www.math.rug.nl/broer/

university of groningen

# Averting a storm?

Dr Peter Stott, Head of Climate Monitoring and Attribution at the Met Office Hadley Centre details how climate change has affected extreme weather worldwide...

There has been no shortage of extreme weather in recent years. For example, last year Australia recorded its hottest year on record. Early this year, many parts of the Eastern US endured weeks of extreme cold, while in the UK we had the wettest winter in England and Wales since records began in 1766. How has climate change affected extreme weather and is it still possible to avoid the worst effects of climate change in future?

The recent report from the Intergovernmental Panel on Climate Change, Climate Change 2013: The Physical Science Basis ( www.climatechange2013.org ) provides a comprehensive assessment of the physical science basis of climate change. It concludes that warming of the climate system is unequivocal and, since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and oceans have warmed, snow and ice have diminished, the sea level has risen, and the concentrations of greenhouse gases have increased. Climate extremes have also changed. There is robust evidence that the frequency of heat waves has increased in large parts of Europe, Asia and Australia and that the frequency of heavy precipitation events has increased in North America and Europe.

What has caused these changes? The atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased to levels unprecedented in at least the last 800,000 years. These increases, resulting from human emissions, enhance the natural greenhouse effect and cause additional warming of the climate system. Observed patterns of warming of the atmosphere and the ocean are consistent with those expected from this additional greenhouse effect and are not consistent with the patterns of temperature expected from natural causes. The IPCC report concluded that human influence on the climate system is clear.

What can we say about individual weather events? Unusual extremes have always happened in our variable climate and

it can be tempting to put the entire blame of a particular heat wave or cold snap on either human-caused climate change or natural climate variability. But the reality is usually that both played a role. It is helpful therefore to consider how anthropogenic factors have changed the risk of such events. This is done by conducting climate model experiments in which simulations are made of the world as it would have been had greenhouse gas concentrations and other human factors on climate not changed. Such attribution studies have shown that human-caused climate change increased the risk of the extreme temperatures seen in Europe in 2003, which brought many thousands of heat-related deaths. Human influence also substantially increased the risk of the record Australian temperatures seen in 2013 which brought devastating forest fires and the destruction of many homes. The risk of such catastrophic heat waves is set to increase with continued emissions. Climate model simulations indicate that by the 2040s half of summers in Europe could be warmer than 2003. With continued greenhouse gas emissions, such summers would be classed as unusually cool relative to the new climate of the end of this century.

"Observed patterns of warming of the atmosphere and the ocean are consistent with those expected from this additional greenhouse effect and are not consistent with the patterns of temperature expected from natural causes."

It is more challenging to determine how much human-induced climate change might have affected the risk of the extreme rainfall and floods seen in the UK this winter. British rainfall varies hugely because our weather patterns are constantly changing. While there may be more moisture feeding storms when they form, the North Atlantic jet stream, the high level ribbon of air that steers our weather systems, could be varying. Further research is needed to better understand these processes and better characterise our changing risk to such wet winters. At the Met Office we are leading a new European project called EUCLEIA (www.eucleia.eu) which aims to develop an attribution system to deliver reliable and user-relevant attribution assessments of recent extreme weather events. Such information will be useful in planning for and adapting to future extreme weather.

While we need to plan for further increases in the risk of extreme weather, the science shows it is still not too late to avoid the worst consequences of human-induced climate change. The latest IPCC report states that aggressive reductions in emissions can make a large difference to changes in climate expected during the latter part of this century and beyond. Such reductions could limit the extent to which hitherto rare extremes such as severe heat waves, floods and droughts become increasingly common. Limiting future emissions will also reduce the risk of large releases of greenhouse gasses from melting permafrost and reduce the risk of very rapid rises in sea level from accelerated melting of the ice sheets in Greenland and Antarctica. However, limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

Dr Peter Stott is the Coordinating Lead Author of one of the chapters of the IPCC Working Group I report on "Climate Change 2013: The Physical Science Basis". For ease of reference the chapter is 10 on "Detection and Attribution of Climate Change : from Global to Regional"

(http://www.climatechange2013.org/images/report/WG1AR5_Chapter10_FINAL.pdf)

**Dr Peter Stott**
**Head of Climate Monitoring and Attribution**
Met Office, Hadley Centre
Tel: 0870 900 0100
www.metoffice.gov.uk

# The sting *is in the tail*

## Weather extremes

Extreme weather events may cause severe damage to our society. Examples are hurricane Sandy in 2012 (the second-costliest hurricane in United States history), European windstorms Lothar and Martin in 1999, and, more recently, the exceptional sequence of floods in southern England in the winter of 2014. Insurance companies need to reserve sufficient capital to cover claims following an extreme weather event. Estimates of expected losses due to catastrophic events crucially depend on the tail width of the probability distribution describing the likelihood of extremes. Hence, understanding the typical tail behaviour of time series generated by climate models is a pressing challenge for the insurance industry and forecasting agencies.

## Our research

The Johann Bernoulli Institute for Mathematics and Computer Science (JBI), based at the University of Groningen, actively participates in current mathematical research on extreme events. The mission of the JBI is the cross-fertilization by modelling of the disciplines mathematics and computer science both with other sciences and with the outside world.

Prof Henk Broer is an internationally renowned expert in Nonlinear Dynamical Systems. Dr Alef Sterk has worked on the mathematical analysis of climate models. We collaborate with Dr Renato Vitolo, Dr Mark Holland (Exeter), and Dr Pau Rabassa (London) who provide us with expertise on climate modelling and ergodic theory. Prof Carles Simo (University of Barcelona) complements our research with state of the art numerical methods for deterministic systems and background mechanisms. We are embedded in a larger, international network of scientists working on extreme events and its applications to climate science.

### Mathematical climate modelling

Mathematical modelling offers a fruitful approach towards an understanding of meteo-climatic extremes. Models for the atmospheric and oceanic circulation are typically derived from first principles, such as Newton's laws, conservation of energy, global balances, etc. This approach leads to deterministic evolution laws in which the present state of the system completely determines its future.

However, since the seminal work of the mathematician and meteorologist E.N. Lorenz in the 1960s it is well known that even deterministic systems can be very unpredictable: small perturbations in the initial state may lead to large differences in later states, see Figure 1. This phenomenon, which is colloquially known as the butterfly effect, hampers long-term weather forecasts and triggered the development of mathematical research on nonlinear dynamics and chaos theory.

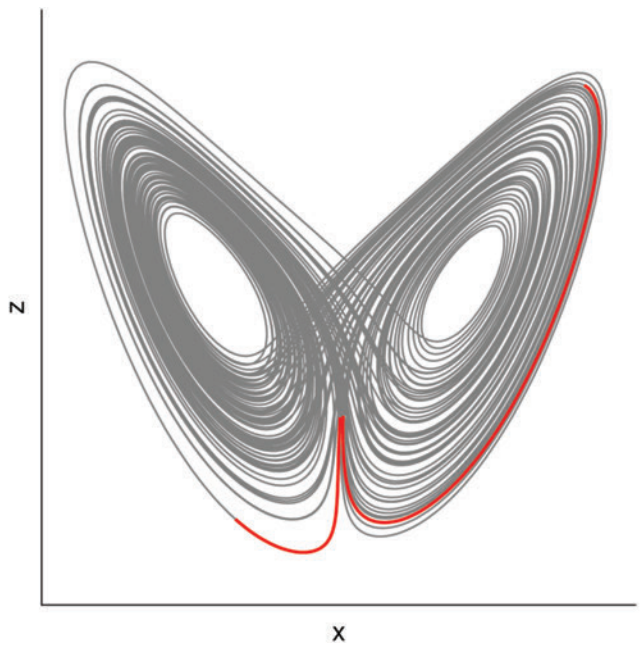


***Figure 1: Butterfly shaped attractor which appears in Lorenz' simplified model for atmospheric convection. Two evolutions starting at nearby initial conditions can separate exponentially fast. This phenomenon hampers long-term weather forecasts and triggered the development of the mathematical theory of nonlinear dynamical systems and chaos.***

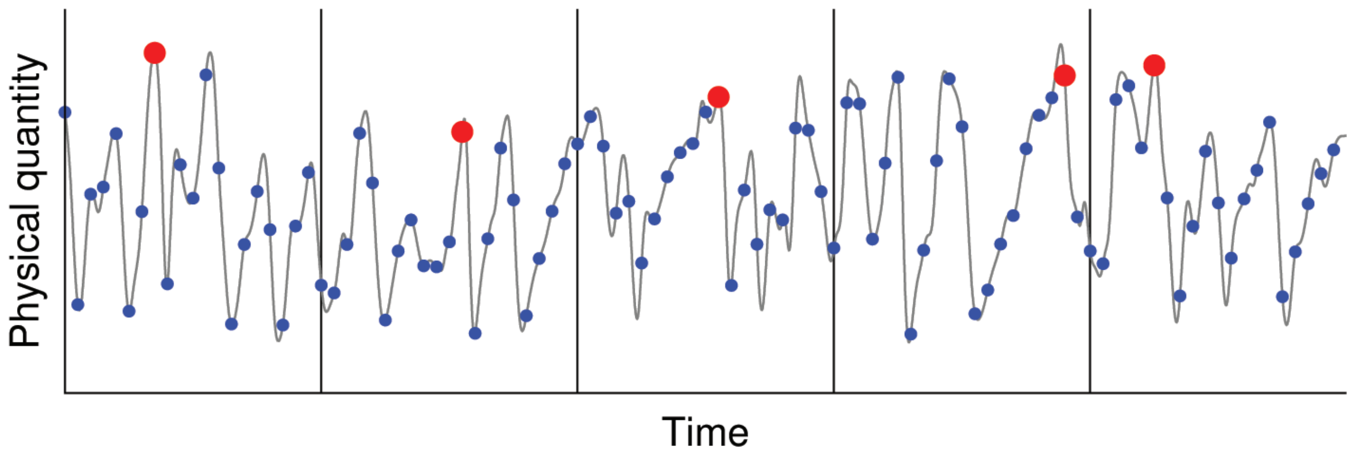


*Figure 2: Illustration of the block maximum method. A time series is divided into sufficiently long blocks and over each block the maximum value is computed (red dots). From these block maxima the parameters of an extreme value distribution can be estimated.*

## Our achievements

Our research is strongly interdisciplinary. Our expertise includes nonlinear dynamical systems, extreme value statistics, and climate modelling. This unique combination enables us to tackle both theoretical and applied problems on extreme weather events.

### Storm clustering

Intense windstorms are a major cause of damage in Europe. Such meteorological extremes may occur in groups (clusters), such as the December 1999 windstorms Anatol, Lothar, and Martin, which produced total damage exceeding $15 B. Such storm clustering is particularly threatening for insurance companies.

We discovered that clustering tends to be stronger for the more intense windstorms over Europe. We analysed how this is related to the time-varying effect of the large-scale atmospheric flow. Specifically, certain features of the atmospheric dynamics, the so-called teleconnection patterns (such as the North Atlantic Oscillation) are found to induce temporal modulation in the windstorm arrival rate. This may lead to the occasional accumulation of several extremes within relatively short time spans.

Analogous explanations have been provided for the clustering of other meteo-climatic extremes, such as intense tropical cyclones (hurricanes, typhoons) and floods, providing enhanced statistical models for the occurrence of such phenomena.

For more details, see:

- R. Vitolo, D.B. Stephenson, I.M. Cook, and K. Mitchell-Wallace. Serial clustering of intense European storms. Meteorologische Zeitschrift 18(4), pp. 411-424, 2009.
- P.J. Mumby, R. Vitolo, and D.B. Stephenson. Temporal clustering of tropical cyclones and its ecosystem impacts. Proceedings of the National Academy of Sciences, 10(43), pp. 17626-17630, 2011.
- G. Villarini, J.A. Smith, R. Vitolo, and D.B. Stephenson. On the temporal clustering of US floods and its relationship to climate teleconnection patterns. International Journal of Climatology, 33(3), pp. 629-640, 2013.

### Estimating the tail index

Classical extreme value theory studies the distribution of large values in time series of independent random variables. Since the early 2000s the theory has been extended to deterministic systems, such as climate models. In this setting the so-called Generalised Extreme Value (GEV) distributions can be used to compute the probability of occurrence of future large values of a quantity, such as wind speed or sea surface level, given a sample of past measurements.

To that purpose one must estimate a couple of unknown parameters of the distribution. Of particular importance is the so-called tail index because it determines the tail width of the distribution, and therefore the frequency and intensity of extreme events. Accurate estimates of the tail index are useful for forecasting agencies like the UK Met Office and the Royal Netherlands Meteorological Institute or reinsurance brokers like Willis Re.

Estimates for the tail index are often obtained by the so-called block maximum method, see Figure 2. In this method one divides a time series, either obtained from data or numerical simulations, in sufficiently long blocks. Under the assumption that the block maxima form a random sample drawn from a GEV distribution the parameters can be estimated using standard statistical methods. Recently, we discovered that the tail index is related to the geometry of the evolutions of the underlying dynamical system, such as the fractal dimension of the attractor. This discovery also explains why sometimes prohibitively long time series are needed to obtain accurate estimates.

For more details, see:

- M.P. Holland, R. Vitolo, P. Rabassa, A.E. Sterk, and H.W. Broer. Extreme value laws in dynamical systems under physical observables. Physica D: Nonlinear Phenomena 241(5), pp. 497-513, 2012.

### Predictability of extremes

We have studied the finite-time predictability of extreme values, such as convection, energy, and wind speeds, in geophysical models. To that purpose we computed the exponential growth rates (Lyapunov exponents) of nearby trajectories over a finite time interval. In general these growth rates strongly depend on the initial condition, see Figure 3.

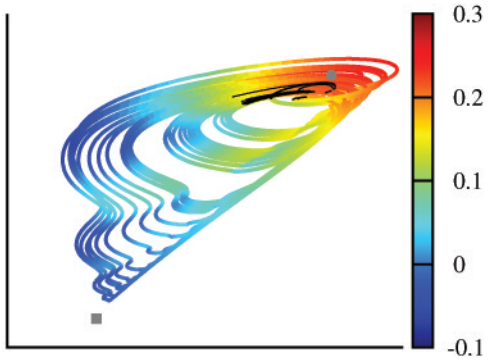


***Figure 3:** The attractor of an atmospheric model. Colours indicate how fast errors in initial conditions can grow, which is a measure of chaos. Black dots indicate initial conditions leading to extreme wind speeds within a fixed time interval. Since these initial conditions have large error growth rates, extreme wind speeds are very unpredictable in this model.*

We studied whether initial conditions leading to extremes typically have a larger or smaller error growth rate. We addressed this question using simplified models for the atmospheric circulation. Our results clearly suggest that the predictability of extreme events strongly depends on the type of event. For example, the predictability of extreme wind speeds strongly depends on the geographical location of interest: extreme wind speeds are typically better predictable in valleys than on mountain tops. This conclusion warrants a further in-depth study on how extreme events depend on landscape characteristics.

For more details, see:

- A.E. Sterk, M.P. Holland, P. Rabassa, H.W. Broer, and R. Vitolo. Predictability of extreme values in geophysical models. Nonlinear Processes in Geophysics 19(5), pp. 529-539, 2012.

## Funding our research

Our past research projects have been funded by the Netherlands Organisation for Scientific Research (NWO) and the Engineering and Physical Sciences Research Council (EPSRC) under the auspices of Complexity-NET. We are interested in new funding opportunities in order to expand our research activities. New projects will lead to novel mathematical techniques for studying extremes in climate models and data. In addition, funding provides the means to educate junior scientists. There are not many mathematicians trained in the application of extreme value theory to climate models and there is a need to increase this pool.

## Contact details

Prof Dr Henk W. Broer
Professor of Dynamical Systems
Johann Bernoulli Institute for Mathematics and Computer Science
**h.w.broer@rug.nl**
**http://www.math.rug.nl/broer/**
**Telephone: +31 50 363 3959**

Dr Alef E. Sterk
Assistant Professor
Johann Bernoulli Institute for Mathematics and Computer Science
**a.e.sterk@rug.nl**

Dr Renato Vitolo
Honorary Research Fellow
University of Exeter
**r.vitolo@exeter.ac.uk**

Dr Mark P. Holland
Senior Lecturer in Mathematics
University of Exeter
**m.p.holland@exeter.ac.uk**

Dr Pau Rabassa Sans
Postdoctoral Researcher
Queen Mary, University of London
**p.sans@qmul.ac.uk**

Johann Bernoulli Institute for Mathematics
and Computer Science
h.w.broer@rug.nl
**http://www.math.rug.nl/broer/**
**Telephone: +31 50 363 3959**