Environmental Research Letters

Supplementary Information for

Attributing ocean acidification to major carbon producers

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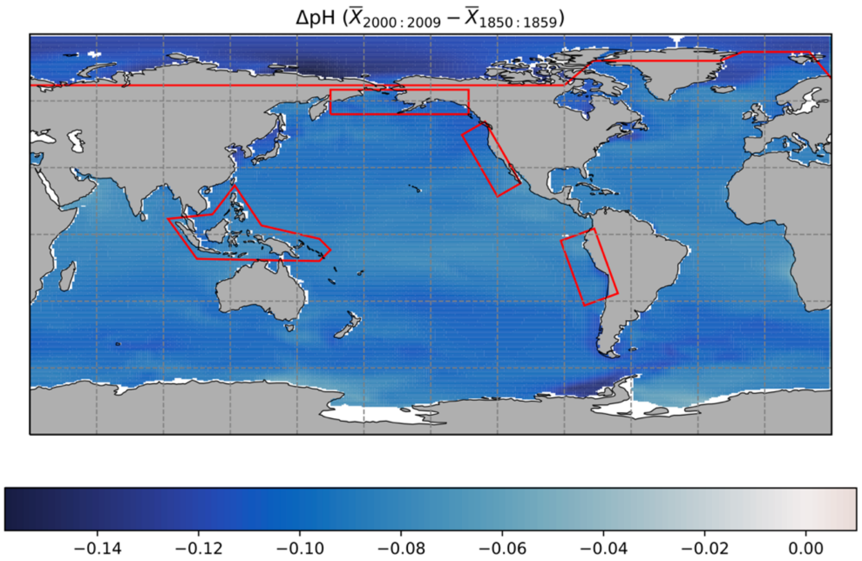
1. Regional pH, aragonite, sea surface temperature, and sea surface salinity change



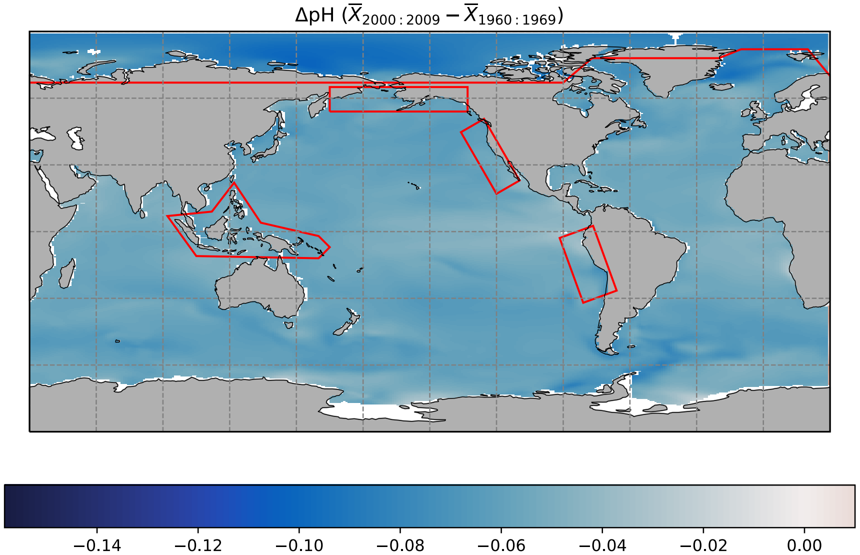


Figure 1. Simulated change in surface ocean pH between (top, difference between an average of 1850-1859 and an average of 2000-2009) and (bottom, difference between an average of 1960-1969 and an average of 2000-2009). Red boxes demarcate the regions whose risk patterns are examined in this study. Note the change in pH scale between top and bottom.

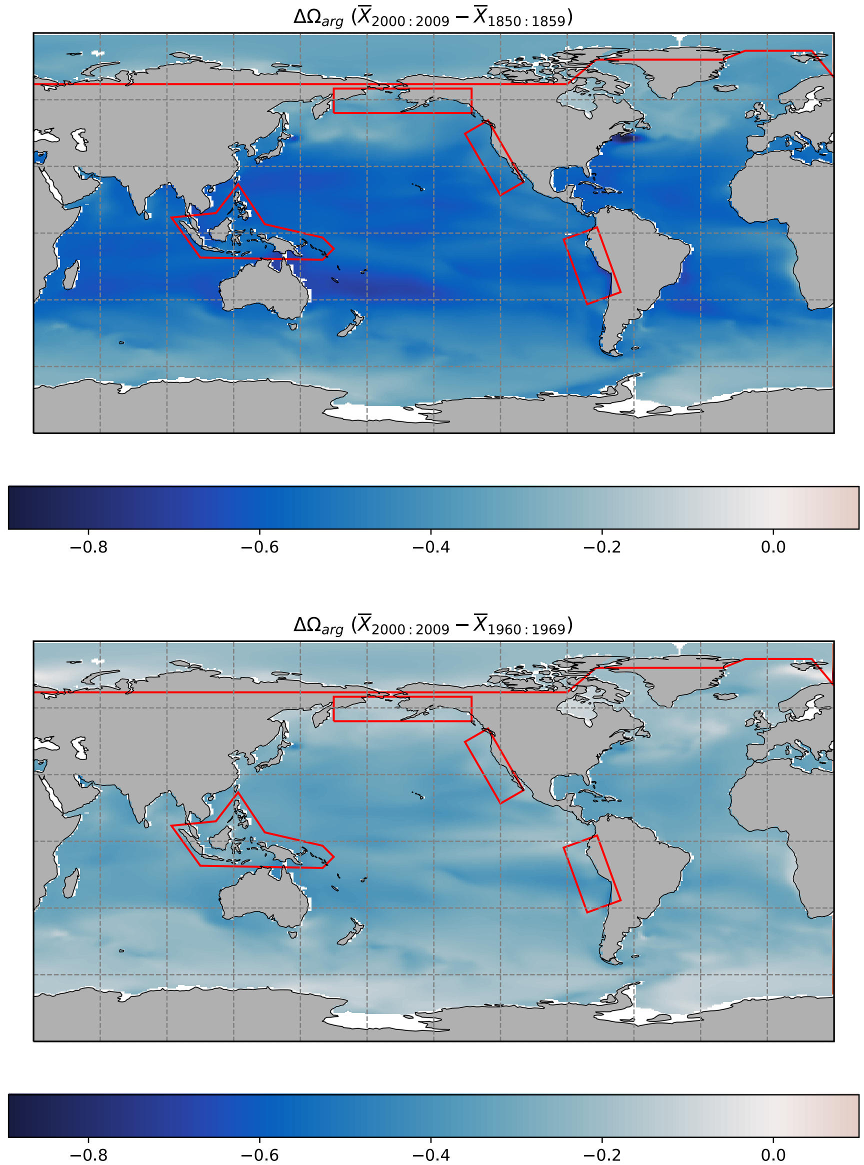


Figure 2. Simulated change in surface aragonite saturation states between (top, difference between an average of 1850-1859 and an average of 2000-2009) and (bottom, difference between an average of 1960-1969 and an average of 2000-2009). Red boxes demarcate the regions whose risk patterns are examined in this study. Note the change in aragonite saturation state scale between top and bottom.

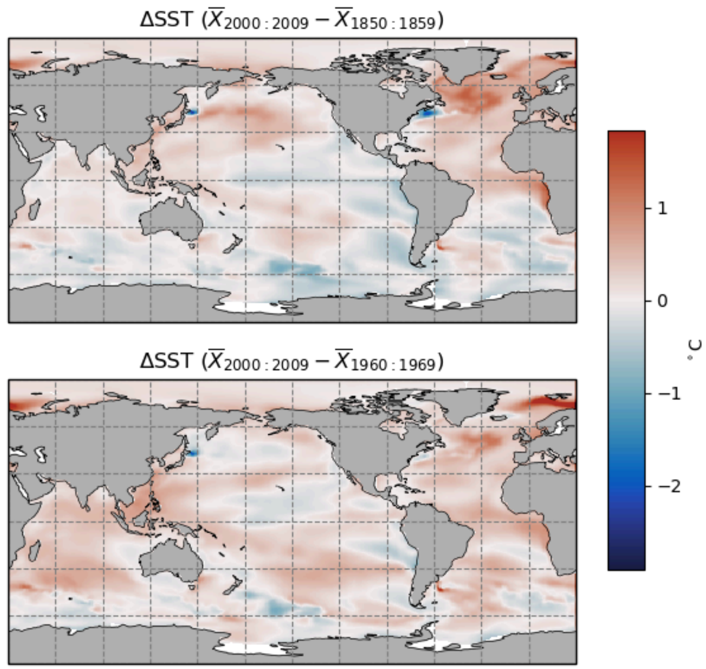


Figure 3. Simulated change in sea surface temperature between (top, difference between an average of 1850-1859 and an average of 2000-2009) and (bottom, difference between an average of 1960-1969 and an average of 2000-2009).

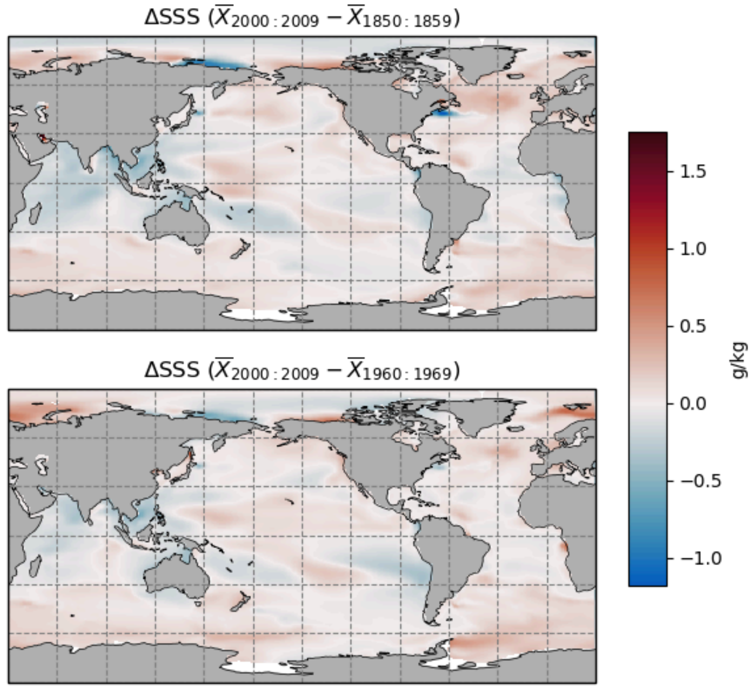


Figure 4. Simulated change in sea surface salinity between (top, difference between an average of 1850-1859 and an average of 2000-2009) and (bottom, difference between an average of 1960-1969 and an average of 2000-2009).

2. Simple climate model sensitivity tests

See Ekwurzel et al., 2017 supplementary information for a description of the carbon cycle energy balance model. Sensitivity tests were simulated using the low through high range of carbon and thermal parameters including equilibrium climate sensitivity and related transient climate response (Myhre et al. 2013; Millar et al. 2015; Millar et al., 2016; Millar et al., 2017). The best estimate parameters had the best fit to atmospheric CO_2 and global mean surface temperature observations.

Table 1 Carbon scaling parameters

Carbon Settings	Low	High	Best
Emissions scaling factor	0.86	1.14	1
Decay time scaling factor	43.8	30.8	35

Table 2. Thermal parameters

Thermal Settings	Low	High	Best
TCR	1	2.5	1.6
ECS	1.5	4.5	2.75
Adjustment to non-GHG forcing	-1.1	0.65	0

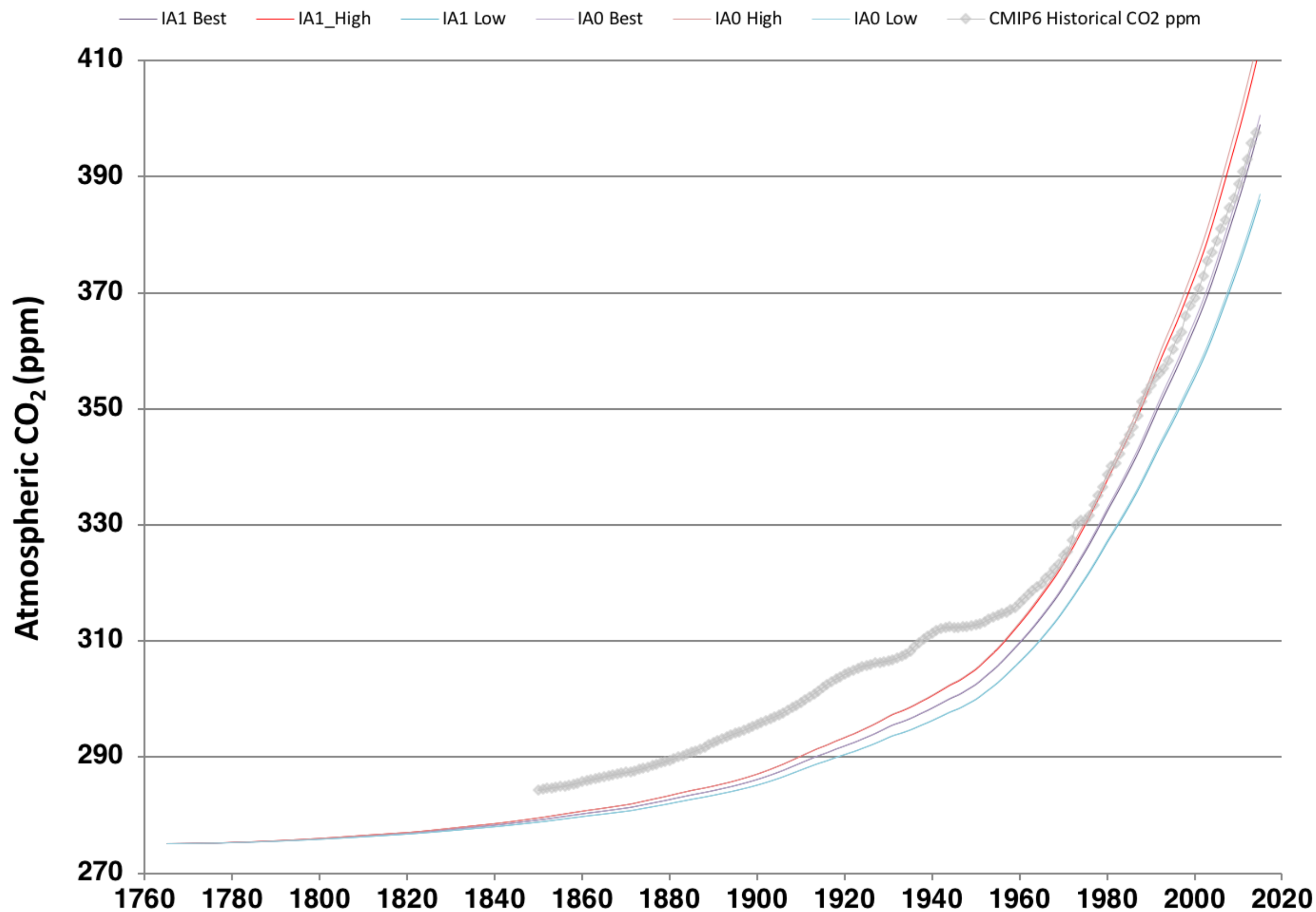


Figure 5. Model simulations for the reference case (i.e. no removal of emissions traced to carbon producers) compared with historical observations CMIP6 historical CO_2 data (Meinshausen *et al* 2017). Abbreviations: IA1 = full forcing including total historical fossil aerosols; IA0 = full forcing minus total historical fossil aerosols; Best, High, Low are parameters that correspond to values in (Ekwurzel *et al* 2017) ESM tables 1, 2 and 3. Given the close relationship to the reference case for global ocean pH in the following year, using equation (1) in Licker et al., 2019, this serves as a sensitivity test for global ocean pH.

3. Largest carbon producers 2010 data and 2015 data comparison

The following transitions occurred between the database release for 1854 - 2010 (see Heede 2014, Ekwurzel *et al* 2017) and the database release extended through the year 2015 in this contribution. This updated database of emissions attributed to the 88 major carbon producers includes both direct operational emissions (scope 1) and indirect product-related emissions (scope 3) for each entity, following the methodology in Heede 2014. The update includes mergers and acquisitions (the acquired company's attributed emissions are shifted to the acquiring entity), updated data on production of oil, natural gas, coal, and cement to 2015, acquisition or divestment of producing assets, and routine revisions of activity data for previous years. Following the method for the 2010 data, emissions traced to the original 90 largest carbon producers are included in the 2015 data release with a slight change in the listing of companies as follows. In cases of acquisitions, the historical emissions from both companies are combined into the annual emissions of the company that acquired another company. In the case of entities that no longer exist (e.g. former Soviet Union) these are listed and have emissions only for the years over the historical period of existence. Subsequent mergers and acquisitions — such as Royal Dutch Shell's acquisition of BG (British Gas) or HeidelbergCement's acquisition of Italcementi in 2016 are not reflected in this database.

- Massey Energy, USA (acquired by Alpha Natural Resources in June 2011)
- Nexen, Canada (acquired by CNOOC in February 2013)
- Lafarge merged with Holcim in 2015 (Still listed as separate entity in this contribution)
- Talisman, Canada (acquired by Repsol May 2015) (Still listed as a separate entity in this contribution)
- Luminant / TXU, USA now listed as Vistra / Luminant, USA

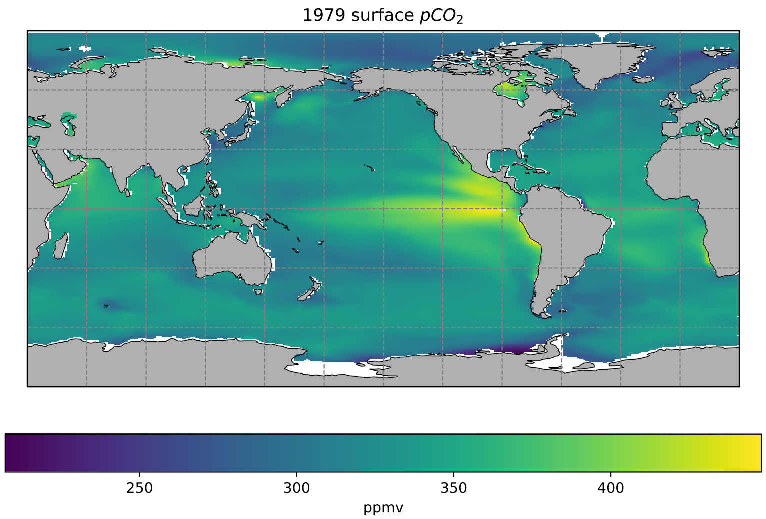


Figure 6. Highlight of areas of disequilibrium in the 3-D model

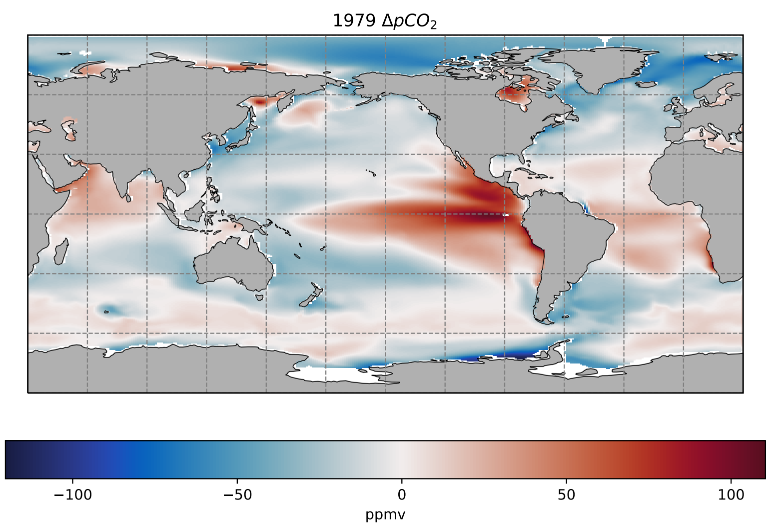


Figure 7. Simulated annual mean surface pCO_2 for 1979

References

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 CO2, surface temperature, and sea level from emissions traced to major carbon producers *Climatic Change* **144** 579–90 https://doi.org/10.1007/s10584-017-1978-0

Heede R 2014 Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010 *Climatic Change* **122** 229–241 https://doi.org/10.1007/s10584-013-0986-y

Meinshausen M, Vogel E, Nauels A, Lorbacher K, Meinshausen N, Etheridge D M, Fraser P J, Montzka S A, Rayner P J, Trudinger C M, Krummel P B, Beyerle U, Canadell J G, Daniel J S, Enting I G, Law R M, Lunder C R, O'Doherty S, Prinn R G, Reimann S, Rubino M, Velders G J M, Vollmer M K, Wang R H J and Weiss R 2017 Historical greenhouse gas concentrations for climate modelling (CMIP6) *Geoscientific Model Development* **10** 2057–116 https://doi.org/10.5194/gmd-10-2057-2017

Millar R J, Nicholls Z R, Friedlingstein P, Allen M R 2016 A modified impulse-response representation of the global response to carbon dioxide emissions. *Atmospheric Chemistry and Physics Discussions* **1–20** doi: 10.5194/acp-2016-405

Millar R J, Nicholls Z R, Friedlingstein P and Allen M R 2017 A modified impulse-response representation of the global near surface air temperature and atmospheric concentration response to carbon dioxide emissions *Atmospheric Chemistry and Physics* **17** 7213–28 https://doi.org/10.5194/acp-17-7213-2017

Millar R J, Otto A, Forster P M, Lowe J A, Ingram W J, and Allen M R 2015 Model structure in observational constraints on transient climate response *Climatic Change* **131** https://doi.org/10.1007/s10584-015-1384-4

Myhre G, Shindell D, Bréon F M, Collins W, Fuglestvedt J, Huang J, Koch D, Lamarque J F, Lee D, Mendoza B, Nakajima T, Robock A, Stephens G, Takemura T and Zhang H 2013 *Anthropogenic and Natural Radiative Forcing*. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker T F, Qin D, Plattner G-K, Tignor M, Allen S K, Boschung J, Nauels A, Xia Y, Bex V and Midgley P M (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.