Hot news from summer 2003

Christoph Schär and Gerd Jendritzky

The European heatwave of 2003: was it merely a rare meteorological event or a first glimpse of climate change to come? Probably both, is the answer, and the anthropogenic contribution can be quantified.

The European summer of 2003 was characterized by highly anomalous meteorological conditions[1], and was extremely hot and dry[2,3]. In the northern parts of the continent, the summer was perceived as beautiful and warm. But in central and southwestern Europe, the heat was prolonged and intense, and the economic and societal consequences were disastrous (as described in Box 1).

Given the heatwave's severe repercussions, the question has arisen whether the summer of 2003 is evidence of man-made climate change. On page 610 of this issue, Stott, Stone and Allen[4] take a major step towards answering this difficult question. Previous studies had found that recent changes in the European summer climate were consistent with climate-change scenarios[5,6], but there had been no attempts at a rigorous attribution of cause and effect. Indeed, because the atmosphere is a chaotic dynamical system, it is impossible to attribute — in a causal sense — an individual episode of extreme weather to changes in atmospheric composition. Nevertheless, it is feasible to estimate the probability or risk of occurrence of a certain weather event under natural and modified climatic conditions. This is the avenue taken by Stott and colleagues.

Using one of the leading global climate models available, the authors derive the probability distributions of European summer temperatures for two sets of climate simulations, each covering the period since 1900. The first set accounts for the past effects on climate that were due to variations in solar and volcanic activity, as well as to man-made influences (including increases in greenhouse-gas concentrations). The second set mimics a natural climate by prescribing natural factors alone. Stott and colleagues then calculate the changed risk of extremely hot summers that is attributable to past anthropogenic emissions of greenhouse gases, using a comparison of observed and simulated summer temperatures to account for uncertainties in man-made warming and natural variability. They find, at a confidence level of greater than 90%, that more than half of the risk of 2003-like extreme European summers is attributable to human influences on the climate system.

Methodologically, Stott and colleagues[4] use an approach developed for detecting global climate change and attributing causes to the changes identified. There is long experience with such studies, all of which find that a significant anthropogenic contribution is required to explain the observed global climate records of the past 30–50 years[7,8]. The new study fits into these results, as the probability of extreme heatwaves must change as mean temperatures increase. The details of the analysis are rather complex. But the basic interpretation of the main result is comparatively straightforward: anthropogenic warming shifts the statistical distribution of summer temperatures towards warmer conditions, and this has a dramatic impact on the chance of temperatures exceeding some threshold out in the upper tail of the temperature distribution.

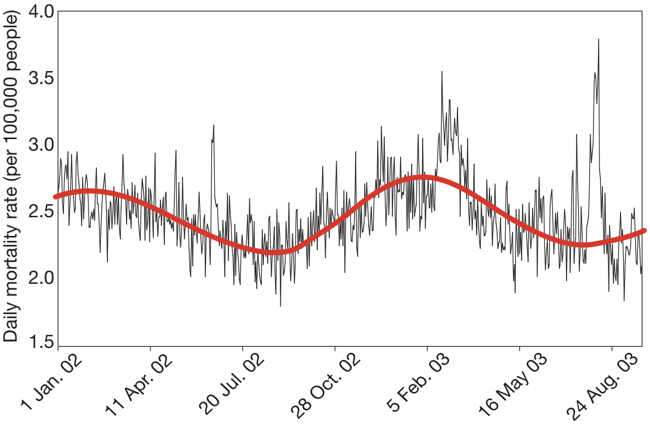
What about the limitations of the new work? We will mention two. First, Stott *et al.* address the whole summer of 2003 (and not the extreme heatwave in early August), and all of continental and southern Europe (not the much smaller central European region where the heatwave was most intense). Consideration of shorter-term and smaller-scale heatwaves will require higher computational resolution[9], and will need to take the complexities of land-surface processes into consideration[1,3]. Accounting for these factors is a challenge. Second, representing natural climate variability is a general difficulty in studies attempting to attribute causes to particular effects. Stott *et al.* show that their model appropriately represents the spectrum of continental-scale European climate variability on interannual to interdecadal timescales. But more detailed

Box 1 Impacts of the heatwave

According to reinsurance estimates, the drought conditions during the summer of 2003 caused (uninsured) crop losses of around US$12.3 billion, while forest fires in Portugal were responsible for an additional US$1.6 billion in damage. The European electricity markets reacted erratically to increases in demands, as power plants had to curtail production owing to the lack of cooling water, and electricity spot prices soared beyond €100 ($130) per MW h. In the Alps, many glaciers underwent unprecedented melting, and the thawing of permafrost led to a series of severe rock falls.

But it was the unusual number of deaths during 1–15 August that caught the headlines. Estimates based on the statistical excess over mean mortality rates amount to between 22,000 and 35,000 heat-related deaths across Europe as a whole[11]. In France the mortality rate increased by 54% during those two weeks, and the increase was statistically significant in all 22 French regions and for all age groups above 45 years[12].

The figure, reproduced from ref. 13, shows the daily mortality rate in Baden-Württemberg, Germany, over a period of 20 months, and puts the August



2003 heatwave in context. Total daily mortality data are in black, with the mean seasonal evolution in red. Notable features are the seasonal cycle, with higher mortality in winter; a heat-related mortality peak in June 2002; the effects of an influenza outbreak in February–March 2003; and the striking peak in August 2003, due to the heatwave, which caused 900–1,300 extra deaths in a population of 10.7 million people. **C.S. & G.J.**

studies will be needed to corroborate this conclusion, as there are large uncertainties in the estimates of natural climate variability-derived from both models and observations[8].

Nonetheless, Stott and colleagues' work constitutes a breakthrough: it is the first successful attempt to detect man-made influence on a specific extreme climatic event. Such events are among the most notable features of a changing climate, not least given their impact on human affairs. Another article in this issue, by Allen and Lord (page 551)[10], discusses how refined analyses might lead to liability claims for costs incurred by climatic shifts. The advent of such 'attribution studies' might profoundly affect the course of international negotiations on ways to mitigate, adapt to and ultimately pay for the consequences of climate change. ■

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Information science

Quantum errors corrected

Andrew Steane

The phrase 'quantum error correction' might sound like a technical fix to a device that ought to be working better. But it is in fact a fascinating piece of fundamental physics with powerful implications.

Quantum error correction is a central concept of quantum information science and is almost the only thing a quantum computer would need to do if it is to work properly. It gives me great pleasure to say that it has now been implemented, in its most simple form, in a laboratory experiment reported by Chiaverini *et al.*[1] on page 602 of this issue.

It is surprising indeed that irreversible changes in quantum systems can be corrected. A correcting machine should first gather information from the faulty system, but for a quantum system this would cause the unavoidable disturbance associated with observation. We need to engineer an observation in such a way as to disturb the error, not the stored information, and to learn what the error is after the influence of our observation. Chiaverini and colleagues[1] have done exactly that.

Traditionally, 'Alice' is the protagonist in any quantum information story. Imagine that Alice wishes to preserve an atom's quantum state in the presence of noise. The state can be thought of as a spin, or rotation, about an axis oriented in three dimensions. (This is a short-hand for a pair of hyperfine levels in the electronic ground state of a $^9\text{Be}^+$ ion.) It is described by the notation $a\uparrow + b\downarrow$, where a and b are complex coefficients, and ↑ and ↓ are two spin directions. We assume that Alice does not know what state her atom is in, because if she did she could circumvent the whole problem by writing on a Post-it note — "Don't forget: *a* is 0.8, *b* is 0.6". Such cases are of no use for quantum computing.

Alice cannot examine the atom, because this would disturb its state. She cannot generate copies of it (that is, prepare further atoms in the same state) because no method to do that is physically possible (the 'no-cloning' theorem, which if broken would lead to various contradictions involving non-local correlations). However, Alice can cause her atom to interact with two others so that the group of three is now in a state described by $a\uparrow\uparrow\uparrow + b\downarrow\downarrow\downarrow$ (I have simplified things a little here, because Chiaverini *et al.*[1] in fact used an elegant, closely related, encoding, but this one is easier to describe). This is akin to radio operators' use of 'alpha' and 'bravo' for 'A' and 'B' to reduce errors: a longer symbol, here the three-atom state ↑↑↑ in which all atoms have spin-up, is used to encode a shorter one, the state ↑ (and similarly ↓↓↓ encodes ↓).

The atoms are now left alone for a while. Suppose the error processes mostly reverse the orientation of individual atoms. Then the state is likely to be corrupted into $(a\uparrow\uparrow\downarrow + b\downarrow\downarrow\uparrow)$ or $(a\uparrow\downarrow\uparrow + b\downarrow\uparrow\downarrow)$ or $(a\downarrow\uparrow\uparrow + b\uparrow\downarrow\downarrow)$, or any combination of these possibilities, through quantum superposition. In the experiment[1], to enable them to make a quantitative study, the team introduced an artificial error of known size, such that the probability of a spin-flip was p per atom. Alice's task is to manipulate the group so as to bring a given atom, say the first one, to the state originally stored $(a\uparrow + b\downarrow)$ — but she must not learn what that state was, or she will have disturbed it. Her operations must somehow reveal or react to the error, without learning the original message.

There is a way to do this: measure pairs of atoms, to determine whether their spins are aligned, without allowing information about any individual atom to be revealed. A general method for this, using quantum logic gates, was discovered in 1995. Such measurements 'project' the state, so that instead of a superposition of the possibilities listed above, the atoms must adopt just one of those possibilities. This is the unavoidable disturbance associated with the act of observation, but in this case it is engineered to make the state better defined and thus easier to correct. Furthermore, the correction can now be completed, because Alice can deduce from her measurements which, if any, atom has an inverted spin.

In Chiaverini and colleagues' experiment[1], these operations were performed by moving atoms in ultra-high vacuum along a segmented array of ion traps, each 100 micrometres in dimension. To control the rotations of the atoms, the team extended a technique of their own invention: a pair of laser beams with a precise frequency difference between them to drive the oscillations of the atoms. In this new work, the laser pulse was made to act on three atoms simultaneously, such that the force cancelled when all spins were aligned, and had the same magnitude for all states in which the spins were not all aligned. This performed most of the encoding or decoding in one step, greatly simplifying the (nevertheless still very demanding) experiment.

Although other experiments in liquid-state nuclear magnetic resonance[2,3] have demonstrated encoding and correcting operations for this and larger codes (more atoms), in these the signal was halved for each further spin introduced, and the fundamental ingredient of either individually measuring, or else reinitializing, the state of the extra spins was not available. Chiaverini *et al.*, however, have demonstrated all of the ingredients of quantum error correction in a single experiment. Their results are summarized by the formula $P \approx q + 2.6p^2|ab|^2$, where P is the probability that the final state was wrong, and $q \approx 0.22$ is the contribution from imperfection of the apparatus. For technical reasons, only a small range of initial spin states could be prepared, but this does not diminish the main achievement. It is also notable that for $p > 0.25$ a net suppression of noise (that is, $P < p$) was attained.

There are several natural steps to take next. One is to replace the rotation by a