

Its nickname is the icebox of the nation. The village of Pellston in Michigan often sees arctic winters, with a thermometer-shattering record low of  $-47^{\circ}\text{C}$  in 1933. Even by late March, it is usually a very chilly place. But not this year. On 22 March the Pellston weather station registered a temperature above  $29^{\circ}\text{C}$ , vaporising the previous record for that date by more than 17 degrees.

This was just one of thousands of weather records smashed by the "summer in March", a 10-day event that affected much of North America. Many people enjoyed the unseasonal warmth, but most of the other extraordinary weather events of the past decade have been far less welcome. In 2003, the summer in Europe was so hot it killed tens of thousands. Russia in 2010 suffered even more staggering heat. Rainstorms brought unprecedented floods to Pakistan in 2010 and again in 2011. Tropical cyclone Gonu in 2007 was the most powerful ever recorded in the Arabian Sea.

Climate scientists have long warned that global warming will lead to more heatwaves, droughts and floods. Yet some of these recent extremes, such as the summer in March, are way beyond the predictions of our climate models. And there have been extremes of cold as well as heat. In Rome, ancient monuments are crumbling because of the big freeze that hit Europe this February. And on the northern edge of the Sahara desert, the streets of Libya's capital Tripoli were blanketed with snow.

It seems that our weather is getting wilder - more variable as well as steadily hotter. The big question is why. Is this just a blip, or are we in for even more freakish weather as global warming accelerates over the coming decades?

Even in an unchanging climate, our weather varies a lot. Each summer will be different. Take the average summer temperature each year, and you will get a series of numbers scattered about a long-term mean, distributed in a pattern more or less like a bell curve. Wait long enough, and you will sweat through a few very hot summers and grumble through a few very cool summers.

Over the past century, the surface temperature of the planet has increased by  $0.8^{\circ}\text{C}$  on average, which has shifted the familiar range of weather into warmer territory. Cooler summers have become less likely and warmer summers more likely. Contrary to what you might think, this kind of shift increases the odds of extremely hot summers by more than it increases the odds of slightly warmer summers.

The rising temperature is leading to other kinds of extreme weather, too. Warmer air can hold more moisture - in fact, its capacity increases exponentially as the temperatures rises. This means that when rain falls it can become a deluge, increasing the chance of catastrophic floods (*New Scientist*, 19 March 2011, p 44).

## **Damper downpours**

Floods are not the only result. When water vapour condenses to form clouds, it releases latent heat, and this heat is what powers most kinds of storms, from thunderstorms to hurricanes. With a wetter atmosphere there may not necessarily be more storms, but those that do occur will tend to be more powerful because there is more heat to power them. The damage done by storms rises rapidly as wind speeds increase.

So simple physics tells us that global warming should make extreme weather more extreme, from stronger storms to hotter heatwaves, drier droughts and damper downpours. This is indeed what has been happening around the world - except that in recent years, the magnitude of some of the record breakers has been jaw-dropping.

In 2003, temperatures in Europe were much higher than any summer for at least 500 years. Stefan Rahmstorf of the Potsdam Institute in Germany points out that in Switzerland the average summer temperature broke the previous record by 2.4°C. It is not unusual for the records for particular days to be broken by fairly wide margins but for the average of an entire season to be so much warmer is extraordinary. Then there was the Russian heatwave of 2010. Even averaged over Europe as a whole, this heatwave was more extreme than the one in 2003.

Most recently, there was the summer in March. Because it was so early in the year, it was a disaster only for fruit growers - trees blossomed too early and then got hit by frost, wiping out over 90 per cent of crops in some places - but it could have been much worse. "If such unusual conditions had occurred during July or August, the impact would have been enormous," says Dim Coumou, a colleague of Rahmstorf.

More and more people are being affected by all this extreme weather. In a recent poll in the US, 82 per cent of people reported that they had personally experienced extreme weather or a natural disaster in the past year, and 35 per cent said they were personally harmed either a great deal or a moderate amount by one or more of these events.

There is little doubt that things are going to get even worse. What is especially worrying, though, is that the rise in extremes can't be accounted for solely by the 0.8°C warming so far. Events like the 2003 and 2010 heatwaves were projected to occur only after much greater warming, towards the end of this century. And while one or two freak events might be dismissed as simple bad luck, there have been suspiciously many of them in the past decade.

James Hansen at NASA's Goddard Institute for Space Studies in New York has analysed records of local temperatures across the globe, in each case totting up June, July and August to get an overall temperature for this period. The results show that an increasing area of the planet's surface is experiencing highly anomalous heat extremes each year, relative to the period 1951 to 1980.

To a large extent, this is just what is expected in a warming world. However, Hansen's analyses show there is more to it than that. The weather is not only getting warmer, but more variable. Between 1951 and 1980, the average range in local summer temperatures across the entire globe was 0.55°C; from 1981 to 2010, it had gone up to 0.58°C. Over land the variability is greater, and its increase is faster. Some locations, especially those far from the stabilising influence of the ocean, see much more variability and more increase. Project that into the future, and we already have more cause for concern than we had with the mere rise in mean temperature.

### **Implausibly hellish**

But even in the context of this somewhat more jittery climate, the mega-heatwaves of the last decade stand out as implausibly hellish. Is something else happening to make temperatures soar like this?

Quite possibly, says climate modeller Pier Luigi Vidale at the University of Reading, UK. He thinks plants and soils might explain some of the unprecedented heatwaves. Where land is covered by vegetation, much of the sun's heat is absorbed by plants. They stay cool - and keep the land cool - by sucking up water and letting it evaporate from their leaves. But when the soil dries out, plants close their pores and stop transpiring. "It is the same as if you don't drink any water and stop sweating," says Vidale. When the sun's heat is no longer channelled into evaporating water, it all goes into the land and the air above it. The result is a jump in temperature.

This has been happening for as long as there have been plants on land, but it is becoming more common and affecting greater areas because winter precipitation has become more erratic, sometimes failing to soak the soil thoroughly. At the same time, the growing season has lengthened and become warmer, so plants are sucking up more water.

In 2004, while he was part of a team led by Christoph Schär at the Swiss Federal Institute of Technology in Zurich, Vidale studied this process in a regional climate model. Although previous models had included drying soils, the representation was too simple, Vidale says, as plants shut down transpiration too suddenly. With the improved model, some of the simulations looked like the summer of 2003, and other models have since produced similar results. They all suggest that over land where soils can dry out, summer temperatures do not follow an exact bell curve. Instead, there are more mega-heatwaves.

However, a lot of uncertainty remains. Part of the problem is accurately modelling the role of plants and soil. Even details such as the species of plant are important, because plants with deep roots will keep transpiring long after those with shallower roots. "The biophysical models are not yet accurate enough," says Robert Vautard at the University of Versailles in Saint-Quentin-en-Yvelines, France.

Measuring the actual moisture content of soils could improve things, but it is not easy. "You can make a measurement here, but a few metres away it's not valid any more," says Vidale. "In Europe we only have a few monitoring stations for soil moisture. Many of us have been arguing for more." Satellites can give an indication of surface soil moisture over a wide area, but not how much is available to deep roots.

While drying soils could be partly to blame for some recent off-the-chart heat extremes, they are not the whole answer. Vidale's model may have reproduced the scorcher of 2003 - but it also predicted that such hot summers would be unlikely before the end of this century. And of course this phenomenon cannot account for all the weird weather we are experiencing. You don't need to be a climate expert to conclude that a heatwave did not cause snow in Tripoli. But some researchers think they know what might be to blame for that - a lazy jet stream.

Jet streams are high-speed winds that carve a snaking path through the upper atmosphere. The two polar jet streams, one in each hemisphere, are driven by the difference in temperature between warm tropics and cold poles. In the tropics, the atmosphere is puffed up by higher temperatures: "It's like there is a hill from the tropics tilted down towards the poles," says Jennifer Francis of Rutgers University in New Jersey.

Gravity pulls some of this air down towards the poles. Because of Earth's spin, the air gets deflected off to one side, which is what drives the polar jet streams from west to the east.

The positions of the jet streams aren't fixed. They move around, shifting south or north and also developing big meanders, or waves. "You can get such a big wave, it breaks off as an eddy that gets left behind, just sitting and stewing in its own juice," says Francis. "When this happens, the weather near the eddy stays the same for days or even weeks."

Humanity is now messing with this vital component of the atmosphere. The Arctic is warming far faster than the rest of the planet, in part because its sunlight-reflecting snow and ice is melting to expose dark, sunlight-absorbing land and sea. This is reducing the temperature difference between the tropics and the Arctic. In work published in 2009, Francis showed that in summers with less sea ice in the Arctic - meaning more heat being absorbed by the ocean - the atmospheric hill had a more gentle slope (*Geophysical Research Letters*, vol 36, p L07503). The upshot is that the engine driving the northern polar jet stream is weakening.

As the jet stream slows down, it takes a more mazy path, with meanders that move around more slowly. That is crucial, because the jet stream pushes weather systems around. So when the stream's position changes more slowly or stays in one place for weeks - what meteorologists call a blocking pattern - the weather is more likely to become extreme. If the jet stream shepherds one low pressure system after another towards you, then you will soak - as happened to the UK this April, producing record rainfall. If the sluggish stream holds a high pressure system in place, you will roast.

"It's not news when you have one or two hot or cold days. If it goes on for a week or two, then

people are freaking out because their harbour is freezing over," say Francis. Blocking patterns have played a part in much of the extreme weather around the northern hemisphere in recent years, including some of the freezing winter weather and record snowfalls, and the summer in March.

Other researchers have confirmed that the jet stream has been weakening, and shown that this leads to more blocking events. Now Francis has found another effect of the warming Arctic. "I got thinking - if you are warming the north more than the south, that will stretch the northern peaks of high-pressure ridges farther northward." Working with Stephen Vavrus of the University of Wisconsin-Madison, she used highly detailed weather models to recreate past events and trace the contours of atmospheric pressure. And indeed the high-pressure ridges have tended to stretch further north in recent years. That makes the meanders of the jet stream more extreme, bringing warm air further north, and cold air further south - to places such as Rome and Tripoli.

So it appears the northern hemisphere is in for more weather chaos as the planet warms. In some years, the jet stream mechanism could cancel out the drying-soils mechanism but in others it could amplify it, because a lazy jet stream will occasionally produce exceptionally dry winters and springs as well as hot spells in the summer. The polar jet stream in the southern hemisphere is unlikely to be affected in the foreseeable future, though, because Antarctica is warming more slowly than other parts of the world.

### **Provoking the elements**

There could well be other, as-yet-unidentified mechanisms contributing to the wildness of our weather now, or which might kick in as the world warms further. For example, having roused the air and the earth against us, we may also be provoking another element. The ocean joins with the atmosphere in a roughly periodic pattern called the El Niño Southern Oscillation, or ENSO, in which warm water sloshes back and forth across the surface of the Pacific Ocean partly in response to changes in the trade winds.

ENSO's changing moods already cause all sorts of mayhem and as the water sloshing around gets even warmer the mayhem is likely to increase. The Australia and Pakistan floods of 2010 and 2011 were due to unusually warm surface waters loading the air with moisture, probably caused by a combination of ENSO and climate change.

A big question is whether things could get even worse. What if ENSO and other climatic oscillations don't just continue as before in an ever hotter world, but become even greater in magnitude? Are we pushing these pendulums in a way that makes them swing more wildly? "So far there is no clear evidence either way," says Rahmstorf, "but we are changing the whole energy balance of the climate system, so in a way it would be surprising if these patterns of variation did not change."

Part of the problem with studying these phenomena is that our climate models are still relatively coarse, although they are improving. A new international collaboration called RESOLVE, which includes Vidale's group in Reading, will run global climate models with a spatial resolution of 2 kilometres, compared with a more typical resolution of tens of kilometres. Vidale hopes this will be able to show how processes are connected across the globe, and allow researchers to tease apart the influence of soils and atmospheric circulation on weather extremes.

Such models might give a better idea of just how extreme future extremes could become, although there is of course no way to predict one-off weather events years in advance. Then again, as earlier models missed the changes in the jet stream, these new ones could still be blind to some unanticipated mechanisms.

In the meantime, there are some things we can do to prepare. European health services now have better contingency plans for a mega-heatwave than they had in 2003. We can design buildings to cope with extreme heat, and planners might consider avoiding putting vital infrastructure in areas at risk of flooding.

But adaptation can be very costly, and the very nature of more variable weather poses problems. Farmers could learn to cope if it was consistently drier or hotter, for instance, but if the weather continues to become more variable and there is no way to know whether to expect frost or floods, hail or heatwaves, then each season will become an ever greater gamble. "It is difficult to adapt to unprecedented extremes, as they always involve some element of surprise," says Rahmstorf.

While no one can say exactly what's going to happen to our weather, all the signs are that we're in for a bumpy ride. "We are seeing these extremes after only 0.8 degrees of global warming," says Rahmstorf. "If we do nothing, and let the climate warm by 5 or 6 degrees, then we will see a very different planet."