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The climate niche of Homo Sapiens

Richard S. J. Tol
University of Sussex, Falmer, UK (Department of Economics)
VU Amsterdam, Amsterdam, the Netherlands (Institute for Environmental Studies
Department of Spatial Economics)

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Richard S.J. Tol[abcdefg]

[a]*Department of Economics, Jubilee Building, University of Sussex, Falmer, BN1 9SL, United Kingdom; r.tol@sussex.ac.uk*

[b]*Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands*

[c]*Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands*

[d]*Tinbergen Institute, Amsterdam, The Netherlands*

[e]*CESifo, Munich, Germany*

[f]*Payne Institute for Public Policy, Colorado School of Mines, Golden, CO, USA*

[g]*College of Business, Abu Dhabi University, UAE*

Abstract

I propose the Dominicy-Hill-Worton estimator to estimate the current climate niche of *Homo Sapiens* and our croplands. I use this to extrapolate the degree of unprecedentedness of future climates. Worton's peeled hull is a non-parametric, N-dimensional generalization of order statistics. Dominicy and colleagues show that Hill's estimator of the tail-index can be applied to any homogeneous function of multivariate order statistics. I apply the Dominicy-Hill estimator to transects through Worton's peels. I nd a thick tail for low temperatures and a thin tail for high ones. That is, warming is more worrying than cooling. Similarly, wettening is more worrying than drying. Furthermore, temperature changes are more important than changes in precipitation. The results are not a ected by income, population density, or time. I replace the Hill estimator by the QQ one and correct it for top-censoring. The qualitative results are una ected.

Keywords: tail-index, convex hull, climate

JEL codes: C46, N50, O44, Q54

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 justi cations for the 2□ target of the Paris Agreement (WBGU, 1995, see also Tol (2007)) and has raised worries about the safety of humankind (Rockstrøm et al., 2009), inspiring such organizations as *Extinction Rebellion*. Unprecedented is not synonymous with detrimental, however (Hume, 1739, Moore, 1903). Furthermore, as 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 to suit their needs, traits shared, to a lesser extent, by other long-lived animals. In this paper, I develop a method to 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 de ned as the annual average temperature and the annual total 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□

2. Methods and data

2.1. Methods

How to estimate a niche? You could de ne 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

together span all possible climate change: warmer, colder, wetter, drier, and any combination. The trajectories are de ned as the intersection of the peeled hulls with straight lines from the population-weighted average temperature and precipitation to their maximum and minimum.

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 coe cients from (1) regressing the natural logarithm of size on the natural logarithm of its rank and (2) regressing log rank on log size.

The former estimator was proposed by Kratz and Resnick (1996). It naturally generalizes to the case of censored data Tobin (1958), Goldberger (1986), as does the inverse estimator. 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.

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 $5\,5^0$ grid, for the last 12,000 years, in time steps of 1,000 (100) years before (after) the birth of Christ. In 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 30^0 30^0 grid for 1901 to 2020. I compute the annual average for the period 1991-2020, as climate is typically de ned 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 re ecting 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 reportoutput as measured by value added. The di erence 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 e ect (Estrada et al., 2017) from their data. Output and income also di er in the oil elds 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.

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.

This conclusion is both illustrated and called into question by Figure 4, which shows three 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 conditions, a smaller distance over cold conditions, and hardly any distance over hot conditions. This explains the estimated relative thinness of the tails. The third convex hull in Figure 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 contradicts the thin tail for heat. We could have lived, indeed may have lived, in hotter places if these were there.

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 graph applies the Pareto distribution estimated above; see Table 2. The tail-index indicates the speed of decline of the likelihood of nding 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. This number is zero by construction without climate change, but increases to an expected value of 300 million for 3.5 of warming.

The di erence between the two graphs is the number of people who would live in unprecedented and unimaginable heat. This number rises to slightly less than 2 billion people for a global warming of 6 .

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 nd the climate niche of Homo Sapiensand its order statistics, and the Dominicy-Hill estimator to determine the thickness of the tails of the distribution of humans in climate space. I nd thin tails at hot end of the distribution, somewhat less thin tails at the cold

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	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Dryer	Dryer	Hotter Dryer
				Temperature				
Hill	628.99	139.99		40.67	34.16	89.71		311.34
	(67.04)	(14.86)		(4.33)	(3.64)	(9.56)		(33.18)
QQ	802.37	144.75		113.35	80.62	240.07		500.51
	(0.00)	(0.00)		(0.00)	(0.00)	(0.00)		(0.00)
				Precipitation				
Hill		3.95	4.04	5.20		1.86	0.00	0.65
		(0.42)	(0.43)	(0.55)		(0.20)	(0.00)	(0.07)
QQ		4.68	4.39	6.17		6.06	1.05	2.11
		(0.03)	(0.03)	(0.02)		(0.02)	(0.14)	(0.07)

Table 2: Estimates of the tail-index of temperature and precipitation along the trajectories of Figure 3 for the human population in the year 2000.

	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Dryer	Dryer	Hotter Dryer
				Temperature				
OLS	828.98	147.13		142.51	93.59	272.57		529.16
	(122.23)	(21.69)		(21.01)	(13.80)	(40.19)		(78.02)
Tobit	783.58	138.56		142.13	93.39	272.08		490.87
	(115.53)	(20.43)		(20.96)	(13.77)	(40.12)		(72.37)
				Rainfall				
OLS		4.79	4.42	6.33		7.07	1.71	2.65
		(0.71)	(0.65)	(0.93)		(1.04)	(0.25)	(0.39)
Tobit		4.47	4.23	6.33		7.06	1.71	2.65
		(0.66)	(0.62)	(0.93)		(1.04)	(0.25)	(0.39)

Table 3: Estimates of the tail-index of temperature and precipitation along the trajectories of Figure 3 for the human population in the year 2000 with (Tobit) and without (OLS) correcting for censoring.

	Area	Perimeter
Hill	7.69	7.63
	(0.33)	(0.33)
QQ	9.90	10.15
	(0.02)	(0.01)

Table 4: Estimates of the tail-index of the area and the perimeter length of the peeled convex hull for cropland in the year 2000.

	Hotter	Hotter Wetter	Wetter	Colder Wetter	Colder	Colder Dryer	Dryer	Hotter Dryer
				Temperature				
Hill	1129.6	184.1		54.7	44.0	100.4		401.9
	(49.1)	(8.0)		(2.4)	(1.9)	(4.4)		(17.5)
QQ	1574.3	240.6		207.5	128.5	383.6		478.8
	(0.0)	(0.0)		(0.0)	(0.0)	(0.0)		(0.0)
				Precipitation				
Hill		4.93	5.34	6.70		2.13	0.42	0.45
		(0.21)	(0.23)	(0.29)		(0.09)	(0.02)	(0.02)
QQ		7.18	6.87	8.34		9.37	2.22	3.36
		(0.01)	(0.01)	(0.01)		(0.01)	(0.03)	(0.02)

Table 5: Estimates of the tail-index of temperature and precipitation along the trajectories of Figure 3 for cropland in the year 2000

Figure 1: The fraction of the human population that would be exposed to an unprecedented climate as a function of absolute warming and relative drying or wettening.

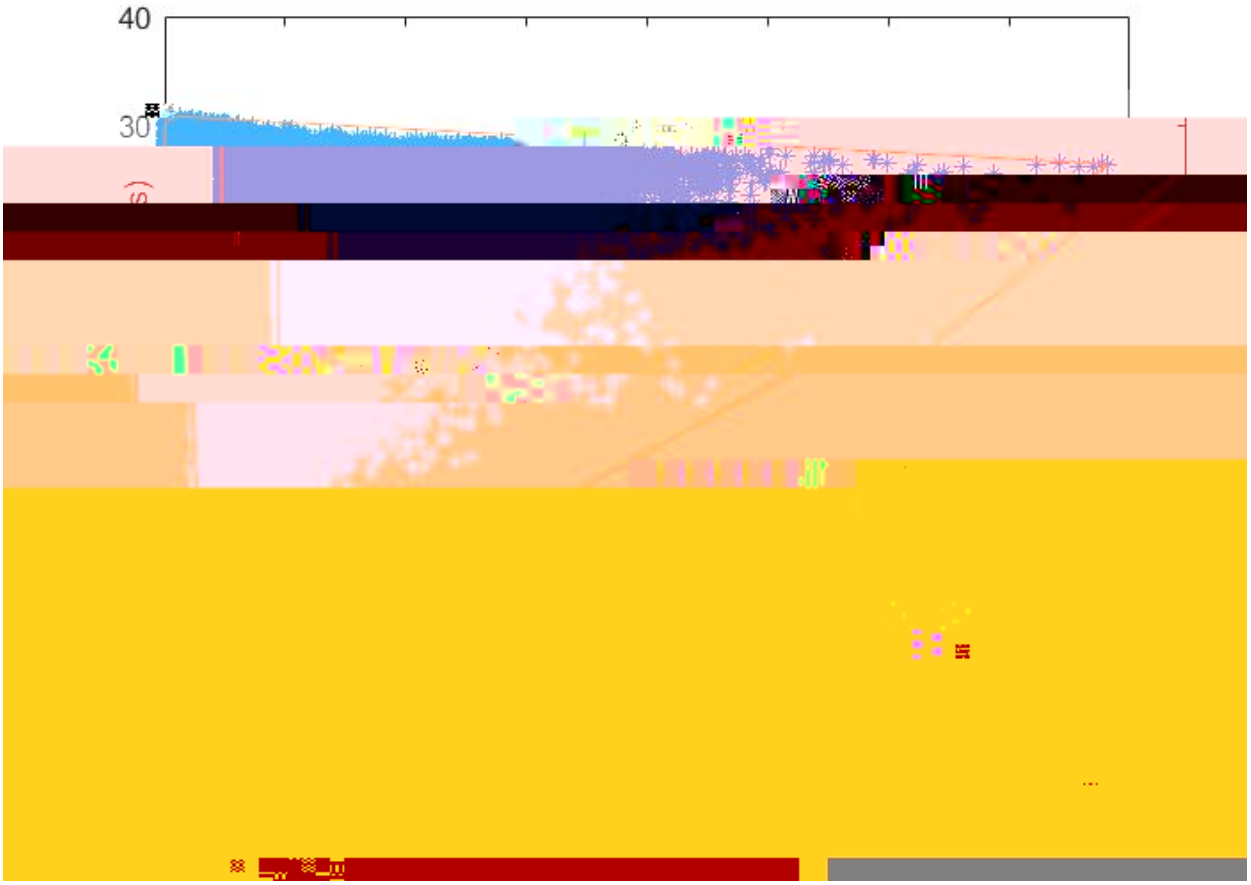


Figure 2: Human occupation of temperature-precipitation space, 2000, and its convex hull.

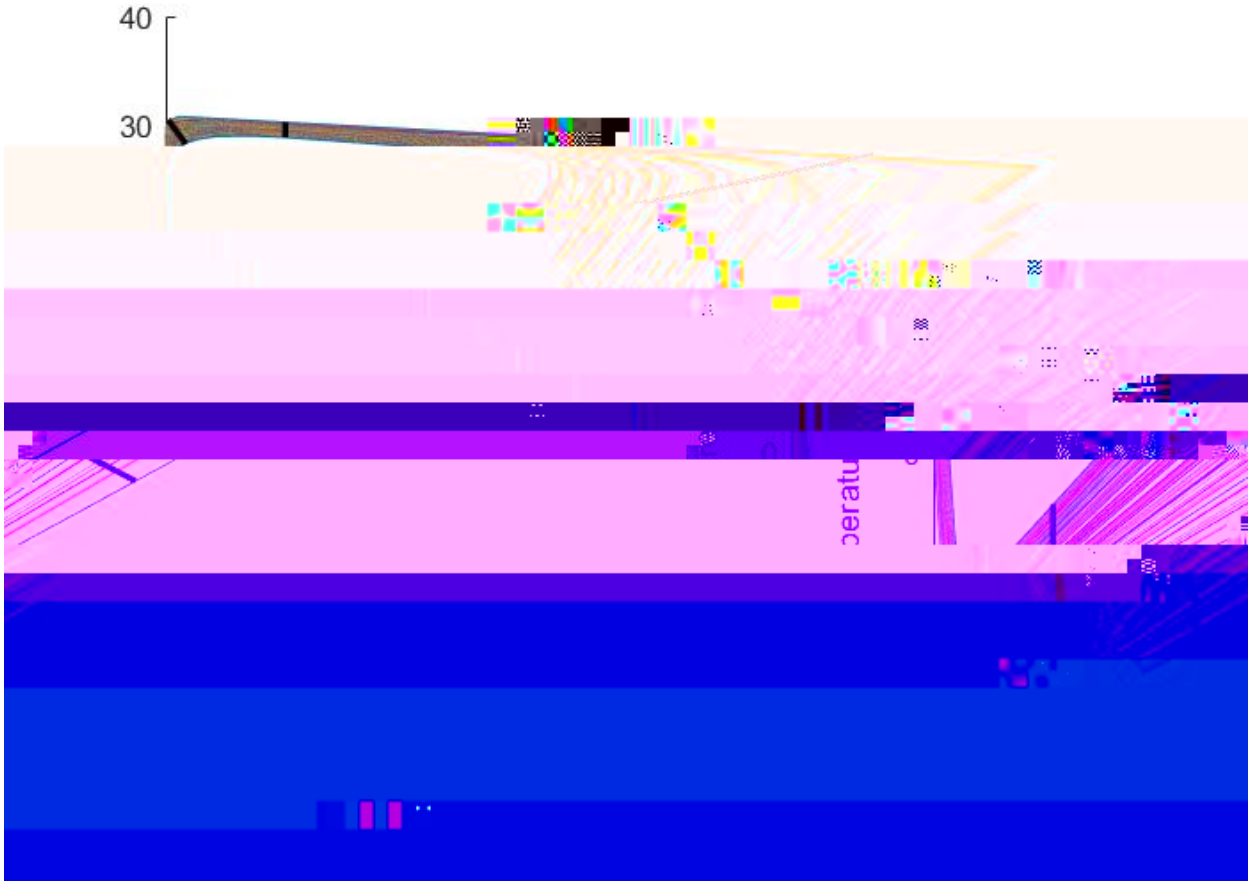


Figure 3: The peeled hull of the human occupation of climate space, 2000, and the studied order statistics of temperature and precipitation.

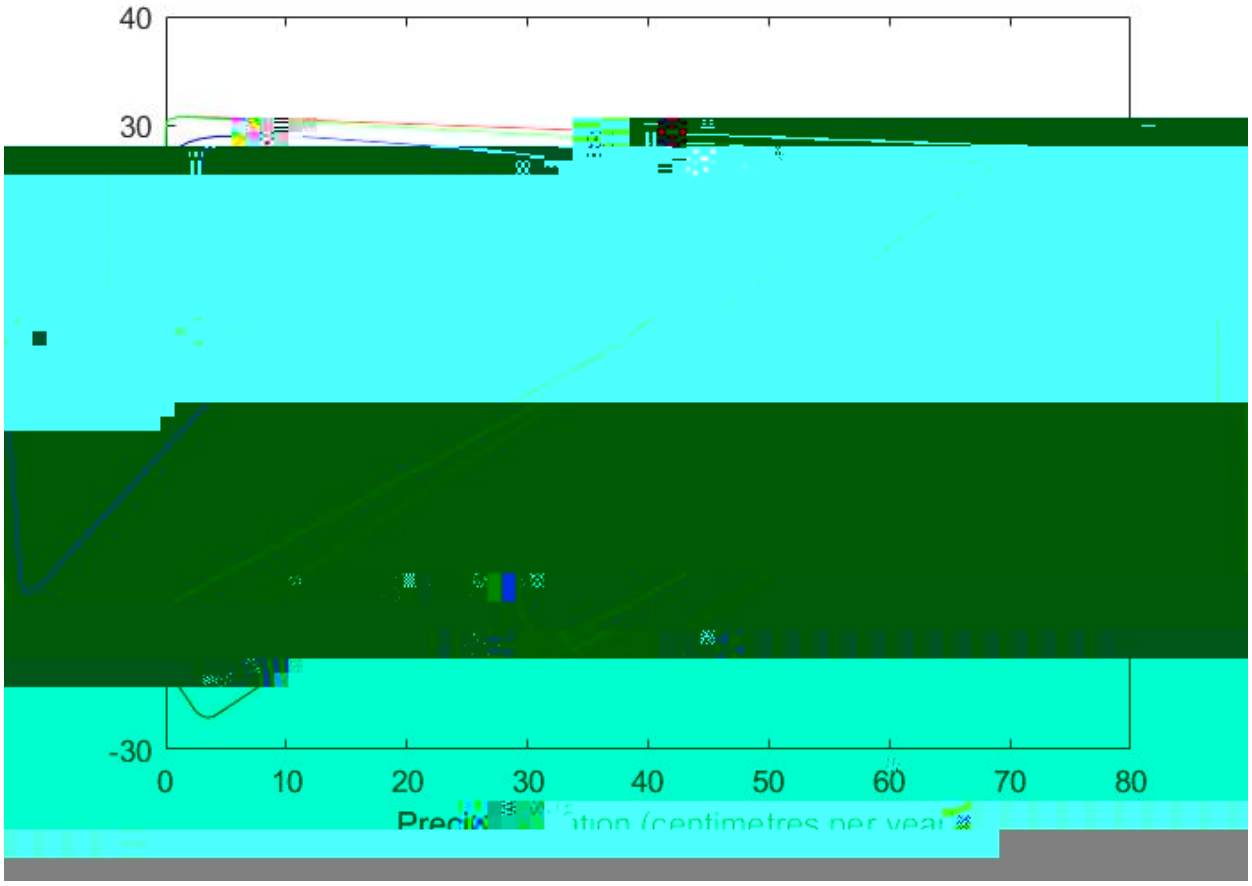


Figure 4: The convex hull of the human occupation of climate space, 2000, the convex hull that contains 95% of all humans, and the convex hull of temperature and precipitation.

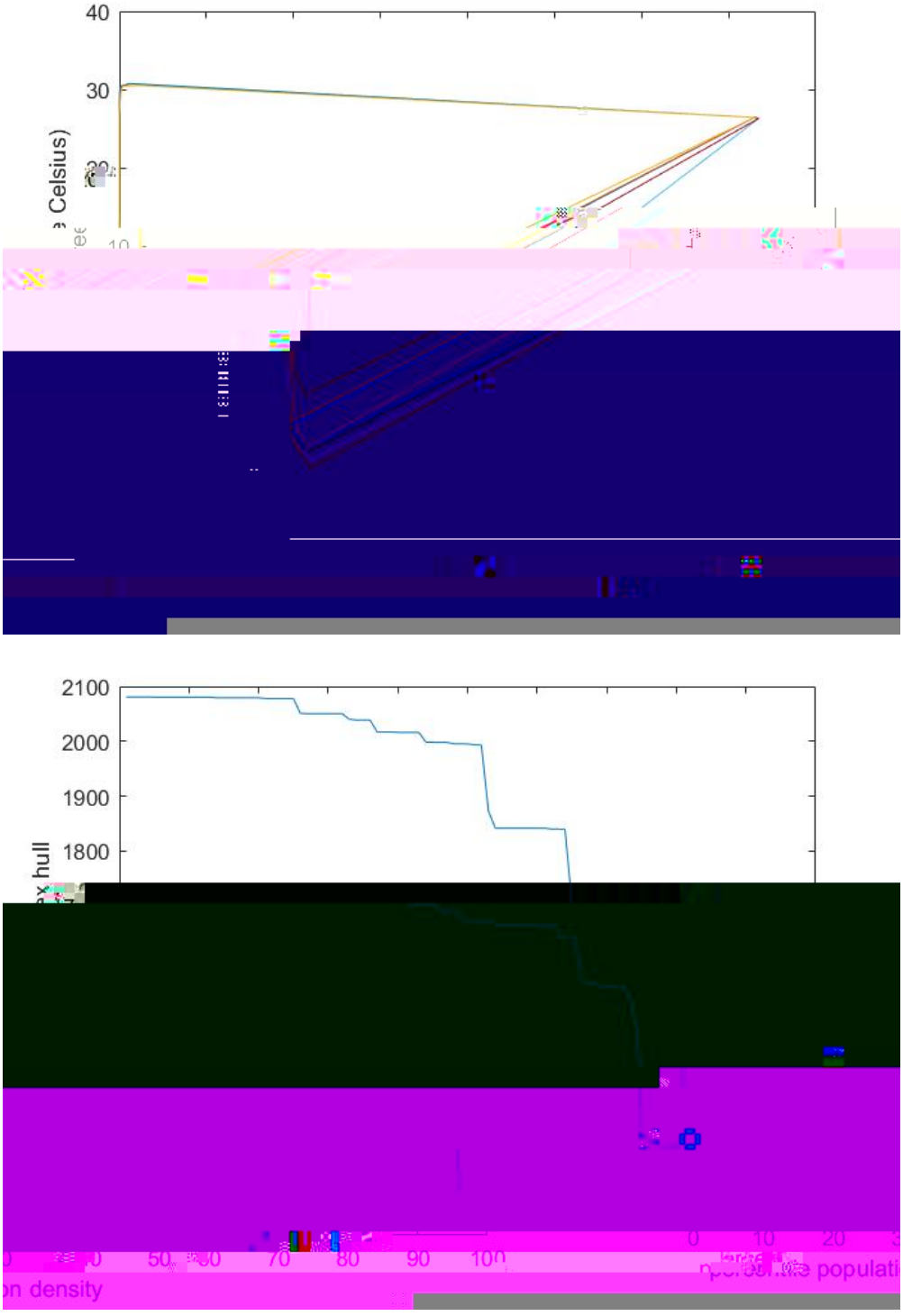


Figure 5: The convex hull of the human occupation of climate space in 2000 for all population densities and its deciles (top panel) and the area of hull for the percentiles of the distribution of population density (bottom panel).

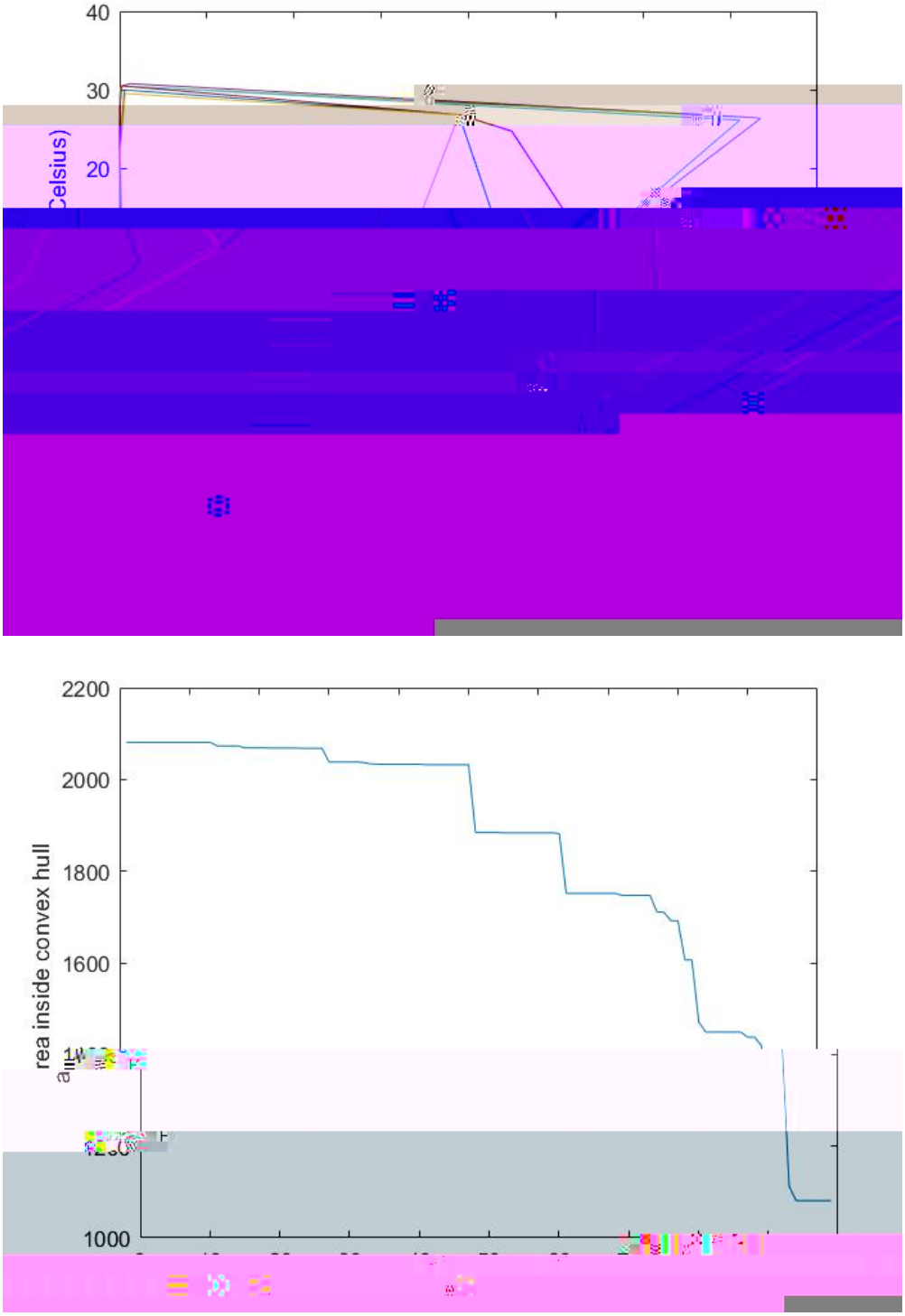
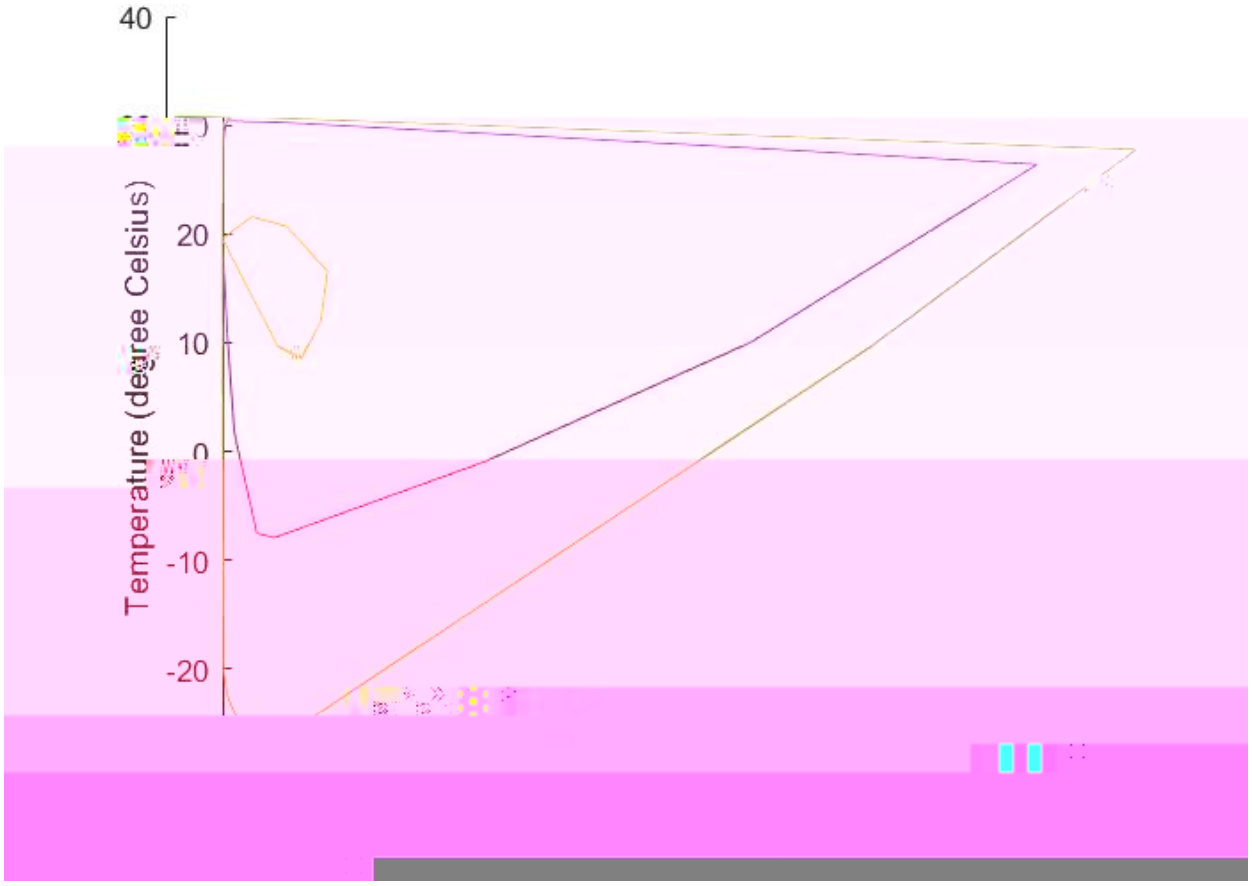


Figure 6: The convex hull of the human occupation of climate space in 2000 for all levels of per capita income and its deciles (top panel) and the area of hull for the percentiles of the distribution of per capita income (bottom panel).

Figure 7: The convex hull of the human occupation of climate space before and after 1200 AD.


40
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Temperature (degree Celsius)

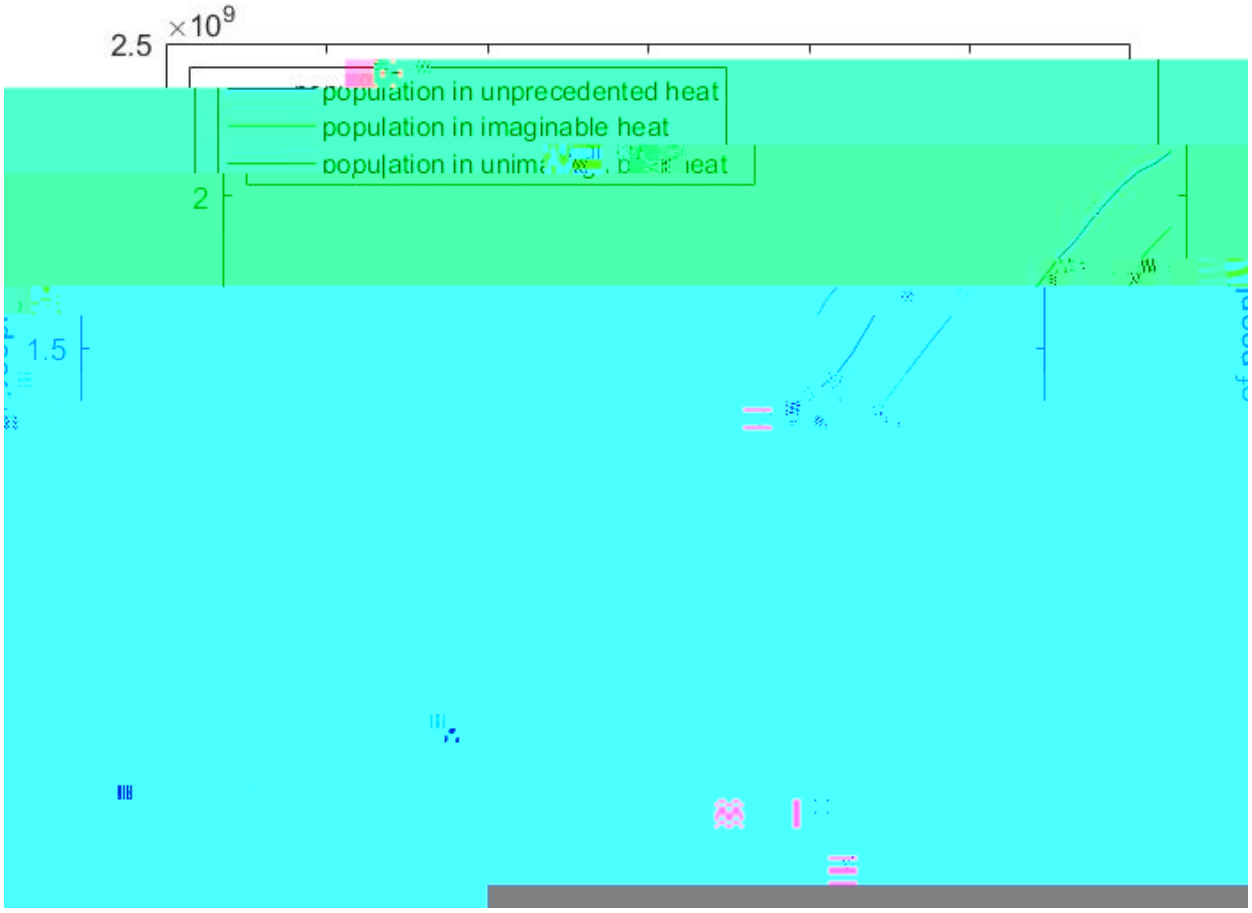

Figure 9: The number of people exposed to unprecedented heat, unprecedented but imaginable heat, and unprecedented and unimaginable heat.