



The climate niche of *Homo Sapiens*

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Abstract

The increasing atmospheric concentrations of greenhouse gases will place humans in climates that are unprecedented in the evolution of the species. I use the ecological definition of the human niche in climate space, and combine this with a new constellation of methods from extreme value statistics to study human occupation near the boundaries of that niche. I find that the temperature distribution has a thin tail whereas the tail of precipitation is thick. This thick tail reflects that humans are used to a wide range of rainfall regimes, so future precipitation changes, although leading to unprecedented rainfall, are less likely to pose a major challenge. An increase in temperature, on the other hand, will put hundreds of millions of people in heat that is not just unprecedented and but also hard to imagine from extrapolating current temperatures. These findings are qualitatively similar but an order of magnitude smaller than previous studies.

Keywords Tail-index · Convex hull · Climate

1 Introduction

A key concern about greenhouse gas emissions is that future climate will be *unprecedented* in the evolutionary history of humankind. It is one of the three justifications for the 2°C target of the Paris Agreement (WBGU 1995, see also Tol (2007)) and has raised worries about the safety of humankind (Rockström et al. 2009), inspiring such organizations as *Extinction Rebellion* and the *Letzte Generation*. Unprecedented is not synonymous with detrimental, however (Hume 1739; Moore 1903). Furthermore, since the *physical* evolution of *Homo Sapiens* is slow because of our slow maturation and low birth numbers, behavioural adaptation is well developed. Humans are very adaptive and actively shape their environment

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to suit their needs, traits shared, to a lesser extent, by other long-lived animals. In this paper, I develop a method to re-assess how a species would fare outside its observed climate niche, and apply this to humans and their sustenance.

Figure 1 illustrates this concern. It takes the current distribution of humans in climate space—here defined as the annual average temperature and the average monthly precipitation—and computes the fraction of humanity that would experience a climate where no human has lived before should temperature increase and rainfall change. Figure 1 shows two things. First, precipitation does not really matter in this regard. Humans live in such a wide variety of rain and snow climates that a 30% increase or a 30% decrease would push few people into unprecedented territory. The opposite is true for temperature. Many people live close to the observed maximum temperature so that 6°C of warming would push 40% of people into uncharted climate territory. Note also that 1°C of warming—roughly 2°C above preindustrial—would have a minimal effect.

Xu et al. (2020) and Lenton et al. (2023) study the same topic using roughly the same data. They argue that human life is fragile to climate change, which would put billions of people in unlivable conditions. Their estimate of the human climate envelope is unfortunately biased. They write that they removed the extreme 1% of the data to avoid “potential bias due to sparse sampling”, but they did not correct their estimates for their censoring. Removal of extreme observations is justified if one believes there may be outliers. However, outliers in the temperature and precipitation data were removed in the pre-processing that produced gridded, long-term averages. The population data record *permanent* occupation. I show below

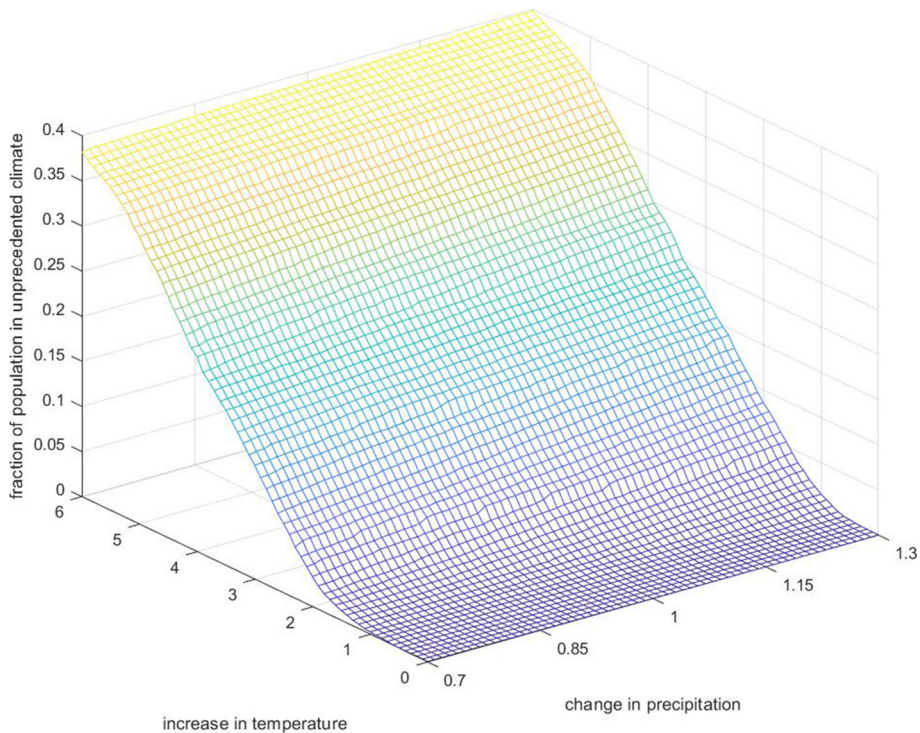


Fig. 1 The fraction of the human population that would be exposed to an unprecedented climate as a function of absolute warming (in degree Celsius) and relative drying or wetting (in fraction of current precipitation)

that the climate pattern of occupation is stable over time, so there are no obvious outliers in these data either. I, therefore, do not censor the data.

Relying on a Gaussian mixture, Xu et al. (2020); Lenton et al. (2023) assume that tails are thin. Unprecedented climates are therefore harsh *by assumption*. I test this assumption and find that the tails are, indeed, thin, but only for temperature. While my distributional assumptions are theoretically superior, they do not account for much of the difference in results.

Xu's alarming conclusion is strengthened by their assumption that the human climate niche is the 90% confidence interval of their population model. In other words, they assume that 10% of the (predicted) world population live in unlivable conditions, an inconsistent assumption. These are not zombies. In contrast, I assume that people are alive regardless of where they are recorded to live. As noted above, the population data are for permanent occupation. Humans can be found mid-ocean, in Antarctica, and in outer space—but they do not *live* there, so these places are excluded. Xu *et al.* go much further than that. They argue that climates, that have been occupied by humans for thousands of years, are unsuitable for humans, and declare a thriving city like Singapore to be unlivable. This assumption adds 2.4 billion people in deadly heat for 2°C global warming.

Like Xu et al. (2020) and Lenton et al. (2023), I find that a warmer and wetter climate would pose problems for humanity—but my numbers of people under threat are much smaller, hundreds of millions rather than billions.

The paper proceeds as follows. Section 2 discusses methods and data. Section 3 shows results for people and crops. Section 4 presents the implications of future climate change. Section 5 concludes.

2 Methods and data

2.1 Methods

How to estimate a niche? You could define a niche as a stochastic frontier. Originally, stochastic frontier analysis estimates the *maximum* possible production, a frontier that cannot be exceeded. Flipping the sign, you can estimate a minimum too. Taking the distance from a central point, you can estimate a perimeter, an area you cannot go outside. The stochastic frontier is parametric, however. If it is approximated by a second-order polynomial in explanatory variables, the niche would be an ellipsoid around the central point. Figure 2 shows the irregular shape of human occupation of climate space in the year 2000, here limited to average temperature and total precipitation. An ellipse badly approximates these observations.

Data envelopment analysis is non-parametric. It allows for a flexible frontier, but not inference or extrapolation. I therefore do not use this method here.

Alternatively, you could construct a multivariate kernel density. However, kernel densities are excellent for describing data but unsuitable for extrapolation. Furthermore, there are parts of climate space that are not occupied by humans but are surrounded by occupied areas. Figure 2 shows that no human lives at 12°C and 25 cm/year—but humans live in colder or hotter places that are just as wet, and in wetter and dryer places that are just as warm. A kernel density would suggest that it is impossible to live at 12°C and 25 cm/year—although no one lives there because there is, in fact, no such climate on Earth.

Therefore, I use the convex hull, a linear combination of observations that envelops all observations. This is also shown in Fig. 2. The convex hull is a multi-dimensional generalization of the uni-dimensional minimum and maximum. In one dimension, all observations

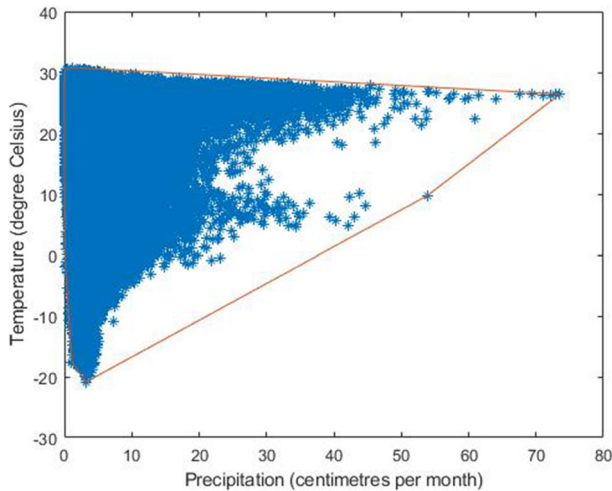


Fig. 2 Human occupation of temperature-precipitation space, 2000, and its convex hull

lie between the minimum and maximum. In two (or more) dimensions, all observations lie within the convex hull.

Like a kernel density, a convex hull is a purely descriptive device with little scope for extrapolation. A convex hull is an extremum. If the data were a *sample* randomly drawn from a population, we could derive its distribution and use that to extrapolate. However, the data used here are the *population*, rather than a sample. Worton (1995) suggested a more promising route to statistical analysis: The peeled hull. The convex hull is a subset of the set of observations. Removing the data *on* the convex hull gives a smaller set of observations, with its own convex hull. You can continue to “peel” the observations until only, say, 95% of the sample or population is left. That is, just as the convex hull generalizes the minimum and maximum, the *peeled* hull generalizes the order statistics. There is only one maximum, but many order statistics, so that we can use statistical analysis. Figure 3 shows the peeled hulls; the smallest includes 95% of the human population.

Dominicy et al. (2017) show that the (Hill 1975) estimator¹ of the tail-index can be applied to any *norm* of the multivariate order statistics. Dominicy et al. (2020) generalize this to any *homogeneous function* of the multivariate order statistics.²—Hill’s statistic, divided by the degree of homogeneity, is a consistent estimator of the tail index. Dominicy et al. (2020) repurpose the algorithm by Rousseeuw and Driessen (1999) to define the order statistics. However, that algorithm is parametric; the order statistics are ellipsoids. I therefore prefer the peeled hull of Worton (1995).

¹ Let $X_{(i)}$ be the order statistics of a data set of size n . That is, $X_{(n)}$ is the maximum, $X_{(n-1)}$ is the second-largest observation, and so on, so that $X_{(1)}$ is the minimum. Define $M(k) = \frac{1}{k} \sum_{i=0}^{k-1} \ln X_{(n-i)} - \ln X_{(n-k)}$. That is, $M(k)$ is the average slope between the k th-largest observation and the larger observations. The maximum likelihood, best linear unbiased, and uniform minimum variance unbiased estimator of the tail-index $\alpha = M^{-1}$. The tail-index is the shape parameter of the Pareto distribution $F(X) = 1 - \left(\frac{\beta}{X}\right)^\alpha$, where $X > \beta > 0$.

² A function f with arguments $x_1, x_2, \dots, x_n$ is homogeneous of degree k if $f(sx_1, sx_2, \dots, sx_n) = s^k f(x_1, x_2, \dots, x_n)$. In words, if all inputs are multiplied by the same factor, then the output is multiplied by that factor to the power k .

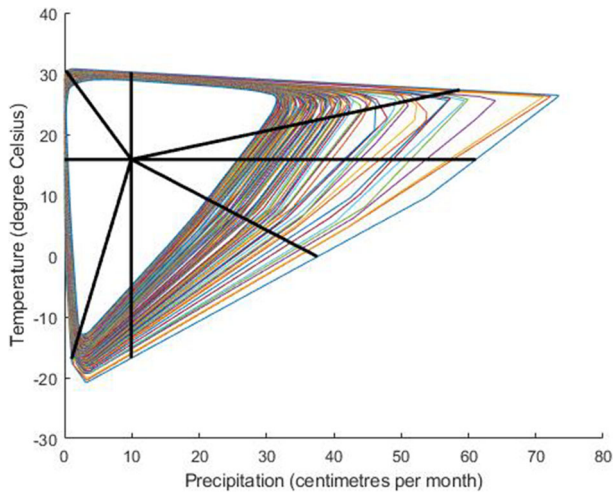


Fig. 3 The peeled hull of the human occupation of climate space, 2000, and the studied order statistics of temperature and precipitation

I apply the proposed Dominicy-Worton-Hill estimator to the area of the convex hull and the length of its perimeter, and to the eight trajectories shown in Fig. 3. The trajectories together span all possible climate change: warmer, colder, wetter, drier, and any combination. The trajectories are defined as the intersections of the peeled hulls with straight lines from the population-weighted average temperature and precipitation to their maximum and minimum. The tail-index is thus estimated for those 5% of the people who live in the most extreme climates.

The distance between two points on a trajectory is homogeneous of degree one. The perimeter length is the sum of such distances and so homogeneous of degree one too. The area is homogeneous of degree two, which is easily seen by dividing the area into triangles.

Hill (1975) proposed the maximum likelihood estimator of the tail-index, valid if the tail of the distribution is exactly Pareto. A quantile-quantile (QQ) estimator is preferred if the distribution is only approximately Pareto. For robustness, I here use the QQ estimator proposed by Brito and Freitas (2003): The geometric average of the coefficients from (1) regressing the natural logarithm of size on the natural logarithm of its rank (Kratz and Resnick 1996) and (2) regressing log rank on log size (Schultze and Steinebach 1996).

The former estimator was proposed by Kratz and Resnick (1996). It naturally generalizes to the case of censored data (Tobin 1958; Goldberger 1986). This Tobit model is relevant as people have occupied the hottest and driest parts of the planet—and may have moved to hotter and drier places if available.

QQ estimators were proposed as robust alternatives to the Hill estimator of the tail-index. I also use the doubly-robust median estimator (Brazauskas and Serfling 2000) and its censored counterpart (Powell 1984).

2.2 Data

The two main data sets are CRU TS and HYDE. HYDE 3.2 (Klein Goldewijk et al. 2010) reports human population counts and densities for the whole world, at a $5' \times 5'$ grid, for the last 12,000 years, in time steps of 1,000 (100) years before (after) the birth of Christ. In

Table 1 Estimates of the tail-index of the area and the perimeter length of the peeled convex hull for the human population in the year 2000. Standard errors are in parenthesis

	Area	Perimeter
Hill	6.27 (0.67)	6.71 (0.72)
QQ	7.38 (1.09)	7.22 (1.07)

10,000 BC, 228,563 grid cells were occupied by humans, increasing to 277,987 grid cells in 2000. HYDE also reports croplands and urbanization.

CRU TS 4.05 (Harris et al. 2020) reports average monthly temperature and total monthly precipitation at a $30' \times 30'$ grid for 1901 to 2020. I compute the annual average for the period 1991–2020, as climate is typically defined as the thirty-year average weather.

Assuming a homogeneous climate within the CRU grid cells, I overlay CRU and HYDE data and then aggregate the population number and grid cell area to every unique combination of temperature and precipitation; average population density by climate cell follows readily. This is the main database: human population in climate space. I follow the same procedure for cropland.

I also consider per capita income, from the Global Data Lab (GDL) (Smits and Permanyer 2019). They report per capita income, in Geary-Khamis dollars reflecting local purchasing power, for subnational administrative units. GDL has a crude spatial resolution compared to KummU et al. (2018) and Nordhaus (2006). However, GDL reports *income* while KummU and Nordhaus report *output* as measured by value added. The difference between income and output is particularly large in inner cities where many work but few live. Harris et al. (2020) removed the urban heat island effect (Estrada et al. 2017) from their data. Output and income also differ in the oil fields of Siberia and the Arabian Desert, which would distort any analysis of the impact of climate on economic *output* per person. I therefore use GDL data. Assuming a uniform income distribution within provinces and states, I overlay GDL and HYDE data and the result with CRU data to find human population in climate space by income.

Table 2 Estimates of the tail-index of temperature and precipitation along the trajectories of Fig. 3 for the human population in the year 2000. Standard errors are in parenthesis

	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Dryer	Dryer	Hotter Dryer
Temperature								
Hill	628.99 (67.04)	139.99 (14.86)		40.67 (4.33)	34.16 (3.64)	89.71 (9.56)		311.34 (33.18)
QQ	802.37 (118.95)	144.75 (21.46)		113.35 (16.80)	80.62 (11.95)	240.07 (35.59)		500.51 (74.20)
Precipitation								
Hill		3.95 (0.42)	4.04 (0.43)	5.20 (0.55)		1.86 (0.20)	0.00 (0.00)	0.65 (0.07)
QQ		4.68 (0.69)	4.39 (0.65)	6.17 (0.92)		6.06 (0.90)	1.05 (0.15)	2.11 (0.31)

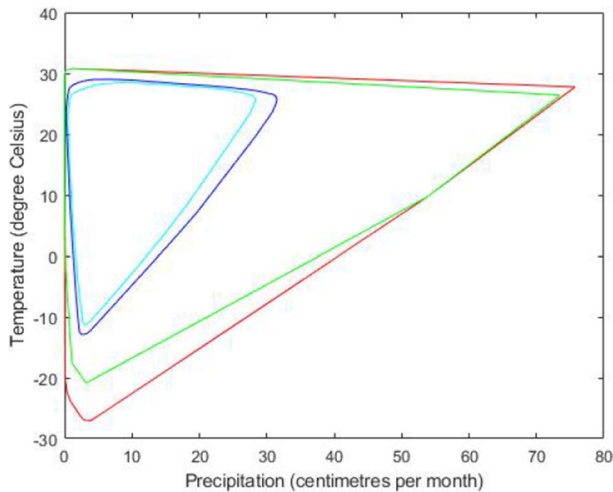


Fig. 4 The convex hull of the human occupation of climate space in the year 2000 (green), the convex hull that contains 95% of all humans (blue), and the convex hull of temperature and precipitation regardless of human occupation (red). For comparison with Xu et al. (2020), the 90% hull is also shown (cyan)

3 Results

3.1 People

Table 1 shows the estimated tail-indices for area and perimeter. The estimates vary between 6.4 and 7.4, indicating a thin tail: The first 6 moments exist, but the 8th moment does not. Table 2 shows a more nuanced picture: Tail-indices are estimated separately for temperature and precipitation, and separately for left and right tail. Table 2 reveals a thin tail for temperature, and a thinner one for hot conditions than for cold ones. The tail for precipitation is less thin for wet conditions and thick for dry conditions.

A thick tail means that there is a reasonable chance of observing something much larger than was observed before. Thick tails are usually a source of concern. A thick tail for stock market returns means the market can drop far fast. A thick tail for rainfall means the next flood may be much worse than anything seen before. In this application, however, thick tails are a good sign. Humans can reasonably be expected to live in areas drier than observed. On the other hand, thin tails are a reason for concern. Human population drops rapidly in hotter conditions. Higher temperatures still would pose a real problem.

Figure 4 shows four convex hulls. Comparing the hull that contains all of humanity to the one that contains 95% of people, we see that the order statistics span a large distance over wet conditions³, a smaller distance over cold conditions⁴, and hardly any distance over hot conditions. This explains the estimated relative tail-indices: fat for precipitation, thick for cold, thin for heat. The third convex hull in Fig. 4 is for the observed temperature and rainfall on the six inhabited continents. Humans have occupied almost the entire available climate space, except for the very cold parts of the planet and its very wet and hot bits. This potentially contradicts the thin tail for heat. We could have lived, indeed may have lived, in hotter places if these were there.

³ that is, a large difference in centimetres of precipitation per month

⁴ that is, a small difference in degrees Celsius

The latter interpretation is supported by Fig. 5. The upper panel shows the convex hull for the whole population, the population in areas where the population density is at the 20%ile or higher, and so on all the way up to the 80%ile. The convex hull is curtailed at the cold and wet end. The lower panel shows the area of the convex hull, removing areas in steps of 1%ile. The convex hull starts to really change only when we exclude everywhere below the median population density—and even restricting attention to the most densely populated cities does not halve the area of the convex hull.

Figure 6 shows the histogram of available and occupied temperature and rainfall regimes. At the warm end, climate and occupied climate show a very similar distribution; but the distribution is very different at the cold end. The temperature distribution is notably thin-tailed, so the occupied temperature distribution has to be thin-tailed too.

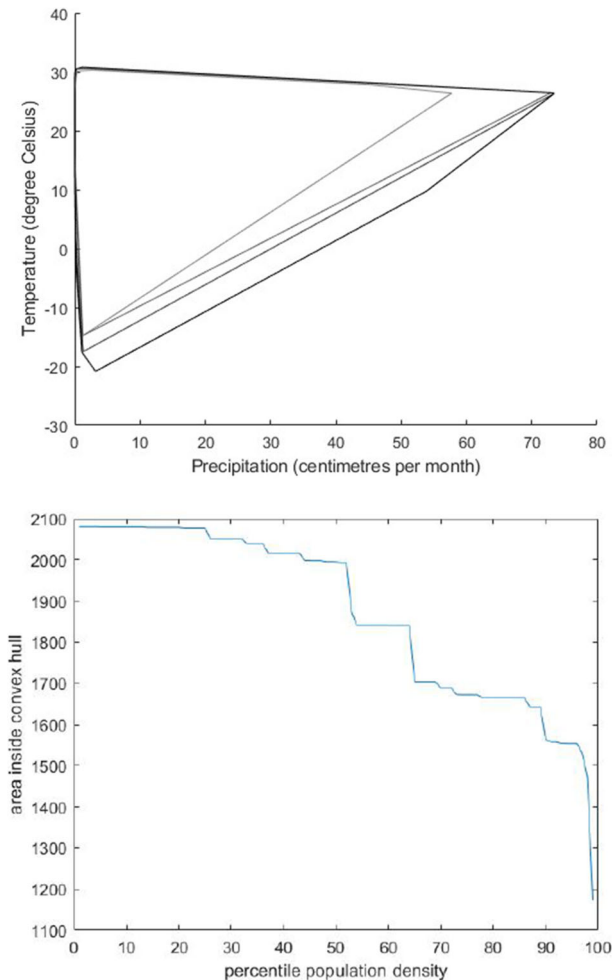


Fig. 5 The convex hull of the human occupation of climate space in 2000 for all population densities (black) and its quintiles (gray tones, with the lightest gray denoting the most densely populated grid cells; top panel) and the area of hull for the percentiles of the distribution of population density (bottom panel)

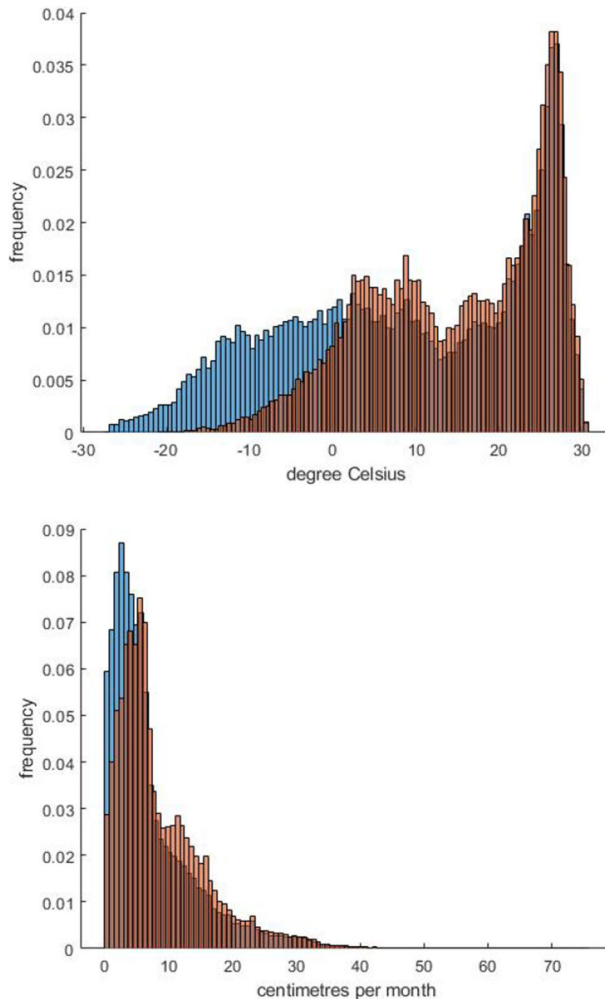


Fig. 6 The histogram of human-occupied (orange) and all (blue) temperature (top panel) and precipitation (bottom panel)

At the dry end, the distributions of climate and occupied climate look very different. At the wet end, climate and occupied climate show a similar distribution. Both show a fat tail. Figure 6 thus supports the hypothesis that we would have chosen to live in hotter and wetter climates had these been there.

However, Table 3 reveals this not to be the case. It shows estimates of the tail-index with and without correcting for censoring the temperature and precipitation data. The top row shows a QQ estimator based on ordinary least squares (Kratz and Resnick 1996). The second row shows the Tobit estimator, which corrects OLS for top censoring (Tobin 1958). This may be dubbed Tobin's QQ estimator. Powell (1984) proposed a censored least absolute deviation estimator that is robust to deviations from normality and homoskedasticity. This is shown on the bottom row. The corresponding median estimator (Brazauskas and Serfling 2000) is on the third row.

Table 3 Estimates of the tail-index of temperature and precipitation along the trajectories of Fig. 3 for the human population in the year 2000 with (Tobit, CLAD) and without (OLS, LAD) correcting for censoring. Standard errors are in parenthesis

	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Dryer	Dryer	Hotter Dryer
Temperature								
OLS	828.98 (122.23)	147.13 (21.69)		142.51 (21.01)	93.59 (13.80)	272.57 (40.19)		529.16 (78.02)
Tobit	783.58 (115.53)	138.56 (20.43)		142.13 (20.96)	93.39 (13.77)	272.08 (40.12)		490.87 (72.37)
LAD	706.91 (104.23)	135.90 (20.04)		134.26 (19.80)	78.54 (11.58)	228.82 (33.74)		510.86 (75.32)
CLAD	622.67 (91.81)	130.46 (19.23)		59.69 (8.80)	45.38 (6.69)	134.69 (19.86)		440.82 (65.00)
Precipitation								
OLS		4.79 (0.71)	4.42 (0.65)	6.33 (0.93)		7.07 (1.04)	1.71 (0.25)	2.65 (0.39)
Tobit		4.47 (0.66)	4.23 (0.62)	6.33 (0.93)		7.06 (1.04)	1.52 (0.22)	2.38 (0.35)
LAD		4.12 (0.61)	4.09 (0.60)	5.58 (0.82)		6.25 (0.92)	2.32 (0.34)	2.71 (0.40)
CLAD		4.01 (0.59)	4.05 (0.60)	4.94 (0.73)		2.70 (0.40)	0.94 (0.14)	1.68 (0.25)

Although estimates are different, these differences are not statistically significant—drying excepted: the tail-index is lower if the robust estimator is corrected for censoring. The qualitative conclusions remain: The tail of the precipitation distribution is thick, perhaps thicker after censoring. The tail of the temperature distribution is thin, also if we take into account that humans live in the hottest places on Earth and therefore could not have been challenged to live in even hotter places.

Figure 7 is similar to Fig. 5 but sample restrictions are based on per capita income rather than population density. As above, the convex hull changes shape at the cold and wet extremes, but not so much at the hot and dry extremes. The convex hull really changes only when we restrict attention to the 20% richest people.

Figure 8 shows the convex hull for all years in the HYDE data, but using modern climate. The convex hulls are the same for the years 10,000 BC to 1000 AD and for the years 1100 AD to 2000 AD. The settlement of Bergen, Norway, in the 11th century makes the difference: Bergen is not particularly cold but it is exceptionally wet.⁵ Figure 7 shows that income and access to technologies to weather extreme climates do not really affect where people live. Figure 8 shows that technology itself has been sufficiently mature for 12,000 years (or more) to sustain people in very hot, very cold, very dry, and very wet places.

One may argue there is a strong interaction between temperature and precipitation so that a convex hull artificially inflates the climate niche. I therefore replace the convex hull with the compact hull in Fig. 9. The compact hull differs substantially from the convex hull on

⁵ Note that HYDE places the settlement of Bergen between 1100 and 1200, somewhat later than the historical date.

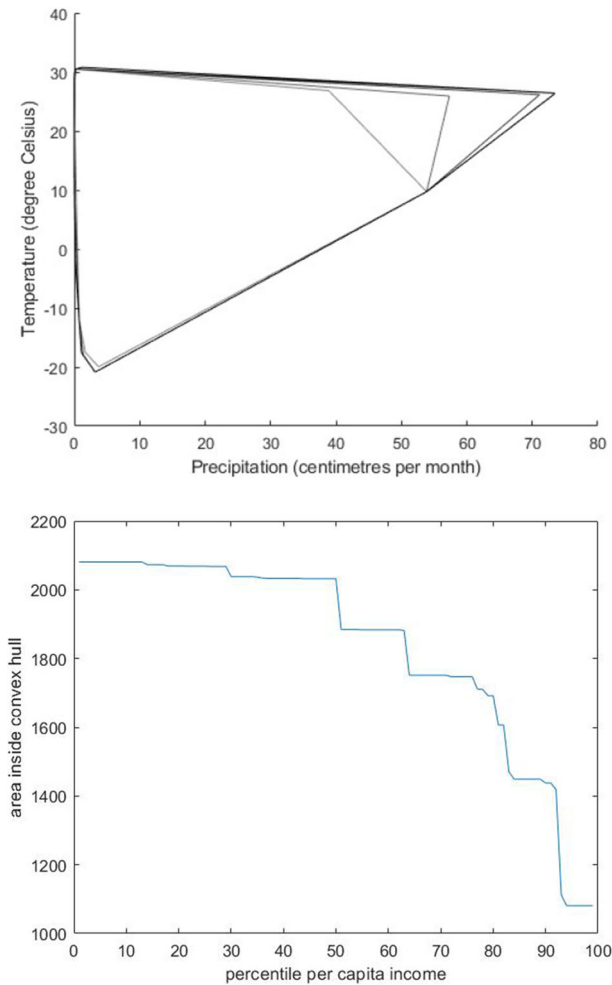


Fig. 7 The convex hull of the human occupation of climate space in 2000 for all levels of per capita income (black) and its quintiles (gray tones, with the lightest gray denoting the wealthiest grid cells; top panel) and the area of hull for the percentiles of the distribution of per capita income (bottom panel)

the cold, wet side, but much less so on the hot side and hardly at all on the dry side. Table 4 re-estimates the tail-indices. Because a compact hull changes much more than a convex hull when peeled, the estimated tail-indices are smaller than in Table 2. The qualitative results remain: Thin tails for temperature and thick, perhaps fat tails for precipitation. That said, the temperature tails are less thin for a compact hull, so that humans are more likely to be able to withstand heating.

3.2 Crops

Tables 5 and 6 show the estimated tail-indices for area and perimeter, and for the trajectories across the peeled hulls for croplands in the year 2000. The results are very similar to the ones for human occupation, except that tails are somewhat thinner for crops than for humans.

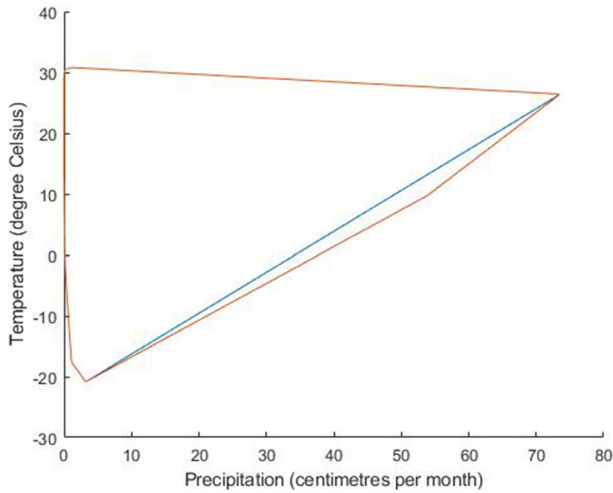


Fig. 8 The convex hull of the human occupation of climate space until 1100 AD (blue) and after (orange)

Cooling is less of a concern than warming, drying is less worrying than wettening, and temperature is more important than precipitation.

Figure 10 shows three convex hulls. The largest is the convex hull of all climates on Earth. The second-largest contains all croplands in the year 2000. A comparison with Fig. 8 shows that there are places with humans but no crops. In earlier times, people relied on hunting, fishing, gathering, and pastoralism in places where agriculture was not possible or not sufficiently rewarding. Later, trade became an important factor too. This may well imply that there are climates where humans have tried and failed to grow crops.

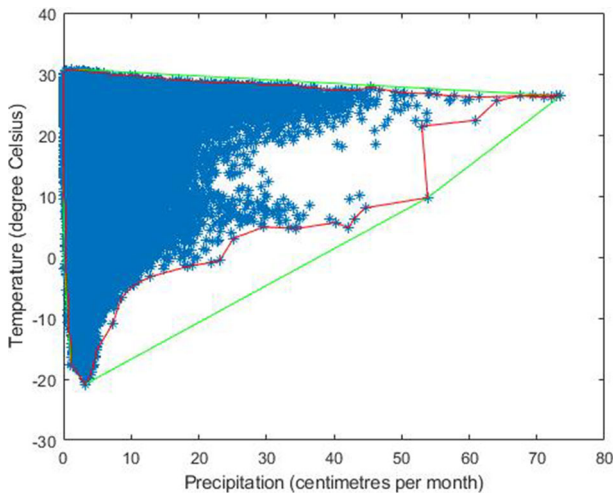


Fig. 9 The convex hull of the human occupation of climate space in the year 2000 (green) and the compact hull

Table 4 Estimates of the tail-index of temperature and precipitation for the peeled compact hull of the human population in the year 2000. Standard errors are in parenthesis

	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Dryer	Dryer	Hotter Dryer
Temperature								
Hill	31.21 (3.33)	53.61 (5.71)		21.15 (2.25)	17.09 (1.82)	32.74 (3.49)		29.87 (3.18)
QQ	64.21 (9.52)	43.88 (6.51)		32.81 (4.86)	20.53 (3.00)	52.32 (7.76)		52.74 (7.82)
Precipitation								
Hill		1.12 (0.12)	1.19 (0.13)	1.23 (0.13)		1.07 (0.11)	0.00 (0.00)	0.44 (0.05)
QQ		1.21 (0.18)	1.20 (0.18)	1.16 (0.17)		2.24 (0.33)	1.00 (0.15)	0.87 (0.13)

The smallest convex hull in Fig. 10 contains all croplands in the year 5000 BC. It is small. While research on the impact of climate change on agriculture and studies of technological progress in agriculture have almost exclusively focused on the *internal* margin⁶—where crops are currently grown—Fig. 10 reveals remarkable progress on the *external* margin—developing varieties and methods to grow crops in climates where they previously would not because it was too hot, too cold, too wet, or too dry. While remarkable, the speed is slow, in the order of 1°C per millennium, much slower than the rate of warming expected for the 21st century.

4 Implications

Figure 1 shows that temperature is more important than precipitation in driving humankind out of our climate niche. The analysis therefore proceeds with temperature only. The top curve in Fig. 11 repeats the information from Fig. 1 but in absolute numbers. Assuming no population growth, over two billion people would live in unprecedented heat should the world warm by 6°C. Note again how 1°C warming above today would have a minimal effect.

Unprecedented is a sharp divide; people either live in a certain climate or they do not. The statistical analysis above allows for a more gradual transition, a measure of the degree of unprecedentedness. The bottom curve applies the Pareto distribution as estimated above using the Hill estimator;⁷ see Table 2. The tail-index indicates the speed of decline of the likelihood of finding people in a certain temperature, as the temperature rises. Normalizing this to unity at the convex hull—the maximum observed temperature is livable as shown by the people who live there—I then calculate the “probability” that people could live at higher temperatures. I refer to this as the number of people living in unprecedented but imaginable heat—where imagination is based on extrapolation from experienced circumstances. Having observed their neighbours in slightly cooler climes, the people at the temperature maximum can picture what life would be like if it were somewhat warmer. Formally, the number of

⁶ Olmstead and Rhode (2011) is an exception.

⁷ The estimated tail-index for high temperatures is so large and so similar for all alternative estimators in Tables 2 and 3 that the results would be very similar.

Table 5 Estimates of the tail-index of the area and the perimeter length of the peeled convex hull for cropland in the year 2000. Standard errors are in parenthesis

	Area	Perimeter
Hill	7.69 (0.33)	7.63 (0.33)
QQ	9.90 (1.47)	10.15 (1.50)

people in imaginable heat equals the number of people in unprecedented heat times survival function $S(T) = \left(\frac{T_{max}}{T}\right)^\alpha$, where T_{max} is the maximum observed temperature and $\alpha = 629$ the estimated tail-index. This number is zero by construction without climate change, but increases to an expected value of 300 million for 5°C of warming. The number of people in unimaginable heat is then what remains, that is the number of people in unprecedented heat times the cumulative distribution function $F(T) = 1 - S(T)$. This number rises to slightly less than 2 billion people for a global warming of 6°C.

5 Discussion and conclusion

What climate is suitable for human habitation? I answer that question by mapping people and their crops on the temperature-precipitation space. I use Worton’s peeled convex hull to find the climate niche of *Homo Sapiens* and its order statistics, and the Dominicy-Hill estimator to determine the thickness of the tails of the distribution of humans in climate space. I find thin tails at the hot end of the distribution, somewhat less thin tails at the cold end, thicker tails at the wet end, and fat tails at the dry end. As future climate is almost certainly hotter and probably wetter, this pattern is the opposite of what would be good for humans. Controlling for population density or average income does not affect the qualitative findings, which also appear to be stable over time and robust to censoring. The distribution of croplands shows the same results, with slightly thinner tails. Extrapolating to a warmer world, some 200 million people would be exposed to unprecedented heat, of which about half would experience unimaginable heat, if the world would warm by a further 2°C.

Table 6 Estimates of the tail-index of temperature and precipitation along the trajectories of Fig. 3 for cropland in the year 2000. Standard errors are in parenthesis

	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Drier	Drier	Hotter Drier
Temperature								
Hill	1129.6 (49.1)	184.1 (8.0)		54.7 (2.4)	44.0 (1.9)	100.4 (4.4)		401.9 (17.5)
QQ	1574.3 (233.4)	240.6 (35.7)		207.5 (30.8)	128.5 (19.1)	383.6 (56.9)		478.8 (71.0)
Precipitation								
Hill		4.93 (0.21)	5.34 (0.23)	6.70 (0.29)		2.13 (0.09)	0.42 (0.02)	0.45 (0.02)
QQ		7.18 (1.06)	6.87 (1.02)	8.34 (1.24)		9.37 (1.39)	2.22 (0.33)	3.36 (0.50)

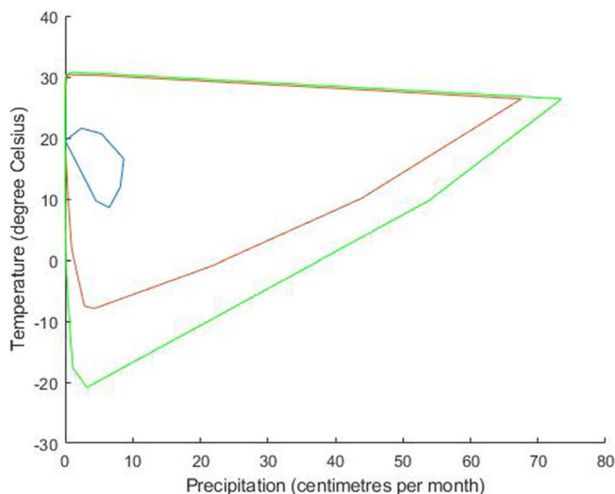


Fig. 10 The convex hull of cropland in climate space in 5000 BC (smallest area, in blue) and 2000 AD (in red), and the convex hull of human occupation (largest area, in green)

Although qualitatively similar to the results of Xu et al. (2020); Lenton et al. (2023), my quantitative results are very different. Xu et al. (2020); Lenton et al. (2023) put 1-5 billion people outside the historical climate niche in the next fifty years, more than an order of magnitude more than the findings here. One reason is that Xu et al. (2020) assume that 10% of the current population—800 million people—already live outside the climate niche. My starting point is that everyone alive is in livable conditions. Adding 800 million to the numbers in Fig. 1 still results in substantially lower numbers than found in Xu et al. (2020);

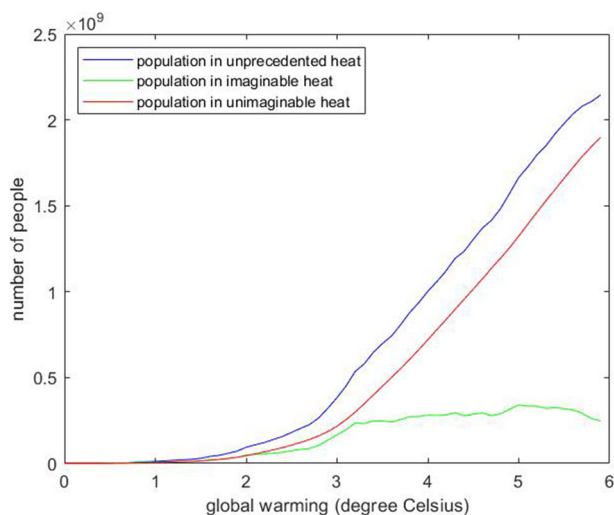


Fig. 11 The number of people exposed to unprecedented heat, unprecedented but imaginable heat, and unprecedented and unimaginable heat

Lenton et al. (2023), because 2°C warming would push some 1.6 billion people out of the 90%ile but not beyond the 100%ile.⁸

There are a number of caveats. Climate is measured by annual average temperature and monthly average precipitation. Although many climate variables are correlated with these two variables, that correlation is not perfect and a richer set of variables may well lead to somewhat different conclusions. More importantly, there is no agency in the model and no microclimate. Humans migrate (Barrios et al. 2006; Marchiori et al. 2012), adjust their behaviour to the weather (Adger 2003; Auffhammer and Mansur 2014; Kousky 2014; Graff Zivin and Neidell 2014), seek cooler places in their immediate environment (Watanabe and Ishii 2016; Yang et al. 2017), and change their environment (Estrada et al. 2017). These features partly determine where people live and are thus included in the statistical analysis. The extrapolation, however, implicitly assumes that future human behaviour is like current human behaviour and future technology is like today's.

These caveats notwithstanding, the results suggest that climate change poses an existential threat to many people. That these are measured in the hundreds of millions rather than billions as in previous studies, is scant comfort. The proposed method applied to other species, that are no generalists like *Homo Sapiens*, is likely to show much larger impacts.

Availability of data and materials <https://github.com/rtol/ClimateNiche>

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References

- Adger W (2003) Social capital, collective action, and adaptation to climate change. *Economic Geography* 79(4):387–404. <https://doi.org/10.1111/j.1944-8287.2003.tb00220.x>
- Auffhammer M, Mansur E (2014) Measuring climatic impacts on energy consumption: A review of the empirical literature. *Energy Economics* 46:522–530. <https://doi.org/10.1016/j.eneco.2014.04.017>
- Barrios S, Bertinelli L, Strobl E (2006) Climatic change and rural-urban migration: The case of sub-Saharan Africa. *Journal of Urban Economics* 60(3):357–371. <https://doi.org/10.1016/j.jue.2006.04.005>
- Brazauskas V, Serfling R (2000) Robust and Efficient Estimation of the Tail Index of a Single-Parameter Pareto Distribution. *North American Actuarial Journal* 4(4):12–27. <https://doi.org/10.1080/10920277.2000.105>
- Brito M, Freitas ACM (2003) Limiting behaviour of a geometric-type estimator for tail indices. *Insurance: Mathematics and Economics*, 33(2):211 – 226. URL <http://www.sciencedirect.com/science/article/pii/S0167668703001355>
- Dominicy Y, Ilmonen P, Veredas D (2017) Multivariate Hill estimators. *International Statistical Review*, 85(1):108–142. URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/insr.12120>
- Dominicy Y, Heikkilä M, Ilmonen P, Veredas D (2020) Flexible multivariate Hill estimators. *Journal of Econometrics*, 217(2):398–410. URL <https://www.sciencedirect.com/science/article/pii/S0304407619302568>
- Estrada F, Botzen WJW, Tol RSJ (2017) A global economic assessment of city policies to reduce climate change impacts. *Nature Climate Change* 7(6):403–406. <https://doi.org/10.1038/nclimate3301>
- Goldberger AS (1986) *Econometric Theory*. Wiley, New York
- Graff Zivin J, Neidell M (2014) Temperature and the allocation of time: Implications for climate change. *Journal of Labor Economics* 32(1):1–26. <https://doi.org/10.1086/671766>
- Harris I, Osborn T, Jones P, Lister D (2020) Version 4 of the cruts monthly high-resolution gridded multivariate climate dataset. *Scientific data* 7(1):109. <https://doi.org/10.1038/s41597-020-0453-3>

⁸ Note that Xu et al. (2020); Lenton et al. (2023) assume population growth, incongruously also in areas they deem to be unlivable, whereas I keep the number of people constant.

- Hill BM (1975) A simple general approach to inference about the tail of a distribution. *The Annals of Statistics*, 3(5):1163–1174. ISSN 00905364. URL <http://www.jstor.org/stable/2958370>
- Hume D (1739) A treatise on human nature. John Noon
- Klein Goldewijk K, Beusen A, Janssen P (2010) Long-term dynamic modeling of global population and built-up area in a spatially explicit way: HYDE 3.1. *The Holocene* 20(4):565–573. <https://doi.org/10.1177/0959683609356587>
- Kousky C (2014) Informing climate adaptation: A review of the economic costs of natural disasters. *Energy Economics* 46:576–592. <https://doi.org/10.1016/j.eneco.2013.09.029>
- Kratz MF, Resnick SI (1996) The QQ-estimator and heavy tails. *Communications in Statistics. Part C: Stochastic Models*, 12(4):699–724. <https://doi.org/10.1080/15326349608807407>
- Kummu M, Taka M, Guillaume J (2018) Gridded global datasets for gross domestic product and human development index over 1990–2015. *Sci Data* 5:1–15. <https://doi.org/10.1038/sdata.2018.4>
- Lenton TM, Xu C, Abrams JF, Ghadiali A, Loriani S, Sakschewski B, Zimm C, Ebi KL, Dunn RR, Svenning J-C, Scheffer M (2023) Quantifying the human cost of global warming. *Nature Sustainability*. URL <https://doi.org/10.1038/s41893-023-01132-6>
- Marchiori L, Maystadt J-F, Schumacher I (2012) The impact of weather anomalies on migration in sub-Saharan Africa. *Journal of Environmental Economics and Management* 63(3):355–374. <https://doi.org/10.1016/j.jeem.2012.02.001>
- Moore GE (1903) *Principia ethica*. Cambridge University Press
- Nordhaus WD (2006) Geography and macroeconomics: New data and new findings. *Proceedings of the National Academy of Science*, 103(10):3510–3517. URL www.pnas.org/cgi/doi/10.1073/pnas.0509842103
- Olmstead AL, Rhode PW (2011) Adapting North American wheat production to climatic challenges, 1839–2009. *Proceedings of the National Academy of Sciences of the United States of America* 108:480–485. <https://doi.org/10.1073/pnas.1008279108>
- Powell JL (1984) Least absolute deviations estimation for the censored regression model. *Journal of Econometrics*, 25(3):303–325. URL <https://www.sciencedirect.com/science/article/pii/0304407684900046>
- Rockström J, Steffen W, Noone K, Persson Å, Chapin III, FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. *Nature* 461(7263):472–475. <https://doi.org/10.1038/461472a>
- Rousseeuw PJ, Driessen KV (1999) A fast algorithm for the minimum covariance determinant estimator. *Technometrics*, 41(3):212–223. URL <https://www.tandfonline.com/doi/abs/10.1080/00401706.1999.10485670>
- Schultze J, Steinebach J (1996) On least squares estimates of an exponential tail coefficient. *Statistics & Risk Modeling* 14(4):353–372
- Smits J, Permanyer I (2019) Data descriptor: The subnational human development database. *Scientific Data* 6:1–15. <https://doi.org/10.1038/sdata.2019.38>
- Tobin J (1958) Estimation of relationships for limited dependent variables. *Econometrica*, 26(1):24–36. ISSN 00129682, 14680262. URL <http://www.jstor.org/stable/1907382>
- Tol RSJ (2007) Europe's long-term climate target: A critical evaluation. *Energy Policy* 35(1):424–432
- Watanabe S, Ishii J (2016) Effect of outdoor thermal environment on pedestrians' behavior selecting a shaded area in a humid subtropical region. *Building and Environment* 95:32–41. <https://doi.org/10.1016/j.buildenv.2015.09.015>
- WBGU (1995) *Scenario zur Ableitung CO₂-Reduktionsziele und Umsetzungsstrategien-Stellungnahme zur ersten Vertragstaatenkonferenz der Klimarahmenkonvention in Berlin*. Technical report, Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, Dortmund
- Worton BJ (1995) A convex hull-based estimator of home-range size. *Biometrics*, 51(4):1206–1215. URL <http://www.jstor.org/stable/2533254>
- Xu C, Kohler TA, Lenton TM, Svenning J-C, Scheffer M (2020) Future of the human climate niche. *Proceedings of the National Academy of Sciences*, 117(21):11350–11355. URL <https://www.pnas.org/content/117/21/11350>
- Yang B, Olofsson T, Nair G, Kabanshi A (2017) Outdoor thermal comfort under subarctic climate of north Sweden- a pilot study in Umeå. *Sustainable Cities and Society* 28:387–397. <https://doi.org/10.1016/j.scs.2016.10.011>