Seasonal cycles enhance disparities between low- and high-income countries in exposure to monthly temperature emergence with future warming

Published version at: http://dx.doi.org/10.1088/1748-9326/aa95ae
To link to this article DOI: http://dx.doi.org/10.1088/1748-9326/aa95ae

Publisher: Institute of Physics

Environmental Research Letters

LETTER • **OPEN ACCESS**

Seasonal cycles enhance disparities between low- and high-income countries in exposure to monthly temperature emergence with future warming

To cite this article: Luke J Harrington *et al* 2017 *Environ. Res. Lett.* **12** 114039

View the article online for updates and enhancements.

Related content

- Poorest countries experience earlier anthropogenic emergence of daily temperature extremes
  Luke J Harrington, David J Frame, Erich M Fischer et al.
- Greater increases in temperature extremes in low versus high income countries
  Nicholas Herold, Lisa Alexander, Donna Green et al.
- Historically hottest summers projected to be the norm for more than half of the world's population within 20 years
  Brigitte Mueller, Xuebin Zhang and Francis W Zwiers

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
5 June 2017

REVISED
5 October 2017

ACCEPTED FOR PUBLICATION
24 October 2017

PUBLISHED
17 November 2017

LETTER

Seasonal cycles enhance disparities between low- and high-income countries in exposure to monthly temperature emergence with future warming

Luke J Harrington[1,2,5], David J Frame[2], Ed Hawkins[3] and Manoj Joshi[4]

1 Environmental Change Institute, University of Oxford, Oxford University Centre for the Environment, South Parks Road, Oxford, OX1 3QY, United Kingdom
2 New Zealand Climate Change Research Institute, School of Geography, Environment and Earth Sciences, Victoria University of Wellington, Wellington 6012, New Zealand
3 National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading RG6 6BB, United Kingdom
4 Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, United Kingdom
5 Author to whom any correspondence should be addressed.

E-mail: luke.harrington@ouce.ox.ac.uk

Keywords: climate change, Seasonal cycles, climate modelling, emergence

Supplementary material for this article is available online

Abstract

A common proxy for the adaptive capacity of a community to the impacts of future climate change is the range of climate variability which they have experienced in the recent past. This study presents an interpretation of such a framework for monthly temperatures. Our results demonstrate that emergence into genuinely 'unfamiliar' climates will occur across nearly all months of the year for low-income nations by the second half of the 21st century under an RCP8.5 warming scenario. However, high income countries commonly experience a large seasonal cycle, owing to their position in the middle latitudes: as a consequence, temperature emergence for transitional months translates only to more-frequent occurrences of heat historically associated with the summertime. Projections beyond 2050 also show low-income countries will experience 2–10 months per year warmer than the hottest month experienced in recent memory, while high-income countries will witness between 1–4 months per year hotter than any month previously experienced. While both results represent significant departures that may bring substantive societal impacts if greenhouse gas emissions continue unabated, they also demonstrate that spatial patterns of emergence will compound existing differences between high and low income populations, in terms of their capacity to adapt to unprecedented future temperatures.

1. Introduction

Understanding how the signal of future anthropogenic climate warming emerges from the noise of internal variability is of significant societal importance (Lehner and Stocker 2015, Stott 2015). When considering the future occurrence of unusual temperatures, a common approach may be to evaluate the distribution of heat anomalies witnessed in a specific month under present-day greenhouse gas concentrations, then make comparisons with the number of occurrences under a future warming scenario, but maintaining a limited focus on that specific month (e.g. Black and Karoly 2016). However, many studies related to climate change-driven temperature emergence highlight the fact that the adaptive capacity of a given location to changes in future temperature distributions could be inferred by looking at the climate experienced by communities in the past (Hawkins *et al* 2014, Huber *et al* 2017, Diffenbaugh and Scherer 2011, Anderson 2011, Mahlstein *et al* 2011, Harrington *et al* 2016, Frame *et al* 2017). In this context, any warming-induced increase in the frequency of, say, dramatically warm autumn months for a temperate location like Sydney, Australia, may just translate to an increase in the occurrence of monthly temperatures historically associated with the summertime. This isn't necessarily something beyond the adaptive capacity for that community, as they would have experienced these temperatures in the past (albeit during a different time of year).

In this study, we assume that the experience of temperatures in the recent past is an adequate proxy for the capability of different populations to cope with emergent changes to their climate in the future. It is of course noted that many factors beyond temperature determine where different populations, ecosystems and crop types can thrive around the world (Mahlstein *et al* 2013), and the timing of climate thresholds during the annual cycle (like the onset of Spring temperatures) are also important for the natural world (Cassou and Cattiaux 2016). Such caveats to the results presented in section 3 are further discussed in section 4.

We hereafter present two different approaches to characterising emergent changes in temperature through time, by comparing (1) whether the same historical temperatures are witnessed during a specified month in the future; and (2) whether a temperature range associated with a given month in the past occurs more or less frequently *at any time throughout the year* within future model projections.

Figure 1 provides a schematic illustration of these two different approaches of interpreting monthly temperature emergence in this study. We focus on two individual grid cells situated approximately over Sydney, Australia (151.8°E, 32.9°S) and Singapore (104.1°E, 1.4°N), using a single climate model simulation (MIROC5) to illustrate both the seasonal oscillation of temperatures at a given location and the expected changes with future warming. One approach to understanding emergent temperature changes for a given month of the year over each location would be to observe changes for a specific month only. Indeed, both locations demonstrate a discernible warming signal when comparing March temperatures (horizontal solid lines) between 1951–2000 and 2051–2100 We hereafter refer to the first time period as 'recent memory' and the second time period as the 'future'. In this framework, one could consider the attributable change in the likelihood of witnessing the hottest March temperature in recent memory, and for this single model, find that it occurs much more frequently in the future for both locations (under a high-emissions, or RCP8.5, scenario). Supplementary analysis (figure S1) available at stacks.iop.org/ERL/12/114039/mmedia also reveals that, under this month-by-month framework, the magnitude of temperature emergence for a given location is mostly similar across all months of the year.

However, an alternative approach is to identify the range of all fifty March temperatures from the first half of the 20th century (vertical dashed lines), and evaluate the likelihood of witnessing monthly mean temperatures within this range *at any point during the calendar year*, comparing the first and second time periods. It is in this context that deviations occur between the temperate and tropical examples of figure 1. The reader will find that in recent memory over Sydney, similar temperatures to March were found during the months of November and December, while in the future these types of temperatures are more commonly seen in the months of October and April. Overall however, there is actually a negligible change between the two time periods, in terms of the total number of months throughout the calendar year which occupy this temperature range.

By contrast, Singapore experiences March-like temperatures for almost eight months of the year in the recent past, but such temperatures are seen only infrequently during January and February months in the future, hence representing a significant change. Understanding how transitions to future climates can be interpreted in this context of prior experience is the primary motivation of this study.

2. Data and methods

To more systematically investigate these contrasting perspectives, temperature data is extracted from 35 models in the Coupled Model Intercomparison Project Phase 5 archive (CMIP5, Taylor *et al* 2012) for the two previously mentioned time periods: 1951–2000 (defined as 'recent memory') and 2051–2100 (defined as the 'future'). 'Historical' and 'RCP8.5' simulations of monthly mean temperature are used for each of the two respective time periods. For those models which ran more than one simulation of the same experiment type, only the first ensemble member (r1i1p1) is considered.

For each model at each grid point (using their native resolution), all individual monthly data are first re-organized from the coldest month (M1) to hottest month (M12), based on the mean monthly temperature climatology over the recent past. This is to facilitate an easier comparison of changes to winter and summer months across both hemispheres. Then for *each individual month,* the maximum and minimum of the 50 available (monthly mean) temperatures are identified. Based on this specified range, n_1 is subsequently calculated as the number of monthly temperature values *from all calendar months* which fall inside this range over the historical period (from a total of $50 \times 12 = 600$). Hence, a fraction $F_1 = n_1/600$ will be found for each month of the year for the late 20th century.

The process is then repeated for temperature data over the latter period: we quantify the number of monthly mean temperatures in the second half of the 21st century which fall inside this *same range* specified from the Historical data, yielding a new fraction $F_2 = n_2/600$. We can consequently define the ratio of witnessing a 20th century month *at some point* in the second half of the 21st century as $R_{AM} = F_2 / F_1$ (R_{AM} denoting 'Ratio across all months'). This is repeated for each grid point in each model and for each month of the year. These fractional numbers are then interpolated onto a common 2.5° × 2.5° grid, and the multi-model median value is calculated at each grid point.

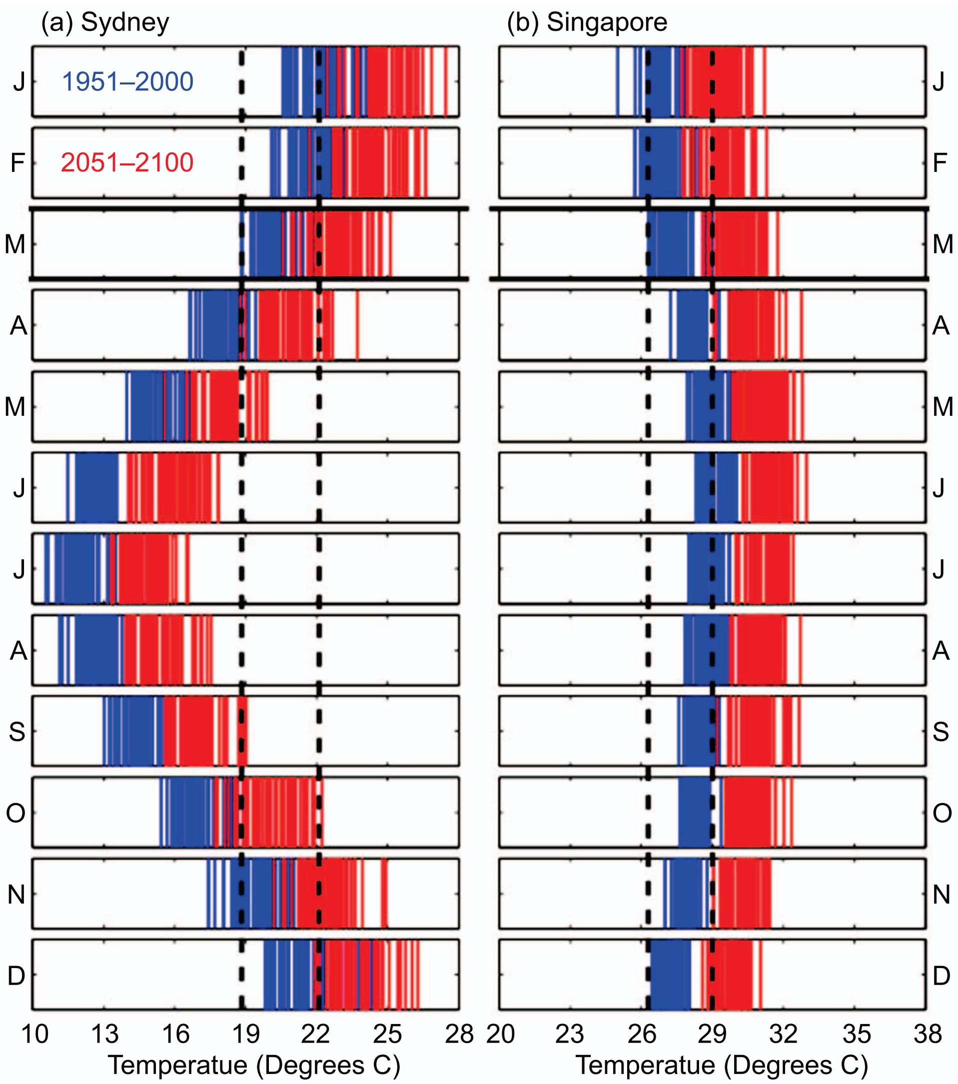

Figure 1. Schematic illustration of the modified approach used to interpret monthly temperature emergence in this study. We focus here on two individual grid cells, approximately situated over (*a*) Sydney, Australia (151.8°E, 32.9°S) and (*b*) Singapore (104.1°E, 1.4°N), using a single climate model (MIROC5) to illustrate both the seasonal cycle of monthly temperatures and the future signal of anthropogenic climate change. To illustrate long-term warming signals, blue lines denote fifty years of monthly temperatures over 1951–2000; red lines show fifty years of monthly temperatures over 2051–2100 The traditional approach to evaluate emergence of March temperatures follows the solid horizonal line; our adapted approach considers considers the number of months in each fifty year period falling within the dashed vertical lines.

3. Results

3.1. Future occurrence of historical monthly temperature ranges

Figure 2 presents a map of these multi-model median R_{AM} values. The historically coldest 3 months are found between 4 and 10 times less frequently in the second half of the 21st century, and this pattern is apparent across most regions globally—such a result is expected with a warming climate and consistent with previous assessments (Collins *et al* 2013). There is also an interesting projected increase in the likelihood of witnessing temperatures historically associated with the warmest 3 months (M10–M12) over Southern Hemisphere mid-latitudes: this is likely due to more transitional months in the future 'looking' like summertime temperatures of the past. Over the mid-to-high latitudes, there are minimal changes apparent in the likelihood of witnessing transitional months (M4–M9) at any point during the year. By contrast, there are significant decreases over tropical latitudes in the future likelihood of witnessing temperatures historically associated with *any* of the twelve months of the calendar year (albeit with M12 exhibiting some regional exceptions). Low latitude regions are therefore projected to witness emergent decreases in historically familiar temperatures year-round.

3.2. Future exceedances of hottest historical monthly temperature

Of course, it is important to consider that a large fraction of monthly temperature anomalies in the future will also be warmer than the historical range of all months (i.e. warmer than the hottest month observed over the entire 50 year climatology period), and these unprecedented temperatures aren't taken into account

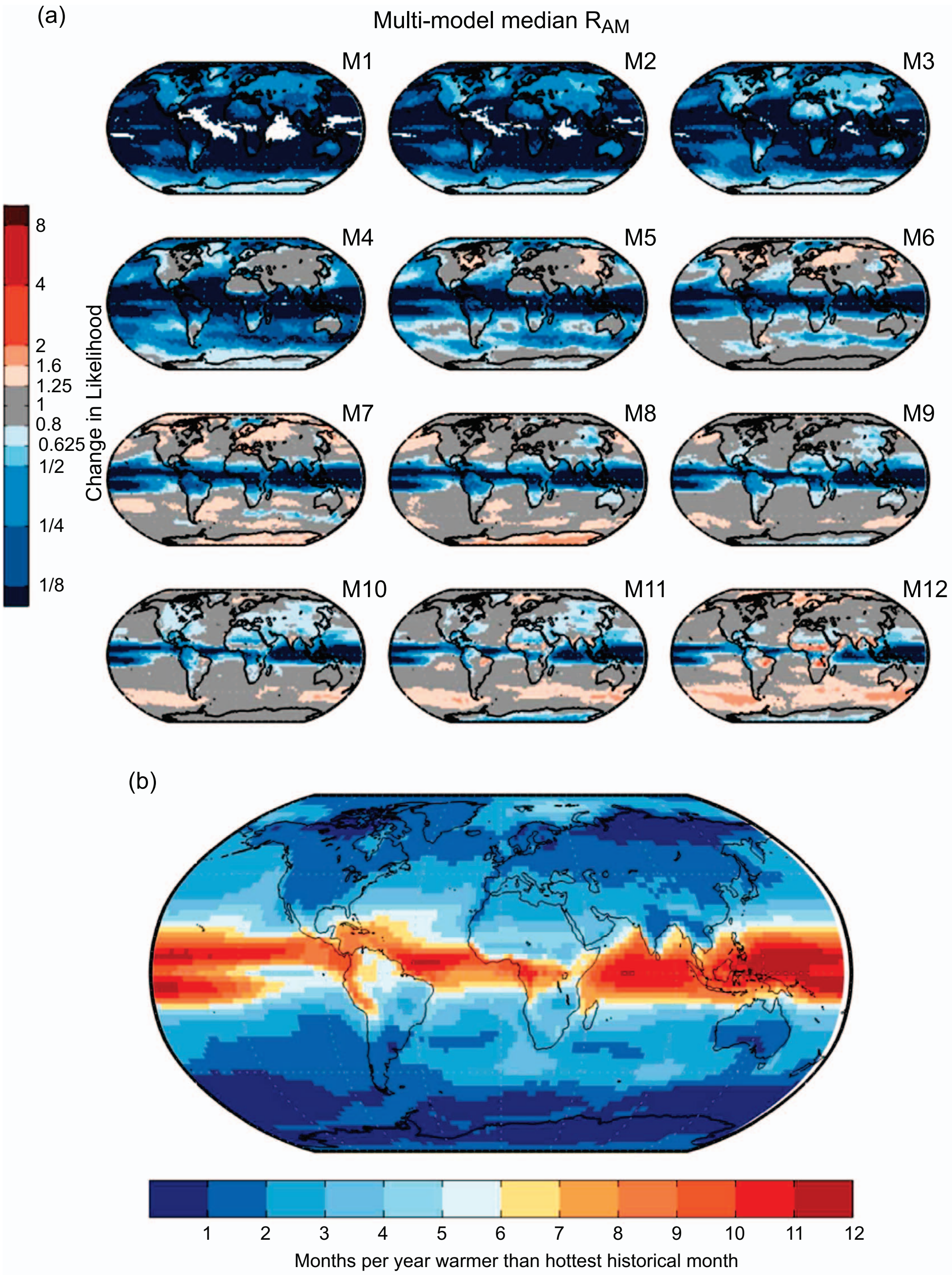

Figure 2. (*a*) Multi-model median R_{AM} metric presented for all twelve months of the year. Months are ordered from coldest (M1) to hottest (M12), based on historical climatologies at each grid point, to facilitate a reasonable comparison between summer and winter months across hemispheres. (*b*) Multi-model mean number of months per year in 2051–2100 which exceed the maximum absolute temperature found across all months from 1951–2000 (corresponding to the maximum of the range of M12). Calculations are made at each grid point within individual models before being concatenated to a common 2.5° × 2.5° scale.

in figure 2(*a*). Figure 2(*b*) shows this fraction of all months warmer than the hottest historical month on record at each grid cell, expressed as the (multi-model mean) number of months per year witnessing such exceedances in the future: this fraction reaches in excess of 60% for the tropics, but remaining less than 20% for most mid-latitude land regions. While both numbers represent significant deviations from recent memory, the contrast between different regions is striking. This further suggests that the strong seasonality in temperatures in higher latitudes means people living there will be more resilient to changes in temperature distributions across most calendar months, when compared against people living in tropical latitudes.

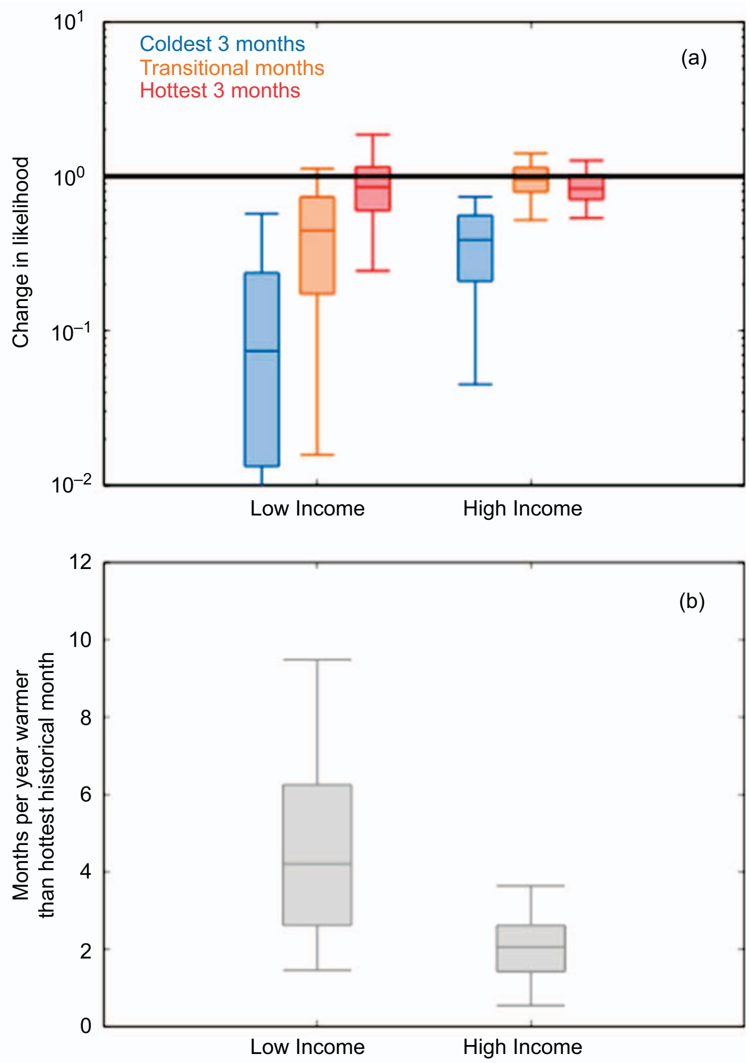

Figure 3. (*a*) Box plot showing the aggregated R_{AM} metric, weighted according to the distribution of people living in low income countries and high income countries, as of 2015. Shaded boxes show the inter-quartile range of all R_{AM} for all people across all CMIP5 models, while the whiskers denote the 5th–95th percentile range. The R_{AM} value has been aggregated according to the three coldest months (M1–M3 in figure 2), six transitional months (M4–M9) and the three historically hottest months (M10–M12). Panel (*b*) is the same format as panel (*a*), but denotes the average number of months per year expected to be warmer than the hottest historical month by 2051–2100.

3.3. Contrasting patterns of future emergence for different population groupings

Several previous studies have highlighted that disaggregating the global population according to different levels of socio-economic development tend to align with these geographic differences in emergence (Harrington *et al* 2016, Green 2016, Herold *et al* 2017). To consider how the results presented in figure 2 map to such a population-orientated framework, we weight the spatial results of R_{AM} and the fraction of months above the historical maxima according to the geographic distribution of all people living in both low income and high income countries. These country selections were made from The World Bank (2016, http://bit.ly/2bBWnzX), and corresponding population data was taken for the year 2015 from the Center for International Earth Science Information Network database (CIESIN 2005). The population data was first aggregated from the 0.25° × 0.25° spatial resolution provided, to the 2.5° × 2.5° resolution of the climate model output.

Figure 3 attempts to aggregate the key patterns from figure 2 into a more simplistic figure. All grid points from all models are aggregated together for the two population groupings to form a distribution of the R_{AM} metric for each month. Then all values are further aggregated for M1–M3 (coldest 3 months), M4–M9 (Transitional months) and M10–M12 (hottest 3 months). The shaded range of the box plots is the interquartile range, with the tails showing 5%–95% confidence range.

Figure 3(*a*) reveals that both low- and high-income populations will experience statistically significant decreases in the likelihood of witnessing historical wintertime temperatures in the future. However, there are no statistically significant deviations from the historical frequency of witnessing transitional monthly temperatures or summertime temperatures in the future for high income countries. Instead, there is a redistribution of when certain temperatures occur to different times of the year. Under the assumption of recent temperature variability serving as a proxy for societal capacity to cope with future changes, these results therefore suggest that most high income locations will experience similar types of climate compared with their recollection from recent memory. By contrast, low income countries witness a much stronger decrease in the likelihood of witnessing 'transitional' months from recent memory in the future.

To best appreciate any possible differences between the two population groupings, figure 3(*b*) again presents population-weighted results, this time showing a modified version of figure 2(*b*) to give the average number of months per year in the future which are expected to be warmer than the hottest monthly temperature experienced in recent memory (across all months). High income countries are expected to witness between one and four months per year with monthly mean temperatures hotter than anything experienced in recent memory under the RCP8.5 scenario—this represents a significant departure from historical norms and will thus present significant challenges for adaptation and coping with these changes in the future. The situation is bleaker still for low income countries, with model results indicating an average of four additional months per year warmer than the hottest month in recent memory, and an upper estimate of ten months per year with previously unprecedented heat anomalies. Such projections represent sustained and significant challenges for any low-income communities currently preparing climate change adaptation strategies.

The reasons for the substantial differences between the two population groupings relates to the fact that low income populations primarily exist in lower latitudes, and a high number of high income countries span the mid-to-high latitudes (Harrington *et al* 2016, Herold *et al* 2017, Davis and Diffenbaugh 2016, Frame *et al* 2017): the latitude-driven contrasts in monthly temperature emergence in figure 2 thus precipitate as more dramatic differences between the two population groupings.

4. Discussion and limitations

The consideration of emergent changes to monthly mean temperature examines only one specific component of the many varying impacts that will result from a warming climate. The focus here remains strictly regarding the capability of different populations around the world to cope with increasingly 'unfamiliar' temperature regimes through time (Frame *et al* 2017): examples of the implications associated with this framework include the health impacts of added heat stress (Mitchell *et al* 2016, Huber *et al* 2017, Fischer *et al* 2013, Im *et al* 2017); economic losses through labour productivity decreases in certain regions of the world (Dunne *et al* 2013, Hansen and Sato 2016, Pal and Eltahir 2016), and the consideration of future adaptation to new and novel climates (Diffenbaugh and Scherer 2011, Stott and Walton 2013, Sippel *et al* 2015a, Diffenbaugh and Charland 2016, Lusk 2017). However, it is also important to emphasise that the framework presented in this study is limited to the explicit purpose outlined in the introductory paragraphs, and should not be interpreted as showing the absence of significant climate change impacts over extra-tropical locations during transitional months. Multiple lines of evidence have demonstrated the adverse effects of changing spatio-temporal patterns with future climate change: these will include, but not be limited to, snow-fed hydrological systems (Diffenbaugh *et al* 2013), changes to locations where crops can grow, the timing of crop harvest and overall yield changes (Lobell and Burke 2008, Lobell *et al* 2011, Lobell and Tebaldi 2014, Asseng *et al* 2015, Mueller *et al* 2015, Liu *et al* 2016), as well as ecosystem impacts driven by warming-induced changes to phenological cues for many different species of flora and fauna (Pacifici *et al* 2015, Cassou and Cattiaux 2016, Pecl *et al* 2017). In short, growing season lengths for crops and melting periods for glaciers depend on the length of temperature exceedance, not just the frequency or magnitude.

The results in this study have utilised climate model simulations and should thus be interpreted only in this context. We chose to analyse all models, rather than attempting some form of validation against historical observations, for three reasons: (1) this ensured future model uncertainty (Hawkins and Sutton 2009) was appropriately sampled; (2) previous studies have found temperature variability on monthly timescales to be well-represented in CMIP5 models (Christidis *et al* 2015); and (3) both warming signals and measures of monthly temperature variability are being explicitly compared over different regions of the world, so any validation techniques would be complicated by observed modes of climate variability in the recent past.

It is also recognised that a non-linear relationship exists between the range of temperatures experienced by a given population, and the relative rates of excess-heat morbidity or mortality with additional warming (Huang *et al* 2011, Gasparrini *et al* 2015). Most targeted studies identify a minimum-mortality threshold which exists within a population's range of historical temperatures, with the occurrence of heat-related health impacts rising rapidly with further warming thereafter (Gasparrini *et al* 2015, Tobías *et al* 2017). Unfortunately, the lack of representative mortality/morbidity records for both low-income and high-income countries remains a significant barrier to characterising such heat impacts using the framework presented in this study (Gasparrini *et al* 2015, Mitchell *et al* 2016, Mora *et al* 2017). Nevertheless, future research should explore techniques to better represent these non-linear relationships between monthly temperature emergence and corresponding changes to heat stress.

5. Summary

Many approaches towards quantifying the emergence of new and novel climates at a sub-seasonal timescale focus on the month of interest in isolation (Sippel *et al* 2015b, Anderson 2011, Diffenbaugh and Scherer 2011, King *et al* 2016, Christidis *et al* 2015). However, the adaptive capacity of a community to future temperature emergence has commonly been interpreted as a function of the climate they have been familiar with in recent memory (Grambsch and Menne 2003, Diffenbaugh and Scherer 2011, Hayden *et al* 2011, Dunne *et al* 2013, Burke *et al* 2015, Huber *et al* 2017). To address this difference in perspectives, this study presents a framework for considering emergent temperature changes by evaluating whether, under a future warming scenario, the range of temperatures historically associated with a specific month occur more or less frequently throughout a calendar year. Our results highlight that the presence of a substantial seasonal cycle in the mid-to-high latitudes translates to a larger adaptive capacity for people living there. Consequently, the magnitude of emergence into genuinely unfamiliar future temperatures, when considered at a monthly timescale, is found to be much more severe for low income countries living at lower latitudes when compared with high income countries inhabiting higher latitudes. This suggests that related climate change impacts may further exacerbate existing societal disparities in the future.

Acknowledgments

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and thanks the climate modelling groups for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. LJH acknowledges support from the Transition into the Anthropocene (TITAN) project, funded by a European Research Council Advanced Grant (EC-320691). LJH and DJF acknowledge support from Victoria University of Wellington and the Deep South National Science Challenge. EH was funded by the UK National Centre for Atmospheric Science and a NERC Advanced Fellowship.

ORCID iDs

Luke J Harrington https://orcid.org/0000-0002-1699-6119

References

Anderson B T 2011 Near-term increase in frequency of seasonal temperature extremes prior to the 2 °C global warming target *Clim. Change* **108** 581

Asseng S *et al* 2015 Rising temperatures reduce global wheat production *Nat. Clim. Change* **5** 143–7

Black M T and Karoly D J 2016 Southern Australia's warmest October on record: the role of ENSO and climate change *Bull. Am. Meteorol. Soc.* **97** S118–21

Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235–9

Cassou C and Cattiaux J 2016 Disruption of the European climate seasonal clock in a warming world *Nat. Clim. Change* **6** 589–94

Center for International Earth Science Information Network—CIESIN—Columbia University, United Nations Food and Agriculture Programme—FAO and Centro Internacional de Agricultura Tropical—CIAT 2005 Gridded Population of the World, Version 3 (GPWv3): Population Count Grid, Future Estimates (https://doi.org/10.7927/H42B8VZZ)

Christidis N, Stott P A and Zwiers F W 2015 Fast-track attribution assessments based on pre-computed estimates of changes in the odds of warm extremes *Clim. Dyn.* **45** 1547–64

Collins M *et al* 2013 Long-term climate change: projections, commitments and irreversibility climate change 2013: the physical science basis *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker, D Qin, G K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press) pp 1029–136

Davis S J and Diffenbaugh N 2016 Dislocated interests and climate change *Environ. Res. Lett.* **11** 061001

Diffenbaugh N S and Charland A 2016 Probability of emergence of novel temperature regimes at different levels of cumulative carbon emissions *Front. Ecol. Environ.* **14** 418–23

Diffenbaugh N S and Scherer M 2011 Observational and model evidence of global emergence of permanent, unprecedented heat in the 20th and 21st centuries *Clim. Change* **107** 615–24

Diffenbaugh N S, Scherer M and Ashfaq M 2013 Response of snow-dependent hydrologic extremes to continued global warming *Nat. Clim. Change* **3** 379–84

Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming *Nat. Clim. Change* **3** 563–6

Fischer E M, Beyerle U and Knutti R 2013 Robust spatially aggregated projections of climate extremes *Nat. Clim. Change* **3** 1033–8

Frame D, Joshi M, Hawkins E, Harrington L J and Roiste M de 2017 Population-based emergence of unfamiliar climates *Nat. Clim. Change* **7** 407–11

Gasparrini A *et al* 2015 Mortality risk attributable to high and low ambient temperature: a multicountry observational study *Lancet* **386** 369–75

Grambsch A and Menne B 2003 Adaptation and adaptive capacity in the public health context *Climate Change Health Risks Responses* ed A J McMichael, D H Campbell-Lendrum, C F Corvalan, K L Ebi and J D Al Githeko Scheraga (Geneva: World Health Organization) pp 220–36

Green D 2016 The spatial distribution of extreme climate events, another climate inequity for the World's most vulnerable people *Environ. Res. Lett.* **11** 091002

Hansen J and Sato M 2016 Regional climate change and national responsibilities *Environ. Res. Lett.* **11** 034009

Harrington L J, Frame D J, Fischer E M, Hawkins E, Joshi M and Jones C D 2016 Poorest countries experience earlier anthropogenic emergence of daily temperature extremes *Environ. Res. Lett.* **11** 055007

Hawkins E *et al* 2014 Uncertainties in the timing of unprecedented climates *Nature* **511** E3–5

Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* **90** 1095–107

Hayden M H, Brenkert-Smith H and Wilhelmi O V 2011 Differential adaptive capacity to extreme heat: a phoenix, Arizona, case study *Weather Clim. Soc.* **3** 269–80

Herold N, Alexander L, Green D and Donat M 2017 Greater increases in temperature extremes in low versus high income countries *Environ. Res. Lett.* **12** 034007

Huang C, Barnett A G, Wang X, Vaneckova P, FitzGerald G and Tong S 2011 Projecting future heat-related mortality under climate change scenarios: a systematic review *Environ. Health Perspect.* **119** 1681–90

Huber V, Ibarreta D and Frieler K 2017 Cold- and heat-related mortality: a cautionary note on current damage functions with net benefits from climate change *Clim. Change* **142** 407–18

Im E-S, Pal J S and Eltahir E A B 2017 Deadly heat waves projected in the densely populated agricultural regions of South Asia *Sci. Adv.* **3** e1603322

King A D, Black M T, Min S-K, Fischer E M, Mitchell D M, Harrington L J and Perkins-Kirkpatrick S E 2016 Emergence of heat extremes attributable to anthropogenic influences *Geophys. Res. Lett.* **43** 3438–43

Lehner F and Stocker T F 2015 From local perception to global perspective *Nat. Clim. Change* **5** 731–4

Liu B *et al* 2016 Similar estimates of temperature impacts on global wheat yield by three independent methods *Nat. Clim. Change* **6** 1130–6

Lobell D B, Bänziger M, Magorokosho C and Vivek B 2011 Nonlinear heat effects on African maize as evidenced by historical yield trials *Nat. Clim. Change* **1** 42–5

Lobell D B and Burke M B 2008 Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation *Environ. Res. Lett.* **3** 034007

Lobell D B and Tebaldi C 2014 Getting caught with our plants down: the risks of a global crop yield slowdown from climate trends in the next two decades *Environ. Res. Lett.* **9** 074003

Lusk G 2017 The social utility of event attribution: liability, adaptation, and justice-based loss and damage *Clim. Change* **143** 201–12

Mahlstein I, Daniel J S and Solomon S 2013 Pace of shifts in climate regions increases with global temperature *Nat. Clim. Change* **3** 739–43

Mahlstein I, Knutti R, Solomon S and Portmann R W 2011 Early onset of significant local warming in low latitude countries *Environ. Res. Lett.* **6** 034009

Mitchell D, Heaviside C, Vardoulakis S, Huntingford C, Masato G, Guillod B P, Frumhoff P, Bowery A, Wallom D and Allen M 2016 Attributing human mortality during extreme heat waves to anthropogenic climate change *Environ. Res. Lett.* **11** 074006

Mora C *et al* 2017 Global risk of deadly heat *Nat. Clim. Change* **7** 501–6

Mueller B, Hauser M, Iles C, Rimi R H, Zwiers F W and Wan H 2015 Lengthening of the growing season in wheat and maize producing regions *Weather Clim. Extrem.* **9** 47–56

Pacifici M *et al* 2015 Assessing species vulnerability to climate change *Nat. Clim. Change* **5** 215–24

Pal J S and Eltahir E A B 2016 Future temperature in southwest Asia projected to exceed a threshold for human adaptability *Nat. Clim. Change* **6** 197–200

Pecl G T *et al* 2017 Biodiversity redistribution under climate change: impacts on ecosystems and human well-being *Science* **355** eaai9214

Sippel S, Walton P and Otto F E L 2015a Stakeholder perspectives on the attribution of extreme weather events: an explorative enquiry *Weather Clim. Soc.* **7** 224–37

Sippel S, Zscheischler J, Heimann M, Otto F E L, Peters J and Mahecha M D 2015b Quantifying changes in climate variability and extremes: Pitfalls and their overcoming *Geophys. Res. Lett.* **42** 2015GL066307

Stott P 2015 Attribution: Weather risks in a warming world *Nat. Clim. Change* **5** 517–8

Stott P A and Walton P 2013 Attribution of climate-related events: understanding stakeholder needs *Weather* **68** 274–9

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

Tobías A, Armstrong B and Gasparrini A 2017 Brief report: investigating uncertainty in the minimum mortality temperature: methods and application to 52 Spanish cities *Epidemiol. Camb. Mass.* **28** 72–6