Temperature emergence at decision-relevant scales

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Keywords: climate change, temperature emergence, decision-making

Abstract
Signal-to-noise (S/N) ratios are a useful method to assess the significance of future climate change relative to past experiences. Most assessments of climate change emergence have focused on S/N ratios of annual mean temperatures. However, averaging the daily experiences of weather across space or time removes the climate variability actually felt by individuals, and thus presents a less informative view of the speed of current climate change. For example, S/N ratios of annual-mean temperatures experienced by the global population after only 1 °C of warming are larger than emergent changes in daily temperatures after 3 °C of warming, and generally four times more significant when comparing the same warming threshold. Here, I examine the emergence of S/N ratios in temperature at decision-relevant scales, with a focus on daily temperatures where people live. I find that 2 °C of global warming will lead to between 30% and >90% of the global population experiencing the emergence of unusual daily temperatures (>1σ), while it is very unlikely (90% confidence) that more than 60% of the global population will also experience the emergence of unfamiliar daily temperatures (>2σ).

1. Introduction
To quantify when detectable changes in the climate system will manifest themselves in response to human influences, recent research has examined when the ‘signal’ of climate change emerges from the background ‘noise’ of internal variability (Hawkins and Sutton 2012). While this ‘time of emergence’ concept has been explored for a range of climate variables over recent years (Giorgi and Bi 2009, Mahlstein et al 2013, Maraun 2013, Lyu et al 2014, Sedláček and Knutti 2014), assessments of emerging signal-to-noise (S/N) ratios have been most common for heat-related variables (Joshi et al 2011, Mahlstein et al 2011, Hawkins and Sutton 2012, Hawkins et al 2014, King et al 2015, Frame et al 2017, Harrington et al 2019), and particularly for annual mean temperatures—both in observations (Hawkins et al 2020) and climate models (Frame et al 2017).

While some of the clearest signs of the global climate response to the accumulation of anthropogenic greenhouse gas emissions can be found in the occurrence of very hot years (Knutson et al 2018), a focus on the emergence of annual mean temperatures can often mischaracterise the detectability of climate change signals at finer temporal scales (Angélil et al 2014, 2018), particularly those which map closer to the impacts and experiences of adverse temperatures experienced by communities (Schewe et al 2019). Indeed, most assessments of the health and economic impacts of extreme heat events quantify relationships between climatic anomalies and their impacts when the former is defined at daily or multi-day timescales (Gasparini et al 2015, Perkins 2015, Carleton and Hsiang 2016, Ferranti et al 2016, Lo et al 2019, Public Health England 2019, Vautard et al 2020).

Quantifying the emergence of S/N ratios in temperature has helped to contextualise climate change relative to past experiences (Lehner and Stocker 2015), with a view to better inform which communities will first experience unprecedented changes in their local climate under future scenarios of climate change (Dahinden et al 2017, King and Harrington 2018, Hawkins et al 2020). Yet the continued focus on S/N ratios in annual temperatures seems problematic, when there is limited evidence of local impacts mapping meaningfully to climatological anomalies of annual mean temperatures.

This study will compare the emergence of S/N ratios in temperatures at annual and daily timescales,
with a view to recalibrate the significance of future changes in local climate to those scales which are more relevant for decision makers when addressing the impacts of warming. After illustrating how temperature emergence at different timescales compares at the time of different global warming thresholds, this analysis concludes by considering the full range of possible changes in daily temperature emergence following exceedance of 2.0 °C and 2.5 °C of warming above pre-industrial levels, thereby examining what ‘dangerous anthropogenic interference’ with the climate system (Smith et al 2009, Zommers et al 2020) looks like in the places where people live, and at the scales at which people actually experience the impacts of a changing climate.

2. Data and methods

For 23 models (see table S1 available online at stacks.iop.org/ERL/16/094018/mmedia) providing the requisite data to the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al 2012), time series of S/N ratios are calculated for annual, monthly and daily mean temperatures over the period 1861–2100, using ‘Historical’ and ‘RCP8.5’ simulations concatenated together. Only a single ensemble member (r1i1p1) is selected from each model.

Efforts to examine any patterns of climate change at specified global warming thresholds necessarily requires subjective methodological choices to be made. While acknowledging multiple methods (James et al 2017) and modelling frameworks (Mitchell et al 2017, Deser et al 2020) exist, and that increases in heat extremes are likely more pronounced under transient warming scenarios than in a comparable quasi-equilibrium climate (King et al 2020), this analysis chooses to implement a framework which has been commonly implemented elsewhere in the literature (Knutti et al 2016, Rogelj and Knutti 2016, Seneviratne et al 2016, Wartenburger et al 2017). Specifically, this involves analysis of a high-emissions, transient warming scenario (RCP8.5), only using one ensemble member from each CMIP5 model, and applying a ‘time sampling’ method (James et al 2017). In-depth sensitivity assessments elsewhere (Wartenburger et al 2017) have found alternative choices would be negligible in the context of comparing S/N ratios across manifestly different timescales, as is the case here.

Also following previously published methods (King et al 2016, 2017, Schleussner et al 2016a, 2017, Rogelj et al 2017, Wartenburger et al 2017, Harrington et al 2018), the signal of each cell at each grid cell is calculated as the mean over a running 21 year time window, relative to the mean over the period 1861–1880. The sample size remains constant irrespective of the timescale considered: this means 21 data points for the period of interest are separately extracted and averaged for each day of the year, each calendar month (by first averaging across all days therein) and each year (by first averaging across all days therein). Similarly, the ‘noise’ component of temperatures at each timescale and for each grid cell is taken by adapting the approach of Fischer and Knutti (2015), extracting data from the last 200 years of the pre-industrial control simulations of each model and then calculating the corresponding standard deviation for each temporal scale. Finally, S/N ratios are calculated for each model at their native resolution first, before being interpolated to a common 2.5° × 2.5° grid to facilitate comparative analysis later. S/N ratios in excess of 1, 2, 3 and 4 will also be hereafter referred to as ‘unusual’, ‘unfamiliar’, ‘unknown’ and ‘unprecedented’ climates, following the nomenclature introduced by Frame et al (2017) and Hawkins et al (2020).

The corresponding estimate of global mean temperature anomalies for each model are also calculated using a 21 year running mean, and a 1861–1880 baseline. It is noted here that global-mean temperatures are calculated simply as the area-weighted average of near-surface air temperatures over all land and ocean regions in each model, with no masking to specific regions on the basis of observational coverage. Where discussing emergence at specific thresholds of global warming, this denotes the S/N ratio corresponding to the 21 year period for which a global mean warming anomaly of X °C is exceeded within each individual model, and remains exceeded until the end of the time-series (2100).

Finally, population exposure to temperature emergence is examined by using gridded global population data for the year 2015 from the Center for International Earth Science Information Network database (CIESIN 2016). Population data is extracted at 0.25° × 0.25° spatial resolution, and then aggregated up to the 2.5° × 2.5° resolution of the climate model output.

3. Results

3.1. Annual-scale emergence at future warming thresholds

Figure 1 reveals patterns of multi-model median annual-scale temperature emergence at half-degree increments of future warming. Consistent with previous studies (Hawkins and Sutton 2012, Frame et al 2017, Hawkins et al 2020), tropical latitudes are found to exhibit faster rates of temperature emergence than mid-high latitude regions for the same amount of warming, while oceans also show faster emergence than corresponding land regions at equivalent latitudes: this is largely an expression of much lower levels of interannual temperature variability seen in these locations (Harrington et al 2017).

While projections of annual temperature emergence in tropical and mid-latitude regions remain under 6σ and 3σ (respectively) after 1.5 °C of global temperature rise, nearly all regions witness the
Figure 1. Multi-model median S/N ratio of annual mean temperatures at (a) 1.5°C, (b) 2.0°C, (c) 2.5°C and (d) 3.0°C of global warming.

exceedance of 6σ, and many well above 10σ of warming, after a 3°C rise in global temperatures. Previous studies have suggested an approximate pattern scaling effect to these signals of change (Wartenburger et al. 2017, King et al. 2018), such that the relative magnitude of emergence in most locations will increase by a similar margin with each additional half-degree of warming.

When considering hotspots over populated areas, the Maritime continent, large swathes of continental Africa (particularly near the Congo Basin) and countries in northern South America are found to exhibit the fastest relative changes in annual temperatures, with a remarkable shift of more than 8σ seen in these places after only 2°C of global warming. Evaporative cooling mechanisms typical of the humid tropical climates in these regions help to suppress year-to-year temperature variability (Sobel et al. 2002, King et al. 2006, Zhang et al. 2021), thereby amplifying the emergence of even modest warming signals under climate change (Hawkins and Sutton 2012).

3.2. Daily-scale emergence at future warming thresholds

Figure 2 reveals how spatial patterns of temperature emergence differ when looking at daily-scale S/N ratios instead of changes at the annual scale. Here, ‘daily-scale’ temperature emergence is calculated for each model and grid cell as the average of individual S/N ratios calculated for each day of the calendar year, before presenting the multi-model median result.

As expected, the magnitude of daily temperature emergence is substantially less significant in figure 2 across all locations and for all warming levels, when compared with the equivalent changes in figure 1. In fact, S/N ratios remain below two for the majority of land regions, even after 3°C of global temperature increase. The reductions in temperature emergence between the annual and daily scale are more pronounced for land regions than over oceans, and this is particularly evident in tropical regions.

Interrogating the physical mechanisms which determine differences between the emergence of annual warming signals and daily warming signals would not only require an examination of the processes which modulate the seasonal differences in future warming signals (Manabe et al. 1992, Stouffer and Manabe 2017), but also the different drivers of temperature variability at annual, seasonal and daily timescales (Fischer and Schar 2009, Holmes et al. 2016), as well as how these mechanisms differ across latitudes spanning from tropical climates to the poles (Thompson et al. 2015, Järvinen et al. 2016). While these clearly represent important topics for future research, such an assessment is beyond the scope of the current analysis, which is instead focused
on quantifying the most decision-relevant interpretations of emerging climate change signals.

3.3. Population-weighted emergence at different timescales

To examine these patterns of temperature emergence for different temporal scales over locations where people actually live (Frame et al. 2017), figure 3 presents population-weighted histograms of S/N ratios at different levels of warming. Where ‘daily-scale’ and ‘monthly-scale’ results are presented, the S/N ratios for each individual calendar day (or month) have all been aggregated to present an average change.

The top figure panel compares population exposure to temperature emergence for the multi-model median outcome following 2 °C of warming. When looking at the S/N ratios associated with the average person, an approximate doubling relationship is found as one shifts from considering temperature emergence at the daily scale, to the monthly scale and annual scale. Specifically, population-weighted experiences of daily-, monthly- and annual-scale temperature emergence are found to centre on S/N ratios of 1, 2 and 4, respectively. Across all timescales, distributions of S/N exhibit a heavy tail, with more than 10% of the population experiencing S/N ratios over double those felt by the median person when looking at the emergence of daily and monthly temperatures.

To further illustrate the disparity in emergence across different temporal scales, the bottom panel of figure 3 compares the magnitude of monthly emergence after 2 °C of warming with the emergence of annual temperatures after 1 °C and daily temperatures after 3 °C of global temperature rise. Remarkably, the emergence of annual temperatures after only 1 °C of temperature rise remains most significant, while the majority of people do not experience the emergence of unfamiliar temperatures (S/N > 2), even after 3 °C of global warming. Such results help to further convey the ambiguity which can appear in the presentation of emergent climate change signals, and the pronounced sensitivity to the spatial and temporal scales chosen to define the ‘noise’ from which the signal of warming can emerge.

3.4. Examining post-Paris temperature emergence at decision-relevant scales

As discussed in depth elsewhere (Schleussner et al. 2016b), the 2015 Paris Agreement placed renewed focus on understanding the impacts of 1.5 °C and 2.0 °C of global warming above pre-industrial levels, with concerns that exceeding these warming thresholds will lead to profoundly negative societal and ecological impacts. While the differential impacts of these two warming thresholds have been extensively assessed, less attention has been paid to the relative impacts of half-degree warming increments.
Figure 3. Population-weighted histograms of multi-model median temperature emergence when calculated at different temporal scales. Panel (a) shows the distribution of population exposure to different S/N ratios for annual-, monthly- and daily-mean temperatures after 2°C of warming. Panel (b) shows the distribution of S/N ratios for annual-scale emergence following 1°C of warming, monthly-scale emergence after 2°C of warming (same as panel (a)), and daily-scale emergence after 3°C of warming.

Several interesting patterns are found. First, the months centred around August and late boreal summer show the most people experiencing the emergence of unusual and unfamiliar daily temperatures; since a larger fraction of the global population lives in the Northern Hemisphere (Jones and O’Neill 2016), this suggests a more pronounced signal of emergent warming over populated land regions during the summertime, a conclusion consistent with previous research (Vogel et al 2017, Hawkins et al 2020). Second, differences in emergence between the half-degree warming increments are insignificant when compared to model uncertainty: while a pessimistic model suggests people will experience the emergence of an unknown climate after 2°C of warming, there are equally optimistic
model projections which show the same amount of global warming generating no more than half the global population experiencing even a 1σ change in local daily temperatures.

Finally, comparing figures 4(b) and (d) helps to contextualise the differences between 2.0 °C and 2.5 °C of global warming in a high-sensitivity model world, thereby serving as a useful high-end benchmark for the purposes of adaptation planning. After 2 °C of warming in this high sensitivity world, the entire global population is projected to experience the emergence of unusual (>1σ) daily temperatures for more than four months of the year. Yet a 2.5 °C world could see more than 10% of the global population experience an unprecedented 4σ warming of daily temperatures at different times of year, while restricting warming to 2.0 °C would see only half the population witnessing unfamiliar temperature changes (>2σ) at some point, and very few experiencing the emergence of unknown climate change (>3σ) at all.

These results also illustrate the importance of avoiding narratives where thresholds of global temperature rise are perceived as definitive boundaries between completely safe climates and apocalyptic outcomes. Rather, figure 4 demonstrates how many impacts of climate change gradually worsen with any incremental rise in global temperatures, and all efforts to reduce carbon emissions will therefore remain fruitful even if specific temperature thresholds (like 1.5 °C) are exceeded.

4. Discussion

Epidemiological studies offer evidence of reductions in the direct health impacts of extreme heat over the last century (Sheridan and Allen 2018), despite concurrent increases in global temperatures and in the severity and frequency of recent heatwaves (Li et al 2018). Some of these reductions can be attributed to deliberate intervention strategies like air conditioning uptake (Barreca et al 2016) or the introduction of heatwave action plans (Toloo et al 2013), while others appear simply a physiological response to the recurrent experience of similar temperatures (Ballester et al 2011, Gasparrini et al 2015, Achebak et al 2019). Moore et al (2019) also found perceptions of ‘normal’ temperatures to decline rapidly following the experience of repeatedly anomalous temperatures, a result
consistent with other research in the social sciences (Howe et al 2019).

Given these already-detected mechanisms and perceptions of societal adaptation to changing temperatures, there are probably few communities worldwide who are optimally adapted to a climate which pre-dates anthropogenic carbon emissions. Rather, the climate to which people are currently ‘most adapted’ likely resembles local temperatures from the middle or perhaps late 20th century—the choice of an 1861–1880 baseline from which to consider S/N ratios may therefore overstate the magnitude of climate change emergence in some regions. However, there currently exists no robust method to identify a ‘baseline’ of past experiences in a globally coherent way, and any attempt to do so would misrepresent heterogeneity at the community scale relating to both the exposure to extreme heat (Hoffman et al 2020, Hsu et al 2021), or indeed the capacity for further adaptation (Green 2016).

There also exists evidence that temperature variability can itself increase in response to future warming (Suarez-Gutierrez et al 2020, Maher et al 2021), particularly over moisture-limited regions in the summertime (Fischer and Schar 2009, Fischer et al 2012). Increasing variability translates to a further increase in the frequency of extreme events when accompanying an increase in the distribution mean (Harrington and Otto 2018), thereby pointing to a potential underestimate of the implications of future temperature emergence when the definition of ‘noise’ is fixed at pre-industrial levels.

However, because the above features likely have competing effects on the results in figure 4, coupled with the high levels of geographic heterogeneity and uncertainty associated with these factors, I have opted to preserve the analytical framework used in previous studies (Hawkins and Sutton 2012, Fischer and Knutti 2015, Frame et al 2017, Hawkins et al 2020) by defining signals of change with respect to the early industrial period and keeping definitions of ‘noise’ fixed through time. Nevertheless, future work is needed to better resolve these other important factors, and understand how perceptions of climate change emergence can be translated most effectively to local contexts.

5. Conclusions

This analysis quantified the differences which arise when defining temperature emergence on the basis of changes averaged over different temporal scales. While the majority of past work has focused on S/N ratios of annual mean temperatures, it is argued here that many heat-related impacts of climate change can be meaningfully understood only when changes are contextualised relative to previous experiences at daily timescales (Gasparrini et al 2015, Carleton and Hsiang 2016, Vautard et al 2020, Watts et al 2021). It is therefore imperative to disaggregate the signals of future temperature change relative to past experiences at these decision-relevant scales, and for the places upon which these changes matter most for decision-makers: where people live.

The results of this analysis confirm that even keeping warming below the higher 2 °C target of the Paris Agreement would ensure over half the global population avoids the emergence of unfamiliar daily temperatures. Furthermore, any incremental rise in global temperatures produces a proportional worsening of emergent signals in daily temperatures, just like with annual temperatures. While an interesting 1–2–4 relationship was found to approximate the ratio of population exposure to daily-, monthly- and annual-scale temperature emergence (figure 3(a)), the regions which experienced the fastest relative changes remained the same irrespective of the timescale considered. As shown elsewhere (King and Harrington 2018), these ‘fast emergers’ are typically lower income countries in tropical latitudes, and those who are least equipped to cope with the impacts of such change (Schleussner et al 2021).

These results collectively emphasise both the importance of avoiding high-warming scenarios, as well as communicating the perceived magnitude of any changes in climate in ways which are as informative and decision-relevant as possible.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/search/cmip5/.

Acknowledgments

The author thanks Dave Frame and Erich Fischer for helpful discussions relating to the manuscript, and acknowledges funding from the New Zealand MBIE Endeavour Fund Whakahura programme (Grant ID: RTVU1906). The author further acknowledges 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 CMIPS, 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.

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