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Biology Faculty

Master Thesis

University degree of “Master of Science” (abbreviated: “M.Sc.”) in Evolution, Ecology, and Systematics

Climate and Humanity, In focus: Population response to short-term changes in aridity and temperature

Presented by

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Sá einn veit
er víða ratar
ok hefir fjölð um farit,
hverju geði
stýrir gumna hverr
sá er vitandi er vits.

Only the one
who travels widely
and has journeyed a great deal knows
each and every mind and heart
that a person may have;
thus one must have their wits in hand.

***From Hávamál- The* Edda *of* Saemund**

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Summary

This thesis explores *Homo Sapiens* relationship to climate, with a holistic approach. The overarching goal is to delimit the ecological capacity of the specie in a biological context and how this capacity has expanded in the cultural context and the challenges this expansion poses. The thesis introduces the evolutionary background of the specie to ascertain the ecological boundaries. Firstly, has the climate affected human populations in the past? This question is answered by looking at the history of human evolution and civilization. Secondly, does the climate continue to affect human populations? Two climate indicators (aridity and temperature) were used to examine the current relationship between climate and population. Changes in these climate indices are compared with changes in the population. The aridity and temperature data come from a reanalysis data set (a synthesis of observed data and satellite data), while demographic data were used for the years 2000, 2005, 2010, 2015 and 2020. The results of this exploratory study signal towards a decoupling of population growth from climate indicators (Aridity and Temperature). As indicative of the results, AMH population is increasing unfavourably in areas that do not correspond to the traditional climate space of the specie. Lastly, the consequences of this decoupling on the human global collective are discussed in the context of Anthropocene.

Zusammenfassung

In dieser Arbeit wird die Beziehung des Homo sapiens zum Klima in einem ganzheitlichen Ansatz betrachtet. Das übergeordnete Ziel besteht darin, die ökologische Kapazität unserer Art in einem biologischen Kontext abzugrenzen und zu ermitteln, wie sich diese Kapazität im kulturellen Kontext erweitert hat und welche Herausforderungen diese Erweiterung mit sich bringt. In dieser Arbeit werden die ökologischen Kapazitäten vor einem evolutionären Hintergrund neu bemessen. Erstens: Hat das Klima in der Vergangenheit menschliche Populationen beeinflusst? Diese Frage wird durch einen Blick auf die menschliche Evolutions- und Zivilisationsgeschichte erörtet. Zweitens: Beeinflusst das Klima menschliche Populationen weiterhin? Um die gegenwärtige Beziehung zwischen Klima und Bevölkerung zu untersuchen, wurden zwei Klimaindikatoren (Aridität und Temperatur) verwendet. Änderungen dieser Klimaindizes werden mit Änderungen der Bevölkerung verglichen. Die Daten für Aridität und Temperatur stammen aus einem Reanalyse-Datensatz (einer Synthese aus beobachteten Daten und Satellitendaten), während für die Jahre 2000, 2005, 2010, 2015 und 2020 demografische Daten verwendet wurden. Die Ergebnisse dieser explorativen Studie signalisieren eine Entkopplung des Bevölkerungswachstums von Klimaindikatoren (Aridität und Temperatur). Die Ergebnisse zeigen, dass die menschliche Bevölkerung vor allem in Gebieten zunimmt, die nicht der traditionellen Klimanische dieser Art entsprechen. Zuletzt werden die Konsequenzen dieser Entkopplung für die Menschheit im globalen Kontext des „Anthropozäns“ diskutiert.

Introduction

1.1.1 Man's place in nature

"Where man is not, nature is barren" – William Blake, Proverbs of Hell[1]

The relatively rapid expansion of *Homo Sapiens* across the globe has had profound ramifications. The answer to what made this possible lies in understanding the climate space we evolved in and the resulting ecological capacities of our species. Many species evolve a myriad of physical adaptations and behavioural repertoire in response to their environment; they alter the natural world to thrive. Robins build nests, beavers construct dams, Man however not only manipulates the physical but is able to manipulate in the abstract (social construction). The agency that our species commands over the natural order is truly unique. Man's place in nature is both a biological and philosophical query. We shall henceforth proceed within our mandate which is of scientific order.

Almost all species fill or create a niche for themselves. Niche dynamics is a central node in ecological studies. A niche can be defined at the risk of oversimplification in ecological terms as to how a species corresponds to the specific environment it is situated in. Here, in this thesis, the focus is on the idea that habitat determines species behavioural or physiological adaption to it. This is akin to what in ecology is termed as 'Grinnellian niche'- it is precisely the range of environmental inputs that form the baseline which allows for species to effectively carry out their life history. [2] What this entails is that the geographic region where the species is found is not exactly its niche rather it is the best indicator of the niche.[2] That is "Under normal conditions of reproduction and dispersal, the species is expected to occupy a geographic region that is directly congruent with the distribution of its niche, and the density of the species within its geographic range is expected to be correlated with the prevalence of these conditions." [3]This concept of the niche is in line with an individualistic approach to ecology rather than a communal one. A species in question will theoretically adapt to its environment in a fashion to best exploit it. How we inhabit the world has transformed with no consideration of our actual evolutionary niche. It is difficult to isolate where biology ends and culture begins, as the two are intertwined when studying Homo Sapiens in any capacity. This statement is echoed by John W. Bennet in his book Ecological transitions "the appearance of Homo sapiens, has featured a growing absorption of the physical environment into the cognitively defined world of human events and actions—indeed, to the point where the argument seriously can be advanced that the concept 'human ecology' is a myth...." [4]. Nonetheless before the emergence of civilization, AMH did exist and hence the question of what is anatomically modern human

(AMH) Grinnellian niche is still of relevance. What environment is man suited to? It is appropriate to first divulge into the evolutionary context of AMH to ascertain the species ecological capacity.

1.1.2 The evolution of anatomically modern human (AMH)

"…with his godlike intellect which has penetrated into the movements and constitution of the solar system - with all these exalted powers - Man still bears in his bodily frame the indelible stamp of his lowly origin."— Charles Darwin, The Descent of Man [3]

The evolution of Man must then be governed by the same principals as that of any other species. Our focus lies in the recent stage of human evolution. Extant mammals occupy the same regions as their extinct cousins so by extension this should apply to AMH as well. The cradle of humanity by fossil, archaeological and genetic evidence coupled with reasoning must be African. The paleoanthropological debate even today is trying to piece together the origins of our species. Where there is robust evidence to point towards a recent African origin of AMH there is no strong consensus as to where in Africa specifically. It is further unclear that the 'modern' morphology that is a large brain and behavioural complexity emerged rapidly around 200 thousand years ago or came about in a gradual fashion over a longer period. Recent research of hominin fossils dated 315 ± 34 thousand years from Jebel Irhoud, Morocco indicates a mosaic composition of AMH and primitive neurocranial and endocranial morphology. [5] This study demonstrates a pan-African origin of AMH. What is clear though is that the stage for humanity has been Africa. The centrality of the continent is well documented. Environmental factors are pivotal in establishing various selective pressures on mammalian species and our clade is not an exception to this rule. The climate of a region on the macro scale is influenced by a multitude of factors like tectonics, orbital forcing, oceanic currents among others. Without divulging into the factors that shape the climate we will use literature to establish the paleoclimate in Africa during the corresponding period to hominin evolution. The paleoclimate is constructed based on proxies such as Stable Isotope Analysis, modelling and congruence of proxies and models. "Proxies from fluvial, lacustrine, and marine records integrate data from different temporal and spatial scales and therefore provide different kinds of information about environmental and climate change." [6]

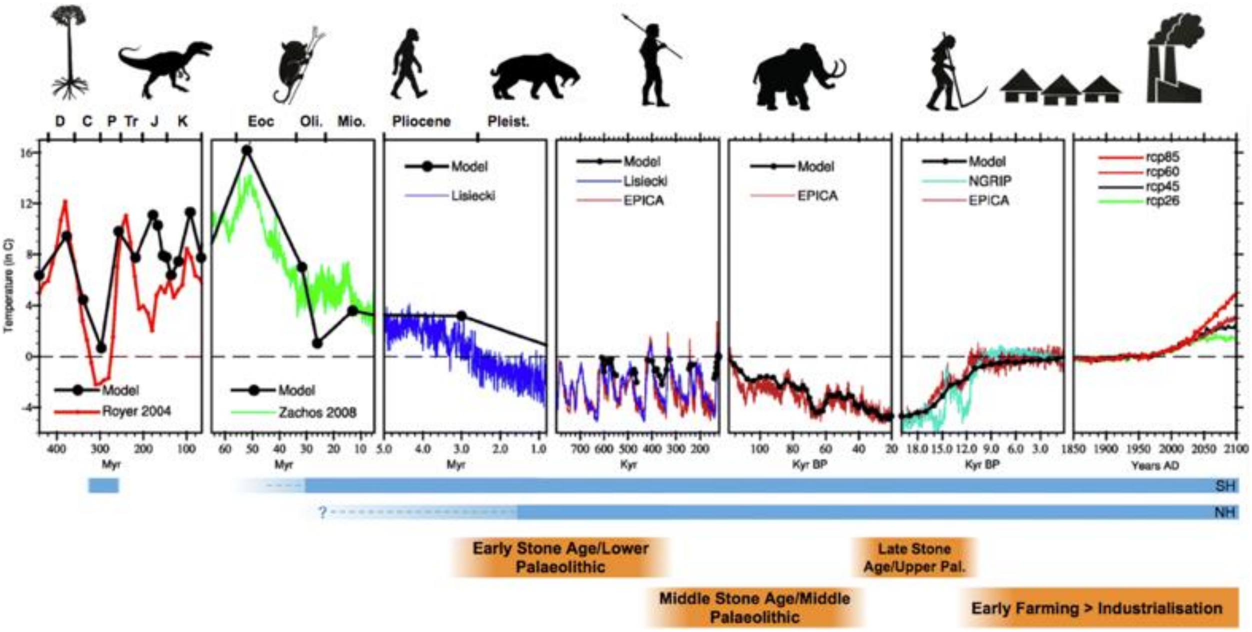

Figure 1 "Global annual mean temperature variation of the Earth through time (last 400 million years) predicted by the Hadley Centre Coupled Climate Model version 3 (HadCM3), compared with geologically derived estimates of temperature variability over the same period.Geological epochs include the Devonian (D), Carboniferous (C) Permian (P), Triassic (Tr), Jurassic (J) Cretaceous (K), Eocene (Eoc), Oligocene (Oli.), Miocene (Mio), Pliocene and Pleistocene (Pleist.)] Future predictions of temperature change are based on HadCM3 simulations using different Representative Concentration Pathways (RCPs). Horizontal blue lines represent geological evidence for ice sheets in the northern (NH) and southern (SH) hemispheres. Major evolutionary characteristics and events over the last 400 million years represented by cartoon silhouettes."[7]

African climate on the macro scale became colder and drier after 2.8 Ma, in East Africa, a long-term drying is recorded evidenced from regional tectonics, the appearance of C_4 plants, and late Cenozoic global cooling.[7,8] Researchers have further demonstrated a long-term trend towards open environments in East Africa over the past 10 Ma but there is a caveat this increase is greatly variable both in a temporal and spatial context.[6] This variability is expounded by the oscillations between extreme humid and dry periods due to various climate factors such as (but not limited to)monsoon dynamics, changes in ocean feedbacks. Marine records of Saharan dust also support shifts towards more arid and variable conditions and amplification of high-latitude glacial cycles markedly at 2.8 (±0.2) Ma, 1.7 (±0.1) Ma, and 1.0 (±0.2) Ma, coupled with muted and variable moisture availability.[8–10]

As illustrated in Figure 1, a cooling trend at the Pliocene-Pleistocene boundary is seen. Note here that the further we go back in time the resolution becomes lower as well. In a paper published in 2015 titled "A synthesis of the theories and concepts of early human evolution" four main stages of human evolution in the fossil record have been suggested, the last two of which are the appearance of the genus *Homo* around the Plio-Pleistocene boundary between 1.8 and 2.5 Ma,[11] and the "appearance of *H. heidelbergensis* at 800 ka and anatomically modern humans around 200 ka."[11] The thesis continues with the emergence of genus *Homo.* Form the literature, it has been established that there is an overall drying signal, but it has significant variability to it which cannot just be attributed to noise. This drying signal was attributed to the spread of grasslands and consequently resulting in the emergence of various traits from habitual bipedalism to making tools, this was termed as the Savanah Hypothesis. However, the fluctuations between wet and dry periods as reported created higher variability in the environment than just a continual drying landscape environment. This is known as the variability selection hypothesis which advocates for the role of environmental unpredictability in selecting for behavioural or ecological flexibility. [12–15] Then there is the *turnover pulse hypothesis* which suggests that acute climate shifts drove adaptation and speciation[16]. When faced with environmental disruption generalists will thrive over specialist species as they can exploit the environment better. If both these hypotheses can be incorporated in the lens of migration/movement to demonstrate that yes, there was a selection for generalists but also generalist traits were favoured due to unpredictability of the environment itself which in turn were assimilated due to frequent turnover of populations. The thesis proposes that like the fossils from Jebel Irhoud demonstrated that even recently in evolutionary time, AMH, had not acquired all physical features it has today, similarly, it can also be argued that various populations throughout the human evolutionary history were under diverse selection pressures, accumulating various physical and behavioural adaptations, and then assimilating through within Africa admixture due to the formation of refugia, especially in East Africa where species coalesced due to prevalent environmental unpredictability. There is ample evidence of periods of extreme environmental variability during the Plio-Pleistocene.[11,12,17–19] Further, the aforementioned oscillations between wetter and drier periods resulted in cycles of range contraction and expansion which again highlights the importance of refugia zones. Throughout most of AMH evolution there were several extant hominin species coexisting, but not now which overtime reduced until there was only one extant representative left, Homo Sapiens. Did AMH acquire cognitive and behavioural adaptations by a synthesis process (variability selection and turnover pulse) that truly made its ecological niche unique?

1.1.3 The ecology of anatomically modern human (AMH)

Understanding the ecological niche of AMH is being stressed because it will meaningfully contribute to how we discuss climate change. According to a study published in 2018, Patrick Roberts and Brian A. Stewart based on comparative analysis of other members of the genus Homo data propose that AMH developed a unique ecological niche, which they term as 'generalist specialist'. [20] A generalist species is one that can exist in a variety of environmental conditions and utilize various resources whereas a specialist specie has a narrower niche and focused dietary specializations. The claim that the authors make is by considering the evidence for human occupation of a huge diversity of environmental settings by Late Pleistocene that AMH has a unique ecological niche which as stated earlier is termed as 'generalist specialist'. "This is so because *Homo sapiens* furnish evidence for 'specialist' populations, such as mountain rainforest foragers or palaeoarctic mammoth hunters, existing within what is traditionally defined as a 'generalist' species ". [20] To tie this back to the previous topic, the thesis suggests that AMH acquired this niche through interacting with the various specialist populations in both genetic and cultural exchanges and thus acquiring a repository of behavioural plasticity. There is growing "evidence for hominin interbreeding and the complex anatomical and behavioural origin of our species in Africa".[20] It is argued for example in the multiregional model that "all archaic human forms worldwide, such as *H. erectus* and Neanderthals, as well as modern forms, subsequently evolved together into the diverse populations of modern *H. sapiens*, which are considered to make up a single, continuously gradient (as distinct from categorically separate) human species".[21] The success of this expansive behavioural plasticity and the underlying adaptive capacity of AMH will come under test in the Anthropocene.

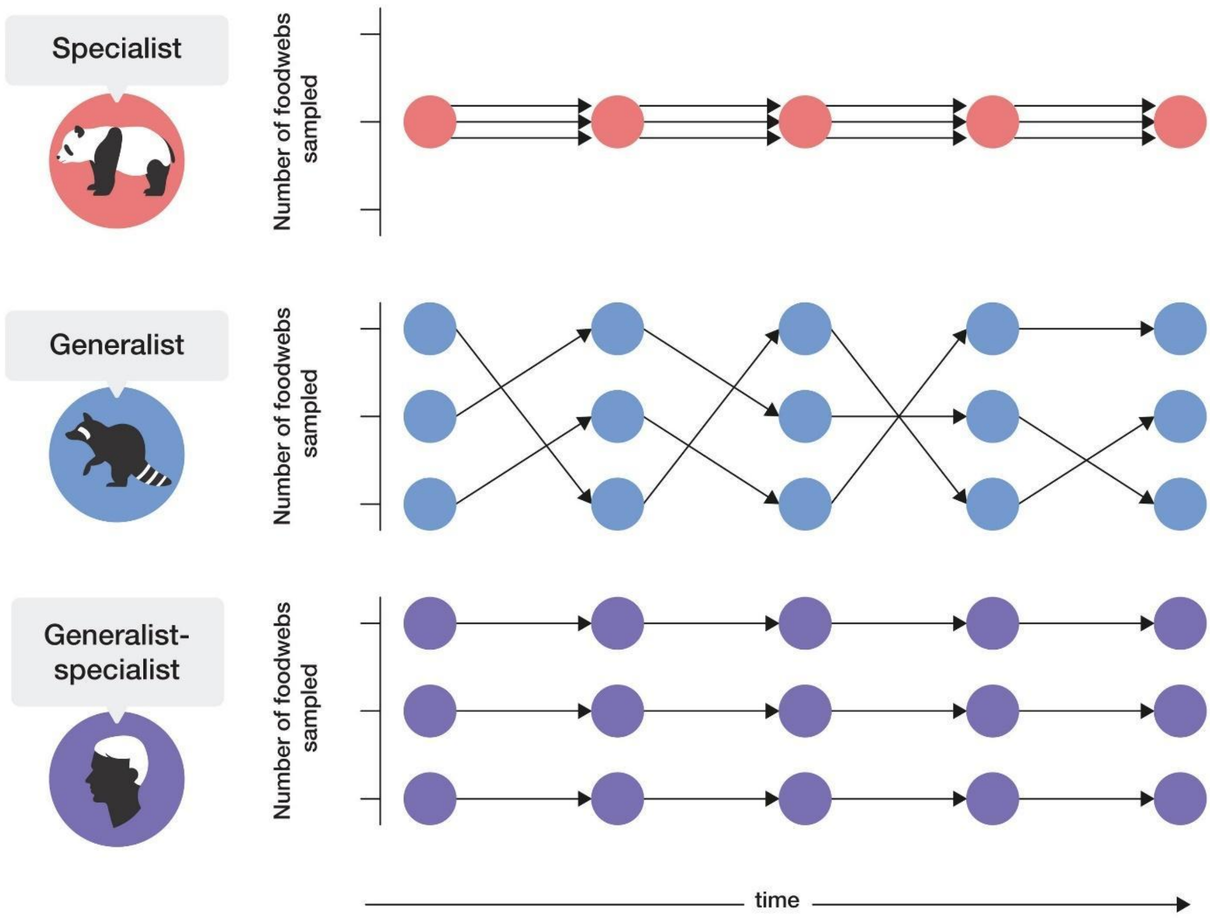

Figure 2 Schematic of the utilization of different numbers of food webs by generalist and specialist populations, and the proposed unique human ecological niche of 'generalist specialist'.[20]

1.2 Climate and civilization

Where we have previously argued that climate instability promoted the emergence of AMH we will now argue that climate stability promoted the emergence of human civilizations. A shift from a hunter-gatherer lifestyle to agrarian settlements is likely to have been mediated by a change in the earth's system.[22] Further, if one is to argue that agriculture was a natural progression for AMH then why did not agriculture emerge earlier in the Pleistocene? It has been reported that last glacial climates were not hospitable for the emergence of agriculture. This has been shown by data from ice and ocean-core which act as climate proxies which reveal that the climate was extremely variable on relatively short time scales, with low atmospheric CO_2 levels and generally drier.[23] With the amelioration of climate in early Holocene what followed was the domestication of plants and animals. In many areas in the world, concurrently, plant-intensive resource use strategies took stronghold.[23] What is notable here is that the emergence of agriculture was not restricted to a certain region. In many parts of the world, the agrarian lifestyle emerged independently. One should keep in mind that climate is one broad parameter; for example, the origin of agrarian practices has been linked to the availability of wild plants and animals that could be domesticated for useful purposes.

Mehrgarh which is situated in modern-day Pakistan provides one of the earliest pieces of evidence for domestication and pastoral life.[24] The earliest record of settlement at Mehrgarh dates to ~ 9000 years BP. [25] Mehrgarh provides a juncture when a switch to a subsistence economy that was centred around agriculture and domestication is observed. Paleomonsoon records show that the early Holocene (~ 10,000–7000 years BP) was an interval of warmer and wetter conditions with intensified southwest monsoon.[22] Further, the major rivers and their tributaries were flowing at their full strength. [22] This evidence of earliest sedentism as can be seen coincided with favourable and predictable climate patterns. It is not then mere conjecture that agriculture allowed for a sedentary which allowed for the formation of permanent villages which gave rise to social systems which then allowed for bigger civilizations. The argument here is domestication was followed by agriculture and agriculture was the foundation for permanent settlements which gave rise to civilizations.

When bigger civilizations did form, they were still at the mercy of climate. Climate fluctuations are attributed to the demise of many ancient civilizations. For example, the disintegration of Harappan cultural domain is stated as a consequence of persistent drought and changing rainfall patterns which may have initiated southeastward habitat tracking.[26] Variations in climate had a direct consequence on food security especially in the pre-industrial cultures and can indirectly result in undermining of social institutions even as far as creating political strife. [26–28] Hence, variability in climate was not conducive to the continual success of pre-industrial cultures. This is not to say that climate no longer has an impact on the post-industrial world; the climate threats to the modern human way of life are ever more concrete. It has been noted that the predictable patterns related to "dry seasons and rainy seasons—on which rainfed agriculture has depended on for several thousand years, has been disturbed in many countries." [29]

Today fifty per cent of the world's habitable land is used by Agriculture compared to an estimated 4% just a millennia ago. [30] As inferred from figure 3, to increase agriculture productivity either we will have to cut into forested land or use the current agriculture land more sustainability(for e.g. innovative technologies) and also responsibly (for e.g. by using plant-based alternatives to meat). The unequal distribution of land use for sustaining livestock and crop for human consumption is also alarming; livestock accounts for 77% of global farming land (fodder production for livestock) .[30] Meat production is further a major source of greenhouse gas emissions. To reach a billion tons of grain production it took 10,000 years in 1969 and then the production doubled in just 40 years. [31] This remarkable feat was the result of using genetically modified crops in parallel with modern agronomic practices. [31]To feed the growing population of the world while at the same time rising to the challenge of climate change requires another 'Green revolution'. Further there is a disruption in established cycles, with disruption in rainfall patterns and extreme events like drought and flooding can potentially result in complete decimation of crops to delayed plantation and harvest interruptions.

Further, there is an argument that a switch to a sedentary lifestyle has reduced the fitness of human populations. Where agriculture is attributed to providing the economic basis for the rise of states and civilizations, the change in lifestyle came at the cost of a decline in quality of life for most human populations in the last 10,000 years.[32] This is evidenced from skeletal remains which indicate that the impacts on "health were immediate—as soon as humans began to farm, health declines commenced due to population crowding, altered workloads, and increased nutritional deficiencies".[32]

Today we are living in a global civilization. Issues like food security, loss of biodiversity and climate change are then too of global nature and have implications for humans around the globe. This global interplay does not lessen but augments the vulnerability to human systems. If we add the reduced fitness of human populations to this equation the vulnerability is again compounded.

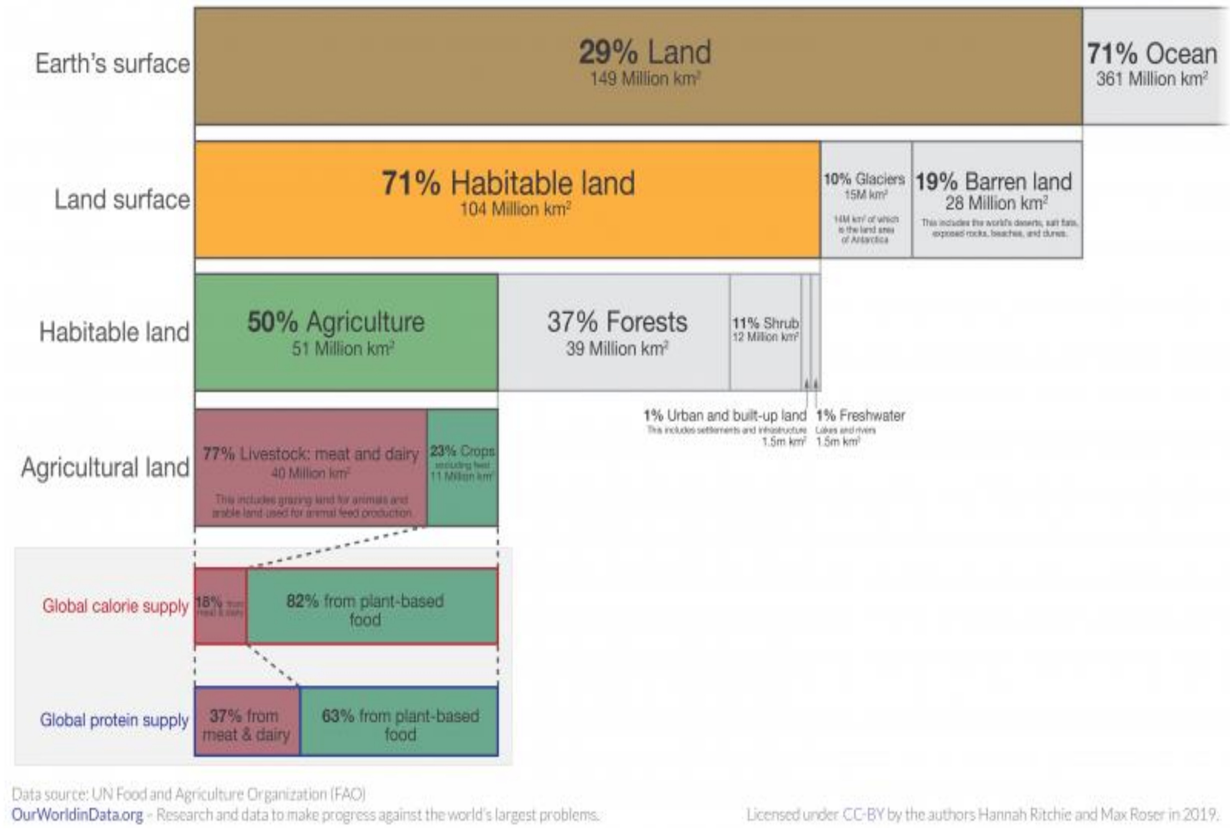

Figure 3 Global land use for food production[30]

1.3 AMH temperature tolerance and caloric requirements.

Even though AMH has proliferated across diverse habitats all over the globe, AMH has certain biological limits just like any other mammal. To asses the tolerable limits of climatic conditions for humans, here, in this thesis, the available literature is used to establish temperature tolerance and caloric requirements for an average person. AMH maintains a core body temperature around 37 °C by homeostasis with slight variation across individuals. Human skin temperature is regulated below the core temperature at 35 °C as skin temperature must be cooler than the core temperature for metabolic heat to be dissipated properly.[33] The human body at rest produces ~100 W of metabolic heat that is in addition to the energy absorbed from solar radiation must then be removed by a combination of conduction, evaporative cooling, and net infrared radiative cooling.[34] Evaporative cooling can only occur if the body's skin temperature is below the wet-bulb temperature. The environmental wet-bulb temperature T_W is measure by covering a standard thermometer bulb with a wetted cloth and fully ventilating it.[34] For humans, this system works until the wet-bulb temperature reaches 35°C if the wet-bulb temperature is crossed then the air is so full of water vapour that sweat no longer evaporates.

Calculating average caloric requirements for AMH is dependent on Basal Metabolic Rate (BMR), lifestyle (physical activity) and thermic effect of food (amount of energy your body uses to digest the food). As there is much variance in this in terms of age, gender and so on we cannot look at the individual but in our case, for a population-level study, we can use the recommended daily calorie intake values which are 2,000 calories a day for women and 2,500 for men. [35]

1.4 Anthropocene

Human activity has fundamentally altered the earth's system. This alteration to the biogeochemical cycles is of unprecedented nature and hence terming a geological epoch Anthropocene then is not just a quirky neologism but a harsh reality. Figures 4 and 5 correspond to how unprecedented the current global temperature and carbon dioxide levels are, clearly implicating AMH and their activities as the main driver of these trends. Further note that historic CO2 levels were higher but in the evolutionary window of AMH , the levels have been well below the current levels. As of today, Anthropocene is not a recognized geological time; we officially still live within the Meghalayan Age of the Holocene Epoch. Both the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS) have not approved the term as a subdivision of geologic time. This, however, does not have any bearing on the validity of human-induced climate change by even an iota. This lack of recognition has more to do with defining the lower boundary for Anthropocene then its affirmation; a Global Boundary Stratotype Section and Point(GSSP) is an internationally agreed-upon reference point on a stratigraphic section which demarcates the lower boundary of a stage on the geologic time scale[36] Simon L. Lewis and Mark A. Maslin proposed 1610 as one of the candidates for the Anthropocene GSSP boundary.[37] They attributed 1610 as a boundary for two reasons. The first being the exchange of flora and fauna between the Old and New world which reshaped ecosystems of both landmasses which can be evidenced in the geological layer in terms of biomass accumulation. The second one pertains to the drop in carbon dioxide levels which came as a result of the genocide of the natives resulting in regrowth of forests. They noted that in 1492 there were somewhere between 54 to 61 million people living in the Americas and by 1650 there were 6 million people.[37]

> "On the basis of the movement of species, atmospheric CO_2 decline and the resulting climate-related changes within various stratigraphic records, we propose that the 7–10 p.p.m. dip in atmospheric CO_2 to a low point… is an appropriate GSSP marker" [37]

They termed this boundary as the 'Orbis Spike'. The thesis acknowledges this boundary, for it has merit not just in the geological record but also heralds repercussions of man-induced changes. As it has been suggested that Orbis spike implies that colonialism, global trade and coal brought about the Anthropocene.[37] This underscores the unequal power relationships between different groups of people, impacts of globalized trade and reliance on fossil fuels.[37] Global inequality is the lens in light of which the distribution and growth of the human population is discussed in the discussion chapter.

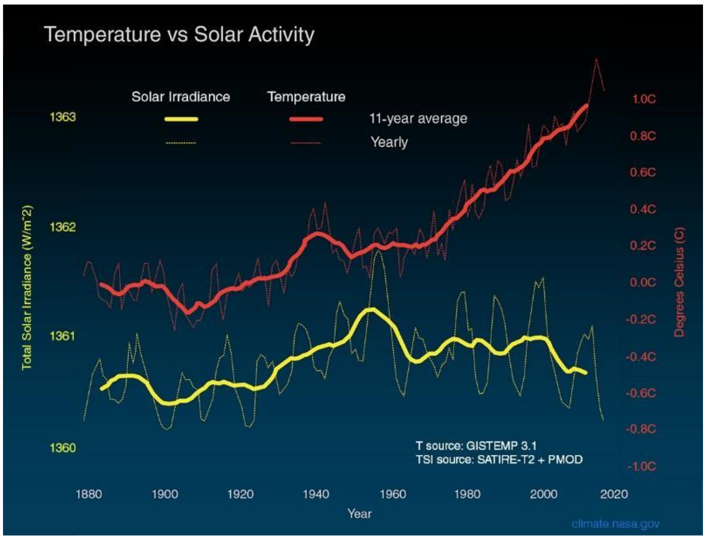

Figure 5 Compares global surface temperature changes (red line) and the Sun's energy received by the Earth (yellow line) in watts (units of energy) per square meter since 1880 Source: climate.nasa.gov

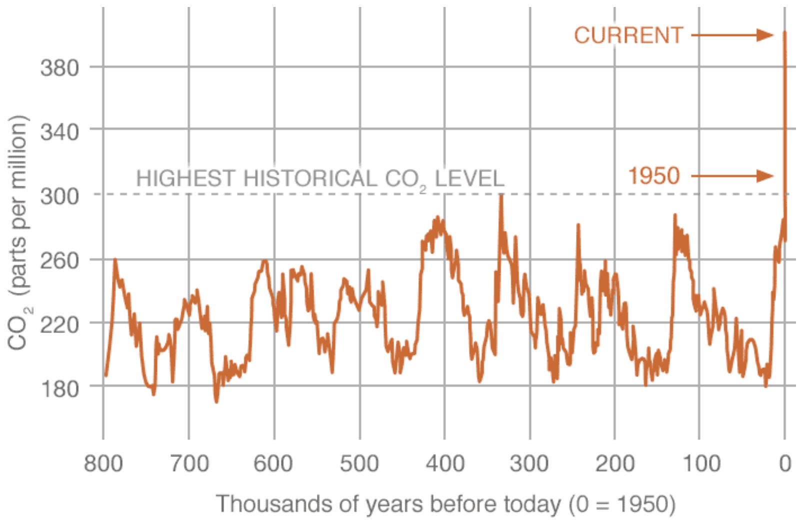

Figure 6 Historic Carbon Dioxide levels. Data source: Reconstruction from ice cores. Credit: National Oceanic and Atmospheric Administration (NOAA)

2. Data and Methods

2.1 Data Sets

2.1.1 Demographic Data

Gridded population data was taken Socioeconomic Data and Application Center (SEDAC) which is a data collection centre in NASA's Earth Observing System Data and Information Systems (EOSDIS). The data was available as global rasters in netCDF format stored in WGS84 (geographic coordinate system) which corresponded with our climate data. The data employed were available at a resolution of 30 Minute (which is approximately 55km). The data provides estimates of the human population consistent with national censuses and population registers.[38] On the temporal end, the projected population data is available for 2000, 2005, 2010, 2015, 2020. The year 2000 and 2015 are compared; the aridity and temperature in 2000 and how it corresponded with population is compared with how aridity and temperature in 2015 and how it corresponded with population. The forthcoming analysis would have yielded greater insight if the gridded population data were available from earlier years. This is because when looking at long term trends in climate a wider temporal window can potentially yield to a more conclusive insight.

2.1.2 ERA-Interim

The analysis is on a global scale. The gridded climate data that is used is ERA-Interim which is a reanalysis dataset formulated on a reduced Gaussian grid. The spatial resolution is 0.5° × 0.5° for the time period 1985-2019 with a daily temporal resolution. Reanalysis datasets are multivariate and combine information from many sources that are essentially a synthesis of observational and modelling. ERA-Interim particularly provides a data set of multiple variables at a high spatial and temporal resolution which is also complete both spatially and temporally.[39,40]

2.1.3 Global Precipitation Climatology Centre (GPCC)

The daily precipitation data sets for the purposes of this analysis were obtained from GPCC. This dataset is gridded, quality-controlled and is based on satellite and gauge-based observations.[41]

2.1.4 Normalized Difference Vegetation Index (NDVI)

NDVI is used as a proxy for vegetation coverage that allows for a comparative analysis of changes in vegetation growth and activity. It is proxy in the sense that it is calculated by measuring the difference between near-infrared (vegetation that is reflected) and red light (which vegetation strongly absorbs). MODIS vegetation index product (MOD13C2) was used for analysis as it is a gridded, quality-controlled data set. [42]

2.2 Methods

2.2.1 Focused time period

The data used was daily recordings averaged to show a mean value for the year and then the years were further averaged to show the conditions pertaining to the year 2000 and 2015. To obtain the climate space for 2000, data from 1985-2004 was used and similarly for 2015, data from 2000-2019 was used to create the average climatic conditions pertaining to the year 2015. The two indices that act as proxies for changing climate that is employed are Aridity Index and Temperature.

2.2.2 Aridity Index

The ratio of annual potential evaporation to precipitation is the Aridity Index. The annual potential evapotranspiration represents the energy available to the system, this was calculated by adding incoming shortwave and longwave radiation and subtracting that from the sum of outgoing shortwave and longwave radiation. These radiation data are available from ERA-Interim. If for example, the available energy is relatively low in comparison to the amount of precipitation, this will result in lower evapotranspiration and consequently a lower aridity index. Whereas if precipitation is lower than the available radiative energy, one will likely observe higher evapotranspiration and consequently a higher aridity index.

$$Aridity\ Index = \frac{Precipitaion}{(Incoming\ Radiation) - (Outgoing\ Radiation)\_}$$

The mean aridity values for each grid cell are calculated for 2000 and 2015. The daily data is converted to yearly averages. Then the 20 years are averaged to give a mean value for each grid cell. In the case of 2000; the years were from 1st Jan 1985- 31st Dec 2004. Similarly, for 2015 a 20-year window opted; the years were from 2000-2019. With a few months missing from 2019 at the time of data analysis.

2.2.3 Temperature

The daily air temperature data is another variable obtained from ERA-Interim. The daily data is converted to yearly averages. Then the 20 years are averaged to give a mean value for each grid cell.

2.2.4 Masks

For the purposes of our analysis, multiple masks were created. The masks were created to understand how population density changes under various climate regimes. Aridity and temperature masks were created based on the conditions in 2000. The global data was divided into five different aridity zones and similarly five different temperature zones.

Temperature Classes (°C)	Aridity Classes (AI)
-10 to 0	<0.5
0 to 10	0.5-1
10 to 20	1-2
20 to 25	2-4
>25	>4

Table 1: Temperature and Aridity masks

3. Results

3.1 Spatial Changes in Aridity and Temperature from 2000-2015

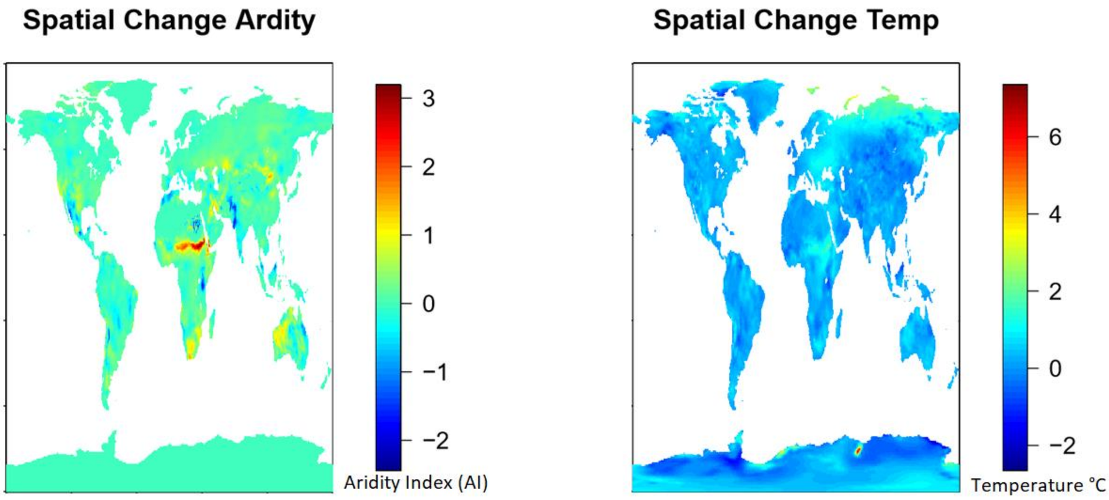

Figure 7 Spatial changes in Aridity (AI) and Temperature(Celsius) from 2000-2015

3.2 Where do people live?

The population was divided on basis of shared temperature and aridity profile. A population can be spatially disconnected but have the same climate regime. For example, in Figure 8, population that corresponds to certain temperature and aridity were placed in one box regardless of where they are spatially situated on the globe. The dimension of the boxes are as follows: 0.25 x 0.25 staring at 0,0 with an increment of 0.25 on each axis.

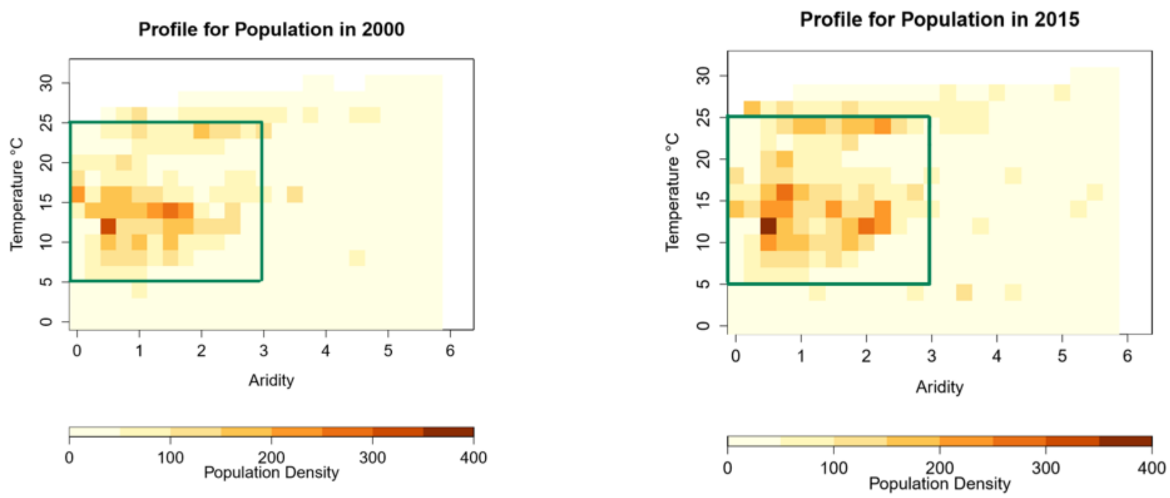

Figure 8 Population Density(million people per km^2) in 2000 and 2015 in relation to Aridity Index (AI) and temperature °C

An arbitrary boundary is defined for human population concentration with the climatic regime from 0 to 3 Aridity Index and 5 °C to 25 °C temperature as reflective of where most of the specie inhabits. This boundary is the green rectangle illustrated in figure 3.

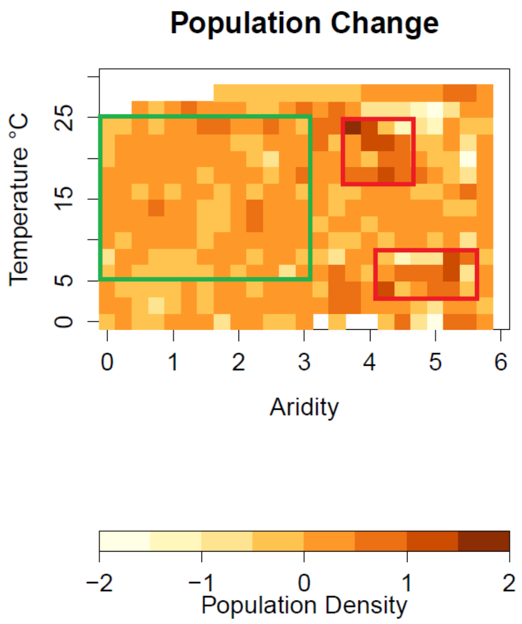

Figure 9 Population Density Changes from 2000 to 2015

3.3 NDVI as a measure of productivity

Normalized difference vegetation index (NDVI) is used here to act as a proxy for vegetation coverage. To see whether the vegetation corresponds to the green box we defined earlier as the climate space for human inhabitance, instead of the human population, we used average annual NDVI data for 2000 and 2015. Note here that NDVI changes seasonally but for the purposes of this analysis a composite average annual NDVI is used.

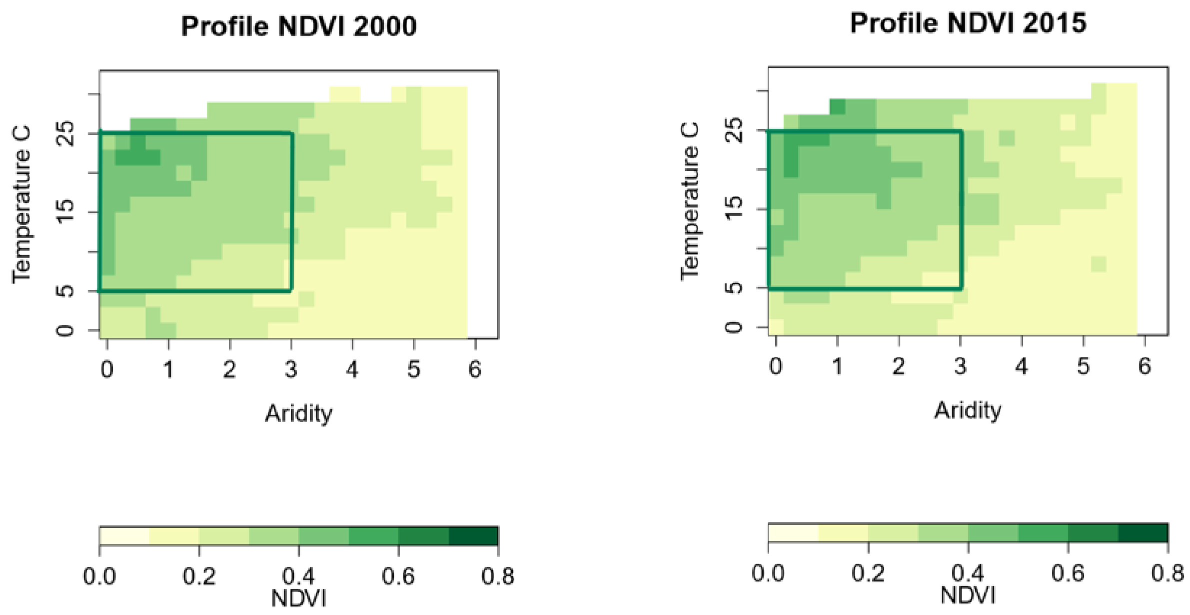

Figure 10 Average annual NDVI values for 2000 and 2015 in relation to aridity (AI) and temperature (C)

Low NDVI values imply barren, rocky or sandy regions. Moderate values imply sparse vegetation such as grasslands or senescing crops, values ranging from approximately 0.2 to 0.5. Higher NDVI values correspond to denser vegetation such as tropical forests. As inferred, major chunk of human population lives in productive/greener areas.

3.4 Do changes in temperature and aridity translate to changes in population?

In order to perform this analysis, masks were created according to the conditions in 2000. The data is then divided into five classes. If for example there is a grid point in the first class that corresponds to <0.5 aridities and the aridity in this grid space has changed by let us assume +1 how has the population responded to that. This was done with all the data to ascertain if the population is more sensitive to changes in aridity and temperature depending on the initial environment. For it can be argued that a change in the aridity of for example +1 in a grid cell of lower aridity will have a greater impact than a similar change in a grid cell from higher aridity. The above reasoning can also be applied to temperature. The data cloud was then smoothed to get trend lines.

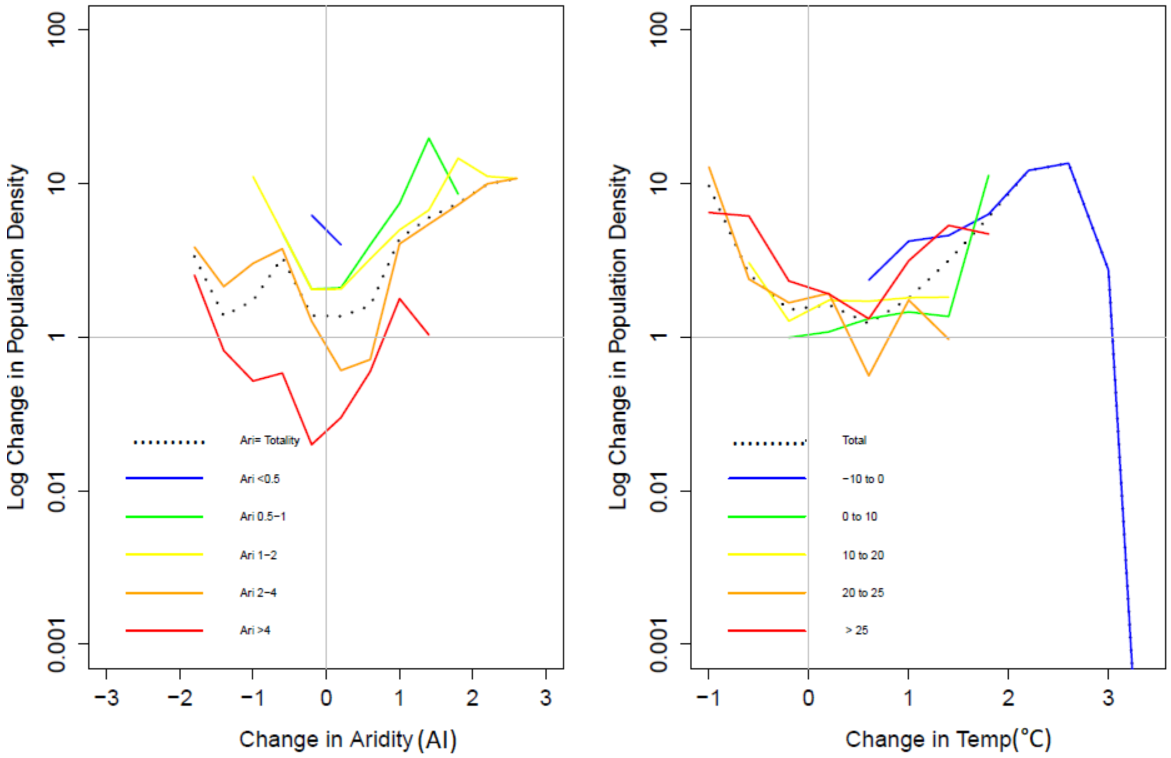

Figure 11 Changes in aridity and temperature vs changes in population density in various initial climate classes

The black dotted line represents composite changes whereas the coloured lines correspond to a selected climate class.

The lines colour schematic is from the colder colour scheme to hotter, that is, blue represents the lowest aridity and lowest temperature while red represents the highest aridity and highest temperature. For example if in 2000 there was a grid cell with the aridity of between 2-4 it will be represented by the orange line, all the cells that showed negative or positive changes starting from initial aridity of between 2-4 then will be plotted and smoothened to show a trend line.

3.5 Global Population trends: Aridity and Temperature classes

The gridded population data were available for 2000, 2005, 2010, 2015 and 2020. The next question that warranted further insight was in which climate regimes is population growing faster in comparison.

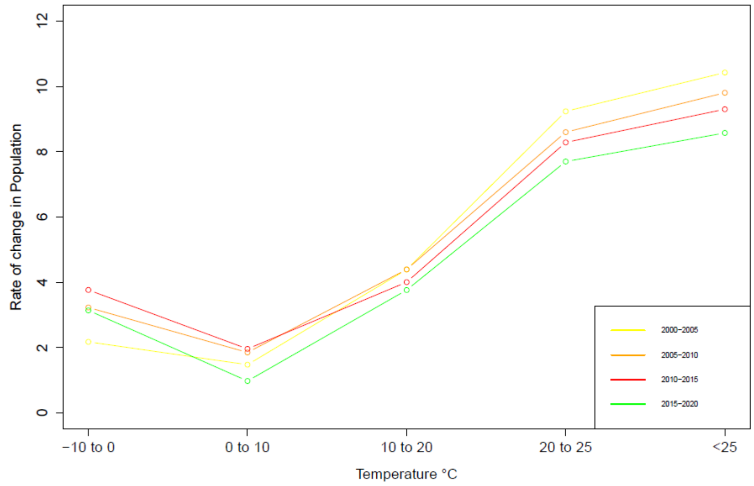

Figure 12 Rate of change of Population in various Temperature Classes

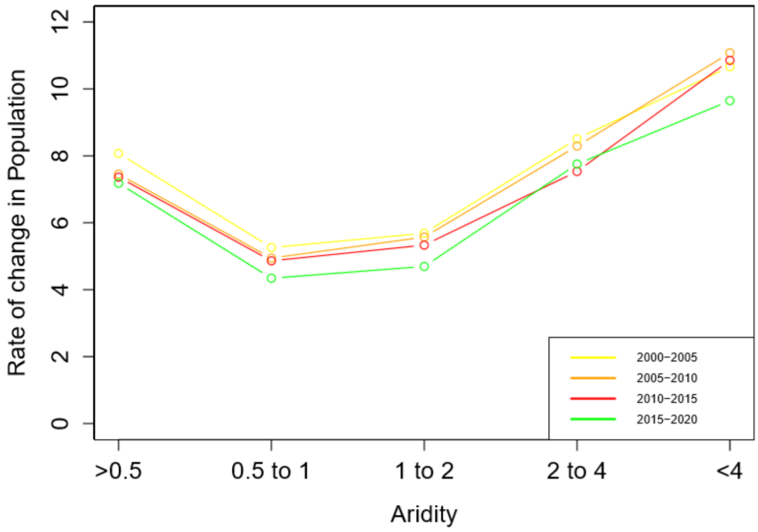

Figure 13 Rate of change of population in various Aridity Classes

The above figures are obtained by using the aridity and temperature masks. They are indicative of how population rate has changed in each five-year period. The absolute population in each mask was extracted for 2000, 2005, 2010, 2015 and 2020. The growth rate was then calculated in each five-year temporal window.

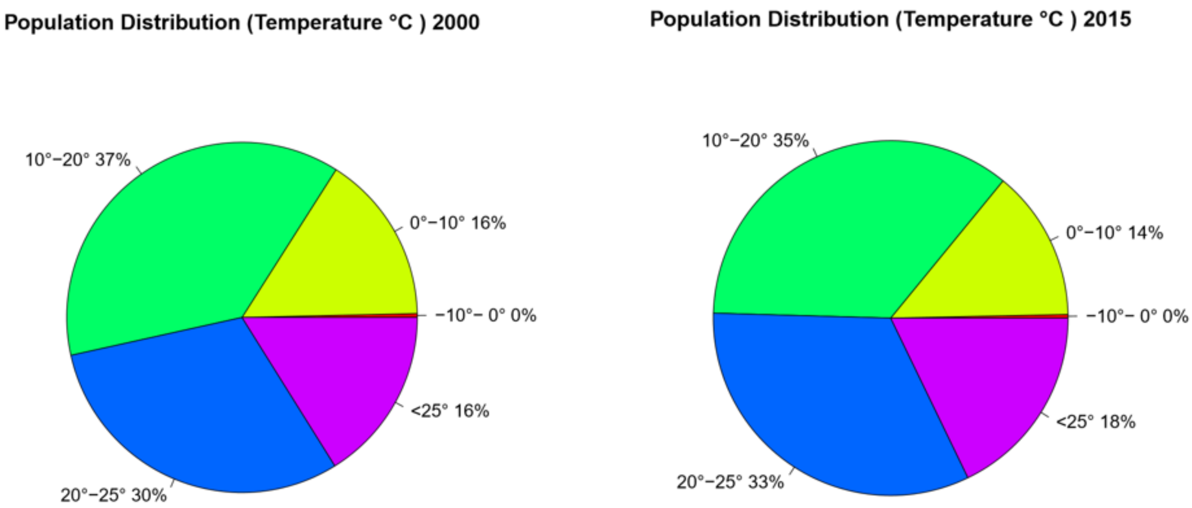

Figure 14 Pie chart distribution of population in various temperature classes 2000 vs 2015

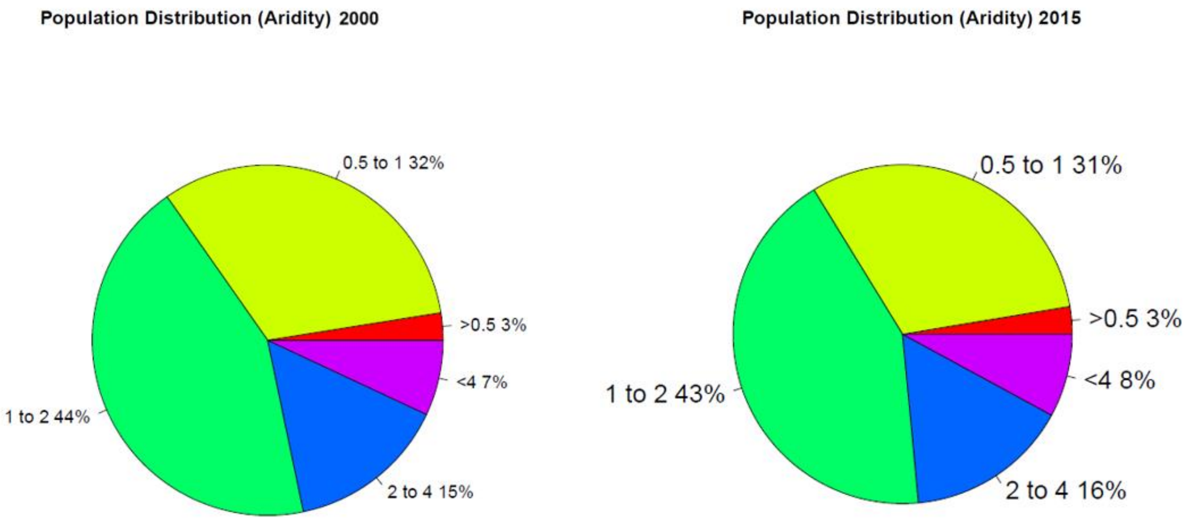

Figure 15 Pie chart distribution of population in various aridity classes 2000 vs 2015

The pie charts in Figure 14 and 15 illustrate the population in absolute terms in each climate window (masks).

3.6 Europe and Africa trends: Aridity and Temperature classes

All countries from the African continent were pooled out from the global data and similarly, all the European countries were pooled out. Regional realities are different from global data, for a greater insight as to which regions are dominant for the global trend, the thesis looks at Europe and Africa separately. The results are indicative of divergent regional trends in population change in Africa compared to Europe.

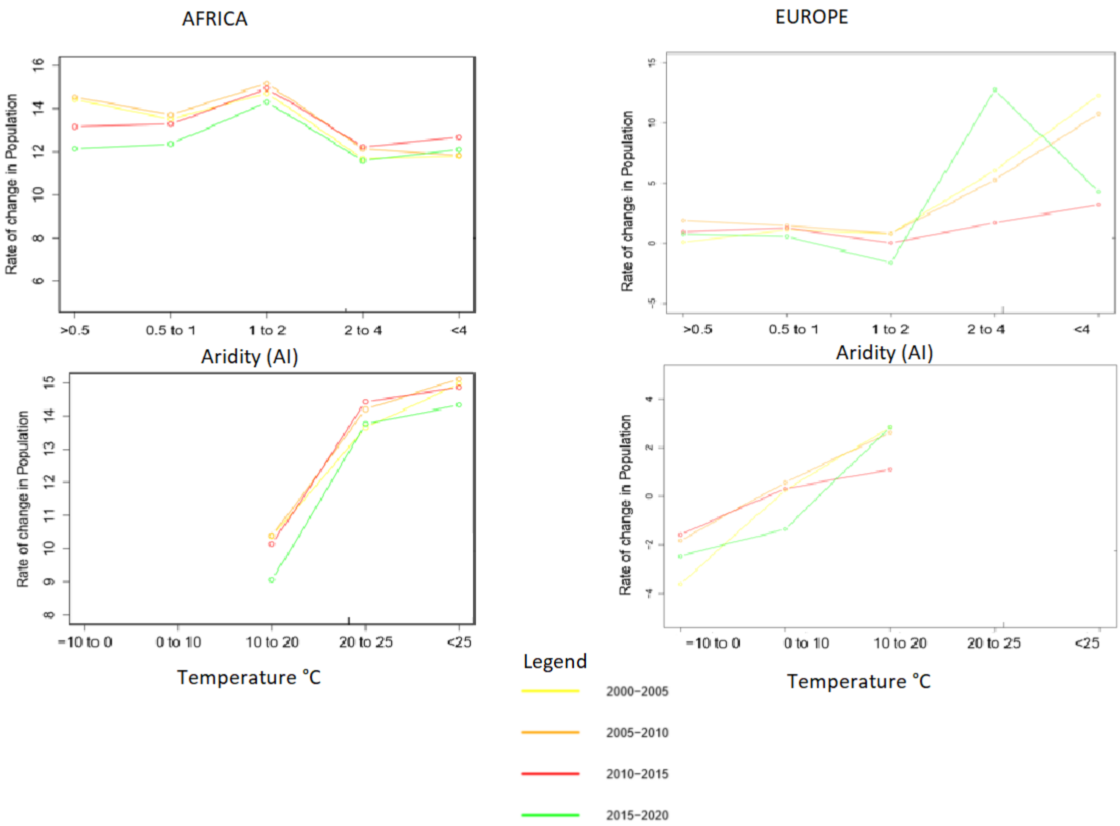

Figure 16 Europe vs Africa; Aridity and Temperature with respect to population growth at five-year intervals (2000-2020)

4. Discussion

To understand the consequence of the anthropogenic change to the human system one must investigate AMH's evolutionary history, its true ecological niche and the artificial niche (civilization) AMH has built since the onset of sedentism. Anthropogenic change is unprecedented; AMH has not faced such global mean temperatures and by continuation neither has the civilization AMH has created (This position has been expressed in detail in the introduction) . Temperature is something that affects AMH directly in terms of tolerance and Aridity has a direct influence on water availability and hence agriculture output. At the beginning of this exploratory study, the working hypothesis was that the human population might respond to changes in Aridity and Temperature. The intuition was that hotter and arid climate regime will discourage population growth. One caveat was that to study the impact of climatic change we need to have a broader time window, perhaps there is a trend towards the initial hypothesis in a longer-range study but in the short term, the analysis paints a different picture.

Global temperature, directly and indirectly, impacts AMH, humans have certain biological and caloric requirements. If parts of the world continue to get hotter, certain regions will become inhospitable to large human populations. When it comes to aridity, lower moisture will make it harder to grow crops, which will be further exacerbated by the growing population provided there are no further technological revolutions.

Where climate change has a global reach, certain regions have been impacted disproportionately. This is illustrated in figure 7, there as disproportionate increment in aridity around deserts. Of interest is, South Africa. Cape Town with a population of around 3.7 million people approached Day zero in early 2018- it was at the risk of being one of the first major metropolitan areas in the world to run out of the water this was mainly due to increased water evaporating from water storage facilities such as dams.[43]

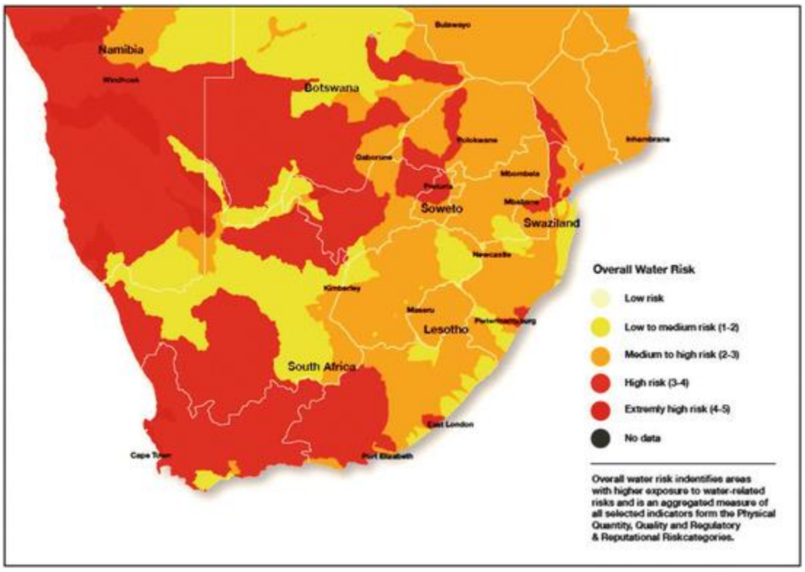

Figure 17 South Africa's rating according to the Water Risk Index [44]

These changes are no longer prospective but are already having an impact on how and where humans live as can be seen in this example from South Africa. This example also demonstrates that there is already a climate-induced stress on human populations. In terms of global temperature, the average annual temperatures have increased significantly in polar regions. It is reported that over recent decades temperature in the Arctic have increased twice the global rate largely as a result of ice-albedo and temperature feedbacks.[45–47]

The Huang He, Indus, Nile, Tigris and Euphrates rivers were host to the first Old World Civilizations and almost entirely were based on alluvium.[48] These mighty rivers, floodplains, and deltas were central to the development of civilization and today are home to home to *c*. 2.7 billion people.[49] Humans are generalist specialists in many environments. For example, the Intuits of Arctic make their home in some of the coldest places on earth, the indigenous Tibetan make a living on high Himalayan altitudes or temperature extremes faced by Bedouins who are desert dwellers. These specialist AMH populations showcase the plasticity of humans as a specie but what is important to note here that these people have over time adapted to live in these extremes both genetically and culturally. According to a comparative sequencing study of human exomes to demonstrate adaption to high altitudes, Ethnic Tibetans possess heritable adaptations to their hypoxic environment which may have involved both cultural and genetic adaptation.[50] The majority of humans are not tolerant to these extremes. Neither is the civilization AMH has built. Further as suggested earlier the fitness of AMH populations has reduced, we then are probably less prepared biologically then ancestor populations in face of climate variability. In figure 8, it is illustrated that humans cluster in moderate climate regimes, with the greatest population density in aridity < 2 and annual temperature mean window of 7-17 degrees Celsius. A broader window of 5 to 25 temperature and

0 to 3 aridity is constructed which also correlates well with the spread of vegetation as demonstrated in figure 10. The NDVI data acts as a proxy for agriculture and hence productivity. If the human population starts rapidly growing outside this window, then one can speculate that there is a climate decoupling.

Figure 9 demonstrates the above reasoning. Human populations are growing much faster in regions with high aridity, hotter temperature and/or both. We still wanted to see if there is climate correlation in the various aridity and temperature classes, perhaps if aridity or temperature rapidly changes there is a climate correlation. The results from Figures 10 and 11 indicate that changes in aridity or temperature regardless of what the initial climate space was in that grid cell had little to no bearing on population increase or decrease.

Turning to figures 12 and 13; In each subsequent five-year window, we see a decline in population growth rate however the trend lines indicate that population growth rate is much higher as we move right on the temperature axis. The colder regions are an exception to this. In 2015-2020 the projected population growth stands at around eight per cent for <25 temperature class compared to less than four per cent for 10-20 Celsius. A similar trend is seen in Aridity classes, with population growth rate relatively much higher in hyper-arid grid cells.

As indicative from the pie charts in figures 14 and 15 we can garner where people have lived traditionally and how in terms of absolute numbers the composition is slowly changing even in a fifteen-year temporal dimension. For example, 37% of the global population lived in a temperature regime of 10-20 Celsius in 2000 and this dropped to 35% in 2015 whereas 16% of the global population lived in grid cells with temperature >25 Celsius in 2000 which increased to 18% in 2015. Then human populations are arguably no longer mediated by climate but by socioeconomic factors. There is a reason why gentler climate regimes had the mammoth share of both aridity and temperature pie charts, the reason being that this climate space was conducive to both our biology and civilization. The restructuring of the composition of this pie chart is a worrying development. All this strengthens the argument that there is a development towards a decoupling of climate and population. The social structure, religious beliefs, economic prosperity and urbanization within each country are likely to affect birth rates as well as abortion rates.[51] Where a decoupling from climate-mediated population change can be viewed as an achievement of the specie, allowing it to spread in regions which were once not conducive to habitation, but it also opens up the debate on the fragility of the global human system this decoupling can result in. As this is artificial and not reflective of the species evolutionary history and ecological niche. Further, this exposes the vulnerabilities to our civilization from inequality to food security.

Europe represents one of the most prosperous collectives on the planet and in contrast Africa the poorest. The trend lines from Figure 16 indicate Africa has much higher population growth rates in all relevant temperature and aridity classes compared to Europe. When this is contrasted with the Gross Domestic Product (GDP) and CO2 emissions (Figure 18) a stark inequality emerges. If the population is no longer reconciled by climate but other factors this then presents a great challenge in terms of land use, food security and rising inequality. In figure 3 it is seen that 50 per cent of the habitable land is under agriculture the rest is forests and shrubs, given there is no major technological green revolution to feed the growing population, there are two options deforestation (given that forests are major carbon sinks, this is not a valid choice) or changing food is produced (that is more grains then land use for meat production). Increasing global temperature and fluctuations in humidity do not only disrupt planting and harvesting times but can induce new pests which can decimate entire crops- further it is reported that generally the yields of crops and productivity of livestock declines at a higher temperature and drought-induced stress.[29]

Note here that while there might be a population decoupling going in short-term with climate indices this does not mean anthropogenic mediated changes have no consequences on human populations.

Figure 18 A comparison of European Union and Sub-Saharan Africa in terms of GDP, Population and per capita CO2 emissions. [52] *Source: World Bank Data*

Society is only as strong as its most vulnerable. Inequality has been on the rise all over the world, where it is true that the number of people living in absolute poverty has declined but at the same time, the economic gap continues to widen over the last several decades. According to the world inequality database in 2016, one per cent of people took 20.4 per cent of national income share whereas the bottom 50 per cent represented 9.7 per cent of national income.[53] As found in Credit Suisse Global Wealth Report, the richest one per cent owns 44 per cent of the world's wealth in comparison 56.6 per cent of the world population holds less than two per cent of the world's wealth. [54] Oxford Committee for Famine Relief (Oxfam) reported that in 2018 just 26 people held as much wealth as fifty per cent of the world.[55] This inequality is also reflected between the developed and the developing world. Developed countries are better equipped to respond and adapt to climatic changes and hence are less vulnerable than developing countries. Climate change affects the poorest the most while at the same time these people have the smallest carbon footprint. In a report from Intergovernmental Panel on Climate change (IPCC), there is consensus supported by robust evidence that "Inequalities influence local coping and adaptive capacity and pose disaster risk management and adaptation challenges from the local to national levels".[56]

The movement of humans in the past was not as restricted as it is since the formation of nation-states and codification of international law. In an imagined scenario, in the past a population sustained around a lake will pack up and leave in response to the drying up of the lake without consideration to abstract borders. This is not the case anymore. As an example of this; Sahara goes through humid and dry periods based on orbital forcing and other factors the last time Sahara was green and dotted with lakes was in the humid cycle which peaked between 9,000 and 6,000 years ago.[57]The abrupt ending of Africa Humid period exemplifies how AMH adapted as Sahara desiccated, by converging around the Nile and adapting a pastoral lifestyle from a hunter-gatherer one.[57–59] As of today, there are 195 countries and two observer states (Vatican and Palestine) recognized by the United Nations. Each nation has its own laws and borders that restrict the movement of people. Refugees are protected under International law. But how do is a 'refugee' defined? According to the United Nations, 1951 Refugee Convention a refugee is defined as:

> "someone who is unable or unwilling to return to their country of origin owing to a well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group, or political opinion." [60]

In the above definition, climate factors do not make a refugee. Hence the term environmental/climate migrant/refugee is merely a descriptive term. IPCC reports that "A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events"[56] These extreme events can and do result in internally displaced people (IDPs). IDPs refer to people forced to move within their respective countries in the face of conflict, development and climate change. Figure 19 shows that most new displacements are disaster related. Figure 20 demonstrates that weather-related disasters contribute to the mammoth share of new displacement in comparison to geophysical disasters (Earthquakes, Volcanic eruptions etcetera). Unlike refugees, as IDPs do not cross international borders, they have no recognized rights. Hence this again is a merely descriptive term. However, these IDPs can potentially spillover across international borders and this exposes the lack of global preparedness in terms of comprehensive policies. Another important parameter is that climate has delayed impacts- for example, a drought might not kill people, but a prolonged drought can cause famine and migration is not an easy option. Affected people place migration as their last option because it entails tremendous risk to their personal security and can have dire consequences if they fail in finding a new home. Many consider migration to be their last option, one that comes with tremendous risks to their personal security and dire consequences if they are unable to complete the journey.[29]

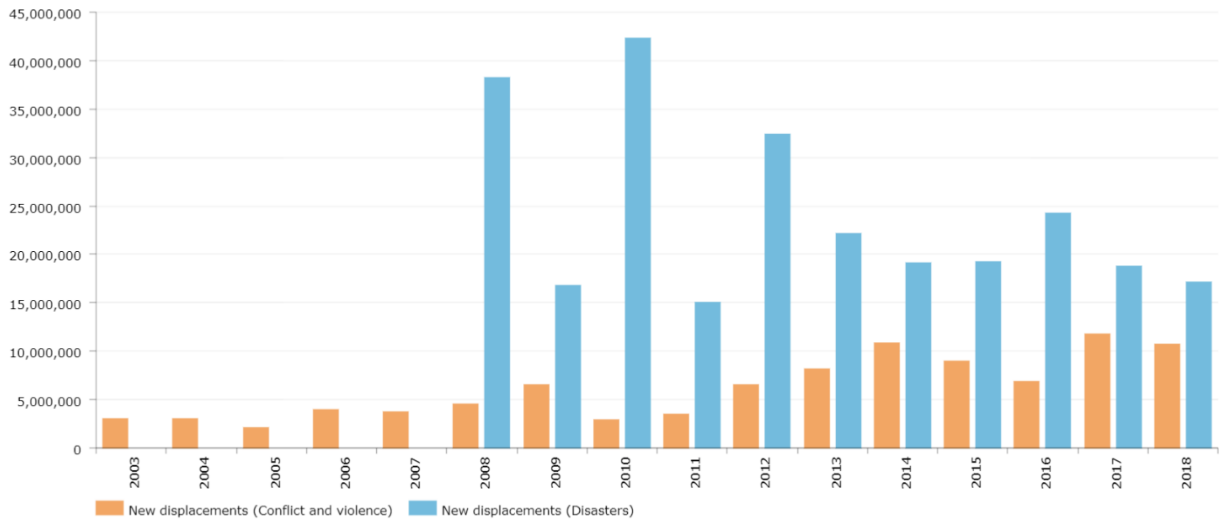

Figure 19 Total annual new displacements since 2003 (Conflict and violence) and 2008 (Disasters) Source: Internal displacement Monitoring Centre (IDMC)

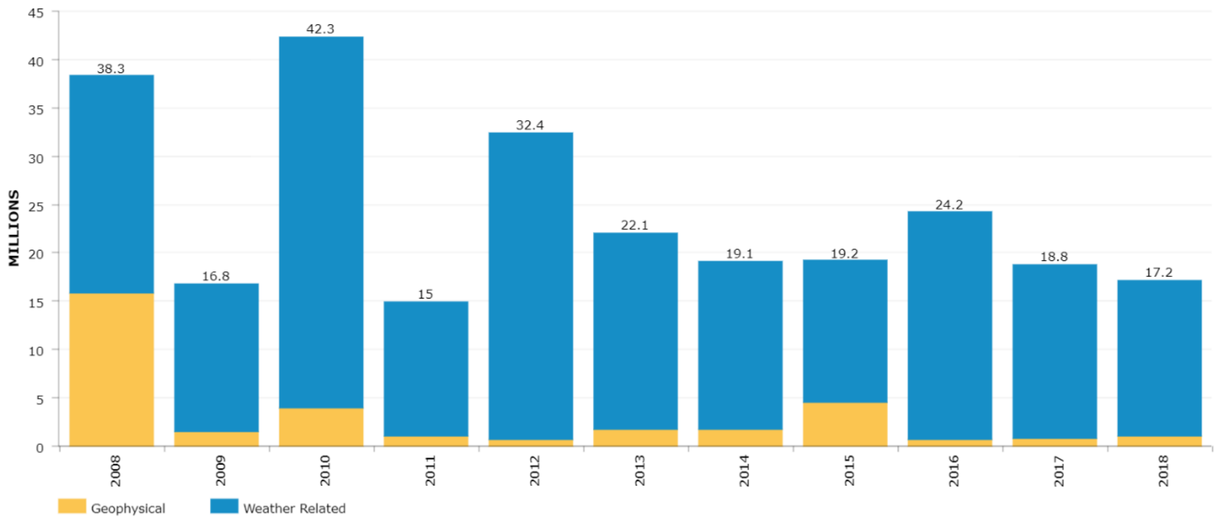

Figure 20 Disaster-related new displacements by hazard category Source: IDMC

With disproportionate growth of population outside the traditional sustainable climate window under the stress of extreme events coupled with widespread inequality the vulnerability to global food security and recurrent displacement are concrete and not speculative threats. Our biology and civilization will both be under climate scrutiny. It was suggested more than two decades ago in a research paper that "social and economic systems may actually be becoming so thoroughly adapted to political, cultural and economic stimuli that they are effectively decoupled from the natural environments in which they operate".[61] As the results also demonstrate a decoupling of human populations from the natural climate order, the consequence of which will be that these populations will become increasingly vulnerable to climatic extremes. Perhaps with mitigation efforts AMH's biology will hold and adapt under environmental stress but the same cannot be said for our civilization. The inflexibility of the society to adapt and rampant inequality results in a muted response to climatic changes. Our evolutionary history and civilization have not seen such global temperatures and if we do not make comprehensive policies to tackle the imminent disruptions, the consequences to the global order can be dire. Climate change is a threat multiplier. The myth of Daedalus and Icarus comes to mind- fly too close to the water and the wings will get wet- fly too close to the sun and the wax will melt. The key to escape is the middle way. Then let's not be Icarus.

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II List of Abbreviations

Anatomically Modern Human (AMH)

Million years- Mega Anum (Ma)

Before Present (BP)

Watts (W)

Basal Metabolic Rate (BMR)

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

Indian Ocean Dipole (IOD)

United Nations (UN)

International Commission on Stratigraphy (ICS)

International Union of Geological Sciences (IUGS)

Global Boundary Stratotype Section and Point (GSSP)

National Oceanic and Atmospheric Administration (NOAA)

Socioeconomic Data and Application Center (SEDAC)

Earth Observing System Data and Information Systems (EOSDIS)

Global Precipitation Climatology Centre (GPCC)

Normalized Difference Vegetation Index (NDVI)

Gross Domestic Product (GDP)

Oxford Committee for Famine Relief (Oxfam)

Intergovernmental Panel on Climate change (IPCC)

Internally displaced people (IDPs)

III List of Figures and Table

VI Declaration of Self-Dependence

Herewith I declare that I prepared this thesis on my own, that I did not use any other sources and resources than those that are specified, that all arguments and ideas that were literally or analogously taken from other sources are sufficiently identified, and that the thesis in identical or similar form has not been used as part of an earlier course achievement or examination procedure.

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Place, Date Signature

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