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Economics of extreme weather events: Terminology and regional impact models ☆

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ABSTRACT

Impacts of extreme weather events are relevant for regional (in the sense of subnational) economies and in particular cities in many aspects. Cities are the cores of economic activity and the amount of people and assets endangered by extreme weather events is large, even under the current climate. A changing climate with changing extreme weather patterns and the process of urbanization will make the whole issue even more relevant in the future. In this paper, definitions and terminology in the field of extreme weather events are discussed. Possible regional impacts of extreme weather events are collected, focusing on European cities. The human contributions to those impacts are emphasized. Furthermore, methodological aspects of economic impact assessment are discussed along a temporal and a sectoral dimension. Finally, common economic impact models are compared, analyzing their strengths and weaknesses.

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1. Introduction

Extreme weather events have always had and will continue to have significant consequences for the society and the economy. Climate projections tell us that changing extreme weather patterns are very likely to increase the exposure to those events. Agglomerations face a special challenge because more and more people and value creation is concentrating there, resulting in a higher vulnerability of society to extreme weather.

Vulnerability is a key concept when assessing possible impacts to a system. The Intergovernmental Panel on Climate Change (2001) defines vulnerability (to climate change) as"the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.' Without going into detail, it can be seen that vulnerability always has to be specified by answering which system is vulnerable to which type of hazard.

There are different concepts of vulnerability and even IPCC definitions of vulnerability have not always been consistent (Brooks, 2003). One main issue seems to be whether the likelihood that a certain system is impacted by a hazard should be included in the vulnerability concept or if vulnerability should only be determined be inherent properties of the system. Brooks (2003) suggests to use the term"biophysical vulnerability' when the likelihood of a hazard is included and"social vulnerability' or"inherent vulnerability' when not. In the context of extreme weather events, the likelihood of impacts is also related to inherent properties of the system, e.g., because of the anthropogenic contribution to climate change. Therefore, it makes sense to use the broader concept of biophysical vulnerability. In Fig. 1, the connection between different terms explaining vulnerability is illustrated.

The figure shows that socio-economic factors are the main determinants of vulnerability.

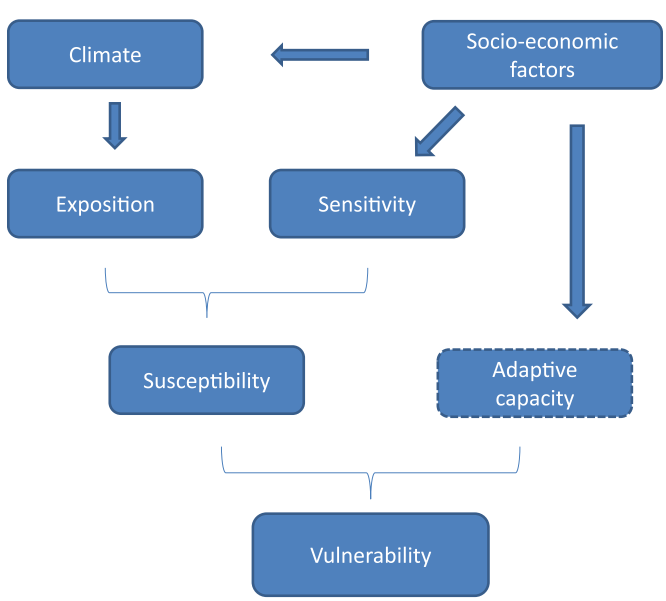

Fig. 1. Concept of vulnerability (to extreme weather). Socio-economic factors are important drivers of vulnerability.
Source: own representation.

The exposure to extreme weather events is influenced by climatic conditions, which again can be influenced by socio-economic factors like the anthropogenic climate change. Sensitivity means how dramatic the impacts of an extreme weather event will affect the system. Together with the exposure, sensitivity constitutes susceptibility. Adaptive capacity plays a more important role, e.g., when assessing social impacts of extreme weather events. Whereas the susceptibility to floods could be the same for all people living in a certain neighborhood, people with higher income might be seen as less vulnerable due to a higher (monetary) adaptive capacity. However, it is not consensual whether the adaptive capacity should be included in the vulnerability concept. This is because adaptive capacity does not have to be"self-realizing' (Brooks, 2003) and therefore might influence the actual vulnerability only theoretically.

Another term that is often used in the context of climate change and especially extreme weather events is risk. Risk is usually defined as the"combination of the probability [of occurrence] of a certain event and its negative consequences' (United Nations International Strategy for Disaster Reduction, 2009). The probability of occurrence of many types of extreme weather events is believed to be affected, most likely increased by climate change. The other part of the definition, the amount of negative consequences, i.e., losses for a specific event can be worsened also by other human contributions like higher asset values in endangered areas or a more complex economy and society in general.

It is interesting to embed the term"risk' into the concept of vulnerability. Brooks (2003) states that the term risk in its usual definition (as above) is broadly equivalent to the biophysical vulnerability. There are many indications that over the last decades the risk of extreme weather events has increased.

As an example, Fig. 2 illustrates the estimated costs of extreme weather events in the US between 1980 and 2012. The fitted quadratic trend suggests that the amount of losses and therefore the risk (probability and/or negative consequence) has increased. Considering the proposed equivalence of risk and vulnerability, it would be equivalent to say that the vulnerability to extreme weather events has increased in the US over the last decades.

So far, the terms damages, costs and losses have been used in a rather general meaning. However, for the economic analysis of impacts of extreme weather events they have to be further specified. In the economic literature, a common distinction is that between"damages' as direct physical destruction of means of production and"losses' as the lost proceeds in the affected company/sector due to the damages (Okuyama, 2003).

Finally,"indirect losses' are defined as the losses that other agents in the economy have, e.g., because they are not supplied by the damaged company/sector.

Later in this paper, the concept above is used along two dimensions. A sectoral dimension, which is already implicitly present in the concept and a temporal dimension since"losses' as a flow measure are connected to time by definition. Especially regarding the combined regional and sectoral dimension of impacts of extreme weather events, there seems to be need for further research and this paper tries to make a contribution. Let it be noted here that the term'regional' will always refer to the subnational scale from now on.

Since extreme weather events are often seen as"natural

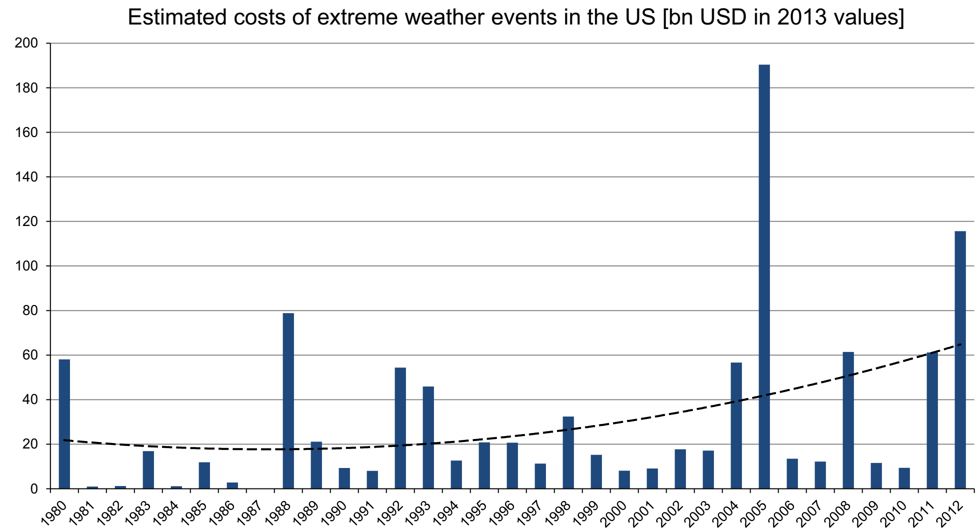

Fig. 2. Estimated costs of extreme weather events in the US from 1980 to 2012 in billion USD (value of 2013). Combined costs of all types of weather events are shown, but only extreme events with costs of more than 1 billion USD are included.
Source: own representation, data obtained from National Climatic Data Center, 2013

disasters' it shall be noted again that socio-economic factors, i.e., human behavior is an important driver regarding their impacts and losses. In Cavallo and Noy (2010) a quote referring to Sen (1981) can be found which illustrates the issue by the example of famines which frequently occur as the consequence of extreme weather in the form of drought. "Starvation is the characteristic of some people not having enough food to eat. It is not the characteristic of there being not enough food to eat." This underlines that what might be perceived as impacts of'natural' extreme weather events like droughts can be at least partly seen as man-made. In any case, whether caused by natural or man-made processes, coping with increasing losses from extreme weather becomes more and more important for countries and cities.

The remainder of this paper is organized as follows: In the next section, concepts of extremity are discussed and an overview about types of extreme weather events and their possible impacts is given, focusing on cities. Human contributions that might be responsible for worsening the impacts are also mentioned. In Section 3, impacts of extreme weather events are structured and discussed methodologically. Section 4 deals with impact models and their ability to capture different impact dimensions. Finally, Section 5 concludes.

2. Terminology and types of extreme weather

The first part in this section is concerned with definitions that were not yet clearly discussed in the introduction. It is not obvious or self-evident what the term"extreme' shall really mean in the context of weather events. First, one can distinguish between occurrence extremity and impact extremity. Occurrence extremity is based on values of meteorological variables[1] that describe the weather event as such and impact extremity is based on measuring the magnitude of certain impacts of the event, interpreting"extreme' in the sense of severe consequences. For both dimensions, a further distinction can be made between absolute extremity and rarity. Stephenson (2008) presents a very detailed discussion of the topic, whereas in this paper, the matter is dealt with in a compact way.

Absolute extremity means that an event is considered to be extreme if a certain characteristic number exceeds/deceeds a predefined absolute threshold. This concept is implicitly used if, e.g., statements like"extremes will become the norm' are made (cf. Stephenson, 2008) because in order to make sense the statement requires that the definition of extreme is independent of observed/projected values which determine the norm. Following this concept, a rain event could be considered extreme if the amount of rainfall on one day exceeds, e.g., 25 l per m^2.

Note that in Fig. 2, extreme events are analyzed along the impact dimension, since not the meteorological properties but the monetary losses are assessed and the concept used is that of absolute extremity, since all events with estimated losses of less than the fixed threshold of 1 billion USD are excluded.

The opposing concept would be the"rarity' or relative extremity. It is derived from the (empirical) distribution of the observed data about the corresponding event and it is frequently expressed in terms of the return period. The latter is defined as the reciprocal of the complementary distribution function[2]. In contrast to an absolute threshold, a threshold quantile is defined as the bound of normality. Using again the rain example, a rain event could be considered rare or relatively extreme if the amount of rain lies outside the empirical 99.9%-quantile of the distribution of daily rainfall, or – in other words – if it has an estimated return probability of 1000 days. Within this concept of extremity, stating that extremes will become the norm is impossible, since the definition of extreme is made relative to the (possibly changing) average/norm.

The difference between the two concepts becomes most apparent when two distributions are compared, for example present and future distributions. Fig. 3 illustrates how climate change is projected to change the occurrence probabilities of extremes, here summer temperatures.

From observation (period 1961–1990), a threshold for an extremely warm summer could be set to 18 °C. Using that same measure of extremity for a different situation, namely the climate scenario for the period 2071–2100, nearly all summers would have to be called extremely hot. This might be true in an absolute way,

[1] Usually, different variables can be chosen for the analysis. For example, intensity, duration and domain are common meteorological variables that describe an extreme weather event.

[2] The complementary distribution function is also called survival function.

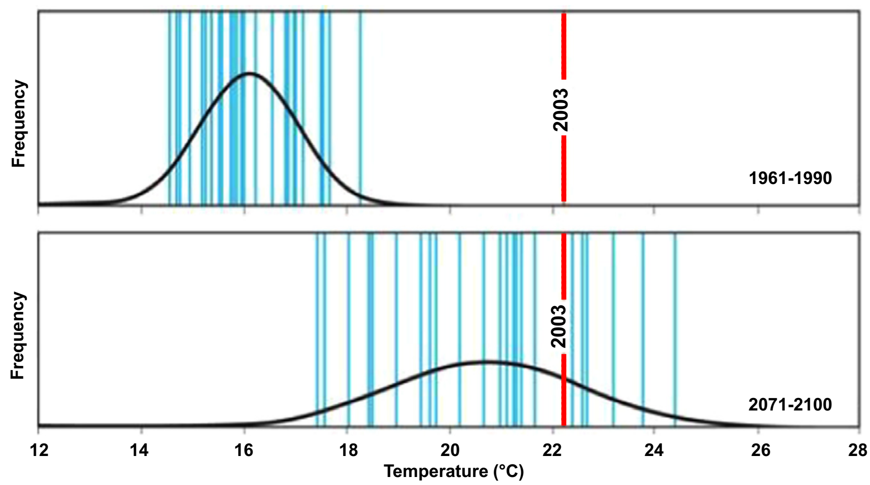

Fig. 3. Distribution of summer temperatures. The annual means of daily mean temperatures of the summer months June, July and August at a grid point in Switzerland are shown according to their historical and scenario distribution.
Source: adapted from Schär et al. (2004)

but it might also be useful to analyze the temperatures relative to the climate of the period in which they occur by using the concept of rarity or relative extremity. In this case, a summer in the period 2071–2100 would probably not be called extremely hot until its mean temperature reaches 24 °C. The red line indicates the mean summer temperature in the summer of 2003. The historical distribution cannot explain this anomaly and it is very plausible that the parameters of the distribution have changed already.

Another discussion is that concerning extremity in the sense of variability. This interpretation aims at characterizing the whole distribution instead of classifying a single event as extreme or not extreme. From a statistical point of view, a distribution is extreme if the observed values vary a lot, that is if the standard deviation is high. When two distributions are compared, the variability is useful since it combines information about the distribution in a single number, the standard deviation. When comparing two distributions with the concept of absolute extremity, statements about changes in the extremity can generally only be made with respect to a specific threshold value. A distribution could be called absolutely more extreme (for high extremes) if the likelihood of excess increases for high threshold values. Within the concept of relative extremity, statements about its changes depend on the choice of the quantile. As a measure for the relative extremity of a distribution one could use the distance of the quantiles to the median. A distribution is relatively more extreme (for high extremes) than another when the distance of the upper quantiles to the median increases. In Fig. 4, three situations of more extreme temperatures are sketched. For the explanation it shall be noted that the focus is on the high extremes.

The first graph (a) corresponds to an increase of absolute extremity, since for predefined thresholds of high temperatures, the likelihood of excess increases. The relative extremity or rarity stays the same because the distance of all quantiles to the median remains the same. The variability does not change either because it does not depend on the location of the distribution. The subfigure (b) corresponds to an increase in variability, which implies also an increase in absolute and relative extremity for high temperatures. This is because for high threshold temperatures, the likelihood of excess increases (absolute extremity) and also the distances of the upper quantiles to the median increase (relative extremity). The bottom graph (c) corresponds to the general findings of, e.g., Hansen et al. (2012) for the projected distribution

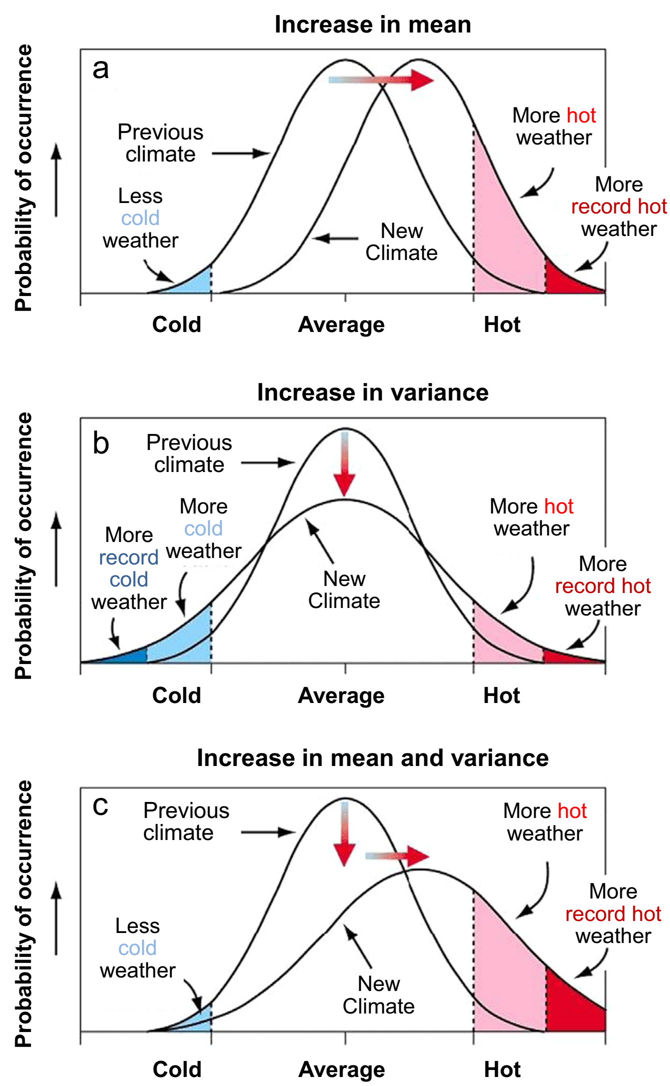

Fig. 4. Different types of more extreme (high) temperatures. The cases of an increase in mean (a), an increase in variance (b) and an increase in both mean and variance (c) are shown.
Source: adapted from IPCC, TAR, 2001, WG1, Chapter 2.7.1, Figure 2.32

of future temperatures which shows an increase of all three types of extremity. The increase in mean and variability imply an increase in absolute and relative extremity for high temperatures.

To sum up, one can say that although the definition of'extreme' is either clear or not so important in most cases, one should have in mind that if one stumbles across statements like"the temperatures will be more extreme' this can just mean warmer/colder or it can mean more variable-or both.

2.1. Impacts of specific extreme weather events

Let us now come to the impacts of different types of extreme weather events relevant on a regional European scale and especially for cities. Five types of events are identified. These five types are based on the European Environment Agency (2012a) definition which considers the first three (flood, drought, heat) in detail and two more types are added (cold/snow, storm).

In order to further analyze the impacts, some kind of categorization has to be used. In this paper, impacts are categorized along two dimensions, a sectoral and a temporal dimension. For the sectoral dimension it makes sense that (a) the considered sectors together constitute the whole society/economy and (b) the sectors are pooled in a meaningful manner. Therefore, the definitions of sectors from input–output tables or social accounting matrices seem very useful since they fulfill both of the above properties (cf. Rose, 2004). Again, the degree of detail is somewhat arbitrary. Here, the sectors agriculture, industry/business, tourism, transport, insurance, housing and health are used and ecosystems are included as an additional"non-market' sector. The choice of sectors is discussed in Section 3.4. Regarding the temporal dimension, it is distinguished between short-term and long-term impacts. However, in this section, impacts of each type of extreme weather are collected in a general manner. The temporal issues are again picked up in Section 3.3.

As already mentioned in the introduction, impacts of natural disasters do not only depend on natural processes but also on human behavior. Therefore, possible human contribution to the vulnerability to different types of extreme weather events described above is also discussed. Adaptation measures to extreme weather events are not treated in this paper, but the corresponding considerations can also give some indications how cities can reduce their vulnerability by changing economic and social processes. Reducing the vulnerability to extreme weather events has two dimensions in practice. On the one hand, crisis management is needed during the actual event. On the other hand, risk management is, i.a., needed to develop a (long-term) adaptation strategy.

2.2. Floods

Floods in Europe belong to the costliest extreme weather events. Loss estimates for the flood events in Central Europe in May/June 2013 range around damages of 12 billion EUR (MunichRe, 2013b). The EEA distinguishes different flood types (pluvial, coastal, flash, groundwater, etc.) mentioning the different causes and also the different time scales (European Environment Agency, 2012a).

From the literature about potential flood losses in cities by the example of simulated flood events in the city of Hamburg (Kowalewski and Ujeyl, 2012), it is known that damages to buildings (industry and housing) and machinery are likely to add up to a big part of flood damages in European cities. Fatalities in European cities due to floods are tragic, but usually and fortunately not so numerous to be economically relevant. Destruction of infrastructure is relevant, especially in the context of indirect losses which will be discussed later.

2.3. Human contribution to floods

The vulnerability to flood events, including coastal, river and flash floods is strongly influenced by human behavior. In European cities, the common high degree of surface sealing (EEA (European Environment Agency, 2012)) prevents water from trickling and increases the discharge flow. Sewage systems of insufficient capacity might not be able to take the water that flows in from the growing impervious area that is connected to it. Furthermore, forcing rivers into narrow river beds can worsen floods because of increased runoff speed and higher pressure on protective embankments. For example, Christiansen (2004) states that from 1850 until 2002 the area of natural flood plains of the river Elbe had been reduced by 86%.

2.4. Droughts

Droughts are the consequence of little or no precipitation over a longer period of time. According to the European Commission, droughts have dramatically increased in number and intensity in the EU over the last decades. The number of areas and people affected by droughts went up by almost 20% between 1976 and 2006 (European Commission , 2012).

The effects of the lack of water for watering (mainly agriculture), business activity (e.g. food industries) and cooling (especially power plants) are believed to be the most relevant. Droughts can also contribute to (forest) fires possibly resulting in destruction of buildings and other assets. Nevertheless, the occurrence of fires also depends on other factors like wind, etc. Regarding health, fatalities as direct consequences of drought have not been reported (European Environment Agency, 2012a), but the water quality can be negatively influenced since a reduced flow in water pipes can increase the pollution with germs. Many climate projections as presented in the EEA report (European Environment Agency, 2012a) suggest that, in the future, there will be less precipitation during the summer, especially in the Mediterranean part of Europe. Expected higher temperatures in the summer and resulting evaporation contribute to the problem.

2.5. Human contribution to droughts

Whereas droughts are specific climatological/weather events, water scarcity is usually used to describe the general problem of supplying the society/economy with enough water. However, general water scarcity can of course aggravate droughts. The main human drivers of water scarcity are increased consumption (not only of water directly), population growth (urbanization) and agriculture (European Environment Agency, 2012a). Deforestation and ineffective water recycling contribute to the problem. In addition, the (local) water markets do not always function well. The absence of (informative) price signals can lead to mismanagement of water resources. Our energy system contributes to the problem of water scarcity and droughts, since in Europe as a whole, 45% of the freshwater demand comes from that sector (European Environment Agency, 2010). This is mainly due to the use of thermal power plants which require large amounts of cooling water (cf. Torcellini et al., 2003 for the US).

2.6. Heat waves

Heat waves in Europe are the type of extreme weather with the biggest impact on human health. The major heat wave of 2003 is believed to be responsible for tens of thousands of additional deaths.

Studies suggest that high temperatures reduce the productivity of workers significantly (Sepännen et al., 2006). The economic impacts like additional energy demand for cooling can further amplify heat waves in cities. Burst and buckled streets as well as low water levels in rivers are likely impacts in the traffic system. In general, heat events and droughts are often connected and certain impacts like wildfires and crop shortfall are the result of the combination of heat and drought. According to the literature (Hansen et al., 2012), global warming will lead to a shift in the probability distribution not only resulting in higher mean temperatures but especially in an increase in the number of heat anomalies (relative to the mean).

2.7. Human contribution to heat waves

The fact that cities and city planning can contribute to heat stress in urban areas has been more and more recognized. The 'heat island' effect is mentioned frequently in the literature (e.g. European Environment Agency, 2012a). Artificial surfaces, less green areas and lack of fresh air passages are some factors aggravating urban heat problems. Furthermore, energy use in cities for various reasons (transport, business, cooling etc.) leads to additional heat production.

2.8. Cold waves

Cold waves frequently hit Europe, especially the continental Eastern part. Cold-related deaths in whole Europe added up to 824 in a 2012 cold wave (Aon Benfield, 2012).

Apart from health impacts, damages to the traffic and energy system are believed to be the most relevant economic impacts. For the future, climate projections assume that winter precipitation, but also winter temperatures will increase in Northern Europe and the snow season is very likely to shorten in all of Europe (Intergovernmental Panel on Climate Change, 2007). However, there is still some uncertainty regarding specific extreme events like cold waves.

2.9. Human contribution to cold waves

The positive human contributions to the impacts of cold waves most likely outweigh the negative contributions. Urban energy production and resulting thermal discharge reduces the cold stress for people and the amount of snow in the city.

2.10. Storms

From the meteorological point of view, storms are low-pressure areas. In this paper, the term''storm' is used in the narrower sense for heavy winds, hail and lightning. Heavy rain and/or storm surges also frequently go along with storms but that is dealt with under the topic floods.

The most severe storm in Europe in recent years was the extra tropical cyclone''Kyrill' in 2007. 49 people were reported dead and the total damages were estimated to be USD 10 billion by MunichRe (2013a).

Compared to other events, storms are relatively well covered by insurance. For the storm''Kyrill' it was estimated that 58% of the damages were insured (MunichRe, 2013a). Regarding future influence of climate change, the fourth IPCC report (Intergovernmental Panel on Climate Change, 2007) states that the''confidence in future changes in windiness is relatively low, but it seems more likely than not that there will be an increase in average and extreme wind speeds in northern Europe.' Other sources (European Environment Agency, 2012a) provide explicit numbers supporting the above statements.

2.11. Human contribution to storms

The (anthropogenic) climate change is believed to rather increase the occurrence of storms. Unfortunately, the precise expected future development is still uncertain (Intergovernmental Panel on Climate Change, 2007), although storms are responsible for a big part of the losses from extreme weather (for the US, see Fig. 2'[3]).

3. Classification of economic impacts

In this section, the impacts described in Section 2 are structured and different structuring methodologies are compared. So far, the term''impact' was used in a general way referring to all economic and non-economic effects. For the further analysis, there is a focus on the economic perspective. Recalling the consideration from Section 1, Okuyama (2003) understands''damages' as direct physical destruction of means of production in a company/sector and defines''direct losses' as the output losses in the affected company/sector due to the damages. Indirect losses are defined as the losses that other agents in the economy have, e.g., because they are not supplied by the damaged company/sector. The total losses (Okuyama: total impacts) are the sum of direct and indirect losses. This definition shall serve as a starting point for the discussion of terminology and definitions.

3.1. Direct and indirect losses

Rose (2004) uses the same definition of direct and indirect losses and emphasizes that damages should not be included in the loss estimation. He states that for loss estimation the focus should be on flows rather than on stocks (of means of production) and therefore damages to the stock should not be counted. Four reasons are presented.

First, losses can occur without damages and therefore yield a broader approach. Second, ignoring damages avoids double-counting of impacts. For example, a destroyed machine could be counted once as damage and a second time as the lost output from not running, although the output is already partly contained in the value of the machine in the sense of net present value of expected (future) output. The third argument is that flow measures are more consistent with''indices of well-being' such as the GDP or income. Finally, since flows refer to time periods, they are the preferable measure for losses during the recovery phase. Stock measures such as replacement costs for an asset are independent of how long it is unavailable for production and therefore inaccurate.

Hallegatte and Przyluski (2010) agree with the distinction between direct and indirect losses made by Okuyama (2003) and Rose (2004). They point out that, in theory, damage and direct loss are equal for market goods but, in practice, the validity of the underlying theoretical equation chain''damage = asset loss = replacement cost = market value = net present value of expected output = output loss = direct loss' has to be verified, in particular the third and fourth equation.

However, they suggest that the total direct losses should be the sum of output losses and replacement costs. They use the term consumption losses to capture replacement costs and output losses; Replacement costs do not represent a loss of output but they are a''forced investment' which also reduces consumption. That would contradict the strict focus on flow losses proposed by Rose

[3] Although not visible in the figure, in the record year of 2005 (among other years), the major part of the losses was caused by hurricanes.

(2004) (issue of double-counting), although he remarks that including both stock damage and flow losses can be reasonable if one interprets the output (flow) losses as"opportunity costs of delays in restoring production'.

It can be seen that even in the scientific literature, terms are not always used consistently and concepts of impacts/losses/damages can be slightly different. On the other hand, there seems to be a consensus about the importance of indirect losses. Many authors emphasize the non-linear relationship between direct and indirect losses in the case of extreme weather events (e.g. Hallegatte, 2008; Kowalewski and Ujeyl, 2012) and find that the larger the damages caused by a disaster the larger the share of indirect losses in the total losses (direct and indirect).

3.2. Non-market effects

Direct non-market losses include all damages that cannot be repaired or replaced through purchases on a market (Hallegatte and Przyluski, 2010). In Rose (2004), non-market effects correspond primarily to losses occurring because public goods are not provided anymore.

This concerns mainly public infrastructure and natural resources. Theoretically, these effects are included in the above loss definition, but they are more difficult to assess, because attributing a price to public goods like, e.g., health is difficult and estimates are rarely consensual (Hallegatte and Przyluski, 2010).

The distinction between direct and indirect non-market losses can be made analogously to the case of market losses. Furthermore, for non-market losses it seems a good idea to concentrate on flow losses because damages to the stock can hardly be accurately priced. For example, if a tourist area of high symbolic value is devastated by a storm, it is nearly impossible to quantify the corresponding non-market losses as stocks, but the lost income in the tourist sector can be captured more easily.

3.3. Time horizon and positive impacts

Time is an important factor regarding impacts. With the concept of flow losses, damages are connected to time. The common idea when using this concept is that damages from an event all occur at a very specific point in time and losses begin to accumulate. In certain cases, also new damages can occur over the course of the extreme weather situation. For example, some crops might survive a 2-day flood but will die in a longer one. In economic impact modeling, however, the period when new damages keep occurring, is still considered short (Okuyama, 2003). Therefore the time horizon of impacts is mainly determined by the length of the recovery and reconstruction period.

Negative losses or gains in a post-disaster situation can occur for two reasons. First, because reconstruction yields additional demand (stimulus effect) and second because the damaged capital is replaced with new capital of higher productivity (productivity effect).

The stimulating effect of reconstruction depends on the pre-disaster condition of the economy, in particular the phase of the business cycle. It is likely to be larger if there are idle means of production as in a recession and it is likely to be smaller if all means are used to the full extent as in a boom (Hallegatte and Przyluski, 2010). Especially if an economy is hit by multiple events in a rather short time period, all available resources might already be fully employed for reconstruction. In this case, no positive stimulus effect occurs.

The length of the reconstruction period is mainly determined by two types of constraints, financial and technical constraints (Hallegatte and Przyluski, 2010). Financial resources might not be sufficient to undertake the reconstruction investment, which is believed to be especially important for less developed economies (cf. Mechler et al., 2006). Technical constraints can arise because resources needed for reconstruction (qualified workers, etc.) cannot be supplied beyond a certain amount even if price adjustments can partly transform this constraint into a financial one.

Regarding the productivity effect, the importance of it is still controversially discussed in the literature. Hallegatte and Dumas (2008) find that the productivity effect has an influence on the output level and can dampen long-term losses but it does not change the equilibrium growth path. Furthermore, they emphasize that a negative long-term growth effect (poverty trap) can also be relevant, especially in less developed countries. This is the case because a) many less developed countries are located in world regions where the frequency/intensity of severe weather events is already higher than elsewhere and b) their (financial) resources are often low, such that the time period between two consecutive events might not be sufficient to bring the economy/society back to the pre-event status. In general, the timing/frequency/order of extreme events is important for the losses. In particular, possible overlapping events (weather or other) can be relevant for the size of losses.

3.4. Direct losses by sector and time

In the following, an attempt is made to combine the regional, temporal and sectoral dimension of losses from extreme weather events, focusing on European conditions. Frei and Kowalewski (2013) have developed a climate change vulnerability index with a regional and sectoral scope. The sensitivity (cf. Fig. 1) for different sectors is measured by the respective water intensity, energy intensity, diversity of inputs and dependence on the traffic infrastructure. The regional scale is implemented via regionalized input–output tables which will be mentioned again in Section 4. The exposition to climate change is quantified by the regional temperature projections. As losses from extreme weather events are one main outcome of vulnerability to climate change, those sectoral and regional vulnerability analyses can be an important tool to understand the economics of extreme weather.

The sectoral structure chosen in this paper is in line with the determinants of sectoral sensitivity identified by Frei and Kowalewski (2013). However, the approach used here also includes different types of extreme weather events. Therefore, the considerations in this chapter cannot fully capture the sectoral, temporal and regional complexity of impacts of extreme weather. The focus is on (potential) losses which are outcomes of exposition and sensitivity of the sectors. Table 1 is meant to indicate – in a very abstract manner – which sector is affected to which extent by which type of extreme event, differentiating between a shorter and a longer time frame. For the long-term, potential gains from, e.g., reconstruction demands are included.

In the **agricultural sector**, destroyed crops can be a major source of losses of floods in the short-term. Necessary purchase of fodder and the dependence on imports might generate additional losses in the long run. Frequently, also the soil quality can be negatively influenced for years due to washed-in heavy metals or other pollutive substances.

Regarding droughts, crop shortfall is a relevant short-term consequence with corresponding long-term implications. Erosion may become a long-term loss when rainfall hits the dried-out soil. Heat can lead to gains in the agricultural sector due to increased yield of some crops in some places but also create losses due to decreased yield of other crops in other place European Environment Agency, 2012b. Cold events can increase the fodder demand and damage plants, but long-term losses of cold events seem negligible. Storms can destroy plants by winds and hail which can yield significant losses. Regarding forestry, long-term losses from windthrow can manifest in lower wood prices.

Table 1
Potential direct impacts by sector, type of event and time frame. A minus (−) indicates a moderate loss, a double minus (− −) a significant loss, a plus (+) indicates a gain and a circle (o) neutral or negligible effects. Source: own representation.

	Flood		Drought		Heat		Cold		Storm	
Sector	Short	Long	Short	Long	Short	Long	Short	Long	Short	Long
Agriculture	− −	−	− −	−	o	o	−	o	− −	−
Industry	− −	+	−	o	−	o	−	o	−	o
Tourism	−	o	o	−	+	o	+	o	−	o
Transport	− −	− −	o	o	−	o	− −	−	− −	o
Energy	− −	−	−	o	−	o	−	o	−	o
Insurance	− −	−	−	o	−	o	−	o	− −	−
Housing	−	+	o	o	o	o	−	+	−	+
Health	−	o	o	o	− −	o	−	o	−	o
Ecosystems	− −	o	−	−	o	o	o	o	−	o

Losses in **industry and business** as rather general sectors are difficult to summarize. Floods can destroy production sites and warehouses resulting in potentially big direct and indirect losses. On the other hand, in the longer run, reconstruction activities might create additional demand, yielding gains. Droughts might cause production losses through lack of (cooling) water in the short run but losses are probably small in the long run. Potential losses from heat are lower productivity and additional cooling costs. Long-term losses are believed to be less important. Apart from additional heating costs, losses from cold events might reach industries and businesses indirectly, e.g., through the transport sector. The impact of storms is also assumed to be moderate for European industries and businesses, good insurance coverage of buildings being one reason for that.

Floods can lead to a decline in **tourist** stays in the short run. The consequences of droughts are usually mitigated as well as possible for the tourist sectors, but losses from water scarcity might become larger over time. Heat waves can be positive for"-refreshing' tourist areas like mountains, forests, lakes and coasts but also negative for cities and in general, if many tourists fear health problems. Similar issues might be the case for cold waves. However, tourism in the winter time is usually concentrated in a few areas which should rather benefit from cold waves and heavy snow events. Storms might result in moderate losses in the tourist sector in the short run but losses in the long run are not assumed to be relevant.

Regarding the **transport sector**, floods can cause enormous losses by destroying streets, bridges, railways, etc. Since reconstruction usually takes at least months, also long-term losses are considered very significant. Droughts as such are believed to leave the traffic system more or less unaffected. Heat can lead to damages to the traffic infrastructure but resulting losses should be only relevant in the short run. Cold waves and snow most likely impact the transport sector much more severely, potentially resulting in complete break-downs of the traffic system. Also long-term frost damages lead to additional costs. The losses from storm events are relevant in the short-term as they may affect all different transport modes, but are not assumed to be long-lasting.

The **energy sector** provides 'lifeline' services. Therefore, also small damages which lead to power outs of a few hours can result in significant losses. In case of major damages, long-term losses become relevant. Due to the afore mentioned dependence of the European energy production on cooling water, droughts and heat events can yield losses in the short run. Cold waves and snow events are more likely to affect the energy grid, also potentially causing power outs. Damages to the grid and resulting power outs can also be caused by storms.

In the **insurance sector**, losses are claims by insurants. Floods are frequently responsible for severe property damage, a part of which is covered by insurance. Actual insurance payments, however, might be made weeks or months after the event and therefore losses are also identified in the long run. Crop losses from droughts are often covered by insurance. Heat or cold events are not so relevant for the insurance sector. On the other hand, storms in Europe belong to the costliest extreme weather events for insurers.

The **housing sector** might suffer from uninsured flood damages to buildings in the short run, but reconstruction can have also positive effects in the longer run. Droughts and heat waves are assumed to have only minor effects on the housing sector. During cold waves and strong winters, construction activity might be interrupted but the resulting losses are compensated with additional gains from catch-up construction later. The situation for storms is similar to the flood situation.

Impacts of floods on human **health** are believed to be mainly physical injuries. However, the experience of major flood events can also lead to psychological trauma. Water pollution can occur but access to clean drinking is usually ensured in Europe, even after a flood. No lethal impacts of droughts on health have been reported (European Environment Agency, 2012a), but water quality can be a problem in case of general water scarcity in the long run. As mentioned before, heat waves have big impacts on human health, resulting in hospital stays and possibly thousands of additional deaths. Cold waves and storms can also be responsible for numerous deaths. For storms, also injuries occurring during clearing work are important related health impacts.

Impacts of extreme weather events on **ecosystems** are often overlooked. However, floods do not only damage commercial crops but also natural organic resources. Long-term soil pollution and recovery periods can lead to loss accumulation over time. Droughts have a negative influence on plants and animals in most ecosystems and can amplify erosion processes. Regarding heat and cold waves, it is believed that ecosystems are able to cope with them unless there is a drought at the same time. Furthermore, storms can damage ecosystems like forests and also marine ecosystems.

This concludes the identification of possible impacts of extreme weather events. It has been become clear that a sectoral categorization of impacts is useful. The temporal dimension was addressed only briefly here, but a combined sectoral and temporal analysis can help to understand the development in the aftermath of an extreme event. Capturing all the different impacts in one framework or model is impossible. Therefore several modeling techniques are available to estimate the economic impacts, all of which have certain pros and cons. These are discussed in the following section.

4. Modeling approaches for economic impact assessment

First, it has to be stressed why models are needed at all for impact assessment. The reason is that simply listing tangible asset damages is not enough. The indirect losses can add up to a big part of the total losses and because of their complexity, they cannot be easily captured by surveys or lists of damages. This complexity is reduced with the help of models, the most prominent of which are discussed in this paper.

In general, modeling techniques for economic impact assessment can be described as either"retrospective' or"prospective' (Rose, 2004). That means that some models are more useful to analyze events that actually happened (retrospective) and others are more useful to simulate possible events (prospective). Retrospective models work with economic data about the time after a disaster and try to identify the impacts caused by the disaster. Prospective models describe the"normal' economic situation and then use data about disasters to simulate the consequences of hypothetical events. Whereas general economic data (output, employment, etc.) is usually available with a decent degree of accuracy, data about a disaster or extreme weather event such as damages, losses, etc. is sometimes inaccurate and unclear regarding the methodology by which it was obtained (Rose, 2004).

The quality of data required also depends on the purpose and therefore the desired accuracy of the model. For damage mitigation or adaptation to extreme weather events, a higher accuracy is needed than for general assessment of severity of certain events. To investigate optimal allocation in immediate post-disaster situation, even more accurate models are needed (Rose, 2004).

Another issue in this paper is the geographical scope. By their nature, extreme weather events are usually local phenomena and therefore it is highly desirable to use small-scale economic models for assessment of impacts. Additionally, a focus on cities implies even more challenges, especially regarding data. However, the economy of European cities can only be accurately modeled by considering also their surrounding area which means that regional models are suitable, possibly requiring some specification. A sectoral dimension is important, too, as it serves to explain how direct losses propagate through the economy.

For the following overview, three main types of impact models that are commonly used and discussed by economists are treated (cf. Okuyama, 2003; Hallegatte and Przyluski, 2010; Rose, 2004).

4.1. Econometric models

Econometric models are frequently used as retrospective models to understand actual events. They were used, e.g., by Guimaraes et al. (1993) to compute possible impacts of hurricane Hugo which hit South Carolina in 1989 or by Berlemann and Vogt (2007) to calculate impacts of the 2002 Elbe flood in Saxony, Germany. The econometric approach is based on forecasting techniques that were applied to pre-disaster economic variables. The forecast values are then compared to the actual observed post-disaster values. It is crucial to include post-disaster national variables or other general indicators in the forecast to obtain meaningful results. Otherwise, processes like a nationwide recession could be falsely attributed to the extreme event. Therefore, Guimaraes et al. (1993) emphasize the importance to really compare the situations"with' and"without' the event instead of"-before' and 'after'.

Regarding the regional scope, key data like employment and output for different sectors are usually available also on a regional scale. Therefore, the data requirements are considered manageable although the amounts can be big when many variables are considered at many points in time. Rose (2004) considers data requirements as a problem but over the last years data availability has increased at least for Europe. The sectoral dimension is not explicitly contained in the model, but time series about the activity of important economic sectors allow for sectoral impact analysis. The temporal dimension is of course explicitly included.

Advantages of econometric models are that the effect of an extreme weather event on any regional variable with a decent time series can be computed without having to know the precise impact channels. In addition, the development of impacts over time can be captured easily. The models can also help to study the still controversially discussed issue of whether disasters or extreme weather events lead to economic growth. Furthermore, the estimates for the change in economic variables obtained by the model can be used for simulation and calibration of other models. A disadvantage is the lack of impact theory, as it is, e.g., difficult to distinguish between direct and indirect losses (Rose, 2004) and to understand in which way losses in different sectors depend on each other.

4.2. Input–output models

The second important model class is the class of input–output (I–O) models. The cores of those models are input–output tables which represent the interdependence of different sectors of the (regional) economy. In the simplest version, the I–O coefficients are assumed to be fixed which corresponds to the assumption of Leontief production functions in the sectors. Further properties of I–O models are that, because prices are fixed, possible supply bottlenecks in case of a shock lead to rationing behavior which has to be specified exogenously.

One reason for the popularity of those models is their simplicity (Okuyama, 2003) and their easy linear structure. Over the last decades, also more sophisticated versions of input–output models have been derived that include price reactions (Hallegatte, 2008) or stocks of inventory of intermediate goods in the production processes (Hallegatte, 2012). Regarding data input on a regional scale, methods have been derived to regionalize input–output tables (Flegg and Webber, 1997) and thus, regional I–O models can be constructed.

The sectoral dimension of impacts is, by definition, comprehensively captured by I–O models. Advantages of I–O models are that reconstruction dynamics after a disaster seem to be replicated quite well, at least by specific I–O models (Hallegatte, 2008). There is an easy, clear theory about how impacts propagate through the economy and the concept of direct and indirect losses is implemented on a sectoral level. Disadvantages are that price reactions are often ignored and therefore some medium-term impacts are not captured. Generally, there is a lack of behavioral content (Rose and Liao, 2005). Long-term impacts are also difficult to assess and at least some support from other model classes (econometric models, growth models) is needed. Many authors (Okuyama, 2003; Hallegatte and Przyluski, 2010) find that I–O models are likely to overestimate indirect losses from disasters because inputs are assumed not to be substitutable.

4.3. CGE models

General equilibrium analysis in the context of economic impacts of disasters was used, e.g., by Shibusawa and Miyata (2011) to assess possible impacts of an earthquake or by Rose and Liao (2005) to analyze economic impacts of regional water service disruptions. CGE models consist of equations of supply and demand functions which are simultaneously solved to obtain equilibrium factor allocation and prices. One way to look at it is that flows of the I–O table are split into a quantity component and a price component (West, 1995), both of which are determined by respective equations. As usual for the CGE model class, the production functions of the economic sectors are of the Cobb–Douglas type, or more general, the CES type. Thus, factor inputs are at least partly substitutable, resulting in price-dependent I–O coefficients. Because of the assumed flexibility in the production function, CGE models are also frequently criticized, in particular their use for disaster impact analysis. First, because an adaptation of the production process towards a different mix of inputs might be difficult to realize in a disaster situation and second, because an adjustment of the production process through prices seems unlikely in the aftermath of a disaster (Hallegatte, 2012). However, Hallegatte and Przyluski (2010) find that modeling input scarcity through can still be reasonable.

Since part of the impact of price changes can be avoided by substitution, CGE analysis generally leads to lower estimated economic losses compared to I–O analysis (Okuyama, 2003).

An advantage of CGE models is their flexibility; supply and demand function can basically take any form. Also, many dynamic CGE models allow to capture medium-term and long-term impacts of disasters. Another advantage is that CGE models often work with a certain overall welfare concept arising from utility functions of households. This implies that basically all indirect and higher-order losses can be captured. For example, if transportation is modeled and commuting times increase due to an extreme weather event, this reduces leisure time which yields a loss of welfare. The welfare concept makes it possible to analyze social and distributional impacts as well as (changing) decisions of households (consumption, labor supply, etc.). Finally, it can help to assess overall social costs and benefits of adaptation strategies to climate change or to extreme weather events in particular.

Disadvantages can be big set of parameters that need to be calibrated which is especially a problem on a regional level where decent data is not always available. Furthermore, impacts might be underestimated as, in contrast to I–O models, some impacts are assumed being avoidable by substitution behavior. Because of the fact that CGE models always assume an optimization behavior and thus, equilibrated market situations, some temporary disequilibria arising from supply bottlenecks or overshooting reconstruction cannot be suitably handled.

5. Conclusion

In the previous sections, an overview about terminology in extreme weather impact analysis was given, types of extreme weather events affecting European regions and in particular cities were collected, addressing their potential sectoral impacts. Section 3 reviewed common approaches to structure the impacts and in Section 4, relevant economic impacts models were discussed. This conclusive section attempts to bring everything together, give advice regarding which model is most useful to cover which impacts and formulate existing difficulties and future research questions.

5.1. Limits in modeling

In Sections 2 and 3, different potential impacts of extreme weather events on cities were listed. As mentioned earlier, models try to reduce the complexity of impacts, thereby trying to capture the most relevant. Therefore, the ability of the three presented model types to deal with certain impacts is discussed in the following.

Econometric models are able to model a variety of impacts, as long as a decent time series is available. Since local/regional variables are of interest, this might reduce the applicability a bit, but information about output, value added, income, employment and public expenditures/deficits are often available on a regional level. On the other hand, behavioral changes of households, psychological effects, etc. belong to those impacts which are not so well covered by time series data. Regarding sectoral impact assessment, there is the advantage that also non-market or very specific sectors can be considered. Another important issue is the availability of national or other higher aggregated variables to construct a baseline scenario. For core economic data mentioned above, this is no problem, but for more specific data it might be.

Input–output models are most useful to analyze the impacts on the production chains and the resulting losses. Impacts on the ecosystem, other non-market impacts and behavioral changes are more difficult to cover since the model capabilities depend, among other things, on the sectoral classification made in the underlying input–output table. A special strength of I–O models seems to be the modeling of the reconstruction period after a disaster because final demand can be exogenously specified. Concerning the regional scale, several models have been developed, such as the adaptive regional input–output model (ARIO) (Hallegatte, 2008) or the economic module of the HAZUS model (cf. Rose, 2004).

CGE models are often constructed top-down with an input–output table or a social accounting matrix, so impacts on the production chain can also be well covered. In contrast to I–O models, a government sector which collects taxes and redistributes income is frequently included in CGE models. Households play a key role, and instead of a top-down approach, a model can also be constructed bottom-up from household expenditures. Their decisions are usually modeled with the help of a utility function. This allows for behavioral and welfare analysis, and depending on the detailedness, also distributional and social impact analysis. What CGE models can not cover so well are very short-term impacts where optimal choices and equilibrated markets are not present. CGE models haven been used for disaster impact analysis, but rather on a national scale (Shibusawa and Miyata, 2011; Ueda and Koike, 2000) than on a regional scale (Rose and Liao, 2005). There are also urban CGE models, for example the regional economy land use and transportation model (RELUTRAN) (Anas and Liu, 2007). This model has been primarily used for policy analysis, but recently also for the economic assessment of flood risk changes (Jahn, 2014).

5.2. Further research issues

There are still many unanswered questions in the field of impact modeling of extreme weather events. For example, the trade-off between complexity and applicability seems to be an important issue. In the I–O and CGE branch, many different specifications of models exist and a further comparison of the accuracy of their loss estimates has to be made to find out which model features are essential.

Also, the cooperation between natural scientists and economists has to be further intensified. A combined knowledge about extreme weather as such and loss estimation is needed to develop successful loss mitigation strategies. As more precise climate projections become available, that allow, e.g., for seasonal and sub-seasonal forecasts of extreme events, the scale of economic models should be adapted correspondingly. Policy makers and the public are further actors who have to be provided with simple yet accurate information by natural scientists and economists to implement adaptation/loss mitigation strategies.

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