LETTER • OPEN ACCESS

Quantifying uncertainty about global and regional economic impacts of climate change

To cite this article: Jenny Bjordal *et al* 2022 *Environ. Res. Lett.* **17** 094020

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Quantifying uncertainty about global and regional economic impacts of climate change

Jenny Bjordal[1,*] , Trude Storelvmo[1,2] and Anthony A Smith Jr[3,4]

1 Department of Geosciences, University of Oslo, Oslo, Norway
2 Nord University, Bodø, Norway
3 Department of Economics, Yale University, New Haven, CT, United States of America
4 National Bureau of Economic Research, Cambridge, MA, United States of America
* Author to whom any correspondence should be addressed.

E-mail: jenny.bjordal@geo.uio.no

Abstract

The economic impacts of climate change are highly uncertain. Two of the most important uncertainties are the sensitivity of the climate system and the so-called damage functions, which relate climate change to economic costs and benefits. Despite broad awareness of these uncertainties, it is unclear which of them is most important, especially at the regional level. Here we construct regional damage functions, based on two different global damage functions, and apply them to two climate models with vastly different climate sensitivities. We find that uncertainty in both climate sensitivity and aggregate economic damages per degree of warming are of similar importance for the global economic impact of climate change, with the decrease in global economic productivity ranging between 4% and 24% by the end of the century under a high-emission scenario. At the regional level, however, the effects of climate change can vary even more substantially, depending both on a region's initial temperature and the amount of warming it experiences, with some regions gaining in productivity and others losing. The ranges of uncertainty are therefore potentially much larger at a regional level. For example, at the end of the century, under a high-emission scenario, we find that India's productivity decreases between 13% and 57% and Russia's increases between 24% and 74%, while Germany's change in productivity ranges from an increase of 8% to a decrease of 4%. Our findings emphasise the importance of including these uncertainties in estimates of future economic impacts, as they are vital for the resulting impacts and thus policy implications.

1. Introduction

Future projections of the economic impacts of climate change are highly uncertain. On the climate side, the most important uncertainty is how sensitive the climate system is to increasing amounts of greenhouse gases. On the economic side, the most important uncertainty is the relationship between climate change and economic impacts, often expressed in models by so-called damage functions. Globally, these two uncertainties have been assessed previously (Hassler *et al* 2018), but how do the uncertainties vary between regions when assessing the economic impacts of future climate change?

A standard measure of how sensitive the climate is to greenhouse gas emissions is the equilibrium climate sensitivity (ECS) (IPCC 2013). This is how much the global mean surface air temperature will eventually increase when the amount of atmospheric CO_2 is doubled. Even after decades of research, the ECS is uncertain, likely within the range 2.5 °C–4 °C, and very likely within 2 °C–5 °C (Forster *et al* 2021). Among the newest generation of climate models, however, there are several models with ECS above 5 °C (e.g. Zelinka *et al* 2020). The validity of these high-sensitivity models is debated (Tokarska *et al* 2020, Hausfather *et al* 2022), yet they cannot be ruled out and provide a low-likelihood, high-impact case

(Forster *et al* 2021) that is of interest when looking at the uncertainty. Since economic impacts of climate change are currently mostly calculated from temperature (van Vuuren *et al* 2012), it is important to understand the implications of this uncertainty.

In economics, integrated assessment models (IAMs) for climate and economy are essential tools for simulating the economic impacts of climate change (see e.g. Nordhaus 1992, Ackerman *et al* 2009, Weyant 2017). Cost-benefit analysis (CBA) IAMs link climate and the economy by expressing changes in economic productivity (or economic damages) as a function of the climate state, typically represented by surface air temperature. This link—the damage function—is an aspect of IAMs that has been criticised for being particularly uncertain (see e.g. Ackerman *et al* 2009, Weitzman 2010, Diaz and Moore 2017, Howard and Sterner 2017), yet it is a crucial part of assessing the impacts of climate change.

A key innovation in the present work is that we study the spatial distribution of damages arising from future climate change. Damage functions have typically been applied to the global mean temperature (e.g. Weitzman 2012, Nordhaus 2018) or to the temperature of a few, large regions (e.g Nordhaus and Yang 1996, Hope 2011, Anthoff and Tol 2014). Here, we ground estimates of regional damages in well-established global (or aggregate) damage functions. We construct four new regional damage functions based on two global damage functions and two different spatial distributions of warming, as simulated by Earth System Models (ESMs) with vastly different climate sensitivity. We use these regional damage functions to quantify how uncertainty about the degree of regional warming and the shape of global damage functions generates, in turn, uncertainty about the spatial distribution of damages across regions. While the method for constructing the regional damage functions follows Krusell and Smith (2022), here we apply it in a novel way to assess the degree of uncertainty about regional damages, a key input into policy discussions about climate change.

2. Method

Our purpose is similar to that of Zheng *et al* (2020) in applying regional damage functions to output from climate models in order to assess the spatial distribution of economic impacts from climate change. Instead of focusing on the current effect of aerosols, however, we investigate instead the future economic impacts of climate change and the uncertainty about them. There are many uncertainties about the economic impacts of climate change (e.g. the carbon cycle, mitigation costs, discounting, etc) but here we focus on climate sensitivity and the aggregate damage function, which are identified as two of the most

important ones (see e.g. Weitzman 2010, Sherwood *et al* 2020). We thus employ data from two climate models that span most of the uncertainty in climate sensitivity, and estimate regional damage functions from two global damage functions with very different economic impacts. All four combinations are applied to four different future scenarios for greenhouse gas emissions.

2.1. Climate model data and scenarios
We used data from a high-sensitivity model, the Community Earth System Model version 2 (CESM2, ECS = 5.3 °C) (Danabasoglu *et al* 2020), and a low-sensitivity model, the Norwegian Earth System Model (NorESM2, ECS = 2.5 °C) (Seland *et al* 2020). Both participate in the 6th phase of the Coupled Model Intercomparison Project (CMIP6) (Eyring *et al* 2015, x), and together the two models span most of the ECS interval of 1.8–5.6 °C found in CMIP6 (Zelinka *et al* 2020).

Specifically, the climate model data we used is the surface air temperatures from four future emission scenarios used in CMIP6, namely SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (see table 1 for details). These are created as combinations of shared socioeconomic pathways (SSPs) and end of century forcings (O'Neill *et al* 2016, Riahi *et al* 2017), and are named using two numbers, where the first refers to the SSP or narrative (evolution of society and natural systems) (O'Neill *et al* 2014), and the second refers to the radiative forcing at the end of the century (Moss *et al* 2010). Generally, lower (higher) numbers refer to lower (higher) emissions, and thus a lower (higher) temperature increase. Since our base year is year 2000, and the scenarios go from 2015 to 2100, we supplemented years 2000–2014 from runs with historical emission.

2.2. Damage functions and economic impacts
Here, we outline the construction of our regional damage functions.

2.2.1. Global damage functions
Total factor productivity (TFP), a measure of the productivity of a set of factors of production (such as physical capital and labour) taken as a whole, is important in CBA. IAMs typically incorporate global (or aggregate) economic damages from climate change as a reduction in global TFP. These damages can therefore be expressed as a fraction of global gross domestic product (GDP), holding fixed productive inputs such as capital and labour, that varies with the change in global temperature. Here, the temperature change (ΔT_t) is the change in global surface air temperature between the pre-industrial period and year t.

The economic damage, $\pi(\Delta T_t)$, is typically represented by an increasing convex function with

Table 1. Summary of the four future scenarios employed in this study. The narrative refers to what kind of world the scenario reflects, with indication of the mitigation and adaptation challenges. The 2100 forcing gives the perturbation to Earth's radiative balance at the end of the century under the scenario, and the pathway explains how the forcing evolves throughout the century.

Scenario name	Narrative/shared socioeconomic pathway	2100 Forcing (W m^{-2})	Pathway of forcing
SSP1-2.6	SSP1: Sustainability (Low challenges to mitigation and adaptation)	2.6	Peak and decline
SSP2-4.5	SSP2: Middle of the Road (Medium challenges to mitigation and adaptation)	4.5	Stabilising
SSP3-7.0	SSP3: Regional Rivalry (High challenges to mitigation and adaptation)	7.0	Rising
SSP5-8.5	SSP5: Fossil-fuelled Development (High challenges to mitigation, low challenges to adaptation)	8.5	Rising

the following functional form (see e.g. Dietz and Stern 2015):

$$\pi(\Delta T_t) = \frac{\phi(\Delta T_t)^2}{1 + \phi(\Delta T_t)^2}, \qquad (1)$$

where ϕ is a coefficient chosen to match estimates of aggregate damages from global warming. A change in the global temperature from T_t to T_{2000} would therefore lead to a percentage change in global TFP (and hence global GDP, holding inputs fixed) given by:

$$D(T_t) = \left(\frac{1 + \phi(T_t - T_{1850})^2}{1 + \phi(T_{2000} - T_{1850})^2} - 1 \right) 100, \qquad (2)$$

where T_{2000}, T_{1850} and T_t is the global mean surface air temperature in years 2000, 1850 (pre-industrial), and t, respectively.

The damage function developed by Nordhaus (Nordhaus 1992, 2018) is one of the most commonly-used damage functions and sets $\phi = 0.0028388$ (see blue line in figure 1). Like many other damage functions, the Nordhaus damage function is only based on estimates of damages up to 3 °C (Tol 2011, Stern 2013), and is strictly speaking not valid for higher temperature increases. Yet, it is frequently used at higher temperature changes, and criticised for being too optimistic, in that it may underestimate damages at large temperature increases (Stern 2013, Revesz *et al* 2014). Since the Nordhaus damage function is known for having low damages we use this as our low-sensitivity damage function.

Another, more sensitive, damage function is the one estimated by Howard and Sterner (2017), which sets $\phi = 0.0100380$ (see orange line in figure 1). We use this as our high-sensitivity damage function. At 1 °C warming, the difference in productivity between the two functions is less than 1%, but as we approach 6 °C warming the difference is more than 17%, ranging from −9.3% with the Nordhaus function to −26.5% with the Howard & Sterner function.

2.2.2. Constructing regional productivity functions
To study how global warming affects regional economies, we employ the method developed in Krusell

and Smith (2022) to construct inverse U-shaped functions that capture how regional productivity varies with regional, rather than the global, surface air temperature. Each such function has the same shape across all regions (i.e. grid cells) and is chosen so that the sum of regional variations in GDP across the globe replicates estimates of reductions in global (aggregate) GDP stemming from increases in the global temperature.

The following paragraphs and the appendix gives the full details on the calculation of the regional productivity function, but the basic procedure is as follows: (1) make an initial assumption on the shape of this function (i.e. the parameter values governing the shape); (2) given this function, calculate how global GDP changes with warming by adding up changes across all regions; and (3) adjust the initial assumption of the parameters so these changes in global GDP (i.e. aggregate damages from global warming) match those predicted by existing estimates of the effects of global warming on global GDP.

We ground our construction of regional damage functions in a simple economic model of regional GDP:

$$Y_{it} = K_{it}^{\alpha} L_{it}^{1-\alpha}, \qquad (3)$$

where, in region (or grid-cell) i in year t, Y_{it} is GDP, K_{it} is the physical capital stock, and L_{it} is the effective supply of labour, measured in so-called 'efficiency units' which capture how productive workers are. The coefficients α and $1 - \alpha$ are the shares of income (GDP) going to capital and labour, respectively.

We further assume that the effective supply of labour evolves according to:

$$L_{it} = A_{it}H(T_{it})N_{it}, \qquad (4)$$

where in region i in year t, N_{it} is the population (assumed to grow at rate n) and $A_{it}H(T_{it})$ is the number of efficiency units per person. The first component of the number of efficiency units, A_{it}, does not depend on regional temperature and is assumed to grow at rate g.
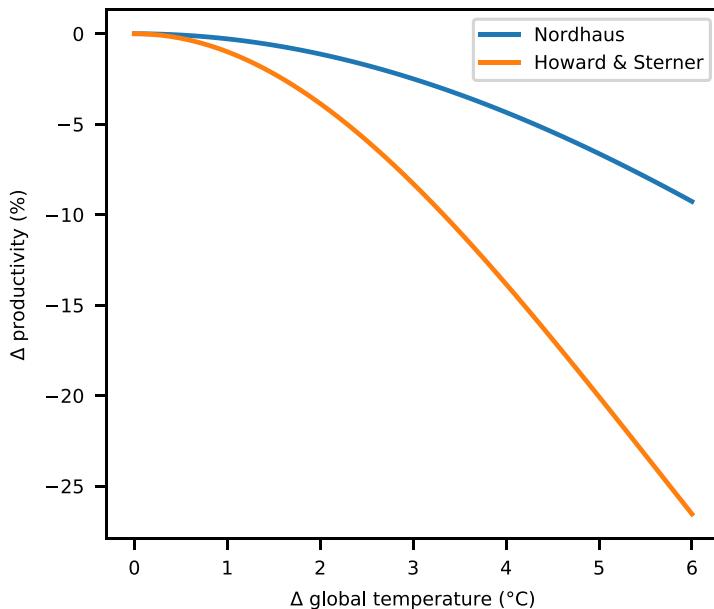
Figure 1. Global productivity change. The percentage change in productivity against temperature changes from pre-industrial for the Nordhaus (blue) and the Howard & Sterner (orange) damage function.

The second component of the number of efficiency units, $H(T_{it})$, is the regional productivity: it depends on regional temperature and captures how changes in regional temperature, T_{it}, affect the regional productivity of labour. The function H has an inverse U-shape and is bounded between 0 and 1. As described in the appendix, we assume that this function depends on three parameters: one parameter governs the temperature of peak productivity, while the other two govern how quickly productivity declines as one moves away from this 'optimal' temperature.

Previous studies have shown the importance of spatial adaptation, particularly in patterns of agricultural production, in accounting for the economic effects of global warming (see, for example, Costinot *et al* 2016, Baker *et al* 2018, Gouel and Laborde 2018). To allow for spatial adaptation in our analysis, we assume capital is freely mobile across regions, so the marginal product of capital (i.e. the extra amount of GDP generated by an incremental amount of additional capital) is equated across regions. As a result, the spatial pattern of production adjusts to shifting regional productivities as the globe warms[5].

Consequently, regional capital-to-labour ratios, K_{it}/L_{it}, are also equalised, implying in turn that global

GDP in year t, $Y_t \equiv \sum_{i=1}^{M} Y_{it}$, where M is the number of regions, has the simple expression:

$$Y_t = K_t^{\alpha} \left(\sum_{i=1}^{M} L_{it} \right)^{1-\alpha}, \qquad (5)$$

where $K_t \equiv \sum_{i=1}^{M} K_{it}$ is the global capital stock. By inserting equation (4) into this equation, and then using a statistical downscaling model to express regional temperature as a function of global temperature (see appendix), we obtain an expression for global GDP as a function of global temperature, given the function H and our assumptions about how GDP varies across regions.

As a final step, the three parameters of the function H are chosen so that the aggregate damages (i.e. reductions in global GDP) from global warming implied by the regional model match those delivered by the aggregate damage function D in equation (2) at three different global temperature changes ranging from 0.5 °C to 5.5 °C (see the appendix for details). The resulting three parameters are consequently the same for every grid cell (as found to be reasonable by Burke and Tanutama 2019), i.e. the same function H applies in every region, but they vary across the four climate model–damage function combinations[6]. The resulting fitted functions H are shown in

---

[5] Krusell and Smith (2022) show that even when capital markets are closed completely—so that autarky prevails—optimal accumulation of capital in each region leads the marginal product of capital to be approximately equalised across regions. Thus the assumption of free capital mobility underlying the formulas in this paper appears to be an innocuous one.

[6] The three nonlinear functions that pin down the three parameters do not have a closed-form expression so we do not have an analytical solution for the parameters, nor can we prove uniqueness. We compute the solution instead using numerical optimisation and find that we converge to the same solution from a variety of starting points, suggesting that the solution is indeed unique.
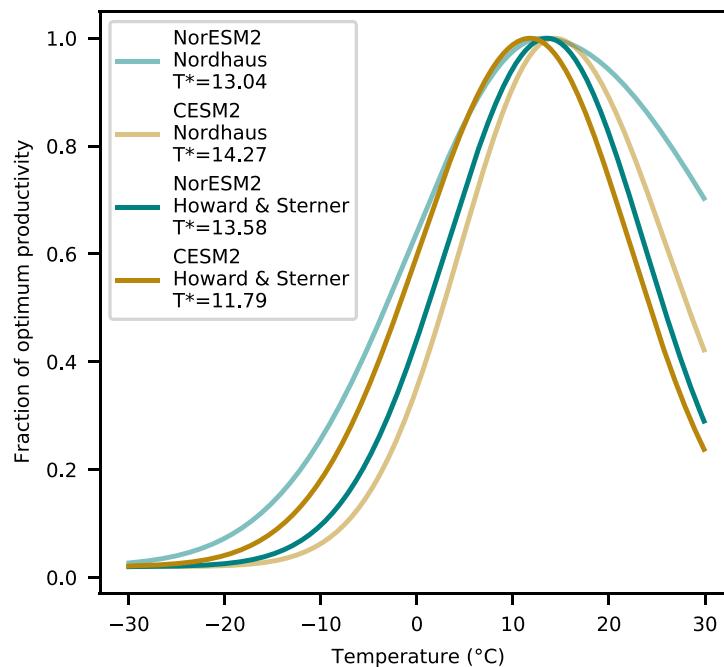
Figure 2. Regional damage functions for the four climate model–damage function combinations, showing the fraction of optimum productivity against temperature, where fraction is one at the optimum temperature T^*.

figure 2 (the parameters can be found in appendix table A1).

2.3. Application of the damage function on the climate data

After constructing the regional damage functions, we applied them to the climate model data. First, we calculated annual spatial temperatures and re-gridded them to fit our $1° \times 1°$ population and GDP data grid from the G-Econ data base (Nordhaus *et al* 2006). We then calculated the fraction of optimum productivity for each year with the regional damage function, and calculated the relative change from year 2000.

3. Results

Here, we present the results at the global, regional, and country levels.

3.1. Global economic impacts

Our results show that global warming decreases global economic productivity, but the size of these economic damages is highly dependent on both climate sensitivity and the steepness of the damage function (see figure 3). The decrease in productivity at the end of the century varies from 0.5% to 7.4% for the low emission scenario (SSP1-2.6), and from 3.8% to 23.5% for the high emissions scenario (SSP5-8.5).

As expected, changing to a more sensitive climate model and a steeper damage function increases the damages. The differences between models and damage functions grow as we reach higher temperatures, as seen from both the increasing distance between the

lines with time in each SSP scenario, and the larger distance between lines in the higher emissions scenarios. While the range in productivity due to the two damage functions shown here is slightly larger than that of the two climate models, the results indicate that the span of damages due to uncertainty in climate sensitivity and uncertainty associated with damage functions are of a similar magnitude globally, supporting previous work (Ackerman and Stanton 2012, Hassler *et al* 2018).

3.2. Regional economic impacts

However, the global estimates of economic impacts of climate change hide a lot of heterogeneity at the regional level. Regionally, our calculations predict decreasing productivity for most of the globe, except in the northern high latitudes and the Tibetan Plateau (figure 4). Figures 4(a), (b), (d) and (e) show the fractional change in the optimum productivity from year 2000 to the end of the century in the SSP5-8.5 scenario for the four climate model–damage function combinations. The other scenarios have the same main patterns but of smaller magnitude (see appendix figures A1–A3). While the area with increased productivity (green) might seem vast, much of the area has a small population and economy, and thus contribute little to the global productivity.

Furthermore, changing between climate models and/or damage functions has different effects in different areas. If we start with the low–low combination (low climate sensitivity—low-sensitivity damage function, figure 4(a)), going to a high sensitivity in
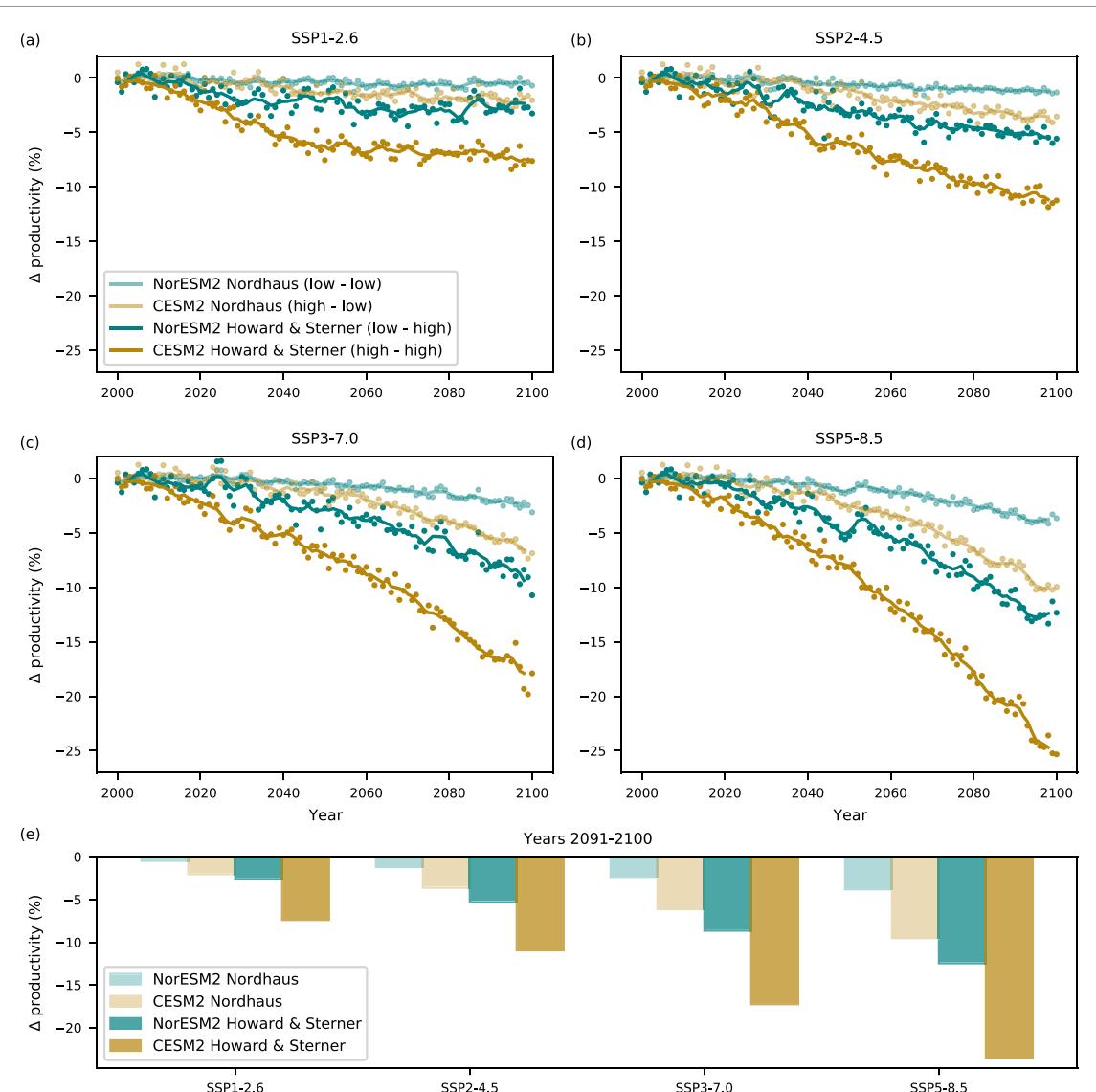
Figure 3. Percentage change in global productivity from year 2000 for the four SSPs. The line is the 5-year moving average, while the dots show each individual year's global productivity change from year 2000 for the four climate model–damage function combinations for SSP1-2.6 (a), SSP2-4.5 (b), SSP3-7.0 (c) and SSP5-8.5 (d). (e) The change between the end of the century (years 2091–2100) and 2000 (1996–2004).

either climate model (high–low, figure 4(c)) or damage function (low–high, figure 4(g)) increases the productivity in cold areas, and decreases the productivity in warm areas. But if we start with either the high sensitivity climate model (high–low) or damage function (low–high), and move to the high–high combination (figures 4(f) and (h), respectively) the productivity decreases almost everywhere.

This can be understood from the different temperature increases between models, and the different optimum temperatures and slopes of the regional damage functions (see figure 2 and appendix table A1 for details). When going from the low–low to the low–high combination we have the same warming and approximately the same optimum temperature. The larger increase in productivity in the cold regions and decrease in the warm regions is thus due to the steeper

slopes of the damage function, making the regions move faster toward or away from the optimum temperature. If we instead move from the low–low to the high–low combination we still have a similar optimum temperature and steeper slopes. Additionally, this effect is strengthened by the higher temperature increase. In the other case, starting from the low–high or the high–low combination and going to the high–high combination, we have a different situation. Now the slopes are not changing much, but the optimum temperature is lower for our high–high combination. This means fewer regions have the potential to increase their productivity, and more regions will cross over the optimum temperature and start decreasing their productivity. Additionally, the baseline temperature difference between the models plays a part when changing model.
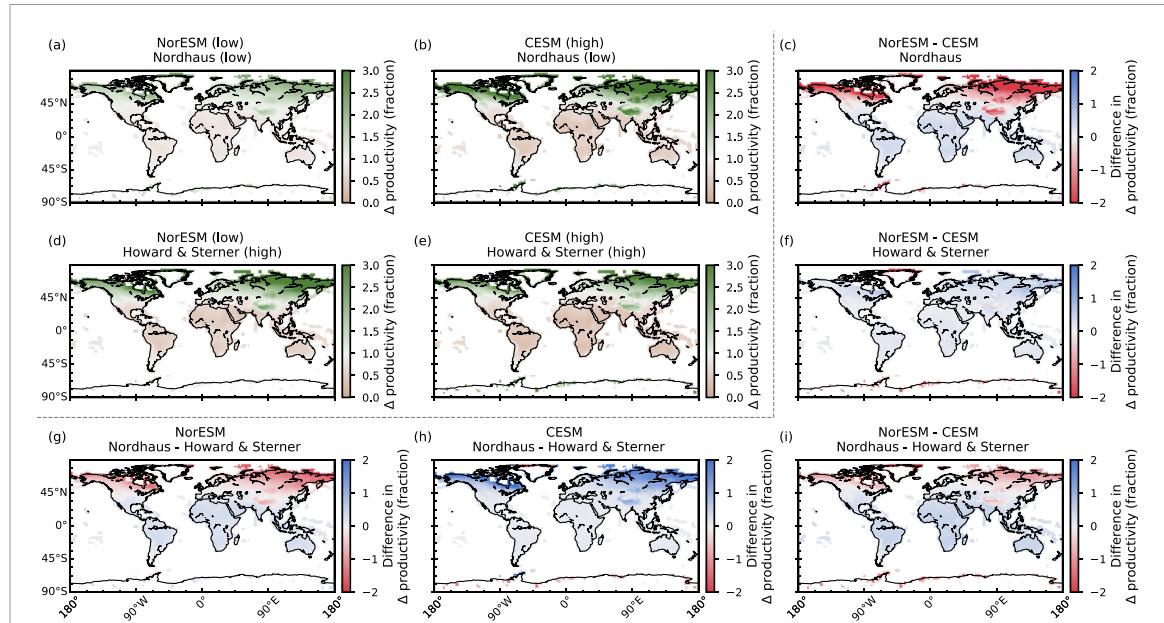
Figure 4. Spatial distribution of change in optimum productivity for SSP5-8.5. (a), (b), (d), (e) Percentage change in optimum productivity at the end of the century (2091–2100) from year 2000 (1996–2004) for the four climate model–damage function combinations for SSP5-8.5. (c) and (f)–(i) The differences in productivity change between the combinations.

3.3. Large variation between countries

On the country level, as indicated by figure 4, the countries with a cool climate benefit, while the warm countries suffer damages. Figure 5 shows how the temperature and productivity change from 2000 to the end of the century for each country in each climate model–damage function combination for SSP5-8.5 (for the other SSPs, see appendix figures A4–A6). Like the global average, the country-level average takes into account each country's economic activity, measured in GDP (indicated by circle size), and population in year 2000. The colour of the circles shows the population-weighted temperature in year 2000. Again, the same three factors that explain figure 4 are important for each country's change in productivity, as well as the countries' distribution of population and economic activity. We see that most countries will experience economic impacts different from the global average (black dot).

Some examples of how countries may be impacted in each scenario and climate model–damage function combination are shown in figure 6. The United States, the biggest country-level economy, follows what we saw for the global productivity (figure 3(e)), while other countries show very different responses. Russia is one of the countries that benefit from climate change independent of scenario and combination, while India and Sudan clearly see economic damages under all circumstances. However, these countries do not follow the same increase in effect with increasing sensitivity as seen globally and for the United States. On the regional level it is not clear that increasing the climate sensitivity and/or

sensitivity of the damage function increases the economic impacts.

Another interesting group of countries is the one with relatively small impacts that lies close to the zero line in figure 5. Germany (figure 6(c)) is a nice example of these, and we see that whether the country will experience benefits or damages due to climate change depends on both the scenario and the climate model–damage function combination. This is because Germany has a temperature lower than, yet close to, the optimal temperature (10.0 °C in NorESM2, 10.4 °C in CESM2) in year 2000. As the climate warms, as decided by both the scenario and the climate model, Germany might cross the optimum temperature. When crossing the optimum temperature, the productivity starts to decrease, and if moving too far away from the optimum temperature the end productivity could be lower than at the starting point in year 2000, depending on the slopes of the damage function.

4. Discussion

Our results show how the large uncertainties in climate sensitivity and damage functions result in large uncertainties in economic impacts. This points out how important it is to include uncertainty estimates when calculating economic impacts of climate change. Particularly, this is important when using estimates of economic impacts for policy purposes, like for example the US government (Auffhammer 2018). The study also points out how different the economic impacts of climate change can be between
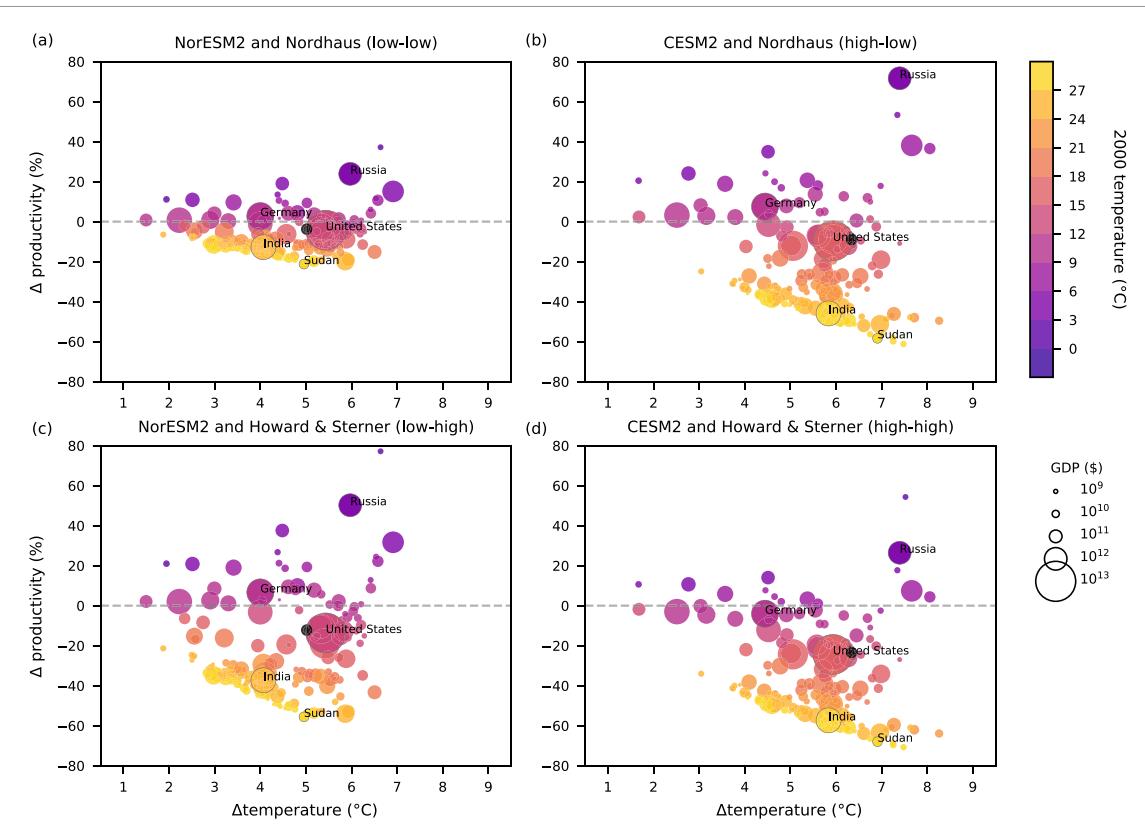
Figure 5. Country-level temperature and productivity change. Showing the four climate model–damage function combinations' productivity change at end of the century (2091–2100) from year 2000 (1996–2004) against population-weighted temperature change for SSP5-8.5. Each country's dot is coloured based on the year 2000 population-weighted temperature, and the size indicates the GDP in year 2000. The black dot is the global average (and does not indicate year 2000 temperature or GDP). The data of each dot, including country name, can be found in the supplementary material.

regions. Especially, we see how the regional economic impacts and uncertainty can be very different from the global.

We also show that when constructing regional damage functions from global damage functions, the regional distribution of warming is important. Two different spatial distributions can result in two different shapes of the regional damage functions, as seen in figure 2, where the regional version of Nordhaus's damage function gets a much wider shape (i.e. slower change with warming) using NorESM2 rather than CESM2. This illustrates that there are large uncertainties also in the shape of these functions, and that economic productivity can vary widely for the same temperature, even when the regional function is constructed from the same global function.

Another question is whether it is reasonable that the shape of the function is the same for every region. One might, for example, expect the shape to be different between rich and poor regions due to different possibilities for adaption. We leave this possibly important extension of our approach to future research.

In a full economic model (such as Krusell and Smith 2022), economic impacts feedback on emissions, so that the path of global emissions is jointly determined with the aggregate economic impact of warming. In our work, instead, future emissions are already set by the SSP scenarios, so this climate-economy feedback is ruled out. Nonetheless, our results give important insights into the relative importance of climate sensitivity and the shape of the damage function in determining the regional economic effects of warming. Both of these factors are also important for the size of the climate-economy feedback, and so this study is a step towards assessing uncertainty about this feedback too.

Our calculations are based on the assumption that population growth is constant over time and across space, and actual future population growth and migration could therefore result in a different path for future global productivity. If people living in less productive areas move northward into more productive areas, global productivity would decrease less with warming. Such migration to more productive areas is expected, and even simulated in some models (Conte *et al* 2021, Cruz and Rossi-Hansberg 2021). It is unlikely, however, that people can move freely across borders (e.g. Held 2016), and often the people most affected by climate change lack the funds necessary to migrate (e.g. Adger *et al* 2014).

An important remaining question is how well temperature serves as a proxy for climate change. The
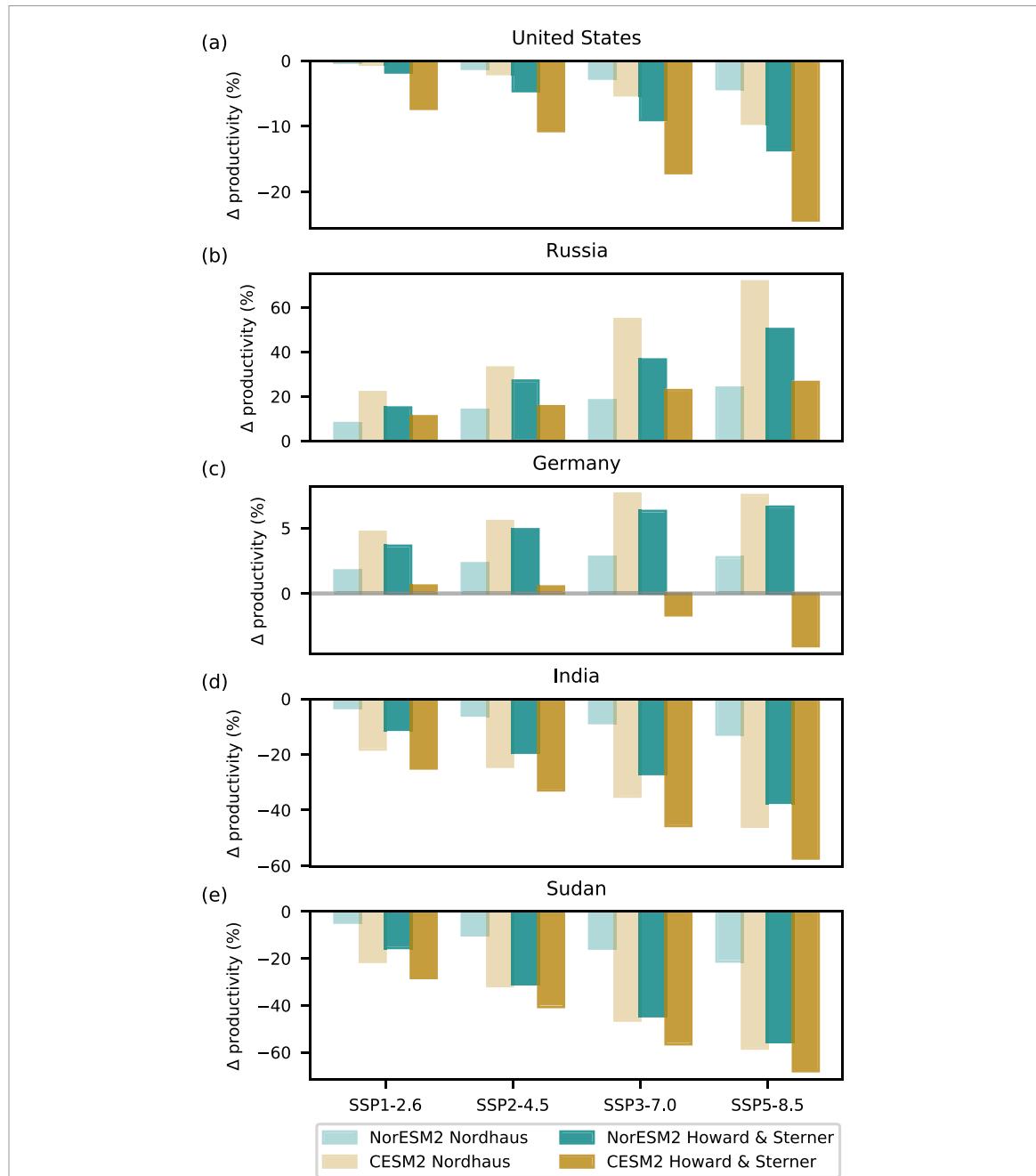
Figure 6. Country-level productivity change. Percentage change in productivity at the end of the century (2091–2100) from year 2000 (1996–2004) for the four climate model–damage function combinations and the four future SSP scenarios for five selected countries.

aggregate damage functions we employ here assume that the global temperature is a good proxy for global climate change. Although this is probably a reasonable assumption at the global level, it might be less so at the regional level. We construct regional damage functions that depend only on regional temperature, but other climate variables which could be important for regional damages, such as rainfall, sea-level rise, and extreme weather events, do not necessarily share the same spatial pattern as changes in regional temperature change (e.g. IPCC 2013).

In our study, we have used damage functions in which climate change affects the level of economic output rather than its growth rate. Yet, this is an area

of some debate (see e.g. Burke *et al* 2015, Moore and Diaz 2015). Since even small changes in growth rates could lead to large economic impacts in the long run, such damage functions could be even more sensitive than the high sensitivity damage function employed here.

5. Conclusion

We have found that uncertainty about climate sensitivity and uncertainty about the shape of the aggregate damage function have similar effects on uncertainty about global economic damages from global warming, consistent with previous work (Ackerman and

Stanton 2012, Hassler *et al* 2018). But we find too that at the regional level the effects of uncertainty about climate sensitivity and aggregate damage functions vary widely, a new contribution. In fact, global productivity tells us little about what will happen regionally or in a given country.

What is clear from this study is that progress toward reliable assessments of economic damages caused by climate change will require both more constrained estimates of the climate sensitivity and improved damage functions. Additionally, many aspects of climate change (such as sea level rise or extreme events) vary a lot regionally, highlighting the importance of a regional focus in further work on constructing damage functions. Complementary to the regional focus, future work on the damage function should focus on including more climatic variables.

Finally, future work should study uncertainty about regional damage functions in a fully-integrated climate-economy model in order to assess uncertainty about the climate-economy feedback, optimal emissions paths, or the effects of different climate policies.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/CMIP/NCAR/CESM2/historical/r1i1p1f1/Amon/tas/gn/v20190308/tas_Amon_CESM2_historical_r1i1p1f1_gn_185001-201412.nc. All NorESM2 and CESM2 simulation output is available through the Earth System Grid Federation's (ESGF) CMIP6 search interface (https://esgf-node.llnl.gov/search/cmip6/) under 'source ID' *NorESM2-LM* and *CESM2*, respectively, 'experiment ID' *historical*, *ssp126*, *ssp245*, *ssp370* and *ssp585*, 'frequency' *mon*, and 'variable' *tas*. The data can also be directly downloaded from the following URLs: http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/CMIP/NCAR/CESM2/historical/r1i1p1f1/Amon/tas/gn/v20190308/tas_Amon_CESM2_historical_r1i1p1f1_gn_185001-201412.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp126/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp126_r11i1p1f1_gn_201501-206412.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp126/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp126_r11i1p1f1_gn_206501-210012.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp245/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp245_r11i1p1f1_gn_201501-206412.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp245/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp245_r11i1p1f1_gn_206501-210012.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp370/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp370_r11i1p1f1_gn_201501-206412.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp370/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp370_r11i1p1f1_gn_206501-210012.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp585/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp585_r11i1p1f1_gn_201501-206412.nc

http://esgf-data.ucar.edu/thredds/fileServer/esg_dataroot/CMIP6/ScenarioMIP/NCAR/CESM2/ssp585/r11i1p1f1/Amon/tas/gn/v20200528/tas_Amon_CESM2_ssp585_r11i1p1f1_gn_206501-210012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_185001-185912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_186001-186912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_187001-187912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_188001-188912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_189001-189912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_190001-190912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_191001-191912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
192001-192912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
193001-193912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
194001-194912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
195001-195912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
196001-196912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
197001-197912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
198001-198912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
199001-199912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
200001-200912.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/CMIP/NCC/NorESM2-
LM/historical/r1i1p1f1/Amon/tas/gn/v20190815/
tas_Amon_NorESM2-LM_historical_r1i1p1f1_gn_
201001-201412.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_201501-202012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/

v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_202101-203012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_203101-204012.nc

http://noresg.nird.sigma2.no/thredds/
fileServer/esg_dataroot/cmor/CMIP6/Scenario
MIP/NCC/NorESM2-LM/ssp126/r1i1p1f1/
Amon/tas/gn/v20191108/tas_Amon_NorESM2-
LM_ssp126_r1i1p1f1_gn_204101-
205012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_205101-206012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_206101-207012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_207101-208012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_208101-209012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp126/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp126_
r1i1p1f1_gn_209101-210012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r1i1p1f1_gn_201501-202012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r1i1p1f1_gn_202101-203012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r1i1p1f1_gn_203101-204012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r2i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r2i1p1f1_gn_204101-205012.nc

http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r2i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r2i1p1f1_gn_205101-206012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r2i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r2i1p1f1_gn_206101-207012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r2i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r2i1p1f1_gn_207101-208012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r2i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r2i1p1f1_gn_208101-209012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp245/r2i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp245_
r2i1p1f1_gn_209101-210012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_201501-202012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_202101-203012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_203101-204012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_204101-205012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_205101-206012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_206101-207012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/

v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_207101-208012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp370/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp370_
r1i1p1f1_gn_208101-209012.nc
http://noresg.nird.sigma2.no/thredds/
fileServer/esg_dataroot/cmor/CMIP6/Scenario
MIP/NCC/NorESM2-LM/ssp370/r1i1p1f1/
Amon/tas/gn/v20191108/tas_Amon_
NorESM2-LM_ssp370_r1i1p1f1_gn_209101-
210012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_201501-202012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_202101-203012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_203101-204012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_204101-205012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_205101-206012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_206101-207012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_207101-208012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_208101-209012.nc
http://noresg.nird.sigma2.no/thredds/fileServer/
esg_dataroot/cmor/CMIP6/ScenarioMIP/NCC/
NorESM2-LM/ssp585/r1i1p1f1/Amon/tas/gn/
v20191108/tas_Amon_NorESM2-LM_ssp585_
r1i1p1f1_gn_209101-210012.nc

Population and GDP data from the Geographically based Economic data (G-Econ) site, version 2.11 (Nordhaus *et al* 2006), is no longer available on the web site, but is available from the authors on request.

Author contributions

All authors helped design the study. J B wrote the paper with help from all authors, performed the calculations and produced the figures. T S helped write the paper. A A S provided the script for calculating the parameters for the regional damage functions, and helped write the paper.

Conflict of interest

The authors declare no competing interests.

Appendix

This appendix completes the description of how we construct a function relating regional productivity to regional temperature, building on the discussion in section 2.2.2.

Economic model
Substituting equation (4) into equation (5) yields an expression for global GDP in year t that depends explicitly on the set of regional temperatures:

$$Y_t = K_t^\alpha$$
$$\times \left(\sum_{i=1}^{M} ((1+g)(1+n))^{t-2000} A_{i,2000} N_{i,2000} H(T_{it}) \right)^{1-\alpha}.$$
(6)

The regional productivity function
We adopt the following functional form for H, the regional productivity function:

$$H(T_{it}) = \begin{cases} (1-b)e^{-\kappa^+(T_{it}-T^*)^2} + b & \text{if } T_{it} \geqslant T^* \\ (1-b)e^{-\kappa^-(T_{it}-T^*)^2} + b & \text{if } T_{it} < T^*, \end{cases}$$
(7)

where T_{it} is the temperature in region i at time t, T^* is the optimal temperature (given in °C) at which H

attains its maximum of 1, and κ^+ and κ^- determine the steepness of the decline on either side of the optimal temperature. The lower bound b is set to 0.02.

The downscaling model
To derive an expression for global GDP that depends only on the global temperature, we used a statistical downscaling model that relates regional temperature to global temperature:

$$T_{it} = T_{i,2000} + \gamma_i(T_t - T_{2000}).$$
(8)

To obtain the region-specific responsiveness coefficients γ_i, we proceeded in three steps. First, we calculated the global temperature change from pre-industrial to year 2000, which is our reference year. Second, we calculated the temperatures in year 2000 for each grid cell ($T_{i,2000}$). For both calculations we used surface air temperature from three historical runs by the climate model, and calculated the average of these three runs using the five years around 2000 (1998–2002). Finally, we calculated how each grid cell's temperature changes relative to the global temperature, the responsiveness coefficients (γ_i). These we calculated by using five different model runs: historical, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. For each run, the difference between the first and the last five years was calculated, and each grid cell's change was divided by the global temperature change. The average of these five coefficients was then used as the final set of responsiveness coefficients for each of the two models (i.e. NorESM2 and CESM2).

Armed with the statistical downscaling model in equations (6) and (8) can now be rewritten:

$$Y_t = S_t G(T_t) K_t^\alpha,$$
(9)

where $S_t \equiv \left[(1+g)(1+n))^{t-2000} \right]^{1-\alpha}$, $G(T_t) \equiv \left(\sum_{i=1}^{M} a_i N_{i,2000} \frac{H(T_{i,2000}+\gamma_i(T_t-T_{2000}))}{H(T_{i,2000})} \right)^{1-\alpha}$, and $a_{i,2000} \equiv A_{i,2000} H(T_{i,2000})$ is efficiency units per person in region i in 2000. Given a regional productivity function H (in our case equation (7)), a change in the global temperature from T_t to T_{2000} would lead to a percentage change in global GDP (again holding inputs fixed) equal to:

$$d(T_t) \equiv \left(\frac{G(T_{2000})}{G(T_t)} - 1 \right) 100.$$
(10)

Constructing regional damage functions
The goal now is to choose H (equation (7)) so that the two 'damage functions', $D(T_t)$ and $d(T_t)$, the first taken from existing estimates of global damages from climate change, as described in section 2.2.1, and the second derived from the simple economic model of regional damages from climate change outlined here, agree for different values of the global temperature T_t.

Regional population and GDP data for the year 2000 are taken from the G-Econ database, version

2.11 (Nordhaus *et al* 2006). The $a_{i,2000}$ are chosen by solving the following two equations for $K_{i,2000}$ and $a_{i,2000}$ in each region:

$$K_{i,2000}^{\alpha} \left(a_{i,2000} N_{i,2000} \right)^{1-\alpha} = Y_{i,2000}$$

$$\alpha K_{i,2000}^{\alpha-1} \left(a_{i,2000} N_{i,2000} \right)^{1-\alpha} = r.$$

The first of these equations ensures that regional GDP in year 2000 equals its value in the data and the second of these equations imposes that the marginal product of capital in each region is equated to a common rate of return r (net of depreciation), here set to 2.53%. Capital's share of income, α, is set to 0.36.

To find the three unknowns, T^*, κ^-, and κ^+, we matched, for three different changes in global temperature, the aggregate damages from summing up the regional damage function (equation (7)) over all regions with the corresponding aggregate damages from the global damage function (equation (2)). To find the solution to this set of nonlinear equations, we expressed the solution as a root-finding problem and then minimised the sum of the squares of the three component functions to compute the root. The three different changes in global temperature used in the three equations were chosen from

Table A1. The parameter values found for the four climate model–damage function combinations.

Damage function	Model	T^*	κ^-	κ^+
Nordhaus	NorESM2	13.0	0.00267	0.00127
Nordhaus	CESM2	14.3	0.00531	0.00365
Howard & Sterner	NorESM2	13.6	0.00457	0.00484
Howard & Sterner	CESM2	11.8	0.00380	0.00459

the three intervals 0.5 °C–1.5 °C, 2 °C–3.5 °C, and 4 °C–5.5 °C. We checked robustness by using different temperatures in each of these intervals with very similar results for the fitted parameter values. The regional temperatures needed for equation (7) were found using the downscaling model described above (equation (8)).

The resulting parameters are given in table A1. The global damages implied by the parameters, in comparison to the global damages implied by the function *D*, are shown in appendix figures A7 and A8. As seen in the figures, the regional model delivers a good, but not perfect, fit for global damages. Considering the large uncertainties surrounding these functions, the resulting regional productivity functions are deemed sufficiently accurate for our purpose.
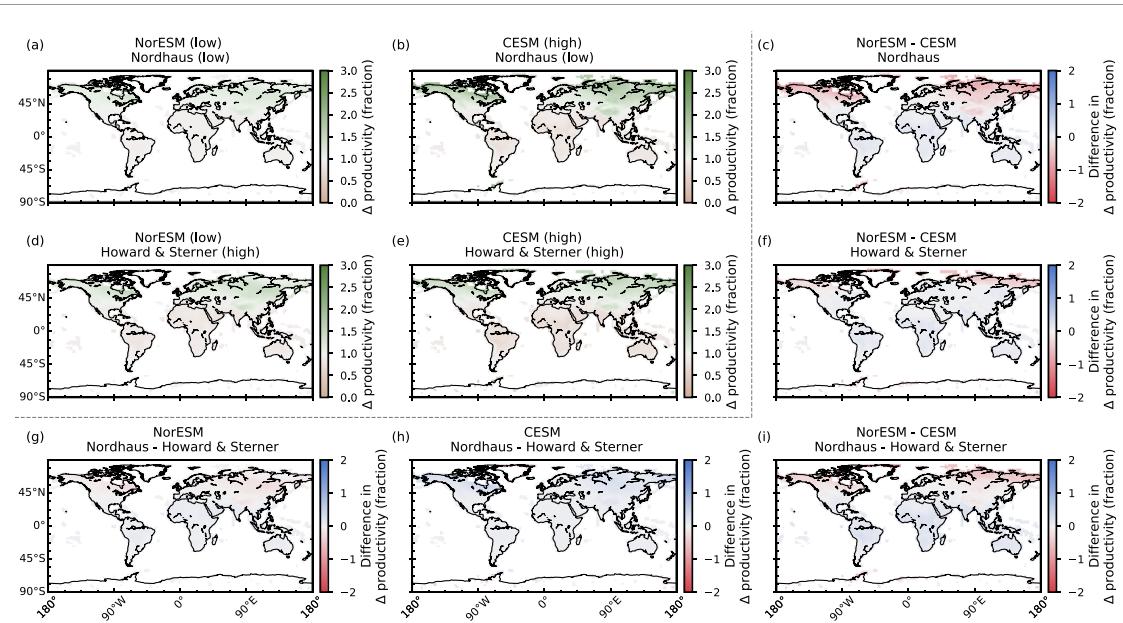
Figure A1. Country-level temperature and productivity change for SSP1-2.6. Showing the four climate model–damage function combinations' productivity change at end of the century (2091–2100) from year 2000 (1996–2004) against population-weighted temperature change for SSP1-2.6. Each country's dot is coloured based on the year 2000 population-weighted temperature, and the size indicates the GDP in year 2000. The black dot is the global average (and does not indicate temperature or GDP).
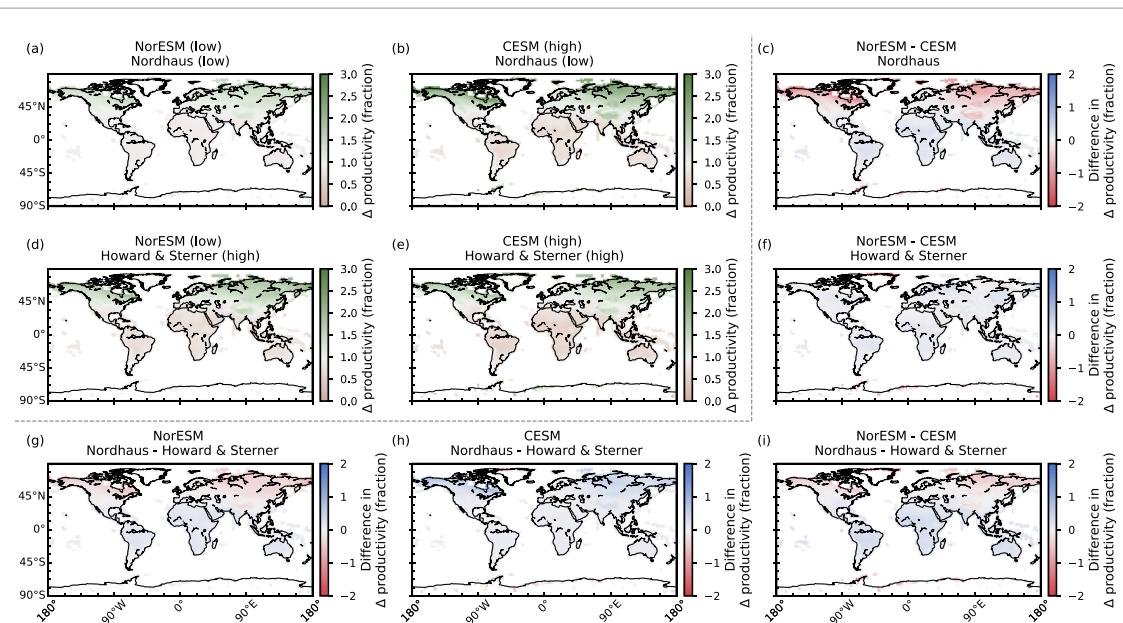

Figure A2. Country-level temperature and productivity change for SSP2-4.5. Same as figure 1, but for SSP2-4.5.
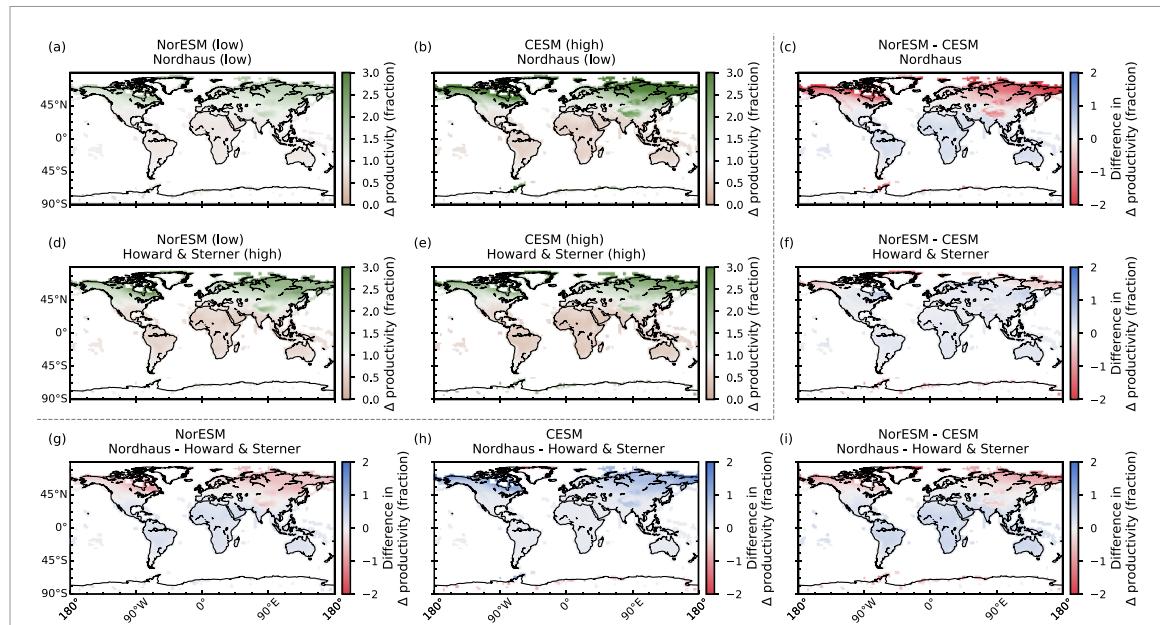
Figure A3. Country-level temperature and productivity change for SSP3-7.0. Same as figure 1, but for SSP3-7.0.
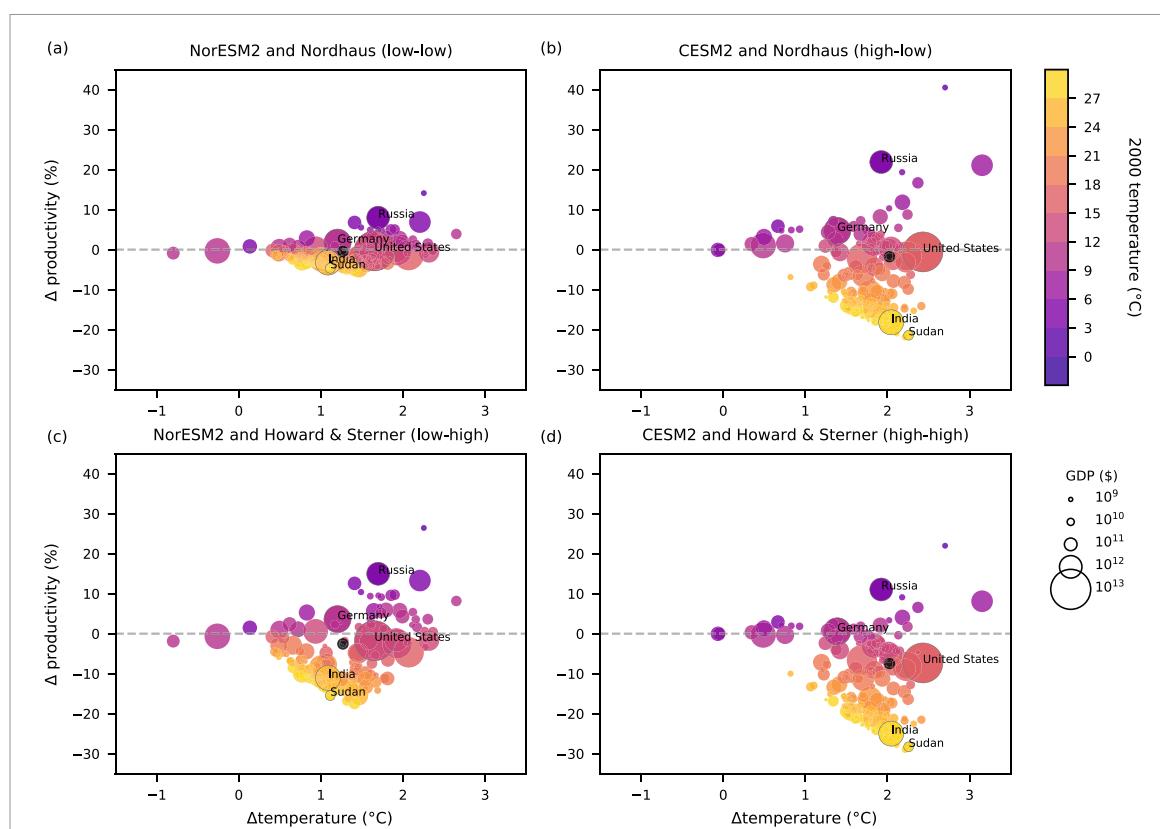
Figure A4. Country-level temperature and productivity change for SSP1-2.6. Showing the four climate model–damage function combinations' productivity change at end of the century (2091–2100) from year 2000 (1996–2004) against population-weighted temperature change for SSP1-2.6. Each country's dot is coloured based on the year 2000 population-weighted temperature, and the size indicates the GDP in year 2000. The black dot is the global average (and does not indicate temperature or GDP). The data of each dot, including country name, can be found in the supplementary material.
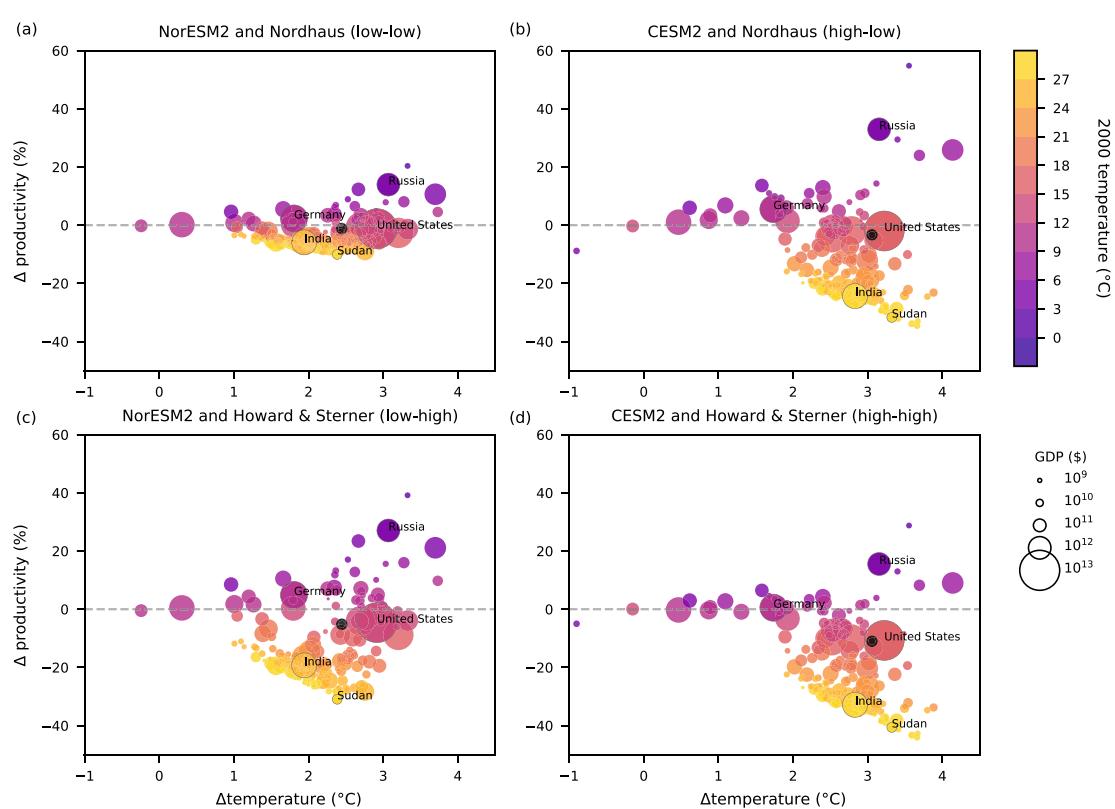
Figure A5. Country-level temperature and productivity change for SSP2-4.5. Same as figure 4, but for SSP2-4.5.
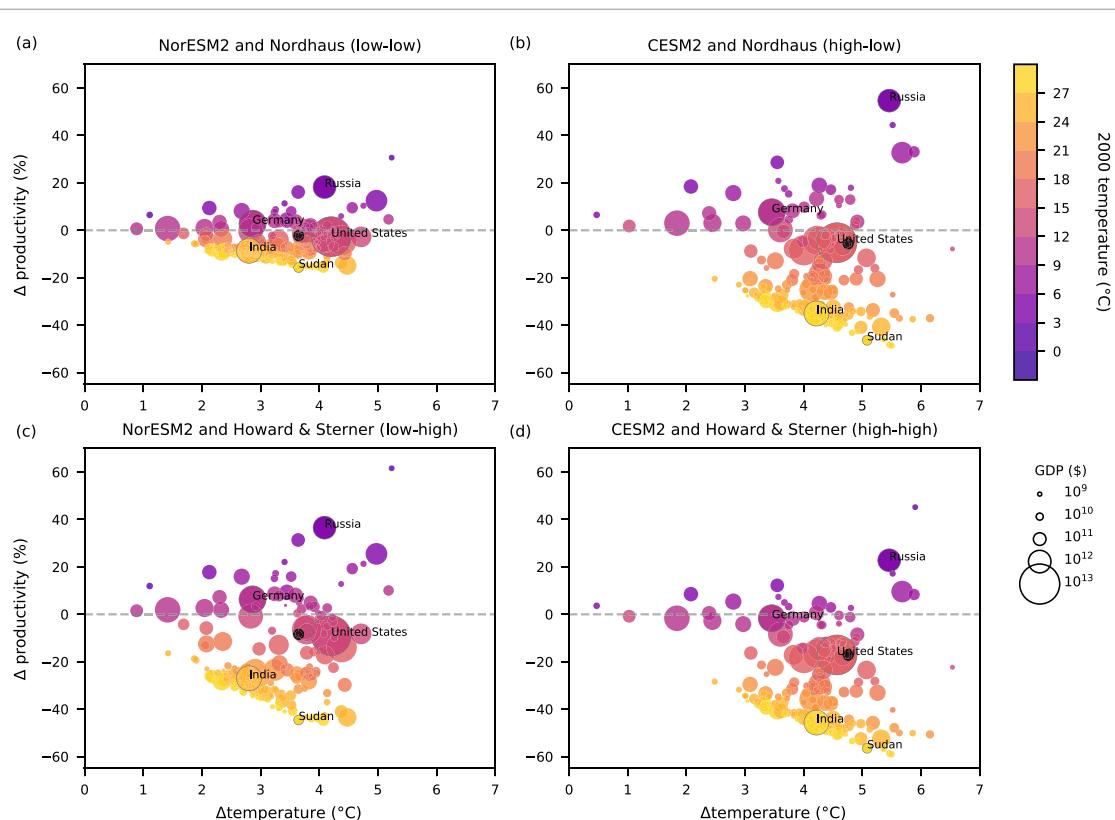
Figure A6. Country-level temperature and productivity change for SSP3-7.0. Same as figure 4, but for SSP3-7.0.
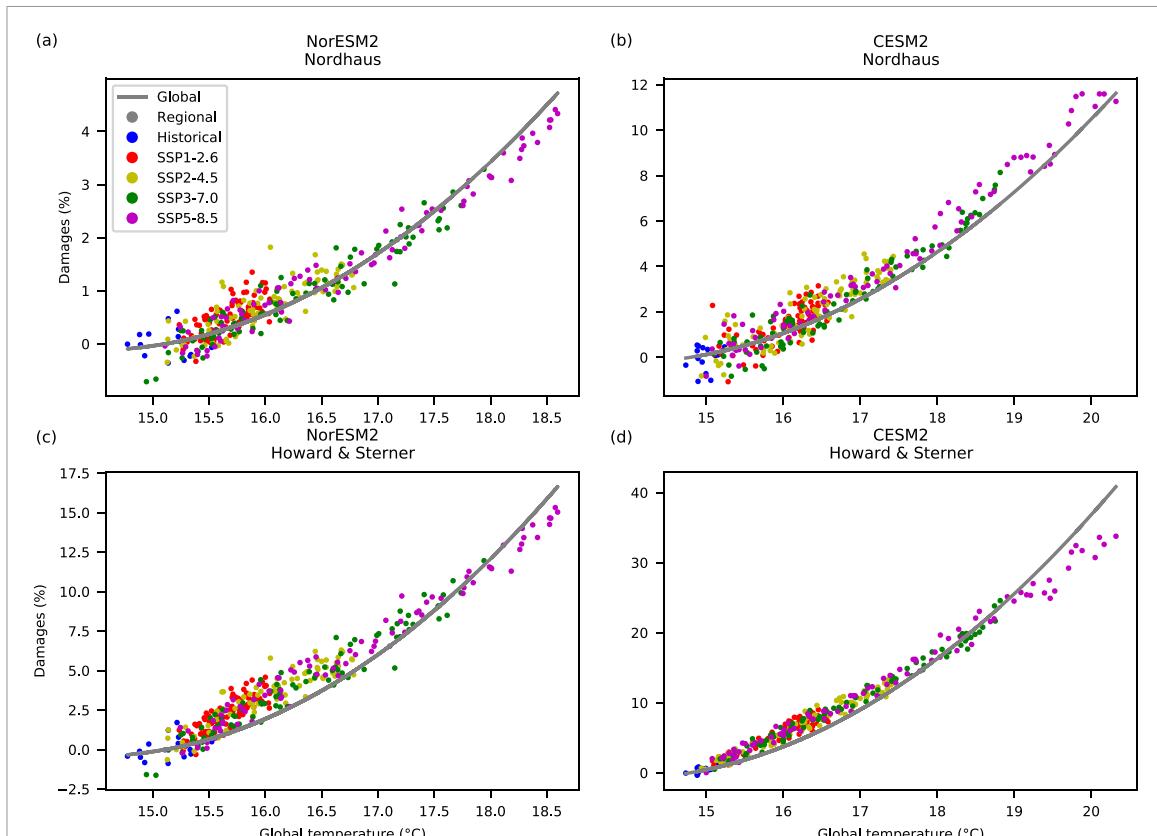
Figure A7. Global and regional damages plotted against temperature. Each year from historical run and the SSP scenarios are plotted for both the global (line) and the regional (dots), for the four climate model–damage function combinations.
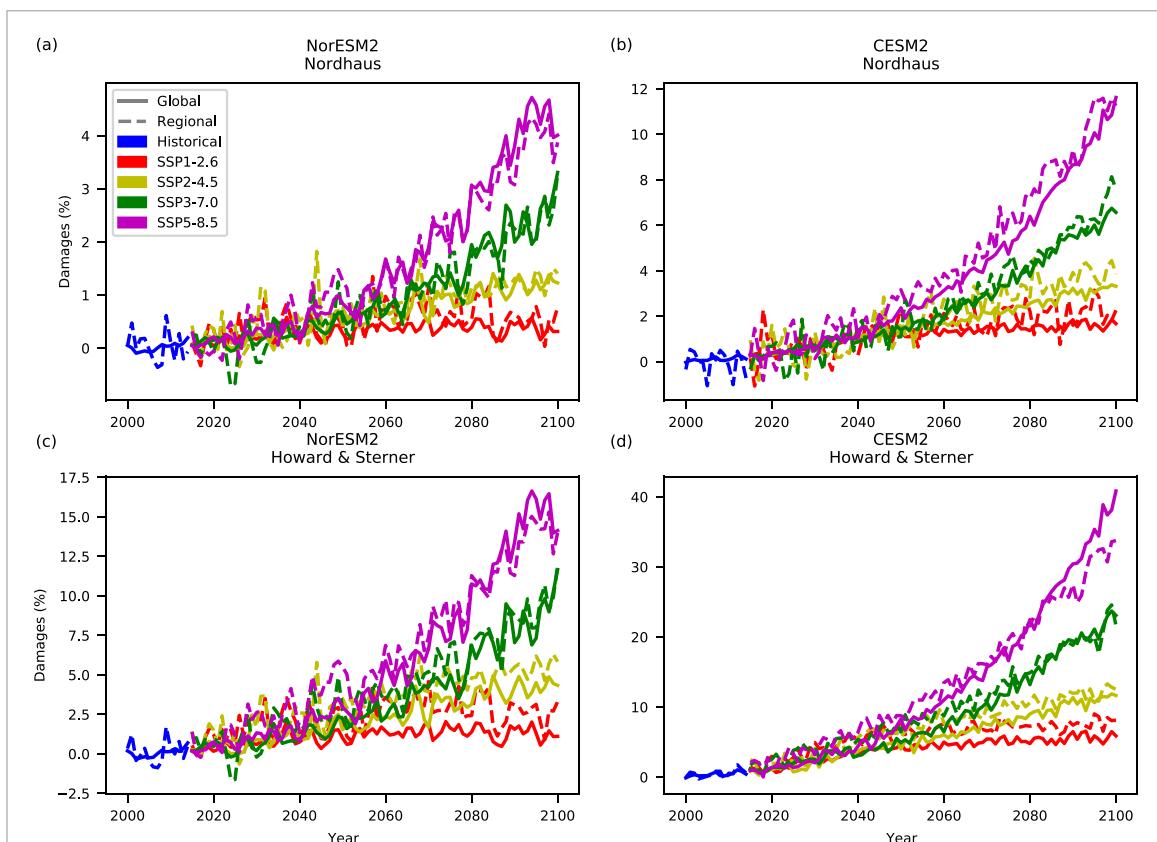
Figure A8. Global and regional damages plotted against time. Each year from historical run and the SSP scenarios are plotted for both the global (line) and the regional (dashed), for the four climate model–damage function combinations.

ORCID iDs

Jenny Bjordal ⬤ https://orcid.org/0000-0002-3789-8059
Trude Storelvmo ⬤ https://orcid.org/0000-0002-0068-2430

References

Ackerman F, DeCanio S J, Howarth R B and Sheeran K 2009 Limitations of integrated assessment models of climate change *Clim. Change* **95** 297–315

Ackerman F and Stanton E A 2012 Climate risks and carbon prices: revising the social cost of carbon *Economics* **6** 20120010

Adger W N, Pulhin J M, Barnett J, Dabelko G D, Hovelsrud G K, Levy M, Oswald Spring U and Vogel C H 2014 Human security *Climate Change 2014—Impacts, Adaptation and Vulnerability: Part A: Global and Sectoral Aspects (Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change)* ed C B Field and V R Barros (Cambridge: Cambridge University Press) pp 755–91

Anthoff D and Tol R S J 2014 The climate framework for uncertainty, negotiation and distribution (fund), technical description, version 3.9 (available at: www.fund-model.org/files/documentation/Fund-3-9-Scientific-Documentation.pdf)

Auffhammer M 2018 Quantifying economic damages from climate change *J. Econ. Perspect.* **32** 33–52

Baker J S, Havlík P, Beach R, Leclére D, Schmid E, Valin H, Cole J, Creason J, Ohrel S and McFarland J 2018 Evaluating the effects of climate change on US agricultural systems: sensitivity to regional impact and trade expansion scenarios *Environ. Res. Lett.* **13** 064019

Burke M, Hsiang S M and Miguel E 2015 Global non-linear effect of temperature on economic production *Nature* **527** 235

Burke M and Tanutama V, 2019 Climatic constraints on aggregate economic output (working paper series) *Working Paper 25779* (National Bureau of Economic Research) (available at: www.nber.org/papers/w25779)

Conte B, Desmet K, Nagy D K and Rossi-Hansberg E 2021 Local sectoral specialization in a warming world *J. Econ. Geogr.* **21** 493–530

Costinot A, Donaldson D and Smith C 2016 Evolving comparative advantage and the impact of climate change in agricultural markets: evidence from 1.7 million fields around the world *J. Political Econ.* **124** 205–48

Cruz J-L and Rossi-Hansberg E 2021 The economic geography of global warming (available at: www.nber.org/papers/w28466)

Danabasoglu G *et al* 2020 The community earth system model version 2 (CESM2) *J. Adv. Model. Earth Syst.* **12** e2019MS001916

Diaz D and Moore F 2017 Quantifying the economic risks of climate change *Nat. Clim. Change* **7** 774–82

Dietz S and Stern N 2015 Endogenous growth, convexity of damage and climate risk: how Nordhaus' framework supports deep cuts in carbon emissions *Econ. J.* **125** 574–620

Eyring V, Bony S, Meehl G A, Senior C, Stevens B, Stouffer R J and Taylor K E 2015 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation *Geosci. Model Dev.* **8** 10539–83

Forster P *et al* 2021 The Earth's energy budget, climate feedbacks and climate sensitivity *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge: Cambridge University Press)

Gouel C and Laborde D 2018 The crucial role of int. trade in adaptation to climate change (working paper series)

Working Paper 25221 (National Bureau of Economic Research) (available at: www.nber.org/papers/w25221)

Hassler J, Krusell P and Olovsson C 2018 The consequences of uncertainty: climate sensitivity and economic sensitivity to the climate *Annu. Rev. Econ.* **10** 189–205

Hausfather Z, Marvel K, Schmidt G A, Nielsen-Gammon J W and Zelinka M 2022 Climate simulations: recognize the 'hot model' problem *Nature* **605** 26–9

Held D 2016 Climate change, migration and the cosmopolitan dilemma *Glob. Policy* **7** 237–46

Hope C 2011 The social cost of CO2 from the PAGE09 model *Economics Discussion Paper* (https://doi.org/10.2139/ssrn.1973863)

Howard P H and Sterner T 2017 Few and not so far between: a meta-analysis of climate damage estimates *Environ. Resour. Econ.* **68** 197–225

IPCC 2013 *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)

Krusell P and Smith A A,Jr 2022 National Bureau of Economic Research Working paper 30338 (https://doi.org/10.3386/w30338)

Moore F C and Diaz D B 2015 Temperature impacts on economic growth warrant stringent mitigation policy *Nat. Clim. Change* **5** 127–31

Moss R H *et al* 2010 The next generation of scenarios for climate change research and assessment *Nature* **463** 747

Nordhaus W D 1992 An optimal transition path for controlling greenhouse gases *Science* **258** 1315–9

Nordhaus W D and Yang Z 1996 A regional dynamic general-equilibrium model of alternative climate-change strategies *Am. Econ. Rev.* **86** 741–65

Nordhaus W 2018 Evolution of modeling of the economics of global warming: changes in the DICE model, 1992–2017 *Clim. Change* **148** 623–40

Nordhaus W, Azam Q, Corderi D, Hood K, Victor N M, Mohammed M, Miltner A and Weiss J 2006 'The G-Econ database on gridded output: methods and data (New Haven, CT: Yale University) vol 6

O'Neill B C *et al* 2016 The scenario model intercomparison project (ScenarioMIP) for CMIP6 *Geosci. Model Dev.* **9** 3461–82

O'Neill B C, Kriegler E, Riahi K, Ebi K L, Hallegatte S, Carter T R, Mathur R and van Vuuren D P 2014 A new scenario framework for climate change research: the concept of shared socioeconomic pathways *Clim. Change* **122** 387–400

Revesz R L, Arrow K J, Goulder L H, Howard P, Kopp R E, Livermore M A, Oppenheimer M and Sterner T 2014 Improve economic models of climate change *Nature* **508** 173–5

Riahi K *et al* 2017 The shared socioeconomic pathways and their energy, land use and greenhouse gas emissions implications: an overview *Glob. Environ. Change* **42** 153–68

Seland Ï *et al* 2020 Overview of the norwegian earth system model (NorESM2) and key climate response of CMIP6 DECK, historical and scenario simulations *Geosci. Model Dev.* **13** 6165–200

Sherwood S C *et al* 2020 An assessment of earth's climate sensitivity using multiple lines of evidence *Rev. Geophys.* **58** e2019RG000678

Stern N 2013 The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models *J. Econ. Literature* **51** 838–59

Tokarska K B, Stolpe M B, Sippel S, Fischer E M, Smith C J, Lehner F and Knutti R 2020 Past warming trend constrains future warming in CMIP6 models *Sci. Adv.* **6** eaaz9549

Tol R S J 2011 The social cost of carbon *Annu. Rev. Res. Econ.* **3** 419–43

van Vuuren D P, Bayer L B, Chuwah C, Ganzeveld L, Hazeleger W, van den Hurk B, Van Noije T, O'Neill B and Strengers B J

2012 A comprehensive view on climate change: coupling of earth system and integrated assessment models *Environ. Res. Lett.* **7** 024012

WCRP CMIP6

Weitzman M L 2010 What is the "damage function" for global warming—and what difference might it make? *Clim. Change Econ.* **01** 57–69

Weitzman M L 2012 GHG targets as insurance against catastrophic climate damages *J. Public Econ. Theory* **14** 221–44

Weyant J 2017 Some contributions of integrated assessment models of global climate change *Rev. Environ. Econ. Policy* **11** 115–37

Zelinka M D, Myers T A, McCoy D T, Po-Chedley S, Caldwell P M, Ceppi P, Klein S A and Taylor K E 2020 Causes of higher climate sensitivity in CMIP6 models *Geophys. Resour. Lett.* **47** e2019GL085782

Zheng Y, Davis S J, Persad G G and Caldeira K 2020 Climate effects of aerosols reduce economic inequality *Nat. Clim. Change* **10** 220–4