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Economic impacts of a glacial period: a thought experiment

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Abstract

Increased knowledge about anthropogenic climate change has raised growing concerns about its potential catastrophic impacts on both ecosystems and human societies. Yet, several studies on damages induced on the economy by unmitigated global warming have proposed a much less worrying image of the future, with only a few points decrease in the world GDP per capita by the end of the century, even for high levels of warming. Here we consider two different empirically estimated damage functions, linking GDP growth or GDP level to temperature, and apply them to a global cooling of -4°C in 2100, corresponding to a return to glacial conditions. We show that the alleged impact on average GDP per capita is comprised between -1.8% and +36%. These results are then compared to the new environmental conditions faced by humanity, taking the last glacial maximum as a reference. The modeled impacts on the world GDP appear clearly unrealistic given the magnitude of climate and environmental changes recorded for that period. We therefore conclude that, if such damage functions cannot reasonably be trusted for a cooling outside their calibration range, nor should they be considered as plausible for the future climate projection under massive greenhouse gas emissions.

Keywords: damage functions, climate change, glacial period

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Abstract

Increased knowledge about anthropogenic climate change has raised growing concerns about its potential catastrophic impacts on both ecosystems and human societies. Yet, several studies on damages induced on the economy by unmitigated global warming have proposed a much less worrying image of the future, with only a few points decrease in the world GDP per capita by the end of the century, even for high levels of warming. Here we consider two different empirically estimated damage functions, linking GDP growth or GDP level to temperature, and apply them to a global cooling of $-4\,^{\circ}$C in 2100, corresponding to a return to glacial conditions. We show that the alleged impact on average GDP per capita is comprised between -1.8% and +36%. These results are then compared to the new environmental conditions faced by humanity, taking the last glacial maximum as a reference. The modeled impacts on the world GDP appear clearly unrealistic given the magnitude of climate and environmental changes recorded for that period. We therefore conclude that, if such damage functions cannot reasonably be trusted for a cooling outside their calibration range, nor should they be considered as plausible for the future climate projection under massive greenhouse gas emissions.

Keywords: damage functions, climate change, glacial period

1 Introduction

Since the first IPCC (1990) report anthropogenic climate change has been the object of large research efforts. Increased knowledge has raised growing concerns about its potential catastrophic impacts on both ecosystems and human societies if greenhouse gas (GHG) emissions continue at a high level. In addition to the worsening of living conditions in many places due to the shift in the mean climate conditions, numerous studies emphasize the risks associated to increased frequency and/or magnitude of extreme events (droughts, heat waves, storms, floods...) and rising sea level (Stocker et al., 2013), which has raised concerns about potential catastrophic outcomes for the world's economy (Weitzman (2012); Dietz and Stern (2015); Bovari et al. (2018)). Yet, several other studies on damages induced on the world GDP by unmitigated global warming have proposed a much less worrying image of the future. Indeed, many damage functions impacting GDP level lead to a decrease of the world GDP by

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only 1-4% for a 3 °C increase in the global mean temperature in 2100 (see Tol (2018) for a review). Even a global temperature increase above +5 °C would allegedly cost less than 7% of the world future GDP (Nordhaus, 1994; Roson and Van der Mensbrugghe, 2012). These estimations have led some authors to conclude that *"a century of climate change is about as good/bad for welfare as a year of economic growth"* and hence that humanity faces bigger problems than climate change (Tol, 2018). More important damages are expected if temperature impacts GDP growth rather than GDP level (Dell et al., 2012; Burke et al., 2015). Using temperature, precipitation and GDP data for 165 countries over 1960-2010, Burke et al. (2015) (hereafter BHM) aim at evaluating the impact of global warming on growth at the country scale. According to their econometric damage function, temperature increase under strong GHG emissions (RCP8.5, Riahi et al. (2011)) would reduce average global income by roughly 23% in 2100. However, this result is a decrease in potential GDP applied to the projected growth trajectory of the baseline scenario, i.e., without climate change and based on the Shared Socio-economic Pathway 5 (SSP5, Kriegler et al. (2017)). As a result, for a global temperature increase of about 4 °C, only 5% of countries are poorer than today in 2100 and global GDP is still higher than today.

Impacts on growth may appear more realistic than level effects. Indeed, it allows global warming to have permanent impacts and also accounts for resources consumption to counter the impacts of warming, reducing investments in R&D and capital and hence economic growth (Pindyck, 2013). But there is no consensus on that issue. In a recent work, Newell et al. (2018) (hereafter NPS) evaluate the out-of-sample predictive accuracy of different econometric GDP-temperature relationships through cross-validation and conclude that their results favor models with non-linear effects on GDP levels rather than growth, implying, for their statistically best fitted model, world GDP losses from unmitigated warming of only 1-2% in 2100.

Such results seem at least surprising when compared to the conclusions of the last IPCC report (Stocker et al., 2013) and to the various rather alarming publications since then (Hansen et al., 2016; Mora et al., 2017; Steffen et al., 2018; Nolan et al., 2018). Damage functions have actually been heavily criticized for their lack of empirical or theoretical foundations or to their inadequacy to evaluate the impact of temperature change outside the calibration range (Pindyck, 2013; Pottier, 2016; Pindyck, 2017). Here we contribute to this critical literature by examining the following thought experiment: what would the econometric damage functions of BHM and NPS predict when faced with a global cooling (as opposed to a warming) phenomenon? Indeed, by design they can be applied to both kind of temperature changes. The strength of this exercise lies in our ability to counter-check the conclusion of a damage function under scrutiny with reconstructions from paleo-climatology — a counterfactual which is of course unavailable for global warming above +2 °C.

The global temperature increase projected by 2100 for the scenario RCP8.5 is roughly of the same amplitude, though of opposite sign, as the estimated temperature difference between the pre-industrial period and the Last Glacial Maximum (LGM), 20 000 years ago, i.e., about 4 °C (Stocker et al., 2013). Hence, the magnitude of climatic and environmental changes during the last glacial-to-interglacial transition can provide an index of the magnitude of changes that may occur for a similar warming amplitude in 2100, as already postulated by Nolan et al. (2018). Therefore, we apply the preferred damage functions of BHM and NPS to a global cooling of −4 °C in 2100. This hypothetical glaciation occurring in less than a century remains a theoretical exercise. The growing of large ice sheets for instance requires millennia, not a hundred years. However, as soon as temperature conditions allow snow accumulation and ice building, economic damages would be tremendous even without several hundreds meters of ice. Secondly, the projected rate of global warming according to RCP8.5 is actually faster than any glacial-inter glacial changes that occurred naturally during the last 800 000 years: about 65 times as high as the average warming during the last deglaciation (Nolan et al., 2018). Besides, the level of warming in 2100 for the RCP8.5 scenario might exceed +4 °C, especially if strong positive feedbacks lead to the crossing of planetary thresholds that could drive the Earth in a “hothouse” state (Steffen et al., 2018). Accordingly, using the LGM-to-present environmental changes as an index of future changes could even be considered as a conservative approach.

2 Material and Methods

We compute the evolution of average GDP per capita by country, with or without climate change, following the methodology described in BHM, using the replication data provided with their publication. Details are available therein. We differ from BHM in two ways:

- For the damage function, we use either the BHM formula with their main specification (temperature impacts GDP growth, pooled response, short-run effect) or the preferred formula of NPS (temperature impacts GDP level, best model by K-fold validation, full details in Newell et al. (2018)).
- Our climate change scenario corresponds to a global cooling of $-4\,^{\circ}\mathrm{C}$, based on LGM temperature reconstructions and assuming a linear temperature decrease, instead of the RCP8.5 warming scenario. Similarly as to BHM who consider only temperature projections for their assessment of future climate change damages, we do not use LGM precipitation reconstructions.

The base case of BHM links the population-weighted mean annual temperature to the GDP growth at the country level. Their model takes the following form:

$$\Delta ln(\mathrm{GDP}cap_{i,t}) = f(T_{i,t}) + g(P_{i,t}) + \mu_i + \nu_t + h_i(t) + \epsilon_{i,t},$$

with $\Delta ln(\mathrm{GDPcap}_{i,t})$ the per-period growth rates in income for year t in the country i, $f(T_{i,t})$ a function of the mean annual temperature, $g(P_{i,t})$ a function of the mean annual precipitation, μ_i a country-specific constant term, ν_t a year fixed effect capturing abrupt global events and $h_i(t)$ a country-specific function of time accounting for gradual changes driven by slowly changing factors. They account for precipitation to ensure that the GDP per capita-temperature relationship they are interested in is not actually caused by precipitation, since both variables tend to be correlated, but they do not find a systematic global pattern linking GDP to rainfall. According to their results, temperature effects are much more important and they do not consider precipitation changes in their projections of climate change impacts on GDP per capita.

In their base case, $f(T_{i,t})$ is defined as:

$$f(T_{i,t}) = \alpha_1 \times T_{i,t} + \alpha_2 \times T_{i,t}^2$$

Hence, future evolution of GDP per capita in country i in year t is given by:

$$\mathrm{GDP}cap_{i,t} = \mathrm{GDP}cap_{i,t-1} \times (1 + \eta_{i,t} + \delta_{i,t}),$$

with $\eta_{i,t}$ the country growth rate without climate change according to SSP5 (taking into account population changes), which corresponds to a "business as usual" scenario, and $\delta_{i,t}$ the additional effect of temperature on growth when the mean annual temperature differs from the reference average:

$$\delta_{i,t} = \alpha_1 \times (T_{i,t} - T_{i,ref}) + \alpha_2 \times (T_{i,t}^2 - T_{i,ref}^2),$$

with $T_{i,ref}$ the reference mean temperature of the country (i.e., the average over 1980-2010), $\alpha_1 = 0.0127$ and $\alpha_2 = -0.0005$.

This GDP per capita-temperature relationship is a concave function of $T_{i,t}$, with an optimum temperature around $13\,^{\circ}\mathrm{C}$ (Fig.1). Therefore, for a country with a reference mean annual temperature below this GDP per capita-maximizing value (e.g. Iceland), the annual growth rate increases (resp. decreases) when the mean temperature increases (resp. decreases). This relationship is reversed for countries with a reference temperature above the optimum value (e.g. Nigeria). Note that for countries already close to the optimum temperature (e.g. France), a small temperature change will have a very limited impact on GDP per capita growth, but any major temperature change of several degrees will move them away from this optimum and have a negative impact on GDP per capita growth.

The preferred model of NPS links the mean annual temperature to the GDP per capita level and excludes any function of precipitation:

$$ln(\mathrm{GDPcap}_{i,t}) = \beta_1 \times T_{i,t} + \beta_2 \times T_{i,t}^2 + ...$$

Using this formula, the GDP per capita with climate change, GDP$cap_{i,t}$, is expressed as:

$$\text{GDP}cap_{i,t} = \text{GDP}cap^*_{i,t} \times \exp[\beta_1 \times (T_{i,t} - T_{i,ref}) + \beta_2(T^2_{i,t} - T^2_{i,ref})],$$

with $\beta_1 = 0.008141$ and $\beta_2 = -0.000314$ and GDP$cap^*_{i,t}$ the GDP per capita of the country without climate change, according to SSP5:

$$\text{GDP}cap^*_{i,t} = \text{GDP}cap^*_{i,t-1} \times (1 + \eta_{i,t})$$

The NPS GDP per capita-temperature relationships is also a concave functions of $T_{i,t}$, with an optimum temperature around 13 °C (Fig.1). The shape is therefore similar to BHM, but the function is conceptually different since the impact of temperature is on GDP per capita level instead of GDP per capita growth. The SSP5 growth rate $\eta_{i,t}$ remains unaffected by the climatic conditions and any negative temperature impact on year t has no impact on the GDP per capita level at year $t+1$, which depends only on the SSP5 scenario and the temperature on year $t+1$.

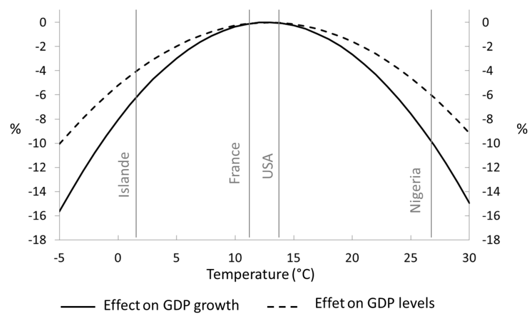

Figure 1: *GDP per capita-temperature relationships, growth (BHM) and level (NPS) effects. The curves are shown on the same plot but are not directly comparable, since their respective impact on GDP is fundamentally different. Vertical lines indicate average temperature for 4 selected countries. Each curve has been normalized relative to its own peak.*

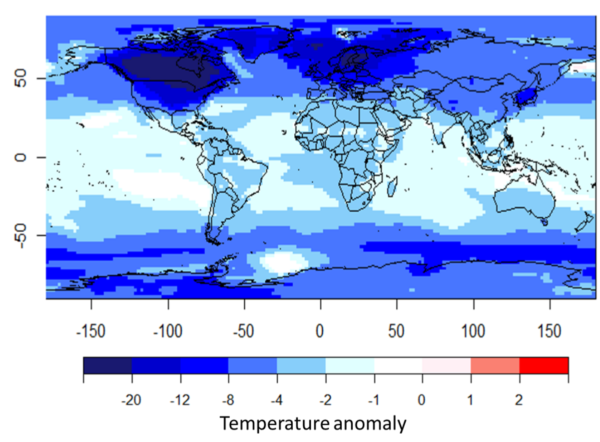

Figure 2: *Reconstruction of the Last Glacial Maximum surface air temperature anomalies (°C) based on multi-model regression. Data source: Annan and Hargreaves (2013).*

To build our "glacial" scenario, we assume a linear decrease in temperature between 2010 (the end of the reference period) and the glacial state projected for 2100. For any year t >2010, the country-specific mean temperature is computed as:

$$T_{i,t} = \Delta T_i \times \frac{t - 2010}{2100 - 2010} + T_{i,ref}$$

with ΔT_i the population-weighted temperature anomaly of country i at the LGM computed from Annan and Hargreaves (2013) (Fig.2) .

Similarly to Burke et al. (2015) who cap $T_{i,t}$ at 30 °C, the upper bound of the annual average temperature observed in their sample period, here we cap the minimum possible value of $T_{i,t}$ at the lower bound of observations (-5 °C).

3 Results and Discussion

All results are expressed as changes of average potential GDP per capita, based on SSP5 and no climate change impacts. According to the NPS damage function, the impact of the temperature decrease on the world GDP is -1.8% in 2100 (Fig.3). 34% countries are poorer in per capita terms than they would be without the glacial climate change, but none is poorer than today. Stronger impacts on GDP, up to -8%, are projected on Northern countries, but these are compensated by increases of 1-2% in Southern countries GDP (Fig.4.a).

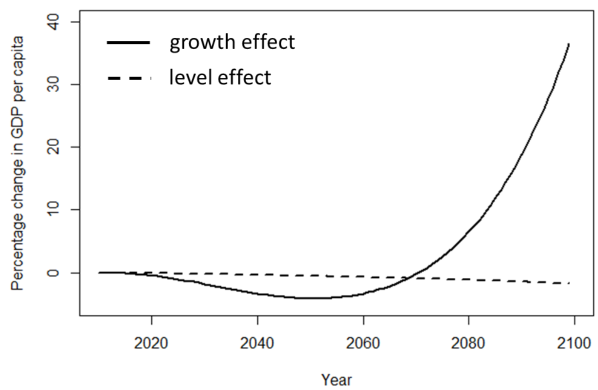

Figure 3: *Percentage change in average GDP per capita (world level) for a global cooling of* -4 °C *in 2100 as projected from non-linear effects of temperature on GDP level (dashed line, Newell et al. (2018) damage function) or growth (plain line, Burke et al. (2015) damage function). Reference GDP path according to the SSP5 scenario.*

With the damage function of BHM, projected impacts are more important, with 31% countries poorer than they would be without climate change and 17% poorer than today. Similarly as with the NPS function, negative impacts are projected in Northern countries and positive impacts in most Southern countries, but at a larger scale (Fig.4.b). Some countries even experience a complete collapse (Fig.5). Negative impacts on Northern countries drive a decrease in the world GDP during the first half of the century, with a minimum of -4% in 2050. In the second half, positive impacts in Southern countries over-compensate impacts in the North and average GDP per capita increases by +36% in 2100 at the world level (Fig.3).

To assess the credibility of these results we now survey the new environmental conditions that human beings would have to face on our planet, taking the LGM as a reference. We acknowledge that for the LGM, ecosystem changes are driven by both climate and CO_2 changes (Jolly and Haxeltine, 1997; Cowling and Sykes, 1999; Harrison and Prentice, 2003; Woillez et al., 2011), but in order to simplify our demonstration we do not distinguish between these two effects in our description of a world cooled by 4 °C. Many reconstructions of the climatic and environmental conditions at that time are available (Kucera et al., 2005; Bartlein et al., 2011; Prentice et al., 2011; Nolan et al., 2018; Clark et al., 2009), as well as numerous modelling studies (Braconnot et al., 2007; Kageyama et al., 2013; Annan and Hargreaves, 2013), for instance within the framework of the Paleoclimate Modelling Intercomparison Project (Kageyama et al., 2018). Despite remaining uncertainties and discrepancies, data-based reconstruction and modelling results provide a fairly good picture of the Earth at that time. For our present purpose, let us assume we have reached the equilibrium and take a closer look

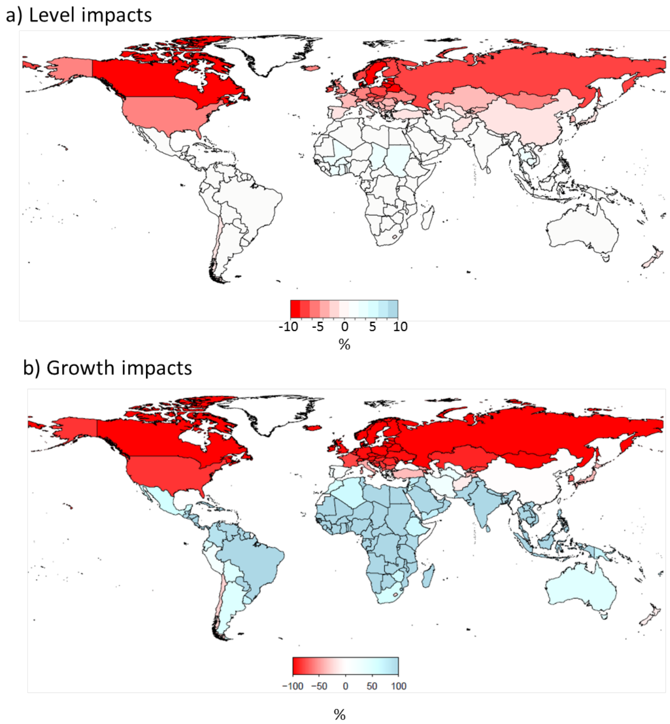

Figure 4: *Projected impacts of a* $-4\,^{\circ}\mathrm{C}$ *global cooling on GDP per capita in 2100. Changes are relative to projections without climate change according to SSP5. a) Changes according to NPS damage function (GDP level effects); b) changes according to BHM damage function (GDP growth effects). NB: color scales have different maximum and minimum values for easier visualization.*

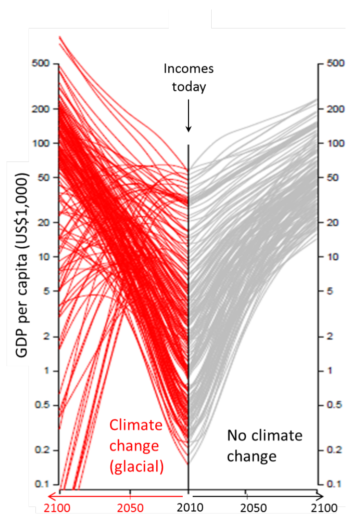

Figure 5: *Country-level average income projections with and without temperature effects of a "glacial" climate change. Projections to 2100 according to SSP5 scenario, assuming high baseline growth and fast income convergence. Centre is 2010, each line is a projection of national income. Right (grey) are incomes under baseline SSP5 assumptions, left (red) are incomes accounting for a non-linear effects of projected cooling on GDP growth.*

at the most obvious consequences for human societies of a -4 °C global cooling.

The most striking feature of the glacial world would be the development of large and thick ice sheets in the North hemisphere (Peltier, 2004; Clark et al., 2009). Canada would be buried under the ice, up to 3-4 km in its central part. Were this to take place today, it would amount to a loss of roughly 2-2.5% of the 2017 world GDP (hereafter GDPw) (not taking into account the externalities induced by the collapse of Canadian trades, the inaccessibility of shale oil and gas, etc.). The Great Lakes region of the United States (app. 5-5.5% of GDPw) and the states Northern of 40 °N on the East coast (at least 0.8% of GDPw) would also be covered by ice. So would be the Scandinavian countries (1.5-2% of GDPw), the North of Ireland and British islands, half of Denmark, the North of Poland and North-East of Germany, Baltic countries as well as the North-East of Russia (at least 1% of GDPw). The Baltic Sea would no longer exist. In Alpine regions, glaciers would cover Switzerland and half of Austria (about 0.9% and 0.2% of GDPw respectively). As mentioned in the introduction section, ice-sheet growing is a slow phenomenon and such ice thicknesses could not be reached within a century. But the conditions for snow accumulation and progressive glaciation in these regions would nonetheless be met, which would be enough to make any significant economic activity dubious. Hence, a rough estimate of the GDP loss due solely to glacial inception is about 11-13% of today's world GDP.

As a consequence of ice storage on land, the global mean sea level would gradually decreases, progressively exposing many continental shelves. At equilibrium, the sea level drop would be -120 m (Yokoyama et al., 2000). The rate would depend on the speed of the ice-sheets and glaciers growing, but it could be fast and ultimately the United Kingdom, Papua New Guinea, Indonesia, Philippines and Japan for example would no longer be islands. Marine activities currently present in these regions would no longer be possible and current worldwide harbor infrastructures would be far from the shoreline. In addition to the problems arising from retreating shorelines, shipping routes in the North Atlantic would be disrupted by the southern expansion of sea-ice up to 50 °N in winter (Gersonde and De Vernal, 2013) and calving icebergs.

In Europe, the mean temperature of the coldest month would decrease by $10 - 20\,°C$ (Ramstein et al., 2007). Forests would be highly fragmented, replaced by steppe or tundra vegetation (Prentice et al., 2011). The Southern limit of the permafrost would approximately reach 45 °N, i.e., the latitude of Bordeaux (Vandenberghe et al., 2014). In such a context, maintaining European agriculture, among other human activities, would be a costly and technically highly demanding challenge. Energy needs for heating would tremendously increase, current infrastructures would be damaged by severe frost and there is no doubt that Europe could no longer sustain its current population on lands preserved from the ice sheets expansion. In Asia, similar problems would occur. The boreal forest would progressively vanished, replaced by steppe and tundra (Prentice et al., 2011). Permafrost would extend in the North-East and North China, as well as in the West of the Sichuan (Zhao et al., 2014). In short, these regions would be about as suitable for humans as present-day Arctic is. It seems fair to us to estimate that this would halve the GDP of these regions, which leads to an additional loss of approximately 15-17% of today's world GDP.

Temperature changes in the tropics would be rather moderate, with a cooling of $2.5 - 3\,°C$ (Wu et al., 2007; Annan and Hargreaves, 2013) (Fig.2). This temperature decrease might be considered as good news, and is indeed the driver of the GDP increase simulated in tropical countries with both damage functions considered here (Fig.3). However, tropical temperature decrease would come with strong changes in the hydrological cycle. The interannual rainfall variability in East Africa would be reduced (Wolff et al., 2011), but so would be the mean rate; the Southwest Indian monsoon system would be significantly weaker over both Africa and India (Overpeck et al., 1996); the Sahara desert and Namib desert would both expand (Ray and Adams, 2001); annual rainfall over the Amazon basin would strongly decrease (Cook and Vizy, 2006). The African humid forest area might be reduced by as much as 74%, and the Amazon forest by 54% compared to their modern extension (Anhuf et al., 2006).

Globally, the planet appears considerably more arid (Kageyama et al., 2013; Ray and Adams, 2001; Bartlein et al., 2011) and dusty (Harrison et al., 2001). Most places would become unsuitable for agriculture and water resources would be largely decreased. Drier regions include currently densely populated areas such as India or Indonesia. Thus, postulating that cooling would provoke a GDP surge in all tropical countries is highly questionable. Let us therefore make the conservative inference that, under our thought experiment, incomes arising from the tropics would remain untouched, assuming that in some places new climatic conditions would indeed be beneficial to some extent for economic activity.

In summary, a global cooling of -4 °C corresponds to strong and widespread changes in climatic conditions, not only temperature, driving major environmental changes (Nolan et al., 2018). According to our back-of-the-envelope estimations, this would induce at least a loss of the order of 26-30% of the world current global income, just by making the locations where this income is produced unsuitable for economic activity. Moreover, growth rates assumed by the SSP5 scenario can no longer be considered as a believable assumption. Thus, we argue that the disruptions in the living conditions on our planet, as briefly described above, cannot plausibly result in a small decrease of 1-2% in the world potential GDP per capita in 2100 as inferred from the NPS damage function. With their specifications, even the Canada experiences only a 8% decrease in its potential GDP per capita, even if it is actually no longer habitable. Such estimations of climate damages remain utterly unrealistic even if we were ready to consider optimistic adaptation skills of human societies, that would prevent them from social calamities such as revolutions, famines or wars. The complete failure of this approach to provide plausible results for a cooling discredits its reliability to account for the impact of a warming.

The BHM damage function gives somewhat more plausible results for Northern countries, with the projection of a complete collapse of their economies. However, we have serious doubts on the large GDP per capita increase in tropical countries given 1) the strong precipitation decrease in many places, threatening water resources and agriculture, that their function fails to capture; 2) the cost of continuously adapting to rapidly changing conditions; 3) the worldwide geopolitical consequences of a complete collapse of (at least) the Northern states. It is difficult to imagine how the world could nonetheless be wealthier than it is now; especially if most places are no longer suitable for agriculture, as it may have been the case during the Pleistocene (Richerson et al., 2001). Agriculture may account for only a few percentages GDP in present-day developed countries, but food production is obviously the first need of any society.

4 Conclusions

Whether temperature changes impact the GDP *growth* or *level* is actually a debate of little relevance. Statistical approaches based on the last decades of temperature and GDP measures cannot accurately account for the impact of large temperature changes outside their calibration range. Nor can they account for the impact of major shifts in seasonality, extreme events, climatic variability and induced shifts in ecosytems compositions, threatening ecosystem services (Reid et al., 2005) as illustrated here. Moreover, they are based on economic data from societies adapted to their current environment. The assumed statistical relationship between GDP per capita and temperature is established for stable conditions and is therefore hardly relevant to assess damages on societies who will experience decades of changing climate and ecosystems and will have to re-adapt endlessly to ephemeral new living conditions.

Should the GHG emissions continue unabated, the climate change expected for the end of the century will be of similar magnitude than the last deglaciation, which did not occurred in a century but in about 10 000 years. Such a change has no equivalent in the recent past of our planet, even less in human history. Trying to establish a robust assessment of future economic damages based on a few decades of GDP and climate data is probably doomed to failure. Such methodologies are irrelevant for what lies ahead. A more modest ambition should be shown by integrated assessment scenarios, namely that of estimating an educated guess on the lower-bound of such damages at regional scales, where the uncertainty surrounding prospective estimations may be more easily dealt with. And these guesses should definitely be consistent with the future described by climate and ecological sciences (Stocker et al., 2013).

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