity	change in supply and demand profiles natural hazards (storm, floods, and other extremes) and their implications
Transport	transport service interruption storm events temperature induced deformation of road surfaces railways air transportation passenger discomfort in vehicles
Manufacturing and Trade	temperature and extreme event induced changes in production processes cooling and heating infrastructure damages shifts in consumption
Cities and urban Green	loss of climate comfort city tourism heat related damage for pavements, tram rails etc.
Catastrophe	disaster relief forces

Management	volunteer relief labour storm events droughts
Tourism	change in water and energy demand change in environmental resources important for tourism extreme events (and business interruption)

Note: For a full list of impact chains not quantified see Chapter 22, Table 22.1.

c. EXTREME EVENTS AND TAIL RISKS

At the global – and continental scale – there is the potential risk of catastrophic events from climate change, so called tipping points or tipping elements. These are defined (by Lenton et al, 2008) as '*subsystems of the Earth system that are at least sub-continental in scale and can be switched—under certain circumstances—into a qualitatively different state by small perturbations´*. These include major discontinuities such as abrupt solid ice discharge from the West Antarctic Ice Sheet – though the likelihood of these events, and the temperatures that might trigger their onset, is highly uncertain.

These risks – and the influence they have on policy - have also been recognised in the economic literature. From his seminal work on the 'dismal theorem' and the implications of catastrophic climate change, Martin Weitzman (2009) concludes:

> "In situations of potentially unlimited damage exposure like climate change, it might be appropriate to emphasize a slightly better treatment of the worst-case fat tail extremes – and what might be done about them, at what cost – relative to defining the calibration of most likely outcomes […]. A clear implication […] is that greater research effort is relatively ineffectual when targeted at estimating central tendencies of what we already know [….]. A much more fruitful goal of research effort might be to aim at understanding even slightly better the deep uncertainty (which potentially permeates the economic analysis) concerning less plausible scenarios located in the bad fat tail." (Weitzman, 2009: 17).

To understand this, we consider private individual behaviour in the face of risk. When engaging in risk aversion, such as protecting ourselves against fire damage, we not only consider the expected damage, we also seek to avoid extreme damage (however small the likelihood). Similar reasoning may be applied to a society in the case of climate change. The only difference is that extreme (so-called 'tail') events are much more likely under climate change than is the likelihood of one´s home burning down), thus raising the importance of the 'tail approach' even further. For instance, using the IPCC's own calibration of the equilibrium climate sensitivity parameter, Wagner and Weitzman (2015) calculate a 10 percent chance of eventual global average surface temperatures exceeding 6°C in a world with 700 ppm of CO_2-equivalent concentrations, a level expected to be reached by 2100 under the International Energy Information's baseline scenario.

At the European scale, Levermann et al. (2012) assessed the potential transitions of six climatic subsystems (tipping elements) which would have large-scale impacts on Europe. Two of these relate to major ice sheets (West Antarctic and Greenland) and thus of low relevance for Austria (at least directly – the indirect effects could still be important). The others – Atlantic ocean circulation, Arctic stratospheric ozone, Arctic sea ice and Alpine glaciers – are more relevant, especially the latter two due to the impacts on Austria and them being potentially triggered already at relatively low warming levels.

These provide some examples of major discontinuities that strengthen the policy argument for mitigation, but they do not provide quantitative evaluations. To address this, the study has undertaken some analysis on extreme event distribution for Austria. These events are lower in scale than the major tipping points or fat tails above, but provide examples of the importance of capturing the distribution as well as the average impacts, when considering economic impacts. Three of the most relevant fields of impact are considered: drought-induced harvest damage in agriculture, premature deaths due to prolonged heat waves, and riverine flooding damage to buildings. See Chapters 9 (Agriculture), 12 (Human Health) and 19 (Catastrophe Management), respectively, for more details.

In agriculture, meteorological and agricultural droughts have been identified as major driver behind inter-annual yield variability in Central Europe (Hlavinka et al., 2009) and global food insecurity (IPCC, 2014b, 37). For instance, the European drought and heat wave in 2003 affected a third of the EU and caused economic damage valued at around € 13 billion (Tubiello et al., 2007). In 2013, Central Europe was hit by a severe summer drought and heat wave with negative impacts on crop harvests. In Austria, corn yields were 19% below the previous year's production and 18% below the ten year average, as reported by Statistics Austria (2014). Due to climate change, drought conditions could potentially become more important in the future, which in some cases (and in the absence of adaptation) could lead to significant crop production losses (Olesen et al., 2011; IPCC, 2014, 30), though there is high uncertainty over these projections. A reference scenario (S1) and two drought scenarios (S2 and S3) for the period up to 2040 (Strauss et al. 2013; combining a dry day index with block-bootstrapping based on historical daily weather data for the period 1975-2007) were applied in order to assess the harvest implications for four crops, namely grain maize, winter wheat, winter rapeseed, and soybean considering three fertilization intensities. Together, these crops represent 81% of Austrian cropland. Drought anomalies during the growing seasons of grain maize and soybean as indicated by S3 occur every ten years in the reference scenario S1. Compared to the ensemble of 31 climate models, these anomalies are expected to occur every three years in 2050. For the economic analysis, we assume an equal weight of the fertilization intensity levels across Austria and similar crop shares as in the past. Real prices are based on the OECD-FAO (2013) projections whereas variable production costs are not taken into account. The results show a decreasing mean annual agricultural production value of about $€_{2010}$ 0.5 billion in S2 and of about $€_{2010}$ 1.3 billion in S3.

For human health, heat waves are of considerable importance. Following Kyselý (2004) heat waves are defined here (for the analysis in Austria) as consecutive periods of at least three days during which the daily maximum/minimum temperature is ≥ 30°C/20°C ("Kyselý days"). The heat wave is said to persist as long as the maximum temperature of each following day does not fall below 25°C and the mean temperature maximum during the whole period does not fall below 30°C (Auer and Korus, 2005). To estimate the effect of extremely hot years, those with a return period of 20 years (95th percentile) for a mid-range climate change scenario were selected. In such hot years the number of Kyselý days increases to 77 for the period 2036 to 2065 (the figure of the expected (medium) materialization was 8 to 27). Evaluation using value of a statistical life, reveals that the economic cost – connected with a doubling of heat related premature deaths in these extreme years – increases to at least $€_{2010}$ 10.6 billion. Should climate change turn out even stronger (i.e. using a hotter than the mid-range climate scenarios) this number rises to $€_{2010}$ 14 billion in the high-range climate scenario. It should be stressed that these estimates account only for a higher number of heat days, not however for their intensity nor other stress increases by them being prolonged. Each of these changes are expected to lead to even more severe effects (D'Ippoliti et al. 2010, WHO and WMO 2012) beyond those quantified here.

Finally, the study has analysed riverine flooding with respect to an event with an average recurrence interval of 100 years (the 99 percentile). The associated damage cost of this extreme year was found to amount to $€_{2010}$ 6.9 billion for residential homes (only HORA method, see Chapter 19 for further details). An even broader sensitivity analysis (low and strong climate change, socioeconomic developments that diminish as well as enhance damage) was also analysed with respect to the end of the century (2071-2100). This found that at the end of the century, there is a 5% likelihood that the annual cost of damage will be in the range of $€_{2010}$ 2.8 to 15 billion.

For a likelihood of 1 %, riverine flooding damage costs are in the range of $€_{2010}$ 8 to over 40 billion.[6] (To give some reference level: 1% is still at least 10 times more likely than an individual Austrian home burning down, for which the scale of potential damage level also is substantially lower).

These three case studies provide succinct examples that the tails of the distribution for climate change is important, and should be considered alongside any central estimates. The example of river floods also highlights that a strong increase in damages can arise when uncertainties are combined, e.g. the range of socio-economic and climate uncertainty leads to a range from 3 to 15 billion (a factor of five) – driven broadly equally from the socio-economic and climate elements.

These case studies – and their implications - also have high relevance for policy. Climate change has a high potential to increase the frequency and intensity of these types of extreme events (e.g. the three case studies above), thus a focus only on central trends is likely to miss the importance of larger and more frequent extremes. A policy maker is likely to be highly interested in the extreme event tails, not least because events of this scale have high political as well as social/economic consequences.

Perhaps one of the most poignant critiques of the standard approach comes from Martin Weitzman (2009: 18):

> "Perhaps in the end the climate-change economist can help most by *not* presenting a cost-benefit estimate for what is inherently a fat-tailed situation with potentially unlimited downside exposure as if it is accurate and objective […] but instead by stressing somewhat more openly the fact that such an estimate might conceivably be arbitrarily inaccurate depending on what is subjectively assumed about the high-temperature damages function along with assumptions about the fatness of the tails and/or where they have been cut off. Even just acknowledging more openly the incredible magnitude of the deep structural uncertainties that are involved in climate-change analysis [….] might go a long way toward elevating the level of public discourse concerning what to do about global warming".

[6] Chapter 19 supplies further details, see in particular Table 19.1.

4. Conclusions

Climate change is a global, long-term challenge, with an enormous degree of uncertainty. In the present book, and in summary form in this chapter, we have identified what we know about the implications of climate change at the national level, exploring the impacts for one country, Austria, in detail. While the book as a whole offers a useful set of tools for devising a comprehensive and consistent approach to deriving the costs of climate change at the national level, we now focus here on the type of results to be expected from such an undertaking.

There is, first, the climate and weather induced damage currently observed. Insurance companies and national relief funds are key suppliers of some of this information, at least in terms of direct damage costs of extreme events (for Austria, related costs have exceeded 1% of GDP in some years recently, the annual average figure to date amounts to around 0.25 % of GDP, or about € 700 million, rising to € 1 billion if average heat related mortality is added). Second, we employ a rich array of sectoral climate impact models to determine future weather and climate induced damage triggered by both additional climate change and socioeconomic development. We then merge the results in a cross-sectoral macroeconomic analysis (we use the CGE approach here), and non-market damage such as the costs related to future premature heat-related deaths are also added. Again, using Austria as an example, the analysis reveals that the cost of damage with respect to a 'medium climate and reference socioeconomic development' scenario will more than double by the 2030s and grow four to fivefold by the 2050s. And these figures only include the impact chains that can be quantified on robust terms. However, the range of uncertainty around these numbers is large – as an indication – typically a factor of 2 for each of the socioeconomic and climate dimensions.

Moreover, these estimates are the result of a standard economic analysis framework, which tends to focus on central estimates. This chapter highlights that it is as important to consider the extreme values, especially given the increase in frequency and intensity of many climate extremes with climate change. The analysis highlights the non-linear increase that can potentially arise, even in current ´1 in 20 year events´, and how these could lead to extremely large economic costs which have far-reaching consequences. It is therefore considered important to present this information alongside the central estimates.

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