much dispersal and mixing had already occurred. Hence, their three cruises were designed to cover a much greater geographic area. Some of their findings are in broad agreement with those of their colleagues: gas represented about half of the pollutant input, although Kessler and colleagues estimated a somewhat lower total gas release of roughly 200,000–250,000 tons. And mid-water intrusion layers were identified by anomalies in dissolved oxygen concentrations and fluorescence, which reveals the presence of residual oil. Kessler and colleagues found no elevated concentrations of methane, however.

Available measurements of sea–air methane fluxes did not indicate a significant transfer of the gas to the atmosphere. The gas that was accidentally released and trapped in Gulf waters must therefore have been entirely consumed by oxidation. Estimates of methane consumption from integrated mid-water deficits in dissolved oxygen concentrations match their calculations of the amount of gas released into the mid-water layers, suggesting that all the methane was probably used up by microorganisms. In a further line of evidence, Kessler and co-workers cloned and sequenced bacterial populations from their water samples, and confirmed a strong community shift toward methanotrophs. These organisms generally represent a tiny proportion of all microbes. Hence, the data identified the remnants of a methanotroph bloom that thrived when methane concentrations reached extraordinarily high levels. Interestingly, observed depletion of local oxygen did not exceed about 20%; in fact, oxygen levels in affected waters remained much higher than in the 400–500-m depth range, where an oxygen minimum naturally occurs.

Notably, the findings by Kessler and colleagues suggest that a large amount of gaseous pollutants was scrubbed from the water within only about 120 days from the start of the spill, with apparently minor implications for marine oxygen levels. In worst-case scenarios of the potential climate impacts of massive methane injections, the dissolution and oxidation of seafloor methane through the oceanic water column has not always been taken into account[3]. In the Gulf last year, these phenomena seem to have largely prevented the spilled gas from escaping to the atmosphere, and therefore from unfolding any climatic relevance.

As ever, more data are required to construct reliable models of the potential climate impacts from deep-sea methane releases. Specific methane oxidation rates of up to 0.15 per day have been measured[4] near hydrothermal seafloor vents, and Kessler and colleagues propose a similar maximum value of 0.2 per day estimated from a simple model. However, methane oxidation rates reach a limit at very high methane concentrations. If sufficiently large releases of the gas occurred, microorganisms would not be able to keep up, and some greenhouse gas could be released to the atmosphere. Determining just how much methane can be oxidized within the water column will need better observational constraints.

Together, the studies by Kessler *et al.*[1] and Joye *et al.*[2] may create the general impression that nature took care of the spill, at least as far as gas is concerned. Nevertheless, the studies should not lead to too much optimism. Although it is true that eventually nature can cope with almost whatever humans do — be it oil spills or greenhouse gas emissions — the environmental and economic costs incurred in the process could be enormous. ❒

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References

1. Kessler, J. D. *et al. Science* **331,** 312–315 (2011).
2. Joye, S. B., MacDonald, E. R., Leifer, I. & Asper, V. *Nature Geosci.* **4,** 160–164 (2011).
3. Harvey, L. D. & Huang, Z. *J. Geophys. Res.* **100,** 2905–2926 (1995).
4. de Angelis, M. A., Lilley., M. D., Olson, E. J. & Baross, J. A. *Deep-Sea Res. I* **40,** 1169–1186 (1993).

CLIMATE SCIENCE

Elusive extremes

Extreme climate events can cause widespread damage and have been projected to become more frequent as the world warms. Yet as discussed at an interdisciplinary workshop, it is often not clear which extremes matter the most, and how and why they are changing.

Gabriele C. Hegerl, Helen Hanlon and Carl Beierkuhnlein

Changes in the frequency, intensity and timing of climate extremes matter to ecosystems and society. Characterizing such changes and their impacts is a challenge, not only for climate scientists but also for statisticians, ecologists and medical scientists. The impacts of rare climate events can be difficult to detect, for example when they arrive with significant delay. To complicate matters further, combinations of extreme climate events — such as heatwaves coinciding with droughts or air quality problems — could cause more severe consequences for humans and ecosystems. At a conference in Cambridge on 'Extreme Environmental Events' in December 2010[1] that brought together climate scientists, statisticians and ecologists, the conclusion evolved that useful prediction of climate change impacts hinges on understanding the right types of extremes, and then producing reliable projections for their changes.

Weather and climate extremes are usually defined as rare events in the context of historical climate data. Alternatively, weather events can be classified as extreme according to the amplitude of their impacts on society or ecosystems. The Russian heatwave of 2010 and the European heatwave of 2003 fulfilled both criteria: they were climatically highly unusual[2], and at the same time had substantial consequences for human health and ecosystems.

Extreme events can span a wide range of spatial and temporal scales. For example, storms are usually short-lived and occur over only a few hours, whereas a drought can extend over months. In the spatial domain, they can range from an anomalously warm summer or cold winter diagnosed on a continental scale, to events such as a hail storm that affect only a small region. When defining extremes, it is therefore easy to drown in choices. It is not obvious whether it is the frequency, intensity or duration of an extreme event that matters — or a combination of all three. Impact researchers may be able to guide the choice of characteristics that matter for society and ecosystems.

The difficulties in framing a useful definition of extreme events proved to be a central theme at the Cambridge conference[1]. Once extremes are characterized, extreme value theory is very effective for quantifying the risk of highly unusual or large events and determine if this probability is changing. Francis Zwiers (University of Victoria) showed, using extreme value statistics, that some of the recent changes in the distribution of temperature extremes can be attributed to increases in atmospheric greenhouse gas concentrations. However, addressing the statistical likelihood of co-occurrence of combined events is still a challenge (P. Naveau, IPSL–CNRS)[3].

Classification of extremes by their impacts follows different rules. From this perspective, combinations of extremes — such as drought and heat — demand particular attention, because they can have much more severe impacts than an extreme in either of the components (A. Jentsch, University of Landau). Nor are the impacts of extreme events necessarily negative: in Arctic ecosystems, for example, unusually warm temperatures that would be considered extreme from a statistical point of view can cause a (short-lived) rise in biological productivity (I. Nijs, University of Antwerp). These effects are harder to analyse on a global level than the statistical aspects of extremes: the impact of a climate event will depend on each ecosystem's physiological threshold against heat, cold or the ability to store water, and the timing of the event in the seasonal cycle.

Perhaps most surprisingly, extremes can bring about long-term changes in vegetation similar to changes that are usually caused by slow shifts in climate over an extended period. A fascinating example is a windstorm that swept over Sweden in the late eighteenth century and triggered a long-lasting transition from mixed forest to pine forest (B. Huntley, University of Durham). Thus, the ecosystem response to long-term climate change can be difficult to distinguish from responses to individual extreme events. Also, a single climatic event can trigger the transition of ecosystems to gradual climate changes, which the inertia in the system may have delayed[4].

Trends in the environmental background will invariably affect the statistical threshold for classifying an event as extreme, because extremes are defined as rare events in comparison with a reference sample or data set. But events that are quite rare at present could become more common in the future, whereas conditions that are currently observed frequently could turn more exceptional. For example, future climate projections suggest that as heatwaves increase in number and intensify in Europe, impacts on human health will become more severe (E. Fischer, ETH Zurich)[5]. Yet these harmful events would no longer be extreme from a statistical point of view, just because they occur more often. Predictions of changes in the probability of extreme events rely on models that still struggle with the simulation of short-term or small-scale extremes. Detection and attribution are necessary to evaluate the models' ability in simulating past changes in extreme events[6].

Extreme meteorological events are generally linked to specific weather situations. For example, a high-pressure system that blocked off low-pressure systems bearing rain and clouds triggered the Russian heatwave in summer 2010. This unusual weather situation led to extremes in other regions as well (O. Martius, University of Bern). One possible reason for shifts in the probability of extreme events in a warming climate is a change in the frequency of the meteorological large-scale patterns that are conducive to these extremes. Alternatively, the strength of extremes occurring with any of these large-scale patterns can change owing to global warming. For example, heavy rainfall can intensify when more moisture becomes available. Studying the relative risk of extreme events with and without rising atmospheric greenhouse gas concentrations, as performed for the 2003 European heatwave[7], is at present the best method of unravelling how and to what extent climate change may have contributed to a given extreme event.


CARL BEIERKUHNLEIN

Figure 1 | Caused by the heatwave and drought period in summer 2003, deciduous trees suffered extraordinary leaf damage in large parts of central Europe. At a conference on 'Extreme Environmental Events' in December 2010 such extreme events were discussed, along with their impacts and potential changes in their frequency in response to global warming.

In a final complication, a rise in the frequency and amplitude of extreme events is likely to have non-linear effects on ecosystems: more frequent events may exceed the resilience capacity of an ecosystem and cause breakdown and loss of functionality, or could lead to adaptation and a decline of sensitivity.

One conclusion of the Cambridge conference[1] on extreme environmental events came across clearly: it will be a while before research on shifting climate extremes and their impacts on ecosystems and society will cease to surprise and fascinate, but also to puzzle and confuse. ❐

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References

1. http://www.esf.org/index.php?id=7048
2. Schär, C. *et al. Nature* **427,** 332–336 (2004).
3. Naveau, P., Gouillou, A., Cooley, D. & Diebolt, J. *Biometrika* **96,** 1–17 (2009).
4. Jentsch, A. & Beierkuhnlein, C. *C. R. Geosci.* **340,** 621–628 (2008).
5. Fischer, E. M. & Schär, C. *Nature Geosci.* **3,** 398–403 (2010).
6. Stott, P. A. *et al. WIREs Clim. Change* **1,** 192–211 (2010).
7. Stott, P. A. & Trenberth, K. E. *Eos* **90,** 184 (2009).