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A decade of weather extremes

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The ostensibly large number of recent extreme weather events has triggered intensive discussions, both in- and outside the scientific community, on whether they are related to global warming. Here, we review the evidence and argue that for some types of extreme — notably heatwaves, but also precipitation extremes — there is now strong evidence linking specific events or an increase in their numbers to the human influence on climate. For other types of extreme, such as storms, the available evidence is less conclusive, but based on observed trends and basic physical concepts it is nevertheless plausible to expect an increase.

For the United States, 2011 was a year of extreme weather, with 14 events that caused losses in excess of US$1 billion each[1]. The US National Oceanic and Atmospheric Administration spoke of "a year seemingly full of weather extremes" after July had set new monthly heat records for Texas, Oklahoma and Delaware[2]. The period from January to October was the wettest on record for several northeastern states, with wet soils contributing to the severe flooding when Hurricane Irene hit the region in August. During spring, the southern United States had been hit by the worst recorded tornado outbreak in history: April saw 753 tornadoes, beating the previous monthly record of 542 (from May 2003) by a large margin[3]. Other regions in the world were affected by extreme weather in 2011 as well: rainfall records were set in Australia, Japan and Korea, whereas the Yangtze Basin in China experienced record drought[1]. In western Europe, spring was exceptionally hot and dry, setting records in several countries (Table 1)[1].

But 2011 was not unique: the past decade as a whole has seen an exceptional number of unprecedented extreme weather events, some causing major human suffering and economic damage[4] (Table 1 and Fig. 1). In August 2010, the World Meteorological Organization issued a statement on the "unprecedented sequence of extreme weather events", stating that it "matches Intergovernmental Panel on Climate Change (IPCC) projections of more frequent and more intense extreme weather events due to global warming"[5]. The Moscow heatwave and Pakistan flooding that year illustrated how destructive extreme weather can be to societies: the death toll in Moscow has been estimated at 11,000 and drought caused grain-harvest losses of 30%, leading the Russian government to ban wheat exports. At the same time Pakistan was hit by the worst flooding in its history, which affected approximately one-fifth of its total land area and 20 million people[6].

The unprecedented meteorological events listed in Table 1 occurred in a decade that was likely the warmest globally for at least a millennium[7]. But are these two observations linked? We focus our discussion on the unprecedented extremes of the past decade, that is, those setting new meteorological records in the observational data available, because these often have the greatest impacts on societies, they grab the headlines and their uniqueness simplifies statistical analysis (compared with analysing extreme events exceeding a given threshold value). A much broader assessment of extreme events by the IPCC[8] was published in March 2012. Unlike our Perspective, this has an emphasis on fixed-threshold extremes, model results and projections of the future, societal impacts and possible policy strategies to deal with extremes. Here, we ask the simpler question of whether the unprecedented extremes observed during the past decade are related to climatic warming. We start with some methodological remarks before discussing specific types of extreme.

Simple physical considerations

For some types of extreme, there are simple physical reasons why they would increase in a warming climate. If the average temperature rises, then obviously so will the number of heat records, all else remaining equal. Cold extremes will decrease, but if the probability distribution for temperature is shifted unchanged towards warmer conditions, the total number of extremes (hot plus cold) will increase[9]. That is fundamentally because what is considered extreme is always based on past experience, and a change in climate moves us out of the familiar range.

Warming will lead to more evaporation, too, and thus surface drying, increasing the intensity and duration of drought[10]. Warmer air can also be expected to enhance precipitation extremes as it can hold more moisture. According to the Clausius–Clapeyron equation, for each 1 °C of warming, saturated air contains 7% more water vapour, which may rain out if conditions are right. Increased atmospheric moisture content also provides more latent energy to drive storms. Furthermore, the potential intensity of tropical storms increases with warmer sea surface temperatures, all else remaining equal.

Such simple physical considerations thus lead us to expect certain weather extremes to increase in a warmer world. However, they are not sufficient to make firm predictions, because all else may not remain equal and a more detailed analysis is needed. First of all, to detect whether extremes have in fact increased, statistical analysis is required. For an attribution of extremes to a physical cause, modelling approaches can be used.

Statistics and the detection problem

Using statistics, scientists can analyse whether the number of recent extreme events is significantly larger than expected in a stationary (that is, unchanging) climate. Statistical methods thus may link extremes to an observed climatic trend, but this does not address the question of whether this trend is anthropogenic or caused by natural factors. Extreme-event statistics are challenging: extremes are by definition rare, so the tails of the probability density function are not well constrained and often cannot be assumed to be Gaussian. There are many types of conceivable extreme, such as for different regional entities or time periods as well as different weather parameters (some 27 indices for extremes have been proposed[11]). To pick the type of extreme *post hoc* — for example, to study Pakistan rainfall extremes after a record-breaking event there — risks selection bias, that is, bias by selecting just the kind of time series that shows recent extremes. Proper statistical analysis of changes in the observed number of extremes thus requires: (1) a single, comparable type of extreme; (2) selection of time series by *a priori* objective criteria; and (3) sufficiently long-running high-quality data.

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Table 1 | List of record-breaking meteorological events in the past decade and their impacts.

Year	Region	Meteorological record-breaking event	Impact, costs
2000	England and Wales	Wettest autumn on record[83] since 1766.	£1.3 billion (ref. 27).
2002	Central Europe	Highest daily rainfall record in Germany[42] since at least 1901.	Flooding of Prague and Dresden, US$15 billion (ref. 84).
2003	Europe	Hottest summer in at least 500 years[30].	Death toll exceeding 70,000 (ref. 31).
2004	South Atlantic	First hurricane in the South Atlantic[51] since 1970.	Three deaths, US$425 million damage[85].
2005	North Atlantic	Record number of tropical storms, hurricanes and category 5 hurricanes[52] since 1970.	Costliest US natural disaster, 1,836 deaths (Hurricane Katrina).
2007	Arabian Sea	Strongest tropical cyclone in the Arabian Sea[53] since 1970.	Biggest natural disaster in the history of Oman[53].
	England and Wales	May–July wettest since records began in 1766 (ref. 43).	Major flooding causing ~£3 billion damage.
	Southern Europe	Hottest summer on record in Greece[33] since 1891.	Devastating wildfires.
2009	Victoria (Australia)	Heatwave breaking many station temperature records (32–154 years of data)[34]	Worst bushfires on record, 173 deaths, 3,500 houses destroyed[34].
2010	Western Russia	Hottest summer since 1500 (ref. 69).	500 wildfires around Moscow, grain-harvest losses of 30%.
	Pakistan	Rainfall records[44].	Worst flooding in Pakistan's history, nearly 3,000 deaths, affected 20 million people[6].
	Eastern Australia	Highest December rainfall recorded since 1900 (ref. 45).	Brisbane flooding in January 2011, costing 23 lives and an estimated US$2.55 billion[86].
2011	Southern United States	Most active tornado month on record (April)[3] since 1950.	Tornado hit Joplin causing 116 deaths.
	Northeastern United States	January–October wettest on record[1] since 1880.	Severe floods when Hurricane Irene hit.
	Texas, Oklahoma (United States)	Most extreme July heat and drought since 1880[2].	Wildfires burning 3 million acres (preliminary impact of US$6–8 billion).
	Western Europe	Hottest and driest spring on record in France[1] since 1880.	French grain harvest down by 12%.
	Western Europe	Wettest summer on record (The Netherlands, Norway)[1] since 1901.	Not yet documented.
	Japan	72-hour rainfall record (Nara Prefecture)[1].	73 deaths, 20 missing, severe damage.
	Republic of Korea	Wettest summer on record[1] since 1908.	Flooding of Seoul, 49 deaths, 77 missing, 125,000 affected.

The selection criterion for this (incomplete) list was that the event was documented to be record-breaking (that is, unprecedented) in a long measurement series.

In a stationary climate, the number of threshold-exceeding extremes should remain constant over time. Therefore, if a trend is detected in their number then this can be attributed to non-stationarity, that is, climatic change. The causes behind such non-stationarity can be a change in the mean, a change in the shape of the probability density function, or a combination of both. Some recent studies[12–16] have focused on record-breaking extremes rather than on those exceeding a fixed threshold value. The advantage of studying record events is that knowledge of the probability density function is not required: the probability of a record in a stationary climate is simply $1/n$ in any year, where n is the number of years in the time series up to that year. This simple but fundamental property makes it easier to detect the amount by which the number of records exceeds that expected in a stationary climate, irrespective of whether this is owing to a change in mean[9] or in variance[12].

Modelling and the attribution problem

Statistical analysis of climate data alone can not, in principle, reveal the physical cause of any changes. To link cause and effect requires a joint analysis of several time series: for example, the record-breaking 1998 high in global temperature can partly be linked to El Niño by correlation analysis[17–19]. More commonly, to tackle this attribution problem, climate models are used to predict the response of the climate system to different driving forces[20–22]. Such attribution studies take a particular event or class of events and try to quantify the contributions from individual forcings[20,23]. To do so, many model simulations are carried out, each driven by different forcings, both natural (for example, solar variability and volcanism) and anthropogenic. To reduce model uncertainty, an ensemble of model runs is needed[20] and a sufficiently long time period should be simulated to improve the signal-to-noise ratio. This requires ample computational power, and the number of such studies has thus been limited, but the approach has been applied both to extreme heat waves[24,25] and rainfall events[26,27].

In general, such studies hinge on the climate model adequately representing extreme-event statistics: models need to get the unforced internal variability of extremes right as well as the spatiotemporal pattern of the forced response. This may well be true for large-scale, continent-wide heat extremes[24,28], but it is more questionable for storms or precipitation extremes, which tend to be underestimated by models[26,29]. In the following, we will discuss specific types of extreme.

Heat extremes

Recent years have seen an exceptionally large number of record-breaking and destructive heatwaves in many parts of the world. Several recent studies indicate that many, possibly most, of these heatwaves would not have occurred without global warming.

In 2003, Europe suffered its hottest summer by far for at least 500 years[30], with temperatures in Switzerland topping the previous record by a full 2.4 °C, equivalent to 5.4 standard deviations[31,32]. Greece experienced its hottest summer in 2007, with summer temperatures in Athens exceeding the 1961–1990 mean by 3.3 °C, corresponding to 3.7 standard deviations[33]. Australia's worst bushfires on record, following an unprecedented heatwave, ravaged the country on the 'Black Saturday' of February 2009 (ref. 34). In 2010, central Russia suffered its worst heatwave since records began, with the July temperature in Moscow beating the previous record by 2.5 °C (ref. 5). Finally, in July 2011, the US Southern Plains were hit by a record-breaking heatwave[2].

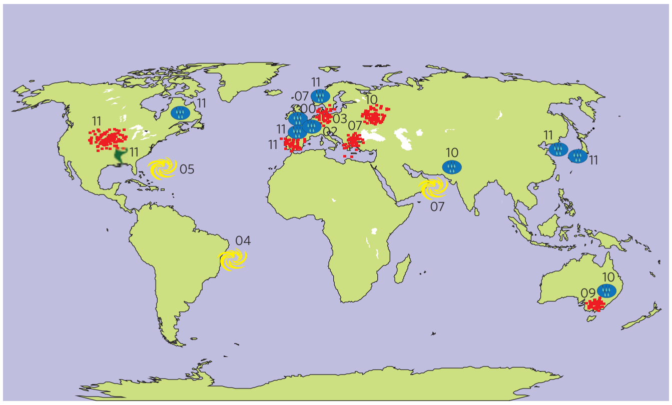

Figure 1 | World map showing the record extremes listed in Table 1. The numbers refer to the year in the twenty-first century. Blue symbols represent rainfall; red symbols represent heatwaves/droughts; yellow symbols represent hurricanes/cyclones; and the green symbol represents a tornado outbreak.

Several recent statistical studies show that the number of heat extremes is indeed strongly increasing. Starting with daily data, a recent study with global coverage shows a widespread (73% of land area) significant increase in the occurrence of warm nights (warmest 10% of nights)[11] during 1951–2003. At present, about twice as many record hot days as record cold days are being observed both in the United States[16] and Australia[35]. Similarly, for Europe nearly 30% of the observed daily heat records are attributable to the warming climate[36]. The length of summer heatwaves over western Europe has almost doubled and the frequency of hot days has almost tripled over the period from 1880 to 2005 (ref. 37). In the eastern Mediterranean, the intensity, length and number of heatwaves have increased by a factor of six to eight since the 1960s (ref. 38).

Monthly heat extremes document the most persistent and thus destructive[39–41] heatwaves. Their number increases faster with climate change than do daily extremes, because more-aggregated data has smaller variance and the number increases in proportion to the ratio of warming trend to variance[9,36]. The number of observed local monthly heat records around the globe is now more than three times as high as expected in a stationary climate[13] (Fig. 2). This observed increase is consistent with that expected from a simple stochastic model including the warming trend[9]. For Moscow, which has experienced strong warming in the past 30 years, this model even gives a fivefold increase in the expected number of monthly heat records. Extremely hot summers (exceeding three standard deviations) are now observed in about 10% of the global land area, compared with only about 0.1–0.2% for the period from 1951 to 1980 (J. Hansen, M. Sato and R. Ruedy, manuscript in preparation).

Results from modelling attribution studies are consistent with these observations: the risk of a heatwave of the magnitude of the 2003 European event has at least doubled but probably quadrupled (best estimate) as a result of human influence on climate[24].

Rainfall extremes

A number of record-breaking and devastating rainfall extremes occurred in the past decade and at least some of them can be attributed to climate change.

In 2000, the wettest autumn on record in England and Wales damaged nearly 10,000 properties, causing losses estimated at £1.3 billion (ref. 27). On 12 August 2002, 312 mm of rain poured down at the weather station of Zinnwald-Georgenfeld: the highest rainfall amount ever recorded in a single day in Germany. The Elbe River at Dresden reached its highest level since records began in 1275 (ref. 42), causing severe flooding. The period from May to July 2007 was by far the wettest in England and Wales since records began in 1766 (ref. 43), with 406 mm of rain (previous record: 349 mm). Two years later in 2009, the United Kingdom set a new 24-hour rainfall record: 316 mm at Seathwaite in Borrowdale. New rainfall records in Pakistan in late July 2010 (ref. 44) caused the worst flooding in its history. Also in 2010, eastern Australia suffered from the highest December rainfall ever recorded (since 1900), following the by far wettest spring on record, while south-western Australia had just experienced the driest ever wet season[45]. Sea surface temperatures around Australia had been breaking records for several months running. In January 2011, the record rainfall caused some of the worst flooding in the country's history. In September 2011, Typhoon Talas set a new Japanese 72-hour rainfall record of 1,625 mm (previous record: 1,322 mm)[1].

Statistical detection of rainfall extremes remains challenging owing to non-Gaussianity and the fact that they are local events requiring a dense observational network[46]. Still, throughout the mid-latitudes, extreme precipitation events (the upper 0.1% of daily rain events) have apparently increased substantially over the past 100 years, in the United States by about 33% (ref. 46). Different precipitation indices (for example, maximum five-day precipitation, extremely wet days) show a tendency towards wetter conditions in regions with sufficient temporal coverage (Europe, the United States and southern Australia)[11]. Extreme rainfall (beyond the ninety-eighth percentile) in European winters has increased nearly eightfold over the past 150 years, related to changing circulation patterns[47].

Furthermore, the average moisture content of the atmosphere has increased by about 4% since the 1970s, as expected from the Clausius–Clapeyron law when assuming constant relative humidity[10]. In some places hourly precipitation extremes have been observed to increase at about twice this rate[48,49]. Such super-Clausius–Clapeyron scaling is explained by dynamical processes: hourly precipitation extremes are often associated with local convective events and those become more frequent with rising temperature[50].

In 2011, the first rigorous modelling studies attributed some of the recent rainfall extremes to human influence on climate. Anthropogenic greenhouse-gas emissions are thought to have substantially increased the risk of autumn floods in England and Wales, such as those observed in 2000, by >20% (with 90% confidence) and possibly by as much as 90% (with 66% confidence)[27]. Furthermore, over approximately two-thirds of the Northern Hemisphere land area, greenhouse gases have contributed to the observed intensification of annual maxima of daily and five-daily precipitation amounts during the second half of the twentieth century[26].

Storms

Several exceptionally strong tropical cyclones have occurred in recent years, but formal detection and attribution are hampered by short or inhomogeneous data series, large variability in the number and intensity of storms and incomplete understanding of the driving forces.

In 2004, the first hurricane in the South Atlantic was registered[51], and in the following year the North Atlantic hurricane season set a number of new records. For the first time, 28 tropical storms arose in one season (previous record: 21), 15 reached hurricane strength (previous record: 12) and 4 reached the maximum category 5 (previous record: 2). One of these, Hurricane Wilma was the strongest ever recorded in the North Atlantic[52]. The year 2007 saw the strongest tropical cyclone, Gonu, ever observed in the Arabian Sea, causing the biggest natural disaster in the history of Oman[53].

The potential intensity of tropical storms increases with warmer sea surface temperatures, all else being equal. However, an increase in shear winds could prevent more tropical cyclones from reaching this intensity. Although the energy dissipation of North Atlantic hurricanes correlates well with increasing ocean temperatures[54] (Fig. 3), this trend is not so clear for other ocean basins. Also,

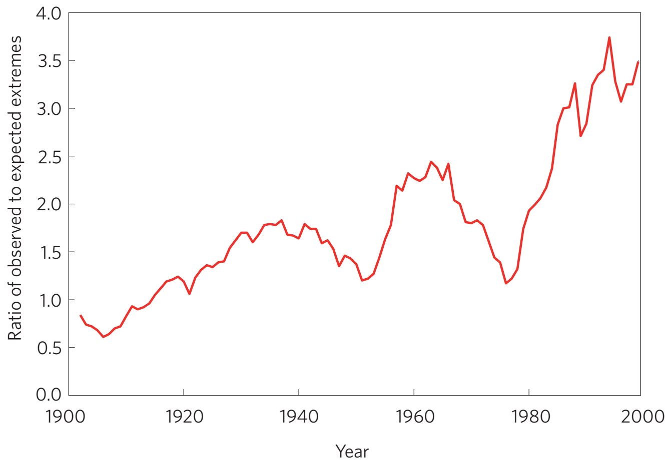

Figure 2 | Century increase in the number of monthly heat records. Ten-year running averages of the number of unprecedented records in monthly mean temperature in 204 time series are shown, namely 17 weather stations from around the world for each calendar month, given as the ratio of the observed number of extremes to that expected in a stationary climate. Based on the data analysis of Benestad[13].

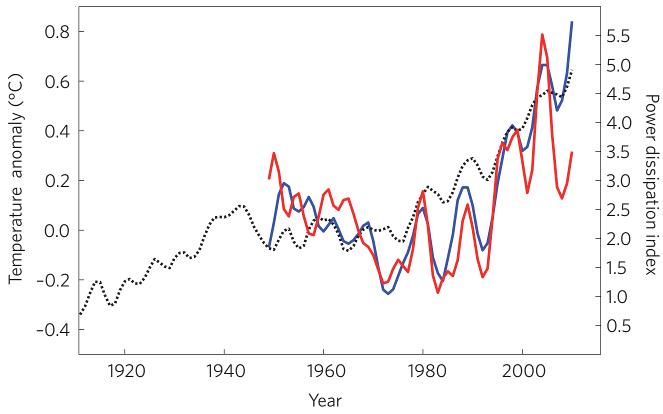

Figure 3 | Power dissipation index for North Atlantic tropical storms linked to tropical sea surface temperature in the main development region for Atlantic hurricanes. Red line denotes North Atlantic tropical storms; blue line denotes tropical Atlantic sea surface temperature. For comparison, the evolution of Northern Hemisphere mean temperature from NASA Goddard Institute for Space Studies is also shown (dotted line). All data are smoothed with a filter of half-width three years.

in recent years, hurricane intensity seems to be lagging behind the correlation found earlier. It is possible that the large increase observed from 1980 to 2005 is partly due to stratospheric cooling, which enhances the vertical temperature gradient, and not just surface warming[55]. Globally, a significant increase in the intensity of tropical storms over the past three decades has been identified in the satellite record[56]. Nevertheless, a recent review concluded that "it remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes"[57].

Storm tracks associated with extratropical cyclones have moved polewards over the past 25 years[58], in conjunction with a poleward movement of the jet stream[59] and an expansion of the Hadley cells[60]. At least for the tropical expansion, there is now robust evidence[60] based on several reanalysis data sets[61] as well as *in situ* observations[62–64]. In the Southern Hemisphere, the total number of storms has declined since the 1970s, but the number of deep cyclones (less than 980 hPa) has increased significantly[65]. Some authors have found evidence for a similar development in the Northern Hemisphere, but the data are not conclusive[66,67].

Complex physics

Statistical detection and formal attribution studies thus at least qualitatively confirm what one would expect from the simple physical considerations mentioned at the outset: especially heat but also precipitation extremes increase strongly in a warming climate. However, climate change does not just consist of a simple background warming. Complex, possibly nonlinear interactions may either reduce or increase the incidence and magnitude of extremes.

Several recent unprecedented extremes were far outside the previous distribution. Why did temperatures in the 2003 European heatwave beat the previous record by 2.4 °C, if local climate warmed much less than that over the past 140 years? A simple shift of the previous, nearly Gaussian, probability distribution towards warmer values cannot explain this[32]. That such outliers are mere freak events, so called black swans, is a possibility[68]. However, the recent clustering of outliers makes this seem highly unlikely. The exceptional heatwave of 2003 was surpassed again in 2010, if the larger Europe is considered (Fig. 4)[69]. In fact, events of these sorts of magnitude are projected to occur only in the last part of the twenty-first century[32,33,70,71]. A widening of the probability density function, in addition to a shift, is often invoked[32], but this is merely descriptive and not a physical explanation.

These outliers indicate that nonlinear, possibly threshold processes are involved and several such mechanisms have been proposed. Schär *et al.*[32] invoked a positive feedback with soil-moisture loss to explain the 2003 European heatwave, where the surface heat budget changes fundamentally once the soil has dried out and no more can be converted into latent heat by evaporation.

Anomalous atmospheric circulation patterns can greatly exacerbate the intensity and frequency of extreme events[47,72], and may also explain some observed outliers[73]. During both of the extreme boreal summers of 2003 and 2010, the Northern Hemisphere jet stream was characterized by a strongly meandering pattern that remained locked in place for several weeks[74]. These blocking situations brought persistent, and thus extreme, weather conditions to different regions in the Northern Hemisphere[75,76]. Such patterns are more likely to form when the latitudinal temperature gradient is small, resulting in a weak circumpolar vortex, which occurred in 2003 as a result of anomalously high near-Arctic sea surface temperatures[77]. Although the probability that a new heat record would be set in Moscow was increased by a factor of five by the warming trend over the past decades in that area[9], this does not explain the large amount by which the previous record was broken. Linking the 2010 Moscow heatwave to warming or to an exceptionally persistent blocking situation, that is, to atmospheric dynamical processes[68], thus provides complementary and not mutually exclusive explanations[25]. Likewise, the 2010 Pakistan[6] and 2011 Australia flooding events have been linked to a strong La Niña. Although this is probably an important factor, it does not explain the unprecedented nature of these events. Naturally occurring mechanisms such as El Niño/Southern Oscillation can cause extremes that, in combination with a changing background climate, turn into unprecedented events.

Conclusion

Many lines of evidence — statistical analysis of observed data, climate modelling and physical reasoning — strongly indicate that some types of extreme event, most notably heatwaves and precipitation extremes, will greatly increase in a warming climate and have already done so.

In 2007, the IPCC concluded that a future increase in the frequency of heatwaves and extreme precipitation events caused by

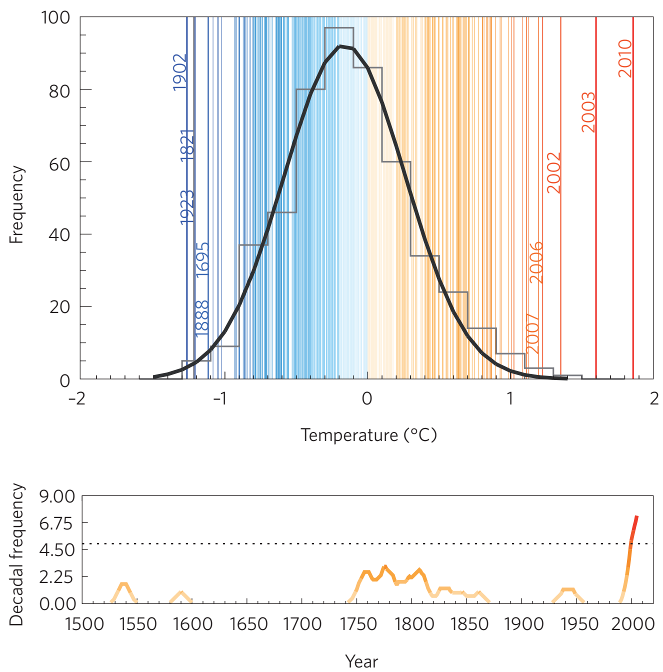

Figure 4 | European summer temperatures for 1500–2010. The upper panel shows the statistical frequency distribution of European (35° N, 70° N; 25° W, 40° E) summer land-temperature anomalies (relative to the 1970–1999 period) for the 1500–2010 period (vertical lines). The five warmest and coldest summers are highlighted. Grey bars represent the distribution for the 1500–2002 period with a Gaussian fit shown in black. The lower panel shows the running decadal frequency of extreme summers, defined as those with a temperature above the ninety-fifth percentile of the 1500–2002 distribution. A ten-year smoothing is applied. Reproduced with permission from ref. 69, © 2011 AAAS.

greenhouse warming in most continental areas is very likely (>90% probability) and an increase in intense tropical cyclone activity and drought-affected areas is likely (>66% probability)[7]. Some extreme events will decrease — extreme cold being the most obvious one. However, the overall number of extremes is expected to increase. Human society has adapted to the kind of extremes experienced in the past, so a lesser number of these will bring only modest benefits. But unprecedented new extremes can be devastating, as the Pakistan flooding of 2010 illustrates.

Future research should focus on a better understanding of the physical and dynamical processes behind some of the recently observed extreme events. Why did summer temperatures in Europe overshoot previous records by such a large margin both in 2003 and 2010? Fractional attribution of notable weather extremes over the past 50 years to specific forcings, as suggested by the International Group on Attribution of Climate-Related Events, is important[78], but can only be as good as the climate models used. Hence, a major effort to improve climate models with respect to their ability to capture extreme events is needed. Global climate models still have a well-known bias in daily precipitation amounts[29] and persistent blocking events are generally poorly represented[79,80]. Therefore, such attribution studies will be truly effective only when the reasons behind such misfits are better understood and model bias can be overcome. Increasing the spatial resolution of models might be one way to do this, but an enhanced understanding of the nonlinear processes likely to be involved is just as important.

As well as improved modelling, there is still much to be learnt by statistical data analysis. To understand observed changes in the frequency of extremes, long time series are needed and further work should be directed at identifying and correcting for inhomogeneities in data sets. For example, changes in observational practice have been shown to artificially enhance summer heat extremes in pre-1950s data from France[81].

Many climate scientists (including ourselves) routinely answer media calls after extreme events with the phrase that a particular event cannot be directly attributed to global warming. This is often misunderstood by the public to mean that the event is not linked to global warming, even though that may be the case — we just can't be certain. If a loaded dice rolls a six, we cannot say that this particular outcome was due to the manipulation — the question is ill-posed. What we can say is that the number of sixes rolled is greater with the loaded dice (perhaps even much greater). Likewise, the odds for certain types of weather extremes increase in a warming climate (perhaps very much so). Attribution is not a 'yes or no' issue as the media might prefer, it is an issue of probability. It is very likely that several of the unprecedented extremes of the past decade would not have occurred without anthropogenic global warming. Detailed analysis can provide specific numbers for certain types of extreme, as in the examples discussed above.

In 1988, Jim Hansen famously stated in a congressional hearing that "it is time to stop waffling so much and say that the evidence is pretty strong that the greenhouse effect is here"[82]. We conclude that now, more than 20 years later, the evidence is strong that anthropogenic, unprecedented heat and rainfall extremes are here — and are causing intense human suffering.

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Additional information
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