Attributing long-term sea-level rise to Paris Agreement emission pledges

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The main contributors to sea-level rise (oceans, glaciers, and ice sheets) respond to climate change on timescales ranging from decades to millennia. A focus on the 21st century thus fails to provide a complete picture of the consequences of anthropogenic greenhouse gas emissions on future sea-level rise and its long-term impacts. Here we identify the committed global mean sea-level rise until 2300 from historical emissions since 1750 and the currently pledged National Determined Contributions (NDC) under the Paris Agreement until 2030. Our results indicate that greenhouse gas emissions over this 280-year period result in about 1 m of committed global mean sea-level rise by 2300, with the NDC emissions from 2016 to 2030 corresponding to around 20 cm or 1/5 of that commitment. We also find that 26 cm (12 cm) of the projected sea-level-rise commitment in 2300 can be attributed to emissions from the top 5 emitting countries (China, United States of America, European Union, India, and Russia) over the 1991–2030 (2016–2030) period. Our findings demonstrate that global and individual country emissions over the first decades of the 21st century alone will cause substantial long-term sea-level rise.

Future global mean sea-level rise (GMSLR) poses a threat to ecosystems (1), the livelihoods of hundreds of millions of people (2), and world heritage (3, 4) along the Earth’s coasts. Global mean sea level has risen by around 20 cm since 1900, with accelerating current rates of around 3 mm/yr (5–7). The key contributors to sea-level change are ocean thermal expansion, glaciers, and the Greenland and Antarctic ice sheets, all of which are now contributing to current sea-level rise at an increasing rate in response to ongoing global warming (5). These contributors respond to warming on multiple timescales, ranging from decades to centuries for glaciers and centuries to millennia for thermal expansion and ice sheets (8, 9). Due to this long integrated response time, the GMSLR from anthropogenic greenhouse gas emissions is only now in its initial stages. A focus on the scenario dependency of GMSLR for the 21st century thus does not reflect the sensitivity of future long-term GMSLR to historical and future emissions as the full response to these emissions will only materialize on a millennial timescale (9–12).

For the near-term future up to 2030, aggregated Nationally Determined Contributions (NDCs), as submitted under the Paris Agreement framework, reflect the global mitigation ambition and result in quantifiable emission trajectories. The level of ambition implied by the NDCs is routinely compared to 2030 emission scenarios in line with 1.5 or 2 °C scenarios (13). Alternatively, the aggregated NDCs are translated into a Global Mean Temperature (GMT) signal up to 2100 for benchmarking against the Long-term Temperature Goal of the Paris Agreement (14). In contrast, the aspect of locked-in post-2100 consequences of near-term emissions has not been a central part of high-level political discourse. In this study, we use GMSLR modeling that can handle emission scenarios flexibly (15, 16) to establish the link between pledged NDC emissions and GMSLR until 2300, thus highlighting the longer-term climate change implications of current climate mitigation efforts. We simulate the GMSLR commitment of greenhouse gas (GHG) emissions over the historical period (from 1750) and up to 2030, globally and for the 5 highest-emitting countries individually.

Attributing Global Mean Sea-Level Change to NDC Emission Pledges

We use a sea-level emulator (15) that includes contributions from thermal expansion, global glaciers, the Greenland Ice Sheet (GIS), the Antarctic Ice Sheet (AIS), and land-water storage. The emulator is part of the MAGICC simple climate model (17). Each component is calibrated to process-based projections consistent with the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) (5) using a maximum likelihood optimization technique. In addition to the IPCC AR5 consistent AIS representation that captures surface mass balance effects (18) as well as solid ice discharge contributions with fast dynamics (19), we also implement an alternative version for AIS loss (20) that captures the higher sensitivity to future global warming from additional nonlinear processes related to Marine Ice Cliff Instability (MICI) (21). We use the MICI version to identify the potential for risk from higher sea-level rise not covered by our main results, but emphasize that the understanding of MICI and its triggers is still limited (22). Our sea-level emulator allows us to project GMSLR for emission scenarios until 2300. No estimates are provided for future global mean sea-level rise poses a threat to coastal areas and will continue for centuries, even after global mean temperature has stabilized. Research assessing the implications of current international climate mitigation efforts usually focuses on 21st century climate impacts. The multicentennial sea-level rise commitment of pledged near-term emission reduction efforts under the Paris Agreement has not been quantified yet. We here estimate this sea-level rise commitment and find that pledged emissions until 2030 lock in 1-m sea-level rise in the year 2300. Our analysis highlights the defining role of present-day emissions for future sea-level rise and points to the potential of reducing the long-term sea-level-rise commitment by more ambitious national emission reduction targets.

Significance

Sea-level rise poses a threat to coastal areas and will continue for centuries, even after global mean temperature has stabilized. Research assessing the implications of current international climate mitigation efforts usually focuses on 21st century climate impacts. The multicentennial sea-level rise commitment of pledged near-term emission reduction efforts under the Paris Agreement has not been quantified yet. We here estimate this sea-level rise commitment and find that pledged emissions until 2030 lock in 1-m sea-level rise in the year 2300. Our analysis highlights the defining role of present-day emissions for future sea-level rise and points to the potential of reducing the long-term sea-level-rise commitment by more ambitious national emission reduction targets.

Author contributions: A.N. and C.-F.S. designed research; A.N. and J.G. performed research; A.N. and J.G. analyzed data; and A.N., J.G., M. Mengel, M. Meinshausen, P.U.C., and C.-F.S. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

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Data deposition: Pathway as well as projection data and code to reproduce the results shown in this study can be accessed at: https://gitlab.com/anauel/sndc slr_atttribution.

See Commentary on page 23373.

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First published November 4, 2019.
beyond this time horizon, as some information from process-based models used for the calibration (i.e., Antarctic solid ice discharge) is not available beyond 2300 (15).

Current NDCs are provided until the year 2030. With respect to GMT rise, the recent IPCC Special Report on Global Warming of 1.5 °C concluded that “pathways reflecting these ambitions would not limit global warming to 1.5 °C” (23). More specific projections regarding the long-term GMT implications of the NDCs are strongly dependent on assumptions about emissions after 2030. Assessments of the end-of-century temperature implications of NDCs commonly assume some form of continuation in ambition reflected in pledged climate mitigation targets (24).

Here we follow a different approach that aims to avoid uncertainties regarding future ambition levels by analyzing stylized emission scenarios with zero Kyoto-GHG emissions after the end of the NDC accounting period in 2030. Assuming abrupt zero aerosol emissions would lead to a short-term increase in GMT (Fig. 1B). In order to avoid artifacts of such abrupt warming on long-term sea-level rise (Fig. 1C), we decrease aerosols and all other gases not regulated under the Kyoto protocol until 2075 (Methods). This stylized approach allows us to isolate the effects of NDCs and country-level emissions on longer-term GMSLR without making assumptions about global or individual country emissions pathways after 2030.

Cumulative NDC CO2 emissions relative to preindustrial are estimated to reach around 765 gigatonnes of carbon (GtC) in 2030. Fig. 1 depicts total anthropic CO2 emission estimates (A) and resulting probabilistic 2100 GMT (B) and GMSLR (C) responses for our 2030 NDC pathway. For illustration purposes, we also provide estimates for a representative 2 °C warming comparison pathway (RCP2.6) and the NDC extension pathway by the Climate Action Tracker (CAT) consortium (24, 25). For the GMT response, we can identify the diminishing influence of short-term climate forcers in the first decades after the year of zero emissions. The global 2030 NDC pathway allows us to quantify the NDC GMSLR commitment in 2100 and 2300, accounting for historical emissions since 1750. The chosen time frame up to 2030 further allows us to assess the contribution of individual emitters. To isolate country-level emission shares, we define 2 emission accounting periods for which country-level information is available (Methods). We call the first period from 1991 to 2030 the “IPCC period” as the first IPCC report was published in 1990. The second period from 2016 to 2030 is termed the “Paris period” as it exclusively covers the emissions after the 2015 Paris Agreement until 2030 (pre-2020 commitments and NDCs). For both accounting periods, emissions of the 5 biggest emitters (China, United States of America [USA], European Union [EU28], India, and Russia) are individually removed from the reference 2030 NDC pathway (Fig. 2). We estimate that China is responsible for 83 (44) GtC, the USA for 59 (21) GtC, the EU28 for 41 (13) GtC, India for 19 (11) GtC, and Russia for 18 (7) GtC of CO2 emissions over the IPCC (Paris) periods (25, 26).

For our global NDC pathway, we project a median peak warming of around 1.5 °C (66% range: 1.3 to 1.7 °C) relative to 1750 for the year 2035, then declining to a committed warming of around 1.3 °C (1.0 to 1.7 °C) in 2100 (Fig. 1B). For the top 5 emitters combined, historical and pledged emissions until the end of the first NDC period cause a 2100 warming of 0.45 and 0.2 °C for the IPCC and Paris periods, respectively (Fig. 2 B and E).

### National-Level GMSLR Commitments

In response to the warming trajectories of historical emissions, pledged NDC emission reductions, and zero GHG emissions after 2030, we estimate that, relative to the IPCC AR5 reference period 1986–2005, GMSLR will rise by 43 cm (66% range: 34 to 54 cm) in 2100 and continue to increase by 105 cm (79 to 135 cm) in 2300 (Fig. 2 and Table 1). The 2300 GMSLR commitments of global emissions prior to the IPCC (1991) and Paris (2016) periods yield around 60 (48 to 75) cm and 84 (66 to 109) cm, respectively. Using the IPCC accounting period (1991–2030), pathways that exclude 1 of the top 5 emitters reduce median 2300 GMSLR by around 10 cm for China, 7 cm for the USA, 5 cm for the EU28, and 2 cm for India and Russia (Table 2). For this 40-y period, the top 5 emitters are therefore responsible for a median of around 26 cm GMSLR in 2300, which is more than the roughly 20 cm observed since the beginning of the 20th century and about 25% of the total 2300 GMSLR NDC commitment. Using the Paris accounting period (2016–2030), the median 2300 GMSLR contribution ranges from roughly 6 cm for China, 3 cm for the USA, 2 cm for the EU28, and about 1 cm for India and Russia. For the 15-y Paris timeframe, the top 5 emitters thus commit GMSLR to a median of around 12 cm, more than 50% of the observed 20th century GMSLR.

For both accounting periods, country-level GMSLR contributions reflect changes in relative emission shares and therefore underline the overall sensitivity of 2300 GMSLR to changes in near-term emissions (Fig. 3). The fossil-fuel-intensive histories of the USA and EU28, for example, move both their CO2 emission...
and resulting GMSLR shares closer to China for the IPCC period, while for the Paris period, the projected decrease in fossil-fuel intensity for the EU28 shifts the country group toward the growing CO₂ emissions and respective GMSLR contributions of the developing economy of India (Fig. 3). Unlike historical emissions until 1991 or 2016, pledged national emissions until 2030 are not yet locked in, but if they are followed, they will cause ∼20 cm of GMSLR in 2300. When focusing on the Paris period, the attributable country contributions to projected long-term GMSLR emphasize the impact of countries’ emissions during both the IPCC and Paris periods and clearly point to the potential of reducing the future GMSLR commitment by more ambitious national emission reduction targets.

We also tested our results to the sensitivity of model choice for Antarctic ice discharge by including the MICI mechanism (20, 21), denoted DP16 in the following. Median sea-level estimates and resulting GMSLR contributions for the IPCC (1991–2030) and Paris (2016–2030) emission accounting periods. GMT is provided in °C relative to 1750; IPCC AR5-consistent GMSLR is provided in centimeters relative to the 1986–2005 average. Shaded GMT and GMSLR uncertainties reflect the 66% model ranges. Bars on the right show median 2300 GMSLR projections, country shares, and overall 66% uncertainty range based on the alternative DeConto and Pollard (DP16) parameterization (19).

Table 1. GMSLR commitment in 2100 and 2300 for cumulative CO₂ emissions until 1991, 2016, and 2030

<table>
<thead>
<tr>
<th>CO₂ emissions, GtC</th>
<th>2100 GMSLR, cm</th>
<th>2300 GMSLR, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991</td>
<td>385</td>
<td>22.2 (18.2 to 27.3)</td>
</tr>
<tr>
<td>2016</td>
<td>608</td>
<td>34.6 (27.2 to 43.6)</td>
</tr>
<tr>
<td>2030</td>
<td>765</td>
<td>43.0 (33.8 to 54.4)</td>
</tr>
</tbody>
</table>

IPCC AR5-consistent GMSLR median projections and 66% ranges are provided relative to the 1986–2005 average. Estimates for anthropogenic CO₂ emissions including land use are calculated relative to 1750.
Our experiment of assuming no further emissions beyond 2030 provides a lower bound for future sea-level-rise impacts. Reaching net-zero GHG emissions from current NDC levels will take several decades (23), which indicates that the real risks implied by 2030 NDC levels will be substantially higher. Our main results exclude the higher sensitivity to global warming introduced by MICI and hydrofracturing processes, but our sensitivity tests indicate that, as currently understood, MICI can increase the contribution of the Antarctic ice sheet for stronger global warming. Finally, our approach does not cover the possibility of greater emissions by 2030 than currently pledged by the NDCs, which may lead to an underestimation of the presented sea-level commitments.

The assessment of future sea-level change needs to address the associated high uncertainties. While the future responses of thermal expansion and glaciers are reasonably well understood, the future responses of the ice sheets, in particular the AIS with its multimeter GMSLR potential, remain poorly constrained. The MICI hypothesis, which was proposed after IPCC AR5, leads to higher estimates for the future AIS GMSLR contribution, especially under strong future global warming (21, 22). However, because MICI is still under debate (22) and new insights are expected from future work, we present sea-level-rise estimates including MICI only as a sensitivity test.

Furthermore, our applied methodology includes a parameterization for the sea-level contribution from land-water storage which is not dependent on climate change (15). This scenario-independent median land-water contribution of around 21 cm for 2300 is based on the extrapolation of the modeled end-of-21st-century response (31). The total NDC GMSLR commitment presented here encompasses this land-water estimate and is sensitive to its changes, highlighting the large uncertainties associated with absolute GMSLR projections. The derived relative GMSLR commitments for the top 5 emitters, however, would not change as they are not sensitive to the absolute land-water contribution but only determined by the climate-driven sea-level responses to the 2030 NDC reference pathway.

### Table 2. GMSLR commitments in 2100 and 2300 for CO2 emission shares of the 5 highest-emitting countries over the specific IPCC (1991–2030) and Paris (2016–2030) accounting periods

<table>
<thead>
<tr>
<th>CO2 emissions, GtC</th>
<th>2100 GMSLR, cm</th>
<th>2300 GMSLR, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IPCC period</strong></td>
<td><strong>Paris period</strong></td>
<td><strong>IPCC period</strong></td>
</tr>
<tr>
<td>Top 5</td>
<td>220</td>
<td>95</td>
</tr>
<tr>
<td>China</td>
<td>83</td>
<td>44</td>
</tr>
<tr>
<td>USA</td>
<td>59</td>
<td>21</td>
</tr>
<tr>
<td>EU28</td>
<td>41</td>
<td>13</td>
</tr>
<tr>
<td>India</td>
<td>19</td>
<td>11</td>
</tr>
<tr>
<td>Russia</td>
<td>18</td>
<td>7</td>
</tr>
</tbody>
</table>

IPCC AR5-consistent GMSLR median projections and 66% ranges are provided relative to the 1986–2005 average. GMSLR contributions and estimates for anthropogenic CO2 emissions including land use are calculated for the 5 highest-emitting countries individually and in an aggregated way (Top 5).

![Fig. 3. GMSLR commitments and 66% uncertainty bars for the year 2300, as well as corresponding cumulative anthropogenic CO2 emissions for the top 5 emitters, using the 1991–2030 IPCC (B and C) and 2016–2030 Paris emission accounting periods (F and G). In addition, 2300 GMSLR commitments for cumulative emissions until 1991 (A) and 2016 (E) are provided together with projected total 2030 GMSLR commitment (D) based on available 2030 NDC emission pledges. IPCC AR5-consistent GMSLR is provided in centimeters relative to the 1986–2005 average. Please note the different y-axis scaling for global GMSLR commitments provided in A, D, and E and the specific emission accounting periods in B, F, C, and G.](https://www.pnas.org/cgi/doi/10.1073/pnas.1907461116)
The 2300 Sea-Level Legacy of Near-Term Emissions

Sea levels will continue to rise long beyond 2300 (9, 12). Constrained by our methodological setup, however, 2300 emerges as a pragmatic focal point for the analysis of commitments as it allows us to assess GMSLR differences for near-term emission reduction trajectories. Our analysis demonstrates that even GHG emissions over the first decades of the 21st century will shape coastlines around the globe for centuries to come. Previous research conducted with different sea-level models and experimental setups reached similar conclusions (11, 12). By linking 2300 GMSLR with combined historical emissions and 2030 NDC emission reduction pledges on a country level, we provide an angle to assess the climate impact implications of near-term national emission reduction targets, extending the scope beyond, for example, NDC implications of extreme temperature (32).

Our findings also underscore the relevance of present-day emissions in shaping the multicitytury sea-level-rise response. About 44% (20%) of the total 2300 GMSLR commitment for emission from preindustrial until 2030 can be attributed to emissions of the IPCC (Paris) period. GHG emissions by the top 5 emitting countries over the same periods contribute to 25% (12%) of the 2300 total. The 15 y from 2016 to 2030 commit about 8 cm of additional sea-level rise in 2100 or 20 cm of additional sea-level rise in 2300 (Table 1), with the latter estimate being roughly equivalent to what has occurred since the preindustrial period. Only stringent near-term emission reductions in line with achieving the 1.5 °C long-term temperature goal of the Paris Agreement would provide a chance of limiting long-term sea-level rise to below 1 m (11). Since the adoption of the Paris Agreement, however, global GHG emissions have not shown a sign of peaking (33), while the current NDCs are inadequate to put the global community on track to meet the Paris Agreement Long-term Temperature Goal by the end of the 21st century (14).

Attributing GMSLR to pledged emission reductions not only highlights the importance of strong near-term mitigation efforts, but also emphasizes the inevitability of future coastal adaptation as well as loss and damage needs related to committed multicitytury GMSLR. Our ability to quantify and attribute such global sea-level commitments raises highly policy-relevant questions with respect to the need and responsibilities of supporting adaptation and loss and damage responses in low-lying coastal zones and small islands that will experience the most severe impacts.

Methods

We use both observed and projected GHG emissions to generate the suite of 2030 pathways used in this study. Until 2014, MAGICC was used to derive pathways. For all pathways, radiative forcing is held constant after 2100 until 2300. For all pathways, radiative forcing is held constant after 2100 until 2300. For all pathways, radiative forcing is held constant after 2100 until 2300. For all pathways, radiative forcing is held constant after 2100 until 2300. For all pathways, radiative forcing is held constant after 2100 until 2300.

Before 2016, we directly use the historical gas shares as available from the PRIMAP-hist dataset (26, 38). Two scenarios are created for each of the top 5 emitting countries, one where the country’s emissions are removed starting in 1991 and one where they are only removed starting in 2016. We only remove Kyoto GHGs and phase out non-Kyoto gases as done for the 2030 reference pathway, as changes in historical emissions for other substances influence the internal calibration of MAGICC. To translate generated GHG emission pathways into GMT responses. For every pathway, probabilistic GMT projections are generated with a historically constrained ensemble of 600 runs, derived by a Metropolis–Hastings Markov chain Monte Carlo approach (39). Model parameters of the ensemble are chosen to capture IPCC AR5 equilibrium climate sensitivity estimates (40, 41) and carbon-cycle uncertainties (42). As such, the probabilistic MAGICC modeling framework consistently covers model and climate-related uncertainties. The model is run for the period 1750–2300.

The MAGICC sea-level model (15) is one of several existing simplified approaches to project sea-level change (16, 43–45) and emulates IPCC AR5 process-based SLR projections (5) and provides GMSLR estimates for all major climate-driven sea-level components including thermal expansion, global glacier mass changes, the surface mass balance, and solid ice discharge components of the Greenland and Antarctic ice sheets, as well as the non-climate-driven land-water storage contribution. For each of the probabilistic 600 ensemble members, calibrated sea-level parameters are sourced randomly for every sea-level component. The Antarctic ice sheet solid ice discharge component was extended (20) to include a threshold-temperature parameterization to capture potentially higher Antarctic sensitivity through hydrofracturing and subsequent MCI that would substantially increase future SLR projections under high-emission scenarios (21). Since the MCI hypothesis is subject to ongoing scientific debate (22, 46), we only use these projections for a sensitivity test. The MAGICC sea-level model provides projections from 1850 to 2300, constrained by the availability of reference data, in particular for the Antarctic solid ice discharge response (19).


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