Zenon Research

RESEARCH NOTE

TOO HOT TO GROW

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The context

As a result of the massive release of greenhouse gases into the atmosphere caused by human activities, the average global temperature is about 1°C higher today than what it was during the preindustrial era[1]. Present and future emissions will cause further global warming, with an amplitude which will depend on the strength of the global effort to reduce emissions and, ultimately, to become carbon neutral[1].

While the signatories of the Paris Agreement have pledged to limit global warming to well below 2°C, pursuing efforts to limit it to 1.5°C, scenarios with no additional effort would put the world

on track for an increased temperature of around 3°C to 4°C above preindustrial levels by the end of this century[1].
Because of its speed and magnitude, climate change could have serious adverse effects, such as excessively high humidity and temperature making large regions on Earth uninhabitable[2,3], sea-level rise[1], more frequent and extreme weather events[1], and large reductions in biodiversity[4]. While all these effects will certainly have an impact on human societies in one way or another, there is no consensus on what the implications on the world economy will be.

Modelling the economic impact of climate change

Efforts to quantify economic damage due to climate change really started with the development of integrated assessment models (IAMs), among which the most famous is the DICE model developed by William Nordhaus[6]. These models try to combine an economic framework with a description of the climate evolution: economic activities produce greenhouse gases that affect the global climate, which in turn affects the economy.

IAMs are meant to provide policy-makers with quantitative arguments. DICE has been used for example to perform cost-benefit analyses of the effect of climate change on the economy, notably to determine what is known as the social cost of carbon. For its development, William Nordhaus was awarded the 2018 Nobel Memorial Prize in Economic Sciences.

Breakpoints are found from 3°C to 5°C, depending on the model considered. When they are reached, damage on growth suddenly increases, so that recession occurs shortly afterwards.

The DICE model, however, has been criticised for being too optimistic[7,8]. Indeed, a relatively modest -8% of income is reported at 6°C of warming[9]. This can be questioned by the fact that such a level of warming is associated with substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year[1].

The damage function jungle

The economic impact of global warming is typically modelled in the form of a damage function that relates economic losses to a climate variable, usually the average global surface temperature change[5,10]. In most cases, losses are expressed as a fraction of a baseline GDP

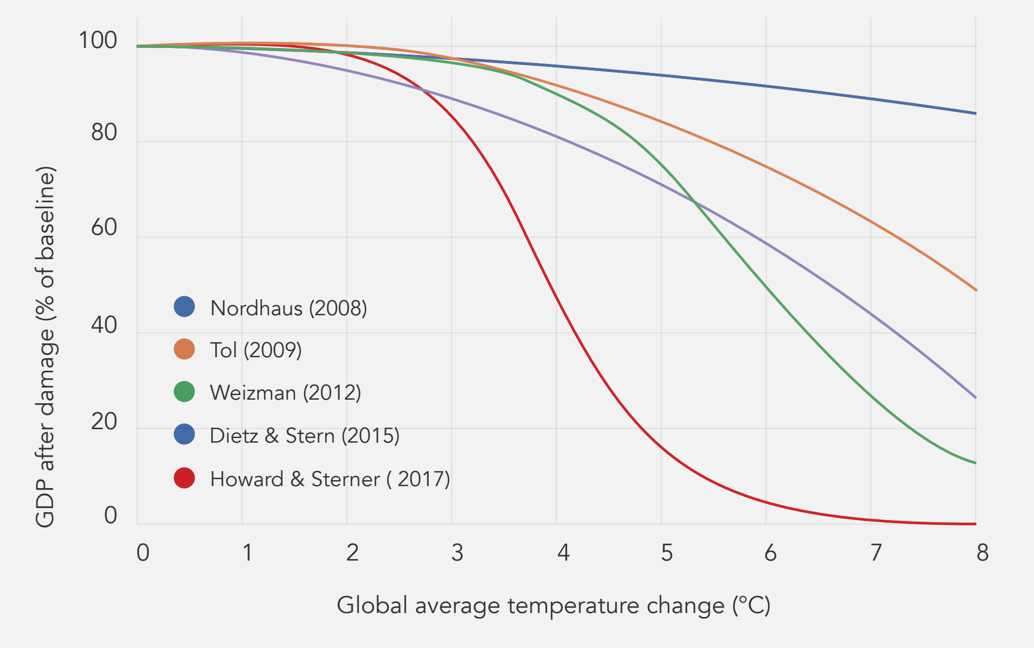


Figure 1. Comparison of several damage functions from the literature. The remaining fraction of the baseline GDP (no climate change) decreases as the global average temperature increases. The expected GDP values at +8°C range from nearly zero to about 90%. This highlights that damage estimates are subject to a large degree of uncertainty, especially for high warming levels.

for which no climate change is assumed. Various damage functions can be found in the literature, as illustrated in Fig. 1.

They differ in their mathematical form, the method used to derive them, and their predicted impact. They can be based either on an "enumerative" or a "statistical" approach[11]. In the first case, they add up the costs of impacts valued separately sector by sector, while, in the second, they extrapolate the overall effect of historical temperature variations on the economic activity. In both cases, their calibration is critical, albeit marred by considerable uncertainty[5].

The mathematical form of the damage function also has a strong influence on the extrapolation of high temperature increases which, moreover, cannot be limited to historical records.

In practice, many damage functions have a quadratic form[5]. This has been criticised for strongly underestimating damage at high warming levels. Martin Weitzman, for example, had suggested that a higher order polynomial should be used instead, so that the world GDP converge to zero past a certain warming level[7].

Another limitation is that, whatever their order, polynomial functions and other smooth functions exclude thresholds and tipping points, while climate change is known to be an inherently discontinuous process[12–14]. Only few works make use of alternative forms, such as piecewise linear functions[15–17].

Climate damage on growth

Seminal works considered damage on the total level of GDP in a particular year, after which the economic output returns to its original trajectory. In doing so, they assumed that the GDP growth rate is left essentially unchanged.

This is of course questionable since level effects, even when they are intentionally increased well beyond realistic values, never cause the economy to contract[18].

As a consequence, interest has been shifting to effects on growth[18–22]. Contrary to level effects, they compound over time, leading to much larger predicted impacts. This approach has been debated among the economic community[23], but there is however empirical evidence that temperature does affect economic growth, as econometric studies of past heat waves reveal[16,22,24].

By altering productivity, climate change may be able to damage economic growth in the long run. It is therefore interesting to explore to what extent and, notably, to investigate if a global recession can occur due to climate damage. Even if negative growth alone is not enough to speak of a recession[25], nor to necessarily imply a decrease in social wellbeing[26], we will consider this criterion based on its strong symbolic impact[27]. It should be mentioned that, in contrast with past business cycles, a climate-driven recession might last for a long time, as damage accumulates while temperature rises.

Compared to traditional, time-limited shock responses, we believe this offers an innovative view on what could be the long-term impact of the global temperature increase on the world economy.

Exploration

In order to explore the possibility of a climate-driven recession, we choose to consider damage functions defined by their additional effect on GDP annual growth rate, rather than by their multiplicative effect on GDP total level:

$$Y_{t+1} = (1 + g_{Yt} + d(\Delta T_t))Y_t$$

where the world GDP Y_{t+1} in future year $t+1$ is deduced from the world GDP Y_t in year t, the baseline level of annual growth rate g_{Yt} (with no climate change) and the level of damage d associated with the global average temperature change ΔT_t in year t, with respect to preindustrial levels.

This definition considers global average temperature changes as a proxy for other effects, including heterogeneously distributed ones such as extreme events and sea-level rise. This is of course a major simplification given the complexity of the climate system. Likewise, ex-post damage on growth is given without focusing on the mechanisms by which capital, labour and productivity are affected.

As a matter of fact, contrary to detailed and comprehensive models including regional or sectoral impacts, we purposefully keep our analysis at a very general level as we want to explore long-term trends, and especially whether or not a climate-driven global recession can occur.

Key Highlights

There is considerable debate about the economic impact of climate change. While seminal works reported modest effects on the total GDP level, focus is now shifting to effects on growth.

As part of its work on quantifying hard limits of the future, *Zenon Research* combines three existing studies to explore if climate-related deterioration may cause a global recession.

This approach highlights the existence of a warming threshold, mainly due to tipping points in the relationship between damage and temperature.

Breakpoints are found from 3°C to 5°C, depending on the model considered. When they are reached, damage on growth suddenly increases, so that recession occurs shortly afterwards.

On the world's current weak mitigation pathway, a global, climate-driven recession is possible by the end of this century.

How to calibrate the damage functions?

As noted earlier, the calibration of the damage functions is critical. For a given temperature increase, significantly different impacts are expected depending on the study considered (Fig. 1). To take the main limitations previously mentioned into account, we choose to build on the work of Marshall Burke and his team, which extrapolates the effect of average temperature variations on growth in GDP into the future, from the annual records of 165 countries for the period 1960 to 2010[28]. We also choose their recent work based on econometrics since older studies were shown to have a significantly downward bias[5].

The paper from Burke et al. also reports impacts within the framework of the Intergovernmental Panel on Climate Change (IPCC), therefore enabling us to use the detailed macroeconomic projections from the SSP Database[29,30] to derive the baseline GDP growth rate g_{Yt} in our model. In particular, they report damage estimates up to the end of the century for all shared socioeconomic pathways (SSPs), the set of alternative scenarios for which key data are available regarding demographics, economy, policies, technology, environment and natural resources[31].

For each scenario, we find that the definition of the damage functions we use is able to reproduce the projected change in global GDP when assuming that the level of damage on growth d is simply a linear function of the global average temperature change ΔT_t.

This implies that the results from Burke et al. on *level* can be used to calibrate our damage functions on *growth* for moderate warming levels. In the following, we will use the mean of the five SSPs when no specific scenario is mentioned, as we find that this changes our results by less than 0.1%. Even if it is associated with no SSP narrative, the mean of the scenarios appears to be close to SSP2 ("middle of the road") until mid-century and then closer to SSP1 ("sustainability"). It may then represent a mixed storyline.

It must be noted that a single calibration based on the results of Burke et al. would likely underestimate damage for extreme warming levels. Indeed, it reduces total GDP by only around 60% at +12°C while it has been shown that such a global average temperature change would render most of the Earth uninhabitable[2], which may translate into a world GDP reduced close to zero[7]. This is because about 95% of the past annual temperature variations have an amplitude of less than 1°C above the mean[22]. Their extrapolation must therefore be limited to moderate warming levels.

Martin Weitzman uses the converge to zero argument to recalibrate the DICE model for extreme warming, assuming 50% and 99% discounts at +6°C and +12°C, respectively[7]. Another calibration of the same damage function was proposed by Simon Dietz & Nicholas Stern, assuming a 50% decrease at +4°C based on the possible crossing of several climate tipping points at such a warming level[32]. Since this latter work has been criticised as being a pessimistic outlier[33], it may provide a suitable basis for estimating an upper limit on damage levels.

These two damage functions are shown in Fig. 1. We find that their tails, i.e., when damage exceeds 50% of the baseline GDP, are well reproduced by the definition of the damage functions we use, with d and ΔT_t again linearly related.

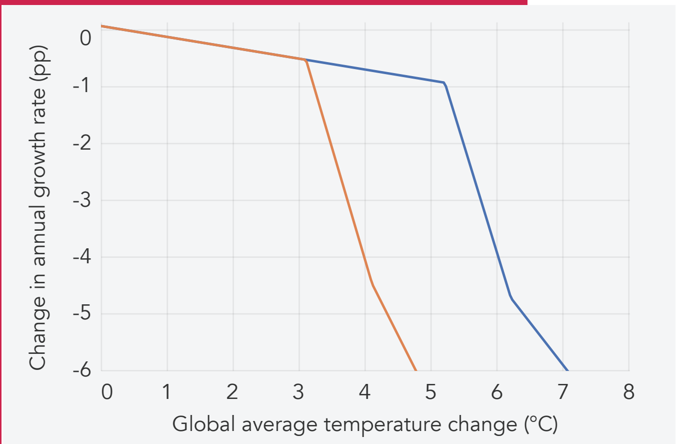
Building unified damage functions

We aim to build a unified model describing both low and high temperature increases. All three damage functions we consider are well reproduced by a linear damage model affecting growth, but with different slopes. Thus, the simplest approach to unify them is to build piecewise linear functions. This allows us to obtain damage functions defined on the entire temperature interval we consider (0-12°C).

We find that simple functions made with two linear pieces, the first one based on Burke et al. (B) for low temperature increases, and the other based either on Weitzman (W) or Dietz & Stern (DS) for high temperature increases, do not satisfactorily reproduce the calibration dataset, except if a third segment is added to properly connect both regimes.

The third linear piece is centred on the temperature at which both damage functions intersect, and we set its length at one degree. We name the two resulting functions BW and BDS, respectively (Fig. 2).

The first two linear pieces join at a breakpoint, which is at about 3.1°C for BDS and 5.2°C for BW (Fig. 2). The breakpoints in the damage functions are consistent with the fact that there is no obvious reason for damage to stay smooth across a wide temperature range. They may be interpreted as the mathematical representation of possible tipping points in the climate system. Indeed, they occur at temperatures typically in the range where abrupt and irreversible changes have a high risk of happening[14].



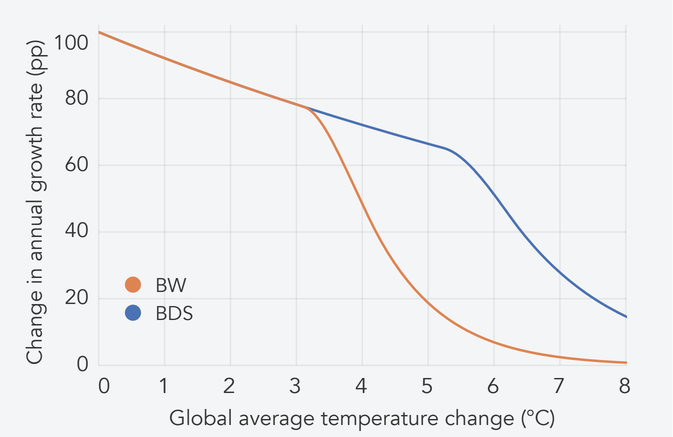


Figure 2. Top: Additive, piecewise linear damage functions on growth calibrated on the damage reported by Burke et al. for limited temperatture change, and either on Weitzman (BW) or on Dietz & Stern (BDS) for high warming levels. Bottom: Associated changes in global GDP derived from the damage on growth applied to the mean baseline GDP growth rate from the SSP Database. The tails reproduce the damage functions shown in Fig. 1.

Is a climate-driven recession possible?

The two functions we build can be used to investigate the possibility of a climate-driven global recession by comparing the level of damage d to the baseline GDP annual growth rate g. Recession occurs in a model when $g_{Yt} + d(\Delta T_t) < 0$.

While the world GDP has exponentially grown at about 3% each year over the past decades, the SSP long-term GDP projections foresee an impending slowdown, with annual growth rates ultimately decreasing to around 1% in 2100. Since temperature increases with time while growth slows down, a recession becomes more and more likely over time.

As a consequence, the possible occurrence of a recession depends not only on the global average temperature change, but also on the future evolution of the world GDP which is obviously uncertain. For instance, the projected annual growth rate in 2100 ranges from 0.62% in SSP4, to 1.50% in SSP5[30].

As a preliminary estimate, we show possible evolutions of the world GDP annual growth rate under different warming scenarios (Fig. 3). We assume that the global temperature increase is a linear function of time, starting from 0.8°C in 2012 to three different values ΔT_{2100} in 2100, and continuing beyond.

We consider an exponential decay model based on the mean of the five SSP projections as our baseline g_{Yt}. It is consistent with current short-term projections in which global growth is expected to gradually slow down to about 3.3% by 2026[34]. Beyond, it is obviously subject to very large uncertainties[30].

As shown in Fig. 3, we find that damage could be of a few tenths of a percentage point every year even if global warming is kept well below 2°C as pledged under the Paris climate agreement. For stronger warming levels, tipping points may be reached, implying a much more severe impact on growth at the end of the century or shortly after.

Strictly speaking, the occurrence of a climate-driven recession depends not only on the damage severity, but also on the baseline level of GDP growth.

Our upper limit estimate, the BDS model, shows that a temperature increase of 3°C or more may lead to a global recession before the end of this century (4°C), or shortly after (3°C). In the BW model, which is more conservative, no recession is found by 2100, even when reaching 4°C above preindustrial levels. However, if warming is not mitigated after 2100, a recession remains possible even with this model in the first half of the next century.

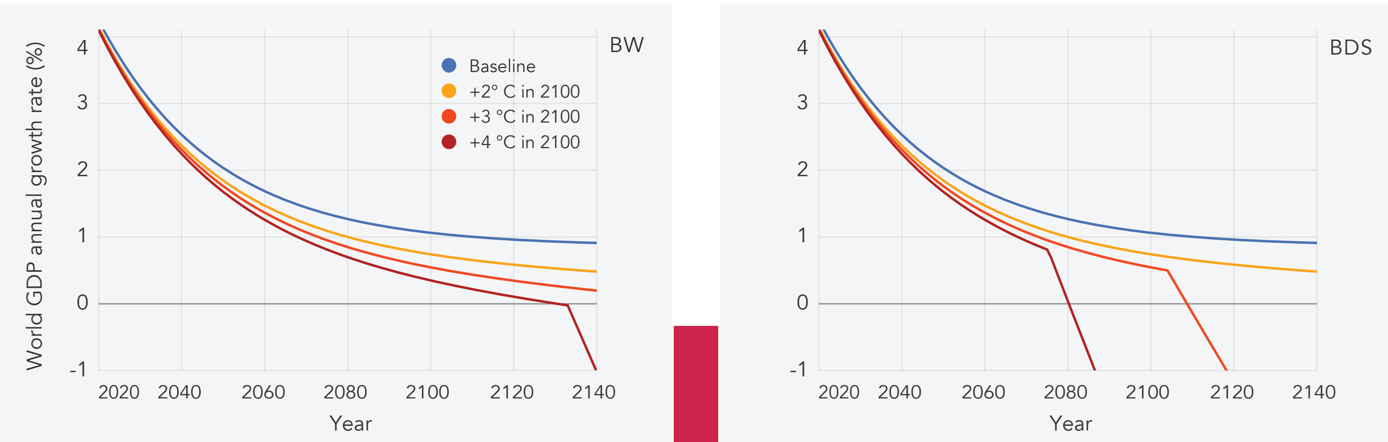


Figure 3. Left: Projections of the world GDP annual growth rate under three different warming scenarios, relative to preindustrial levels, with damage estimated by the BW model. Right: Same figure with the BDS model. The baseline projection (blue line) is based on the mean baseline GDP growth rate from the SSP Database fitted by an exponential decay model. Temperature increases are assumed to be linear with time.

Strictly speaking, the occurrence of a climate-driven recession depends not only on the damage severity, but also on the baseline level of GDP growth.

As the SSP long-term GDP projections expect the global economy to slowdown in all scenarios, a recession becomes more likely to occur as time goes by, even in moderate warming projections. But more importantly, our piecewise models show that recession essentially occurs when a breakpoint is reached, and then damage becomes so significant that the baseline growth level has virtually no more impact. Avoiding abrupt and irreversible changes is therefore pivotal.

Linking climate and economy

The three warming scenarios we present are based on ad hoc values of the temperature change ΔT_{2100} in 2100 that are fixed independently of the level of economic growth. However, in reality, the global average temperature evolution depends on the level of economic activity through greenhouse gas emissions, as recently reminded by the COVID-19 pandemic[35]. Pushing our analysis forward requires taking this relationship into account.

This can be achieved by using the set of nine SSP-RCP combinations considered in the Scenario MIP project[36]. In this framework, the existing SSPs are combined with greenhouse gas emission scenarios, namely representative concentration pathways (RCPs).

Each RCP is given a label based on the value it assumes for the net change in the energy balance of the Earth system by 2100, relative to 1750, expressed in watts per square metre (e.g., 6.0 W/m^2 for RCP6.0). A useful rule of thumb to keep in mind is that, when emissions stabilise, every watt per square metre gained will roughly lead to a 1°C global temperature increase by the time the climate system readjusts to radiative equilibrium[37].

We choose to focus on three combined SSP-RCPs: SSP3-7.0, which represents an unmitigated baseline scenario leading to +4°C in 2100, and much more beyond that; SSP1-1.9, which best reflects the Paris Agreement's temperature goal, with a likely probability of staying below 1.5°C in 2100; and SSP4-3.4, which is of interest as an intermediate mitigation trajectory allowing the world to stabilise around 2°C above preindustrial levels[36].

Each scenario is provided with the global growth rate g_{Yt} and the global average temperature change ΔT_t for every year t until 2100. Thus, the temperature evolution with time is also more realistic than when it is assumed linear, especially for moderate warming levels (Fig. 4).

The damage functions BW and BDS are used to determine two alternative levels of damage d from ΔT_t. Their negative outputs are then added to g_{Yt} to obtain damaged growth values (Fig. 4).

We find that the two functions give similar results for SSP1-1.9 and SSP4-3.4, since no tipping point is reached. As our preliminary analysis suggests, global growth is reduced by a few tenths of a

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percentage point every year, and even by half by 2100 in SSP4-3.4, i.e., 0.3% instead of 0.6%.

More worrying is the SSP3-7.0 scenario, in which the global average temperature reaches 4°C above preindustrial levels in 2100. At this level, the global economic growth is low, but still positive in the BW model (+0.2%), while the BDS model shows a possible recession starting several decades before, around 2075. Growth is projected to decline down by 3% per year in 2100 in this model.

Unlike classic shock models that expect growth to rapidly return to its original trajectory after a single-year shock, climate-related damage worsens as temperature goes on increasing, making a rapid offset of their adverse effects less likely.

Of course, the values we report are not a description of what will happen, but rather a simplified exploration of the possible effects on growth of climate change. A more detailed economic modelling would be required to confirm these findings and take feedback mechanisms into account, such as the implementation of recovery policies. Nonetheless, both our BW and BDS models confirm that climate-related damage can significantly hamper economic growth by the end of this century.

Depending on the extent of the damage, which is unfortunately impossible to foresee so far, a climate-driven structural recession is even possible in the latter half of this century if the world continues on its current weak mitigation trajectory, as other recent works also anticipate[38,39].

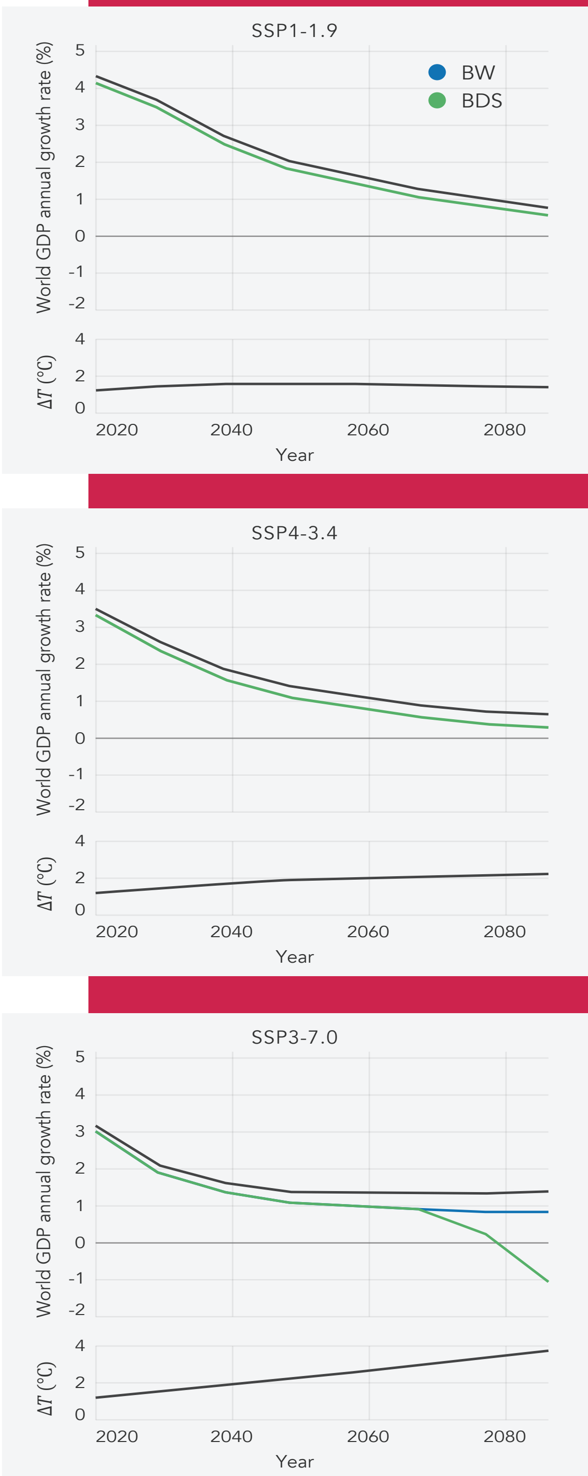
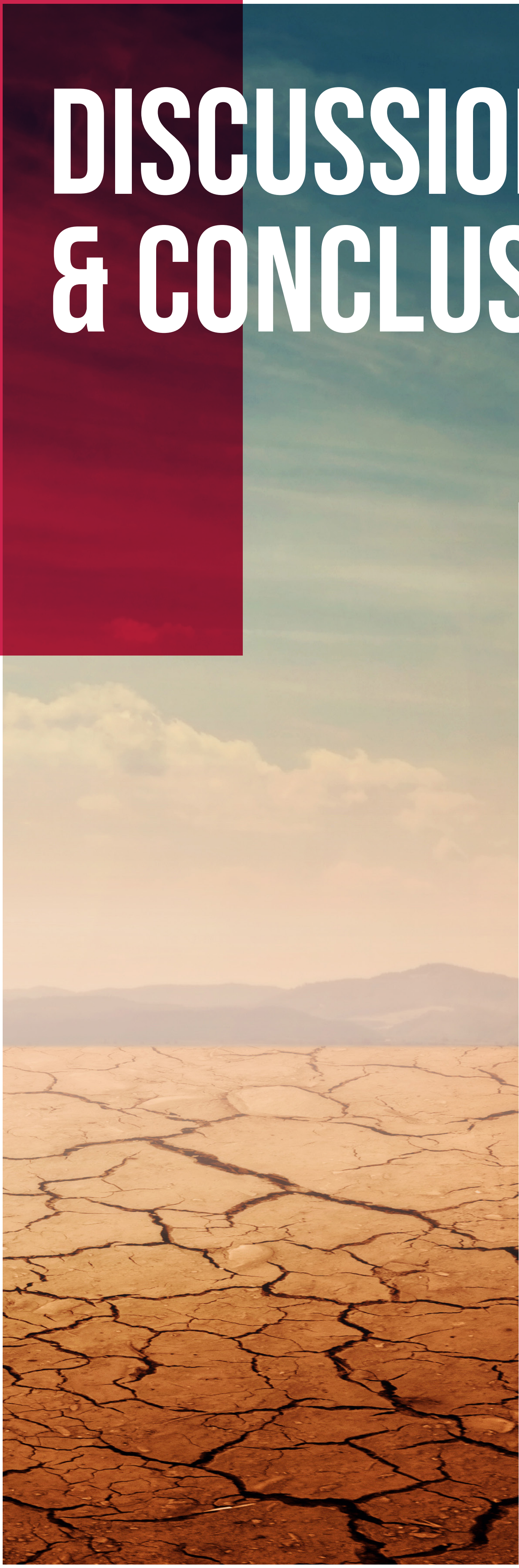


Figure 4. Possible evolutions of the world GDP annual growth rate under SSP1-1.9 (top), SSP4-3.4 (middle) and SSP3-7.0 (bottom) scenarios. Black lines show the baseline projections. Solid coloured lines show the damaged growth rates given by our piecewise damage functions BW (blue) and BDS (green). For SSP1-1.9 and SSP4-3.4, the blue line is not visible as both lines are overlaid on each other. The associated average surface temperature change (°C) relative to preindustrial levels is displayed under each plot.

DISCUSSION & CONCLUSION



This research note features a high-level approach to explore if global warming can cause a global recession. It makes use of the standard framework in which climate-related effects aggregate in a so-called damage function, a simplified formulation of economic damage relative to a baseline scenario in which the Earth's climate is kept unchanged.

The damage functions we consider here are additive, continuous piecewise linear functions applied to the world GDP annual growth rate rather than more current multiplicative, polynomial functions, applied on the GDP total level. This is not only because we focus on the effects on growth, but also because there is growing empirical evidence that temperature does affect economic growth.

In order to reconcile small impacts of moderate warming with potential catastrophic changes expected for extreme levels of warming, we propose two alternative calibrations, each based on two existing studies. In both cases, the work of Burke et al. is used for limited temperature rise, as it extrapolates the effect of average annual temperature variations on the growth of GDP into the future. For higher warming levels, the two alternative calibrations we use are extensions of the famous DICE model taking account of possible tipping points in the climate system.

The combination of these three existing studies results in two alternative models, BW and BDS. They provide constraints that we believe are more plausible than previous studies known to have a downward bias[5,8,18], albeit the three studies we use have also been criticised for being too pessimistic[23,33].

However, using more optimistic estimates like DICE, would make little sense here, precisely because they assume by construction that the growth rate of the global economy is virtually never reduced by climate change.Breakpoints are created by the connection of calibrations based on distinct warming levels. They correspond to temperature increases of 3.1°C for BDS and 5.2°C for BW. Interestingly, these values are typically in the range where abrupt and irreversible changes in the climate system have a high risk of happening[14].

When such tipping points are reached, damage increases all of a sudden, and it seems that a recession is bound to follow shortly afterwards, whatever the baseline growth level. In SSP3-7.0, the global average temperature is 4°C above preindustrial levels in 2100. By this time, the BW model gives a slightly positive growth value (+0.2%) while the more pessimistic BDS model shows a possible recession starting several decades before, around 2075.

When such tipping points are reached, damage increases all of a sudden, and it seems that a recession is bound to follow shortly afterwards, whatever the baseline growth level.

Our BW and BDS models show that growth could also be significantly hampered *before* reaching tipping points. For instance, the world average annual growth rate in 2100 may be half the baseline level in SSP4-3.4, i.e., 0.3% instead of 0.6%, even if global warming is limited around 2°C.

Unlike classic shock models that expect the economy to rapidly recover after a limited period of negative growth, climate-related damage worsens as temperature increases, making a rapid offset of their adverse effects less likely. As a consequence, a climate-driven recession may greatly differ from past economic crises. This emphasises that quickly addressing climate change could not only preserve the total level of economic output compared to a baseline scenario, but also prevent the world from entering a deep, structural economic recession.

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About Zenon Research

Zenon Research is a think tank whose mission is to highlight the key factors leading to changes in the long-term future.

When it comes to the future, the best we can do is to define scenarios and study their respective likelihood. In a constrained world, it is essential to separate plausible scenarios from what will remain in the realm of science-fiction.

Our aim is to estimate hard limits and boundaries within which possible futures can happen. With this approach, we help decision-makers on vision and planning.

Zenon Research produces original works with a cross-disciplinary approach in the form of white papers, reports, and videos for the general public.

Our approach is pragmatic and combines science and economics, as we believe that both economic and technical aspects are key driving forces shaping the future.

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