UNIVERSITY OF DELAWARE

GERARD J. MANGONE
Climate Change Science & Policy Hub

LOSS AND DAMAGE TODAY:

HOW CLIMATE CHANGE IS IMPACTING OUTPUT AND CAPITAL

DR. JAMES RISING

NOV. 2023

Loss and Damage Today: How climate change is impacting output and capital
Gerard J. Mangone Climate Change Science and Policy Hub Report
Author: James Rising[1]
University of Delaware

Cover picture by Md Hasanuzzaman Himel on Unsplash

Contents

1. Executive Summary

This report presents headline results on the macroeconomic losses caused by climate change today. The methodology draws on 58 economic models and employs machine learning to develop "best estimates" of the current GDP and capital wealth losses from climate change.

The research reveals significant disparities in the impacts of climate change across regions and economic groups. The findings emphasize the vulnerability of low-income countries and tropical regions, which are already experiencing substantial GDP losses. Meanwhile, many wealthier nations are seeing smaller impacts or are even benefiting from climate change for the time being.

Globally, climate change has led to a population-weighted GDP loss of 6.3% in 2022, considering direct, spill-over, and capital losses. The unweighted percentage of global GDP lost is estimated at 1.8%, or about $1.5 trillion, and the difference between those two results reflects the uneven distribution of impacts.

Least developed countries[2] are exposed to an average population-weighted GDP loss of 8.3%, and Southeast Asia and Southern Africa are particularly affected, with countries losing an average 14.1% and 11.2% of their GDP, respectively. These losses highlight the disproportionate burden imposed by climate change on developing nations.

Climate change is also exacerbating existing global inequalities, with many high-income countries currently experiencing net gains, including an average increase of 4.7% to the GDP of European countries.

With COP28 expected to make progress on the new Loss and Damage Fund to compensate vulnerable countries for natural disasters caused by climate change as decided at COP27, the report also provides impact estimates at the level of relevant UNFCCC negotiating groups (such as G-77, African Group, Aosis, LDCs, and Ailac).

The analysis also reveals the complex dynamics between climate change, economic outcomes, and capital investments. Low and middle-income countries face significant capital losses, posing challenges to their long-term economic resilience and growth. Low and middle-income countries have experienced $2.1 trillion in produced capital losses due to climate change.

When GDP and capital losses are combined, low and middle-income countries have experienced a total loss of $21 trillion since 1992 (the Rio Convention). All UNFCCC party groupings except for the EU have experienced total losses, with the greatest losses on the G-77 (which includes high-income countries such as Saudi Arabia and the UAE) at $29 trillion. These losses are expected to be conservative estimates, since important impact channels and non-market losses are not included in the analysis.

Climate changes are already depressing economic activity across the globe. These findings underscore the urgent need for global cooperation and support to address the impacts of climate change.

2. Introduction and Background

Global temperatures in 2022 were 1.06 °C above pre-industrial levels, tied for fifth hottest year on record[3], and 2023 is on track to be one of the hottest ever recorded[4]. These high temperatures have driven extensive heatwaves, droughts, and other weather extremes across the globe. As the climate shifts, recent evidence has shown that the whole state of an economy and the growth of economic output can also be affected. Already, today we are likely to be poorer as a world because of climate change.

In lower-income, tropical, and agriculturally-dependent countries, existing losses from climate change are expected to be particularly large. These are typically the countries that are most vulnerable to many forms of future climate change and most in need of development assistance.

Climate-driven loss and damage will be a central discussion at COP28, taking place in UAE this December. Impacted countries need high-quality estimates of the losses they have already experienced to articulate evidence-based demands for support from the Global North. A strong basis for developing these estimates exists, in the form of sophisticated statistical models describing the historical relationship between economic growth and weather.

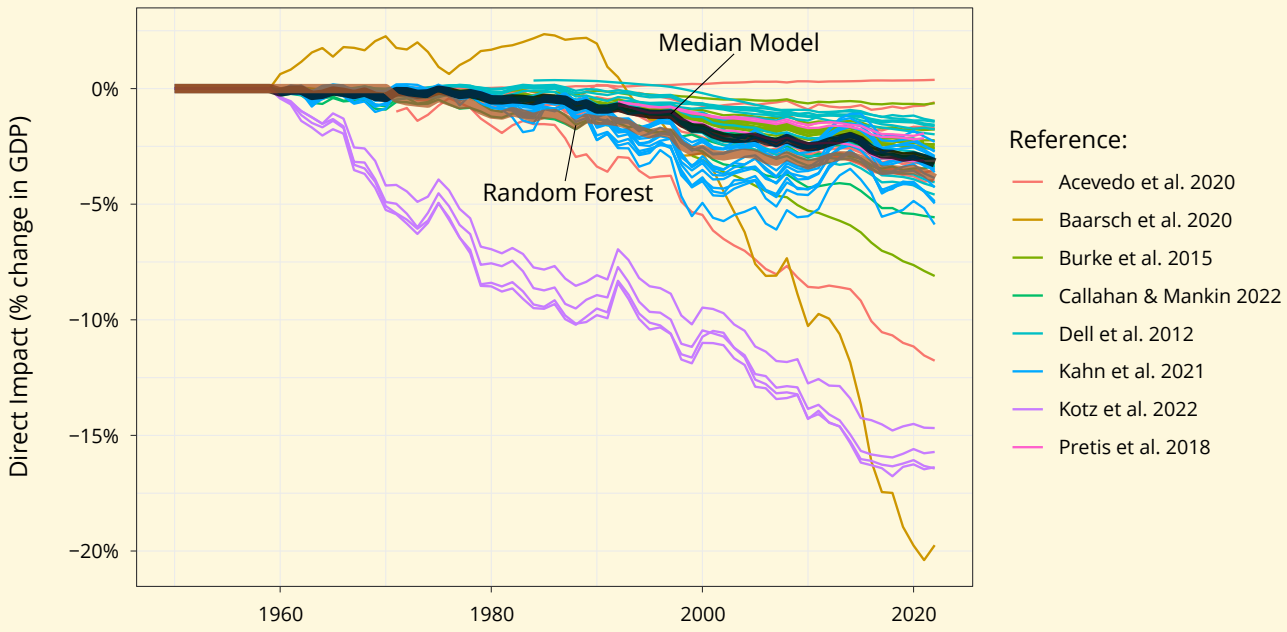
This report develops "best estimates" of the current macroeconomic losses from climate change, for each country across the globe. The main outcome is percent reductions in gross domestic product (GDP) and percent reductions in capital wealth today, relative to a world without the climate change experienced since 1950.[5] As a measure of economic output, GDP is a useful, if incomplete, proxy for estimating government tax receipts and average personal income levels. At the same time, a reduction in GDP may imply the long-term destruction of productive human-built and natural capital. We develop an estimate of those capital losses, providing new evidence on the true losses borne by countries due to climate change. Recognizing that economic losses are not limited by national boundaries, we also estimate how climate-induced losses may affect other economies through trade networks.

Box 1: Methodology

Our methodology for estimating the economic impacts of climate change follows a three-pronged approach: model collection, machine learning application, and the modeling of indirect effects.

Our research involved a detailed examination of key literature that has produced econometric estimates of macroeconomic damages from annual temperature changes, particularly from eight pivotal studies published 2012 - 2022. All of these papers study the observed link between GDP and weather or climate, grounded in extensive datasets. From these, we employed and assessed an array of models (58 in total) to capture diverse perspectives and assumptions. The impacts from these models are shown in Figure 1. These models provide a "top-down" look at how climate and weather have affected GDP since 1950, implicitly integrating consequences throughout each country's economy, as well as the responses and adaptations that have been undertaken as they are reflected in GDP. Impacts are also assumed to have a partially persistent effect, where reductions in growth require about 5 years to return to a baseline growth trajectory.[6]

Figure 1: Projected change in population-weighted GDP, relative to a counterfactual without climate change, according to 58 statistical models from 8 papers, accounting for partial persistence. The heavy line shows the median across all models.



These models make different choices concerning their use of short-term weather and long-run climate, differences in vulnerability across countries, and the role of adaptation. To synthesize this evidence, we use an innovative machine learning approach called a 'Random Forest' to develop a best estimate of economic losses accounting for the robustness of different modeling decisions, in terms of the models' flexibility, causal (rather than correlative) foundations, and data quality. The result is a robust estimate of economic costs for every country, reflected in their GDP impacts.

Lastly, we developed estimates of indirect effects. First, we estimate how climate-induced losses could spill over to other economies through the international trade network using results from global economic modeling. Second, we incorporate important capital investment dynamics and direct and indirect impacts on natural capital, building upon the Inclusive Wealth Report (2018).

Throughout, we account for uncertainty arising from baseline conditions, model parameters, the machine learning synthesis, and the role of capital losses in explaining persistence in climate damages. This uncertainty is shown as the range of the middle 50% of the possible outcomes (the interquartile range or IQR). There is further, unmeasured uncertainty associated with omitted impacts, such as sea-level rise and a host of country-specific impact channels that are not captured in global statistical analyses - which means actual economic impacts are most likely more negative than what our estimates suggest.

In summation, our methodology is a unique blend of traditional literature review, cutting-edge machine learning, and careful economic modeling. For a more detailed technical exposition, see the online appendix.[7]

3. Results and Findings

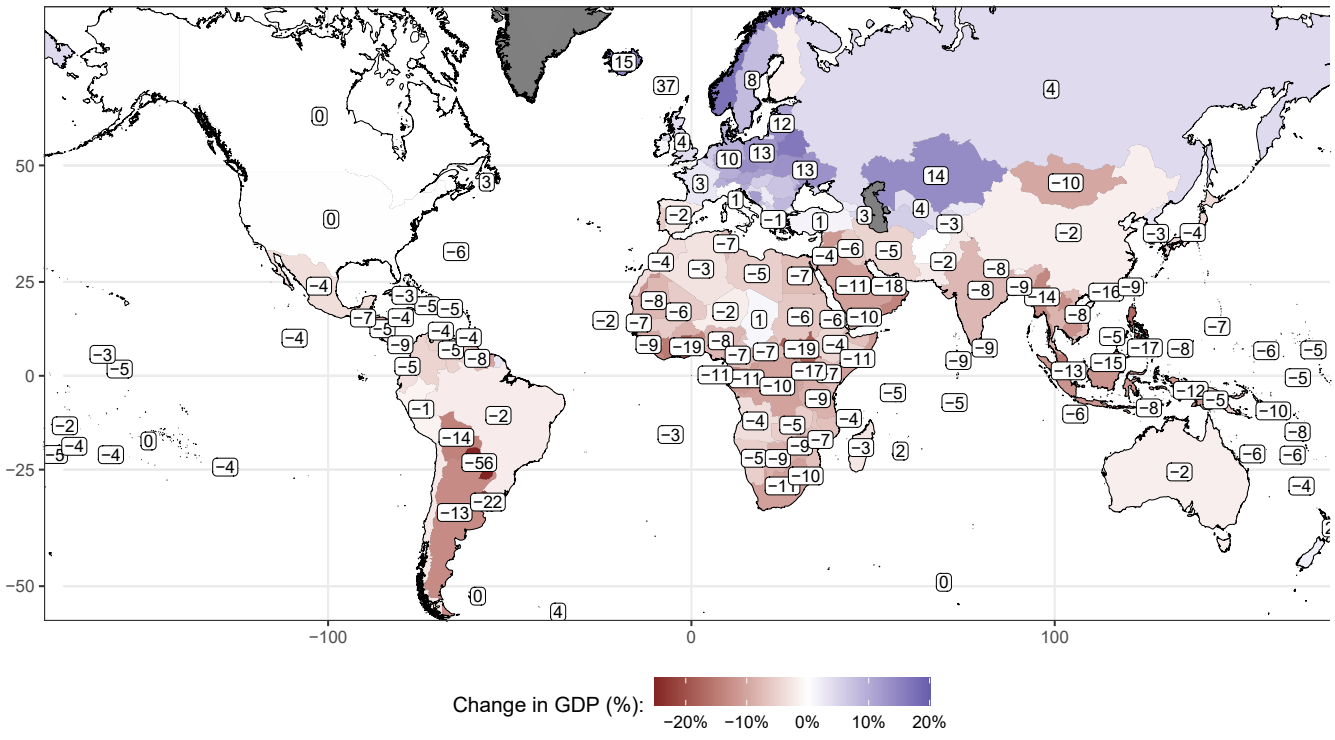
The climatic changes experienced since the mid-20th century have resulted in evident and significant economic impacts across the globe. Our analysis of the relationship between climate change and GDP losses is built on a solid foundation of existing research and enriched with machine learning techniques. Here, we discuss economic impacts due to climate change today. These impacts, either positive or negative, vary widely by region and are largely dependent on the underlying economic structure and climatic vulnerability of each country.

Global and Regional Impacts Today

Globally, the population-weighted GDP loss due to climate change in 2022 is substantial at 6.3%, taking into account the direct, international, and capital losses related to climate. Yet, the percentage of the global GDP lost is 1.8%, about $1.5 trillion, as many wealthier nations have smaller impacts or benefits. That is, the world is estimated to be $1.5 trillion poorer than it would have been without climate change.

A useful comparison for this work is an expert review in 2017 evaluating how global losses stack up as climate change continues.[8] When the results of that study are applied to the climate change that we have already experienced, it suggests that by 2023 annual losses may already be 2.05% of global GDP [0.9 - 3.4%], about $2.1 trillion.[9] This is about equal to the GDP of Canada.

Figure 2: Total GDP impacts by country in 2022, shown in percent.



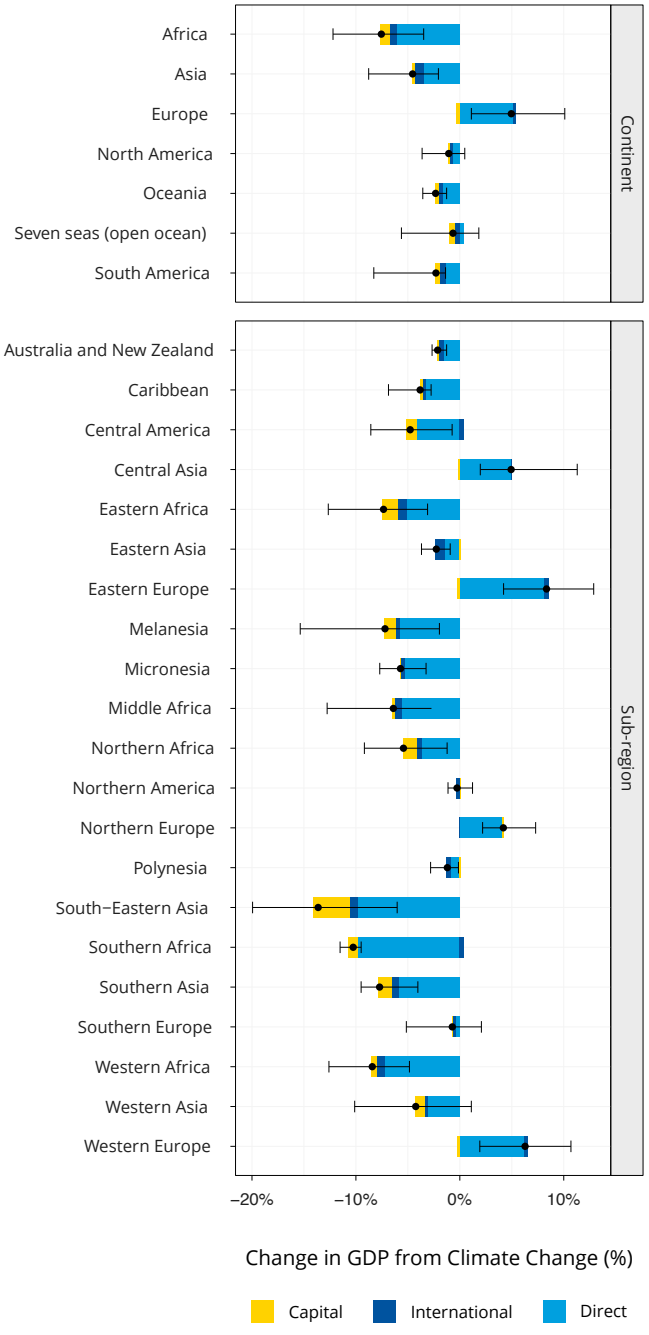
Our analysis vividly illustrates the inequality in the impacts of climate change across regions and economic zones, as demonstrated by the map of losses across the globe (See Figure 2).

In the remainder of the results, we report population-weighted losses when reporting groups of countries. When combining GDP losses across countries, taking a population-weighted average represents the impacts borne by the average person within the group. In contrast, an output-weighted average would be biased toward the richest countries within the group. Our reported percent losses in GDP are relative to a world without climate change, so that the observed GDP growth in most countries is projected to have been lower than it would have been.

In contrast with the global average, the Global South and particularly tropical regions have borne the brunt of climate-related losses. African nations have experienced an average loss of 8.1% in GDP in 2022. The most severely impacted region is Southeast Asia, which has suffered an average loss of 14.1% of GDP (See Figure 4). These staggering numbers underscore the vulnerability of these regions to climate disruptions and their negative socio-economic effects.

Interestingly, some regions, particularly Europe and northern Asia, are seeing economic benefits from climate change. Europe and Central Asia are both estimated to have GDPs 4.7% higher than they would have had without climate change (See Figure 3). These benefits arise from reduced winter chill, which lowers energy consumption and mortality rates, among other factors. Yet as the planet continues to warm, these benefits are poised to erode and eventually turn negative, with the energy and health effects of hotter summers gradually offsetting benefits from mild winters. The United States and China are currently near the point where losses under hotter temperatures outweigh benefits from milder winters. The US saw essentially no gain or loss in GDP in 2022 [IQR 2% loss to 2% gain] relative to a non-climate-changed world, while China experienced a 1.8% loss [3 - 0%].

Figure 3: Percent GDP impact in 2022 across regional groups. Direct, international, and capital impact combine to make the total GDP impact.



Box 2: Channels of Impact

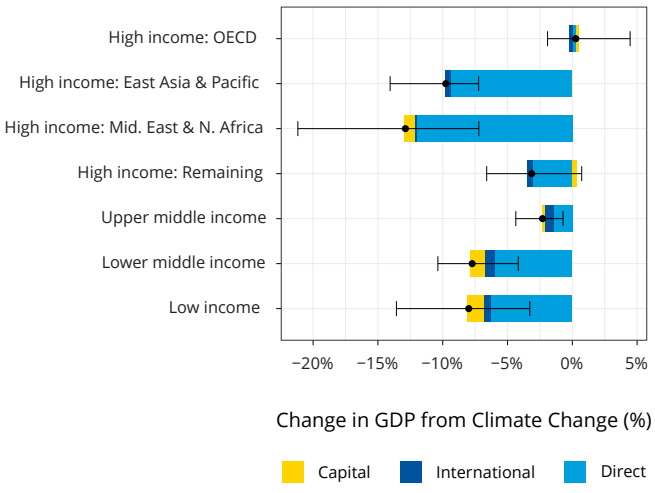
Multiple sectors and channels aid in understanding these effects, as well as the differences in results seen in different regions around the world. Agriculture and manufacturing are more sensitive to climate risks than service industries.[10] Outdoor workers are particularly vulnerable, such as those engaged in agriculture, fishing, forestry, mining, and construction[11]. High temperatures can also undermine health, while other extremes from climate change, such as flooding, can damage infrastructure.[12] Furthermore, poor countries have been shown to be more vulnerable to all of these effects[13], and those countries that are already hot are estimated to experience greater losses for each additional degree of warming.[14]

While the direct impacts from local temperature remain the dominant factor in most regions, there were also significant international effects and capital losses. In countries outside Europe and North America, international impacts amplified losses by about 1 percentage point, highlighting the global connectivity of economies. In negatively impacted regions, these international effects tend to reinforce direct effects since these countries typically trade heavily with neighbors who experience similar losses. Capital effects further increase losses by up to 2 percentage points in most regions. The capital effect is more variable due to the long-term consequences of differences in savings rates and renewable resources.

Economic Group Results and Implications

Consistent with the overall regional results, the economic impacts of climate change present a stark contrast between developed and developing nations. For OECD countries, climate change has had little net impact (0.3% gain [IQR 3% loss to 5% gain]). These countries are collectively seeing a net gain of approximately $636 billion (constant 2015 USD). Meanwhile, the rest of the world has experienced an estimated net GDP loss of $1818 billion (see Table 1) and countries in the Global South have experienced an average 8.3% loss of GDP [3 - 14%]. This exacerbates already glaring global inequality and underscores the disproportionate burden of climate change on these nations.

Figure 4: Percent GDP impact in 2022 across economic groups. BRIC includes Brazil, Russia, India, and China. MIKT includes Mexico, Indonesia, South Korea, and Turkey.



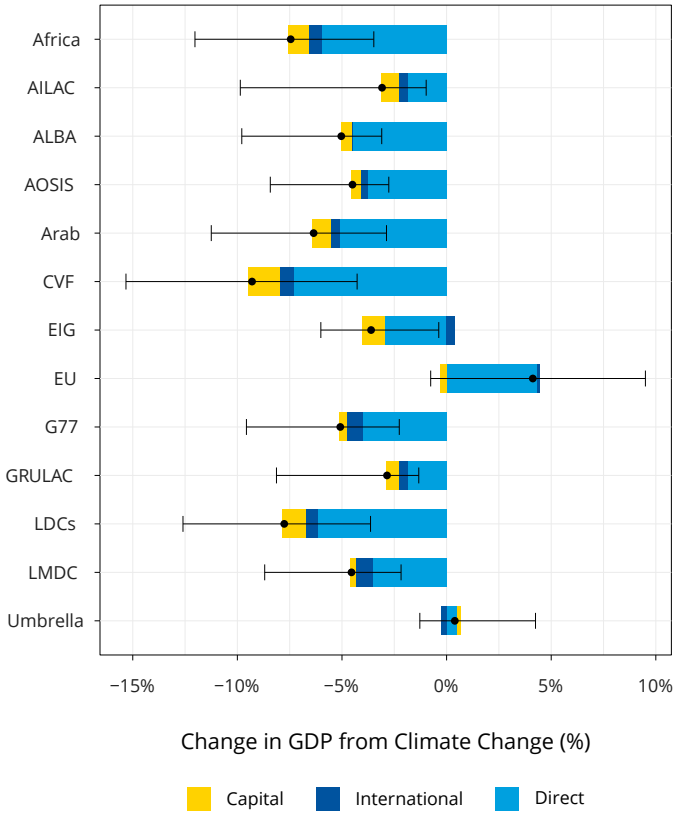
UNFCCC Party Groupings and Economic Impacts

Many coalition groups that represent developing countries at COPs have experienced average losses in 2022 of 5-10% of their GDP. Figure 5 provides a visualization of these results by UNFCCC party groupings. This signifies the substantial economic burdens already faced by all groups except the EU and Umbrella groups due to climate change impacts.

For instance, the average loss for the G-77 is 5.5% of GDP [2 - 11%], for Africa is 8.0% [4 - 13%], and for LDCs is 8.3% [4 - 14%]. In 2022, this represents a total GDP loss of $1.9 trillion for G-77, $240 billion for Africa, and $110 billion for LDCs. This approach estimates that the Small Island Developing States (SIDS) under the Alliance of Small Island States (AOSIS) have experienced an average loss of 4.3% [2 - 10%], or a $70 billion loss. However, it is worth noting that these estimates likely underestimate the actual losses for SIDS, as they do not fully account for the impacts of sea-level rise, a particularly significant concern for these nations. Another relevant stakeholder is the Climate Vulnerable Forum (CVF), which is estimated to have an average loss of 9.9% of their GDP [4 - 17%] in 2022 and a total GDP loss in 2022 of $190 billion.

In contrast to the economic losses experienced by many developing countries, the European Union (EU) demonstrates average gains in GDP of 4.2% [1% loss to 9% gain]. The EU's positive economic impacts mostly reflect the benefits many of its countries now derive from reduced winter chill (Figure 3).

Figure 5: Percent GDP impact in 2022 across countries UNFCCC party groupings.



Global and Country Trends in GDP Losses

Our study suggests a strong correlation between GDP losses attributable to climate change and rising temperatures. Since 1970, we have observed a nearly linear increase in global temperatures of 1°C, in pace with a corresponding reduction in global population-weighted GDP by approximately 6.3% (Figure 6). Incremental increases in temperature have consistently mapped to escalating losses in GDP, and these losses are expected to accelerate in the future, as long as temperatures keep rising.

Our geographic analysis of these trends, however, reveals marked disparities across territories. Climate change is not an indiscriminate phenomenon; its effects manifest divergently across different regions and in varying magnitudes, as seen in Figure 7.

Figure 6: The evolution of global population-weighted GDP impacts since 1950. Unweighted GDP loss is also shown as a grey line. The grey band shows the interquartile range for the total impact.

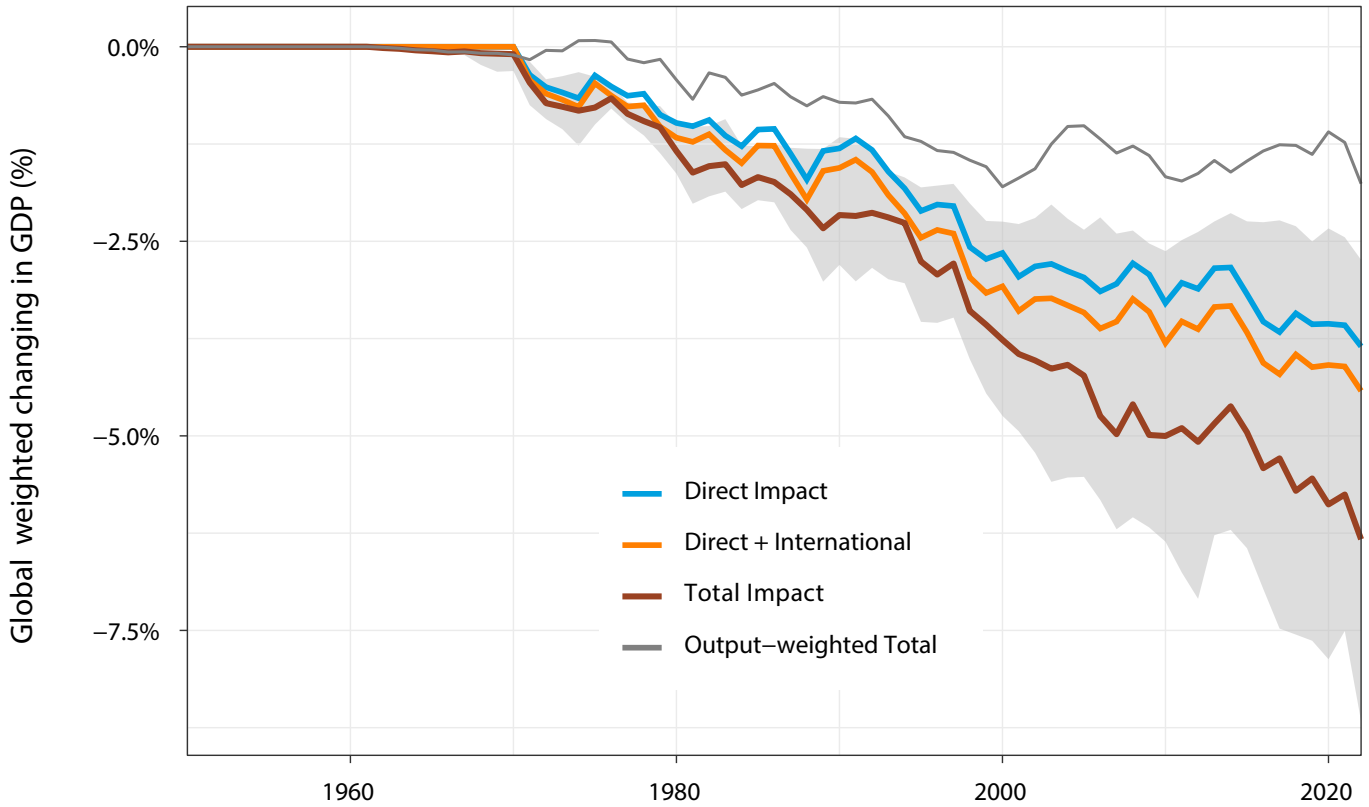
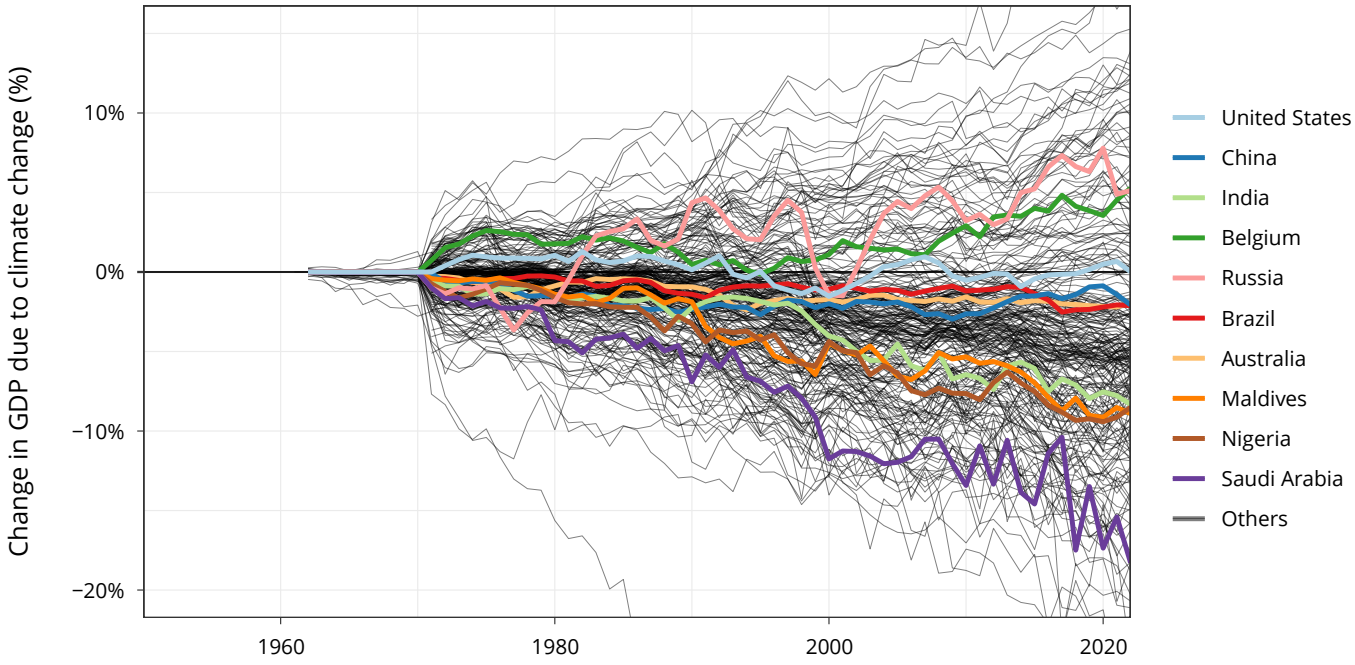


Figure 7: The evolution of country-specific GDP impacts since 1950. There is insufficient evidence for many countries until 1971, when models with long-run climate are available.



A case in point is Russia, which has seen a 4.2% increase in GDP [2 - 8%] attributable to climate change. Milder winters may have catalyzed economic activities, leading to the counter-intuitive GDP increase.

Contrastingly, Saudi Arabia has endured a 11.3% [8 - 24%] drop in GDP owing to climate change. Several channels are expected to have contributed to this loss, including reduced labor productivity and infrastructure loss (see Box 2).

Figure 7 also shows the effects of climate change on the world's two biggest economies: the US and China. The United States hovers near the break-even point, revealing neither large GDP losses from excessively high temperatures nor substantial gains from comparatively milder winters. As noted above, these impacts are expected to worsen as temperatures continue to climb, leading to unprecedented economic strain both in these countries and across the globe through trade. Meanwhile, China is already experiencing significant losses from climate change, losing 1.8% of its GDP [3 - 0%], or $290 billion per year.

There is also considerable short-term variability. The impact on the median country varies by ±1 percentage point in the GDP effect of climate change from year to year as global climate change contributes not only to rising temperatures but also increased variability and extreme events.

Capital Losses and the Erosion of Productive Capacity

The repercussions of climate change extend beyond immediate GDP losses; they also reverberate through capital investments, resulting in a decline in a country's total stock of manufactured capital. Manufactured capital refers to the human-produced physical entities that contribute to production and economic activity, such as roads, buildings, machines, and equipment.[15]

Broadly speaking, countries confronted with climate impacts have reduced funds to invest in productive capital, which exacerbates the erosion of their economic capacity over time. The extent of these capital losses carries critical implications for long-term economic resilience and the ability to sustain growth.

Our analysis reveals significant heterogeneity in the magnitude of capital losses experienced across different income groups and geographic regions.

OECD countries have witnessed substantial increases in the total value of their manufactured capital, estimated at $980 billion additional manufactured capital in 2022 than they would have had in the absence of climate change (Table 1). At the same time, climate change has reduced the value of their renewable natural capital by $130 billion.

Table 1: Total changes to GDP and capital bases, reported in 2015 USD. GDP and capital changes are measured in 2015 USD in 2022, and Total Loss/Gain equals the sum of GDP losses from 1993 to 2022 plus the capital losses in 2022 (since capital losses are inherently cumulative), columns 2 - 5.. OECD countries have experienced net gains from climate change, while the rest of the world has experienced losses.

Income Group	2022 GDP Change ($billion)	30-year GDP Change ($billion)	Produced Capital Change ($billion)	Renewable Capital Direct Change ($billion)	Renewable Capital Feedback Change ($billion)	Total Loss/Gain ($billion)
High income: OECD	640	7,310	980	-330	200	**8,160**
High income: non-OECD	-360	-6,070	-440	-80	80	**-6,510**
Upper middle income	-600	-9,210	-920	-1,260	1,770	**-9,620**
Lower middle income	-750	-9,810	-1,080	-2,320	2,760	**-10,450**
Low income	-100	-1,340	-90	-80	110	**-1,400**
High income (total)	280	1,240	540	-410	280	**1,650**
Low and middle income	-1,450	-20,360	-2,090	-3,660	4,640	**-21,470**

In middle- and low-income countries, there have been even more substantial manufactured capital losses, totaling $2090 billion in 2022. The vast majority of these losses occur in middle-income countries, which typically have more produced capital.

Many of these countries depend heavily on their natural capital. Renewable natural capital such as forest resources, fisheries, and agricultural land is heavily affected by climate change. Our models consider two factors that simultaneously exert opposing influences on renewable capital.

Firstly, we model temperature increase as having a generally negative effect on the natural world's ability to generate ecosystem services, thus potentially tempering the growth of renewable capital. On the other hand, reductions in GDP resulting from climate change can alleviate strain on the natural world, so that a world with climate change may deplete its natural resources less quickly. In our model, we observe this economic feedback on natural capital, so that direct impacts are negative while net impacts are positive (the sum of Renewable Capital Direct Change and Renewable Capital Feedback Change in Table 1) . This effect is likely to be overstated, however, since a world without climate change would offer more opportunities to readjust economies away from natural resource use.

Higher temperatures across the low- and middle-income countries produce a direct loss of renewable capital of $3660 billion. However, due to the negative GDP impact of climate change, lower demand for natural goods is projected in these countries. This counteracts the direct loss that is experienced due to climate change. When these effects are weighed, renewable capital is projected to be $980 billion greater today than it would have been without climate change, due to the reduced economies exerting less pressure on natural resources.

GDP losses and capital losses both contribute to the total losses that countries have experienced. To compute this, we add all GDP losses from 1993 to 2022 to the capital losses in 2022. GDP losses cover the 30-year period since the Rio Convention, since the world was aware of climate risks by this time. These losses are not discounted, and standard discounting would further inflate the values. The capital losses are naturally cumulative, so we only include the final value of these at the end of the period.

We find that low- and middle-income countries have experienced a total loss of $21 trillion, about half of the total 2023 GDP of the developing world ($44 trillion).[16] In contrast, OECD countries may be $1.6 trillion richer due to climate change.

Table 2 reports loss estimates across UNFCCC party groupings. The G-77, which includes both lower-income countries and high-income countries such as Saudi Arabia and the UAE, represents the largest losses of nearly $29 trillion, but all party groupings except for the EU show considerable losses.

Table 2: Total changes to GDP and capital bases, reported in 2015 USD, for UNFCCC party groupings. GDP and capital changes are measured in 2015 USD in 2022, and Total Loss/Gain equals the sum of GDP losses from 1993 to 2022 plus the capital losses in 2022 (since capital losses are inherently cumulative), columns 2 - 5.

Party	2022 GDP Change ($billion)	30-year GDP Change ($billion)	Produced Capital Change ($billion)	Renewable Capital Direct Change ($billion)	Renewable Capital Feedback Change ($billion)	**Total Loss/Gain ($billion)**
Africa	-240	-3,910	-300	-1,380	1,400	**-4,190**
AILAC	-100	-1,480	-130	-20	40	**-1,590**
ALBA	-10	-160	-60	-20	20	**-220**
AOSIS	-70	-1,030	-120	-20	20	**-1,150**
Arab	-320	-5,350	-450	-1,420	1,380	**-5,840**
CVF	-190	-2,430	-210	-120	170	**-2,590**
EIG	-20	-1,440	-110	-60	40	**-1,570**
EU	700	9,750	1,310	-140	60	**10,980**
G-77	-1,860	-27,070	-2,720	-3,600	4,660	**-28,730**
GRULAC	-320	-5,540	-550	-100	140	**-6,050**
LDCs	-110	-1,700	-110	-120	170	**-1,760**
LMDC	-1,070	-15,000	-1,630	-3,380	4,370	**-15,640**
Umbrella	-70	-1,490	-210	-260	180	**-1,780**

4. Conclusions

The report investigates the current macroeconomic losses resulting from climate change and provides valuable insights into the impacts on global GDP and capital wealth. There are significant disparities in the effects of climate change across different regions and economic zones, with the worst effects in low-income countries and tropical regions. The findings support the urgent need for developing countries to be granted support and assistance by wealthier nations in mitigating the adverse impacts of climate change.

Globally, climate change has already caused a substantial average GDP loss of 6.3% in 2022 when considering direct, international, and capital losses.

However, the distribution of these losses is highly uneven, with wealthier nations experiencing smaller impacts or even benefiting from climate change for the time being, while the Global South suffers the most significant losses. Southeast Asian and African nations, particularly Southern Africa, bear the brunt of these impacts, with an average annual GDP loss of 14.1%, 8.1% and 11.2%, respectively.

In terms of economic groupings, developed countries exhibit minimal losses or gains from climate change, while least developed countries face an average GDP loss of 8.3%. This exacerbates existing global inequality and calls for comprehensive strategies to address the disproportionate burden faced by developing nations.

Furthermore, the analysis reveals the complex interplay between climate change, economic dynamics, and capital wealth. While the high-income world is projected to experience relatively minor impacts or gains to manufactured capital, the rest of the world, comprising low and middle-income countries, experiences significant capital losses, highlighting the challenges faced by these nations in sustaining growth and resilience.

The report provides valuable insights for policymakers and international organizations, particularly in anticipation of COP28. The comprehensive methodology employed, which combines literature review, machine learning techniques, and economic modeling, contributes to a detailed understanding of the potential economic losses caused by climate change.

Nevertheless, the approach used in this study has some significant limitations. As a top-down statistical estimate, it provides little information on the specific channels that result in the predicted GDP and capital losses. While individual events, such as newsworthy droughts and storms, have shaken economies across the globe, these estimates generally find a surprisingly muted role for rainfall and other natural disasters. Furthermore, since they are calibrated to weather variability, these models do not capture the effects of sea-level rise, slow-moving changes to the natural environment, or the consequences of country-specific institutions. Our synthesis using a random forest model is also limited to the range of available estimates and alternative decisions about model quality can produce different results.

GDP is also, by definition, an incomplete measure of climate impacts. Many kinds of climate impacts operate through non-market channels, such as increased risks of premature mortality and loss of welfare to outdoor workers. Other non-market channels are not human-centered, such

as biodiversity loss. Finally, there are a range of missing channels, such as the consequences of climate tipping points, vector borne disease, and human capital loss, which have not been included here and are more challenging to robustly quantify. The risks associated with these missing risks is nonetheless an important policy concern.

In conclusion, the findings of this report underscore the urgent need for global cooperation and concerted efforts to address the economic impacts of climate change. It highlights the inequalities in the distribution of losses, with low-income countries bearing the heaviest burden and many wealthier nations benefiting or experiencing significantly reduced impacts. The report provides the necessary groundwork for informed decision-making, enabling countries to pursue strategies that mitigate the adverse effects of climate change and promote sustainable, inclusive development worldwide.

Notes

1. The author would like to acknowledge the helpful review of this work by A. R. Siders, Bob Ward, Leonie Wenz and Benjamin Jullien. The University of Delaware Gerard J. Mangone Climate Change Science and Policy Hub also provided valuable input. This report has been published by the Gerard J. Mangone Climate Change Science and Policy Hub. While it has been commented upon by other researchers, it has not been subject to a full peer review. The accuracy of the work and conclusions reached are the responsibility of the author and not the Climate Hub or the University of Delaware.

2 . We follow the UN's classification of Least Developed Countries (https://unstats.un.org/unsd/methodology/m49/), included in the Natural Earth geospatial data archive (https://www.naturalearthdata.com/).

3. From a NASA analysis, https://climate.nasa.gov/news/3246/nasa-says-2022-fifth-warmest-year-on-record-warming-trend-continues/

4. Li, Z., Li, Q., & Chen, T. (2023). Record-breaking High-temperature Outlook for 2023: An Assessment Based on the China Global Merged Temperature (CMST) Dataset. Advances in Atmospheric Sciences, 1-8.

5. The 1950 starting point removes a portion of the damages. As an approximation of these, consider that the FaIR simple climate model estimates that warming in 1950 was 0.24 °C, which is associated under the Howard & Sterner damage function with a 0.1% loss in global GDP.

6. Calibrated to Nath, I. B., Ramey, V. A., & Klenow, P. J. (2023). How Much Will Global Warming Cool Global Growth?. Working paper.

7. Available at https://zenodo.org/records/10199433.

8. Howard, P. H., & Sterner, T. (2017). Few and not so far between: a meta-analysis of climate damage estimates. Environmental and Resource Economics, 68(1), 197-225.

9. This is based on the climatological warming level of 1.34 °C above pre-industrial temperatures produced by the FaIR simple climate model. Global GDP is estimated to be $104.48 trillion in current prices in 2023, from the International Monetary Fund (IMF) 2023 World Economic Outlook report.

10. Acevedo, S., Mrkaic, M., Novta, N., Pugacheva, E., & Topalova, P. (2020). The effects of weather shocks on economic activity: what are the channels of impact?. Journal of Macroeconomics, 65, 103207.

11. Rode, A., Baker, R. E., Carleton, T., D'Agostino, A., Delgado, M., Foreman, T., ... & Yuan, J. (2022). Labor disutility in a warmer world: The impact of climate change on the global workforce.

12. Carleton, T. A., & Hsiang, S. M. (2016). Social and economic impacts of climate. Science, 353(6304), aad9837.

13. Dell, M., Jones, B. F., & Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. American Economic Journal: Macroeconomics, 4(3), 66-95.

14. Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. Nature, 527(7577), 235-239.

15. Definitions and country-level estimates are from Managi, S., & Kumar, P. (2018). Inclusive wealth report 2018. Taylor & Francis.

16. Individual country results are included in the Appendix Archive, at https://zenodo.org/records/10199433.

17. Rising, J., Tedesco, M., Piontek, F., & Stainforth, D. A. (2022). The missing risks of climate change. Nature, 610(7933), 643-651.

GERARD J. MANGONE CLIMATE CHANGE SCIENCE AND POLICY HUB

ROBINSON HALL
NEWARK DE 19716

CLIMATECHANGEHUB@UDEL.EDU
SITES.UDEL.EDU/CLIMATECHANGEHUB

UNIVERSITY OF DELAWARE