Extending a Global Climate-Population Model to Simulate Impacts on Human Well-Being

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Abstract: An existing simulation model of global climate, population, economy, and governance is extended, through statistical and other data analysis, to include several measures of human well-being and population displacement. The revised model is used to explore (in testing to the year 2060) vicious cycles and causal cascades that, some have warned, could lead to acceleration of climate change in the coming decades. Model scenario testing addresses two uncertainties, namely the strength of the effect of climate change on governance erosion, and the strength of the "heat trap" effect from physical tipping points such as ice loss and permafrost thaw. This testing indicates that the heat trap effect could very well accelerate climate change, but that the governance erosion effect (even if relatively strong) is unlikely to do so. Governance erosion would certainly hurt human well-being but probably does not pose much of a threat, in and of itself, for further acceleration of climate change. These results are tentative but point to the possibility of formally modeling causal cascades beyond what the larger climate models have done to date.

Keywords: Climate change; well-being; population displacement; governance; tipping points; statistical regression; global modeling; simulation; system dynamics.

1. Introduction

Large simulation models of climate change, such as those used by the United Nations [1], have been criticized in recent years for certain limitations. These models include highly detailed portrayals of climate, energy use, and economic development, but they have generally not addressed potential vicious cycles and cascades or tipping points in the physical environment and in society. Some scientists have urged the modeling of climate-related cascades, despite the inherent difficulties and uncertainties of doing so, citing evidence that we may be soon entering an era of catastrophic tipping [2-6].

A related line of research on climate change explores its potential adverse effects on individuals and society. Regional studies have estimated the potential effects of climate change on health and mortality [7-10] and on food availability [11, 12]. They have also documented the social and governmental chaos, as well as the population displacement, that persistent droughts and other climate-related natural disasters can cause [13-18]. If climate change undermines social stability and governance, one may imagine that individual physical and emotional well-being might suffer. Stable and supportive conditions are necessary for life satisfaction or "thriving", and a lack of thriving can lead to physical or mental illnesses or even death [19, 20].

This paper reports an effort to incorporate the recent research on physical and social cascades in an existing system dynamics simulation model of global climate, population, economy, and governance [21, 22]. This model is smaller, and thus perhaps less precise, than the UN's climate models and is also smaller than the publicly available En-ROADS model [23] of which it is an offshoot [21].

One of the virtues of smaller models is the ability to quickly revise and extend them into important new areas. The model was adapted to address potential climate impacts on society and human well-being and was also used to address the possible impacts of climate tipping points. The intent was to explore these phenomena and draw general conclusions, rather than to give precise answers. This seemed like an appropriate first step toward addressing some of the modeling gaps that currently exist in the field of climate change.

2. Materials and Methods

The analysis was done in the following steps (see the following sections for more details):

First, annual data on five different quality-of-life variables (suicide rate, homicide rate, happiness, poverty, and undernourishment), from the 1990s to the present (as available), were tabulated for a large number of countries and for the world overall. Statistical regression analysis indicated how these well-being variables appear to be affected by a country's economic status and by aspects of governance.

Second, based on the first step, two additional governance indicators were introduced in the model, and statistical regressions were run to estimate the strength of the linkage from economic status to these governance indicators. The two new governance indicators were Rule of Law and Stability & Peace, which joined the indicators of Government Effectiveness and Regulatory Quality, already in the model [22].

Third, annual data on two measures of population displacement (refugees 1990-2020, internally displaced by conflict 2009-2020) were tabulated for the world overall. Algebraic slope analysis was used to estimate the extent to which post-2000 changes in these variables have been affected by global temperature increases that occurred during the same period.

Fourth, a multiplier was introduced in the model to reflect the erosion of social stability and governance that can occur with climate change, as has been described for the cases of Syria [13, 14] and Sub-Saharan Africa [15]. The strength of this governance erosion effect is uncertain, and a range of possible values was simulated, creating three alternative model scenarios out to 2060.

Fifth, an existing lookup function in the model related to climate tipping was tested. This function shows how heat transfer from the atmosphere to seas and land masses will become increasingly impaired as global temperature rises beyond 1°C above preindustrial, where it was in about 2010. This "heat trap" effect summarizes all climate tipping phenomena, including ice loss, permafrost thaw, forest loss, and coral reef loss [2-4]. This function was initially calibrated based on assumptions in line with larger climate models that have typically projected a temperature of about 2.5°C by 2060 [21]. A steeper version of the lookup function would correspond to a situation in which climate tipping points are encountered sooner, leading to accelerating temperature increase. An additional model scenario was simulated with a much stronger heat trap effect, in order to see how this might play out on the way to 2060.

3. Data and Statistical Analysis for the Well-Being Measures

Annual data were gathered at the country and worldwide level on seven different measures of well-being. A country was included in the dataset for a given variable if it had a 2020 population of one million or more and if it reported consistently on the variable over the years (at least one data point every 5 years). These data supplemented those previously gathered for 150 countries on population size, GDP per capita (GDPPC), and several worldwide governance indicators [22, 24]. The newly gathered well-being data ("D") included five quality-of-life measures (describing personal circumstances) and two measures of mass population displacement, as follows:

- D1. Suicide rate (1990-2019, N=148 countries reporting consistently and worldwide): The worldwide rate per 100,000 declined from 15.0 to 9.5, a 37% reduction. Of the

148 countries, the one with the highest suicide rate during 2015-2019 was Lesotho at a rate of 44 [25].

- D2. Homicide rate (1990-2019, N=148 and worldwide): The worldwide rate per 100,000 declined from 7.5 to 5.3, a 29% reduction. Of the 148 reporting countries, the ones with the highest homicide rate during 2015-2019 were El Salvador (at a rate of 60) and Honduras (at 49) [25].
- D3. Happiness (2005-2021, the Cantril/Gallup 1-10 life satisfaction scale, N=131 and worldwide): The worldwide average declined slightly from 5.3 to 5.2. Of the 131 reporting countries, the least happy during 2015-2021 was Central African Republic at 3.1 [26].
- D4. Poverty fraction (World Bank, 1990-2018, N=86 and worldwide): The worldwide figure declined from 0.55 to 0.26, a relative reduction of 53%. Of the 86 reporting countries, the poorest during 2015-2018 was Malawi at 89%, followed by Rwanda (80%), Tanzania (77%), and Zambia (74%) [27].
- D5. Undernourished fraction (1991-2020; N=94 and worldwide): The worldwide figure declined from 0.15 to 0.08, a relative reduction of 47%. Of the 94 reporting countries, the most undernourished during 2015-2021 was Central African Republic at 47%, followed by Madagascar (45%) and Haiti (42%) [28].
- D6. Refugees (1990-2020, all countries): The worldwide total declined from 19.9 million in 1990 to a low of 13.0 million in 2005, and then climbed steadily to 26.4 million by 2020. The country of origin with the most refugees in 2020 was Syria (6.0 million), followed by Afghanistan (2.6 million) and Sudan/South Sudan (2.6 million) [29, 30].
- D7. Population internally displaced by conflict (2009-2020, all countries): The worldwide total declined from 25.0 million in 2009 to a low of 22.4 million in 2011 and then climbed steadily to 48.0 million by 2020. The country with the most people displaced by conflict in 2020 was Syria (6.6 million), followed by Colombia (4.9 million), Sudan/South Sudan (3.7 million), Yemen (3.6 million), Afghanistan (3.5 million), Somalia (3.0 million), and Nigeria (2.7 million) [31].

Statistical regression analysis was performed for the first five variables above, the quality-of-life measures. For Suicide rate, Homicide rate, Poverty fraction, and Undernourished fraction, the gathered data were averaged across 5-year time periods, starting with 1995-2000 and going through 2015-2020. For these variables, 1995-2000 was designated as the baseline period, and differences against the baseline were calculated for each subsequent 5-year period. In the case of Happiness (first measured in 2005), the gathered data were averaged across three time periods: 2005-2010, 2010-2015, and 2015-2021. For this variable, 2005-2010 was designated as the baseline period, and differences against the baseline were calculated for 2010-2015 and 2015-2021.

Linear regressions were performed for each non-reference time period separately, looking for strong associations that are consistent across most or all of the time periods. Insignificant factors (with higher p-values) were winnowed sequentially to maximize adjusted R-squared. The regressions were performed to test the hypothesis that a given well-being measure might be influenced by the country's economic health (namely, the natural logarithm of GDPPC, hereafter lnGDPPC, and/or the annual growth rate of GDPPC) and by one or more of the six worldwide governance indicators. Key results of the regression analysis are shown in **Table S1** in the supplementary file. These results show consistent significant contributions from lnGDPPC for each of the quality-of-life measures, as well as effects on Suicide rate, Homicide rate, and Happiness from three of the governance indicators, namely Government Effectiveness, Rule of Law, and Stability & Peace.

It was previously hypothesized that the governance indicators themselves may be positively influenced by lnGDPPC, and regressions showed strong effects of lnGDPPC on Government Effectiveness and Regulatory Quality [22]. In light of regression results showing the influences of not only Government Effectiveness but also Rule of Law and Stability-Peace on several of the quality-of-life measures, a similar regression analysis was performed for these two governance indicators. These results show significant contributions of lnGDPPC for Rule of Law and Stability-Peace.

4. Estimating Effects of Climate Change on Well-Being and Governance

The literature suggested direct adverse effects of climate change for some of the well-being measures (undernourishment, refugees, internal displacement, and possibly homicide), as well as examples of how climate change could erode the quality of governance. These effects were estimated as follows.

Undernourishment (see [11, 12]): Springmann [11] projected 529,000 additional deaths from climate-related food crop failures in 2050, or about 7% beyond the approximately 7.5 million deaths from hunger predicted otherwise. With a 1.0˚C increase in temperature expected from 2017 to 2050 (see [21]), this implies a 7% boost in hunger-related deaths, which may suggest also a 7% boost in undernourishment more broadly. (This 7% assumption also lies within the range of projections of global crop failures found in [12], pages 45-46.)

Refugees (see [13-15]): A coefficient for the effect of climate change on refugees was estimated as 0.90 (that is, an increase of 90%) per 1.0˚C of additional warming. This coefficient was estimated by focusing on the 2000-2015 period (when both the refugee rate and temperature were rising) and calculating a slope or derivative of change. With this assumption, the revised climate-population model (with all its baseline assumptions) projects refugees will rise from 26 million in 2020 to 60 million in 2050 and 73 million in 2060.

Internally Displaced Population (see [13-15, 32]): A coefficient for the effect of climate change on internal displacement was estimated at 2.65 (that is, an increase of 265%) per 1.0˚C of additional warming. This coefficient was estimated in two ways. First, a slope of change was calculated over the 2009-2020 period, resulting in an average slope of 3.33. Second, the World Bank's "Groundswell" report [32] projects 170 million people internally displaced due to climate change by 2050, a number that suggests about 195 million internally displaced for all reasons (climate-related or not). The revised climate-population model matches this 2050 projection when the coefficient is set to 2.65. In deference to the World Bank's analysis, the coefficient was set to 2.65.

Homicide (see [18, 33, 34]: The literature is divided on whether increased temperatures leads to more interpersonal violence including homicide. A meta-analysis of 55 studies seems to support the hypothesis [33], but a more recent study of temperature and homicide, which (unlike previous analyses) controls for economic and other trends, calls the hypothesis into question [34]. In deference to this last study, the revised climate-population model does not include such a relationship, but it could be added in the future if further studies warrant it.

Governance (see [13-16]): The revised model also includes an adverse effect of climate change on governance, assuming the same multiplier for all four governance indicators. Although the literature is informative, the worldwide strength of this effect is uncertain. For comparison, one may consider the model's existing adverse effect of climate change on GDP per capita, which reduces global GDPPC by about 5.3% against what it would be without the projected 1.0˚C of additional warming from 2017 to 2050. For the effect on governance, coefficient values were tested over a wide range of 0% to 10%, including a midrange value of 4%.

5. Revised Model

An overview of the revised climate-population model is shown in **Figure 1**. New elements include the five quality-of-life measures, as well as the global counts of refugees and internally displaced people. These well-being measures are outputs of the model, capturing the human effects of climate change beyond economic damages and mortality.

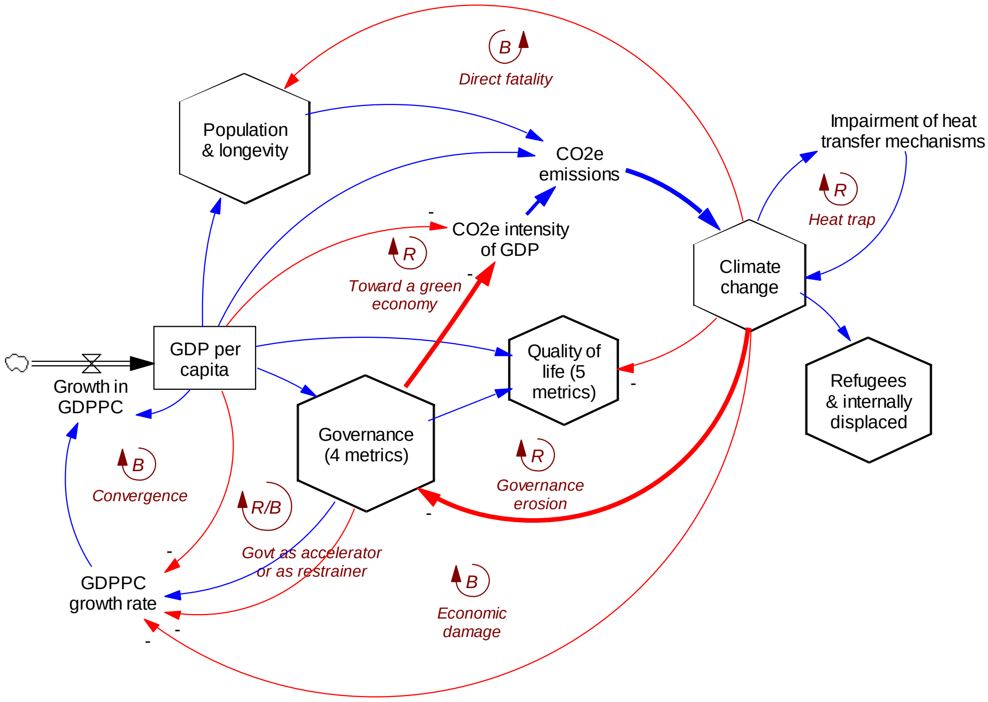

Figure 1. Overview of revised model structure. The four measures of governance are government effectiveness, regulatory quality, rule of law, and stability-peace. The five quality-of-life metrics are suicide rate, homicide rate, happiness, poverty, and undernourishment. Blue arrows indicate positive link polarity; red arrows negative. "B" feedback loops are balancing; "R" are reinforcing. The revised model includes 268 active equations and parameters, with (as before) 20 population age groups and 3 broad causes of death [21].

Also new is the adverse effect of climate change on governance, which creates a reinforcing feedback loop (the circle of thicker arrows) labeled as "Governance erosion". This loop has the potential, via diminished regulatory quality (a key aspect of governance [22]), to undermine progress on CO2-equivalent emissions, and thus further accelerate climate change to some degree.

Figure 1 also includes the reinforcing "heat trap" effect noted above, reflecting climate tipping points that impair heat transfer from the atmosphere to the seas and land masses. This loop has always been part of the model but is made explicit here to underscore the goal of testing the possibility of earlier climate tipping.

The revised model includes 12 new or revised equations, presented in **Table 1**. These twelve equations ("E") were formulated and estimated as follows:

Table 1. Twelve new or revised equations in the model, based on regression results, adjustment for historical fit, and inferences from other studies.

(1) Suicides per 100 thou = 15.6 – (ln GDPPC ratio to 1990 × 10.5) - (Govt effectiveness delta vs 1990 × 35)

(2) Homicide per 100 thou = 7.5 – (ln GDPPC ratio to 1990 × 5.5) - (Rule of law delta vs 1990 × 15.0) - (Stability peace delta vs 1990 × 3.75)
(3) Happiness = 4.9 + (ln GDPPC ratio to 1990 × 0.75) + (Govt effectiveness delta vs 1990 × 1.5) + (Rule of law delta vs 1990 × 0.85) + (Stability peace delta vs 1990 × 0.15)
(4) Poverty fraction = 0.55 – (ln GDPPC ratio to 1990 × 0.63)
(5) Undernourished fraction = 0.16 × (1 + Temperature delta vs 2017 × 0.07) – (ln GDPPC ratio to 1990 × 0.20)
(6) Govt effectiveness = (0.48 + (ln GDDPC ratio to 1990 × 0.08)) × Climate change multiplier on governance
(7) Regulatory quality = (0.46 + (ln GDDPC ratio to 1990 × 0.06)) × Climate change multiplier on governance
(8) Rule of law = (0.48 + (ln GDDPC ratio to 1990 × 0.065)) × RAMP(from 1.0 [1995] to 0.93 [2005]) × Climate change multiplier on governance
(9) Stability peace = (0.44 + (ln GDDPC ratio to 1990 × 0.10)) × RAMP(from 1.0 [1995] to 0.78 [2005]) × Climate change multiplier on governance
(10) Climate change multiplier on governance = 1 – Temperature delta vs 2017 × 0.04
(11) Refugees per thou (starting 2017) = 3.2 × (1 + Temperature delta vs 2017 × 0.90)
(12) Internally displaced per thou (starting 2017) = 5.4 × (1 + Temperature delta vs 2017 × 2.65)

- E1. Suicide rate: The regressions indicated significant influence of lnGDPPC and Government Effectiveness. The parameters were adjusted to achieve a close fit to history. (**Figure S1** in the supplementary file shows the historical fit to data for this and all output variables in Table 2 except #10.)
- E2. Homicide rate: The regressions indicated significant influence of lnGDPPC, Rule of Law, and Stability-Peace. The parameters were adjusted to achieve a close fit to history.
- E3. Happiness: The regressions indicated significant influence of lnGDPPC, Government Effectiveness, Rule of Law, and Stability-Peace. The parameters were adjusted to achieve a close fit to history.
- E4. Poverty fraction: The regressions indicated significant influence of lnGDPPC. The parameters were adjusted to achieve a close fit to history.
- E5: Undernourished fraction: The regressions indicated significant influence of lnGDPPC. The parameters were adjusted to achieve a close fit to history. The equation also includes the adverse effect of climate change on undernourishment described above.
- E6-E10: Governance indicators: Regression-based equations for Government Effectiveness and Regulatory Quality were described previously [22]. For Rule of Law and Stability-Peace, the regressions were used to estimate the coefficients for lnGDPPC, and downward ramps from 1995 to 2005 (7% for Rule of Law and 22% for Stability-Peace) were introduced exogenously to help produce closer fits to history. The revised model also includes an adverse effect of climate change on governance (eqn. 10), assuming the same multiplier for all four governance indicators. The coefficient is uncertain, as described above; equation 10 shows a mid-range value of 4% erosion in governance per 1.0°C of additional warming.
- E11. Refugee rate: The worldwide refugee rate (refugees per thousand population) follows history until 2017 when its value was 3.2. After 2017, that 3.2 is multiplied by an adverse effect of climate change that increases refugees with a coefficient of 0.90 per 1.0°C of additional warming, as described above.
- E12. Internally displaced rate: The worldwide internal displacement rate (per thousand population) follows history (available starting 2009) until 2017 when its value was 5.4. After 2017, that 5.4 is multiplied by an adverse effect of climate change

that increases the internally displaced rate with a coefficient of 2.65 per 1.0°C of additional warming, as described above.

6. Scenario Testing

The revised model was simulated from 1990 to 2060 under four alternative scenario settings. The first three scenarios vary the assumed strength of the climate-related governance erosion effect, with alternative values of 0% (least pessimistic), 4% (midrange), and 10% (most pessimistic). The fourth scenario is even more pessimistic, layering on top of the third scenario a much stronger heat trap effect, which triples the strength of the lookup function for impaired heat transfer. In other words:

- Scenario 1: 0% governance erosion effect, default (1x) heat trap effect;
- Scenario 2: 4% governance erosion effect, 1x heat trap effect;
- Scenario 3: 10% governance erosion effect, 1x heat trap effect;
- Scenario 4: 10% governance erosion effect, 3x heat trap effect.

Selected time graphs of scenario simulation results are presented in the six panels of **Figure 2**. Numerical results for 15 output variables for the years 2010 and 2060 are presented in **Table 2**. Taken together, these simulation outputs tell a story as follows:

First, the governance erosion effect of climate change puts downward pressure on all measures of governance, so that, instead of continuing to climb with improving GDPPC (as in Scenario 1), they start declining by the 2030s (in Scenario 2) or by the 2020s (in Scenario 3); see Government Effectiveness and Rule of Law in **Figure 2**. This erosion in governance, in turn, directly hurts the quality-of-life measures to varying degrees. As Table 2, shows, the Suicide and Homicide rates are quite sensitive to the erosion in governance (e.g., the Suicide rate ends 86% higher in Scenario 3 compared with Scenario 1), whereas the Happiness index is much less sensitive (only a 4% reduction). The erosion in governance also hurts GDPPC, which ends 4% lower in Scenario 3 compared with Scenario 1; this reduction in GDPPC, in turn, reduces average life expectancy by 0.3 years (from 75.8 to 75.5).

Second, despite the significant erosion in governance in Scenarios 2 and 3, the reinforcing feedback to emissions (via declining regulatory quality) does not have much of an impact on climate change nor on climate-affected well-being measures. Comparing Scenarios 3 and 1 in 2060, the 14% decline in regulatory quality results in only a 1.5% increase in CO_2e emissions, a 0.02°C increase in temperature, a 1.0% increase in refugees, and a 1.3% increase in the internally displaced.

Third, whereas governance erosion does not have much impact on climate change, a more severe heat trap effect clearly does so. This climate tipping effect results in a temperature vs. preindustrial of 3.21°C in Scenario 4 compared with 2.54°C in Scenario 3. As a consequence, governance is further eroded, and all well-being measures are adversely affected, as are GDPPC and life expectancy. Most tellingly, refugees increase by 25% and the internally displaced by 36%.

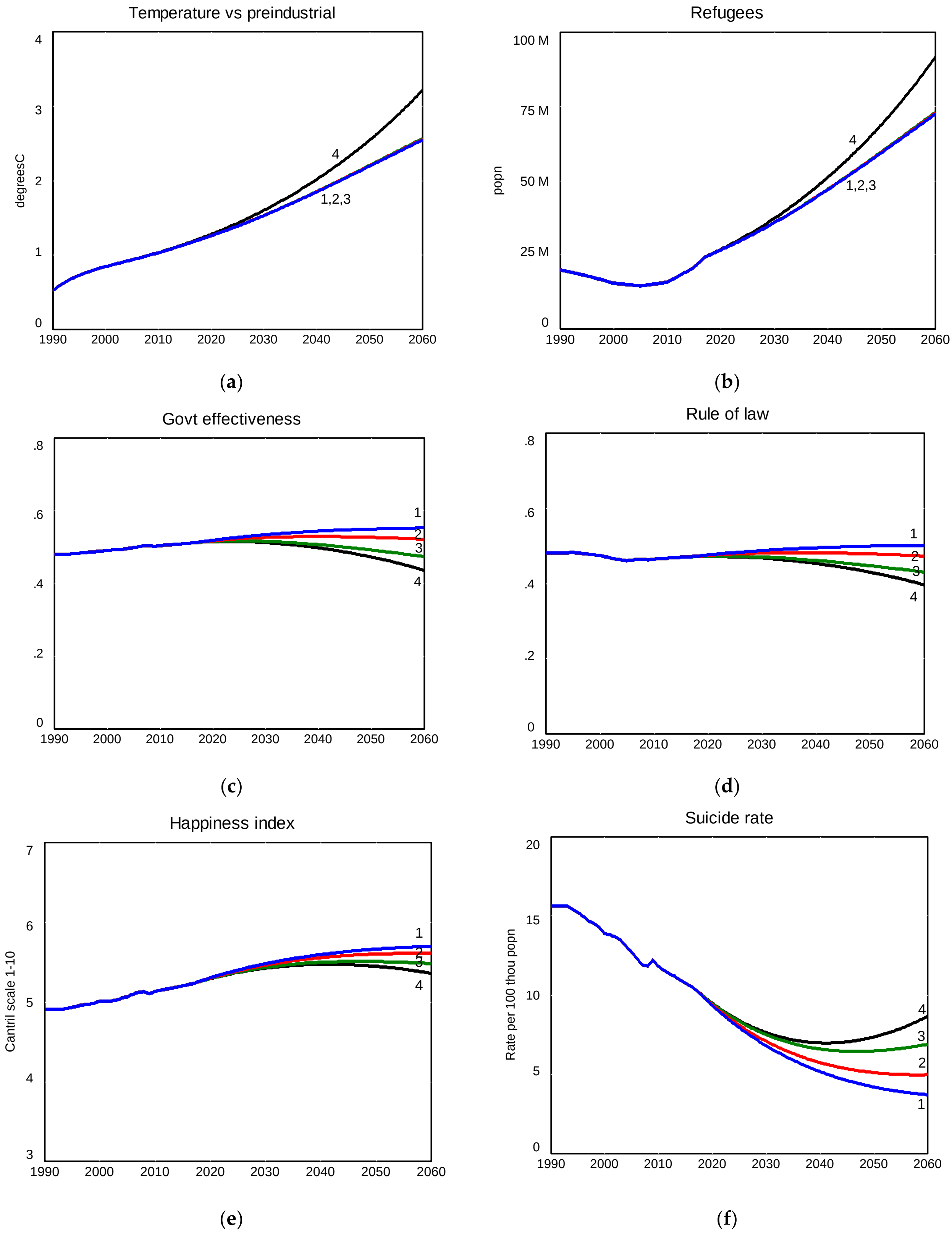

Figure 2. Four scenarios varying uncertain governance erosion and heat trap effects of climate change. 1-Blue: 0% erosion, 1x trap; 2-Red: 4% erosion, 1x trap; 3-Green: 10% erosión, 1x trap; 4-Black: 10% erosión, 3x trap. Simulated results for six output variables 1990-2060: (a) Temperature delta vs preindustrial (°C); (b) Refugees (millions); (c) Government effectiveness (0-1 index); (d) Rule of law (0-1 index); (e) Happiness (1-10 index); (f) Suicide rate (per 100,000 population). .

Table 2. Simulated results of four scenarios as of 2060. S1: 0% governance erosion, 1x heat trap; S2: 4% erosion, 1x trap; S3: 10% erosion, 1x trap; S4: 10% erosion, 3x trap.

	2010	2060 value by scenario			
Output variable	**value**	**S1**	**S2**	**S3**	**S4**
Temp. vs preindustrial (°C)	1.03	2.54	2.55	2.56	3.21
CO2e emissions (gtonnes/yr.)	51.5	90.4	91.3	91.8	90.4
Refugees (million)	15.6	72.2	72.5	72.9	91.5
Internally displaced (million)	23.6	252.2	253.5	255.4	348
GDP per capita ($/person/yr.)	9545	17552	17272	16859	16163
Life expectancy (years)	70.6	75.8	75.7	75.5	75.2
Government effectiveness (0-1)	0.503	0.552	0.52	0.473	0.435
Regulatory quality (0-1)	0.477	0.514	0.485	0.441	0.406
Rule of law (0-1)	0.464	0.501	0.472	0.429	0.396
Stability-peace (0-1)	0.365	0.413	0.389	0.353	0.325
Happiness (1-10 index)	5.12	5.69	5.61	5.47	5.35
Suicide rate (per 100,000)	11.80	3.70	4.96	6.88	8.64
Homicide rate (per 100,000)	6.45	2.37	2.97	3.88	4.72
Poverty fraction (0-1)	0.370	0	0	0.012	0.038
Undernourished fraction (0-1)	0.103	0	0	0.005	0.020

7. Discussion

Climate change is a looming crisis for the entire world, creating concerns for future human well-being. Regional studies have demonstrated the risks climate change poses for health, food availability, and social and governmental stability [7-18]. At the same time, scientists have identified several worrisome potential tipping points that threaten to accelerate climate change and make it worse than has been previously projected [2-4]. Some have warned moreover that the physical and social effects could cascade and compound one another, leading to a potential "climate catastrophe" in the coming decades [5-6]. However, to date these cascades have only been described rather than quantified and simulated.

This paper has used a relatively compact climate-population simulation model to explore the possible speed and strength of climate-related cascades. This model includes effects of climate change on life expectancy [21] and governance [22] and has now been extended (with the support of extensive data analysis) to also incorporate multiple measures of well-being and climate-related population displacement.

Scenario analysis addressed two areas of uncertainty involving effects of climate change: the strength of the heat trap effect, and the strength of the governance erosion effect. The model suggests that both effects could reverse worldwide progress on human well-being.

In particular, the heat trap effect could accelerate climate change, hurting some aspects of well-being directly (undernourishment, refugees, internally displaced) and others indirectly through the adverse effect of climate change on governance.

In addition, erosion of governance (in three areas: government effectiveness, rule of law, and stability and peace) could strongly undermine progress on suicide and homicide. It could also hurt economic growth and undermine improvements in life expectancy.

However, the feedback loop from climate change through erosion of regulatory quality (the fourth area of governance in the model) does not appear to be strong and fast enough to noticeably accelerate climate change in the way the heat trap effect does.

These findings, though tentative, may help clarify the significance of various causal cascades. Such clarification could inform larger, more detailed climate models ([1, 23]), whose primary purpose is projection of climate change and not social effects. The work here suggests that better modeling of physical tipping points (the heat trap) may be critical for more accurate climate change projection. On the other hand, although it is possible and important to model social and governance effects of climate change, the modeling of governance erosion is not critical for more accurate climate change projection per se. Even without governance erosion, the world is proving itself sadly capable of pushing past the physical tipping points [2-4].

Because the model used here is less detailed than larger climate models, its limitations are obvious. Nonetheless, the smaller model is still strongly evidence-based and may help us (as scientists and citizens) turn productively from vague omnidirectional fears to more focused and warranted concerns.

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References

1. UNFCCC (United Nations Framework Convention on Climate Change). 2023. Integrated Assessment Models (IAMs) and Energy-Environment-Economy (E3) Models. https://unfccc.int/topics/mitigation/workstreams/response-measures/modelling-tools-to-assess-the-impact-of-the-implementation-of-response-measures/integrated-assessment-models-iams-and-energy-environment-economy-e3-models
2. McKay DIA, Staal A, Abrams JF, Winkelmann R, Sakschewski B, Loriani S, Fetzer I, Cornell SE, Rockström J, Lenton TM. 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377(6611).
3. Lenton TM, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W, Schellnhuber HJ. 2019. Climate tipping points-too risky to bet against. Nature 575(7784):592-595.
4. Zaelke D, Picolotti R, Dreyfus G, and others. 2020. The need for fast near-term climate mitigation to slow feedbacks amd avoid tipping points. Institute for Governance & Sustainable Development (IGSD) and Center for Human Rights and Environment (CHRE). 15 September 2023, 168 pp. https://www.igsd.org/wp-content/uploads/2020/09/Science-Supporting-Need-for-Fast-Near-Term-Climate-Mitigation-Sept2020.pdf
5. Rocha JC, Peterson G, Bodin Ö, Levin S. 2018. Cascading regime shifts within and across scales. Science 362(6421):1379-1383.
6. Kemp L, Xu C, Depledge J, Ebi KL, Gibbins G, Kohler TA, Rockström J, and others. 2022. Climate endgame: exploring catastrophic climate change scenarios. PNAS 119(34); 9 pp.
7. WHO (World Health Organization). 2014. Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. 18 September 2014. 128 pp. https://www.who.int/publications/i/item/9789241507691
8. Ebi KL, Hess JJ, Watkiss P. 2017. Health risks and costs of climate variability and change. Chapter 8, pp. 153-169. In: Injury Prevention and Environmental Health (3rd edition), eds. Mock CN, Nugent R, Kobusingye O, Smith KR. The World Bank: Washington, DC. https://www.dcp-3.org/chapter/2487/health-risks-and-costs-climate-variability-and-change
9. WHO (World Health Organization). 2018. COP24 special report: health & climate change. 3 December 2018. 74 pp. https://www.who.int/publications/i/item/9789241514972
10. WHO (World Health Organization). 2023. Climate change. 12 October 2023. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
11. Springmann M, Mason-D'Croz D, Robinson S, Garnett T, and others. 2016. Global and regional health effects of future food production under climate change: a modelling study. Lancet 387:1937-1946.
12. World Bank. 2012. Turn Down the Heat: Why a 4°C Warmer World Must be Avoided. World Bank Group: Washington DC. November 2012, report 74455, 105 pp. https://documents.worldbank.org/en/publication/documents-reports/documentdetail/865571468149107611/turn-down-the-heat-why-a-4-c-warmer-world-must-be-avoided

13. de Châtel F. 2014. The role of drought and climate change in the Syrian uprising: untangling the triggers of the revolution. Middle Eastern Studies 50(4):521-535.
14. Kelley C, Mohtadi S, Cane M, Seager R, Kushnir Y. 2015. Climate change in the Fertile Crescent and implications of the recent Syrian drought. PNAS 112 (11):3241-3246.
15. Adano WR, Daudi F. 2012. Links between climate change, conflict and governance in Africa. Institute for Security Studies Paper No. 234. May 2012, 16 pp. https://www.files.ethz.ch/isn/145415/Paper_234.pdf
16. Obradovich N, Tingley D, Rahwan I. 2018. Effects of environmental stressors on daily governance. PNAS 115(35):8710-8715.
17. Schleussner C-F, Donges JF, Donner RV, Schellnhuber HJ. 2016. Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. PNAS 113(33): 9216-9221.
18. Burke M, Hsiang SM, Miguel E. 2015. Climate and conflict. Amer Rev Econ 7:577-617.
19. Arora A, Spatz E, Herrin J, Riley C, Roy B, Kell K, Coberley C, Rula E, Krumholz HM. 2016. Population well-being measures help explain geographic disparities in life expectancy at the county level. Health Affairs 2016;35(11):2075-82.
20. Botchwey N, Dannenberg A, Frumkin H. 2022. Making Healthy Places: Designing and Building for Well-Being, Equity, and Sustainability. 2nd ed, 552 pp. Island Press: Washington DC. https://islandpress.org/books/making-healthy-places-second-edition
21. Homer J. 2020. Modeling global loss of life from climate change through 2060. Sys Dyn Rev 36(4):523-535.
22. Homer J. 2022. Can good government save us? Extending a climate-population model to include governance and its effects. Systems 10(37): 11 pp.
23. Climate Interactive. 2023. The En-ROADS climate solutions simulator. https://www.climateinteractive.org/en-roads/
24. Kaufmann D, Kraay A. 2023. Worldwide Governance Indicators, 2023 Update. https://www.worldbank.org/en/publication/worldwide-governance-indicators
25. IHME (Institute of Health Metrics and Evaluation). 2023. Global Health Data Exchange: deaths by homicide and suicide. https://ghdx.healthdata.org/
26. Helliwell JF, Layard R, Sachs JD, Aknin LB, De Neve J-E, Wang S (Eds.). 2023. World Happiness Report 2023 (11th ed). Sustainable Development Solutions Network (using Gallup World Poll data). https://worldhappiness.report/ed/2023/#appendices-and-data
27. World Bank. 2023. Poverty headcount ratio at $3.65 a day (2017 PPP). https://data.worldbank.org/indicator/SI.POV.LMIC
28. FAO (Food and Agriculture Organization of the United Nations). 2023. Suite of Food Security Indicators. https://fao.org/faostat/en/#data/FS
29. UNHCR (The UN Refguee Agency). 2023. Refugee Data Finder. https://www.unhcr.org/refugee-statistics/
30. World Bank. 2023. Refugee population by country or territory of asylum. https://data.worldbank.org/indicator/SM.POP.REFG
31. IDMC (Internal Displacement Monitoring Centre). 2023. Global Internal Displacement Database. https://www.internal-displacement.org/database/displacement-data
32. Clement V, Rigaud KK, de Sherbinin A, Jones B, Adarno S, Schewe J, Sadiq N, Shabahat E. 2021. Groundswell Part 2: Acting on Internal Climate Migration. World Bank: Washington DC. http://hdl.handle.net/10986/36248
33. Ronson M. 2014. Crime, weather, and climate change. J Envir Econ and Mgmt 67(3):274-302.
34. Lynch MJ, Stretesky PB, Long MA. 2020. Climate change, temperature, and homicide: a tale of two cities, 1895-2015. Weather Climate and Society 12(1):171-181.

Supplementary File S1: Extending a Global Climate-Population Model to Simulate Impacts on Human Well-Being
Jack Homer, 2024

TABLE S1. Statistical regression results across many countries, by 5-year time period, based on variables expressed as changes (delta) against a reference period. (ns = not significant and not present in best regression equation.)

	Regressions maximizing adjusted R-squared: Coefficients (1st row) and p-values (2nd row)			
time period:	**2000—05**	**2005—10**	**2010—15**	**2015—20**
Y1: Suicide rate per 100,000 (N=148), delta vs 1995-2000				
X1: ln GDPPC	–2.30	–1.91	–2.17	–1.83
p-value	*0.045*	*0.078*	*0.062*	*0.108*
X2: Govt Effectiveness	–8.36	–7.07	–9.77	–11.13
p-value	*0.118*	*0.225*	*0.066*	*0.030*
X3: Rule of Law	–6.80	–6.11	ns	ns
p-value	*0.203*	*0.320*		
Y2: Homicide rate per 100,000 (N=148), delta vs 1995-2000				
X1: ln GDPPC	ns	ns	–1.74	ns
p-value			*0.287*	
X2: GDDPC growth rate	ns	–8.26	ns	ns
p-value		*0.201*		
X3: Rule of Law	–16.61	–21.95	–18.70	–11.04
p-value	*0.004*	*4×10^{-4}*	*0.018*	*0.132*
X4: Stability,& Peace	ns	ns	ns	–7.51
p-value				*0.073*
Y3: Happiness (1-10 scale) (N=131), delta vs 2005-2010				
X1: ln GDPPC			1.041	0.447
p-value			*2×10^{-4}*	*0.093*
X2: Govt Effectiveness			0.271	2.662
p-value			*0.217*	*0.006*
X3: Rule of Law			1.718	ns
p-value			*0.216*	
X4: Stability & Peace			0.297	ns
p-value			*0.134*	
Y4: Poverty percentage (N=86), delta vs 1995-2000				
X1: ln GDPPC	–14.33	–27.66	–31.14	
p-value	*0.06*	*6×10^{-6}*	*8×10^{-7}*	
X2: Stability & Peace	–14.39	ns	ns	
p-value	*0.231*			
Y5: Undernourishment percentage (N=94), delta vs 1995-2000				
X1: ln GDPPC	–8.67	–7.74	–8.12	–15.20
p-value	*0.277*	*0.057*	*0.010*	*4×10^{-6}*
X2: Govt Effectiveness	–27.59	ns	ns	ns
p-value	*0.317*			
Y6: Rule of Law (0-1) (N=150), delta vs 1995-2000				
X1: ln GDPPC	0.030	0.049	0.055	0.074
p-value	*0.141*	*0.006*	*0.001*	*5×10^{-6}*
Y7: Stability & Peace (0-1) (N=150), delta vs 1995-2000				
X1: ln GDPPC	0.058	0.089	0.098	0.101
p-value	*0.127*	*0.004*	*7×10^{-4}*	*4×10^{-4}*

FIGURE S1. Eleven graphs showing the model's fit to history.

A previous paper (Homer 2020) showed how the Climate-Population model could reproduce historical data and official projections for global population size, births, deaths, life expectancy, CO_2 emissions, and temperature. The new paper extends the model into areas of human well-being. It describes (in Section 5, Revised Model) a "close fit to history" for the model's 7 well-being variables and 4 governance variables. The graphs below demonstrate this fit, with a solid blue graph line for simulation output and red dots for data. Two of the graphs also include a thin green line showing what the simulated output would be if the only input were the assumed exogenous ramp for the variable (see equations 8 and 9 in the main paper.)

All 11 graphs also report the MAEM summary statistic, which calculates the Mean Absolute Error between simulation and data and divides it by the mean across the data points used for comparison. (The number of comparison points for each graph is reported below as "Ncompare".) The MAEM statistic is a robust and straightforward alternative to other goodness-of-fit statistics including MAPE, RMSE, and R-squared. For relatively smooth data series, such as those in the graphs below, a MAEM value of less than 0.10 indicates an acceptably close fit to history (Sterman 2000, Homer & Wakeland 2020, Wakeland & Homer 2022).

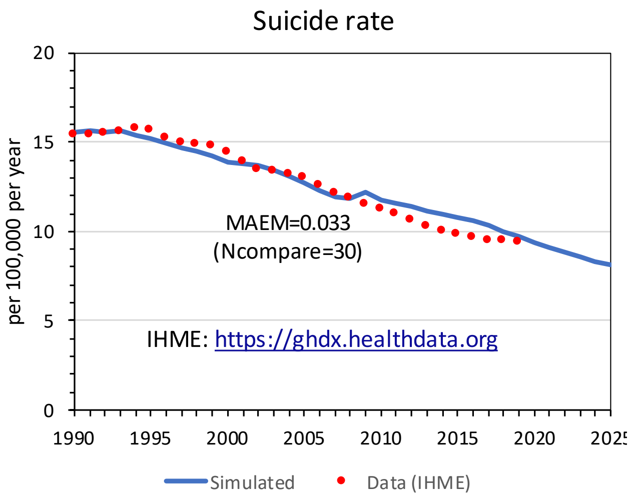
References

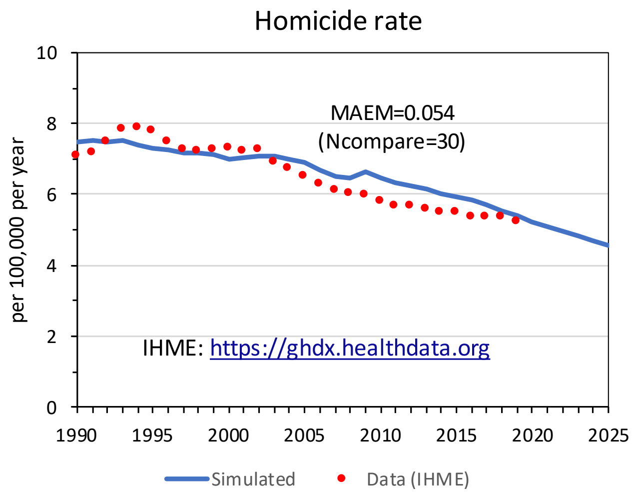
a. Homer J. 2020. Modeling global loss of life from climate change through 2060. Sys Dyn Rev 36(4):523-535.

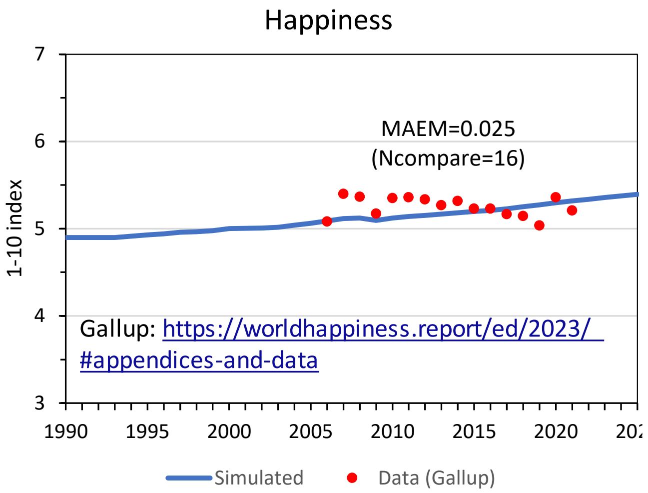
b. Sterman JD. 2000. Business dynamics: systems thinking and modeling for a complex world. Boston: Irwin McGraw-Hill.

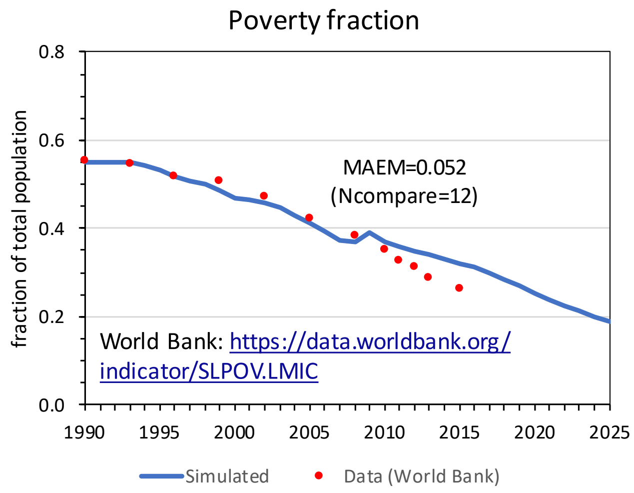
c. Homer J, Wakeland WW. 2020. A dynamic model of the opioid drug epidemic with implications for policy. Am J Drug and Alcohol Abuse, 11 pp. https://www.tandfonline.com/doi/full/10.1080/00952990.2020.1755677

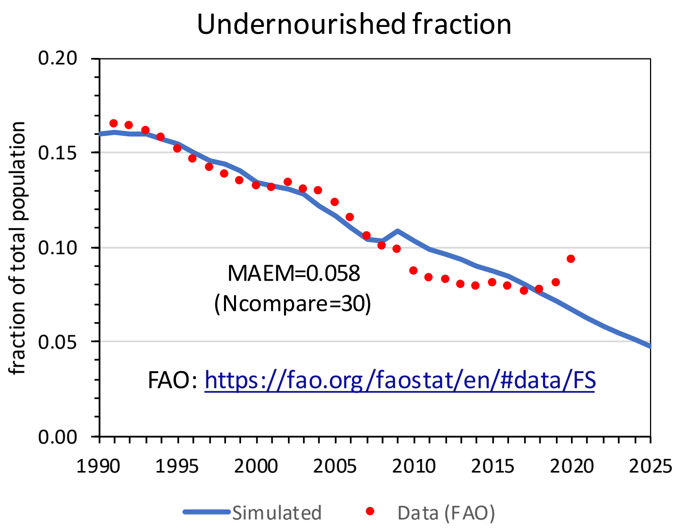
d. Wakeland W, Homer J. 2022. Addressing parameter uncertainty in a health policy simulation model using Monte Carlo sensitivity methods. Systems 10(225), 17 pp. https://doi.org/10.3390/systems10060225

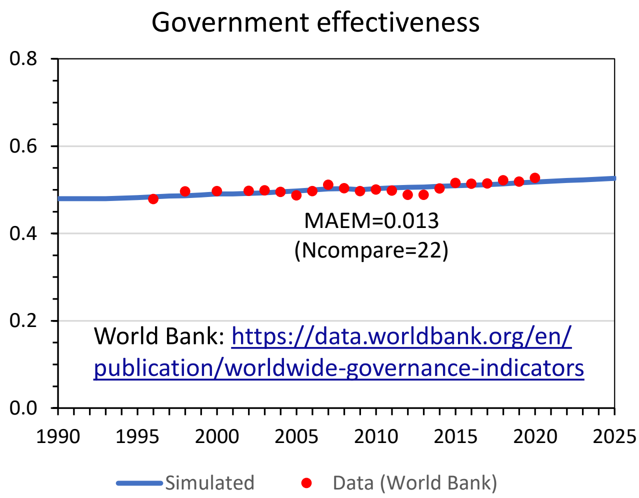

Suicide rate
per 100,000 per year
MAEM=0.033
(Ncompare=30)
IHME: https://ghdx.healthdata.org
Simulated
Data (IHME)

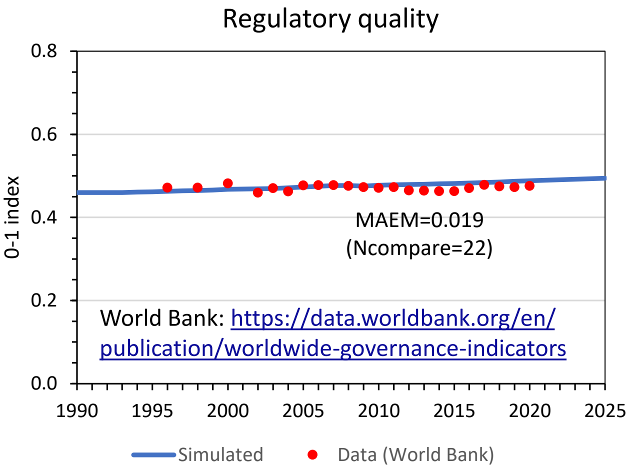

Homicide rate
per 100,000 per year
MAEM=0.054
(Ncompare=30)
IHME: https://ghdx.healthdata.org
Simulated
Data (IHME)

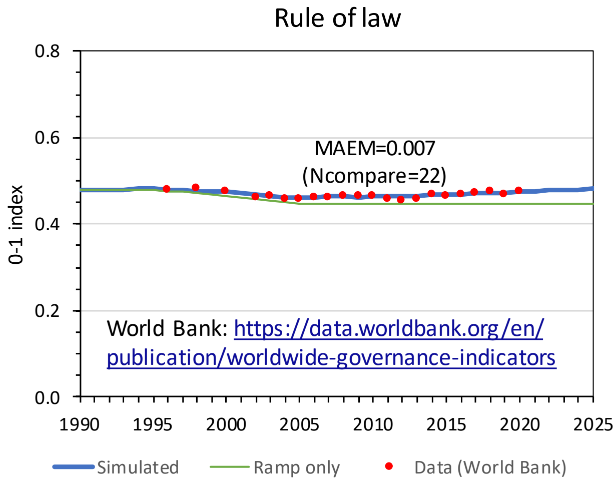

Happiness
1-10 index
MAEM=0.025
(Ncompare=16)
Gallup: https://worldhappiness.report/ed/2023/ #appendices-and-data
Simulated
Data (Gallup)

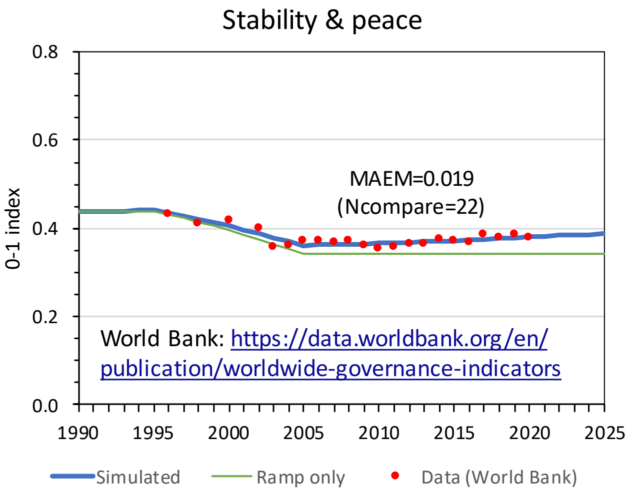

Poverty fraction
fraction of total population
MAEM=0.052
(Ncompare=12)
World Bank: https://data.worldbank.org/ indicator/SLPOV.LMIC
Simulated
Data (World Bank)

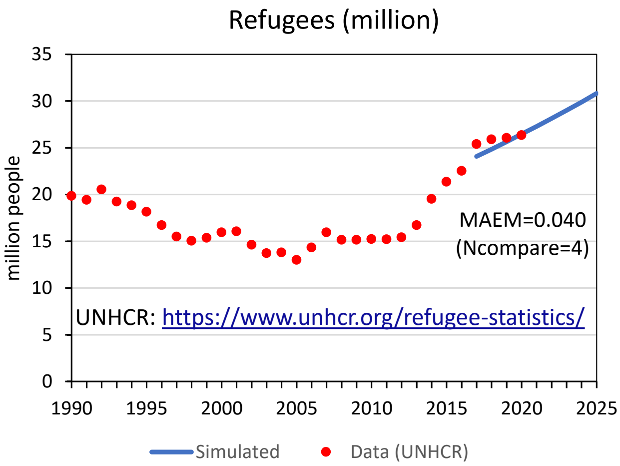

Undernourished fraction
fraction of total population
MAEM=0.058
(Ncompare=30)
FAO: https://fao.org/faostat/en/#data/FS
Simulated
Data (FAO)

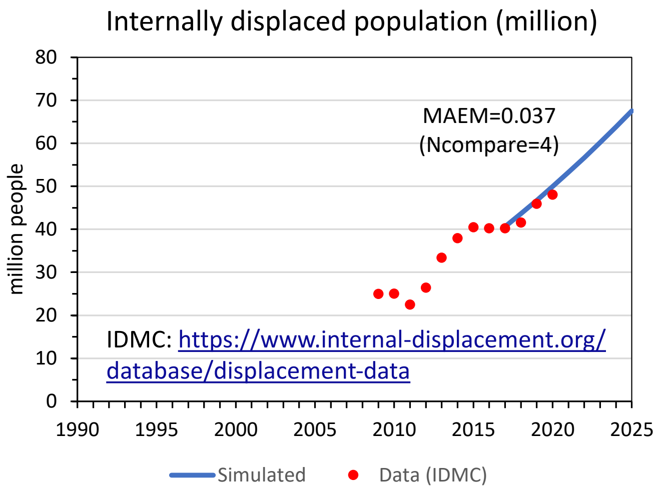

Government effectiveness
MAEM=0.013
(Ncompare=22)
World Bank: https://data.worldbank.org/en/ publication/worldwide-governance-indicators
Simulated
Data (World Bank)


Regulatory quality
0-1 index
MAEM=0.019
(Ncompare=22)
World Bank: https://data.worldbank.org/en/publication/worldwide-governance-indicators
Simulated
Data (World Bank)


Rule of law
0-1 index
MAEM=0.007
(Ncompare=22)
World Bank: https://data.worldbank.org/en/publication/worldwide-governance-indicators
Simulated
Ramp only
Data (World Bank)


Stability & peace
0-1 index
MAEM=0.019
(Ncompare=22)
World Bank: https://data.worldbank.org/en/publication/worldwide-governance-indicators
Simulated
Ramp only
Data (World Bank)


Refugees (million)
million people
MAEM=0.040
(Ncompare=4)
UNHCR: https://www.unhcr.org/refugee-statistics/
Simulated
Data (UNHCR)


Internally displaced population (million)
million people
MAEM=0.037
(Ncompare=4)
IDMC: https://www.internal-displacement.org/database/displacement-data
Simulated
Data (IDMC)