CLIMATE SCIENCE

Autopsy of two mega-heatwaves

Record-breaking heatwaves in 2003 and 2010 surprised both the public and experts. Observations provide new insights into how temperatures escalated to unprecedented values through the interaction of boundary-layer dynamics and land surface drying.

Erich M. Fischer

The European heatwave of 2003 and the Russian heatwave of 2010 broke numerous temperature records[1,2], and are thus often referred to as mega-heatwaves. Climate scientists have investigated these two extreme events with a fervour reminiscent of the medical world examining the surprise deaths of two victims from a mysterious disease. Before speculating about an epidemic, a doctor's first step would be to conduct an autopsy. Likewise, the climate science community has been dissecting these two mega-heatwaves: we now have vertical and horizontal cross-sections of temperature, air pressure and humidity from observations and reanalyses, the two events have been compared and contrasted, and the culprit physical mechanisms have been investigated. As they report in *Nature Geoscience*, Miralles and colleagues[3] have now added a crucial puzzle piece to the diagnosis by demonstrating that the atmospheric boundary layer — the layer between Earth's surface and the free atmosphere — plays a key role in escalating a heatwave to the point of fever.

Periods of warm weather are part of the natural weather cycle. In the northern mid-latitudes, summer heatwaves are often related to a high-pressure system that persists for a series of days and brings clear skies and little rain. Direct heating from the Sun, together with advection of air from warmer regions, leads to a warm period that lasts until the pressure pattern shifts, usually within a week or two. The mega-heatwaves of 2003 and 2010 started with a similar pattern. But instead of settling at a moderate temperature and then decaying, the temperature rose quickly and well beyond normal levels. As it had already been a dry spring in many places[4,5], soils quickly desiccated during the heatwaves.

Miralles *et al.*[3] examine satellite observations and balloon soundings in the regions of the two heatwaves to understand why temperatures peaked at record levels. Building on previous work that reported a role for the atmospheric boundary layer in the 2003 heatwave[6], Miralles and colleagues find that, for both events, heat progressively accumulated in the atmospheric boundary layer over the course of several days. The warming boundary layer interacted strongly with the underlying soil, which progressively dried. As a result, cooling of the land surface by evapotranspiration declined and the land surface warmed, which, in turn, led to increased sensible heat flux from the surface into the atmosphere[4,7]. In response to these changes, the atmospheric boundary layer became warmer and also deeper. That is, the part of the atmosphere under immediate influence of the land surface extended further up into the troposphere.

Miralles and colleagues[3] observed that a layer of warm air persisted throughout the night in both heatwaves. This layer was detached from the surface, but stored the heat that had accumulated during the day until the next morning. Thus, the next day started off in a warmer state than the previous day and, as this cycle repeated, the heat progressively built up in the boundary layer. Miralles and colleagues suggest that the cycle of heat storage and soil desiccation was similar in both events and raised the temperatures to record levels.

Ultimately, the location and duration of a heatwave is determined by the large-scale weather patterns. The anomalous boundary layer and the dry land surface potentially interact with these patterns[4,8], but how exactly and to what extent remains relatively poorly understood.

Using a simple mechanistic column model of the atmosphere and soil moisture that is initialized and constrained by the

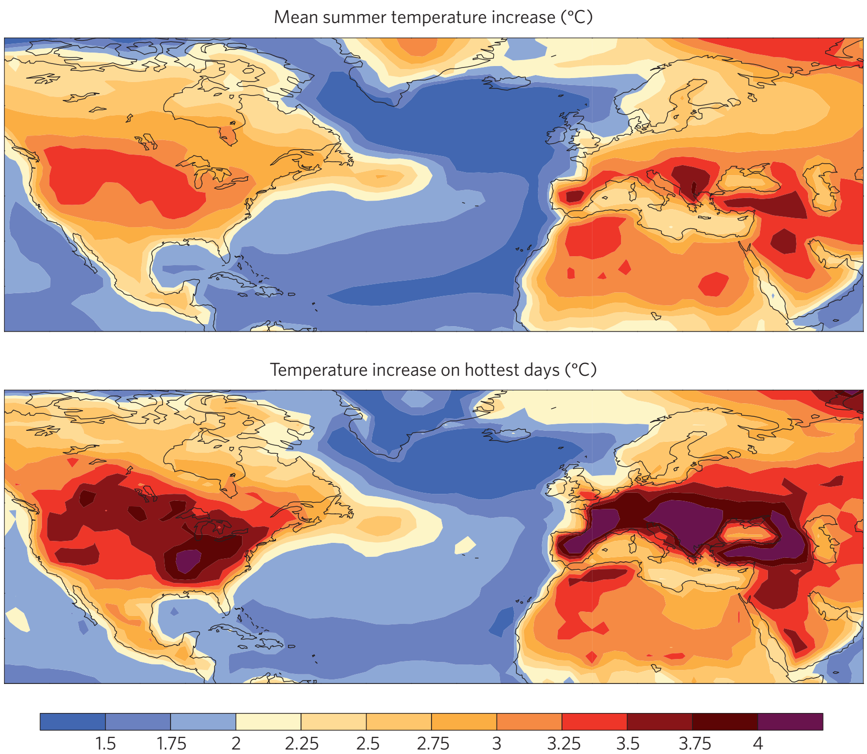

Figure 1 | Warmer summers and hotter extremes in a 2 °C warmer world. The change in mean summer temperatures (top) and hottest daily maximum temperature (bottom) for 25 models of the Coupled Model Intercomparison Project Phase 5 (CMIP5) averaged across the 20-year period in which their respective global mean temperatures are 2 °C warmer than in 1986–2005. Redder colours indicate temperature increases exceeding the global mean warming. Miralles *et al.*[3] analyse the processes that led to the European and Russian mega-heatwaves of 2003 and 2010, and that may account for some of the differences between the mean warming and air temperature increases on the hottest days.

observational data, Miralles and colleagues[3] suggest that, at least at northern mid-latitudes, temperatures exceeding 40 °C are only possible if dry soils, heat inflow from warmer regions and the accumulation of heat over several days occur in concert. This implies that heatwaves that start with a rapid 10–15 °C temperature rise — reaching more than 40 °C within a day, as observed in places such as Melbourne, Australia — are not expected in the areas where the mega-heatwaves occurred. Such sudden temperature jumps result primarily from advection of hot air rather than a local build-up of heat over several days.

The improved understanding of heatwaves enables us to scrutinize weather and climate models used for predicting heatwaves and estimating human contributions to their frequency as the climate warms. If the world warms, for example, by 2 °C, we would not expect every day to be 2 °C warmer. Climate models project that for some regions temperature increases on the hottest days may be substantially higher than the mean warming[2,9] (Fig. 1), depending on which model is employed. The amplified warming of hot days partly results from feedback mechanisms, such as those highlighted by Miralles and colleagues[3]. However, models are known to have limitations in representing some of the key heatwave-generating processes, including the frequency and persistence of atmospheric blocking, variability of soil moisture and soil moisture feedbacks with precipitation[10]. Thus, it is important to understand whether heatwaves in models occur for the same reasons they occur in nature. Ultimately, our confidence in the prediction of future climate does not come from more models or faster computers to run them, but from understanding the relevant processes and reliably representing them in models.

Anthropogenic warming has more than doubled the risk of mega-heatwaves such as those of 2003 and 2010[11,12]. If the variability in weather is like rolling a die, anthropogenic influence has loaded the die and increased the odds for rolling a six, a mega-heatwave. But should we expect future events that are more intense than those possible in today's climate — the equivalent of rolling a seven or even an eight on the weather die? There is a limit to the scorching heat during mega-heatwaves: we do not expect temperatures to reach 70 °C or more, even in a bone-dry desert under clear skies. There are physical constraints on maximum temperatures at the Earth's surface, simply based on the length of the day and the season. The observational record is too short — and will remain so for a long time — to tell us what is possible. The only way to identify the bounds on extreme temperatures, and understand how they are affected by climate change, is to employ physical models that incorporate what we know from observations, and that reliably describe all relevant physical processes.

Miralles *et al.*[3] reveal that the progressive build-up of heat in the atmospheric boundary layer helped hot weather in Europe in 2003 and Russia in 2010 escalate into mega-heatwaves. We have been surprised again and again by the extreme heatwave, rainfall and windstorm events that nature has thrown at us. There is much we do not yet understand about present-day weather and climate, let alone how they will change in the future. Thus, dissecting the underlying processes is crucial so that we will be better prepared for when the next surprise record-breaking event hits. ❐

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GEOCHEMISTRY

A piece of the deep carbon puzzle

Carbon loss from subducting slabs is thought to be insufficient to balance carbon dioxide emissions at arc volcanoes. Analyses of ancient subducted rocks in Greece suggest that fluid dissolution of slab carbonate can help solve this carbon-cycle conundrum.

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The carbon cycle in Earth's near-surface reservoirs — the atmosphere, oceans, biosphere and sedimentary rocks — has received widespread attention[1,2]. Yet there is another carbon cycle that operates on the planetary scale: carbon is buried in the mantle where one tectonic plate slides under another, and it returns to the surface from the deep Earth, mainly through volcanism[3]. The mass of carbon involved in the familiar, shallow cycle merely reflects the balance between the two principal transfers of this deep carbon cycle. In essence, the carbon that is so essential to life and modern society is available to us only with the permission of the deep Earth[4]. The deep carbon budget is poorly constrained, however, largely because the mechanisms for transferring carbon from subducting slabs to arc volcanoes are unclear. Ague and Nicolescu[5] now suggest in *Nature Geoscience* that significant amounts of carbonate minerals are dissolved from subducting slabs by infiltrating fluids, aiding the transfer of carbon back to Earth's surface.

Carbon-bearing minerals in sediments and oceanic lithosphere are carried into the Earth by subduction[6–8]. Conversely, magmas erupted at volcanoes above subduction zones contain carbon, which is mainly degassed to the atmosphere as carbon dioxide during crystallization or eruption of the magma[9]. The mantle beneath arcs contains only small amounts of carbon[10], so much of the carbon that is emitted by these volcanoes must come from the subducting slab. The transfer of carbon during subduction therefore lies at the heart of any attempt to constrain Earth's deep carbon cycle (Fig. 1), and the quantity of carbon retained in the slab and carried into the deep mantle, compared to that released from the slab and returned to the surface, is under debate[9,11–13]. The ultimate solution