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REVIEW PAPER

Impacts of a Changing Climate on Economic Damages and Insurance

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Abstract Weather and climate extremes cause huge economic damages and harm many lives each year (∼35000/year). There is evidence that some types of weather and climate extremes, like heat waves and flooding, have already increased or intensified over the last few decades, and climate projections reveal a further intensification for many types of weather and climate extremes in many regions though the uncertainties still remain large. While there is evidence for increases in economic losses it is uncertain whether this is due to an increase in the number and intensity of extreme events or can be attributed to socio-economic changes. However, there is agreement that the increasingly complex and internationally distributed supply chains of global companies make them more vulnerable to extreme weather events. It is also thought that global warming will adversely affect the global food supply chain and especially developing countries. Here I survey how weather and climate extremes impact our economies and how we can mitigate their impacts using financial and insurance products.

Keywords Weather risks · Climate risks · Extremes · Insurance · Reinsurance · Catastrophe modeling

Introduction

Weather and climate extremes do not only cost too many human lives each year (∼35000/year on average), but also cause significant economic damages (Seneviratne et al.

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2012; Geo Risks Research 2015; Carleton and Hsiang 2016). For instance, European Windstorms can cause insured damages of more than €1.9Billion each (Malmquist 1999) and insurance pay outs of €1.4Billion on average per year (1990-1998). Other examples of such extremes are: Hurricanes, Tornadoes, Storm surges, Heat Waves, Droughts, etc.

Weather and climate affect everyone, from individuals and small businesses to industry, governments and societies. Societies vulnerability is likely to increase in a globally warming world and the developing world is at particular risk. While the big picture is easy to understand (Stocker et al. 2013), individual regions will be differently affected, needing their specific mitigation and adaptation approaches. However, in general we can anticipate that what used to be extreme weather and climate events will become the new normal, i.e. we can expect a widening of the weather spectrum with more frequent floodings and droughts, more heat waves and storms. Hence, the volatility of weather and climate will increase, making predictions more difficult. Also changes in extreme events are amongst the first manifestations of global warming while changes in the mean are less visible because of their smooth incremental evolution over long periods of time. This poses difficult questions for policy-makers and many businesses since the response of the climate system in terms of extreme events to global warming will be very volatile in the sense that extremes on both sides of the spectrum are likely to become more frequent; i.e. more flash floods but also more droughts in the same regions (Seneviratne et al. 2012; Forzieri et al. 2016). This will require ma jor adaptation measures, especially in the developing world. Some long-term adaptation projects might also prove controversial because they seem counter-intuitive to the local public if they have not experienced the kind of extreme events in the recent past the impact the project is to mitigate against; especially if they have experienced the opposite in the recent past. This might also lead individuals to stop having insurance for certain kinds of weather and climate extremes.

Many businesses are getting more and more aware about the potential impact of weather and climate extreme events on their operations (Allianz 2016; Air Worldwide 2016). Natural catastrophes, including weather and climate extremes, are the leading risks for engineering and construction companies (Allianz 2016). They are amongst the top 5 risks for manufacturing, power companies, utilities and the transportation sector. Weather and climate extremes threaten to interrupt businesses and supply chains. Hence, a deep understanding of the risks posed by extreme weather and climate events is becoming increasingly important. While extreme events pose economic risks they also offer business opportunities especially for insurance and finance (Lenton et al. 2009) as companies become more aware of their vulnerability to weather and climate extremes.

Weather and climate extremes clearly affect society and the economy, and their changes due to global warming are important (Committee on Natural Resources 2012). However, policy and decision makers and the climate system also operate on different time scales. For instance, risk management of insurance, reinsurance and other businesses operate on time scales from days up to one year, while insurance portfolio management operates on somewhat longer time scales: from months up to 5 years (Fig. 1). Government planning occurs on longer time scales from months to 10 years (Fig. 1). Many severe weather events occur on fast time scales of days; examples are storms, hail and flooding. Heat waves and cold spells can last for weeks up to 1-2 months (Fig. 1); and droughts can last for a few years (for example the current California drought started in 2011 and is still going on at the time of writing). These time scales are within the scope of risk management. However, climate change, which occurs on decadal time scales is beyond the typical risk management time scale. While insurance companies can renew contracts every year and thereby adjust premiums to the current weather and climate risk conditions, financial portfolio management

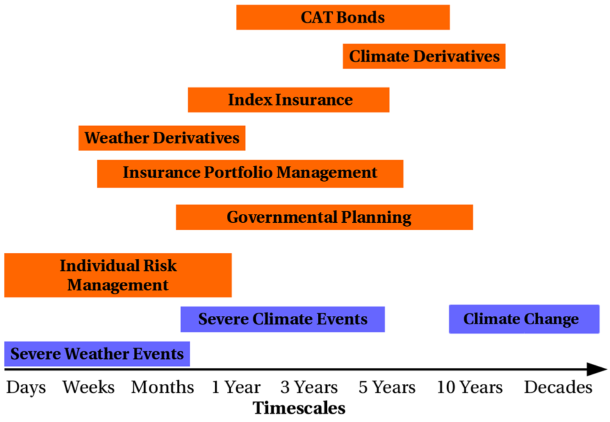

Fig. 1 Timescales of weather and climate impacts together with economic and risk management time scales. Blue boxes denote the time scales of weather and climate events, while orange boxes denote the time scales of risk management and financial measures

has to consider the potential impact of global warming on the financial markets (Clapp et al. 2015; Cambridge Institute for Sustainability Leadership 2015). The time scales on which businesses operate are not necessarily the ones scientists are interested in or during which impacts will become discernible due to climate change. However, increased collaboration between academics and decision-makers is essential in order to provide better and tailored scientific advice under great uncertainty (Clapp et al. 2015; Kousky and Cooke 2009; Kunreuther et al. 2013).

In this survey I provide an overview of the many facets in which weather and climate extremes will affect economic damages and especially the insurance sector and how this will likely change in a warmer world. I also discuss recent financial products like CAT bonds and climate derivatives. Weather and climate risks are a very wide ranging field so in this review not every aspect can be covered so the chosen topics reflect my personal bias. Much of the socio-economic work and results in this area are published in the grey literature which is typically less well known by many academics. Thus, there is a need to provide an overview of this field. In "Weather and Climate Extremes and Their Economic Impact" I focus on the taxonomy of extremes and their economic impact while "Trends and Long-Term Variability in Economic Losses" deals with trends in economic losses. In "Managing Weather and Climate Risks with Derivatives and Insurance" I briefly review weather and climate derivatives and insurance applications and in "Conclusions" I conclude this survey.

Weather and Climate Extremes and Their Economic Impact

Taxonomy of Extremes

There are different kinds of weather and climate extremes which also occur on different temporal and spatial scales (Fig. 2). These events range from small-scale and fast wind gusts, long lasting large-scale droughts to global climate change. A taxonomy of weather and climate extremes (Fig. 3) shows that not all extreme events also are socio-economically significant (Stephenson et al. 2008). First, weather and climate extremes are rare events which

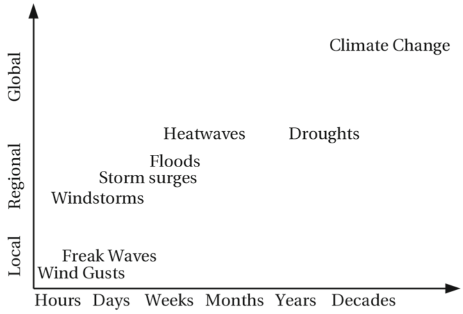

Fig. 2 Spatial and temporal scales of weather and climate extremes

are themselves extremes by having very high short-term values (like wind speeds) or have high accumulated values (like extreme amounts of precipitation). From a meteorological or climatological point of view extreme events have large magnitudes and occur rarely (e.g. exceed a high prescribed threshold of the wind speed). However, from an applied perspective weather and climate extremes can produce extreme impacts without being themselves necessarily extreme, though often they are extreme. For instance, the 2007 UK flooding was caused by several persistent cyclones whose short-term rainfall rates were in the normal range (Blackburn et al. 2008). From an insurance point of view it also matters whether the extreme events cause damage or not. For example, a hurricane over the Southern Atlantic ocean is interesting from a meteorological point of view but is unlikely to cause any economic damage (for instance, only land-falling Hurricanes or Hurricanes hitting oil drilling platforms cause significant damages) and, thus, is not of interest to insurance and decision-makers. Decision-makers care about whether specific thresholds (e.g. storm surge height, flooding levels, etc) will be exceeded and consequently cause significant economic damages and fatalities. This might be the most relevant definition of extremes because it will likely activate a stakeholder and political response. Future research should focus on these decision-relevant thresholds.

Another characteristic is of course the duration of extreme events. Some extremes such as hurricanes, tornadoes or winter storms occur on time scales of days and are, thus, rapid extremes. Many slow or persistent extreme events like droughts can last for years. They can increase mortality and are, thus, sometimes called the silent killer. Droughts can also affect crop insurance and micro-insurance schemes in the developing world (Hochrainer et al. 2009). The time scale is also correlated with the corresponding spatial scale (Fig. 2). Rapid extremes have typically a relative small spatial extent (e.g. tornadoes and storms) while slow extremes can affect whole regions or even continents (e.g. drought). The time

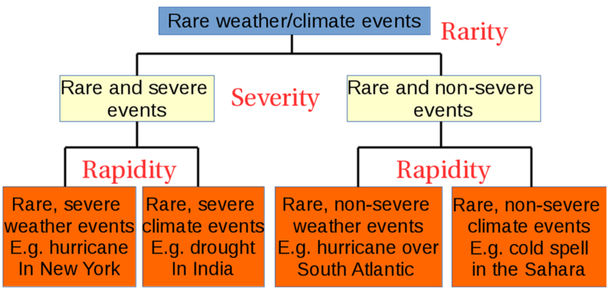

Fig. 3 Taxonomy of weather and climate extreme events. Adapted from (Stephenson et al. 2008)

scales of extremes have also implications for the way to adapt to them. For slow extremes like droughts the impacts can partially be mitigated during the event by e.g. using drought tolerant crops and using water more efficiently; however also long-term adaptation measures are necessary to mitigate future extreme events. On the other hand, fast extremes like storms, require more long term adaptation measures like improved building codes. For instance, future economic losses from tropical cyclones (Pielke 2007) are sensitive to societal change and global warming. While climate change is projected to affect the intensity and frequency of occurrence of extremes, such extreme weather and climate events would also occur without anthropogenic climate change. This suggests that adaptation to extreme events is a necessary step to make our society more resilient. Moreover, Pielke (2007) shows that adaptation to storm damages is much more effective than mitigation measures of greenhouse gas emissions.

Insurance, Reinsurance and Micro-Insurance

Severe weather and climate events cause significant insurance losses, having major impacts and cause responses from the insurance and reinsurance industries (Changnon et al. 1997). Reinsurance is when an insurance company buys insurance from one or more different insurance companies in order to reduce their own risks (Patrik 2006). For insurance and reinsurance companies it is very important to properly estimate the risks in order to appropriately price their premiums they charge their customers. This risk estimation is particularly difficult in a changing climate as I will discuss below.

After hurricane Andrew hit South Florida in 1992, which was at the time the most destructive hurricane hitting the US, leading to 65 facilities and over $26 billion (1992 USD) in damages (Blake et al. 2017). These great losses were unexpected and changed the way insurance and reinsurance companies looked at natural extreme events and how to price them and natural catastrophe risk in general. This event led to the development and wide spread use of Catastrophe (CAT) models in estimating the risks of extreme events to insurance and reinsurance portfolios (Grossi 2005). Many regulatory agencies now require that insurance and reinsurance companies use CAT models to estimate their risk exposure. Before hurricane Andrew, traditional risk-assessment techniques were based on historical claims data which can underestimate actual losses if extremes did not occur for long periods of time in the respective location. CAT models use our understanding of the physics of extreme events, engineering knowledge of building structures and property portfolios to estimate the probable maximum loss. CAT models led to much more accurate risk assessments and allow to make first damage estimates in the immediate aftermath of extreme events. As a consequence the insurance sector raised premiums, restricted the availability of insurance in high-risk areas (Botzen 2013) and its estimation of weather risks is now based on CAT models (Changnon et al. 1997). One consequence was that the reinsurance industry raised premiums but financial markets responded with innovations by, for instance, creating new financial products, like CAT bonds (Cummins 2008; Johnson 2014). CAT bonds are high yield bonds whose owner can lose the principal in case the insured weather extreme occurs at the specified location and exceeded the specified magnitude.

The Global Climate Risk Index (Kreft et al. 2015) shows that less developed countries are most at risk to suffer weather and climate related losses. As Fig. 4 shows the ten most affected countries by extreme weather events were less developed countries in the period 1995-2014. However, some European countries such as Germany and France rank among the top 20 countries world-wide most affected by extreme weather and climate events during that period. This has been largely due to the 2003 European heat wave which has claimed

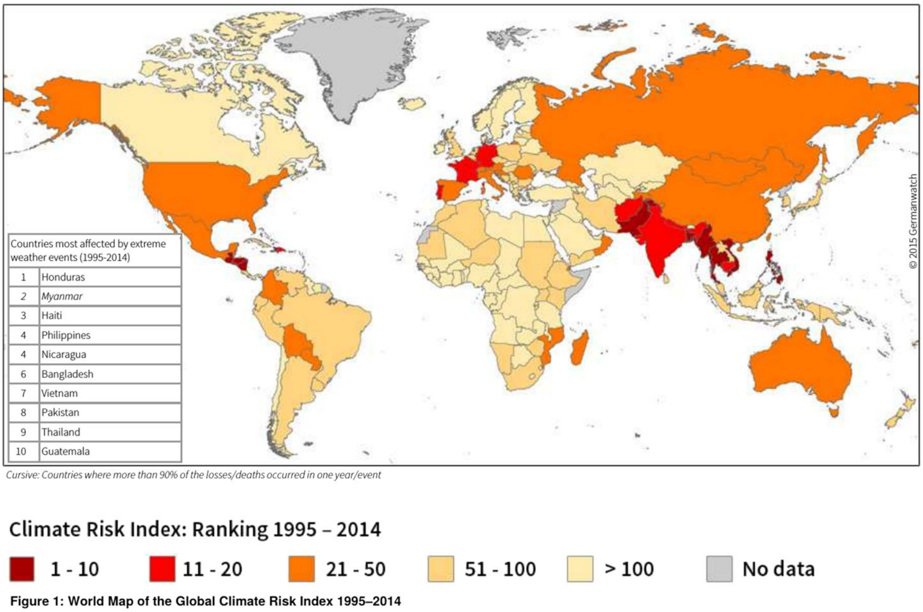

Fig. 4 Climate risk index: ranking 1995-2014. ©2016 Germanwatch (Kreft et al. 2015)

tens of thousands lives especially in France (Robine et al. 2008) and has been linked to climate change. However, in general developed countries can afford higher building standards, have higher insurance penetration and are better able to manage the aftermath of extremes, thus, reducing the overall impact of them.

The overall positive effect of insurance in developed countries suggests that micro-insurance schemes might be a good tool to help manage natural disasters in developing countries (Surminski et al. 2016). Micro-insurance is a tool to help poor people protect themselves against specific hazards for a premium. While this does not differ substantially from typical insurance schemes, micro-insurance has a clear target audience: poor people, which are typically ignored by mainstream insurance schemes. Micro-insurance schemes might improve economic activity by protecting poor people when disaster strikes and potentially allows them to take risks to improve their economic situation (Churchill 2006) for example by starting their own business. Micro-insurance schemes might help to address the problem that if people and companies in developing countries know that a single extreme event can destroy all their assets, they might decide not to accumulate assets, instead consuming them quickly, or keeping their savings in less productive assets. This has a negative impact on development and economic growth. Because the poor are the most exposed, they are amongst the most risk averse and might forgo investments in fertilizers or high yield crops which would potentially increase their income in the longer term (Hallegatte 2014a).

Evidence for a link between the impact of extreme events and the income per capita level of countries has been provided by Kellenberg and Mobarak (2008). They show that there is a nonlinear relationship between income and damage risk from extreme weather and climate events. The risk first increases for low-income populations and then decreases for GDP per capital levels of about $5000 (based on 1995 Purchasing Power Parity). Their main conclusion is that the dual aim of natural disaster risk reduction and poverty reduction might be hard to achieve because poor people have to first reach a certain income level before they can spent part of their income on risk reduction. But by reaching higher incomes they also become more vulnerable to disasters. Moreover, natural extreme events have a clear impact on the economic development of countries. Shabnam (2014) reviews the link between natural disasters and economic growth. This study provides evidence that flooding, a typical weather extreme event in many countries, significantly decreases the growth rate of Gross Domestic Product (GDP) per capita.

Complexity of Extremes and their Socio-Economic Impact

Natural disasters are the combination of a natural extreme event with socio-economic systems. An extreme event which does not affect human systems is a hazard but poses no risk. Leonard et al. (2014) developed for this purpose a compound event framework for better understanding extreme impacts. Compound events depend on the necessary physical quantities and the stakeholders who define the impact. For instance, for a heat wave to occur it is not only necessary to have the right meteorological conditions during that period but also the soil moisture conditions are important. The wetter the soil is the more moisture can evaporate by converting thermal heat into latent heat. This latent heat then can get transported away. This would reduce the intensity of the heat wave. On the other hand, if the soil is very dry, due to reduced rain fall in the preceding period, the heat wave can become very intense (Hirschi et al. 2011). This shows that anthropogenic changes to the land surface, due to land use changes, agriculture or urbanization, can exacerbate weather and climate extremes even without global warming.

Another example are the 2011 floods in Thailand which caused interruptions to the global supply chain of many global businesses. Some manufacturers across the world were unable to receive components for electronics, vehicles and other goods which resulted in about $3.3 billion in insurance claims. Many Thai production facilities had to close for about 1 month or longer. This significant impact on the supply chain took many internationally operating companies by surprise and such companies are now examining their supply chains for hidden risks to their business (Guy Carpenter 2011). Also the global food supply chain is at particular risk (Maynard 2013, 2015; Chavez et al. 2015). The report by Maynard (2015) reports on a scenario were an El Nino event leads to a significant decrease in global food production due to torrential rainfall, landslides and severe droughts. This then leads to food riots, crop epidemics and falls in US and EU stock markets. The report also shows that such a scenario has a higher return period than 1 in 200 years. This also shows that the globalized food supply chain is now exposed to threads not seen in the past and it is unclear and uncertain how shocks to the global food supply chain will cascade through the global interconnected economy. There are not only economic risks involved with food crisis but also social risks such as social instability and forced migration (World Economic Forum 2016).

Modeling compound extremes is a complex and interdisciplinary task and requires a deep understanding of the mechanisms and it is too easy to overlook potentially disastrous outcomes. This is especially important for globally operating companies (Air Worldwide 2016). Furthermore, global companies should also look at more than just one type of weather or climate extreme event in all their operating and supply chain regions. In this respect the aggregate risk and exposure should be examined (Air Worldwide 2016). It is expected that due to anthropogenic global warming these interrelated complex risks are increasing (Mills 2005).

Weather and climate extreme events have not only a direct economic impact on countries but can also trigger or amplify other destructive events. The global risks report of the World Economic Forum (World Economic Forum 2016) discusses the interactions between climate events and other risks such as: economic, geopolitical, societal and technological risks. For instance, extreme weather and climate events can lead to food or water crises which then can lead to infectious diseases, social instability and involuntary migration (World Economic Forum 2016). Especially forced migration is of heightened interest (Scheffran et al. 2012); the recent drought in Syria is thought to have contributed to the onset of civil war in Syria and the subsequent refugee migration towards Europe (Kelley et al. 2015). However, such violent conflicts arise typically from many interlinked stressors (Gleick 2014). But intensifying weather and climate extreme events might increase their number and subsequently migration pressures in the future.

Cavallo and Noy (2009) review the literature on the economics of natural disasters and find that they are inconclusive, especially the indirect economic impacts are not well studied and understood, though they find that the impacts are negative in the short-run. Part of the problem is that it is hard to produce helpful counterfactuals such as: What would have happened in the absence of the disaster? How would have economic growth evolved without anthropogenic global warming? Would the Syria civil war have erupted in the absence of the 2006-2011 severe drought? So one is forced to either use econometric methods or compare with comparable countries which did not experience a natural disaster. How accurate and reliable these approaches are for non-stationary economies is unknown. So one has to be careful in interpreting these results. Furthermore, modeling studies show that the long-term impact of natural disasters on economies is likely to depend on the state of the economy (Hallegatte 2014a). For an economy close to its peak a disaster produces bad outcomes because there is no spare capacity available hindering a rapid reconstruction, while for an economy close to its trough a disaster might be a beneficial boost because there will be a lot of spare capacity which can quickly be activated in the aftermath of the disaster leading to an economic boost. Jahn (2015) provides a critical overview of the terminology and of regional impact models for the economic impact of extreme weather events.

Weather and climate extreme and global warming have also impacts on financial markets (Johns et al. 2016). For instance, Clapp et al. (2015) argue that the financial performance of green bonds could benefit by better taking into account climate science and climate projections. Green bonds are fixed-income financial instruments aimed at reducing environmental risks and improving ecologically friendly businesses. For the financial markets to better incorporate climate science requires a better risk communication between financial institutions, investors and the climate science community. Climate change, by globally intensifying extremes, has the potential of influencing financial markets and potentially creating unhedgeable risks (Cambridge Institute for Sustainability Leadership 2015). For instance, the perception of climate risks could lead to shifts in market sentiment causing significant losses in investor portfolios even on short time scales relevant to investors.

Trends and Long-Term Variability in Economic Losses

Trends in Economic Losses

An important topic in weather and climate risks are trends in extremes and socio-economic losses. Every year Munich Re's NatCatService publishes a report about trends in weather and climate related losses (Geo Risks Research 2015; Hoeppe 2015). These economic losses show an increasing trend (Fig. 5) due to meteorological (tropical storms, extra-tropical storms and convective storms), hydrological (floods and landslides) and climatological (heat

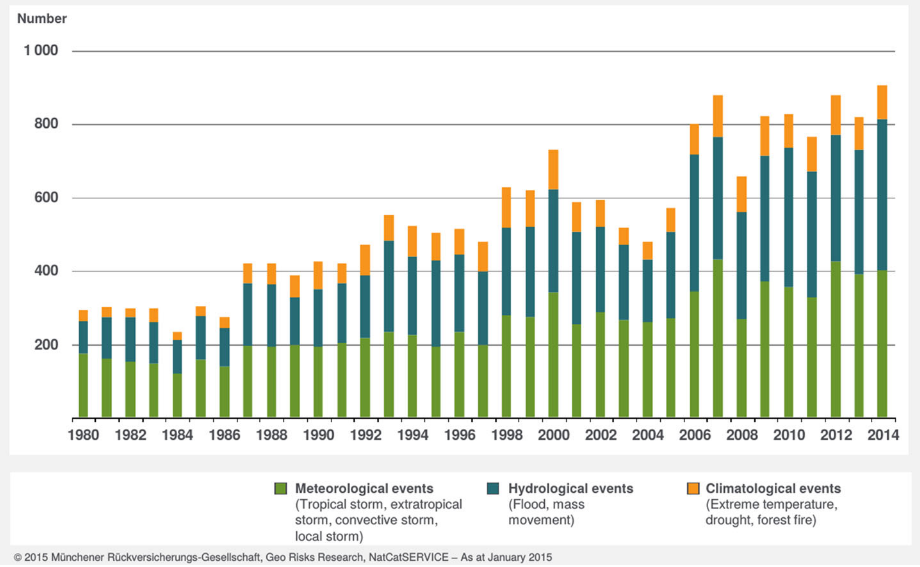

Fig. 5 Trend in weather and climate related economic losses. ©2015 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE (Geo Risks Research 2015)

waves, drought and forest fires) events. Figure 5 shows increases in all three event categories over the last 25 years.

Weather related damages have increased at a much faster rate than inflation, population, insurance penetration and also non-weather related insurance events (Mills 2005). Looking even further back, since 1950 there has been a trend in damages due to natural disasters (Smolka 2006) even after accounting for the observed inflation (which ranged from −0.4% to 11% per year in the US) over this period. This increase is mainly driven by urbanization in coastal areas, which are mainly affected by storms, storm surges and flooding, increasing economic values and the increasing complexity of modern societies (e.g. supply and transport chains; just in time delivery and construction, etc.). These losses are a function of weather and climate extremes but also of societal and economic changes (Hallegatte 2014b). In general, the increasing trends in economic losses have two potential major contributions: 1) an increase in the number and intensity of extreme weather and climate events (Seneviratne et al. 2012) and 2) an increase in the number of valuable properties and industries in vulnerable locations or the increase in the value of those properties and industries (Barthel and Neumayer 2012). Also the increasing urbanization and population size in many vulnerable regions makes society and economies more vulnerable because extreme weather events if they occur hit more people and businesses due to their increased density. Many of the currently fastest growing cities are coastal cities which are threatened by rising sea levels and consequently higher storm surges.

Whether economic damages have increased due to anthropogenic climate change is a current research question (Bouwer 2011). Changnon et al. (2000) argue that mainly human factors are responsible for these increased losses. Bouwer (2011) examined 22 studies about extreme weather induced economic damages. He concludes that when normalized there is no evidence for an increase in losses due to anthropogenic climate change.

Pielke et al. (2008) examined hurricane damages in the US for the period 1900-2005. When accounting for changes in inflation, wealth, population and urbanization no significant trend in economic damages has been found. However, this is in contrast to the findings by Smolka (2006) who finds a significant increase in economic losses. Also Estrada et al. (2015) find an increase in damages which cannot be explained by socio-economic variables. This suggests that an important uncertainty in these estimates is the data quality and how to properly normalize the economic data (Barthel and Neumayer 2012). This requires more research and better socio-economic data.

It is expected that anthropogenic climate change will increase socio-economic losses in the future (Dietz et al. 2016); especially sea level rise threatens many coastal megacities around the world (Lloyd's Market Association 2016) and in particular large parts of the southeast US. For instance, a sea level rise of 0.5 meters by 2050 would expose assets of a combined value of about $US28000 billion (Lenton et al. 2009). This also has significant insurance aspects; for instance, the impact of a hurricane hitting New York City could cause damages of about $US5 trillion by 2050. Insurers would be heavily impacted through property insurance but also as investors in real estate and government bonds.

As it is still uncertain whether disaster losses have already increased due to global warming (Bouwer 2011) it has been proposed that it might be more useful to examine future climate projections for this purpose (Bouwer 2011; Hallegatte et al. 2007a). While climate models allow to investigate different scenarios and ensembles they still suffer from biases. And more importantly, how well they simulate extreme events, especially how these extremes will change in a globally warmer world, is unclear and an active research topic.

Economic Losses and Long-Term Climate Variability

While trends are very interesting and important, natural long-term climate variability also exerts a significant impact on economic losses. Natural climate variability occurs due to the nonlinear character of the climate system independently from global warming. However, global warming will likely affect the characteristics of the natural climate variability. Examples of important modes of natural climate variability are El Nino-Southern Oscillation (ENSO) (Wang and Fiedler 2006), the Atlantic Multidecadal Oscillation (AMO) (Knight et al. 2006) and the North Atlantic Oscillation (NAO) (Feldstein and Franzke 2017).

Figure 6 shows how the AMO affects the aggregate amount of economic damages. The AMO is a mode of Atlantic sea surface temperature variability on decadal time scales. It can be seen that during warm AMO years the damage index from the CAT modeling company EQECAT increases and decreases in cold AMO years (Chartered Insurance Institute 2009). This suggests that the amount of damages are long-term predictable in a probabilistic sense based on large-scale teleconnection patterns. The climate phenomenon ENSO, which appears at irregular intervals between 2–7 years and lasts for about 9–24 months, has widespread impacts on tornado and hail frequencies of occurrence (Allen et al. 2015). In principle, this provides predictive skill for these perils.

Seo and Mahul (2009) show in a study that when CAT models (Lloyd's Market Association 2013; Institute for Atmospheric and Climate Science 2015) are conditioned on the near term climate conditions instead of on the long-term climate conditions that expected North Atlantic hurricane damages increase by about 30%. However, damages due to hurricanes in the US are consistent with being forced by global warming (Estrada et al. 2015). Thus, we can expect increasing hurricane damages but natural climate variation, like the global variations due to ENSO, can still affect individual hurricane seasons by increasing or decreasing economic damages.

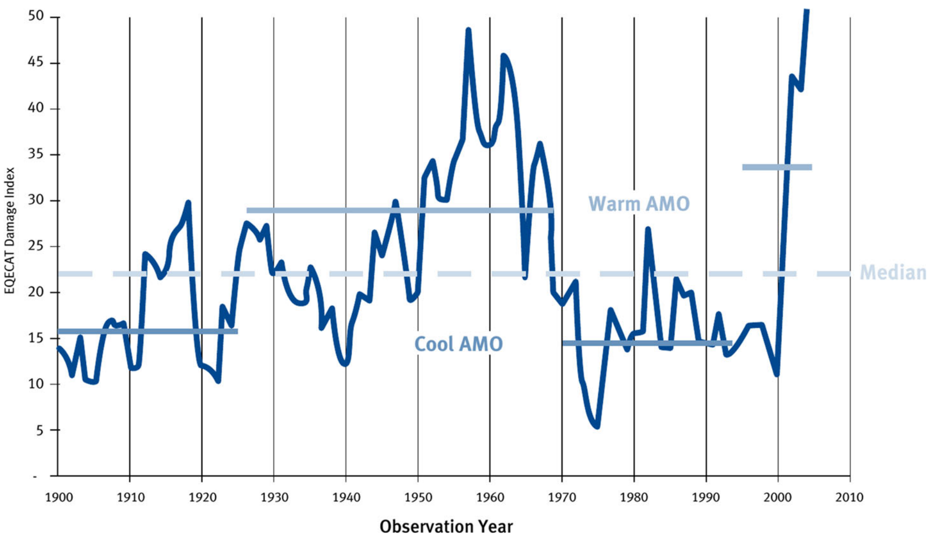

Fig. 6 EQECAT Damage Index by year (seven-year averaging) with indication of high and low AMO periods. ©CoreLogic EQECAT (Chartered Insurance Institute 2009)

European winter wind storm losses (Schwierz et al. 2010; Klawa and Ulbrich 2003) like extra-tropical cyclones and their corresponding risks are linked to large-scale circulation indices like the NAO (Hunter et al. 2015). Aggregate risk of all storms occurring in one season is an important variable for insurance (Hunter et al. 2015). Assuming independence between the storm magnitude and their frequency of occurrence can lead to biases in the variance and extremes of the aggregate risk (Hunter et al. 2015). Since large-scale circulation patterns undergo significant interannual and decadal natural variations (Woollings et al. 2015) the aggregate risks also will vary on these long time scales.

Managing Weather and Climate Risks with Derivatives and Insurance

The financial sector deals with the impacts of weather and climate via derivatives (Jewson and Brix 2005; Alexandridis and Zapranis 2012; Zeng 2000). A derivative is a contract whose value is derived from an underlying variable. In our case this would be an weather or climate index (Jewson and Brix 2005). Weather derivatives are important for power companies, utilities and many other businesses. A more recent development is the use of climate derivatives. Here counter parties try to hedge the impacts of climate change using climate derivatives. Climate adaptation requires large investments and climate derivatives would be one way of receiving the funding for these investments from the financial markets. For instance, in Tasmania the aquaculture industry hedges their climate change risk based on an index of Sea Surface Temperature (Little et al. 2015).

Benefits of using climate derivatives is that they are based on a quantification of the risks and, thus, allow to make systematic and informed decisions on adaptation measures. However, it is also claimed that derivatives are hindering a rapid market based solution of the climate change problem (Ravensbergen 2013). Ravensbergen (2013) argues that capitalism cannot effectively respond to global warming because it aims to commodify everything, including the negative effects of global warming. Weather and climate derivatives allow investors to financially benefit from devastating weather and climate extreme events. It seems that while the cost of mitigating and adapting to global warming are increasing all the time the potential profits from betting on those costs increase even faster, thus, making investing in ’green technologies’ less lucrative at least in the short to medium term.

Another way of dealing with the costs of climate change is through insurance (Botzen 2013). Insurance is potentially one way of raising awareness amongst the public about the risks of extreme but infrequent weather and climate events and also climate change. Botzen (2013) proposes that when property owners invest to mitigate risks then they should be rewarded with lower premiums.

Dlugolecki (2008) argues that climate change will intensify extreme events which in turn will affect insurers and reinsurers. However, the scale of the impacts is hard to assess and, thus, hard to actuarially quantify. Furthermore, insurance works by pooling risks from diverse locations, thereby reducing the overall risk associated by the pool. However, climate change might act to increase risks simultaneously across most regions, thus, reducing the beneficial effect of diversification in the insurance industry. This highlights the potential threats to the insurance and reinsurance sectors posed by climate change but also offers new opportunities (Herweijer et al. 2009). The insurance industry needs to incentivise risk reduction through risk based premium pricing and offer climate change risk management advise. A lack of adaptation might lead to uninsurability in many areas (Kunreuther and Michel-Kerjan 2007; Herweijer et al. 2009).

Insurance can potentially play a significant role in developing countries trying to adapt to climate change (Linnerooth-Bayer et al. 2009). Insurance might help vulnerable countries adapt to climate change by mitigating the effects of weather disasters. Insurance schemes such as micro-insurance can help increase economic growth by allowing poor people to mitigate their risk exposure (Peterson 2012). Micro-insurance schemes (Churchill 2006; Hochrainer et al. 2009) in developing countries are typically for agricultural production (Johansson et al. 2015; Heim 2015; Lesk et al. 2016) and are based on weather indices like a growing degree index or accumulated rainfall amount (Hochrainer et al. 2009). While micro-insurance scheme have many positive development aspects their financial long-term viability is still not clear (Hochrainer et al. 2009).

Conclusions

How global warming will affect extremes is still very uncertain and an open research question (Shepherd 2014; Vallis et al. 2015). Future climate projections show that the frequency and intensity of extremes will increase (Stocker et al. 2013). While the physical processes of extreme weather and climate events and how they will change in a warmer world are important to better understand, it is also essential to improve our understanding of the corresponding socio-economic impacts. A better grasp of the impacts is necessary for robust decision making under great uncertainty. Hence, robust decision making tools are needed for evaluating climate policies because studies on the distribution of exposure, vulnerability and potential outcomes do seldom reach any kind of consensus (Kunreuther et al. 2013). Climate change will also require us to adapt how we envision, anticipate and manage risks (Kousky and Cooke 2009). Because we expect that extremes will become the new normal, we have to adapt our view what constitutes expected outcomes in terms of weather and climate extremes but also their socio-economic impacts. This might lead to significant correlations between investment products, insurance policies and CAT bonds, fatter tails and changes in the tail behavior. When such variables are aggregated the correlations of the aggregations will increase. Neglecting this effect will lead to the underestimation of risks and might pose limits to securitization (Kousky and Cooke 2009).

Not only the impact of global warming on socio-economic losses are important but also how natural climate variations (Kunkel et al. 1999; Woollings et al. 2015; Feldstein and Franzke 2017) play an important role in the variability of socio-economic damages (Chartered Insurance Institute 2009). Thus, it is also important to be able to distinguish between these two causes in order to better prepare for the future. While it might be possible to distinguish between natural and anthropogenic climate variability and it is a much harder task to do this for the socio-economic damages and will require further research and longer time series of socio-economic damages.

To robustly quantify the risks and their impact on stakeholders mathematical and statistical models are becoming more and more important (Coles 2001; Embrechts et al. 2013; McNeil et al. 2015; Franzke 2017). Two books by Woo (1999, 2011) provide an accessible introduction to the interactions between natural catastrophes, insurance, finance and mathematical modeling. The creation of sophisticated models representing these interactions is a major ongoing effort and new mathematical methods will be needed, especially for the modeling of extremes (Blender et al. 2016; Franzke 2017). Furthermore, the modeling of the impact of weather and climate risks on socio-economic systems is very complex and requires the imagination of risks which have not occurred so far for a robust risk estimation.

It is also important to be able to model the economic impact of climate change (Nordhaus 2013; Stern 2007; Hallegatte et al. 2007b), especially their cross-sectoral interactions (Harrison et al. 2016) and also the economic impact of extreme events (Hallegatte and Ghil 2008). Estimates of these impacts are important for many decision-makers relating to the question whether the consequences of climate change can still be insured in a globally warmer world (Cambridge Institute for Sustainability Leadership 2015). However, most of the models currently used for estimating the economic impact of climate change (Integrated Assessment Models (IAM)) do not incorporate climatic extreme events, potential tipping points and widespread conflicts. Hence, this generation of models is likely to underestimate the risks of climate change (Stern 2016). This calls for the explicit inclusion of extreme events in IAMs.

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