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PERSPECTIVE

Hottest summers the new normal

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Abstract

With the rise in temperature due to anthropogenic climate change, the occurrence of hot summers, temperature extremes and heat waves is increasing globally. Projections for the coming decades to century indicate increases in the occurrence, magnitude and duration of these events. In a recent paper, Mueller *et al* (2016 *Environ. Res. Lett.* **11** 044011) showed that half of summers are expected to be 'hot' (warmer than the warmest on record) across much of the world in one or two decades. While these results are consistent with earlier work, what is new here includes (i) an earlier timing of emergence of the hot summer signal and (ii) additional confidence due to the rigorous statistical examination of the observations and the analyses of the latest improved suite of model experiments. The potential impacts of these projections on society are extremely serious.

Among all the consequences of global climate change, the rise in temperature is the most well known, understood and discussed. However, the potential impacts of global warming require analysis beyond global mean temperature increase. A small shift towards higher mean temperature, for example, can lead to increases in the occurrence of hot and extreme hot temperatures. As the mean temperature shift during summer months becomes larger in the coming decades, average summer temperatures can approach or exceed the threshold for what was considered 'hot' in the past.

Heat waves and hot summers have numerous socio-economic impacts regionally. While the definition of heat waves can vary, they are often implicated in the hottest summers and their consequences are well known [2]. In particular, health impacts in the most vulnerable populations are seen in hot summers, as well as in agriculture, power outages and wildfires [3]. The 2003 European heat wave, which led to thousands of deaths in western Europe, mainly in the elderly population, is one of the many examples of important impacts of heat waves [4, 5]. It is often asked whether these anomalously hot summers and heat waves are already more common than they were in the past, and also how frequently they might occur in the future. With a focus on food security, Battisti and Naylor [6] examined shifts in the probability distributions of model projected mean summer temperatures globally and found large areas in the tropics and subtropics where 50% of summers would be hotter than the hottest on record by mid-century, and more than 90% of summers would be as such by end of the 21st century. A similar question is posed again recently with updated climate projections by Mueller and co-authors, who take further steps to show recent observed hot summers in many regions are 10 times more likely to occur than without greenhouse gas forcing. They also examine the fraction of human population to be affected by the increasing frequency of the hottest summers.

Recent trends in global surface temperature are seasonally dependent with the largest regional contributor to global temperature trends over the past two decades being land surface temperatures in the northern hemisphere extra-tropics, especially during summer seasons [7]. On the other hand, there has been a continued increase of hot extremes over land and this trend is greater for the most extreme events [8]. These extreme heat events tend occur during heat waves, especially in urban areas [9]. While heat waves last a few days, the increase in their frequency and duration can be linked to the higher occurrence of the hottest summers. By the end of the 21st century climate model projections suggest increases in the frequency, magnitude and duration of heat waves [10]. These changes are a direct consequence of the increase in seasonal mean temperatures. The expected increase in temperature variability on intraseasonal to interannual time-scales will also contribute to the changes in the occurrence and characteristics of heat waves (e.g. [11]).

There is a high level of confidence in the attribution of heat waves to anthropogenic climate change, and a good understanding of the role anthropogenic climate change plays in heat waves, as discussed in the recently released National Academy of Sciences report on extreme events [12]. Already a rich literature is developing to attribute individual heat wave events to anthropogenic climate change, as exemplified by a discussion of the western Russian heat waves of 2010 using different methodologies [13], as well as heat waves in various regions of the globe in the past few years in the annual special supplement on extreme events of the Bulletin of the American Meteorological Society (e.g. [14]). Furthermore, in almost all of the 2014 heat wave events analyzed, an increase in the likelihood of their occurrence was found in regions across the world, including Australia, South Korea, Europe, China and Argentina [15].

Temperature extremes are amplified by soil-moisture feedbacks in the model projections, leading to the largest projected increases in the magnitude of warm extremes to be expected over mid-latitude continental areas [16, 17]. The occurrence of heat waves is also commonly associated with an atmospheric pattern known as blocking, in which a high-pressure system is locked in place for an extended period of time, allowing tropical air to move poleward and remain intact in the mid-latitudes. In a warming climate the question arises if atmospheric blocking will occur more often. The answer to this question is still a topic of debate [18, 19], with some scientists arguing for an increase of the blocking frequency related to Artic amplification [20, 21]. Others, however, do not encounter evidence for this in the current model projections [22, 23], or find a reduction of blocking frequency [24]. Further research into the physics of blocking, as well its response to anthropogenic forcing is clearly necessary in order to clarify the role of blocking in heat waves and the hottest summers in the future.

In their recent paper Mueller and co-authors [1] describe a worrisome picture for the world's population regarding summer temperatures. In their analysis, hot summers are defined as summers with higher mean temperatures than the historically hottest summer over a region. Their results indicate that 'within the next two decades, half of the world's population will regularly (every second summer on average) experience regional summer mean temperatures that exceed those of the historically hottest summer,' even under a moderate emissions pathway. This early occurrence of regular hot summers is a new and important result. Mueller and co-authors provide projections of likelihood of hot summers in various regions of the world using a statistical technique, which takes into account the models' performance during the historical period constraining future projections. This statistical analysis is another important feature of their analysis, which is posing the questions about hot summers on a more rigorous way. Their results suggest that the Sahara region will be the first to experience hot summers, with frequency of nine out of ten summers within fifteen years, due to the region's strong warming trend and low natural variability. Eastern Asia is another region that will be soon affected, with one out of two summers being hot by 2020. Hot summers are projected to soon be norm in the Mediterranean, large parts of Asia, as well as western US and Canada. In their analysis, under a stronger emissions pathway, half of the population will be affected by hot summers in only a decade.

Recently, the attribution of heat waves to anthropogenic warming has become widespread and frequent. Mueller and co-authors also show that hot summers are now about ten times more likely in many regions of the world than they would have been in the absence of greenhouse gases. They describe a world in which most people will suffer under frequent hot summers and that hot summers will become the norm for a large part of the world within one or two decades (depending on the emissions scenario). In the particular case of heath related deaths, Li and co-authors [25] showed that in the future hot summers could lead to a positive net increase of annual temperature-related deaths. There has been large observed trends in wildfires in the western US and continuing changes in climate are expected to contribute to larger, more frequent fires in the region [26]. While hot summers have substantial impacts on society, infrastructure and ecosystems, additional factors in a warming climate could moderate or further aggravate the effects of temperature increases. Human and ecosystem health, as well as agriculture often depend on the combined effects of humidity and temperature [27]. Future research will need to examine the combined influence of heat, humidity and wind changes on various impacts. Nevertheless, the results paint a grim picture and suggest greater urgency to both mitigate global warming and to prepare for the coming heat.

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