Global maps of climate change impacts on the favourability for human habitation and economic activity

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Abstract

This paper analyzes the statistical relationship between climatic factors and the global distribution of population and economic activity. Building on this analysis, a new method is developed for assessing geographically explicit impacts of climate change on the suitability of regions for human habitation and economic activity. This method combines information about differences in the conditional distributions of population density and economic activity across climate categories with climate change projections from an ensemble of general circulation models. In contrast to other cross-sectional analyses of the economic impacts of climate change, the method applied here does not require specific assumptions about the functional form of the relationship between climatic and non-climatic factors on the one hand, and population density and economic activity on the other. The results indicate that climate change will improve the habitability of some scarcely populated regions, in particular in Canada, Scandinavia, Russia, Mongolia, northern China, Tibet, and parts of Central Asia, but it will impair the habitability of many densely populated regions in the eastern USA, southern Europe, northern and southern Africa, eastern China, and parts of Australia. Most parts of India, South-East Asia and Oceania, Central America and northern South America, the Sahara and the Sahel are projected to experience climatic conditions during this century that have no geographical analogue in the present climate. Hence, a large majority of the world's population is living in regions whose habitability is either projected to decrease or that are projected to experience globally unprecedented climate conditions within this century under a business-as-usual emissions scenario.

Keywords:

Climate change; macroeconomics; population; cross-sectional analysis

JEL Codes:

C21; Q54

1 Introduction

The population and economic prosperity of a region are determined by a complex interplay of climatic, geographical, environmental, technical, political, institutional, historical, and cultural factors. While the importance of climate for human welfare has long been recognized [Ritter (1852), Huntington (1915), Mills (1942), Lamb (1982), Diamond (1999), Sachs (2003)], most research in the last decades has attempted to explain the wide divergence in wealth by cultural and political factors [Landes (1998), Acemoglu et al. (2001), Rodrik et al. (2004), Engerman and Sokoloff (2005)]. Increasing interest in the potential impacts of anthropogenic climate change, however, has led to a renaissance of research on the influence of climatic factors on economic prosperity. In this context, the present study addresses two questions: First, what is the relationship between climatic factors and the current distribution of population and economic activity? Second, what are the potential impacts of global climate change on the favourability of world regions for human habitation and economic activity?

Several recent studies have extrapolated the observed relationship between climatic and economic variables to estimate the impacts of climate change on global and regional economic productivity. In particular, [Nordhaus (2006), Nordhaus (2008)] has developed the G-Econ dataset, which combines a variety of data sources to estimate key climatic, geographic, demographic and economic variables for all 1°-by-1° terrestrial grid cells of the world. Future economic impacts of global climate change are then estimated based on the extrapolation of regression coefficients derived from a multivariate linear regression of economic density on several climatic and geographical variables from the G-Econ dataset. Earlier cross-sectional analyses have estimated economic impacts of climate change on agriculture based on Ricardian analysis [Mendelsohn et al. (1994)] and developed "climate response functions" for other climate-sensitive sectors [Mendelsohn and Schlesinger (1999), Mendelsohn et al. (2000)]. Other studies have analyzed the impact of climate variability and change on income distribution and economic growth based on panel data at the national level [Dell et al. (2008)] and on cross-sectional data at the national, state, and municipal level [Dell et al. (2009)]. [Kleidon (2009)] has combined an Earth system model with a thermodynamic model of the human metabolism to estimate the influence of climate, and global climate change, on human habitability of the natural environment.

This study complements and extends the existing body of knowledge in two main areas. The first part uses an updated version of the G-Econ 1.3 dataset to assess the relationship between climatic factors and the distribution of population and economic activity. This analysis assesses the robustness of the "climate-output reversal" postulated in [Nordhaus (2006)], analyzes the combined effect of temperature and precipitation on economic density[1], and assesses the relative importance of population density and output per capita on the distribution of economic density. The second part combines the updated G-Econ dataset with geographically explicit scenarios of future temperature and precipitation change to assess potential impacts of climate change on regional population density and economic activity. The analysis compares the conditional *distributions* (rather than just the conditional *means*) of population density and economic density across different climate categories and uses these differences to estimate future changes in the favourability of regions for human habitation and economic activity.

This study partly draws on the same data as [Nordhaus (2006), Nordhaus (2008)] but there are several important differences between these studies. First, the main goal of the present analysis is to describe the geographical pattern of climate change impacts rather than to estimate the impacts of climate change on global economic output. Secondly, this study applies a non-parametric method to address various statistical problems of the G-Econ dataset,

[1] Economic density (or output density) is defined as the product of population density and economic output per capita; it is measured in US$ (based on purchasing power parities) per km^2.

including strong positive skew and heteroskedasticity of the explained variables, excess zeros, and non-monotonicity of the relationship between climatic and economic variables [Füssel (2009b)]. Third, this analysis applies a state-of-the-art climate change scenario derived from an ensemble of GCMs (general circulation models, also known as global climate models) rather than stylized climate change scenarios as in [Nordhaus (2006), Nordhaus (2008)]. Finally, this analysis assesses changes in the favourability for human habitation in addition to the economic variables considered in earlier studies.

The remainder of this paper is organized as follows. Section 2 presents the data applied in this study. Section 3 analyzes relationship between climatic factors and the current distribution of population and economic activity. Section 4 assesses the potential impacts of global climate change on the favourability of regions for human habitation and economic activity. Section 5 concludes this paper.

2 Data

2.1 G-Econ+

Data on current climate, population, and economic activity (see Figure 1 and Figure 2) is derived from G-Econ+, an update of G-Econ 1.3 [Nordhaus (2006)]. G-Econ 1.3 comprises climatic, demographic, and economic data for 17,940 terrestrial 1°×1° grid cells (including Greenland but not Antarctica) from the following sources: (i) climate data are available for each grid cell based on direct observations and interpolations in data-poor regions [New et al. (2002)]; (ii) population data are available for most grid cells from a variety of sources, including census data and extrapolations from night-time lights [Balk and Yetman (2004)]; (iii) data on economic output in local currency have been collected at the first subnational level for most large countries; and (iv) currency conversion factors to the US$ are based on market exchange rates and purchasing power parities at the national level. G-Econ+ corrects several errors in G-Econ 1.3, including inconsistent currency exchange rates in China and the USA (they vary by several orders of magnitude in G-Econ 1.3), inconsistencies between different variables for the same grid cell (e.g., a grid cell has zero population but non-zero output), and inconsistencies between G-Econ and the underlying country files (see [Füssel (2009b)] for details).[2]

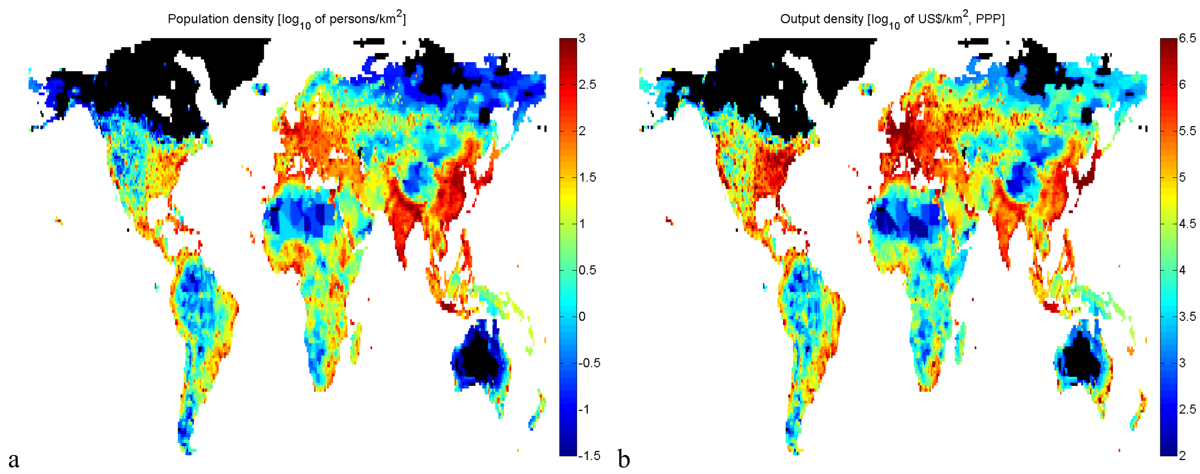

Figure 1: Global distribution of: (a) population density and (b) economic density in 1990.

[2] These data problems may have been addressed in G-Econ 2.11 (http://gecon.yale.edu/documents/GEcon_211_121608_post.xls), which was published after completion of G-Econ+.

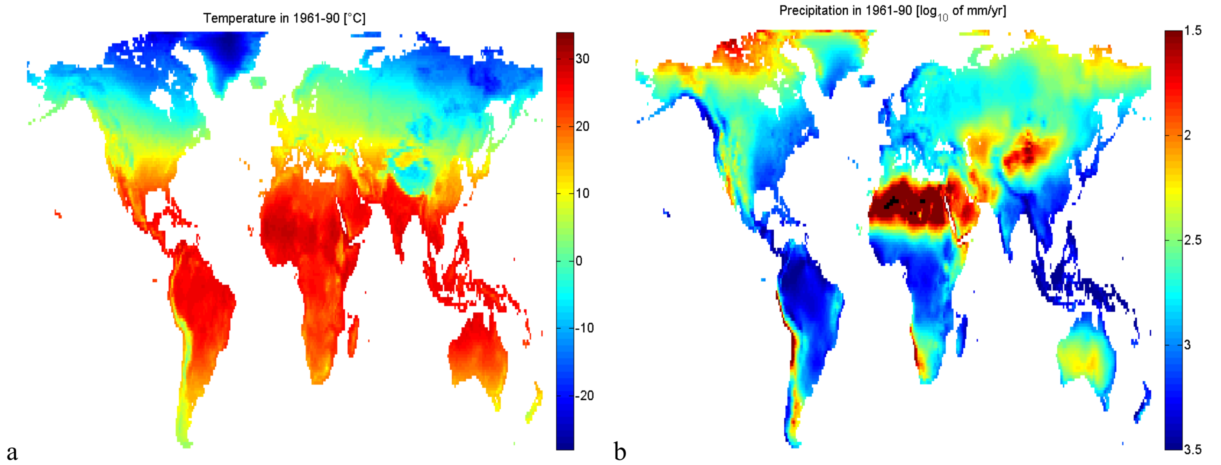

Figure 2: Global distribution of: (a) annual mean temperature and (b) annual precipitation in the baseline climate (1961–1990).

2.2 Statistical challenges

The G-Econ+ dataset is associated with several statistical problems that are relevant for this study. First, the explained variables (i.e., economic density, population density, and output per capita) are strongly right-skewed and they exhibit strong heteroskedasticity. Because alternative measures of central tendency can differ significantly for highly skewed data (see Section 3 for examples), the favourability of different climate regimes should not be compared based on a single central estimator. Skewness and heteroskedasticity also bring about challenges for regression analysis. These challenges are typically addressed by appropriate data transformations (in particular Box-Cox power transformations, of which the log transformation is a special case) and retransformations allowing for heteroskedasticity [Johnson et al. (1994), Manning (1998)], alternative weighting approaches, complex data models, or robust regressions such as quantile regression [Koenker (2005)]. Second, G-Econ data on population density and economic density contains excess zeros: 3,170 out of 17,940 terrestrial grid cells (i.e., 17.6 %) have zero population and economic output. Among others, the presence of excess zeros complicates the application of data transformations to address heteroskedasticity. In particular, the log transformation cannot be applied directly because the logarithm is not defined for zero values of the explained variable. Third, averaging of economic density and population density should apply area weights because the size of a data point in G-Econ depends on the absolute latitude of a grid cell and the potential inclusion of sea coasts and national borders. Averaging of output per capita should apply area or population weights, depending on the context of the analysis.

2.3 Climate change projections

Data on future climate change is derived from an ensemble of 19 GCMs that have contributed to the IPCC Fourth Assessment Report [IPCC (2007)]. These models were forced by the SRES A2 emissions scenario, which projects a substantial increase in global greenhouse gas emissions during this century [Nakicenovic and Swart (2000)]. In order to obtain a "best estimate" of regional climate change for that scenario, the mean response of surface air temperature and precipitation from monthly data of 19 different GCM realizations for the SRES A2 scenario was utilized. This technique is commonly used to limit the biases of individual GCM projections. First, all data was interpolated from the original GCM resolution to a regular 0.5° grid using bilinear interpolation. Second, the climate anomalies for each variable and each future period were calculated based on the average anomaly relative to the 1961–1990 mean climate from the GCM simulations and the observed climate for the same period [Mitchell and Jones (2005)] using a modified delta approach [Füssel (2003)]. Finally, the resulting data was temporally aggregated to obtain annually averaged changes in precipitation and temperature for each grid cell (see Figure 3).

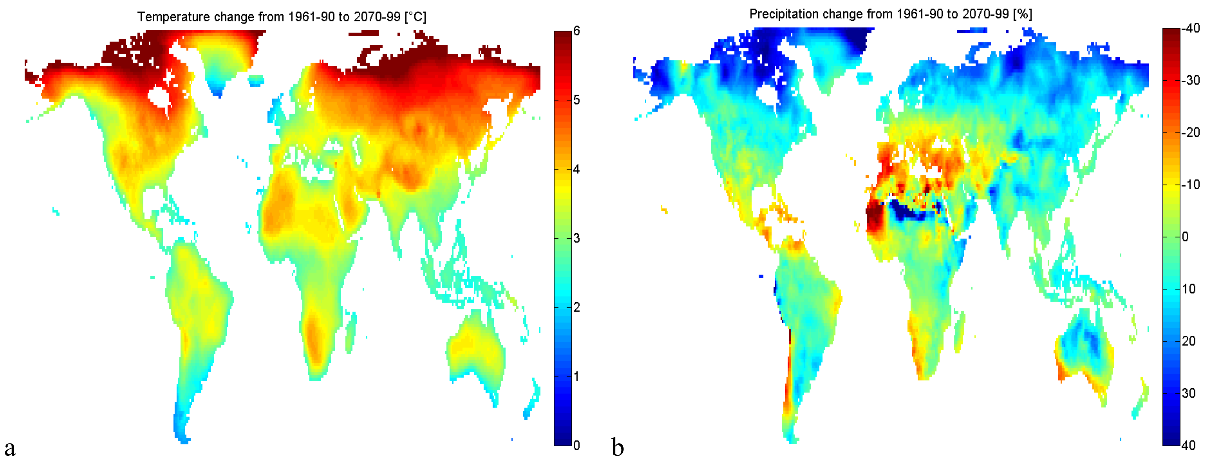

Figure 3: Projected changes in: (a) annual mean temperature and (b) annual precipitation between 1961−1990 and 2070−2099, calculated as the ensemble mean from 19 GCMs forced by the SRES A2 emissions scenario.

3 Relationship between climatic factors and the distribution of population and economic activity

This section analyzes the relationship between annual temperature and precipitation on the one hand and the current distribution of human population and economic activity on the other. To this end, grid cells are assigned to discrete temperature and/or precipitation bins, and the explained variable is aggregated across all grid cells within a climate bin. The robustness of the relationship is tested by using different central estimators (arithmetic mean, geometric mean with cutoff, and median) and weighting schemes (equal weights, area weights, and population weights) for the aggregation. The arithmetic mean is not affected by the presence of excess zeros and it is insensitive to the size of grid cells. However, the arithmetic mean of economic density and population density is highly sensitive to the presence of grid cells with very high population density (i.e., urban centres) whose specific location is generally determined by non-climatic rather than by climatic factors. The geometric mean corresponds to applying a log-transformation without allowing for heteroskedasticity in the retransformation, and it requires applying a lower cutoff value to unpopulated grid cells. The geometric mean is highly sensitive to the choice of this cutoff value (see below), and it scales positively with the size of grid cells[3]. The median is fairly insensitive to the presence of urban centres but collapses in climate bins where the majority of the grid cells are unpopulated.

3.1 Relationship between temperature and economic activity

Figure 4 depicts the statistical relationship between temperature and several central estimators of economic density (Figure 4.a) and output per capita (Figure 4.b). The box plots denote the first, second, and third quartile of the explained variable within each temperature bin, and the whiskers denote the 5th and 95th percentile. The 50 black triangles at the top show the distribution of land area (Figure 4.a) and population (Figure 4.b) across temperature. Each pair

[3] For example, consider four neighbouring grid cells of 100 km^2 each, one of which has a population of 40,000 whereas the other three are unpopulated. The average log-transformed population density of these four grid cells (with a cutoff value of 0.01 persons per km^2) is $(\log_{10}(40{,}000/100)+3\ \log_{10}(0.01))/4 \approx -0.85$. If these four grid cells are merged into one larger grid cell, however, the log-transformed population density of the merged grid cells is $\log_{10}(40{,}000/400)=2.0$.

of neighbouring triangles encloses 2 % of land area or population, respectively, whereas 1 % each is located below the leftmost and above the rightmost triangle.

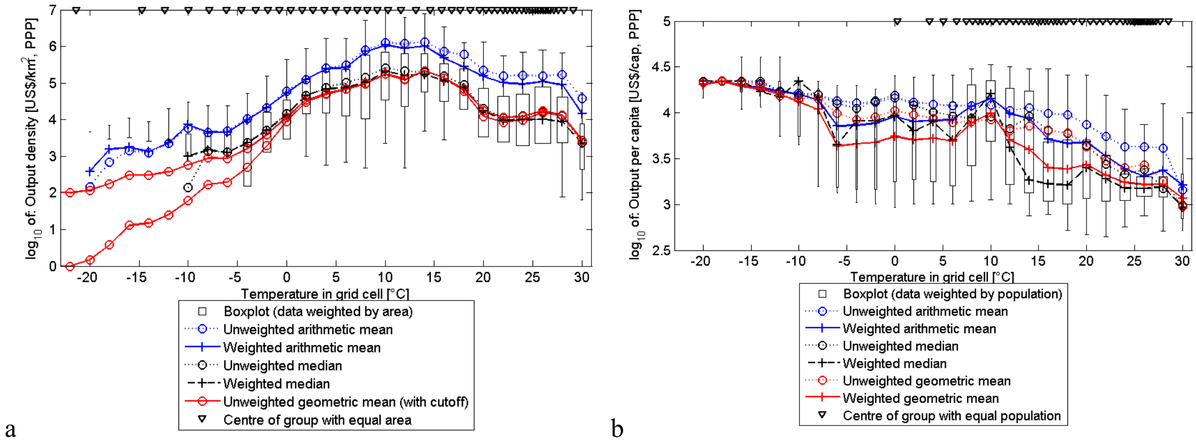

Figure 4: Relationship between temperature and: (a) output density and (b) output per capita.

Figure 4.a shows that the relationship between temperature and economic density is non-monotonous. Economic density assumes a global maximum in the 10-14 °C temperature bins with slight variations across central estimators. Most estimators show a local maximum in the 26-28 °C bins, which coincides with maximum precipitation in this temperature range (not shown here). The variation in economic density within temperature bins is large; the interquartile range generally spans more than one order of magnitude. The arithmetic mean (blue curves) is much larger (typically by about one order of magnitude) than the geometric mean with cutoff (red curves) and the median (black curves). The geometric mean was calculated for two different cutoff values: 1 US$/km^2 (lower red curve, as in [Nordhaus (2006)]) and 100 US$/km^2 (upper red curve). The choice of the cutoff value has a strong effect on the geometric mean of economic density in climate bins with a large fraction of unpopulated grid cells. Interestingly, the geometric mean for a cutoff value of 100 US$/km^2 is similar to the median where the latter is not zero. Area-weighted and unweighted averages do not differ substantially for any of the central estimators.

Figure 4.b depicts the statistical relationship between temperature and several central estimators of output per capita. The location of the left-most triangle indicates that only about 1 % of global population lives in regions with a mean temperature below 0 °C. For that reason, considerable caution should be applied when interpreting the statistical relationship between temperature and economic activity outside the range spanned by the first and last triangle. All central estimators suggest that output per capita assumes a maximum in the coldest regions (below -10 °C). Except for the 10 °C bin and the sparsely populated regions below -6 °C, population-weighted estimates are generally much lower than unweighted and area-weighted estimates (not shown here). In other words, in most temperature bins output per capita is significantly higher in scarcely populated grid cells than in densely populated grid cells. The exception is the 10 °C temperature bin, which creates a "population-area-paradox": population living around 10 °C is wealthier on average than population in any other temperature bin above -8 °C even though population in an average 0 °C grid cell is wealthier than population in an average 10 °C grid cell. The interquartile range and the difference between the arithmetic and the geometric mean of output per capita are somewhat smaller than for output density; they vary substantially across temperature bins.

Why is output per capita highest in very cold regions? A possible explanation for this somewhat surprising result involves the strong prevalence of capital-intensive activities in very cold regions, such as mining and oil extraction. Unfortunately, the available data do not allow testing this hypothesis because data on GDP from oil extraction in G-Econ 1.3 is incomplete and often inconsistent [Füssel (2009b)]. If there was a systematic variation of output per capita with temperature within the coldest administrative units, the result could also be an artefact of the difference in spatial resolution between the climatic variables (available for each grid cell) and output per capita (available for administrative units only). In the view of this author, the best explanation for the observed combination of high income but very low population density in the coldest regions is that most people would live in very cold locations only if the non-climatic conditions enable them to achieve an income that is high enough to compensate for the unfavourable climate.

[Nordhaus (2006)] has suggested the existence of *"opposite relationships between climate and output depending on whether we look at output per person or output per area"* (p. 4). This allegation has been based on a comparison of the unweighted geometric mean curves of output density (with a cutoff value of 1 US$/km^2, see lower solid red curve in Figure 4.a) and of output per capita (see solid red curve in Figure 4.b). The author made considerable attempts at explaining this "striking paradox" labelled as the "climate-output reversal"[4] yet without coming to a clear conclusion. Figure 4 shows that the climate-output reversal clearly does not apply above 10 °C because all central estimators of output density and output per capita decrease substantially above this temperature level. Regions below -6 °C are so sparsely populated that the relationship between temperature and output per capita below this temperature level does not appear reliable. Between -6 °C and 10 °C, [Nordhaus (2006)] finds a negative relationship between temperature and output per capita, based on one unweighted central estimator that relates variables at different spatial aggregation units. The present analysis finds that the relationship between temperature and output per capita between -6 °C and 10 °C varies across central estimators, weighting schemes, and spatial aggregation units (not shown here). Population-weighted estimators show a positive trend whereas unweighted and area-weighted estimators show no clear trend. Hence, this reanalysis does not support the existence of a robust "climate-output reversal".

The results in this section have important implications for the assessment of the impacts of climate change in Section 4. In particular, they suggest that this assessment needs to account for the non-monotonous relationship between temperature and output density, for the strong skewness and heteroskedasticity of output density, and for excess zeros.

3.2 Bivariate relationship between climate factors and regional favourability for human habitation and economic activity

The analysis above has assessed the univariate relationship between temperature and the distribution of economic activity. Figure 5, in contrast, depicts the bivariate relationship of temperature *and* precipitation with output density. Figure 5.a shows that the area-weighted median is highest in regions between 4 °C and 20 °C with annual precipitation above 400 mm; these climatic conditions are generally sufficient for high output density. The median is lowest in regions below -6 °C. The relationship between temperature and output density is inverse U-shaped for most precipitation levels. Precipitation generally has a positive relationship with output density across the full temperature range. Figure 5.b shows that the area-weighted arithmetic mean of output density exhibits a similar pattern as the median. However, it also assumes high values in many tropical (i.e., very warm and humid) regions where the median is rather low. Apparently, these climatic conditions are not sufficient in themself for high output density but they can support high output density if the non-climatic conditions are favourable.

[4] This term is retained here even though "temperature-output reversal" would be a more accurate description of the alleged phenomenon.

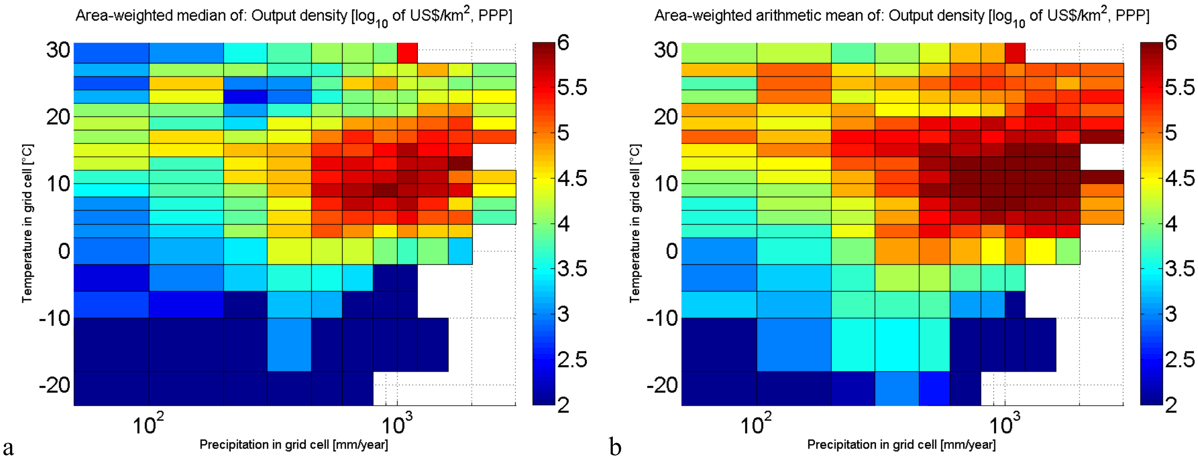

Figure 5: Bivariate relationship of temperature and precipitation with output density: (a) area-weighted median; (b) area-weighted arithmetic mean

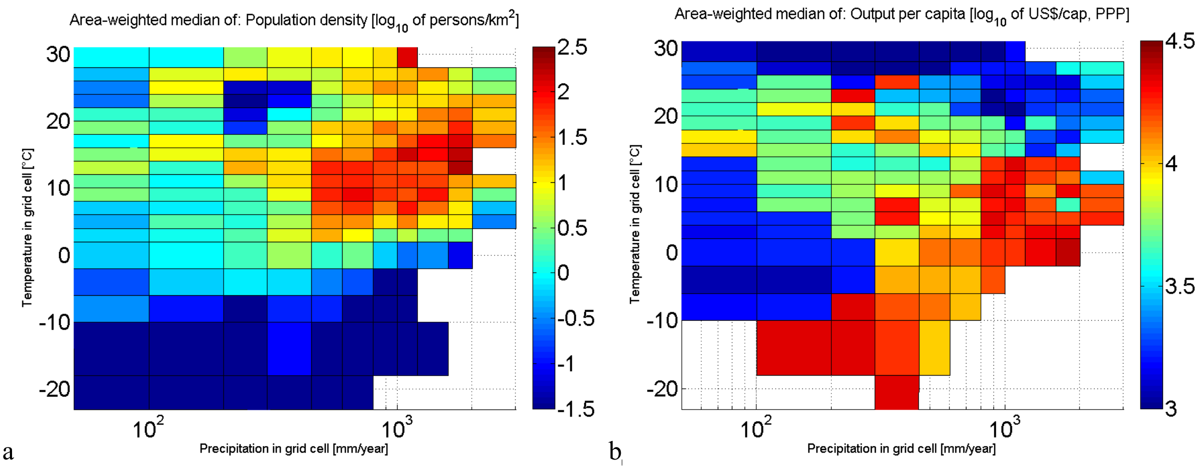

Figure 6: Bivariate relationship of temperature and precipitation with the two determinants of output density: (a) population density; (b) output per capita

Output density is the product of population density and output per capita. How important are these two factors for the distribution of output density? The rank correlation of output density with population density and output per capita across all inhabited grid cells is ρ=0.890 and ρ=0.079, respectively. Hence, the distribution of economic output is dominated by the distribution of population; output per capita clearly plays a secondary role only. This finding is corroborated by Figure 6, which depicts the relationship of temperature and precipitation with the area-weighted median of the two determinants of output density. The climatic distribution of population density (Figure 6.a) is very similar to that of output density (Figure 5.a); it is highest in the 6-18 °C temperature range with annual precipitation above 400 mm. In contrast, Figure 6.b shows two distinct climate regimes with very high output per capita: temperate and humid regions with a temperature between -2 °C and 14 °C and precipitation above 600 mm, and very cold regions with a temperature below -6 °C. Three climate regimes are associated with very low output per capita: cool/temperate and dry regions with a temperature between -6 °C and 14 °C and low precipitation, hot regions with a temperature above 26 °C, and warm and humid regions with a temperature above 14 °C and precipitation above a temperature-dependent threshold. Temperature has a negative relationship with output per capita for precipitation levels above 400 mm and a variable relationship in drier regions. Precipitation generally has a positive relationship with output per capita up to 14 °C and a negative relationship at higher temperatures. The strong relationship between output density and population density implies that knowledge on the climatic, geographic, historical and other determinants of population distribution will go a long way in explaining the current distribution of economic activity.

4 Climate change impacts on human habitability

The previous section has shown that temperature and precipitation have a complex, and often non-monotonous, relationship with economic density and its determinants. These results suggest that assessments of the macro-economic effects of climate change need to consider future changes in temperature as well as precipitation, including their synergistic effects. Further challenges for cross-sectional analysis are caused by the strong skewness and heteroskedasticity of the distribution of economic density, and the presence of excess zeros. All existing analyses of the macro-economic impacts of climate change based on G-Econ and similar datasets for specific regions have applied multivariate linear regression. In response to the various challenges for regression analysis just described, this study applies a different method for assessing the impacts of climate change on the favourability of regions for human habitation and economic activity. This non-parametric method does not require making assumptions about the distribution of economic activity or the form of the relationship between climatic factors, non-climatic factors, and economic activity.

4.1 Method

The determinants of population and economic activity in a region can be distinguished into climatic and non-climatic factors. The basic idea of this analysis is to determine the aggregated non-climatic favourability of a grid cell implicitly by comparing its economic density[5] with the conditional distribution of economic density across all grid cells with a "similar" climate. In other words, if the economic density in a grid cell is high (low) in comparison to other grid cells with a similar climate, this is attributed to favourable (unfavourable) *non-climatic* conditions in this grid cell. More specifically, the *aggregated* non-climatic favourability of a grid cell is measured by the area-weighted percentile of its economic density according to the conditional distribution of economic density in all grid cells with a similar climate. This approach is very different from regression analysis, which estimates the influence of selected climatic and non-climatic factors on the variable of interest (e.g., economic density) *individually*.

This analysis assumes that humans attempt to maximize economic activity in a region contingent on climatic, environmental, socio-economic, technical, and other conditions. Thus, an increase in the *climatic* favourability of a region will increase economic activity in the long term whereas a decrease in *climatic* favourability will lead to a decrease in economic activity unless it is compensated by improvements in *non-climatic* conditions (e.g., education, institutions, technology, and infrastructure) [Brooks (2006), Kleidon (2009)]. There are two alternative approaches for measuring the potential impacts of future climate change on the favourability of regions based on this general idea, which will be explained by a hypothetical example.

Let us consider a grid cell with an annual precipitation of 600 mm, a current mean temperature of 8 °C, a projected warming of 4 °C, and an economic density of 2 million US$ per km^2. This economic density is assumed to correspond to the 50th and 75th area-weighted percentile of all grid cells with an annual precipitation of approximately 600 mm and a mean temperature of approximately 8 °C and 12 °C, respectively. The first metric for the impacts of climate change is the ratio of potential future economic density to current economic density, whereby the former is calculated based on the conditional distribution of economic density for the *future* climate in the grid cell of interest. In our example, the potential future economic density equals the 50th percentile of economic density in all grid cells with a mean temperature of approximately 12 °C and an annual precipitation of approximately 600 mm. The second

[5] The text in this section refers to economic density only but all statements apply equally to population density.

impact metric is the change in non-climatic favourability that would balance the change in climatic conditions. To this end, the equivalent percentile of *current* economic density is determined according to the conditional distribution of economic density for the projected *future* climate in the grid cell of interest. In our example, the equivalent percentile of *current* economic density in a future climate is determined by comparing the current economic density of 2 million US$ per km^2 with the distribution of economic density in all grid cells with a mean temperature of approximately 12 °C and an annual precipitation of approximately 600 mm. If the percentile according to the future climate (here: 75th percentile) is larger than the percentile according to the current climate (here: 50th percentile), the impacts of climate change are assessed as adverse because non-climatic conditions would need to improve in order to maintain current economic density in the future. Neither metric is defined if the future climate in a grid cell lies outside the range of Earth's current climate.

Both impact metrics rely on two assumptions. First, the influence of non-climatic factors on economic density is assumed to be similar under current and future climate conditions. For example, if proximity to coasts and rich soils are beneficial in an 8 °C climate, they would also be beneficial in a 12 °C climate. This assumption is also made in multivariate linear regression analysis. Second, the distribution of non-climatic factors is assumed to be similar under current and future climate conditions. For example, the share of coastal regions and the conditional distribution of soil types are assumed to be similar in the 8 °C bin and in the 12 °C bin. The latter assumption is more problematic because climatic factors are significantly correlated with some non-climatic factors (e.g., altitude, institutional quality, and technologies). However, this assumption is still regarded as defensible given the limited magnitude of climate change considered here.

The two impact metrics always agree on the sign of climate change impacts in a grid cell. The results presented in this paper apply the second impact metric, which (in the case of adverse impacts) quantifies the improvement in non-climatic conditions (i.e., the adaptation need) required to compensate for the impacts of climate change.

The global maps of climate change impacts on the favourability of regions according to the second metric are calculated in four steps:

1. **Assign grid cells to discrete climate categories:**
   Grid cells with a similar climate are grouped together by assigning each grid cell to a discrete climate category based on its annual mean temperature and precipitation. Each climate category needs to contain a sufficient number of grid cells so that the distribution of economic density is unlikely to be strongly influenced by special conditions in a few grid cells. At the same time, the climate categories need to be small enough to allow for a detailed assessment of climate change impacts, in particular in the vicinity of changes in the sign of the relationship between climate factors and economic density. Balancing these two competing objectives has lead to the choice of ca. 200 climate categories (see Figure 5) based on 19 categories of annual mean temperature (with boundaries at -18, -10, -6, -2, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, and 28 °C) and 11 categories of annual precipitation (with boundaries at 100, 200, 300, 450, 600, 800, 1000, 1200, 1600, and 2000 mm). A few climate categories that comprise less than 10 grid cells were excluded from the analysis.
2. **For each climate category, determine the conditional distribution of economic density:**
   The conditional distribution of economic density for a climate category is calculated based on all grid cells belonging to this climate category. This conditional distribution assigns an (area-weighted) percentile to each value of economic density, and *vice versa* (see Figure 5.a for an illustration of the 50th percentile of economic density for each climate category).
3. **For each grid cell, determine the *current* non-climatic favourability as well as the non-climatic favourability required to maintain current economic density in a future climate:**

The current non-climatic favourability of a grid cell, p_{curr}, is defined as the area-weighted percentile of its economic density (i.e., a value between 0 and 100) according to the distribution of current economic density conditional on current climate as determined in the previous step (see Figure 7.b). The non-climatic favourability required to maintain current economic density in a future climate, p_{fut}, is determined as the area-weighted percentile of *current* economic density according to the conditional distribution of economic density corresponding to the projected *future* climate. p_{fut} is set to 0 (to 100) if current economic density is below the minimum (above the maximum) of the conditional distribution for the future climate, respectively. p_{fut} is undefined if the projected future climate of a grid cell lies outside the range of Earth's current climate. In order to avoid discontinuities at the boundaries of climate categories, p_{curr} and p_{fut} are calculated by bilinear interpolation based on the percentiles of the (up to) four adjacent climate categories.

4. **For each grid cell, calculate the impact of climate change as the difference between current non-climatic favourability and required non-climatic favourability in a future climate:**
   The impact of climate change on the *climatic* favourability of a grid cell for economic activity is calculated as the difference between current *non-climatic* favourability (p_{curr}) and required *non-climatic* favourability in a future climate (p_{fut}), whereby $p_{fut}>p_{curr}$ indicates a decrease in the *climatic* favourability of a grid cell. If the projected future climate of a grid cell lies outside the range of current climate, p_{fut} is undefined. These grid cells are marked distinctly in the global impact maps (see Figure 8) to emphasize that cross-sectional analysis cannot reliably assess the favourability of unprecedented climate states when extrapolation beyond the current climate is hindered by the complex statistical relationship between explanatory and explained variables.[6]

4.2 Results

Figure 7 depicts global maps of current non-climatic favourability (p_{curr}) for human habitation (Figure 7.a) and economic activity (Figure 7.b), as calculated in step 3 of the above algorithm. Grid cells marked in red (blue) have population or economic activity levels that are higher (lower) than the majority of grid cells with a similar climate, which indicates favourable (unfavourable) *non-climatic* conditions. Uninhabited regions are marked in black; the few grid cells marked by black hatches belong to climate categories with fewer than 10 grid cells that have been excluded from the analysis. Regions with particularly favourable non-climatic conditions for human habitation and economic activity include many coastal regions and islands (e.g., Indonesia), regions with major rivers and/or a long civilizational history (e.g., northern India, the Nile valley, and Italy), and regions with significant extractive resources (e.g., Saudi Arabia and Eastern Russia).

[6] The results presented in Figure 5 and Figure 6 suggest that further warming will impair the habitability of regions that are currently hot and dry but no such statement can be made with certainty for regions that are currently hot and humid.

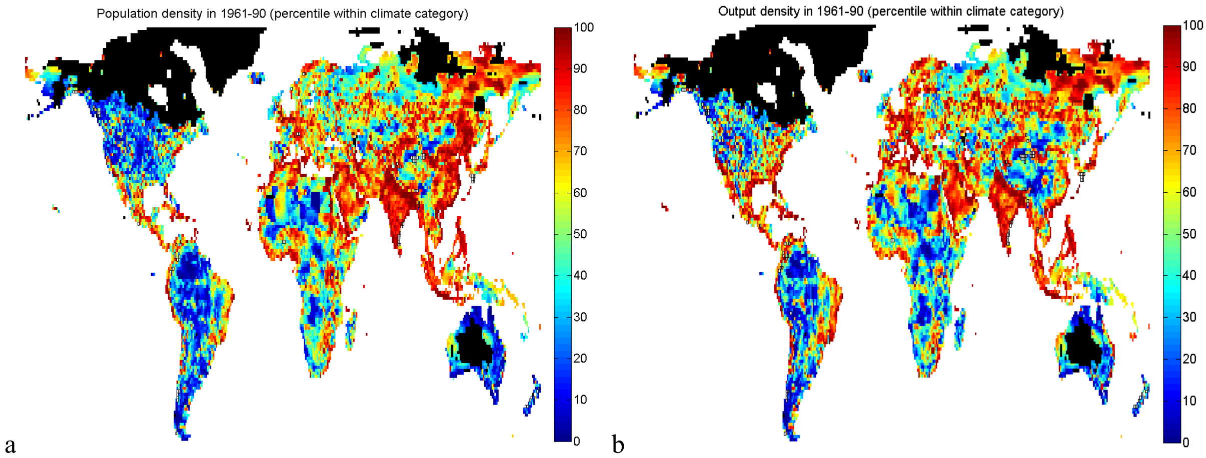

Figure 7: Global maps of non-climatic favourability for: (a) human habitation and (b) economic activity.

Figure 8 depicts global maps of climate change impacts on the favourability of regions. The individual maps refer to changes in the favourability for human habitation and economic activity for three time periods: the 2020s, 2050s, and 2080s. Red (blue) colours denote regions where it will be more difficult (easier) to sustain current population or economic activity following the projected changes in temperature and precipitation. Currently uninhabited areas are shown in solid black; areas whose future climate has no geographical analogue in the current climate are marked by black hatches.

Climate impacts in the 2020s (Figure 8.a/b) are generally small. Significant positive impacts on habitability and economic favourability are projected for parts of Russia; significant negative impacts are projected for some regions around the Mediterranean, in southern Africa, and in southern Australia. Climate impacts in the 2050s (Figure 8.c/d) are already significant, and they show a distinct spatial pattern. Positive impacts are projected for the northern part of North America, Scandinavia, Russia, Mongolia, northern China, Tibet, and parts of Central Asia. Negative impacts are projected for the south-eastern USA, northern Argentina, large parts of the Mediterranean region, southern Africa, parts of eastern China, and southern Australia. Significant areas are projected to experience climate conditions without a geographical analogue in the current climate, in particular in Central America, the Amazon, West Africa, and South-East Asia. The projected changes in the favourability for human habitation are similar to those for economic activity in most regions. Climate impacts in the 2080s (Figure 8.e/f) generally intensify those projected for the 2050s, whereby the division between projected "winners" and "losers" becomes more pronounced. Regions with unprecedented climate conditions are projected to expand considerably, including most of Central America, northern South America, India, South-East Asia, Oceania, and the population centres of West Africa. Hence, a large majority of the world's population is living in regions whose habitability is either projected to decrease or that are projected to experience globally unprecedented climate conditions by the 2080s.

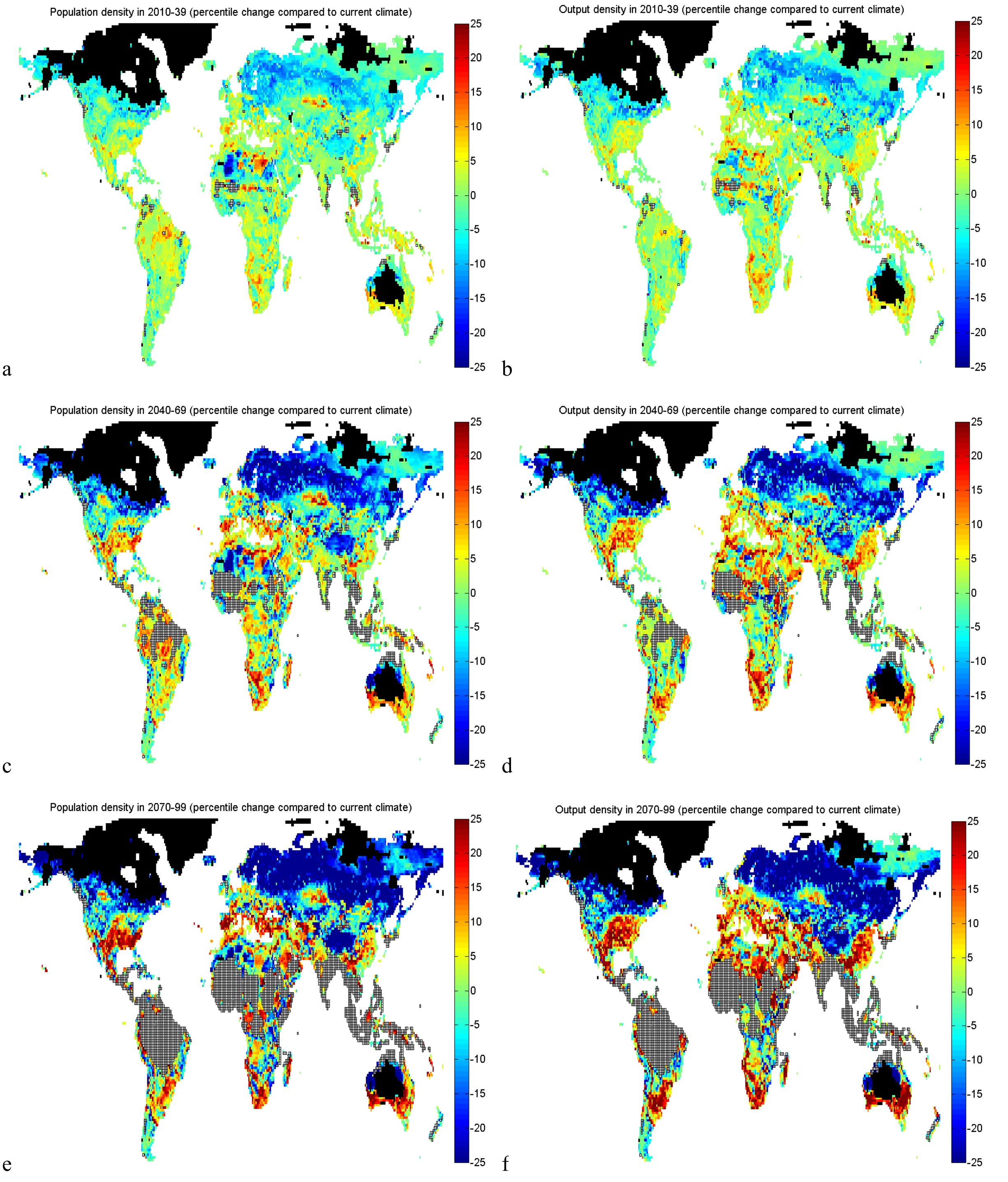

Figure 8: Global distribution of climate impacts on the favourability for: (a,c,e) habitation and (b,d,f) economic activity for three future time periods: (a,b) 2020s, (c,d) 2050s, and (e,f) 2080s.

The results of this study are largely consistent with those of earlier studies that have assessed the global distribution of potential winners and losers of climate change based on cross-sectional analysis [Mendelsohn and Williams (2004), Mendelsohn et al. (2006)] or process-based modelling [Tol et al. (2004), Kleidon (2009)]. However, the climate impact projections presented here have a much higher resolution than these earlier studies. The impact projections for a few regions may initially be surprising. For example, small beneficial impacts are projected for some subtropical and tropical regions (e.g., parts of north-western Australia). These beneficial impacts generally occur in regions where temperature is projected to increase only moderately and precipitation is projected to increase (see Figure 3), which underlines the importance of considering the complexity of climate change.

5 Summary and conclusions

Climate is an important determinant of the current distribution of population and economic activity, and there is significant interest in assessing the implications of future climate change on these variables. This study has presented global maps of climate change impacts on the favourability for human habitation and economic activity. These maps were derived by combining datasets on the global distribution of climate, population and economic activity with projections of future climate change derived from a GCM ensemble. The results presented here provide much more detailed information on the differential impacts of climate change across regions than earlier cross-section analyses. A particularly important and robust result of this study is that the large majority of global population lives in regions whose habitability is either projected to decrease or that are projected to experience unprecedented climate conditions within this century under a business-as-usual emissions scenario. Thus, unmitigated climate change may be a significant threat to the desired economic development in many world regions, in particular if projected population growth is taken into account.

The first part of this study (Section 3) involves two main innovations. First, the use of different central estimators provides more detailed information on the statistical relationship between climatic factors and economic activity than earlier studies, which allows assessing the robustness of the climatic influence on the explained variables. Second, analyzing the distribution of economic activity conditional on temperature *and* precipitation allows assessing the complex influence of these two climate factors on the habitability of regions.The second part of this study (Section 4) also involves two key innovations. First, the use of spatially explicit climate change scenarios based on a GCM ensemble allows producing maps of climate impacts on the favourability of regions for human habitation and economic activity. In contrast, the stylized climate change scenarios applied in earlier studies can only be used to estimate the macroeconomic effects of climate change at the continental or global scale. Second, comparison of the conditional *distributions* of population density and economic density subject to current and projected future climate conditions provides more robust information on the potential economic impacts of climate change than the regression analysis applied in earlier studies, which only considered the conditional *means*. This is particularly important because the results in Section 3 show that the statistical relationship between temperature and economic density can be sensitive to the choice of central estimator (e.g., median, arithmetic mean, and geometric mean). Furthermore, the non-parametric method applied here requires fewer assumptions on the statistical distribution of the explained variables and on the functional form of the relationship between climatic factors, non-climatic factors, and economic activity than previous analyses of the macroeconomic impacts of climate change based on regression analysis.

Despite its many innovative features, this study has several potential limitations. First, the consideration of climate change is restricted to regional changes in mean temperature and precipitation. Other changes such as the rise in sea level and in atmospheric CO_2 and the effects of melting glaciers on downstream areas are not considered. This is a fundamental limitation of climate change studies based on observed (cross-sectional or panel) data because there are no geographical or temporal analogues for increased sea level and elevated CO_2. Insofar as the relationship between average climate conditions and climate variability remains unchanged, future changes in regional climate variability are, however, considered in this analysis. Second, the current analysis does not consider the dynamics of adaptation to climate change, which may cause substantial costs even if the equilibrium impacts of climate change are beneficial. For instance, rising temperature tends to increase the habitability of cold regions but may involve substantial adjustment costs if existing infrastructure becomes unviable. Third, the current analysis does not consider demographic and technological developments that may aggravate or alleviate the changes in climatic favourability estimated here. For example, the availability of air conditioning has certainly influenced this relationship, and the potential availability of an effective and affordable malaria vaccine would further do so. Analogous to other cross-sectional studies, however, this analysis has intentionally focussed on assessing the potential impacts of climate change for current non-climatic conditions. Fourth, this analysis does not make projections for regions whose future climate has no geographical analogue in the current climate. Therefore, the results cannot be aggregated to estimate the global economic impacts of climate change. However, the explicit recognition of regions that will enter climatic *terra incognita* as a result of anthropogenic climate change provides important information to decision makers, which is not generally available from studies based on regression analysis.

There are several options for further research building on the results presented here. It would be interesting to test the robustness of the results for alternative impact metrics (e.g., as described in Section 4.1), for alternative climate variables (e.g., aridity [Kopf et al. (2008)]), and with more sophisticated techniques for categorizing current climate (e.g., cluster analysis). Another worthwhile topic for future research is the combination of estimated changes in habitability with projections of future demographic and/or economic development. Even a cursory analysis of Figure 8 suggests that many of the areas where climate change is expected to decrease habitability coincide with regions that are currently experiencing significant population growth. Finally, panel data could be used to assess how the relationship between climatic factors on the one hand and population and economic activity on the other, has developed over time as a result of technical progress and socio-economic development.

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