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Research frontiers in climate change: Effects of extreme meteorological events on ecosystems

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Abstract

Climate change will increase the recurrence of extreme weather events such as drought and heavy rainfall. Evidence suggests that modifications in extreme weather events pose stronger threats to ecosystem functioning than global trends and shifts in average conditions. As ecosystem functioning is connected with ecological services, this has far-reaching effects on societies in the 21st century. Here, we: (i) present the rationale for the increasing frequency and magnitude of extreme weather events in the near future; (ii) discuss recent findings on meteorological extremes and summarize their effects on ecosystems and (iii) identify gaps in current ecological climate change research. ***To cite this article: A. Jentsch, C. Beierkuhnlein, C. R. Geoscience 340 (2008).***

Résumé

Limites de la recherche dans le domaine des changements climatiques : effets des évènements météorologiques extrêmes sur les écosystèmes. Les changements du climat vont augmenter la récurrence des évènements météorologiques extrêmes tels que sécheresse et pluviosité intense. Il est suggéré qu'à l'évidence, les modifications des évènements météorologiques extrêmes menacent le fonctionnement des écosystèmes de façon plus drastique que les tendances et les glissements dans des conditions moyennes. Comme le fonctionnement des écosystèmes est connecté aux services écologiques, des retombées sur les sociétés sont prévisibles au XXI[e] siècle. Dans l'article sont présentés le rationnel pour une fréquence et une magnitude croissantes des évènements météoriques extrêmes dans un futur proche ; une discussion à propos de récentes découvertes sur les évènements météorologiques extrêmes et un sommaire de leurs effets sur les écosystèmes ; une identification des lacunes existant dans la recherche sur le changement de climat et ses implications écologiques. ***Pour citer cet article : A. Jentsch, C. Beierkuhnlein, C. R. Geoscience 340 (2008).***

Keywords: Biodiversity; Drought; Precipitation; Experiment; Ecosystem service

Mots clés : Biodiversité ; Sécheresse ; Précipitations ; Expérimentation ; Service des écosystèmes

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1. Climate change and the growing importance of extreme weather events

For the near future, a considerable increase in the frequency and magnitude of weather extremes has been predicted over a broad range of ecosystems across all continents [21,22]. Considering a given probability distribution of occurrence for any climatic parameter, changes in mean values such as increased temperature, as well as increased variance in amplitude, will inevitably lead to more frequent and more intense extreme events at one tail of the distribution ([39]; Fig. 1). Extremes at the minimum end of a given parameter will virtually disappear when climatic mean values increase, whereas historically unprecedented intensities will arise at the maximum, so that biota will face novel events and habitat conditions. Although there is a high degree of uncertainty regarding the details of a changing climate, we propose that extreme climatic events might have a greater influence on ecosystems and societies than gradual shifts and trends of mean temperatures and the precipitation regime [13,27]. Globally, the risk of natural hazards will increase. In Europe, severe floods and erosion, winter storms and summer heat waves are expected to occur more frequently [7]. Over recent decades, evidence of increases in extreme weather events such as hurricanes, droughts, heat waves and heavy precipitation events has accumulated. However, science has not yet generated sufficient knowledge on the effects of extreme weather events on ecosystems and their functioning [27], in order to advise society on coping and adaptation strategies.

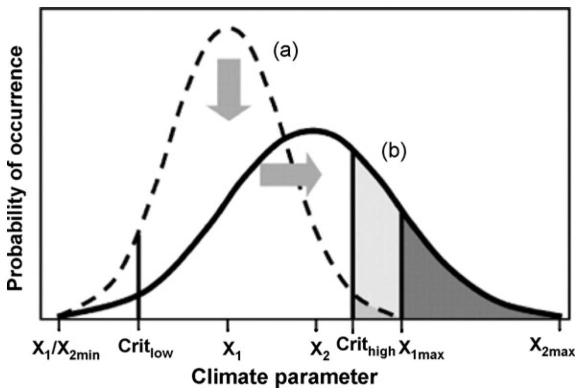

Fig. 1. Future climate changes are expected to be accompanied not only by a shift in mean values (e.g., in temperature) but also with increasing temporal variability. Hitherto, rare extreme events are likely to become more frequent (light grey). Additionally, novel extremes are expected (dark grey). Low critical temperatures that may control the occurrence of pest species will decline (based on [40]).

Les changements climatiques futurs devraient être accompagnés, non seulement par un glissement des valeurs moyennes (par exemple, en température), mais aussi par une variabilité croissante avec le temps, d'où les rares évènements extrêmes devraient devenir plus fréquents (gris clair). En outre, de nouveaux extrêmes sont attendus (gris foncé). Les températures critiques basses qui peuvent entrer en jeu dans la lutte phytosanitaire vont diminuer (d'après [40]).

1.1. Cyclones

The maximum wind speed, the intensity and the duration of hurricanes have increased [14,31,53]. Some previously unaffected regions can now be reached by hurricanes (Canary Islands on 22 November 2005). It is very likely that return intervals that are currently calculated on the basis of historical records will no longer apply. Return intervals represent the potential time frame for ecosystem recovery. However, the predictability of cyclone activity is low. The year 2005 was the most active hurricane season according to the number and intensity ever recorded. The year 2006 was a rather normal if not quiet year in the North Atlantic Ocean. Many coastal regions in the subtropics and tropics will have to adapt to these developments. Tremendous risks exist due to the fact of dense coastal settlement and the concentration of megacities in coastal areas.

1.2. Drought and heat waves

Drought is affecting vast surface areas of the continental subtropics, and therefore plays a significant role spatially. At the global scale, an increase in precipitation is expected as the turnover of the water cycle is stimulated by global warming. Regionally, precipitation patterns will react differently. Heat waves and drought events are expected to increase for parts of Africa [42] where ecological and social resilience is already threatened. Migration processes are stimulated when the supply of drinking water and food is no longer sufficient to maintain social or even political structures and oncoming shortages in the food and water supply might spark off latent ethnic conflicts. Aggression or even wars could result in war-torn regions abandoned by refugees. However, increasing drought will not be limited to arid and semiarid climates. Previously, rather constant and humid tropical ecosystems, such as the vast Amazon rainforest, are expected to suffer from a temporarily limited water shortage. Degradation and even the breakdown of tropical rainforests are predicted [20] and a loss of biodiversity is likely. Global repercussions on the precipitation regime and on the

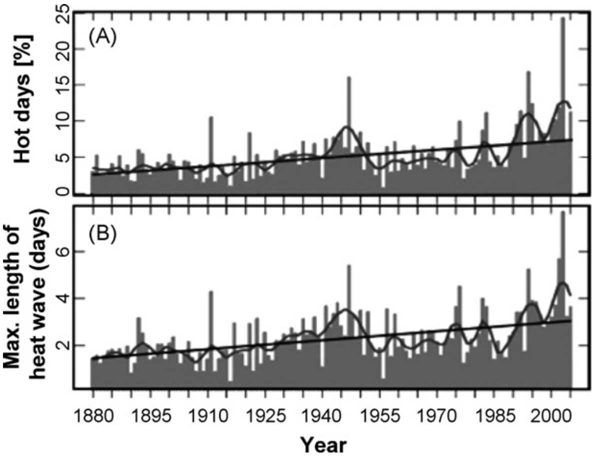

Fig. 2. Percentage of warm summer days (A) and the maximal length of heat waves (B) over the last 120 years. Data are based on sources from central European weather stations (modified from [12]).
Pourcentage de journées estivales chaudes (A) et longueur maximale des vagues de chaleur (B) sur les 120 dernières années. Les données sont basées sur des sources en provenance de stations météorologiques d'Europe centrale (modifié d'après [12]).

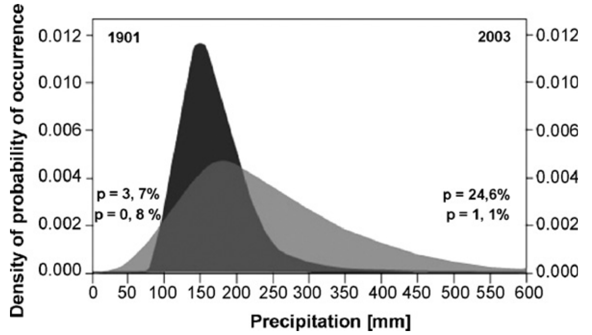

Fig. 3. Alterations in the density of probability of occurrence of winter precipitation in central Europe (Weather Station Eppenrod) during the last century, with respect to 5% and 95% percentile. Strong precipitation events (amount of precipitation greater than 300 mm) became more likely between 1901 and 2003. Also, the variability of the density curve (amount of precipitation less than 100 mm) increased substantially (modified from [52]).
Changements dans la densité de probabilité d'observation des précipitations hivernales en Europe centrale (station météorologique Eppenrod) pendant le siècle dernier, en percentile 5 et 95 %. Des évènements pluvieux intenses (taux de précipitation supérieur à 300 mm) ont été plus probables entre 1901 et 2003. La variabilité de la courbe de densité (taux de précipitation inférieur à 100 m) a augmenté substantiellement (modifié d'après [52]).

carbon cycle are expected [8]. An extension of hot spells is also reported for moderate climates (Fig. 2). In Central Europe, such spells have doubled in length over the last 120 years [12].

1.3. Heavy rainfall and flooding

With ongoing climate change, a divergence of precipitation patterns is predicted [21,22]. Some biogeographic regions of the world will experience more annual precipitation and a more regular seasonal distribution of rainfall events, while other areas will experience less annual amounts of precipitation and a higher variability in rainfall events. In the latter case, in particular, the frequency of very heavy rainfall will increase. For example, the likelihood of extreme precipitation events in Central Europe has shifted from 1.1% in 1901 to 24.6% in 2003 (Fig. 3; [52]). Frequently, such events are accompanied by extreme flooding. However, human perception tends to overestimate natural hazards that affect people directly such as flooding. Even if there have been some very remarkable flood events in large valleys of continental Europe, their frequency and magnitude does not yet exceed that from the historical record and probability [18,46]. The multidecadal variance in the frequency of flood events is driven by a complex network of external factors including atmospheric circulations [24].

2. Effects of meteorological extremes on ecosystems

The ecological effects of extreme events have been identified as one of the main gaps of knowledge in community ecology [1]. Evidence suggests that vegetation reacts to severe weather events depending on many environmental factors [45], as well as to species diversity [30], functional diversity [33,34] and timing during succession [51]. With global climate change, there is an increasing number of ecosystems that are experiencing weather events of novel magnitudes, with timing and durations that are out of synchrony with the stress thresholds of organismic communities [39,47]. Plant communities and ecosystems that suffer from a single event can rapidly switch into alternative ecological regimes [38,48]. The thresholds of ecosystem shift however are unclear.

Over the last 20 years, key findings on the ecological effects of extreme weather events have accumulated. These include effects on diversity, productivity, reproduction, phenology, nutrient cycling and community resistance to invasion. For example, alterations to species compositions of plant communities after severe drought events [35,49], heavy rainfall events [3,10] and heat waves [54] have all been documented. Shifts in plant phenology due to rain and drought events have been observed [16,28,36].

However, the effects from drought, heat, rain and frost on community productivity appear to be controversial. While many experimental studies report reduced aboveground productivity due to extreme weather events [15,17,37,43,56] and reduced belowground productivity due to extreme weather events [2,4], other studies have found productivity to remain surprisingly stable [32,33] in the face of simulated 100-year extreme weather events. However, it is important to realise that global biomass production has increased considerably over recent decades and any long-term comparisons need to be adjusted to account for this trend.

Soil biotic processes have only been partially investigated. Case studies report an astonishingly low impact from drought and heavy rainfall [32]. Evidently, soils are able to buffer short-term extremes at the surface. Nevertheless, drought enhanced carbon uptake in experimental grassland [41]. Generally, it is expected that climate warming will increase soil fauna activity and microbial enzymatic activity, therefore also increasing decomposition rates.

In contrast, the resistance of communities against invasions can be significantly and divergently altered by drought and heavy rainfall events [34], with drought decreasing and heavy rain increasing invasion rates. This is in accordance with the "fluctuating resources hypothesis" [10]. Finally, the reproductive success of plants will also be influenced by climatic extremes as it appears to be reduced after heavy rainfall, heat waves and drought [49].

Long life cycles and a limited dispersal potential of particular species may delay or slow down a rapid adaptation to changing environments. Considering the fact that global climate change is proceeding within decades, many woody species are living over much longer time periods. It is part of their strategy to cope with suboptimal phases and react for example by simply reducing reproduction effort. It is very likely that many biotic communities will perform inertia to the shift in species composition and delay natural adaptation towards more competitive communities from a long-term perspective. This in turn may promote a loss of biodiversity and bring about the above-mentioned restrictions in ecosystem functioning and resilience. Here, extreme weather events (storms, fires, floods) may remove this ecological inertia enabling species that are nonnative but better adapted to the novel environment to establish [26].

Interactions in ecological communities must also be considered as these might reverse trends that reflect climate warming. At the ecotone between the Atlantic boreal forests and the Arctic tundra, birch forests (*Betula pendula*) predominate. These forests would tend to extend northwards when warming takes place; however, warming may also stimulate the gradations of herbivorous insects (e.g., *Epirrita autumnata*). Until now, insect outbreaks have been cyclic with return intervals of nine to 10 years and the rejuvenation of completely defoliated birch stands possible [51]. If the frequency of outbreaks was increased, this could result in a southward shift of the boreo-arctic ecotone. Recently, it was shown that outbreaks of *Epirrita autumnata* moved as a result of a warmer climate into areas in Northern Norway, where they had not previously been recorded [29].

Weather extremes can have far reaching impacts on human communities by altering the performance of ecosystem services [44]. For example, in northern New Mexico, an ecotone shift as a consequence of only one severe drought event [9] resulted in accelerated soil erosion. This example illustrates just how regime shifts may have significant impacts on ecological services such as the protection of soil surfaces [19]. There, additional disturbance interactions were caused by the drought event such as infestations of bark beetles.

3. Gaps in ecological climate change research

Understanding the factors governing the response of biodiversity to extreme weather events will increase our ability to predict the future behaviour of ecosystems. This is one of the forthcoming great challenges in the life and environmental sciences. There is a substantial lack of knowledge on how extreme weather events affect biodiversity and ecosystem functioning. Here, we discuss emerging research challenges including:

- extreme weather events in climate models and databases;
- the significance of extreme weather events for local establishment and extinction;
- the modulating role of event regimes and biodiversity for community dynamics;
- ecological inertia, induced tolerance and regeneration dynamics after extreme weather events;
- the effects of extreme weather events on ecosystem functioning.

3.1. Climate models and databases

A major challenge in studying the effects of extreme weather events on ecosystems lies in the very nature of such phenomena. Extreme weather events are relatively rare in occurrence, their effects are out of proportion to their short period of duration and their predictability is low [25]. Moreover, extreme weather events are hardly ever explicitly addressed in current numerical climate models. This may be due to the fact that causal explanations for connections between large-scale climatic circulation patterns and the local occurrence of extreme weather events (downscaling) are still missing [7]. Moreover, a comprehensive database on extreme weather events of consistent data quality with high temporal and spatial resolution spanning long time scales is not available. Strong events of supraregional and global extent have only been well documented for recent decades and going further back in history, only rough proxies indicate the importance of large floods, storms or fires. Thus, ecologists have started to perform experimental climate change research by simulating extreme weather events and studying their effects on ecological processes, biotic interactions and ecosystem functions [5,17,27].

3.2. Species establishment and extinction

A further research gap is the role of extreme weather events for the local establishment and extinction of species. The rules of species composition and hence management decisions in restoration ecology can be influenced substantially by weather event regimes. Recruitment events can be bound to extreme conditions. Rare events of overgrazing can create open soil and safe sites for the germination of species with low competitive capacity such as *Gentiana ciliata* in Central European limestone grasslands. In the understory of many forests, only a few cohorts of tree species populations exist even when light is sufficient. This again indicates the importance of temporal irregularities. However, it is difficult to associate cause and effect due to insufficient data. Another example is the extensive planting of trees in semi-arid areas of Peru, which proved to fail in all years except for El Nino years when extraordinary high amounts of precipitation occurred during the sensitive growth and establishment phases of the introduced tree individuals. In such a climate, pulses of precipitation also enhance biomass growth and reproduction for the native vegetation.

3.3. Community dynamics and diversity

Evidence is required for the modulating role of event regimes on the competitive balance in plants, on plant–animal interactions including herbivory and pollination, on functional trade-offs between various plant growth forms, between above and below ground dynamics or between microbial communities and higher organisms (compare [50]). For example, during a drought event, deep-rooting plants can provide a ‘hydraulic lift’ resulting in increased water availability in higher soil horizons for shallow-rooting plants [11,23]. Here, the diversity of various growth forms can act as an insurance effect in the face of extreme events. Until now, knowledge is lacking on the relative importance of redundancy versus complementarity for functional stability under novel extremes.

3.4. Ecological inertia and regeneration dynamics

A fundamental research question deals with the role of inertia in established biotic communities. We do not have a satisfactory understanding of the speed or time lag with which biotic communities of different taxa can evolve or respond when subjected to sudden environmental change. The concept of ‘‘disturbance-induced community tolerance’’ points to the importance of history in climate change experiments. Where is the limit of tolerance of biocoenoses to new climatic conditions and event regimes that have established under prior climatic conditions? Will disturbance events function as a catalyst of change? Most species and ecosystems are prone to a certain degree of variability in conditions. Here, an important research gap is the effect of weather dynamics beyond historical contingency on the performance of species within communities, i.e., their competitive ability or reproductive fitness. Evidence suggests, for example, that the potential distribution of the European beech (*Fagus sylvatica*) is limited by the occasional occurrence of late frost events in early summer rather than by mean annual temperature. On the other hand, the population dynamics of insects are equally limited by the occurrence of extreme weather events. Hence, missing cold events in the near future can lead to insect pest outbreaks of an unprecedented magnitude. The implications of such a scenario are uncertain but a lot of research has demonstrated synergistic effects between insect calamities and catastrophic fire events [40]. Nevertheless, the significance of extreme weather events on regeneration dynamics and ecosystem trajectories is barely understood.

3.5. Ecosystem services

For the effects on mankind, it is most relevant to address research gaps in the effects of extreme weather events on ecosystem functioning, resilience and the performance of ecological services. Currently, most scientific activities in ecological climate change research focus on the effects of climate warming and increasing atmospheric carbon dioxide levels on plant productivity in grasslands [27]. Analyzing the effects of extreme weather events on ecosystem functions such as disturbance regulation, water regulation, erosion control, nutrient retention, pollination and biological control will assist in developing adaptation strategies for society and mankind.

Most research on ecosystem services is connected to the loss of biodiversity. The biodiversity–ecosystem functioning debate has stimulated ecological theory [6]. However, the roots of this stem from the anxieties that were caused when the ''biodiversity crisis'' was recognised [55]. A loss of biodiversity was mainly related to land use, habitat loss and fragmentation. Nowadays, we have to come to terms with the fact that climate change is becoming a more and more important driver of ecosystem functioning. Additionally, it can have a strong impact on biodiversity and theory suggests that positive effects of biodiversity happen, when the environment is changing [57]. Nevertheless, all of these concepts do not integrate short-term extreme events. In the face of prognoses that point to a greater significance of such events, research that integrates various levels of biodiversity and extreme events is urgently required.

Landscapes where ecosystems predominate that show low resilience towards extreme events and yet deliver important ecosystem services to mankind have to be identified. These areas are highly vulnerable and may result in catastrophic regime shifts connected with threats to human lives and political stability. Currently, we do not have the sufficient ecological knowledge to detect ecosystems that might crash or develop in a way that could be harmful to local people. However, ecosystem traits such as biodiversity and turnover rates can be used to indicate forthcoming risks.

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