ENVIRONMENTAL RESEARCH LETTERS

PURPOSE-LED PUBLISHING™

LETTER • OPEN ACCESS

Estimating the sea level rise responsibility of industrial carbon producers

To cite this article: Shaina Sadai *et al* 2025 *Environ. Res. Lett.* **20** 044012

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
8 November 2024

REVISED
27 January 2025

ACCEPTED FOR PUBLICATION
13 February 2025

PUBLISHED
18 March 2025

LETTER

Estimating the sea level rise responsibility of industrial carbon producers

Shaina Sadai[1,2,*], Meghana Ranganathan[3], Alexander Nauels[4,5], Zebedee Nicholls[4,5,6], Delta Merner[1], Kristina Dahl[1,7], Rachel Licker[1] and Brenda Ekwurzel[1]

[1] Union of Concerned Scientists, Two Brattle Square, Cambridge, MA, United States of America
[2] Department of Geology and Geography, Mount Holyoke College, 50 College Street, South Hadley, MA, United States of America
[3] Department of Geophysical Sciences, University of Chicago, S Ellis Ave, Chicago, IL, United States of America
[4] Energy, Climate, and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, Laxenburg, Austria
[5] School of Geography, Earth and Atmospheric Sciences, The University of Melbourne, Level 1/221 Bouverie St, Carlton, VIC, Australia
[6] Climate Resource, Level 3/105 Victoria St, Fitzroy, VIC, Australia
[7] Climate Central, Princeton, NJ, United States of America
[*] Author to whom any correspondence should be addressed.

E-mail: ssadai@mtholyoke.edu

Keywords: sea level rise, climate change, fossil fuels, climate attribution

Abstract

Global mean sea levels have risen at an accelerating rate over the past century in response, primarily to greenhouse gas emissions from the combustion of fossil fuels. We use MAGICC7, a reduced complexity climate-carbon cycle model, to quantify how emissions traced to the Carbon Majors, the world's 122 largest fossil fuel and cement producers, from 1854–2020 contributed to present-day surface air temperature rise, and sea level rise both historically and projected through 2300. We find that emissions traced to these industrial actors have contributed 37%–58% to present day surface air temperature rise and 24%–37% to the observed global mean sea level rise to date. Critically, these emissions through 2020 are expected to contribute an additional 0.26–0.55 m of global sea level rise through 2300. We find that attribution of past emissions to projected future sea level rise is robust regardless of how emissions trajectories evolve in the coming centuries.

1. Introduction

Global mean sea levels rose by 0.2 ± 0.05 m from 1901–2018 (Fox-Kemper *et al* 2021), driven primarily by the energy imbalance resulting from anthropogenic greenhouse gas emissions (Oppenheimer *et al* 2019, Fox-Kemper *et al* 2021). The resulting impacts include heightened storm surge, flooding, erosion, and salinization of freshwater, all of which inequitably affect human and nonhuman life (Hardy and Hauer 2018, Buchanan *et al* 2020, Fox-Kemper *et al* 2021).

Sea level rise is a slow onset event that evolves over centuries in response to a given forcing due to heat storage in the oceans and the long response times of the Greenland and Antarctic ice sheets (Fox-Kemper *et al* 2021). This long-term response presents substantial risks for distributive injustice and intergenerational inequity (Clark *et al* 2016, Sadai *et al* 2022). Sea level rise is driven by processes of ice mass loss, from the Greenland and Antarctic ice sheets and global glaciers, ocean density changes, and land water storage changes. The global sea level budget, which determines the relative contribution of each factor to the total observed global mean sea level rise (GMSLR), has recently been closed (Frederikse *et al* 2020). From 1901 to 2018, ice loss and ocean thermal expansion contributed nearly equally to observed GMSLR. In recent decades, ice loss from global glaciers and ice sheets has accelerated, becoming the dominant contributor to sea level rise from 2006–2018 (Fox-Kemper *et al* 2021). Earth's energy imbalance from 2006–2018 was 0.79 (0.52–1.06) W m^{-2} with 91% of the excess accumulated energy being taken up by the oceans where it drives thermal expansion, which directly contributes to sea level rise, as well as basal melting of floating ice shelves which indirectly contributes to sea level rise through the destabilization of grounded ice (Forster *et al* 2021). The recent closures of both the sea level budget and energy budget give confidence in the understanding of the drivers of sea level change (Fox-Kemper *et al* 2021).

Understanding how greenhouse gas emissions sourced from particular countries or companies are driving climate impacts is important for guiding mitigation action and attributing impacts to specific actors. Anthropogenic greenhouse gas forcing is dominated by the release of carbon dioxide into the atmosphere (Gulev *et al* 2021), and fossil fuel combustion has been the dominant source of carbon dioxide emissions since 1950 (IPCC 2023). Since 1990, the largest growth in emissions has come from carbon dioxide resulting from fossil fuels and industrial processes, followed by rising methane emissions (IPCC 2023).

Long-lived climate forcers like carbon dioxide remain in the atmosphere for prolonged periods and constitute the dominant forcing driving GMSLR; however, modeling has shown that short lived climate forcers like methane also have multi-century impacts on thermosteric sea level rise that far outlast their atmospheric lifetimes (Zickfeld *et al* 2017). Prior work has sought to quantify the long-term commitment of rising seas due to anthropogenic emissions (Price *et al* 2011, Levermann *et al* 2013, Strauss *et al* 2015, Zickfeld *et al* 2017, Mengel *et al* 2018). One study found that the long-term GMSLR response to historic greenhouse gas emissions and emissions corresponding to pledged Nationally Determined Contributions from 1750 through 2030 yield 1 m of committed sea level rise by 2300 (Nauels *et al* 2019). Of this, emissions from 2016–2030 were responsible for 20% of the total committed GMSLR, with the five highest emitters (China, United States of America, European Union, India, and Russia) responsible for 26 cm over this time period (Nauels *et al* 2019).

Historical analyses have shown that a substantial proportion of carbon dioxide emissions can be traced to a relatively small number of corporations, specifically fossil fuel producers (Heede 2014), and that some fossil fuel companies have been aware of the climate risks associated with their products since the mid-1950 s (Franta 2018). Instead of mitigating these risks, these companies invested in extensive campaigns to mislead the public and delay regulatory action (Supran and Oreskes 2017, Franta 2022, Supran *et al* 2023). Prior source attribution research on sea level rise, which found emissions traced to these industrial producers account for 0.018–0.127 m of the observed GMSLR from 1880–2015 (Ekwurzel *et al* 2017, Licker *et al* 2019), has underpinned legal arguments that seek to establish corporate accountability and enforce mitigation obligations (Wentz *et al* 2023).

While previous research has quantified the contribution of major emitters to global sea level rise to date, there is little known about how the products produced by industrial fossil fuel and cement producers are projected to contribute to long-term sea level rise. Here we use MAGICC7, a reduced complexity climate-carbon cycle model, to quantify the contributions of emissions from the Carbon Majors, the 122 largest industrial fossil fuel and cement producers, to not only present day temperature and sea level rise but also multi-century projected sea level rise. The chosen simplified methodological approach has been successfully used to explore GMSLR resulting from national emission shares (Nauels *et al* 2019).

2. Methods

2.1. Model

To assess climatic change resulting from emissions traced to the fossil fuel industry, we use MAGICC7 and the associated MAGICC sea level model v2 (Meinshausen *et al* 2011, Nauels *et al* 2017a, 2019). MAGICC7 is a reduced complexity atmosphere-ocean climate-carbon cycle model with a hemispheric upwelling-diffusion ocean component (Meinshausen *et al* 2011, 2020). The model is run with emissions driven forcing using OpenSCM-Runner (Nicholls *et al* 2024) and run with a probabilistic framework generating 600 ensemble members through a Metropolis–Hastings Markov chain Monte Carlo method (Meinshausen *et al* 2009).

The MAGICC sea level model v2 projects sea level responses based on emulation of process-based models for the Greenland and Antarctic ice sheets, global glaciers, and land water storage (Nauels *et al* 2017a, 2017b). Thermosteric sea level rise is calibrated to CMIP5 models within MAGICC's hemispheric upwelling-diffusion ocean model component (Nauels *et al* 2017a, 2017b). The MAGICC sea level model v2 is calibrated with projections from process-based models rather than observations. We therefore ran a validation exercise to evaluate the model's performance in the historical time period by comparing modeled GMSLR to observations from IPCC AR6 (Fox-Kemper *et al* 2021). IPCC AR6 WGI assessed modern GMSLR as 0.2 (0.15–0.25) m (median value with 5th to 95th percentile confidence intervals) from 1901–2018 (Fox-Kemper *et al* 2021). Over the same time period and using the same confidence intervals our modeled responses in the control scenario yield 0.19 (0.15–0.22) m, giving confidence in the robustness of our modeled results.

2.2. Emissions forcing

The simulations presented here are modeled with historical counterfactual emissions scenarios generated by subtracting emissions traced to the products produced by the largest fossil fuel producers from the full historical emissions used in the 6th cycle of the coupled model intercomparison project (CMIP6) (Gidden *et al* 2019). Here we use the emissions compilation created for the reduced complexity model intercomparison project (RCMIP) (Nicholls *et al* 2020, 2021), although all sources of this data give the same result.

The historical emissions data used in CMIP6 and RCMIP span 1750–2015 (Hoesly *et al* 2018, Gidden *et al* 2019). After 2015 they are harmonized to extend into the future via the shared socioeconomic pathways (SSP) (Meinshausen *et al* 2020, Kikstra *et al* 2022b). The IPCC AR6 WGIII infiller database is used to fill missing emissions ensuring that all scenarios have complete sets of anthropogenic emissions forcing (Kikstra *et al* 2022a). The emissions data includes 51 species, including Kyoto gases (CO_2, CH_4, N_2O, NH_3, HFCs, PFCs), Montreal gases, aerosols (BC, SO_2F_2, OC), NH_3, NO*x*, Sulfur, and VOCs.

Fossil fuel emissions are derived from the Carbon Majors database (InfluenceMap 2024) which compiles data based on the methods of Heede (2014). The dataset contains fossil fuel production quantities for each product (oil and natural gas liquids, natural gas, cement production, and a variety of types of coal) and their associated CO_2 and CH_4 emissions. The data spans from 1854–2022 and includes products produced by the 122 largest investor and state-owned fossil fuel companies around the world (InfluenceMap 2024) accounting for mergers throughout the historical time period. This dataset includes Scope 1 and Scope 3 emissions classes (Heede 2014). We aggregate all companies in the dataset to produce a single time series for each gas. Emissions forcing in the historical and SSP datasets is yearly from 1750–2015, then has a data point in 2020, and every 10 yrs following 2020 until 2300. Due to this, Carbon Majors emissions are not subtracted out in counterfactual scenarios in 2016–2019 or 2021–2022 as the model internally interpolates values during those years.

2.3. Scenario construction

We evaluate three counterfactual scenarios representing different time periods: the 1854 counterfactual (hereafter denoted CF1854) removes fossil fuel emissions from 1854–2020; the 1950 counterfactual (CF1950) removes these emissions from 1950–2020; and the 1990 counterfactual (CF1990) removes these emissions from 1990–2020 (figures 1(a) and (b)). The total cumulative emissions in each scenario are in table 1. CF1854 represents a world in which industrial fossil fuel development never occurred. CF1950 represents how the climate system would have evolved if the fossil fuel industry had acted to halt emissions at the time when they were becoming aware of the harms their products were projected to cause. CF1990 provides insight into how the evolution of the climate system since 1990 would have differed if emissions had been swiftly halted when international efforts to address climate change, such as the establishment of the Intergovernmental Panel on Climate Change and United Nations Framework Convention on Climate Change, first began. These modeled pathways help us understand how emissions tied to industrial fossil fuel and cement production impact modern day temperature and sea level rise as well as projected contributions to long-term sea level rise in the coming centuries. We compare our counterfactuals to a control scenario which contains full historical emissions forcing.

To assess the robustness of our future sea level projections, we conduct an additional sensitivity test assessing the counterfactual scenarios with three post-2020 emissions scenarios: SSP1-1.9, SSP2-4.5, and SSP5-8.5 (Meinshausen *et al* 2020). This allows us to assess contributions to long-term GMSLR from historical emissions without making assumptions about how emissions trajectories will change in the coming decades and centuries.

3. Results

3.1. Present day attribution

Under the control scenario (following SSP2-4.5 emissions after 2015), the average surface air temperature (SAT) change for the period from 1990–2020 is 1.00 (0.83–1.13) °C (median value with 10th to 90th percentile confidence interval) above the preindustrial baseline (1850–1900 average). In CF1854 (table 2 and figure 2), SAT rise over the same time period is 0.54 (0.39–0.65) °C, whereas in CF1950, modern SAT rise is 0.56 (0.41–0.66) °C. The minor differences between CF1854 and CF1950 stem from the relatively small quantity of emissions released from 1854–1949, compared to the cumulative emissions released thereafter (table 1). In CF1990, in which emissions are removed starting in 1990, present day SAT is 0.78 (0.65–0.90) °C above preindustrial. Across these historical counterfactual scenarios, emissions traced to the 122 largest fossil fuel producers are responsible for 45%, 44%, or 21% (median values) of present day warming respectively for CF1854, CF1950, and CF1990 (table 2).

The amount of warming modeled with each counterfactual is consistent with the cumulative emissions associated with the fossil fuel and cement producers through 2020 (table 1). The difference in cumulative emissions between CF1854 and CF1950 is small, which then results in a small difference in the modeled temperature responses between those two counterfactuals (table 2). The relatively smaller

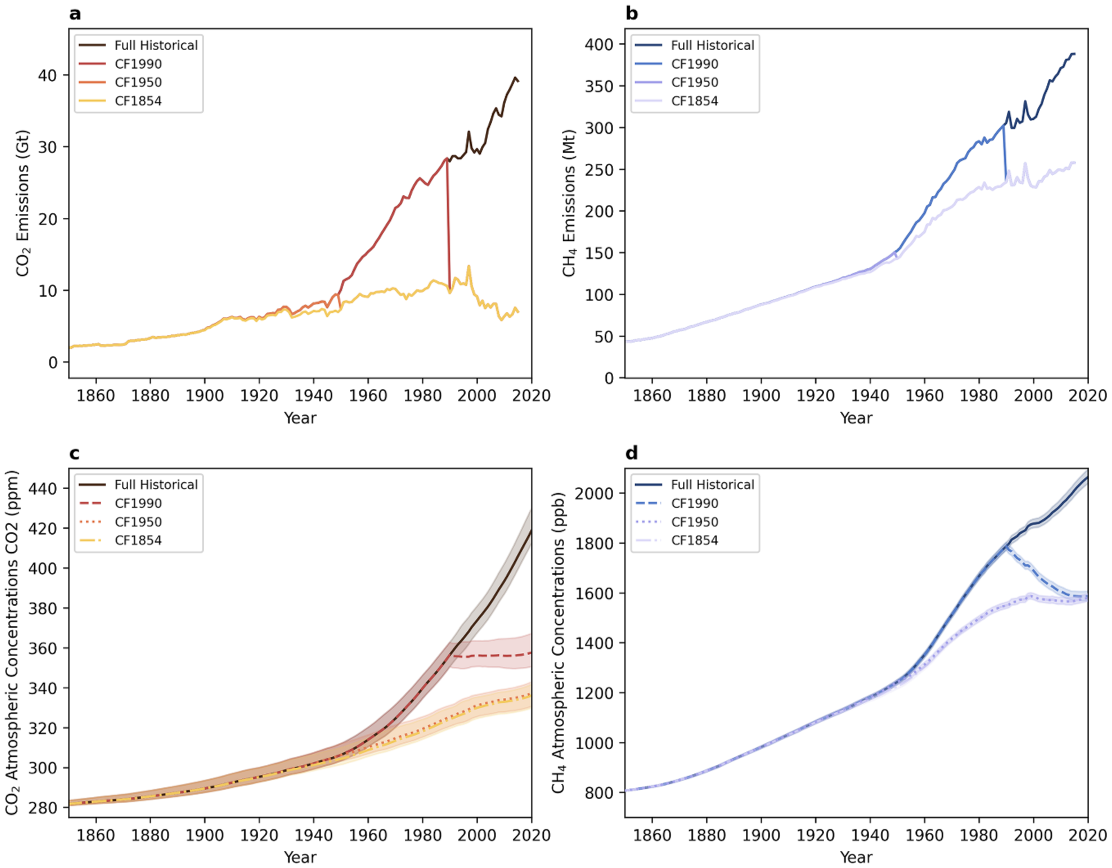

Figure 1. Greenhouse gas emissions and atmospheric concentrations. (a) Carbon dioxide emissions from 1850–2020 in the counterfactual scenarios and the control, (b) same as (a) but for methane emissions, (c) atmospheric concentrations of carbon dioxide from 1850–2020, (d) same as (c) but for methane. Curves are plotted to depict the median and 10th and 90th percentile confidence intervals.

Table 1. Greenhouse gas emissions and atmospheric concentrations across scenarios. CO_2 and CH_4 are the two gases that are altered between the control and counterfactual scenarios, while all other gas quantities are the same across all scenarios. The upper portion of the table includes total cumulative emissions for each of these two species from 1750–2020 for each scenario, and differences in cumulative emissions between each counterfactual scenario and the control scenario (δCO_2 and δCH_4). The lower portion includes the atmospheric CO_2 and CH_4 concentrations at 2022 for each scenario, and differences between each counterfactual scenario and the control scenario (δCO_2 and δCH_4). Atmospheric concentrations are rounded to the nearest whole number.

Cumulative greenhouse gas emissions 1750-2020				
Scenario	CO_2 (Gt)	δCO_2 (Gt)	CH_4 (Gt)	δCH_4 (Gt)
Control	2263.83		30.25	
CF1854	1176.40	1087.43	26.04	4.21
CF1950	1202.07	1061.75	26.13	4.13
CF1990	1615.40	648.43	27.63	2.62
Atmospheric concentrations in 2022				
Scenario	CO_2 (ppm)	δCO_2 (ppm)	CH_4 (ppb)	δCH_4 (ppb)
Control	424 (417–436)		2081 (2053–2112)	
CF1854	337 (331–343)	88 (85–93)	1590 (1576–1606)	491 (469–511)
CF1950	339 (332–344)	87 (84–92)	1589 (1575–1605)	492 (471–512)
CF1990	359 (352–369)	66 (64–68)	1592 (1574–1611)	490 (477–503)

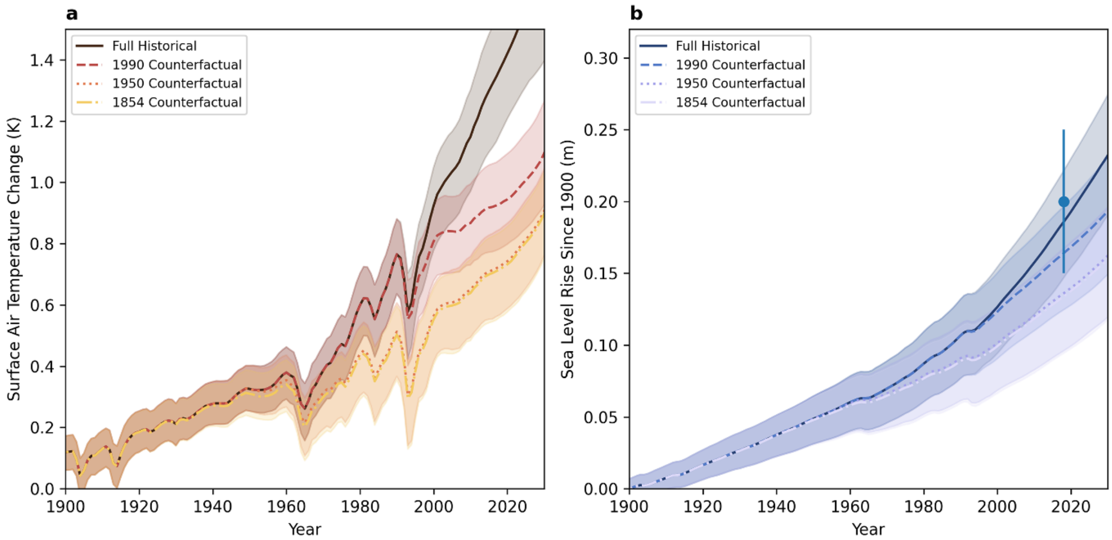

Figure 2. Modeled temperature and sea level rise at present day. (a) Global mean surface air temperature response for the control scenario and the three historical counterfactual scenarios. Temperature curves are plotted to depict the median and 10th and 90th percentile confidence intervals. (b) same as (a) for global mean sea level rise since 1900. Post-2015 emissions follow SSP2-4.5. Sea level curves are plotted with 5th and 95th percentile confidence intervals. The observational sea level rise in 2018, as given in IPCC AR6 WGI (IPCC 2021), is shown as a single data point and 5th and 95th confidence intervals overlaid on our projections.

Table 2. Modeled surface air temperature and sea level rise at present day. Surface air temperature (SAT) change is given as the 1990–2020 average above the 1850–1900 baseline. Global mean sea level rise is shown as the median rise in 2022, as compared to median sea level at 1900. Values are given as the median with 10th to 90th percentile confidence intervals in parentheses. After 2015, the historical emissions scenario follows SSP2-4.5. Percentages are rounded to the nearest percent.

Scenario	SAT Change (K)	SAT Attribution	GMSLR (m)	GMSLR Attribution
Control	1.00 (0.83–1.13)		0.20 (0.17–0.23)	
CF1854	0.54 (0.39–0.65)	45 (37–58)%	0.14 (0.12–0.17)	29 (24–37)%
CF1950	0.56 (0.41–0.66)	44 (36–57)%	0.14 (0.12–0.17)	28 (23–36)%
CF1990	0.78 (0.65–0.90)	21 (17–26)%	0.17 (0.15–0.20)	14 (11–17)%

contribution to total warming in CF1990 is in part due to the warming and sea level rise effects of emissions closer to the end of the historical time period not having been fully realized yet, particularly for the long atmospheric lifetime of CO_2. The differences in modeled temperatures between the counterfactuals translates to similar differences in the amount of sea level rise modeled by the counterfactuals (table 2).

Under the SSP2-4.5 control scenario, we model a GMSLR of 0.19 (0.15–0.22) m above the 1900 median value by 2018, which is consistent with the globally observed GMSLR of 0.2±0.05 m over this time period (Fox-Kemper *et al* 2021) (median value with 5th to 95th percentile confidence intervals) (figure 2). Comparing all scenarios at 2022, we find GMSLR since 1900 to be 0.14 (0.12–0.17) m in CF1854 and CF1950 and 0.17 (0.15–0.20) m in CF1990 (table 2, median values with 10th to 90th percentile confidence intervals). Emissions traced to the 122 largest fossil fuel and cement producers therefore contributed to 29%, 28%, and 14% (median values) of sea level rise by 2022, respectively, under CF1854, CF1950, and CF1990.

3.2. Projected long-term sea level rise modeled with historical counterfactual scenarios

Each counterfactual historical scenario was run with a series of future emissions scenarios (SSP1-1.9, SSP2-4.5, SSP5-8.5), producing a series of scenarios constructed to have emissions removed during the historical period, then increased after 2020 to follow future SSP scenarios. This allows us to understand the long-term projected sea level rise from historical emissions using standard future projection scenarios rather than making assumptions about future emissions from major fossil fuel producers and cement manufacturers. Control versions of these scenarios, which have full historical emissions forcing, span a range of future projections. In SSP1-1.9 there are net-zero CO_2 emissions by 2050–2055 which limits warming to 1.5 °C above preindustrial at 2100 with a greater than 50% likelihood (Meinshausen *et al* 2020, Lee *et al* 2021, Riahi *et al* 2022). In SSP2-4.5 CO_2 emissions peak by 2030–2035, limiting warming to 3 °C by 2100 with a greater than 50% likelihood, while in SSP5-8.5 CO_2 emissions peak by 2080–2085 and 21st century temperatures exceed 4 °C above

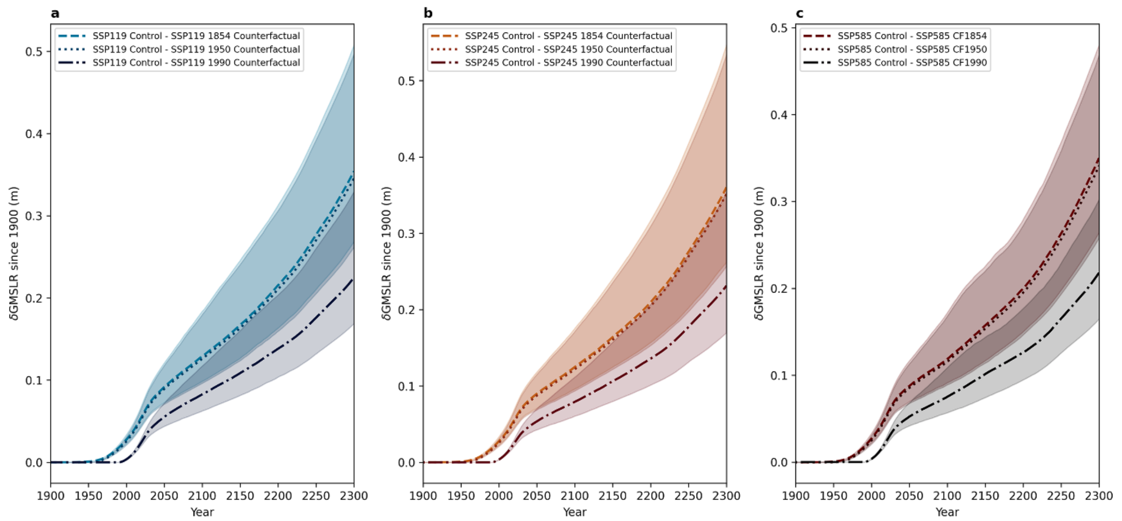

Figure 3. Difference in projected future sea level rise through 2300. The difference in projected GMSLR (δGMSLR), since 1900, between the control scenario and each counterfactual historical scenario for each of three future emissions trajectories (a) SSP1-1.9, (b) SSP2-4.5, and (c) SSP5-8.5. Curves are plotted to depict the median and 10th to 90th percentile confidence intervals.

Table 3. Difference in projected GMSLR at 2300. The difference in projected GMSLR (δGMSLR), since 1900, between the control and counterfactual scenarios at 2300 under each future emissions scenario. Values are given as the median with 10th to 90th percentile confidence intervals in parenthesis.

Scenario	δGMSLR SSP1-1.9 (m)	δGMSLR SSP2-4.5 (m)	δGMSLR SSP5-8.5 (m)
CF1854	0.35 (0.27-0.51)	0.36 (0.26-0.55)	0.36 (0.26-0.48)
CF1950	0.35 (0.26-0.50)	0.35 (0.26-0.53)	0.35 (0.26-0.47)
CF1990	0.22 (0.17-0.33)	0.23 (0.17-0.35)	0.23 (0.16-0.30)

preindustrial (Meinshausen *et al* 2020, Lee *et al* 2021, Riahi *et al* 2022).

These modeled pathways are analyzed and visualized by taking the difference between the control and each counterfactual within a given SSP scenario (δGMSLR). We focus on δGMSLR rather than the overall magnitude of GMSLR to assess the attributable long-term response of past emissions which necessitates a comparison between the control and each counterfactual for a given future emissions scenario. Results show that the difference in long-term projected sea level for a given historical counterfactual is largely independent of which SSP scenario occurs post-2020 (figure 3 and table 3). The median δGMSLR at 2300 is 0.35–0.36 m for CF1854, 0.35 m for CF1950, and 0.22–0.23 m for CF1990 (table 3). As noted for scenarios through the present day, the small differences in cumulative emissions between CF1854 and CF1950 result in very similar projected δGMSLR. Meanwhile CF1990 yields lower contributions due to the shorter time period of emissions removal. This attribution method is robust regardless of which SSP scenario is chosen with the difference between SSP5-8.5 and SSP1-1.9 being at most 0.016 m for a given counterfactual (figure 4). The difference in uncertainty in δGMSLR across the scenarios is more complex. While the results are broadly similar, the details are a result of a number of factors including the overshoot (or lack thereof) in each scenario and how this interplays with the feedbacks in the climate forcing, carbon cycle, other greenhouse gas cycles and energy uptake. Exploring these dynamics and their interplay is beyond the scope of this study, but would be an area for future research.

4. Discussion

The findings of this study have several important implications for understanding and addressing the long-term impacts of emissions traced to industrial fossil fuel and cement producers on GMSLR. Our results indicate the products produced by the Carbon Majors between 1854–2020 have substantially altered the climate by contributing 37%–58% of present day SAT rise and 24%–37% of modern GMSLR. While the quantities of fossil fuels produced by these companies into the future are, as yet, undetermined, the impacts of their past production on the climate system will continue for centuries. Here we find that the multi-century contribution to rising sea levels from past fossil fuel and cement production by these companies from 1854–2020 is projected to be 0.26–0.55 m GMSLR at 2300.

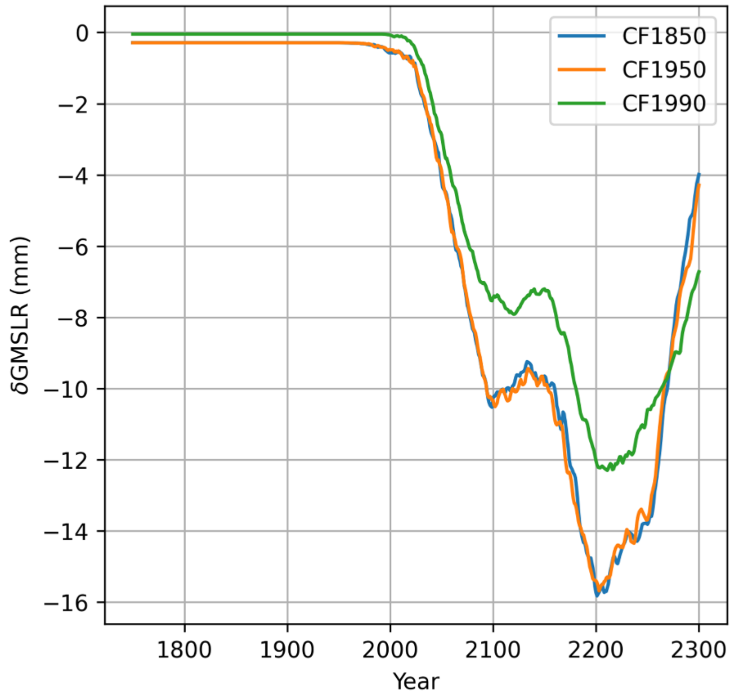

Figure 4. Difference in projected future sea level rise across scenarios. The difference in median projected GMSLR (δGMSLR), in millimeters since 1900, between the SSP5-8.5 and SSP1-1.9 scenarios for each counterfactual historical scenario.

By integrating historical counterfactuals into scenario based GMSLR analyses, the method presented here allows for evaluation of the effects of past corporate emissions on atmospheric greenhouse gas concentrations, SATs, and GMSLR. In addition to maintaining emissions-intensive business models that drive climate change (Ekwurzel *et al* 2017, Licker *et al* 2019, Dahl *et al* 2023), the fossil fuel industry has played a role in spreading disinformation and delaying regulatory action (Supran and Oreskes 2017, Franta 2018) despite awareness of the impacts of their products (Supran *et al* 2023). We show here that the delayed mitigation illustrated by CF1950 and CF1990 has led to additional sea level rise at present day compared to what would have occurred in the absence of these emissions. Delayed mitigation and the long-term impacts of sea level rise present a temporal distributive climate injustice in which actions in the past have impacts on those living in the future (Sadai *et al* 2022).

Estimates for the attributable present day signal and projected sea level rise rely on model assumptions and the specific construction of the emissions scenarios. The production of fossil fuels is associated with co-emitted species, particularly aerosols, which can partially offset the warming effect of fossil CO_2 and CH_4 emissions. The Carbon Majors dataset does not contain attributable aerosol data, and therefore we include all historical aerosols in these simulations. The inclusion of changes in aerosol emissions would reduce the short-term impact of emissions from major fossil fuel emitters (Ekwurzel *et al* 2017), however the impact of aerosols is short-lived. As a result, the removal or inclusion of aerosols will not affect the paper's key results for long-term impacts, although it may impact present-day attribution.

MAGICC7 takes a simplified modeling approach to representing the interactions between elements of the earth system. The MAGICC7 sea level rise model v2 includes contributions from thermal expansion, glaciers, ice sheets, and land water storage (Nauels *et al* 2017a, 2019). While this simplified framework allows for an investigation of the climate system response to emissions by simplifying the dynamics and computational cost of simulation, there are dynamics that the model is unable to capture. As an example, the model cannot represent small-scale feedbacks and interactions, such as those between ice sheets and oceans (Alley *et al* 2019, Anselin *et al* 2023, Vankova *et al* 2023). Furthermore, the model used in this study provides a simplified representation emulating ice sheet dynamics and, in this model configuration, does not include uncertain processes such as the marine ice cliff instability (MICI) (Fox-Kemper *et al* 2021) or explicit representation of inherent nonlinearities such as the marine ice sheet instability (MISI) (Weertman 1974, Schoof 2007). MICI, in particular, has been shown to produce a significant sea level rise response, but the process itself and its application to natural systems is not yet understood (Clerc *et al* 2019, Edwards *et al* 2019, Morlighem *et al* 2024). The role of MISI as well is still being evaluated in natural systems (Pegler 2018, Robel *et al* 2022, Sergienko 2022, Sergienko and Haseloff 2023, Ranganathan and

Minchew 2024). Therefore, the results presented here are conservative estimates of future sea-level rise that do not capture high-risk processes that may produce significant sea level rise.

The projected sea level rise presented in this study represents global mean values, but it is important to note that spatial variation leads to regional sea level change that can differ substantially from the global mean (Gomez *et al* 2024). Regional variations in sea level as compared to the global mean are mainly due to spatial variation in heat, freshwater flux, and changes in gravitational, rotational, and Earth deformational effects due to barystatic changes (Fox-Kemper *et al* 2021). From 1993 to 2018 the western Pacific experienced higher rates of sea level rise than the global mean, which has exacerbated risks for low-lying Pacific islands (Fox-Kemper *et al* 2021, Mycoo *et al* 2022). Higher regional sea level rise in locations that are responsible for negligible amounts of greenhouse gas emissions, such as many Pacific island states, has previously been highlighted as an issue of distributive climate injustice (Sadai *et al* 2022). Understanding regional differences in sea level rise is important for developing targeted adaptation strategies that effectively address the unique challenges posed by sea level rise in different parts of the world. Future research should explore the contribution of industrial emissions to sea level rise in regions around the world.

5. Conclusion

This study quantifies the contributions of the Carbon Majors, the world's largest fossil fuel and cement producers, to present day temperature and sea level rise, as well as to projected GMSLR over the coming centuries. Our results emphasize the impacts of delayed mitigation and the long-term consequences of industrial carbon dioxide and methane emissions. Our analysis shows that ongoing sea level rise—resulting from past and ongoing emissions—will continue to unfold over centuries. Counterfactual scenarios suggest that if emissions reductions had been implemented when the fossil fuel industry first recognized the risks of carbon dioxide emissions, or at the onset of international negotiations, present day sea level rise would be 0.03–0.06 m lower. The level of global fossil fuel infrastructure that exists today is projected to result in emissions that will exceed 1.5 °C (IPCC 2023). Immediate and near-term mitigation is crucial to meeting global climate goals and reducing the long-term impacts, such as sea level rise, which will evolve over centuries. This study underscores that the past actions of fossil fuel and cement producers will have consequences long into the future. Future climate action should consider corporate accountability measures to prevent the continuation of practices that exacerbate climate change, and to mitigate the intergenerational harm associated with these impacts.

Data availability statement

The MAGICC7 climate model is available from https://magicc.org/. The Carbon Majors dataset is available at https://carbonmajors.org/. The historical and SSP emissions were provided by Zebedee Nicholls via https://www.rcmip.org/.

The data that support the findings of this study are openly available at the following URL/DOI: https://osf.io/23dkn (Sadai and Ranganathan 2025).

Acknowledgment

We are grateful for funding from the Hitz Family Foundation as well as the Grantham Foundation for the Protection of the Environment, Rockefeller Family Fund, and Zegar Family Foundation. We thank Samuel Dotson for coding assistance. Thank you to two anonymous reviewers for their helpful comments.

ORCID iDs

Shaina Sadai https://orcid.org/0000-0002-6723-6531
Meghana Ranganathan https://orcid.org/0000-0002-8099-4775
Alexander Nauels https://orcid.org/0000-0003-1378-3377
Zebedee Nicholls https://orcid.org/0000-0002-4767-2723
Delta Merner https://orcid.org/0009-0006-1217-312X
Kristina Dahl https://orcid.org/0000-0001-6471-8845
Brenda Ekwurzel https://orcid.org/0000-0003-3950-281X

References

Alley K E, Scambos T A, Alley R B and Holschuh N 2019 Troughs developed in ice-stream shear margins precondition ice shelves for ocean-driven breakup *Sci. Adv.* **5** eaax2215
Anselin J, Reed B C, Jenkins A and Green J A M 2023 Ice shelf basal melt sensitivity to tide-induced mixing based on the theory of subglacial plumes *J. Geophys. Res. Oceans* **128** e2022JC019156
Buchanan M K, Kulp S, Cushing L, Morello-Frosch R, Nedwick T and Strauss B 2020 Sea level rise and coastal flooding threaten affordable housing *Environ. Res. Lett.* **15** 124020
Clark P U *et al* 2016 Consequences of twenty-first-century policy for multi-millennial climate and sea-level change *Nat. Clim. Change* **6** 360–9
Clerc F, Minchew B M and Behn M D 2019 Marine ice cliff instability mitigated by slow removal of ice shelves *Geophys. Res. Lett.* **46** 12108–16
Dahl K A, Abatzoglou J T, Phillips C A, Ortiz-Partida J P, Licker R, Merner L D and Ekwurzel B 2023 Quantifying the contribution of major carbon producers to increases in

vapor pressure deficit and burned area in western us and southwestern Canadian forests *Environ. Res. Lett.* **18** 064011
Edwards T L *et al* 2019 Revisiting Antarctic ice loss due to marine ice-cliff instability *Nature* **566** 58–64
Ekwurzel B, Boneham J, Dalton M W, Heede R, Mera R J, Allen M R and Frumhoff P C 2017 The rise in global atmospheric CO_2, surface temperature and sea level from emissions traced to major carbon producers *Clim. Change* **144** 579–90
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 (Cambridge University Press) pp 923–1054
Fox-Kemper B *et al* 2021 Ocean, cryosphere and sea level change *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 (Cambridge University Press) pp 1211–361
Franta B 2018 Early oil industry knowledge of CO_2 and global warming *Nat. Clim. Change* **8** 1024–5
Franta B 2022 Weaponizing economics: Big oil, economic consultants and climate policy delay *Environ. Politics* **31** 555–75
Frederikse T *et al* 2020 The causes of sea-level rise since 1900 *Nature* **584** 393–7
Gidden M J *et al* 2019 Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century *Geosci. Model Dev.* **12** 1443–75
Gomez N *et al* 2024 The influence of realistic 3D mantle viscosity on Antarctica's contribution to future global sea levels *Sci. Adv* **10** 1470
Gulev S *et al* 2021 Changing state of the climate system *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 (Cambridge University Press) pp 287–422
Hardy R D and Hauer M E 2018 Social vulnerability projections improve sea-level rise risk assessments *Appl. Geogr.* **91** 10–20
Heede R 2014 Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers 1854-2010 *Clim. Change* **122** 229–41
Hoesly R M *et al* 2018 Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the community emissions data system (ceds) *Geosci. Model Dev.* **11** 369–408
InfluenceMap 2024 Carbon majors dataset (available at: https://carbonmajors.org/Downloads)
IPCC 2023 Climate change 2023: synthesis report *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H L Core Writing Team (Cambridge University Press) (https://doi.org/10.59327/IPCC/AR6-9789291691647)
IPCC 2021 Summary for policymakers *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 University Press) (https://doi.org/10.1017/9781009157896.001)
Kikstra J S *et al* 2022a Infiller database for silicone: IPCC AR6 WGIII version (1.0) [Data set] (https://doi.org/10.5281/zenodo.6390767)
Kikstra J S *et al* 2022b The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures *Geosci. Model Dev.* **15** 9075–109
Lee J-Y *et al* 2021 Future global climate: Scenario-based projections and near-term information *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 (Cambridge University Press) pp 553–672
Levermann A, Clark P U, Marzeion B, Milne G A, Pollard D, Radic V and Robinson A 2013 The multimillennial sea-level commitment of global warming *Proc. Natl Acad. Sci. USA* **110** 13745–50
Licker R, Ekwurzel B, Doney S C, Cooley S R, Lima I D, Heede R and Frumhoff P C 2019 Attributing ocean acidification to major carbon producers *Environ. Res. Lett.* **14** 124060
Meinshausen M *et al* 2020 The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500 *Geosci. Model Dev.* **13** 3571–605
Meinshausen M, Meinshausen N, Hare W, Raper S C, Frieler K, Knutti R, Frame D J and Allen M R 2009 Greenhouse-gas emission targets for limiting global warming to 2 °C *Nature* **458** 1158–62
Meinshausen M, Raper S C and Wigley T M 2011 Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - part 1: model description and calibration *Atmos. Chem. Phys.* **11** 1417–56
Mengel M, Nauels A, Rogelj J and Schleussner C-F 2018 Committed sea level rise under the Paris Agreement and the legacy of delayed mitigation action *Nat. Commun.* **9** 1–10
Morlighem M, Goldberg D, Barnes J M, Bassis J N, Benn D I, Crawford A J, Gudmundsson G H and Seroussi H 2024 The West Antarctic Ice Sheet may not be vulnerable to marine ice cliff instability during the 21st century *Sci. Adv.* **10** 94
Mycoo M *et al* 2022 Small islands *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed H O Pörtner (Cambridge University Press) (https://doi.org/10.1017/9781009325844.017)
Nauels A, Gütschow J, Mengel M, Meinshausen M, Clark P U and Schleussner C-F 2019 Attributing long-term sea-level rise to Paris Agreement emission pledges *Proc. Natl Acad. Sci. USA* **116** 23487–92
Nauels A, Meinshausen M, Mengel M, Lorbacher K and Wigley T M 2017a Synthesizing long-term sea level rise projections-the MAGICC sea level model v2.0 *Geosci. Model Dev.* **10** 2495–524
Nauels A, Rogelj J, Schleussner C F, Meinshausen M and Mengel M 2017b Linking sea level rise and socioeconomic indicators under the shared socioeconomic pathways *Environ. Res. Lett.* **12** 114002
Nicholls Z R J *et al* 2020 Reduced complexity model intercomparison project phase 1: Introduction and evaluation of global-mean temperature response *Geosci. Model Dev.* **13** 5175–90
Nicholls Z *et al* 2021 Reduced complexity model intercomparison project phase 2: Synthesizing earth system knowledge for probabilistic climate projections *Earth's Future* **9** 1–25
Nicholls Z *et al* 2024 OpenSCM-runner (available at: https://github.com/openscm/openscm-runner)
Oppenheimer M *et al* 2019 Sea level rise and implications for low-lying islands, coasts and communities *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* ed H-O Pörtner (Cambridge University Press) pp 321–445
Pegler S S 2018 Suppression of marine ice sheet instability *J. Fluid Mech.* **857** 648–80
Price S F, Payne A J, Howat I M and Smith B E 2011 Committed sea-level rise for the next century from Greenland ice sheet dynamics during the past decade *Proc. Natl Acad. Sci.* **108** 8978–83
Ranganathan M and Minchew B 2024 A modified viscous flow law for natural glacier ice: scaling from laboratories to ice sheets *Proc. Natl Acad. Sci.* **121** 21
Riahi K *et al* 2022 Mitigation pathways compatible with long-term goals *Climate Change 2022: Mitigation of Climate Change.*

Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change ed P Shukla (Cambridge University Press) (https://doi.org/10.1017/9781009157926.005)

Robel A A, Pegler S S, Catania G, Felikson D and Simkins L M 2022 Ambiguous stability of glaciers at bed peaks *J. Glaciol.* **68** 1177–84

Sadai S and Ranganathan M 2025 Estimating the sea level rise responsibility of industrial carbon producers(available at: https://osf.io/23dkn)

Sadai S, Spector R, DeConto R and Gomez N 2022 The paris agreement and climate justice: inequitable impacts of sea level rise associated with temperature targets *Earth's Future* **10** 40

Schoof C 2007 Ice sheet grounding line dynamics: steady states, stability and hysteresis *J. Geophys. Res.* **112** 64

Sergienko O V 2022 No general stability conditions for marine ice-sheet grounding lines in the presence of feedbacks *Nat. Commun.* **13** 2265

Sergienko O and Haseloff M 2023 stable' and 'unstable' are not useful descriptions of marine ice sheets in the earth's climate system *J. Glaciol.* **69** 1–17

Strauss B H, Kulp S and Levermann A 2015 Carbon choices determine us cities committed to futures below sea level *Proc. Natl Acad. Sci. USA* **112** 13508–13

Supran G and Oreskes N 2017 Assessing ExxonMobil's climate change communications (1977–2014) *Environ. Res. Lett.* **12** 084019

Supran G, Rahmstorf S and Oreskes N 2023 Assessing ExxonMobil's global warming projections *Science* **379** 6628

Vankova I, Winberry J P, Cook S, Nicholls K W, Greene C A and Galton-Fenzi B K 2023 High spatial melt rate variability near the totten glacier grounding zone explained by new bathymetry inversion *Geophys. Res. Lett.* **379** 50

Weertman J 1974 Stability of the junction of an ice sheet and an ice shelf *J. Glaciol.* **13** 3–11

Wentz J, Merner D, Franta B, Lehmen A and Frumhoff P C 2023 Research priorities for climate litigation *Earth's Future* **11** e2022EF002928

Zickfeld K, Solomon S and Gilford D M 2017 Centuries of thermal sea-level rise due to anthropogenic emissions of short-lived greenhouse gases *Proc. Natl Acad. Sci. USA* **114** 657–62