HOW SOILS SEND MESSAGES ON HEAT WAVES

Extreme heat waves cost lives and money. We're destined to see more in the future, so better predictions of where they're going to strike next are important. **Brigitte Mueller** and **Sonia I Seneviratne** highlight a strong link between soil moisture and heat waves that could pave the way for more accurate forecasts.

A decade ago, Europe endured brutally hot temperatures. More than 20,000 people died prematurely, including many elderly people living in major cities. Rivers ran low, forest fires dotted the landscape, glaciers melted and crops withered as the region set records for highest temperatures in up to 500 years in some places.

Another heat wave in 2010 bathed the Northern Hemisphere in more record-breaking heat, most strongly affecting Russia, where temperatures were 10°C or more higher than usual in July. And in 2011, a drought began in Texas that drew international attention, as farmers lost cattle and a heat wave led to fires and more agricultural losses.

These high-impact hot weather events underscore the importance of understanding the evolution of heat waves and predicting the occurrence of hot temperature extremes. Predictions will help people to reduce the impacts of these events. And the tools to do it lie beneath our feet: soils, and the moisture they hold, are apt indicators of hot times to come.

A lack of soil moisture can trigger a spike in air temperatures – and a heat wave.

Climate modelling with soil

With new analyses, we show that soil moisture can be a powerful indicator of approaching extreme weather cycles, similar to the longer-term forecasting role played by sea-surface temperatures. Researchers have long used anomalies in sea-surface temperature patterns, El Niño–Southern Oscillation or the North Atlantic Oscillation, to make seasonal predictions. The underlying reason is the high heat capacity of water, which makes the ocean an effective sink for storing heat.

On land, the analogue to sea-surface temperature is soil moisture. Water can be stored in soil like a sponge, in the pore spaces in between soil particles or coated on them. That means that soil acts as storage for both energy (in the form of heat) and water. In addition, the water content also affects the heat exchanges at the land surface.

If the amount of water stored in soils is high, then an increase in temperature and sunlight (or radiation) leads to some important changes. As the heat causes the soil moisture to evaporate, this process requires a substantial amount of energy, which cools the temperatures of both soil and air, a process known as evaporative cooling. This mechanism buffers increases in temperature in the soil and the air above it.

If atmospheric conditions favour heat-wave development, whether that heat wave grows or collapses often depends on soil moisture. Sufficient moisture could trigger enough evaporative cooling to hamper or at least dampen the severity of an oncoming heat wave.

On the other hand, on the heels of a long hot spell, soils may have already released any moisture they contained. Dried-out soils have lost their ability to buffer temperature increases, which means that a lack of soil moisture can trigger a spike in air temperatures – and a heat wave.

Indeed, our study published last year in the journal *Proceedings of the National Academy of Sciences* (10.1073/pnas.1204330109) shows that in several regions of the planet, the evolution of heat waves requires a lack of soil moisture.

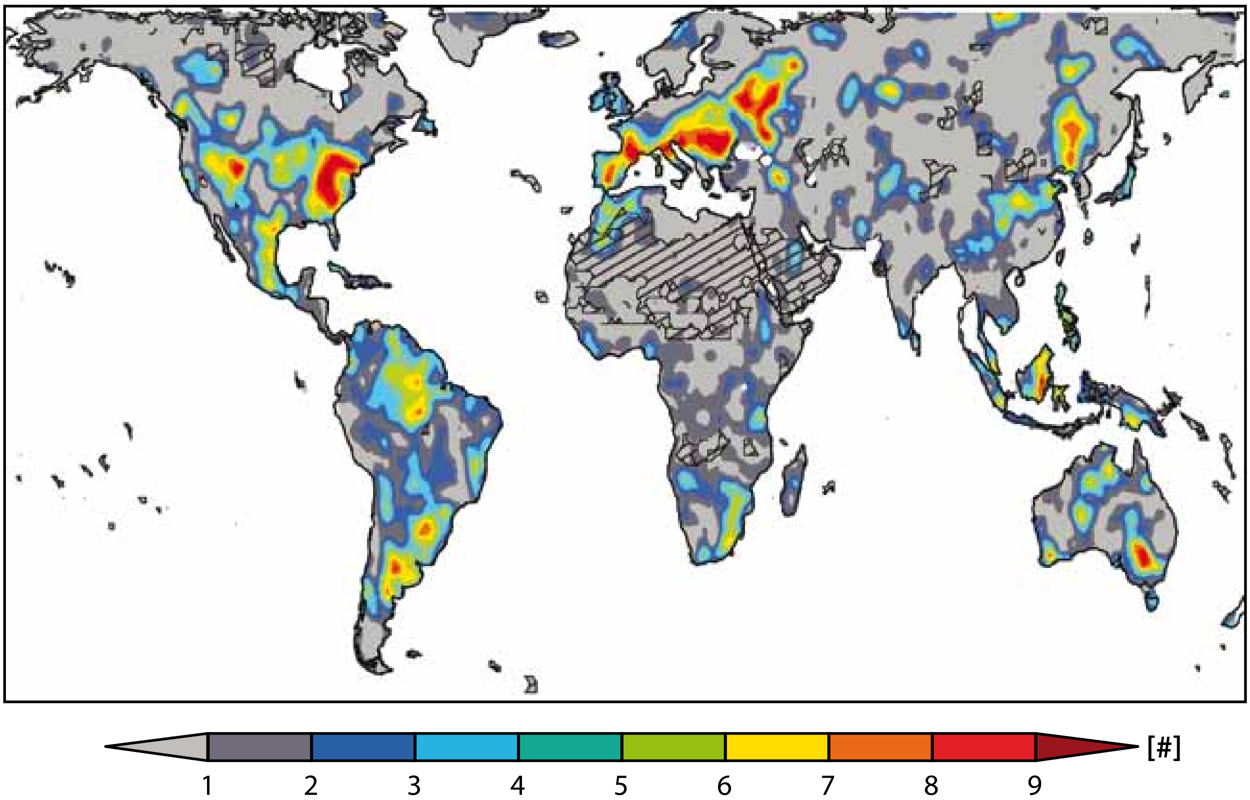

Figure 1: Coloured regions show the number of dataset combinations (out of 9) that exhibit significantly negative correlations between the number of hot days and preceding drought conditions. For these regions, a better seasonal prediction of hot temperature extremes may be possible with enough data on soil moisture availability (Mueller and Seneviratne 2012).

Neither too wet nor too dry

In the last decade, studies of the relationships between soil moisture and temperatures have made some headway (e.g. Koster *et al.* 2006, Seneviratne *et al.* 2010, Hirschi *et al.* 2011). In particular, researchers have shown that soil moisture has a strong influence on air temperatures in regions that can be considered "transitional" between wet and dry climate zones. These transitional regions are "just right" – a change in soil moisture here makes a difference, versus in regions that are either really wet or really dry.

In the case of wet climate regions, soils always have enough moisture, the rate of evaporation does not depend on it, and foreseeing the development of heat waves with the aid of soil moisture is impossible. In dry areas, moisture levels in soils are always very low and do not contribute much towards evaporative cooling. But in transitional regions, where the moisture levels are neither too high nor too low, we expect soil moisture and evaporation to influence temperature.

With enough data, scientists could improve the prediction of very hot days or heat waves.

While models and regional studies agree overall on the feedbacks of soil moisture on temperature, global-scale observations of the real world are lacking. A main limitation for these investigations is that researchers are missing a baseline for soil moisture around the world, measured with satellite instruments or field observations (see e.g. Seneviratne *et al.* 2010 for an overview). But there are plenty of rain, snow and other precipitation observations, which can be used to build records of drought and water scarcity. These data underlie the standardized precipitation index (SPI), developed two decades ago for drought planners, that we used as the missing baseline – and as our proxies for soil moisture.

A previous study examining heat waves in southeastern Europe (Hirschi *et al.* 2011) demonstrated a strong link between moisture deficits (or droughts) estimated from the SPI and rising temperatures that developed into extremely hot temperature days. In our study, we expanded that analysis to the global scale. Because spikes in temperature are deadlier and costlier during hot summer months, we first determined the hottest month of each year in grid cells plotted across the globe. We then took counts of the number of days with hot temperature extremes in that hottest month, and related that information to the SPI drought indicator over the three months preceding the hottest one.

Analysing results from several temperature and precipitation datasets, we could see a strong correlation in many areas between low soil moisture levels and the very high temperatures that followed. This relationship between soil moisture and hot temperature extremes shows that a lack of soil moisture during a drought would lead to later temperature spikes.

Spain is a good example of such a relationship (a so-called negative correlation): the country's hottest month of the year is July. If April to June have been unusually dry, the number of hot days in July is usually higher than if those previous three months were wet. We looked at 32 years of data; of those, 22 years had dry conditions from April to June. In more than 70% of those years with dry springs, the number of hot days in July was above average.

That same relationship holds elsewhere: the likelihood of an above-average number of hot days in the hottest month of each year, following on the heels of dry periods, is 70% in most of South America, the Iberian Peninsula and eastern Australia. After wet conditions, the probability falls to 30–40%.

We can see this relationship between low soil moisture after drought and spiking temperatures in hot months, for example, in the eastern US, south and southeastern Europe, and New South Wales in Australia (see Figure 1). These regions where soil moisture affects temperature are much more widespread than previously assumed, based

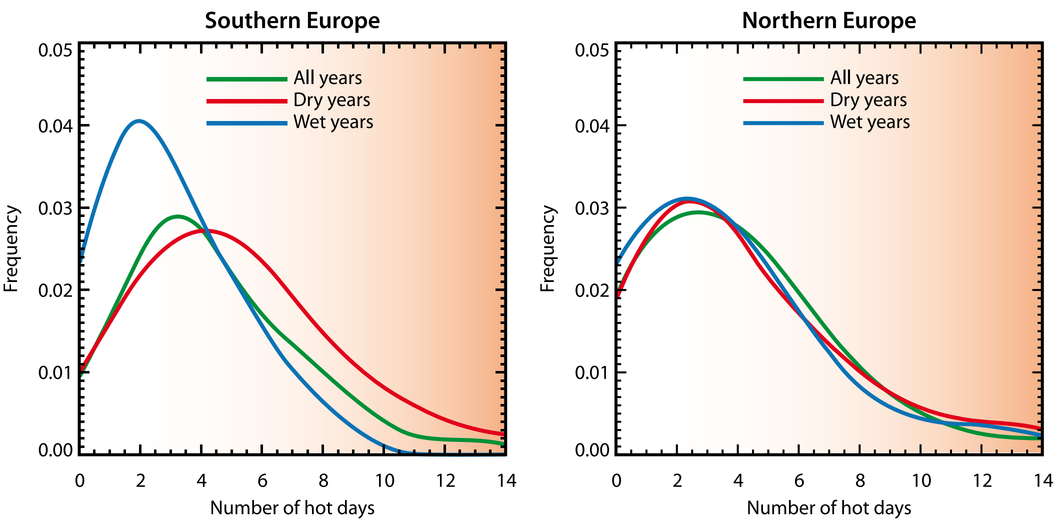

Figure 2: In southern Europe (left), during years with low soil moisture levels, the occurrence of hot temperature extremes (red probability curve) shifts towards more hot days compared to the distribution for all years (green curve). The slightly broader shape of the curve indicates an increase in the probability that the number of hot days will be very high. On the other hand, if soil moisture is high (blue curve), low numbers of hot days are more likely. In northern Europe (right), the differences between the occurrence after dry, normal and wet conditions is much smaller; soil moisture conditions do not influence the occurrence of high temperature extremes in that region.

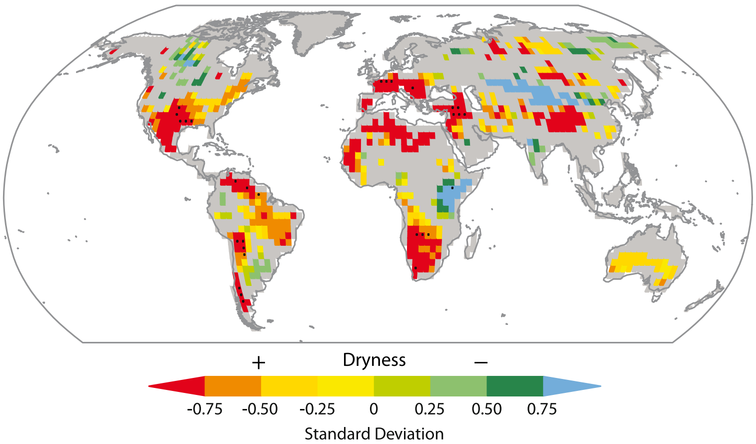

Figure 3: Model simulations of projected changes in soil moisture (or dryness) from 2081 to 2100 compared to values from 1980 to 1999, based on global climate simulations under the International Panel on Climate Change (IPCC) emission scenario SRES A2. Increased dryness is indicated with yellow to red colours, and decreased dryness with green to blue. Coloured regions show where more than 10 out of 15 models (>66%) agree on which way soil moisture will change (grey shading elsewhere).
Credit: IPCC 2012.

on model estimates and boreal summer evaluations (e.g. Koster *et al.* 2006). Our findings imply that with enough data, scientists could improve the prediction of very hot days or heat waves over a large part of the Earth's land surface, in both hemispheres.

Compare and contrast

We can compare two neighbouring regions, northern and southern Europe, to further illustrate the role of land-surface moisture conditions for temperature extremes (see Figure 2). Northern Europe is less sensitive to any shifts in soil moisture: that means that the region's total numbers of hot days don't really change, no matter whether the few months leading into the hottest summer months have been wetter or drier than usual. Meanwhile, southern Europe is more sensitive to shifts in soil moisture: the region gets a lot more hot days or cools more dramatically when the months leading up to summer are drier or wetter, respectively.

Southern Europe is what we would call a soil-moisture-limited evapotranspiration regime, and is a transitional region between wetter and drier climates overall. Meanwhile, northern Europe has a radiation-limited evapotranspiration regime, where soils are moister in general and sunlight (or lack thereof) drives changes in water levels in soil through evaporation.

But with climate change, regional sensitivities to soil moisture might change in ways we have yet to explore – in part because climate change could lead to changes in dryness (e.g. Seneviratne *et al.* 2006). Global climate models show that some regions might get wetter, while others dry out (see Figure 3). Although these projections remain ambiguous for now in most regions, models show consistently that some places like the Mediterranean are getting drier with warming global temperatures (Seneviratne *et al.* 2012, Orlowsky and Seneviratne 2012).

We need more data and a better understanding of relevant feedbacks and mechanisms within the climate system to assess more precisely what could happen in the future with droughts and climate extremes. One step forward will be an assessment of how soil moisture conditions have responded to past anthropogenic emissions that drive climate changes, and how they are likely to respond to future emissions.

The feedbacks identified in our work are a first step in this direction. These feedbacks also provide new angles for better seasonal forecasting of temperature extremes and the knowledge we will need to adapt to future climate changes.

With climate change, regional sensitivities to soil moisture might change.

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