Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change

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Key Points:
• 22% of populated and agricultural areas of the Northern Hemisphere concurrently experienced hot extremes between May to July 2018
• These 2018 Northern-Hemispheric concurrent heat events could not have occurred without human-induced climate change
• We would experience a GCWH18-like event nearly two out of three years at +1.5 °C and every year at +2 °C global warming
Abstract

Extremely high temperatures pose an immediate threat to humans and ecosystems. In recent years, many regions on land and in the ocean experienced heatwaves with devastating impacts that would have been highly unlikely without human-induced climate change. Impacts are particularly severe when heatwaves occur in regions with high exposure of people or crops. The recent 2018 spring-to-summer season was characterized by several major heat and dry extremes. On daily average between May and July 2018 about 22% of the populated and agricultural areas north of 30 degrees latitude experienced concurrent hot temperature extremes. Events of this type were unprecedented prior to 2010, while similar conditions were experienced in the 2010 and 2012 boreal summers. Earth System Model (ESM) simulations of present-day climate, that is, at around +1 °C global warming, also display an increase of concurrent heat extremes. Based on ESM simulations we show that it is virtually certain (using IPCC calibrated uncertainty language) that the 2018 North-Hemispheric concurrent heat events would not have occurred without human-induced climate change. Our results further reveal that the average high-exposure area projected to experience concurrent warm and hot spells in the Northern Hemisphere increases by about 16% per additional +1 °C of global warming. A strong reduction in fossil fuel emissions is paramount to reduce the risks of unprecedented global-scale heatwave impacts.

1 Introduction

Record-breaking temperatures occurred concurrently in multiple regions including North America, Europe and Asia in late-spring/summer 2018 (NOAA, 2018a, 2018b, 2018c). Europe experienced late spring and summer temperatures that were more than 1°C warmer than 1981-2010 (Copernicus, 2019). The contiguous US had the warmest May since 1895 (NOAA, 2018c) and the hottest month ever observed was in July in the Death Valley (NOAA, 2018a). The 2018 hot temperatures are in line with an increase in intensity and frequency of extreme temperature events over many regions on land and in the ocean in recent years (Christidis, Jones, & Stott, 2014; Coumou & Rahmstorf, 2012; Fischer & Knutti, 2015; Frölicher, Fischer, & Gruber, 2018; Rowe & Derry, 2012; Seneviratne, Donat, Mueller, & Alexander, 2014). Owing to their devastating impacts, understanding changes in extreme temperature events is highly relevant for society and ecosystems. Recent heatwaves with particularly severe impacts include the 2010 Russian and 2015 Indian heatwaves. The 2010 Russian heatwave was associated with the death of tens of thousands of people, major crop failure, millions of hectares affected by fires and around 15 billion US$ economic loss (Barriopedro, Fischer, Luterbacher, Trigo, & García-Herrera, 2011). During the 2015 heatwave in India at least 2500 people died (Ratnam, Behera, Ratnajeevan, & Yamagata, 2016). Impacts were particularly severe because they occurred in agricultural regions and/or regions with high population density.

Given the tremendous impacts of recent heatwaves the question arises how much they can by attributed to human activities. Most recent heatwaves have been attributed to a smaller or larger extent to anthropogenic climate change (NAS, 2016). For instance, anthropogenic climate change has tripled the occurrence rate of heatwaves similar to the 2010 heatwave in Russia (Otto, Massey, van Oldenborgh, Jones, & Allen, 2012; Rahmstorf & Coumou, 2011). Heatwaves of the magnitude of the Indian heatwave in May/June 2015 are two to eight times more likely due to human-induced climate change (Wehner, Stone, Krishnan, AchutaRao, & Castillo, 2016). A near-real time attribution study concluded that the extreme heat in northern Europe in the 2018 summer was on average two times more likely due to human-induced climate change (World Weather Attribution, 2018). However, in these cases, as in many other heatwave attribution studies, natural variability cannot be excluded as a driver.
In the future, the intensity, frequency and global heatwave area over land are projected to drastically increase (Christidis et al., 2014; Coumou & Robinson, 2013). These projected increases can strongly affect future heatwave impacts and risk of concurrent extremes. While locally confined climate extremes often lead to devastating impacts at the local scale, spatially correlated extremes can have much more severe societal impacts due to their effect on integrated variables. For instance, concurrent heatwaves in different agricultural regions can affect global food production (Sarhadi, Ausín, Wiper, Touma, & Diffenbaugh, 2018) and consequently increase global food prizes and food insecurity (Tigchelaar, Battisti, Naylor, & Ray, 2018). Similarly, synchronized river floods can cause excessive damages (Berghuijs, Allen, Harrigan, & Kirchner, 2019).

In the present study, we investigate the exceptional nature of the 2018 North-Hemispheric heatwave in the context of anthropogenic climate change. We firstly synthesize reported heat-related impacts across the entire Northern Hemisphere in the spring to summer season. Subsequently, we investigate the fraction of the land area in the northern mid-latitudes that is either densely populated or used for agricultural production and that was affected by extremely hot conditions. We then study whether current Earth System Models simulate a 2018-like area fraction under present-day conditions and whether the event could have occurred without climate change. Finally we provide estimates of how such an event will develop under unabated global warming.

2 Material and Methods

2.1 Newspaper articles about heat-related impacts

We collected information from newspaper articles about heat-related impacts from the 2018 event. This does not include information about record-breaking temperatures, which were much more widespread. However, an exhaustive media overview was not the scope of this study.

2.2 Observation-based data

As an observational data basis, we use daily temperature from ERA-40 (40-yr European Centre for Medium-Range Weather Forecasts Re-Analysis) (Uppala et al., 2005) for the period 1958-1999 and ERA-Interim (European Centre for Medium-Range Weather Forecasts Interim reanalysis) (Dee et al., 2011) data for the period 1979-2018. We merged the ERA-40 and ERA-Interim data to cover a period from January 1958 until July/August 2018, with ERA-Interim starting in January 1979. We tested the consistency between ERA-40 and ERA-Interim by computing the root mean squared error and mean bias between both datasets for the overlapping period (1979-1999). Both metrics show rather small difference between the datasets, in particular in the study region (see Section 2.4 and Supplementary Figure S1).

2.3 Climate models

We use single runs from 29 climate models from the Coupled Model Intercomparison Project phase 5 (CMIP5) from the historical and future simulations (Taylor, Stouffer, & Meehl, 2012) under a high emission scenario (RCP8.5) from 1870-2100 (van Vuuren et al., 2011). We analyse daily air temperature (tas in CMIP5) over land to estimate concurrent hot days areas and also used sea surface temperature (tos in CMIP5) for computing global mean temperature (see below). The complete list of models is provided in Supplementary Table S1.
2.4 Study region

We focus on latitudes north of 30° of the “human-affected and -affecting” regions that either have a high population density (above 30 per square kilometer) or are important agricultural areas as defined in Seneviratne et al. (2018) with a total area of 23.7 million square kilometer. This study regions is referred to as NH AgPop area hereafter (Figure 1a).

![Figure 1a: Considered hot day area and time frame. (a) Regions north of 30° latitude that either have a high population density (at least 30 people per square kilometer) or are agricultural regions (NH AgPop area) are highlighted in grey.](image)

![Figure 1b: Annual time series of daily concurrent hot day area fraction of the NH AgPop area for 1959-1988 (grey) and 2018 (purple).](image)

**Figure 1.** Considered hot day area and time frame. (a) Regions north of 30° latitude that either have a high population density (at least 30 people per square kilometer) or are agricultural regions (NH AgPop area) are highlighted in grey. (b) Annual time series of daily concurrent hot day area fraction of the NH AgPop area for 1959-1988 (grey) and 2018 (purple).

2.5 Definition of hot days and concurrent hot days area

In this study we investigate the extensive spatially distributed heat impacts of the 2018 boreal summer as a single event. We compute the daily 90th temperature percentile using a 31-day moving window for the reference period 1958-1988, resulting in a 90th percentile climatology of the reference period for each model and the observed data. Each day between May and July that exceeds the temperature of the respective calendar day in the 90th percentile climatology is defined as a hot day. We then regrid results from each model to the NH AgPop area grid and only consider the NH AgPop area for subsequent analyses. The average concurrent hot days area of a year is then defined as the average daily spatial extent of locations that experience a hot day between May and July. To obtain relative concurrent hot days areas the average yearly concurrent hot days area is divided by the total area of the NH AgPop area. In addition to the concurrent hot days area between May to July we also compute the concurrent hot days area between May to August and May to September (Supplementary Figure S2).

2.6 2018 North-Hemispheric heat extreme

The daily concurrent hot days area fraction over the target region is illustrated in Figure 1a. For the base period from 1958-1988 the daily area fraction that is concurrently affected by extreme warm or hot conditions covers on average 10% of the focus region (since we define hot days based on 90th percentile exceedances, see Section 2.5). The 2018 area fraction exceeds the 1958 to 1988 areas by around a factor of 2 on average every day between May and July. The daily 2018 area peaks in the end of July reaching a maximum of 37.5% (Figure 1b). Hereafter, we focus on the temporal average between May
to July 2018 as considered Global Concurrent Warm and Hot 2018 event, in short, GCWH18 extreme event.

2.7 Event attribution

To estimate the human influence on climate extremes, a common approach is to compute the change in likelihood of events such as heatwaves, droughts and heavy precipitation events. Hereby, the ratio is calculated between the likelihood of the event in a climate with anthropogenic forcing ($p_{CC}$) and the likelihood in a reference period with smaller or no anthropogenic forcing ($p_0$) (Fischer & Knutti, 2015; NAS, 2016; Stott et al., 2016; Stott, Stone, & Allen, 2004). We quantify to what extent anthropogenic climate change has contributed to the probability of the GCWH18 event. To this end, we calculate the probability $p_0$ that the concurrent hot days area of 2018 would have occurred with little/without anthropogenic climate change. We further compute the probability $p_{cc}$ that the concurrent hot days area of 2018 occurred with climate change. The ratio between the two probabilities $\frac{p_{cc}}{p_0}$, often referred to as risk ratio or probability ratio, allows statements about the human contribution to the event (NAS, 2016). If $p_0 = 0$, that is, the probability ratio equals $\infty$, the event could not have occurred without anthropogenic climate change. We compute $p_0$ for exceeding different concurrent hot days areas between 0 and 65% for the reference period (1958-1988) for CMIP5 models and observations. Since the climate has already warmed since pre-industrial times by $+0.28 \degree C$, we perform the same computation for a pre-industrial period (1870-1900). We further compute $p_{cc}$ for different concurrent hot days areas for 31-year periods in which global warming reached $+1 \degree C$, $+1.5 \degree C$ and $+2 \degree C$ for the same area thresholds (this results in slightly different 30-year periods for each model). For comparison, we also compute $p_{cc}$ for the time period 1988-2018 (Supplementary Figure S3).

2.8 Global mean temperature

We estimate global mean temperature increase in CMIP5 models by computing 31-year moving averages of global mean temperature ($T_{glob}$) for all models between 1958 and 2100 and determine changes relative to the observational reference period 1958-1988. We estimate $T_{glob}$ as weighted mean between $tas$ over land and (dynamic) sea ice regions and sea surface temperature ($tos$ in CMIP5) over the oceans, similar to observations (also called “blended temperatures” (Cowtan et al., 2015)). The multi-model mean warming between the reference period and 1870-1900 is $+0.28 \degree C$ and is added to changes relative to the reference period. The warming levels of $1 \degree C$, $1.5 \degree C$ and $2 \degree C$ are determined as 31-year periods such that $T_{glob}$ in the center year is closest to the respective warming level. For the scaling of $T_{glob}$ with the concurrent hot days area, we relate the center year of each 31-year mean $T_{glob}$ with the its respective concurrent hot days area. We use a distance-weighting of each individual model to obtain values closest to the global mean temperature and then compute multi-model median and inter-quartile range. We then apply a linear filter by 0.1 $\degree C$ to smooth the data and improve the visual appearance.

3 Results

3.1 Concurrent 2018 heat impacts across the Northern Hemisphere

Between May and July 2018, heat-related impacts have been described for at least 18 countries in the northern mid-latitudes for a number of different sectors, Figure 2 showcases a number of reported impacts. The URLs and news agencies of the media articles are provided in Table 1. Affected countries include Canada and the United States in North America, many European countries, as well as Russia, China, Japan and South Korea in Asia. The wide spatial extent of impacts illustrates the global dimension of the ex-
xtreme temperatures. News agencies reported direct heat-related impacts on humans, but also on agriculture, power plants and infrastructure (Figure 2b). For instance, in Quebec, more than 70 people died from heat strokes. In the United States, around 35 million people lived with regular heat warnings through July. In Japan, at least 30 people died and more than 2500 were sent to hospital. Devastating fires destroyed vast amounts of intact forests in Canada, the United States, Norway, Sweden, Finland, Latvia, Greece and South Korea. The hot temperatures also caused crop loss particularly for grains in Germany, Russia, Switzerland and the United Kingdom. The heatwave conditions further led to power shortages and reduction in power production in the United States, Germany, France and Switzerland. Roads melted and train tracks buckled in the Netherlands and the United Kingdom.

Table 1. Overview of media articles for heat-related impacts 2018

| Reference | Press agency | Country | Article URL | Published |
|-----------|--------------|---------|-------------|-----------|
| a         | New York Magazine | United States | http://nymag.com/daily/intelligencer/2018/07/a-global-heat-wave-has-set-the-arctic-circle-on-fire.html | 20 July |
| b         | Deutsche Welle | Germany | https://www.dw.com/en/the-global-heat-wave-thats-been-killing-us/a-44699601 | 18 July |
| c         | Canadian Broadcasting Corporation (CBC) | Canada | https://www.cbc.ca/news/caitlin-columbia/state-emergency-bc-wildfires-1.4803546 | 30 August |
| d         | XinhuaNet | China | http://www.xinhuanet.com/english/2018-07/31/c137359563.htm | 31 July |
| e         | The Guardian | United Kingdom | https://www.theguardian.com/environment/2018/au/31/http://www.theguardian.com/environment/2018/au/31/heatwave-sees-record-high-temperatures-set-around-world-this-week | 19 August |
| f         | Los Angeles Times | United States | http://www.latimes.com/world/la-fg-wildfires-europe-20180728-story.html | 28 July |
| g         | British Broadcasting Corporation (BBC) | United Kingdom | https://www.bbc.com/news/world-europe-45070499 | 6 August |
| h         | Bloomberg | United States | https://www.bloomberg.com/news/features/2018-07-25/heatwave-hits-commodities-from-crops-in-texas-to-french-power | 25 July |
| i         | Frankfurter Allgemeine Zeitung (FAZ) | Germany | http://www.faz.net/aktuell/wirtschaft/stromproduktion-getroesselt-kraftwerke-wegen-hitzes-vorabschaltung-1709562.html | 26 July |
| j         | Japan Times | Japan | https://www.japantimes.co.jp/news/2018/07/23/national/temperature-tokyo-hits-nationwide-high-year-mercury-rises-40-8-western-city-one/#.W3pq5Jx9jOG | 23 July |
| k         | Washington Post | United States | https://www.washingtonpost.com/news/capital-weather-gang/wp/2018/08/11/red-hot-planet-this-summer-punishing-and-historic-heat-in-7-naps-and-charts/?noredirect=on&utmterm=.e878c76a8f3a | 17 August |
| l         | The Guardian | United Kingdom | https://www.theguardian.com/environment/2018/jul/13/heatwave-sees-record-high-temperatures-set-around-world-this-week | 13 July |
| m         | Tagesanzeiger | Switzerland | https://www.tagesanzeiger.ch/wirtschaft/unternehmen-kon-junktur-hitze-fuehrt-anerheblichen-ernteausfaellen/story/10299748 | 27 July |
| n         | 20 Minuten | Switzerland | https://www.20min.ch/schweiz/news/story/ AKW-Muehleberg-drosselt-Leistung-wegen-Hitzewelle-11777563/1?predirect | 27 July |
| o         | The Guardian | United Kingdom | https://www.theguardian.com/uk-news/2018/jul/01/ten-top-facts-about-uk-summer-weather-heatwave | 1 July |

1Last access for all articles 7 May 2019.
Figure 2. Heat-related impacts in 2018 as reported by news agencies. (a) Approximate locations of heat-related impacts in the northern mid-latitudes (above 30 degrees north). The impacts are categorized according to heat impact (cross, purple text), fires (fire, red text), agricultural and ecological damages (wheat, orange text), damages to infrastructure (railway track, brown text) and impacts on power production reduction/shortage (warning signal, blue text). (b) Detailed heat-related impacts per country. The color refers to the categories in (a). The sources where this information is taken from are listed in Table 1.
3.2 Extensive 2018 North-Hemispheric concurrent hot days area

Between May and July 2018, some regions experienced hot days for up to two months, including Scandinavia, central Europe and the United States (Figure 3a). The mean temperature anomaly of the hot days in these regions was up to 0.7 °C warmer than the 90th percentile daily temperatures in the reference period (Figure 3b). Because of the associated exposure, heatwave impacts were particularly severe over the NH AgPop regions (see Section 2.5).

Between May and July 2018, a daily average of about 22% of the NH AgPop area experienced a heatwave (Figure 4a). This extreme spatial extent of the GCWH18 event is unprecedented in the observational record when considering heatwave between May and July, and nearly 8% larger then the second largest event of this kind in 2012. Computing the concurrent hot days area between May to August, 2010 and 2018 have a similar extent (23% and 22%, Figure S2a) and also for May to September (both 21%, Figure S2b).

For the high-emissions scenario (RCP8.5, Section 2.3), the average concurrent hot days area during May and July is projected to cover more than 70% (multi-model median) of the NH AgPop area every day at the end of the 21st century (Figure 4b). The average concurrent hot days area scales approximately linearly with global mean temperature increases between +1 °C and +4 °C, with an increase of about 16% of the NH AgPop area per °C warming (Figure 4c). The warming in 2018 in the CMIP5 models since 1870-1900 is about +1.2 °C, which is slightly larger than current estimates based on observations (IPCC, 2018), and is related to data coverage, the choice of reference period and interannual variability (see Section 4).

3.3 Human influence on the 2018 concurrent hot days area

The intense warming over the last decades has strongly shifted the odds of experiencing a GCWH18-like event and we determine the human influence on a GCWH18-like area. A 2018-like event with an average 22% concurrent hot days area between May and July is not uncommon in climate simulations of a present-day climate with anthropo-
Figure 4. Temporal evolution of average concurrent hot days areas between May and July in observations and Earth system models. (a) Observed average concurrent hot days area between May and July in percent of the NH AgPop area for the time period 1958 to 2018. (b) Modeled average concurrent hot days area from 1958 to 2100 based on CMIP5 models. The observed time series is shown in black, the range of (a) is highlighted in grey. (c) Modeled concurrent hot days area as a function of global mean temperature (Tglob) increase (see Section 2.8). The 2018 event is highlighted by a horizontal purple line in each subpanel. For the models, we used a high-emission scenario (RCP8.5). We show the model median (grey), interquartile range (IQR, red) and the full model range (yellow).
Figure 5. The 2018 North-Hemispheric concurrent heat extremes in an attribution framework. Shown are average North-Hemispheric concurrent hot days area thresholds (May to July) relative to the full NH AgPop area (0 to 65%) versus probabilities of exceeding that concurrent hot days area. The GCWH18 area is highlighted by a vertical purple dashed line in each sub-panel. (a) Probabilities for exceeding concurrent hot days areas in the reference period 1958-1988 ($p_0$) for the multi-model ensemble (grey range) and observations (black line). The grey arrow indicates concurrent hot days area thresholds where $p_0 = 0$ and thus the probability ratio $p_{cc}/p_0$ is infinity independent of $p_{CC}$. (b) Probabilities for exceeding concurrent hot days areas in the pre-industrial period 1870-1900 ($p_0^*$). Each grey line represents one model simulation ($n = 29$). (c) Multi-model range of probabilities for exceeding concurrent hot days areas for global warming of +1 °C (orange), +1.5 °C (red) and +2 °C (dark red) with respect to 1870-1900. The boxplots indicate the distributions of the exceedance probabilities of the multi-model ensemble for the 2018-like concurrent hot days area (22%) for the different warming levels.

Pogonic forcing ($p_{CC} > 0$). However, it does not occur in the model simulations of the reference period about 50 years earlier with much smaller anthropogenic forcing ($p_0 = 0$). Thus, conditional on the analysed climate models, the probability ratio of this event is infinity. Hence, the analysis based on the 1958-1988 reference period suggests that average concurrent hot days areas that exceed 20% of the NH AgPop area could not have occurred without human-induced climate change. For the reference period, the observed probabilities of exceeding specific average concurrent hot days areas fall within the model range, which provides confidence in the model simulations of concurrent hot days areas with large extent (Figure 5a). However, this reference period is relatively short and already includes a mean warming signal of about 0.3 °C compared to the pre-industrial period 1870 to 1900. During that period, the occurrence of a 2018-like heatwave occurs in two years in one out of 29 models (Figure 5b). Hence, considering all model simulations, this results in an approximately 0.2% probability for a GCWH18-like area to have occurred under pre-industrial conditions. These findings confirm that it is virtually certain (Mastrandrea et al., 2010) that the 2018 heat event would not have occurred without human-induced greenhouse gas emissions.

North-hemispheric 2018-like or larger heatwave areas are rare in today’s climate (+1 °C mean warming (IPCC, 2018)), with a likelihood of occurrence of 16% in the multi-
Figure 6. North-Hemispheric concurrent hot days area thresholds (May to July) relative to the full NH AgPop area (0 to 65%) versus multi-model range of probabilities of exceeding that concurrent hot days area for global warming of +1 °C (a), +1.5 °C (b) and +2 °C (c) with respect to 1870-1900. The GCWH18 area is highlighted by a vertical purple dashed line in each subpanel. The boxplots indicate the distributions of the exceedance probabilities of the multi-model ensemble for the 2018-like concurrent hot days area (22%) for the different warming levels.

model median (Figure 6a). Using a present-day period from 1988-2018 (with RCP8.5 forcing after 2005), the multi-model median probability of a GCWH18-like event is reduced to 6% (Supplementary Information Figure S3).

In a +1.5 °C and +2 °C world, the probability of experiencing a heatwave with at least the size of the GCWH18 event increases to 65% (Figure 6b) and 97% (Figure 6c) in the multi-model median, respectively. This implies that even if global warming is limited to +1.5 °C, we would experience a GCWH18-type event on average nearly two out of three years and nearly every year at +2 °C warming.

4 Discussion and conclusions

Over the recent decades we have seen a strong increase in land areas that are concurrently affected by warm and hot temperatures (Figure 4a). The four largest events in the observational record occurred within the last 12 years, consistent with a strong
recent increase in heatwave occurrence (Christidis et al., 2014; Rowe & Derry, 2012; Seneviratne et al., 2014). Generally, the large interannual variability of concurrent heatwave occurrence can be driven by different processes. While years with El Niño events are typically associated with warmer temperatures at a global scale (Seneviratne et al., 2014), this effect is less relevant for the boreal summers in the NH AgPop region. Furthermore, changes in large-scale circulation and land–atmosphere feedbacks could increase the areas concurrently experience warm and hot temperatures. A recent study shows that in 2018 a specific atmospheric pattern connected heatwaves in North America, Western Europe and the Caspian Sea region (Kornhuber et al., 2019). Additionally, central Europe experienced concurrent dry and hot conditions from spring to summer in 2018 that were exceptional at least within the last 500 years (Toreti et al., 2019). The dry conditions in central and Northern Europe possibly amplified extreme temperatures in these regions via land-atmosphere feedbacks.

Overall, our results suggest that we have entered a new climate regime in which the occurrence of extraordinary global-scale heatwaves cannot be explained without human-induced climate change. In particular, the simulations show that a GCWH18-like event does not occur in historical simulations. The saturation effect of the probability ratio will become more dominant in a warmer climate where unprecedented events will have a probability ratio in the mathematical limit of $p_{\text{cc}}/p_{0} = \infty$ (Harrington & Otto, 2018).

The importance of global warming targets for limiting the occurrence of global-scale heatwaves becomes even more apparent when considering climate model projections. We find that the probability of devastating 2018-like areas to occur will increase drastically (from 65% to 97%) if global mean temperatures shift from +1.5 °C to +2 °C. This is consistent with the recently approved IPCC special report on Global Warming of 1.5 °C, which finds significantly stronger climate-related impacts for +2 °C compared to +1.5 °C warming (IPCC, 2018).

However, determining impacts conditioned on global mean temperature targets is not free of uncertainties. Using only 2-m air temperature ($tas$ in CMIP5) for computing $T_{\text{glob}}$ leads to an overestimation of the CMIP5 multi-model median of global mean temperature of 0.18 °C compared to observed temperatures for the time period 2000-2009 with respect to 1861-1880 (Richardson, Cowtan, Hawkins, & Stolpe, 2016). This offset is partly related to a reduced coverage in the observations (Cowtan et al., 2015). For instance, Antarctica is not well covered by observations and warms faster than the global average (Cowtan & Way, 2014). It is not clear how the coverage will change in future, hence here we consider the whole globe instead of assuming future changes in coverage. In addition to the effects of data coverage, observation-based estimates of global mean temperature use air temperature over land and sea ice but sea surface temperatures over oceans (Cowtan et al., 2015; Medhaug, Stolpe, Fischer, & Knutti, 2017; Richardson et al., 2016). To account for this, we compute $T_{\text{glob}}$ as “blended temperatures” (Cowtan et al., 2015), that is, using air temperature over land and (dynamic) sea ice regions and sea surface temperature over the oceans (see Section 2.8). This leads to a present-day warming of +1.22 °C compared to +1.29 °C when only $tas$ is considered (Supplementary Figure S3). Further differences between models and observations can be related to internal climate variability, overestimated radiative forcing in models and model response error (Flato et al., 2013). Observations themselves are also uncertain with differences in mean global warming in the early 2000s of up to +0.4 °C (Medhaug et al., 2017). Finally, the global mean temperature change also depends on the pre-industrial reference period, which can lead to a shift of a decade to reach a specific warming level (Hawkins & Sutton, 2016). Overall, because of these systematic differences between CMIP5 models and observations, our estimates of future exceedance probabilities at specific global mean temperature targets are conservative estimates.

Our results demonstrate that the GCWH18 extreme event could not have occurred without human-induced climate change. Due to taking averages over large areas, the signal-
to-noise ratio is high for such events, and we could exclude that it could have occurred as part of natural variability. To our knowledge, so far only for marine heatwaves it could be concluded that their occurrence would not have been possible without climate change (Oliver, Perkins-Kirkpatrick, Holbrook, & Bindoff, 2018; Perkins-Kirkpatrick et al., 2019). Thus the GCWH18 event possibly constitutes the first climate phenomenon on land that has been uniquely attributed to human-induced global warming.

Heatwaves will likely reach highly dangerous levels for ecosystems and societies over the coming decades. However, if other factors that contribute to such impacts change as well, assessing environmental risks associated with heatwaves becomes much more complex. For instance, the impact of expanding concurrent hot days areas is often aggravated by population increases. In the United States, population exposure to extreme heat has increased four to six fold in the late 20th century due to a combined increase in temperatures and population growth (Jones et al., 2015).

In contrast to the local heat impacts on population, widely spread agricultural regions can serve as an integrator of heat-related impacts on crop yields (Lobell & Field, 2007). Concurrent heat extremes in different agricultural regions can amplify heat impacts as simultaneous production shocks can increase global food prizes and food insecurity (Tigchelaar et al., 2018). Multiple heatwaves that occur subsequently in the same region can amplify heatwave impacts and are projected to increase with global warming (Baldwin, Dessy, Vecchi, & Oppenheimer, 2019). Furthermore, a higher probability of experiencing a heatwave naturally increases the likelihood of compound extremes. In particular, the co-occurrence rate of compound drought-heatwave events will increase even if there is no trend in drought occurrence (Diffenbaugh, Swain, & Touma, 2015; Zscheischler & Seneviratne, 2017) and may exacerbate heat-related impacts (Miralles, Gentine, Seneviratne, & Teuling, 2018; Seneviratne et al., 2010). Such compound events in space and time are challenging to analyze but require immediate attention because climate change will shift many aspects of those events (Zscheischler et al., 2018).

The provided scaling relationship for concurrent hot days areas (Figure 4c) can help to assess future risk of heat-related impacts. However, it also illustrates that concomitant heatwaves in large parts of the inhabited and agricultural land area in the northern mid-latitudes can be effectively prevented by limiting global warming. To avoid major future impacts associated with human-induced global heatwaves, we have to take ambitious mitigation actions to strongly reduce greenhouse gas emissions.

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| Country    | Reported heat-related impact                                                                 | Source |
|------------|---------------------------------------------------------------------------------------------|--------|
| Canada     | Quebec, 90 deaths in early July, more than 70 deaths                                         | a, b   |
|            | British Columbia, wildfires, more than 12,984 km²                                           | c      |
| China      | heat warnings                                                                              | d      |
| Finland    | Lapland, wildfires                                                                         | e, f   |
| France     | heat warnings                                                                              | d      |
|            | closing of 4 nuclear power plants, reduction of nuclear power production                     | g, h   |
| Germany    | reduction of some power plants, reduction of power production from 3 coal-fired power plants | h, i   |
| Greece     | 91 deaths (heat strokes, forest fires)                                                       | e      |
|            | 80 deaths due to wildfires, more than 90 deaths due to wildfires                            | f, g   |
| Japan      | 30 deaths, 119 deaths (heat strokes, forest fires), 77 heat deaths                           | b, e, j|
|            | 2,605 sent to hospitals in Tokyo, 30,000 people hospitalized                                | a, j   |
| Latvia     | wildfires, 1,600 acres                                                                      | f      |
| Netherlands| melting of roads                                                                            | g      |
| Norway     | wildfires                                                                                  | f      |
| Portugal   | heat/fire warnings                                                                         | g      |
|            | forest fires, more than 1,000 hectares in Algarve                                           | g      |
| Russia     | crop loss                                                                                  | h      |
| South Korea| 29 death (heat strokes, forest fires)                                                       | e      |
| Spain      | 3 deaths (heat strokes)                                                                     | g      |
|            | fires                                                                                      | g      |
| Sweden     | 49 fires, 62,000 acres, dozens of wildfires                                               | a, f, g|
|            | health warnings                                                                            | f      |
| Switzerland| crop loss                                                                                  | m      |
|            | reduction of nuclear power production in Muehleberg                                        | n      |
| United Kingdom | wildfires, blazes, threat for garden birds, increase in the number of bloodsucking horseflies | b, o   |
|            | crop failure                                                                               | o      |
|            | melting of roads, buckling of train tracks                                                | o      |
|            | melting of the roof of a building                                                          | o      |
|            | reduction of power production of natural gas plants                                       | h      |
| United States | heat warnings for 35 million people                                                       | a      |
|            | California, 9 deaths (heat strokes, forest fires)                                          | e      |
|            | New York City, at least 90,000 students who fail exams due to heat                         | b      |
|            | California, wildfires, 750,000 acres                                                       | k      |
|            | power shortage                                                                             | o      |
Probability ratio = \frac{p_{cc}}{p_0}

1958–1988 [p_0]

ERA 1955–1988

ERA 2018

Probability ratio = \infty

1870–1900 all simulations
| Country       | Reported heat-related impact                                                                                                                                                                                                 | Source |
|---------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
| Canada        | Quebec, 90 deaths in early July, more than 70 deaths                                                                                                                                                                         | a, b   |
|               | British Columbia, wildfires, more than 12,984 km²                                                                                                                                                                           | c      |
| China         | heat warnings                                                                                                                                                                                                              | d      |
| Finland       | Lapland, wildfires                                                                                                                                                                                                           | e, f   |
| France        | closing of 4 nuclear power plants, reduction of nuclear power production                                                                                                                                                     | g, h   |
| Germany       | reduction of some power plants, reduction of power production from 3 coal-fired power plants                                                                                                                                     | c, h, i|
| Greece        | 91 deaths (heat strokes, forest fires)                                                                                                                                                                                          | e      |
|               | 80 deaths due to wildfires, more than 90 deaths due to wildfires                                                                                                                                                             | f, g   |
| Japan         | 30 deaths, 119 deaths (heat strokes, forest fires), 77 heat deaths                                                                                                                                                            | b, e, j|
|               | 2,605 sent to hospitals in Tokyo, 30,000 people hospitalized                                                                                                                                                                   | a, j   |
| Latvia        | wildfires, 1,600 acres                                                                                                                                                                                                          | f      |
| Netherlands   | melting of roads                                                                                                                                                                                                             | g      |
| Norway        | wildfires                                                                                                                                                                                                                 | f      |
| Portugal      | heat/fire warnings                                                                                                                                                                                                           | g      |
|               | forest fires, more than 1,000 hectares in Algarve                                                                                                                                                                             | g      |
| Russia        | crop loss                                                                                                                                                                                                                 | h      |
| South Korea   | 29 death (heat strokes, forest fires)                                                                                                                                                                                          | e      |
| Spain         | 3 deaths (heat strokes)                                                                                                                                                                                                          | g      |
| Sweden        | 49 fires, 62,000 acres, dozens of wildfires                                                                                                                                                                                  | a, f, g|
|               | health warnings                                                                                                                                                                                                            | f      |
| Switzerland   | high fish mortality in the Rhine                                                                                                                                                                                               | m      |
|               | crop loss                                                                                                                                                                                                                 | m      |
|               | reduction of nuclear power production in Muehleberg                                                                                                                                                                           | n      |
| United Kingdom| wildfires, blazes                                                                                                                                                                                                            | b, o   |
|               | threat for garden birds, increase in the number of bloodsucking horseflies                                                                                                                                                     | o      |
|               | crop failure                                                                                                                                                                                                              | b      |
|               | melting of roads, buckling of train tracks                                                                                                                                                                                  | o      |
|               | melting of the roof of a building                                                                                                                                                                                              | o      |
|               | reduction of power production of natural gas plants                                                                                                                                                                          | h      |
| United States | heat warnings for 35 million people                                                                                                                                                                                           | a      |
|               | California, 9 deaths (heat strokes, forest fires)                                                                                                                                                                             | e      |
|               | New York City, at least 90,000 students who fail exams due to heat                                                                                                                                                           | b      |
|               | California, wildfires, 750,000 acres                                                                                                                                                                                        | o      |
|               | power shortage                                                                                                                                                                                                             | o      |

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Probability ratio $= \frac{p_{cc}}{p_0}$

1958–1988 [$p_0$]

ERA 1955–1988

ERA 2018

Probability ratio $= \infty$

1870–1900 all simulations
a

Probability \([p]c\)

Area [%]

0 0.2 0.4 0.6 0.8 1

10 20 30 40 50 60

+1 °C

ERA 2018

b

Probability \([p]c\)

Area [%]

0 0.2 0.4 0.6 0.8 1

10 20 30 40 50 60

+1.5 °C

c

Probability \([p]c\)

Area [%]

0 0.2 0.4 0.6 0.8 1

10 20 30 40 50 60

+2 °C

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