From 1.5ºC to 2.0ºC: the global increase in cooling degree days

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Abstract

This paper shows the impact on global cooling demand of moving from a 1.5ºC to 2.0ºC temperature increase. African countries have the highest increase in cooling requirements. The United Kingdom, Switzerland, and Norway (traditionally unprepared for extreme heat) will suffer the largest relative cooling demand surges.

Main

This work identifies hot spots of future global cooling energy demand using 2100 simulation runs of the global mean surface temperature through HadAM4[1,2] across three global warming scenarios: historical (2006-2016), 1.5ºC, and 2ºC. Rising extreme heat is already driving a surge in cooling demand, with the energy required for cooling by 2050 predicted to be equivalent to the combined electricity capacity of the United States, European Union and Japan in 2016[3]. But how much more cooling would be required if the Paris Agreement's[4] preferred 1.5ºC limit is overshot, and instead, warming increases to 2.0ºC? The question is urgent, given the growing consensus that there is currently 'no credible pathway to avoid 1.5ºC of warming[5]'.

Cooling degree days (CDDs) are widely used to examine warming and quantify cooling demand. Here, we map the CDDs and examine countries the most affected by 2.0ºC, instead of 1.5ºC, of warming. These are identified by absolute and relative cooling demand increases. Absolute changes show where human exposure to hotter weather will be severe. Relative changes indicate large adaptation challenges in regions not traditionally prepared or accustomed to the heat.

Previous work has mainly reported CDDs using historical data[6,7]. Model-based studies for specific areas of the world have been reported[8–11]. Global model data has only been analysed for specific years, leaving an important gap in predicting cooling demand in 1.5ºC and 2.0ºC scenarios. To calculate CDDs, we simulate 10 years per scenario using the citizen-science project climateprediction.net[12] (CPDN), obtaining 6-hourly mean temperatures at a spatial resolution of 0.883º x 0.556º.

Results

Figure 1a maps the difference in CDDs between 1.5ºC and 2.0ºC scenarios, while Table 1a highlights the top ten countries with more than 5 million inhabitants that will experience the largest changes (SI includes the top 100 countries with more than 1M population). To examine variability, we map the standard deviation of results in SI.

The results show that regions surrounding the Equator, particularly the Sub-Saharan region, will experience the largest increase in cooling demand (Fig. 1a). Table 1a shows that nine African countries are among the ten nations with the largest change in CDDs. These countries align in a west-east band in central Africa. They mainly border Mauritania, Niger, and Sudan, identified by Biardeau et al.[6] to have the highest extreme heat historically. Mali and Chad experience the combined highest historical CDD[6] and increment in CDDs from a 1.5ºC to a 2.0ºC scenario. The central African population not only has had the highest requirements for cooling historically (2009–2018)[6] but will also experience the highest surge in these needs.

Notably, the results of relative changes in CDDs (Fig. 1b and Table 1b) show that the Global North will experience dramatic relative increases in the number of days that require cooling. Table 1b is the first to rank the top ten most affected countries by their relative increases in CDDs. Nine of ten are European nations, which are traditionally unprepared for high cooling demand and will require large-scale adaptation to heat resilience.

The United Kingdom will see the largest relative variation in cooling demand (31%) globally. However, current cooling studies for the UK are, at best, limited[13]. Only one 2009 predictive study is found[14], which aligns with the large relative change of our results (but for different temperature increases), and reports that the energy (and emissions) from air conditioners almost double from 2004–2030 in London. For Switzerland (the country with the second largest relative increase in CDDs), two previous studies[15,16] have warned of the accelerating demand for cooling (compared to heating demand). Those results were not set in the global context that we provide.

A published study examining predictions of CDD in Europe[17] reports absolute and relative changes in CDDs between Representative Concentration Pathways (RCP45 and RCP85) at different years (< 2100) and historical data (1986–2005). They model temperature at different years, rather than our model, which forces specific global warming scenarios. Like our results, they find that the highest absolute increase in Europe is in Mediterranean countries. However, there are no relative changes reported. One study is found to report European CDDs (i.e., Mediterranean) in a 2.0ºC scenario (with spatial resolution > 200km^2)[18], reporting that the further south (i.e., northern Africa) increases the absolute CDD change.

Other large regions of high CDD relative increase are the mountain ranges of the Andes in South America, crossing the continent from North to South, and the Himalayas in Central Asia, which extend into the Southwest of China. Previous CDD predictions[19] for China under different RCP scenarios did not highlight this region for its relative increase in cooling demand.

Discussion

An increasing number of stocktake studies[5] make clear that avoiding a global increase in temperature of 1.5ºC is increasingly out-of-reach. We show that moving from a 1.5ºC to 2.0ºC warmer planet would dramatically exacerbate heat exposure and energy demand for cooling. There has already been an increase in global surface temperature of 1.09°C above pre-industrial levels between 2011–2020[4,21]. The total difference in cooling demand from today to a 2.0°C warmer planet would thereby be larger than what we have mapped.

The differences in CDDs reported are built on the largest ensemble of 700 simulations per scenario, and at the highest temporal resolutions of temperatures. The 6-hourly temperature predictions result in aggregated high granularity of cooling demand variations. The geographical resolution of 0.833x 0.556º allows examining the whole planet under one lens while managing the computational intensity of large datasets.

The map of absolute changes in CDD identifies African countries as those that will experience the highest increase in cooling demand. This would further pose stress the continent's socio-economic development and energy networks, particularly given the limited literature on this rising threat in the African context. Further, the results on relative changes indicate that countries that will experience the most drastic increases in CDDs are traditionally prepared for heating, not cooling. These countries will require rapid adaptation to make their populations and built environment more heat resilient, with broad cooling access through sustainable supply chains[22,23].

The main limitation of the CDD metric is that it is not a direct proxy for energy demand. Further economic-demographic or technical factors are needed for energy estimations from CDD, e.g., other weather parameters, building archetypes, population, and cultural behaviours. However, it is useful here to enable a top-down comparison of climate exposure between countries.

Several policy implications stem from these results. First, this work clearly indicates that every small increase in global warming will affect heat exposure and cooling demand worldwide, driving the need for quick and unprecedented adaptations. Second, it is in the national interest of countries, including in the Global North, to work towards the 1.5ºC target, given that they will be the most affected by the relative change in CDDs. Current planning and implementation of energy policies and energy systems across countries must be designed to be prepared for and resilient to a hotter climate. It is important to recognise that cooling demand can no longer be a blind spot in sustainability debates and rather must be addressed through socio-technical levers of change[24] which support sustainable cooling and heating needs holistically.

Table 1

Ranking of the top ten countries that will suffer a higher increase (absolute and relative) in area-weighted mean CDDs from 1.5ºC to 2.0ºC.

a, Top ten countries by absolute change	*abs-ΔCDD_{18}*	**b, Top ten countries by relative change**	*rel-ΔCDD_{18}*
Central African Republic	266	United Kingdom	31%
Hong Kong	256	Switzerland	30%
Burkina Faso	254	Norway	30%
Mali	253	Sweden	28%
South Sudan	251	Finland	28%
Nigeria	245	Denmark	27%
Congo	241	Canada	25%
Democratic Republic of The Congo	240	Austria	24%
Chad	236	New Zealand	24%
Uganda	234	Netherlands	21%

Countries with more than 5 million inhabitants in 2020[25] are listed. Annual CDDs were calculated using a temperature baseline of 18°C. The rankings use the area-weighted mean values per country rather than grid-specific relative values, as the latter can distort results with large percentage values for specific latitude-longitudes that go from no/negligible CDDs in a 1.5ºC to having significant CDDs in a 2.0ºC.

Methods

Ensembles of 700 climate simulations for three global scenarios were generated using the HadAM4 Atmosphere-only General Circulation Model[1,2] (AGCM) from the UK Met Office Hadley Centre. The scenarios followed the half-a-degree additional warming prognosis and projected impacts (HAPPI) experiment design protocol[26], being: historical (2006-16), 1.5ºC and 2ºC above pre-industrial levels. The simulations output 6-hourly mean temperatures at a horizontal resolution of 0.833 longitude and 0.556 latitude. This simulation experiment ran within the climate*prediction*.net (CPDN) climate simulation environment[12]. CPDN uses the Berkeley Open Infrastructure for Network Computing (BOINC)[28] framework, tasking more than 30,000 globally distributed volunteer members of the public.

Biases in simulated temperature were identified and corrected using a quantile mapping approach[29]. The bias correction was performed through a cumulative distribution function-transform method of the entire ensemble and using reference temperature data from ERA5[30] for the same timeframe of the historical scenario. Biases are calculated for each percentile in the cumulative distribution function from the historical scenario compared with ERA5 observations. Then, the calculated biases are added to the simulations of the historical, 1.5ºC and 2ºC scenarios to correct the biases of each percentile. This ensures the preservation of the ensemble's internal variability, and the cumulative distribution of the ensemble aligns with the cumulative distribution of the observations. In turn, this implicitly means that biases are entirely comprised in the model uncertainties[31], assuming that the bias is unchanging between scenarios.

Cooling degree days (CDDS) were calculated for the ensemble members (700 runs per scenario) in all coordinates as follows:

$$CDD = \frac{\sum_{t=0}^{m} (T_t - T_{base})}{n}, T_t > T_{threshold}$$

1

where t is the time step, n is the number of time steps in one day (n = 4, given 6-hourly data), T_t is the mean outdoor temperature at time t, T_{base} is the reference temperature used to calculate the temperature difference, and $T_{threshold}$ is the outdoor temperature above or below which one starts to calculate the temperature difference. $T_{threshold}$ and the baseline temperature, T_{base}, was defined as 18ºC. This methodology can have several modifications depending on available data, context and application[32].

Then, annual mean CDDs and standard deviation per coordinate were obtained for the 1.5ºC and 2ºC scenarios, and deltas were computed. Finally, the area-weighted statistics per country were calculated using QGIS geographic information system.

The Supplementary Information provides additional results from the analysis.

Declarations

Data and code availability

The data of absolute and relative changes in CDD (to reproduce the maps of this work) are found in the Oxford University Research Archive ORA at https://doi.org/10.5287/bodleian:pd8XeZB5N.

Further data and Python code are available from the authors on request.

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Author contributions

NM and JL contributed equally. NM and JL coordinated the study and performed the data pre-processing and data analytics of the models. They developed the bias correction, final statistics, visualisations, and jointly wrote the manuscript draft. SS and DW ran the CPDN model, and led the extraction of data. SS provided expertise in data analytics and bias correction. MZW extracted data from the model. RK, DW and MM conceptualised the work, and proposed and reviewed the content of the manuscript.

Competing interests

The authors have no competing interests to declare.

Additional information

Supplementary information is available for this paper.

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Figures

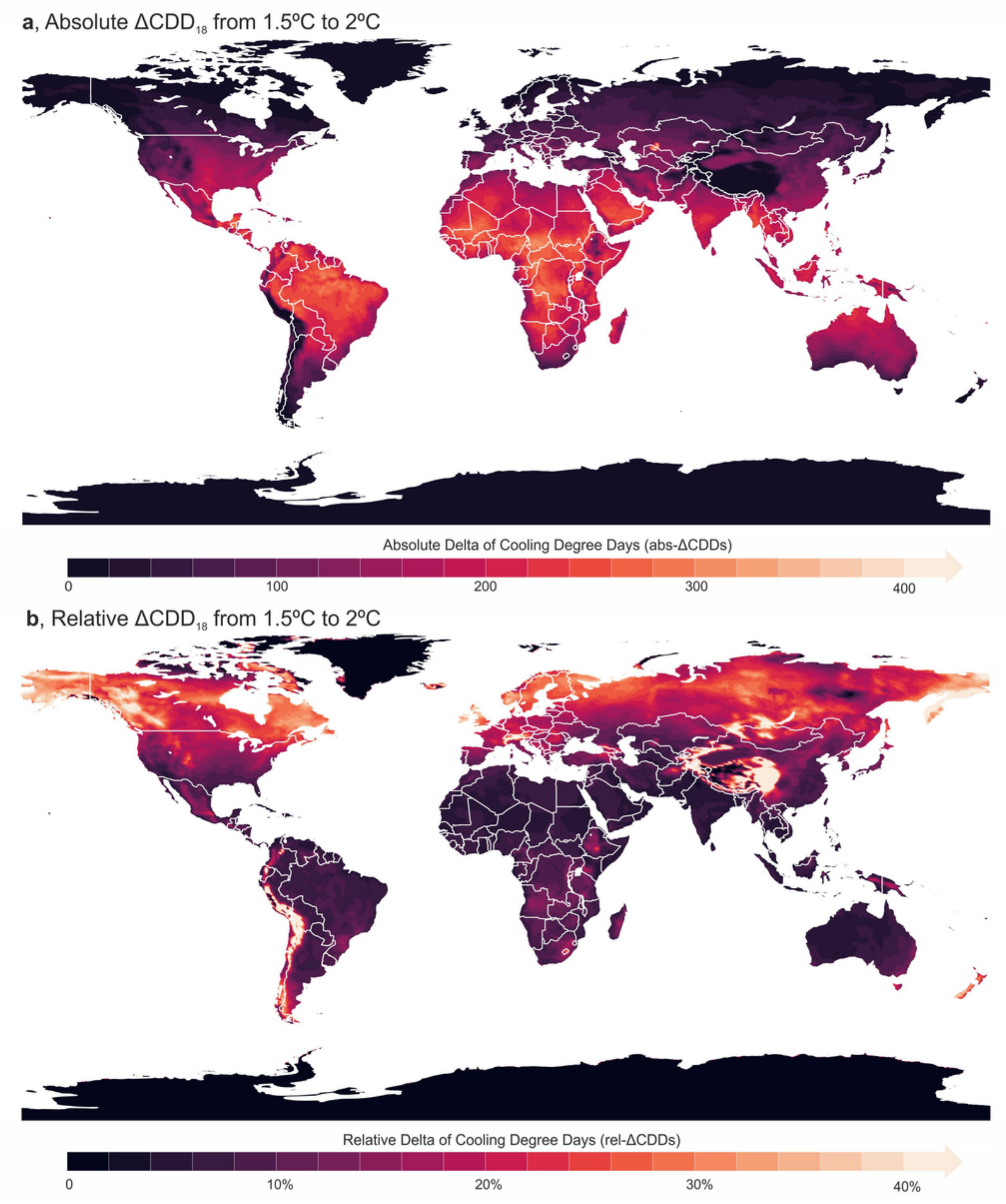

Figure 1

Global CDD difference between 1.5ºC and 2ºC global warming scenarios. a,Absolute Delta Cooling Degree Days (abs-ΔCDD) from 1.5º to 2ºC global warming scenarios. **b,** Relative Delta Cooling Degree Days (rel-ΔCDD) from 1.5º to 2ºC global warming scenarios.

Supplementary Files