PCIC SCIENCE BRIEF: THE HUMAN CLIMATE NICHE: PAST PRESENT AND FUTURE

As the climate continues to warm due to anthropogenic greenhouse gas emissions, it is important to contextualize this warming. To do so, we can ask, what are the climatological conditions that have favoured humans in the past and in the present day? Is there such a climatic niche and, if there is, how will this niche change in space and time as the climate continues to warm?

Publishing in the *Proceedings of the National Academy of Sciences*, Xu et al. (2020) use global climate model (GCM) output, weather station data, estimates of historical global population density, and data on global gross domestic product (GDP), crop and livestock production, to determine if there has been a human climate niche. They determine that such a niche has existed. For the past 6000 years, human populations have lived largely in a fairly narrow range of climates and populations clustered around two temperature ranges, with most people living in a range of about 11°C to about 15°C for mean annual temperature and a smaller, but significant portion living in a range around 20°C to about 25°C.

They then examine how this niche may change in the future. They find that, under a high emissions scenario, this niche is projected to shift spatially more in the upcoming 50 years than it has in the past 6000, leaving a third of the projected future human population in regions where the mean annual temperature is greater than 29°C.

Introduction

Every species of life that is known has a range in which it commonly occurs that is determined, in part[1], by environmental conditions that are favourable to that species. In particular, species that live on the continents tend to be distributed in climate niches[2], determined by the large-scale, long-term meteorological conditions of given regions. These climate niches and the plant and animal species occupying them have co-evolved over time[3], with some species having wider niches or having niches that have evolved more rapidly. As anthropogenic climate change continues to reshape the global climate, areas with conditions that constitute a given climate niche can shrink, expand and shift.

The resilience of species to shifting climate niches depends on the width and continued existence of those niches, their ability to migrate, and a host of other factors including the changing range of competitors, predators and pathogens, and the distribution of resources in climatically suitable regions.

Humans are unique on Earth in our ability to use technology to adapt to changing climate conditions. In part because of this, our species can currently be found on every continent and in every climate on the planet, though there are upper limits to the humid heat that humans can tolerate[4]. Despite our adaptability, it is still sensible to ask if our species has a climate niche. If it exists, this raises a number of further questions: what are the climate conditions that comprise it? Where are such conditions found and how might the geographical position and extent of the niche change in the future? And to what extent will human populations be affected by this shift in the regions in which this climate niche exists?

1. A number of factors govern the range of the species, including the extent to which it can be dispersed (through its own movement or by external influences), the spatial distribution of environmental conditions and resources that are favourable to the species, and the distribution of the species' competitors, predators, and pathogens that affect it. For more on ecological niches see Holt (2009) and Soberón (2007). For an early description of the notion of a climate niche, see Grinnell (1917).
2. Climate niches can vary in size and some species live in different niches during different parts of their life cycle. For example, migratory birds live in different climate niches when they are breeding and when they are not breeding. For more on this, see: Ponti et al. (2019).
3. For more on how the evolution of climate niches occurs for different species, see Liu, Ye and Wiens (2020).
4. Above a wet-bulb temperature of about 35°C, humans can no longer shed excess body heat through sweating. Though wet-bulb temperatures exceeding 33°C are rare and there have been no recorded instances of wet bulb temperatures above 35°C. Under a high emissions scenario, such heat extremes are projected to occur regularly in some regions in the Middle East and Southeast Asia by the closing quarter of the 21st century. For more on this, see Raymond, Matthews and Horton (2020).

In order to answer some of these questions, Xu and co-authors bring together GCM output, weather station data, estimates of historical global population density going back 6000 years, and data on global GDP, crop and livestock production.

Evidence for a Historical Human Climate Niche

The Earth presents a wide range of possible climates in which people could potentially live (Figure 1, Panel G). Xu and colleauges look back over the past 6000 years, a period in which agriculture rose to the fore in multiple locations independently. Over this time, agrarian civilizations developed, with populations supported through an increased and reliable food supply[6]. These gradually became the dominant mode of living for the vast majority of the world's human population, to eventually be succeeded by the current industrial society, still supported through agriculture. It is natural then to include not only the distribution of the human population, but also the crops and livestock that supports them, and the distribution of fertile soil in an analysis of any potential climate niche. In addition, as a marker of productivity, the authors use the distribution of GDP.

Xu and colleagues find that human populations, both in the present day and going back 500 and 6000 years (Figure 1, Panels A, B and C) take up only a small portion of the total available climate space. The same is true of the areal distribution of crops, livestock and GDP (Figure 1, Panels D, E and F). In particular, the authors find that, while human populations have been spread out quite widely from moist to arid conditions, avoiding only the dryest and wettest extremes, they are largely circumscribed by a comparatively narrow temperature range. The same is true of the distribution of the crops and livestock that support civilization and productivity as captured by GDP. Importantly, these patterns do not match the distributions of soil fertility or net primary productivity[7]. This means that human populations aren't simply following the distribution of fertile soil or the richest areas of biomass. This population distribution is remarkably similar today as to how it was 6000 years ago, with populations clustered around two temperature ranges, with most people living in a range of about 11°C to about 15°C for mean annual temperature, and a smaller, but significant portion living in a range around 20°C to about 25°C, which the authors have determined lies largely in the Indian Monsoon region.

With a geographical population distribution that is found within a relatively narrow temperature range identified, the authors then try to establish causality. After all, people could aggregate in various areas purely due to historical contingencies. Perhaps they originally settled in some regions due to the needs of their agrarian ancestors that are

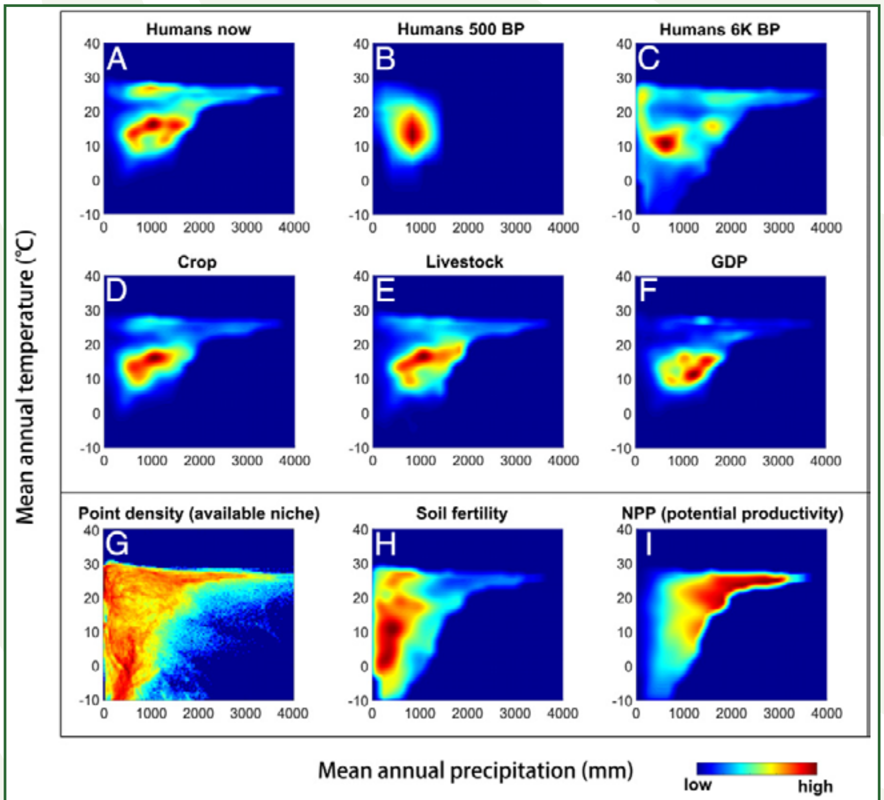

Figure 1: Distributions of human populations, crops, livestock, gross domestic product, available climates, soil fertility and net primary productivity (from Xu et al., 2020).
This figure shows the density distributions of: the current human population (A), the human population 500 years ago (B), the human population 6000 years ago (C), current crops (D), current livestock (E), current gross domestic product (F), available climates (G), soil fertility (H) and net primary productivity (I), by temperature, on the vertical axis, and precipitation, on the horizontal axis. Low and high densities are represented by the colours in the legend on the bottom right-hand side.

5. For more information on the various datasets used by the authors, see the supplemental material to their paper, Xu et al. (2019).
6. For more information about this period see the Roberts, 2014, especially chapter 3, or the first chapter of Starr (1991).

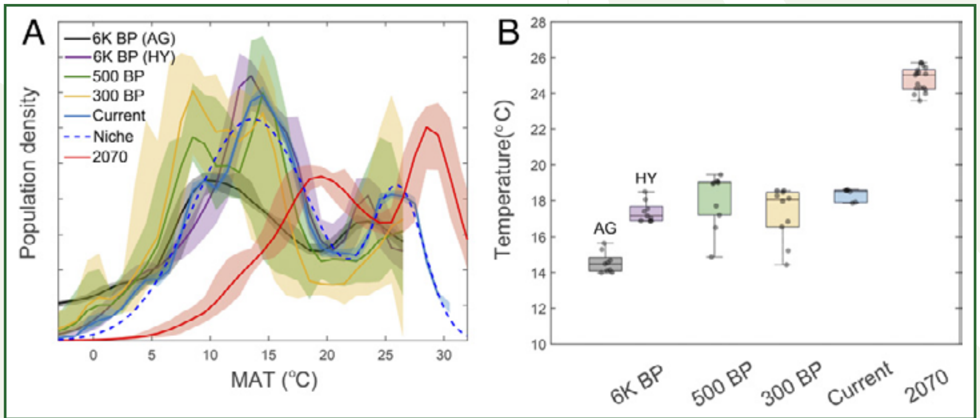

Figure 2: Mean air temperatures experienced by humans (from Xu et al., 2020). This figure shows (A) human population density plotted against the mean air temperatures experienced by a human, and (B) the mean air temperature experienced by an average human for multiple time periods in the past, the present and the projected future. Time periods and colours are related as per the legends and 2070 projections are for the high emissions RCP8.5 scenario and high population growth SSP3 scenario. The bands in Panel A represent the 5th to the 95th percentiles of climate and population estimates. In Panel B, the "box and whiskers" plots represent the distribution of historical estimates and future projections of the temperature experienced by the average human. Top and bottom "whiskers" indicate the highest and lowest values, the tops and bottoms of the boxes indicate the first and third quartiles, the lines inside the box indicate the median (second quartile) values, and grey dots indicate individual data points. The blue dotted line in Panel A represents the authors' estimate of the human temperature niche.

no longer relevant, or due to political happenstance, and then populations simply grew out from there? Identifying a temperature range in which people happen to live, while suggestive, doesn't establish the causal relationship needed to confirm that there is a human climate niche.

In order to argue that they have plausibly identified a human climate niche, the authors rely on three arguments. Their first argument is that about half of all global agricultural production relies on smallholder farms, on which much of the labour is supplied by the farmers themselves, whose work output can be affected by temperature extremes. The authors' second argument is that high temperatures negatively affect people's moods, ability to do labour, behaviour and mental health. Presumably, humans would not settle and flourish in regions with detrimental temperature extremes. For their third argument, the authors point to earlier research[8] that investigated whether there was an optimum for economic productivity by examining year-to-year differences in economic productivity in 166 countries, agricultural and non-agricultural, rich and poor. This earlier work using independent data sets found that there was an optimum, at about 13°C, close to the climate niche identified by Xu and coauthors.

If we accept that the authors have identified a plausible human climate niche that humans have mostly lived within for the past 6000 years, a natural question to raise is, how might this niche change or shift with the changing climate?

Projected Changes to the Human Climate Niche

The projected change to the human climate niche varies with the assumptions underlying the projection. The number of people living within the proposed climate niche depends on the emissions scenario chosen, the assumed future population growth and the future population distribution. The authors use three emissions scenarios[9] developed for the fifth phase of the Coupled Model Intercomparison Project (CMIP5), Representative Concentration Pathway[10] (RCP) 2.6, RCP 4.5 and RCP 8.5. They also use six scenarios for future population growth: zero growth and five population projections that are being used for the Intergovernmental Panel on Climate Change's sixth assessment report. These are taken from Shared Socioeconomic Pathways (SSP) one through five[11].

Xu and coauthors find that, among every combination of emissions scenario and population projection except

7. Net primary productivity is the difference between the amount of carbon dioxide that autotrophs take in from the air and water for photosynthesis (and, to a lesser extent, chemosynthesis) and to build their biomass, and how much carbon dioxide they release during respiration as the mitochondria in their cells metabolizing sugars and starches for energy. Autotrophs are those organisms that make organic compounds using energy from light or inorganic chemical compounds, including plants on land and algae in the ocean.
8. For more on this, see Burke, Hsiang and Miguel (2015).
9. For the results for all three of the emissions scenarios and all six population growth projections, see the supplementary material for Xu et al. (2020).
10. The Representative Concentration Pathways are four trajectories of atmospheric greenhouse gas concentration, used for the fifth phase of the Coupled Model Intercomparison Project CMIP5 (Taylor et al., 2012) and for the Intergovernmental Panel on Climate Change's Fifth Assessment Report. The four trajectories are denoted by the change to radiative forcings that would result from each concentration, e.g. RCP 4.5 would result in an increase of 4.5 Watts per square meter as compared to the preindustrial period (taken to be the year 1750). For more information on CMIP5 and the RCPs, see van Vuuren et al., (2011).

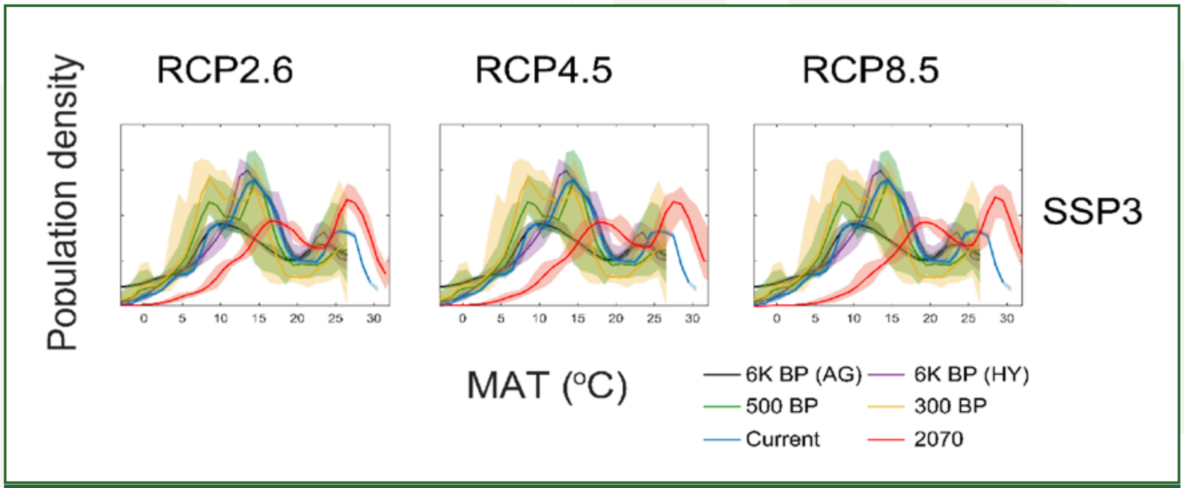

Figure 3: Mean air temperature experienced by humans and projected future air temperatures assuming multiple emissions scenarios (from Xu et al., 2020).
As with Figure 2, Panel A, this figure shows the mean air temperatures experienced by humans plotted against population density for multiple time periods in the past, the present and the projected future. This figure shows a range of projections for 2070, using population growth as in SSP3 (a high population-growth scenario) and different assumed emissions scenarios, as labelled. Time periods and colours are related as per the legends. As with Figure 2, the bands represent the 5th to the 95th percentiles of climate and population estimates.

one, RCP2.6 and zero population growth, the mean temperature experienced by a human being is projected to be outside of the human climate niche (Figure 2, Panel B illustrates this for one emissions scenario and population growth scenario combination). It should be noted that, while the SSPs used by the authors for their population growth projections contain assumptions about migration (along with other factors that affect population growth, such as fertility, mortality and education) for each region, they do not assume that humans move to stay in the climate niche identified by Xu et al. For the high-emissions scenario, the temperature experienced by an average human is projected to change more by 2070 than it has in the past 6000 years, due in part to warming being amplified over land and in part to population growth in warmer regions. The authors note that, under a high-emissions scenario, most of the areas that are close to the current population cluster that is between about 11°C and 15°C, close to 13°C, will have a mean air temperature of around 20°C, edging toward the conditions of the regions that the second population cluster live in today, close to the current day temperatures found in North Africa, Southern China and the Mediterranean (Figure 2). Those living in hotter regions would experience climate conditions currently found in few locations. This would result in approximately 3.5 billion people being exposed to mean annual air temperatures in excess of 29°C, conditions only found in about 0.8% of global land surface in the present day, mostly around the Sahara Desert but projected to expand to cover about a fifth of the global land surface. This is dependent on anthropogenic greenhouse gas emissions. The shift of global temperatures in comparison to the historical human climate niche as concerns the distribution of the human population can be seen in Figure 3. The geographical changes to the climate niche, including how humans would need to move to track the current climate and the physical displacement of the temperature and precipitation niche itself, can be seen in Figure 4.

The overall pattern that the authors see in the projections they use is one of increasing population, predominantly at lower latitude regions, while the human climate niche

11. The Shared Socioeconomic Pathways (SSPs) are a set of potential trajectories of societal development that include plausible future population growth, human development, economic growth, changes to lifestyles, policies and institutions, developments in technology, and management of the global environment and natural resources. In brief: SSP1 depicts a world with lower population growth, and reduced material inequality and resource use. SSP2 is a "middle of the road" scenario with moderate population growth, inequality and resource use. SSP3 is a divided, nationalistic scenario with large inequality and overall large population growth that is centered in poorer countries. SSP4 is a scenario with high inequality and high technology growth, and equivalent population growth to SSP2. SSP5 is characterized by rapid economic growth, fossil fuel use, but an eventual shift to sustainable practices, and low-to-moderate population growth. Note that because the authors only extract population growth figures from the SSPs, this leads to a duplication of results for SSP2 and SSP4. Note also that the SSPs are complicated stories that form part of a toolkit for the interdisciplinary analysis of the climate and development, and so have a depth that might not be apparent in the simple overviews presented here to provide context for the work of Xu and colleagues. For more information, the interested reader is directed to O'Neill et al. (2017) and O'Neill et al (2014).

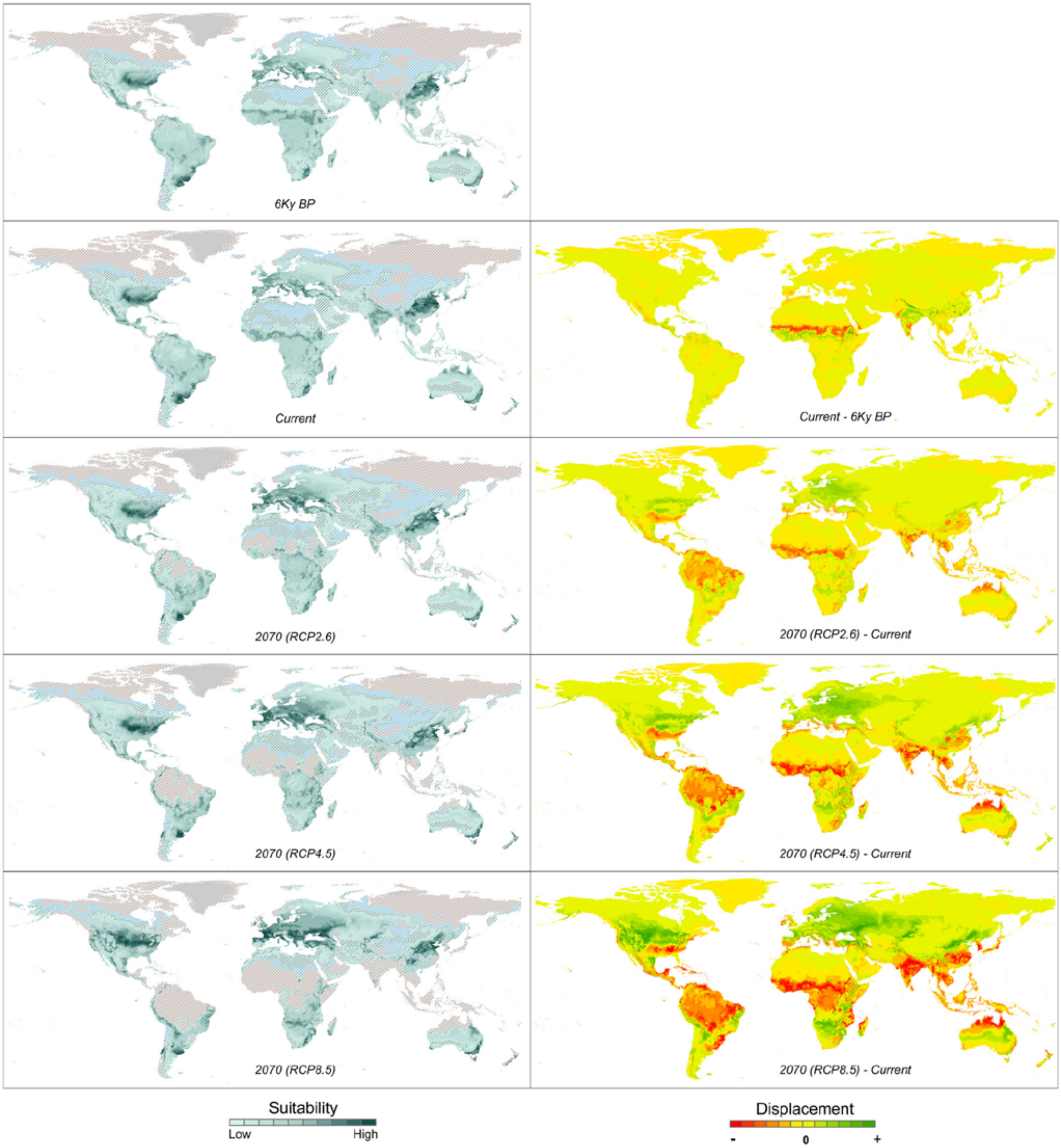

Figure 4: Geographical changes to the human climate niche (from Xu et al., 2020).
This figure shows the geographical changes of the human climate niche in the past and future for three future emissions scenarios. The panels in the left column show what the relative distribution of humans would have to be, if they were distributed following the current conditions of mean annual temperature and precipitation, with areas of greater population density indicated higher suitability. The panels in the right column show the displacement of the human climate niche relative to 6000 years before present (top) and the present day (bottom 3). Suitability and displacement are as marked in their respective legends. The areas outside of the 90th, 95th and 99th percentiles of suitability are indicated by black, blue and red hatching, respectively.

moves toward higher latitudes. Without population redistribution, Xu et al. find that this results in about a billion people being excluded from the human climate niche, for each degree of warming above the current baseline. The exact number varies with the projections of population growth and emissions scenario considered, from about 1.06 billion people—just under a seventh of the human population—assuming zero population growth and the low emissions RCP2.6 scenario, to about 3.64 billion people—about a third of the population—assuming the high population growth of SSP3 and the high emissions RCP8.5 scenario.

The authors note that it is difficult to determine to what extent the mismatch between the human climate niche and future populations will lead to climate migration. Given the nonlinear response of migration in the face of changing climates and the fact that migration decisions tend to be a last resort, the authors suggest that the realized migration will likely be smaller than the discrepancy between their proposed climate niche and projected population distributions.

Summary

Xu and colleagues use a variety of archeological, demographic and climate data to see if human populations are, or have been, circumscribed within a climate niche in the past 6000 years, in the past few centuries and in the present day. They find that human populations have been found within a relatively narrow range of available temperatures, with populations clustered around two temperature ranges, with a larger cluster around 11°C and 15°C, and a smaller cluster between about 20°C and 25°C. This is true of the spread of crops, livestock and GDP. Human populations have spread through most of the available range of available precipitation, largely avoiding all but the driest and wettest extremes. Xu et al. find that the population distribution does not follow a similar pattern for soil fertility or net primary productivity. They argue that disparate lines of evidence from the effects of temperature extremes on labour, physical and mental health, and the coinciding of optimum regions of economic production suggest that they have identified a plausible human climate niche.

The authors examine future projections and find that under nearly all scenarios, the mean temperature experienced by a human being would be outside of their proposed human climate niche by 2070 assuming minimal migration. Moreover, the niche is projected to shift to higher latitudes, while populations grow primarily in lower latitude regions, leaving some portion of the human population outside of niche. The magnitude of these changes and the number of people outside of the climate niche is dependent on the scenarios chosen, with just under a seventh of the population left outside of the niche for the low-emissions, low-population scenario and a third outside of the niche in the high-emissions, high-population scenario. For the combination of the high emissions and high population scenarios, about 3.5 billion people experience mean air temperatures in excess of 29°C, as areas with such conditions expand to cover a fifth of the Earth's land surface area.

The authors' results underline the magnitude and pace of current anthropogenic climate change, which is almost certainly unprecedented in all of human history prior to the industrial revolution. Having substantial regions in which people are subjected to mean air temperatures above 29°C, conditions currently mostly found in the Sahara, could have significant impacts on societies with outdoor labour and place populations at increased risk of heat stress and mortality. Impacts also tend to be disproportionately distributed within societies, with the greatest impacts on those who work outdoors in the hottest regions; these are often also the people with the fewest rights. While it is difficult to move from a shifting climate niche to migration, as the authors note, climate change has triggered migration multiple times in the past, such as during the coldest phase of the Little Ice Age[12] (1560 - 1660 CE) in Europe.

While the results of Xu and colleagues suggest that Canada will move closer to the human climate niche, this does not mean that Canada will avoid having internal population displacements due to the shifting climate, due to flooding, wildfires and other hazards. In addition, Canada is one of the most important refugee resettlement countries, leading the world in the number of refugees welcomed per capita. Climate-induced migration may present a new challenge for Canada's refugee system. A historic ruling by the UN Human Rights Commission[13] found that countries may not deport people who face climate change conditions that violate their right to life. While the onset of climate change is comparatively slow over a human lifespan, the climate signal in migration is not yet clear. Populations

12. The Little Ice Age is generally used to describe a period that began either around the fourteenth century or sixteenth century and lasted until around the nineteenth century that was characterized by generally cold conditions in Europe and regionally in some other areas of the Northern Hemisphere. It is not a true ice age, which simply refers to a period during which the Earth has continental ice sheets and alpine glaciers.
13. The case involves the asylum application in New Zealand of a man from Kiribati. The ruling, from January 2020, found that countries may not deport refugees who face climate induced conditions that violate their right to life. For more information, see: https://www.ohchr.org/EN/NewsEvents/Pages/DisplayNews.aspx?NewsID=25482&LangID=E

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do not constantly alter their geographical distributions to follow the changing climate, but tend to shift after critical climate thresholds are passed—for instance, after prolonged drought. Research on climate migration is ongoing, including here in BC, being undertaken by PCIC's sister organization, the Pacific Institute for Climate Solutions, the Centre for Global Studies at the University of Victoria, and the Climate Migrants and Refugees Project.

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