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Extreme events defined—A conceptual discussion applying a complex systems approach

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ABSTRACT

'Extreme event', a term today most commonly understood and used in relation to extreme weather phenomena and experiencing an upsurge in its usage due to their increased frequency caused by climate change, is applied in a variety of scientific disciplines. Its multitude of users understands and defines the term differently. However, consistency in language is vital to eradicate confusion, support the transfer of knowledge from one field to another, and make results from different disciplines comparable. Therefore, this work gives an in-depth discussion of the various aspects of relevance, ultimately proposing a comprehensive, systems-based definition of the term.

Novel to this definition is the complex systems approach, utilized throughout to allow the definition to be applied for both macrolevel and microlevel occurrences and across various disciplines. In contrast to most authors who separate incident and impacts and use either the former or the latter in definitions of extreme events, it is shown that a disruption to a system or systems is prerequisite. Only by applying this perspective can interdisciplinary research be successfully conducted on extreme events. This and other central aspects come particularly to light in a case study of the 2006 European Blackout, on which the meta-definition is tried.

1. Introduction

Occurrences that receive the label 'extreme event' in scientific literature are as varied as droughts, tsunamis (IPCC, 2012), earthquakes, meteorite collisions (Sanders et al., 2002), acts of terrorism (Comfort, 2002), epidemics, power outages (Jentsch, Kantz, & Albeverio, 2006), epileptic seizures (Nadin, 2006), or becoming paralysed (Lyubomirsky & Lepper, 1999). While some authors apply the term without defining it, many give their own definition. These are as diverse as the disciplines in which the term is in use; however, a rough division into two groups can be established: some include impacts in their definitions of extreme events, others omit them, focussing only on the magnitude of the initial occurrence as decisive factor for declaring an event 'extreme' (McPhillips et al., 2018). Usually, those explicitly defining 'extreme events' also use the term adjusted specifically to their scientific field (see, e.g., IPCC, 2012; Sanders, 2005; Sideratos & Hatziargyriou, 2012).

The array of divergent definitions among disciplines and, particularly, the lack of any definition in some, cause ambiguity as to what the term's meaning is in essence. At the same time, a rise in the term's popularity can be seen, making one common and comprehensive definition more crucial than ever. Reason for its growing prevalence are two current trends causing an increase in

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impacts:

First, due to climate change extreme weather and climate events are rising significantly in frequency and magnitude (IPCC, 2018; Kharin et al., 2018). These events' impacts are felt now with phenomena such as the heatwave and drought across Europe in 2018. They will likely be the main direct adverse effects of climate change for all systems, human or natural (Easterling et al., 2000; Kharin et al., 2018).

Second, there is a rise in vulnerability because of population growth and demographic shifts, mainly in the form of urbanization, settlement in higher risk areas exposed to, e.g., floods, which should be kept as buffer zones, lifestyle changes, along with more property exposed to hazards (Kunkel, Pielke, & Changnon, 1999). In fact, it is predicted that even if there were no climate change and no accompanying increases in severe weather phenomena, losses would all the same climb because societal trends, like those named above, are the dominant factors (Changnon, Pielke, Changnon, Sylves, & Pulwarty, 2000).

The issue is compounded by humanity's increasing dependence on critical infrastructures, those assets imperative for the normal functioning of society providing potable water, energy, health services, telecommunications, and more (Turoff, Bañuls, Plotnick, Hiltz, & Ramírez de la Huerga, 2016). Events hitting such critical infrastructures will severely impact society far beyond the affected facility. Furthermore, increasing interdependencies cause the spreading of impacts through cascade-like chain reactions (Helbing, Ammoser, & Kühnert, 2006). Thus, humanity will be exposed to a greater extent and more vulnerable in the face of occurrences labelled 'extreme events'.

Apart from inconsistency in the term's assigned meaning, the situation is further exacerbated by a large number of synonyms or terms similar in meaning to 'extreme event' used instead or interchangeably, chief among them 'disaster', 'catastrophe', and 'Black Swan'. What Garcia and Calantone (2002) delineate regarding the term 'innovation' and the inconsistent language in use for it in related scientific literature, can be just as easily transferred to 'extreme events' and the many terms used in a largely synonymous fashion: Inconsistencies could impede the exchange of scientific knowledge, reinforcing a more disciplinary approach, while interdisciplinary research is gaining more and more relevance (Bridle, Vrieling, Cardillo, Araya, & Hinojosa, 2013).

An overarching and generic definition can function as a basis on which scientists from different fields can build, employing their more specific definitions according to their disciplines' needs. This will be particularly helpful in fields where no explicit definition exists to gain clarity, but more importantly, in interdisciplinary work to create comparability and allow knowledge transfers through consistent language. This is the case in purely scientific settings, as well as including a wide variety of practitioners requiring the term for different tasks like, for example, risk assessment, resilience building efforts, the management of potential events, or, in the aftermath of an event, the mitigation and management of impacts in disaster relief efforts. Congruent language allows them to learn and apply knowledge attained in scientific research without having to make sense of the barrage of terms and their meanings first; it helps to avoid misinterpretation (McPhillips et al., 2018).

McPhillips et al. (2018) recommend a clear separation of occurrence and impact, excluding the latter from the definition of 'extreme events'. According to them the inclusion of impacts impedes the evaluation of progress in resilience efforts. However, this could cause the underestimation of the importance of resilience efforts for minor events with major impacts. Furthermore, a narrow definition focussing on the occurrence alone – though maybe in some areas advisable – would exclude vital aspects in other scientific fields and spheres of application. In order not to exclude any of the various pathways that could be taken to define 'extreme events' and to develop a common understanding so that scientists of all groups can work with it as a basis for their more specific definitions, extreme events are defined via their systemic effects. As will be shown this approach does not pose a contradiction to those disciplines' definitions focussing on the occurrence of events alone, but is merely a different perspective on the same events, essential for bringing together all fields of science using the term extreme events.

While most are looking at large-scale events when applying the term 'extreme event', there are also those that use the term for comparatively small incidences such as epileptic shocks (Lehnertz, 2006), unusually high nutrient availability for a plant (Gutschick & BassiriRad, 2003), material ruptures, and chemical contaminations (Jentsch et al., 2006). In order to create a definition fitting events of all scales, i.e. from a multilevel perspective, the complex systems approach is uniquely suited.

After reviewing how the two dominant approaches to defining 'extreme events' developed in Section 2, all aspects playing a significant role in the construct of the term will be discussed in order to provide a universally operational meta-definition at the end of Section 3. In the then following section the proposed definition will be applied in a case study to highlight the variability and complexity of the subject matter. The case study centres on an event that afflicted a critical infrastructure, i.e. the European energy system: the 2006 European Blackout. After a discussion in Section 5, conclusions will be reached and an outlook given.

2. Literature review

The beginnings of the term's usage were in disciplines such as meteorology, climatology, geology, and mathematics, and focussed on the magnitude of an event alone; however, quickly the term was adopted in social sciences that widened the understanding to also encompass an event's impacts in its definition, an approach later also adopted by some in natural sciences.

One of the earliest scientific documents found using the term 'extreme event' is a report by the National Weather Service (at the time called U.S. Weather Bureau) on rainfall intensity and frequency (U.S. Weather Service, 1959). Scientific sources from the 1960s likewise use the term exclusively in relation to natural events and do not include impacts in their understanding of the term (see for example: Appel, 1968; Benson, 1967; Burton, Kates, & White, 1968; Freier & Webber, 1963; Wolman & Miller, 1960). In the 1970's the term appears for the first time in behavioural sciences and psychology unrelated to natural occurrences (e.g., Azrin & Nunn, 1973; Kun & Weiner, 1973; Wachs, 1979), being used as a synonym for 'extreme situation', a phrase commonly applied before that time in the field (e.g. Bettelheim, 1943). There, usually, the term is used for rare accidents that have severe impacts on individuals, like psychological trauma (Azrin & Nunn, 1973).

Since then the term has spread and is used for a growing variety of events: human-caused accidents (e.g. Kreps, 1984; Spiro et al., 2012), financial crises and incidents on financial markets (e.g., Jackwerth & Rubinstein, 1996; Longin, 2000; Pagan & Sossounov, 2003), terrorism (e.g., Grossi & Kunreuther, 2005), or more generally risk management (e.g., Haimes, 1991; Slovic & Weber, 2002), engineering (e.g. Castillo, Hadi, Balakrishnan, & Sarabia, 2005), and medicine (e.g., Sanders, 2005; Tramèr et al., 2001). The overwhelming majority of these scientific writings does not give a definition for 'extreme events'. While some seem to exclude impacts in their implicit understandings of the term, others clearly focus primarily on impacts when declaring an event extreme (e.g., Grossi & Kunreuther, 2005; Kreps, 1984; Sanders, 2005; Slovic & Weber, 2002). Additionally, this approach of centring on impacts has moved beyond social sciences and can be found in medicine, all the way to natural sciences (e.g., Descamps et al., 2015; Gutschick & BassiriRad, 2003; Smith, 2011; Tramèr et al., 2001; Zedler, Gautier, & McMaster, 1983).

A Web of Science's Results Analysis on the frequency of the term's usage – starting with articles from 1967 to today – reveals a steady growth in the use of 'extreme event' since 1991 (Web of Science, 2018). This upsurge in popularity is due to a rising interest in phenomena of climatic change. Early examples to actively link anthropogenic climate change with the occurrence of extreme (weather) events were Borrego and Lopes (1970), Gleick (1986), Kates, Ausubel, and Berberian (1985), Mearns, Katz, and Schneider (1984), Parry (1978), Riebsame (1988), and Wilson and Mitchell (1987). Though even in the first IPCC impact assessment reports there was consensus only regarding the severe impact any 'extreme event' would have, but great uncertainty regarding the influence of climate change on the frequency and magnitude of these so-called extreme events (IPCC, 1990, 1993, 1996). Hence the quest for proof of the hypothesis that global warming affects 'extreme events' brought with it the term's frequent use – once again with a focus on the occurrence rather than impacts in their definition, explaining the dominance of related scientific fields and the exclusion of impacts in the majority of texts to this day.

The study of 'extreme events' did not only begin with the application of the phrase but with several other terms, in particular 'disaster' and catastrophe'. The Web of Science's Results Analysis likewise reveals: these terms rose in use already since the 1970s. But while 'catastrophe' experienced slow growth, 'extreme event' grew significantly since the early 1990s overtaking 'catastrophe' by 1996. Till today 'disaster' is still the term most in use.

It is important to elucidate that the terms often applied in a synonymous fashion are frequently not congruent. For instance, in the case of 'disaster' the core defining characteristic is a different one; it is neither the event's occurrence, nor its impacts, but rather the response to it. Any event that required exceptional responses, but for which response was insufficient or even failed would be a 'disaster' in conjunction with the definition put forth by Quarantelli (1985), who contributed significantly to the issue of finding the ultimate definition for the term (see, e.g., Perry & Quarantelli, 2005; Quarantelli, 1989, 1998). Therefore, 'extreme event' and 'disaster' cannot be interchangeably used since focus is laid differently.

The discussion above reveals divergent understandings of what characterizes extreme events. At the same time, the differing definitions overlap, impeding a close exchange of scientific knowledge beyond the disciplinary boundaries. Since interdisciplinarity of different disciplines is getting ever more relevant (Bridle et al., 2013; Wickson, Carew, & Russell, 2006), a broad and comprehensive definition will allow the transfer of knowledge from seemingly unrelated fields that might lead to cogent academic advancements. The following section aims at proposing a comprehensive, i.e. meta-definition of extreme events.

3. Extreme events defined

Generally speaking, a definition of extreme events demands a clear conception of the terms events, event's impacts, and extremes. At first the terms will be analysed in more detail in isolation and then merged into a novel definition. However, since the definition shall allow for a multilevel and interdisciplinary perspective, the complex systems approach is used as methodological foundation. It permits events and their impacts to be displayed within, but also between systems.

3.1. Methodological foundation: the complex systems approach

Complex systems can be characterized as a set-up of systems, which are determined by systems' elements, i.e. components, and their *numerosity* as well as their correlations (Ladyman, Lambert, & Wiesner, 2013). These define the structure and functioning of a system and thus, distinguish the systems. Interdependencies between elements can create *nonlinearity* via *feedback loops*. Because of a *lack of central control* these systems exhibit *spontaneous order*, which also leads to a certain level of robustness. The level of robustness can differ between the systems (Ladyman et al., 2013). The *emergence* of higher levels of organisation through the interaction of systems creates a *hierarchical* structure of systems within complex systems. A biological organism is such a complex system, its elements, or components, are the organism's cells; likewise, cells are complex systems (Bodenschatz, 2010).

3.2. Events

Event originates from the Latin *evenire* meaning "to come" (Weekley, 1921), i.e. it describes a non-stationary situation. The sophistication of this definition has been much discussed in philosophy (e.g. Steward, 1997), which led to the identification of the following characteristics: events occur in a short period of time, but have no such restrictions in spatial terms (Casati & Varzi, 2015), they occupy time and within that have different stages, thus they develop and change quickly (Hacker, 1982). Each event is unique in its appearance, i.e. events are entities of which no two are the same (Davidson, 1969, 1980). Thus, an event is a dynamic occurrence within a limited time frame fixed in time. Typically, events are not strictly spatially bounded, although ex post the spatial extent of an event should be clearly definable.

Transferring this characterization to the systems perspective, elements – as a core of systems – are “capable of behaviour”, meaning they have properties prone to change (Jones, 1982). Thus, in the context of complex systems events can be defined, therefore, as *the dynamic behaviour of an element within a limited timeframe*.

3.3. Impacts

Impact in its general usage simply means “marked effect or influence” (Oxford Dictionaries, 2018). Within the complex systems' approach this definition implies impacts to be the *effects one or more elements' behaviours have on the behaviour of one or more other elements*. The ‘other elements’ could belong to the system of the driving force(s), but also to one or more other systems. Furthermore, the effects on other elements could occur simultaneously or in cascading fashion.

The size of the impact depends amongst other aspects crucially on the vulnerability of the affected system(s) because the susceptibility of a system to react or change at the instant of an event occurring is instrumental in eliciting substantial impacts. While complex systems are said to have a certain level of robustness (Ladyman et al., 2013), its flip side is a system's vulnerability, which Gallopín (2003, p. 2) defines “as its propensity to undergo significant transformations […].”

3.4. Extremes

The word ‘extreme’ has its origins in the Latin *extremus* meaning “utmost” (Weekley, 1921). Extremes occur rarely, or with low probability. In the most general sense, the term can be defined as *outliers to the normal condition*. Normal condition in this instance means the usual, i.e. typical behaviour an element displays, either as initial event, or as impact.

Traditionally in extreme events research, there are but two aspects of an event that can turn extreme: occurrence and impact (Jahn, 2015). Combining the considerations on extremes with the earlier definition of events, *occurrence extremes are those instances in which an element displays atypical behaviour*. In the case of an occurrence extreme or an unfortunate coinciding of events, common in themselves, *other elements may be impacted in such a way as to likewise display atypical behaviour*. This is an *impact extreme*.

The assumption is that elements within a system are accustomed to each other's usual behaviour and remain within the normal range of their own behaviour, adjusting it minimally in relation to each other. This condition is probably best compared to and described as a dynamic equilibrium. In that state the overall system is functioning normally, i.e. operates in the intended or usual way. The question of how to determine whether a system is functioning the way it usually does, or was created for (in instances of human-made systems) depends on the system's complexity (its various functionalities) and the mode of operation it most frequently adheres to over time.

A more tangible definition is beyond the scope of this paper, as the comparison of the two following examples will highlight: The system under observation in our case study in Section 4 is the electricity system. Its normal function is the provision of electricity to consumers. In the incident described in the case study electricity was no longer provided, a blackout occurred, which is not its usual or intended mode of operation. A system highly different to this one is the human brain. Its normal functioning is by far more difficult to define, as discussed by Lehnertz (2006) in detail. Its main functions are so diverse – processing information provided by the senses, regulating organ functions and thus, for example, blood pressure and breathing, and releasing hormones to name but a few – that it is easiest defined by the neuron activity it displays most of the time while maintaining these functionalities.

3.5. A proposed meta-definition

Depending on the system's robustness, any extreme behaviour by one or more of its elements may be absorbed within the system, not impeding its overall functioning. From a systems perspective, the instance, in which the overall system or related systems within the complex systems structure malfunction, is of interest.

Bringing the above discussed and defined terms together, the following definition is proposed:

An extreme event is a dynamic occurrence within a limited timeframe that impedes the normal functioning of a system or systems.

The proposed meta-definition highlights the importance of the complex systems perspective while at the same time not excluding those approaches used to determine extreme events in the various disciplines. Solely those events are excluded that do not disrupt the functioning of an entire system or even systems.

The flowchart in Fig. 1 expands upon the definition and depicts how to go about identifying, or even predicting an extreme event.

Events occur within systems, which by definition consist of interrelating elements that affect each other. Any behaviour an element displays within a limited timeframe is an event. Any event marked by an occurrence extreme, i.e. an element's extreme behaviour, or not, will have impacts on other elements within that system, or even within a higher-level system, of which the original system is a part. Should that impact be severe so that the impacted elements display extreme behaviour in turn, be it for only a short amount of time or longer-term, then the event is also characterized by an impact extreme. Occurrence extremes and impact extremes are strong indicators for an *extreme event*, however neither necessary nor sufficient condition in this systems-based meta-definition. Thus, the proposed definition allows for several ‘pathways’ to characterize an event as extreme:

If a system does not display elements with atypical, i.e. extreme behaviour initially or subsequently, but is nevertheless impeded in its normal functioning, it means that the extreme event originated from within a different, but linked system. Such a systemic disturbance can also be caused by extreme behaviour of some element(s) within the system, can also feature significant impacts, but

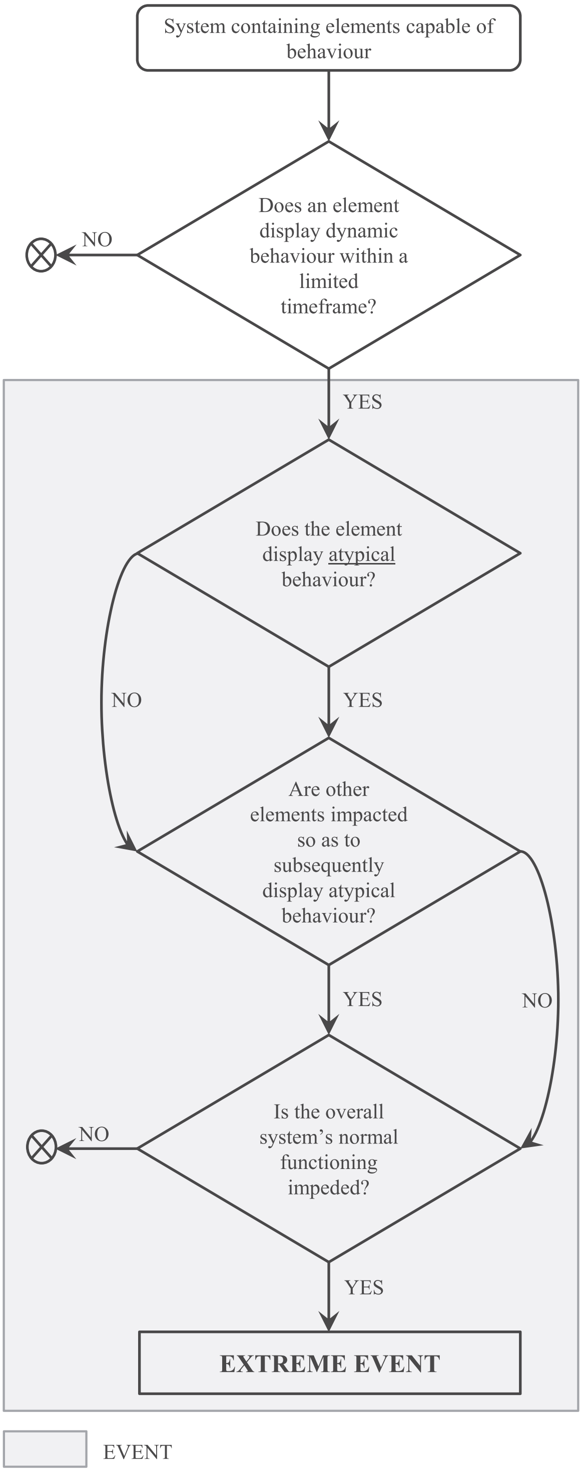

Fig. 1. Identifying extreme events (source: authors' conception).

can likewise be caused by an unfortunate compounding of commonplace events, or by an ordinary event befalling a vulnerable system. A particular case of such vulnerability are elements critical to the overall functioning of the system, e.g. critical infrastructures. In such circumstances one ordinary event hitting that one vulnerable element can result in an extreme event.

Fig. 1 gives only a simplified picture. Conceptually speaking but also observable in practice, the phenomenon of other factors playing a role, or other events coinciding, is not indicated directly in the flowchart. Furthermore, attributing any impact to a particular event, i.e. one causal agent, with absolute certainty will not be possible.

At first glance, the proposed definition may seem to be at odds with those disciplines and authors who exclude impacts in their definitions of extreme events for systemic effects can be seen as impacts of a higher order. Reviewing the literature not a single event labelled extreme was found that did not also fit this meta-definition. There seems to be a pattern of explicitly excluding impacts when defining extreme events while simultaneously implicitly only declaring events extreme that cause severe impacts on the systemic level (see e.g. IPCC (2012) for examples).

From a practical point of view arises the question of empirical evidence for the presented definition. The definition shall be understood as a conceptual base for interdisciplinary exchange of knowledge. An overarching empirical benchmarking seems to be dependent on the precise context – an extreme event analysed in climate research will happen under other circumstances than e.g. in cytology. Additionally, the perception of impacts by researchers and affected persons – if present in the event under observation – could differ significantly, influencing what impacts will be identified in the first place, and whether these impacts will be declared extreme (Leonard et al., 2014). This superordinate, systems-based definition escapes these subjectivities to a large extent by not collecting individual impacts but looking at the overall picture of an event.

Thus, the proposed meta-definition is uniquely fitting for interdisciplinary research because it is non-arbitrary and does not require thresholds to be set, and therefore no measurements, while at the same time not forbidding to do so on a disciplinary level where this is possible, as in natural sciences. Simultaneously, it grants disciplines in the social sciences, e.g. history, that are less able to define clear cut-off points to apply the proposed definition as well. If utilized consistently across disciplines, their results become comparable and knowledge transfers are facilitated. Furthermore, the possibility arises to categories, i.e. create a classification system, for extreme events across disciplines and of all scales despite their multidimensionality. As will be shown in the following case study, the proposed definition is ideal for cascades of (extreme) events. Each event in a causal chain can be identified separately, as well as how they are connected and how each is extreme in it's own unique way. The application of the systems approach highlights the possibility for various scientific fields to gain insights from complexity and systems science where the behaviour of systems is studied methodically and conceptually.

4. Applying the definition – the 2006 European Blackout as a case study

The following section will highlight particular aspects of applying the definition and the complexity of the topic extreme events by using the 2006 European Blackout, a historic event that had large ramifications for the European electrical system, as a case study.

4.1. The system

Silvast and Kaplinsky (2007) describe the electricity system as “a series of tightly interlocking technical and social networks”, of which one is the transmission grid. It is crucial for a wide variety of social and economic activities, with its importance further increasing due to technological development, the proliferation of electrical devices in all areas of human activity, and a dependence of other infrastructure services on a steady supply of electricity. Through these developments on the consumption side, vulnerability is increasing (Reichl, Schmidthaler, & Schneider, 2013). A disruption in electricity supply can have severe impacts, especially in highly developed and technologized countries. Thus, it is part of the group of critical infrastructures and a system interlinked with many other systems.

4.2. The event(s)

The course of events, which ultimately led to the 2006 Blackout affecting consumers of electricity all over Europe, is described in detail in several reports (e.g. BNetzA (2007), ERGEG (2007), GRS (2014), and UCTE (2007)). On November 4, 2006, a shipyard requested to advance the disconnection of a high-voltage power line crossing the Ems River, so a ship could be transported safely towards the North Sea. A later date had already been approved by *E.ON Netz*, the transmission system operator (TSO) of the power line in question. They informed adjoining TSOs and performed analyses that showed the system would be alright, though highly loaded. The adjoining TSOs did likewise. All approved the action though none had actually calculated the n-1 criterion, which states that if a single component is disconnected, the power transmission network should all the same be able to function normally (Cadini, Agliardi, & Zio, 2017). Because of little advance notice of the changed date, the exchange of power between Germany and the Netherlands, which used the power line in question, could not be reduced. Additionally, several network components were off-grid due to maintenance work (Yamashita, Joo, Li, Zhang, & Liu, 2008). E.ON turned off the line at 9:39 p.m. local time.

In the time following the line-disconnection warning systems informed of high power flows on lines accommodating the removed line’s load. At 10:07 p.m. the load increased on one of the lines beyond the safety limit value. E.ON reacted by coupling busbars in a nearby substation. RWE, a TSO also affected by the immediate situation, was not informed of it. Contrary to expectations, this did not resolve the situation but led to a rise in the current on the line which was automatically tripped at 10:10 p.m.

Within seconds load flow increased on other lines and a cascade of line trippings throughout Europe followed at the end of which Europe’s UCTE system split into three sub-systems of different frequencies with the Western area – a map of the zones can be found in the UCTE report (2007) – far below the necessary 50 Hz because of too little power generation, the same of slightly less severity was observed in the South-Eastern zone, while the North-Eastern zone had a higher than necessary frequency due to over-production. In the Western area the deficit was so severe that it led to automatic load shedding and, as a result, blackouts in almost all countries within that zone. Countermeasures were taken by the involved TSOs, and after less than two hours the three sub-systems were resynchronized, consumers reconnected, and all functions back to their original state.

4.3. The impacts

Though the European Blackout of 2006 is often cited as one of the major incidents of large scale power interruptions in the world (e.g. Bompard et al., 2011; Kröger, 2008; Yamashita et al., 2008), no in-depth study on its impacts has been conducted. Thus, information is rudimentary with estimates remaining rough and largely incomplete. A reason might be its rather short duration of less than two hours with most experiencing power outage for just half an hour. This fact is likely also the reason why this blackout has been put forward as proof for the counter-argument: it showed how robust the system is; the system failure was contained and repaired efficiently (Van der Vleuten & Lagendijk, 2010a).

Sources list the following impacts: Some 20 European countries along with Morocco, Algeria, and Tunisia in North Africa were affected (Van der Vleuten & Lagendijk, 2010b). Over 15 million European households experienced power outages, which lasted up to 1.5 h (BNetzA, 2007). Furthermore, 100 trains – the majority of which in Germany – were delayed, and subways had to be evacuated (CRO Forum, 2011).

Probably a more accurate depiction of the blackout's severity is the amount of load shedding that occurred, which was almost 17,000 MW (UCTE, 2007). Due to the changes in frequency some generation units were also tripped: 60 percent of wind turbines generating power at the time, 30 percent of combined-heat-and-power, along with one thermal generation unit of about 700 MW in Spain, resulting in a total of some 10,900 MW (UCTE, 2007). Several generating units in Poland had to be turned off, and generation output had to be decreased from full load in several nuclear power plants in Germany and Switzerland (GRS, 2014). On the other hand, generation units – the majority of which, hydropower plants – had to be started manually in the Western area so frequency would be restored to its usual 50 Hz. An evaluation of the impacts in monetary terms, even as rough estimates, is challenging, as studies by Growitsch, Malischek, Nick, and Wetzel (2013) and Piaszeck, Wenzel, and Wolf (2013) have shown and was therefore not attempted in this study.

Beyond these obvious and immediate impacts, the European electricity system was affected far more fundamentally longer term. The blackout was used as an example to underline the vulnerability of the European power grid in debates by EU policy makers demanding reforms towards centralized governance (Van der Vleuten & Lagendijk, 2010b). Consequently actions were taken towards reinforcing the EU's authority by creating an EU-wide regulator for power grids, the Agency for the Cooperation of Energy Regulators (ACER), and terminating the UCTE and the Nordic Electricity Union (NORDEL), which merged to become the European Network of Transmission System Operators for Electricity (ENTSO-E) in 2009 (Van der Vleuten & Högselius, 2012). Though these developments cannot be attributed solely to the 2006 Blackout, but also a previous blackout in 2003, which lasted for up to 18 h and affected some 56 million people (Panteli, 2013), and political ambitions within the EU (Van der Vleuten & Lagendijk, 2010b), these developments need to be included in considerations of the occurrence's impacts.

4.4. Discussion of the case study

The 2006 Blackout, clearly a dynamic occurrence within a limited timeframe and thus an event, is arguably rare in occurrence, considering major blackouts in developed regions similar to the European Union (see lists of major blackouts in, e.g., (Bompard et al., 2011; Kröger, 2008; Yamashita et al., 2008)). The geographical scale of the 2006 Blackout (the UCTE and parts of North Africa were affected) adds to the Blackout being an occurrence extreme. Taking into consideration the number of consumers affected and the number of countries involved, an impact extreme appears to be at hand, despite the fragmentary information on its effects.

The reason as to why the 2006 Blackout is labelled an extreme event, becomes obvious when returning to the context of the definition: the complex system approach. In the short term, the incident caused the disruption of the entire UCTE system's normal functioning; during the two-hour time frame Europe's entire electricity system was in turmoil, triggered by the removal of just one high-voltage power line. Its long-term impacts, together with other factors irrevocably changed the EU regulatory bodies of the electricity system.

Thus, the event highlights the necessity of defining extreme events not via singular elements' behaviour, which would cause difficulties and imprecision through arbitrarily defined thresholds – as for instance, the number of households left without electricity – but as disruptions for the larger system. Additionally, the interplay of many elements within a complex system is highlighted. Often it is not the event alone, but an unfortunate compounding of incidents and factors that lead to extreme impacts, as can be seen by the changes to the regulatory bodies of the European electricity grid.

The case study also distinguishes the role the system, in which the event occurs, has on whether the event is labelled extreme. A minor occurrence hitting a vulnerable system as vital to the hierarchically higher system as critical infrastructure, can cause extreme effects by cascading through the system and into other, related systems. In the end, this interdependence is at the core of such far-reaching impacts and not the initial incident alone.

While the blackout is an extreme event, it is, assertably, not a disaster when applying Quarantelli's (1985) definition. This can also explain the dispute among experts whether the event proved the system's vulnerability, or instead robustness. The response was adequate, and the original functionality of the system was re-established within the time frame of two hours. Therefore, in this instance, the two terms, extreme event and disaster, are not congruent.

Cascading effects are typical features of complex systems (Holling, 2001; WEF, 2018), in particular through interconnectedness, which, in turn, is especially inherent to critical infrastructures. The cascade described in this case study concerns the surge of power line trippings that ultimately led to the load shedding and blackout across parts of Europe. Each of these line trippings is an event with each power line constituting an element within the electrical grid, i.e. the system. Likewise, the entire blackout is an event if the power grid is seen as an element of the energy system. Thus, the case study highlights an issue intrinsic to the proposed definition: scale. Microlevel and macrolevel occurrences alike can be declared extreme events. However, in this particular case, only the latter is actually the extreme event since each single line tripping is only an event, but did not have systemic impacts, only in coming together, did they have the disruptive effect on the electricity system's functioning.

5. Discussion

Interestingly, the shortcomings of the classic definition of extreme events by the IPCC (2007), focussing on the extreme of one variable, has been recognised in part in its special report "Managing the Risks of Extreme Events and Disasters…", in which the term 'compound event' is introduced (IPCC, 2012). It observes that many events, frequently declared prime examples for extreme events, e.g. floods and droughts, are not caused by one factor alone. A compounding of events and the condition of the system, within which it occurs, together cause the event. However, considering the attribute "complex" that most of the world's systems receive, there exist a wide variety of factors defining an event. Therefore, the difficulty arises of regarding all the right factors. The issue is further exacerbated when extremes are to be empirically determined and thresholds need to be set, which can never be definitively done. This is also the cause for the murky discussion of occurrence as well as impact extremeness in the case study of the European Blackout of 2006. It makes the definition of extreme events via occurrence extremes and impact extremes alone highly problematic. The systemic approach taken here is not hampered by thresholds. Undoubtedly, their determination can represent a challenge as well for a system's functionalities must be known and its typical behaviour well studied.

Because of the complex systems approach the definition is not impervious to the issue of scale. A system can be both large and relatively small. An extreme event is caused by the behaviour of an element which is embedded within a system and evokes effects beyond itself within the system, or even in hierarchically higher systems. Epileptic seizures are frequently cited as prime examples of extreme events (see, e.g., Lehnertz, 2006; Sornette, 2009), with the brain as the complex system under observation. On a vastly different scale an earthquake can be an extreme event just as well.

Furthermore, systemic disruptions and thus extreme events demand to be looked at from a different perspective as well: they can be seen as drivers of transformations. Gunderson and Holling (2001) and Holling (2001) describe extreme events as triggers for the collapses of human and natural systems. In the same vein Sornette (2017) sums up their relevance for complex systems: The behaviour of complex systems is shaped significantly by few extreme events, and their evolutionary process is marked, not by continual dynamics but rather "quasi-stasis interrupted by episodic bursts of activity and destruction" (Sornette, 2017, p. 19). Therefore, extreme events from a systems perspective are those instances expediting the evolution of a system. As catalysts for change the effects of events cannot automatically be judged as negative. In essence, this is the idea of Schumpeterian *creative destruction* (Schumpeter, 1950), in which, in the wake of an event generating extreme impacts on the systemic level, the reconstruction and rebuilding phase sees innovation and improvement of the system.

6. Conclusions and outlook

The term extreme events, in use in a wide variety of disciplines, is understood to mean either an event extreme in its occurrence, or because its impacts can be defined as extreme. The beginnings of the term's usage in a scientific context were in disciplines such as meteorology, climatology, and mathematics, and focussed on the first option. Starting with social sciences, then quickly spreading into natural sciences, an event's impacts were included in the term's definition.

After applying a complex systems approach to dissect and look at the term's separate elements, i.e. events, impacts, and extremes, we propose a meta-definition that allows the initial occurrence as well as its impacts to be extreme but demands a malfunction in the larger system to be prerequisite. We argue that this way of defining events does not go against the term's previous usages across disciplines, rather that it is applicable in all instances and uniquely suited for interdisciplinary research. The wide variety of events falling under the category extreme events, make it impossible to define clear-cut thresholds for when an event is to be called extreme. The resulting definition is therefore broad; it includes small- and large-scale events alike.

The application of the proposed definition in a case study of the Europe-wide blackout in 2006 throws the spotlight on some particularities of extreme events and the proposed definition: First of all, there are cascading effects, caused by systems' proliferating interconnectedness and vulnerability and resulting in increasing impacts. This phenomenon of several initial events ordinary in isolation coming together to cause a cascade of ever-worsening impacts resulting in an extreme event is of particular importance for systems modelling where such occurrences are rarely looked at conjointly. Second, the description of the European electricity system, in which the case study's event occurred, and particularly the events and the impact's extensive nature, revealed vulnerability of systems as significant in causing extreme events.

The debate in the aftermath of the 2006 European Blackout on whether the incident proved the system's robustness, or conversely vulnerability, highlighted an issue that could only be hinted at within the scope of this paper: extremeness of impacts is inherently dependent on how the impacts are perceived. Only if stakeholders subjectively consider the event's impacts to be extreme, can they be declared as such. In future research, it may be interesting to ponder how and to what extend perception and attitudes towards occurrences shape the definition of extreme events across disciplines with a focus on impacts in their definitions.

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References

Appel, C. A. (1968). A note on the average probability of extreme events. *Water Resources Research, 4*(6), 1359.
Azrin, N., & Nunn, R. (1973). Habit-reversal: A method of eliminating nervous habits and tics. *Behaviour Research and Therapy, 11*(4), 619–628.
Benson, M. A. (1967). Average probability of extreme events. *Water Resources Research, 3*(1), 225.
Bettelheim, B. (1943). Individual and mass behavior in extreme situations. *The Journal of Abnormal and Social Psychology, 38*(4), 417.
BNetzA (2007). *Report by the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railways on the disturbance in the German and European power system on the 4th of November 2006*.
Bodenschatz, E. (2010). In Max Planck Society (Ed.). *Complex systems* (pp. 56–57). Research Perspectives 2010+ of the Max Planck Society.
Bompard, E., Huang, T., Tenconi, A., Wu, Y., Zelastiba, D., Cremenescu, M., et al. (2011). *Analysis of historic outages. Report for the SESAME-project (Securing the European electricity supply against malicious and accidental thrEats)*.
Borrego, C., & Lopes, M. (1970). Climate change and coastal zone: The importance of atmospheric pollutant transport. *WIT Transactions on Ecology and the Environment, 25*.
Bridle, H., Vrieling, A., Cardillo, M., Araya, Y., & Hinojosa, L. (2013). Preparing for an interdisciplinary future: A perspective from early-career researchers. *Futures, 53*, 22–32.
Burton, I., Kates, R. W., & White, G. F. (1968). *The human ecology of extreme geophysical events.* FMHI Publications. Paper 78.
Cadini, F., Agliardi, G. L., & Zio, E. (2017). A modeling and simulation framework for the reliability/availability assessment of a power transmission grid subject to cascading failures under extreme weather conditions. *Applied Energy, 185*, 267–279.
Casati, R., & Varzi, A. (2015). *Events.* Retrieved 18 May 2018, from Stanford Encyclopedia of Philosophy https://plato.stanford.edu/entries/events/.
Castillo, E., Hadi, A. S., Balakrishnan, N., & Sarabia, J.-M. (2005). *Extreme value and related models with applications in engineering and science.* Wiley.
Changnon, S. A., Pielke, R. A., Jr., Changnon, D., Sylves, R. T., & Pulwarty, R. (2000). Human factors explain the increased losses from weather and climate extremes. *Bulletin of the American Meteorological Society, 81*(3), 437–442.
Comfort, L. K. (2002). Managing intergovernmental responses to terrorism and other extreme events. *Publius: The Journal of Federalism, 32*(4), 29–50.
CRO Forum (2011). *Power blackout risks - risk management options: Chief risk officer forum, emerging risks initiative - position paper*.
Davidson, D. (1969). *The individuation of events. Essays in honor of Carl G. Hempel*. Springer216–234.
Davidson, D. (1980). *Essays on actions and events*, *Vol. 1*. Oxford University Press.
Descamps, S., Tarroux, A., Varpe, Ø., Yoccoz, N. G., Tveraa, T., & Lorentsen, S. H. (2015). Demographic effects of extreme weather events: Snow storms, breeding success, and population growth rate in a long-lived Antarctic seabird. *Ecology and Evolution, 5*(2), 314–325.
Easterling, D. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R., & Mearns, L. O. (2000). Climate extremes: Observations, modeling, and impacts. *Science, 289*(5487), 2068–2074.
ERGEG (2007). *ERGEG final report: The lessons to be learned from the large disturbance in the European power system on the 4th of November 2006*E06-BAG-01-06, Brussels, 35.
Freier, P., & Webber, W. R. (1963). Radiation hazard in space from solar particles. *Science, 142*(3599), 1587–1592.
Gallopín, G. C. (2003). A systemic synthesis of the relations between vulnerability, hazard, exposure and impact, aimed at policy identification. In ECLAC, & UN (Eds.). *Handbook for estimating the socio-economic and environmental effects of disasters* (pp. 2–5). United Nations, Economic Commission for Latin America and the Caribbean (ECLAC) & International Bank for Reconstruction & Development (The World Bank).
Garcia, R., & Calantone, R. (2002). A critical look at technological innovation typology and innovativeness terminology: A literature review. *Journal of Product Innovation Management, 19*(2), 110–132.
Gleick, P. H. (1986). Methods for evaluating the regional hydrologic impacts of global climatic changes. *Journal of Hydrology, 88*(1–2), 97–116.
Grossi, P., & Kunreuther, H. (2005). *Catastrophe modeling: A new approach to managing risk*, *Vol. 25*. Springer Science & Business Media.
Growitsch, C., Malischek, R., Nick, S., & Wetzel, H. (2013). *The costs of power interruptions in Germany—An assessment in the light of the Energiewende. EWI Working Paper, No 13/07*.
GRS (2014). *Störungen im Stromnetz und Notstromfälle in Kernkraftwerken in den Jahren 2003 bis 2012.* Gesellschaft für Anlagen-und Reaktorsicherheit (GRS) mbH.
Gunderson, L. H., & Holling, C. S. (2001). *Panarchy: Understanding transformations in human and natural systems.* Island Press.
Gutschick, V. P., & BassiriRad, H. (2003). Extreme events as shaping physiology, ecology, and evolution of plants: Toward a unified definition and evaluation of their consequences. *New Phytologist, 160*(1), 21–42.
Hacker, P. M. S. (1982). Events and objects in space and time. *Mind, 91*(361), 1–19.
Haimes, Y. Y. (1991). Total risk management. *Risk Analysis, 11*(2), 169–171.
Helbing, D., Ammoser, H., & Kühnert, C. (2006). *). Disasters as extreme events and the importance of network interactions for disaster response management. Extreme events in nature and society*. Springer319–348.
Holling, C. S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems, 4*(5), 390–405.
IPCC (1990). In W. J. Tegart, G. W. Sheldon, & D. C. Griffiths (Eds.). *Climate change. The IPCC impacts assessment*.
IPCC (1993). In W. J. M. Tegart, & G. W. Sheldon (Eds.). *Climate change 1992: The supplementary report to the IPCC impacts assessment*.
IPCC (1996). In R. T. Watson, M. C. Zinyowera, & R. H. Moss (Eds.). *Climate change 1995. Impacts, adaptations and mitigation of climate change: Scientific-technical analyses*.
IPCC (2007). *Climate change 2007: 4th assessment synthesis report.* Intergovernmental Panel on Climate Change.
IPCC (2012). In C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, & P. M. Midgley (Eds.). *Managing the risks of extreme events and disasters to advance climate change adaptation. A Special report of working groups I and II of the inter-governmental panel on climate change*. Cambridge University Press.
IPCC (2018). *Global Warming of 1.5 °C—An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty - summary for policymakers*.
Jackwerth, J. C., & Rubinstein, M. (1996). Recovering probability distributions from option prices. *The Journal of Finance, 51*(5), 1611–1631.
Jahn, M. (2015). Economics of extreme weather events: Terminology and regional impact models. *Weather and Climate Extremes, 10*, 29–39.
Jentsch, V., Kantz, H., & Albeverio, S. (2006). Extreme events: Magic, mysteries, and challenges. In S. Albeverio, V. Jentsch, & H. Kantz (Eds.). *Extreme events in nature and society* (pp. 1–18). Springer.
Jones, L. M. (1982). Defining systems boundaries in practice: Some proposals and guidlines. *Journal of Applied Systems Analysis, 9*, 41–55.
Kates, R. W., Ausubel, J. H., & Berberian, M. (1985). *Climate impact assessment.* John Wiley & Sons.
Kharin, V. V., Flato, G., Zhang, X., Gillett, N. P., Zwiers, F., & Anderson, K. J. (2018). Risks from climate extremes change differently from 1.5 °C to 2.0 °C depending on rarity. *Earth's Future, 6*(5), 704–715.
Kreps, G. A. (1984). Sociological inquiry and disaster research. *Annual Review of Sociology, 10*(1), 309–330.
Kröger, W. (2008). Critical infrastructures at risk: A need for a new conceptual approach and extended analytical tools. *Reliability Engineering & System Safety, 93*(12), 1781–1787.

Kun, A., & Weiner, B. (1973). Necessary versus sufficient causal schemata for success and failure. *Journal of Research in Personality, 7*(3), 197–207.
Kunkel, K. E., Pielke, R. A., Jr., & Changnon, S. A. (1999). Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society, 80*(6), 1077–1098.
Ladyman, J., Lambert, J., & Wiesner, K. (2013). What is a complex system? *European Journal for Philosophy of Science, 3*(1), 33–67.
Lehnertz, K. (2006). Epilepsy: Extreme events in the human brain. In S. Albeverio, V. Jentsch, & H. Kantz (Eds.). *Extreme events in nature and society* (pp. 123–143). Springer.
Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., et al. (2014). A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change, 5*(1), 113–128.
Longin, F. M. (2000). From value at risk to stress testing: The extreme value approach. *Journal of Banking & Finance, 24*(7), 1097–1130.
Lyubomirsky, S., & Lepper, H. S. (1999). A measure of subjective happiness: Preliminary reliability and construct validation. *Social Indicators Research, 46*(2), 137–155.
McPhillips, L. E., Chang, H., Chester, M. V., Depietri, Y., Friedman, E., Grimm, N. B., et al. (2018). Defining extreme events: A cross-disciplinary review. *Earth's Future, 6*(3), 441–455.
Mearns, L. O., Katz, R. W., & Schneider, S. H. (1984). Extreme high-temperature events: Changes in their probabilities with changes in mean temperature. *Journal of Climate and Applied Meteorology, 23*(12), 1601–1613.
Nadin, M. (2006). Anticipating extreme events. In S. Albeverio, V. Jentsch, & H. Kantz (Eds.). *Extreme events in nature and society* (pp. 21–45). Springer.
Oxford Dictionaries (2018). *Impact.* Retrieved 18 June 2018, fromhttps://en.oxforddictionaries.com/definition/impact.
Pagan, A. R., & Sossounov, K. A. (2003). A simple framework for analysing bull and bear markets. *Journal of Applied Econometrics, 18*(1), 23–46.
Panteli, M. (2013). *Doctoral dissertation: Impact of ICT reliability and situation awareness on power system blackouts.* University of Manchester.
Parry, M. L. (1978). *Climatic change, agriculture and settlement.* Folkestone: Dawson, Studies in Historical Geography Series.
Perry, R. W., & Quarantelli, E. L. (2005). *What is a disaster?—New answers to old questions.* Xlibris Corporation.
Piaszeck, S., Wenzel, L., & Wolf, A. (2013). *Regional diversity in the costs of electricity outages: Results for German counties. HWWI Research Paper 142*.
Quarantelli, E. L. (1985). What is disaster? The need for clarification in definition and conceptualization in research. In B. Sowder (Ed.). *Disasters and mental health—Selected contemporary perspectives* (pp. 41–73). .
Quarantelli, E. L. (1989). Conceptualizing disasters from a sociological perspective. *International Journal of Mass Emergencies and Disasters, 7*, 243–251.
Quarantelli, E. L. (1998). *What is a disaster?: A dozen perspectives on the question.* Routledge.
Reichl, J., Schmidthaler, M., & Schneider, F. (2013). The value of supply security: The costs of power outages to Austrian households, firms and the public sector. *Energy Economics, 36*, 256–261.
Riebsame, W. E. (1988). Adjusting water resources management to climate change. *Climatic Change, 13*(1), 69–97.
Sanders, D. (2005). The modelling of extreme events. *British Actuarial Journal, 11*(3), 519–557.
Sanders, D., Brix, A., Duffy, P., Forster, W., Hartington, T., Jones, G., et al. (2002). The management of losses arising from extreme events. *Paper presented at the convention general insurance study group GIRO*.
Schumpeter, J. A. (1950). *Capitalism, socialism and democracy.* Harper & Row.
Sideratos, G., & Hatziargyriou, N. D. (2012). Wind power forecasting focused on extreme power system events. *IEEE Transactions on Sustainable Energy, 3*(3), 445–454.
Silvast, A., & Kaplinsky, J. (2007). *Project understand: White paper on security of European electricity distribution.* Eskilstuna: Swedish Energy Agency.
Slovic, P., & Weber, E. U. (2002). Perception of risk posed by extreme events. *Discussion paper; conference "risk management strategies in an uncertain world"*.
Smith, M. D. (2011). An ecological perspective on extreme climatic events: A synthetic definition and framework to guide future research. *Journal of Ecology, 99*(3), 656–663.
Sornette, D. (2009). Dragon-kings, black swans and the prediction of crises. *International Journal of Terraspace Science and Engineering, 2*(1), 1–18.
Sornette, D. (2017). *Why stock markets crash: Critical events in complex financial systems.* Princeton University Press.
Spiro, E. S., Fitzhugh, S., Sutton, J., Pierski, N., Greczek, M., & Butts, C. T. (2012). Rumoring during extreme events: A case study of Deepwater Horizon 2010. *Paper presented at the proceedings of the 4th annual ACM web science conference*.
Steward, H. (1997). *The ontology of mind: Events, processes, and states.* Oxford Philosophical Monographs.
Tramèr, M. R., Carroll, D., Campbell, F. A., Reynolds, D. J. M., Moore, R. A., & McQuay, H. J. (2001). Cannabinoids for control of chemotherapy induced nausea and vomiting: Quantitative systematic review. *BMJ, 323*(7303), 16.
Turoff, M., Bañuls, V. A., Plotnick, L., Hiltz, S. R., & Ramírez de la Huerga, M. (2016). A collaborative dynamic scenario model for the interaction of critical infrastructures. *Futures, 84*, 23–42.
U.S. Weather Service (1959). *Rainfall intensity-frequency regime. Part 4 - Northeastern United States. Hydrologic services division of the U.S. Weather bureau (former name of the national weather service)*.
UCTE (2007). *Final report - system disturbance on 4 November 2006: Union for the Co-ordination of transmission of electricity*.
Van der Vleuten, E., & Högselius, P. (2012). Resisting change? The transnational dynamics of European energy regimes. In G. Verbong, & D. Loorbach (Eds.). *Governing the energy transition: Reality, illusion or necessity?* (pp. 75–100). New York: Routledge.
Van der Vleuten, E., & Lagendijk, V. (2010a). Interpreting transnational infrastructure vulnerability: European blackout and the historical dynamics of transnational electricity governance. *Energy Policy, 38*(4), 2053–2062.
Van der Vleuten, E., & Lagendijk, V. (2010b). Transnational infrastructure vulnerability: The historical shaping of the 2006 European "Blackout". *Energy Policy, 38*(4), 2042–2052.
Wachs, T. D. (1979). Proximal experience and early cognitive-intellectual development: The physical environment. *Merrill-Palmer Quarterly of Behavior and Development, 25*(1), 3–41.
Web of Science (2018). *Results analysis for TOPIC: Extreme event.* Retrieved 24 October 2018, fromhttp://wcs.webofknowledge.com/RA/analyze.do?product=WOS&SID=E5y6M5VtaP9rxjJupWV&field=PY_PublicationYear_PublicationYear_en&yearSort=true.
Weekley, E. (1921). *Extreme. An etymological dictionary of modern English.* London: John Murray.
WEF (2018). *The global risks report 2018*(13th edition). Cologny/Geneva, Switzerland: World Economic Forum.
Wickson, F., Carew, A. L., & Russell, A. W. (2006). Transdisciplinary research: Characteristics, quandaries and quality. *Futures, 38*(9), 1046–1059.
Wilson, C., & Mitchell, J. (1987). Simulated climate and CO2—Induced climate change over Western Europe. *Climatic Change, 10*(1), 11–42.
Wolman, M. G., & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. *The Journal of Geology, 68*(1), 54–74.
Yamashita, K., Joo, S. K., Li, J., Zhang, P., & Liu, C. C. (2008). Analysis, control, and economic impact assessment of major blackout events. *International Transactions on Electrical Energy Systems, 18*(8), 854–871.
Zedler, P. H., Gautier, C. R., & McMaster, G. S. (1983). Vegetation change in response to extreme events: The effect of a short interval between fires in California chaparral and coastal scrub. *Ecology, 64*(4), 809–818.