Global Surface Ocean Acidification Indicators from 1750 to 2100

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① Abstract

Accurately predicting future ocean acidification (OA) conditions is crucial for advancing OA research at regional and global scales, and guiding society's mitigation and adaptation strategies. This study presents a new model-data fusion product covering 10 global surface OA indicators based on 14 Earth System Models (ESMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6), along with three recent observational ocean carbon data products. The indicators include fugacity of carbon dioxide, pH (total scale), total hydrogen ion content, free hydrogen ion content, carbonate ion content, aragonite saturation state, calcite saturation state, Revelle Factor, total dissolved inorganic carbon content, and total alkalinity content. The evolution of these OA indicators is presented on a global surface ocean 1°×1° grid as decadal averages every ten years from preindustrial conditions (1750), through historical conditions (1850-2010), and to five future shared socioeconomic pathways (2020-2100): SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. DOI: 10.1029/2022MS003563.

② Methods

A model-data fusion product was created by applying adjustments to the outputs of 14 CMIP6 Earth System Models with the latest observational data:

1. Observational data based SSS, SST, DIC and TA were extracted or calculated from SOCAT (version 2022), GLODAPv2 (version 2022), and CODAP-NA (version 2021).
2. The temporally adjusted DIC (to the year of 2010), as well as SST, SSS, and TA were interpolated onto a global surface ocean 1°×1° grid.
3. Proxy-based DIC and TA calculated with gridded temperature, salinity, and DO from the World Ocean Atlas (WOA-2018) were used to further quality control (QC) the gridded observational DIC and TA data.
4. The temporal evolution of global surface ocean temperature, salinity, DIC, and TA from 1850 to 2100 out of 14 ESMs was adjusted with offsets that were derived based on the differences between the model output in 2010 and the corresponding observational data in 2010 at that grid point.
5. The adjusted trajectories of SST, SSS, DIC, and TA from these ESMs, as well as constant phosphate and silicate content from WOA-2018, were used to calculate all surface OA indicators at all locations of the global surface ocean grid in all decades from 1850 to 2100.

Table 1. CMIP6 Earth System Models (ESMs) used for this analysis.

No.	Model	Variant	Scenarios (SSP)	Full name	Institution	Citation
1	**ACCESS-ESM1-5**	r1i1p1f1	1-2.6, 2-4.5, 3-7.0, 5-8.5	Australian Community Climate and Earth System Simulator (ACCESS) - Earth System Model	Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia	Ziehn et al., 2020
2	**CanESM5**	r1i1p1f1	1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5	Canadian Earth System Model	Canadian Centre for Climate Modelling and Analysis, Canada	Swart et al., 2019
3	**CESM2**	r11i1p1f1	1-2.6, 2-4.5, 3-7.0, 5-8.5	Community Earth System Model	Climate and Global Dynamics Laboratory, United States	Danabasoglu et al., 2020
4	**CMCC-ESM2**	r1i1p1f1	1-2.6, 2-4.5, 3-7.0, 5-8.5	CMCC Earth System Model	Centro Euro-Mediterraneo Sui Cambiamenti Climatici (CMCC), Itlay	Lovato et al., 2022
5	**CNRM-ESM-2**	r1i1p1f2	1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5	CNRM Earth System Model	Centre National de Recherches Météorologiques (CNRM), France	Séférian et al., 2019
6	**EC-Earth3-CC**	r1i1p1f1	2-4.5, 5-8.5	Earth System Model EC-Earth3	Swedish Meteorological and Hydrological Institute, Sweden	Döscher et al., 2021
7	**GFDL-CM4**	r1i1p1f1	2-4.5, 5-8.5	GFDL Climate Model	NOAA Geophysical Fluid Dynamics Laboratory (GFDL), United States	Held et al., 2019; Dunne et al., 2020b
8	**GFDL-ESM4**	r1i1p1f1	1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5	GFDL Earth System Model	NOAA Geophysical Fluid Dynamics Laboratory (GFDL), United States	Dunne et al., 2020a; Stock et al., 2020
9	**IPSL- CM6A-LR**	r1i1p1f1	1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5	IPSL Climate Model	Institut Pierre-Simon Laplace (IPSL), France	Boucher et al., 2020
10	**MIROC-ES2L**	r1i1p1f2	1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5	Model for Interdisciplinary Research on Climate, Earth System	Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan	Hajima et al., 2020
11	**MPI-ESM1-2-LR**	r1i1p1f1	1-2.6, 2-4.5, 3-7.0, 5-8.5	MPI Earth System Model	Max-Planck-Institut (MPI), Germany	Mauritsen et al., 2019
12	**MRI-ESM2-0**	r1i2p1f1	5-8.5	MRI Earth System Model	Meteorological Research Institute (MRI), Japan	Yukimoto et al., 2019
13	**NorESM2-LM**	r1i1p1f1	1-2.6, 2-4.5, 3-7.0, 5-8.5	Norwegian Earth System Model	NorESM Climate Modeling Consortium, Norway	Seland et al., 2020; Tjiputra et al., 2020
14	**UKESM1-0-LL**	r1i1p1f2	1-1.9, 1-2.6, 2-4.5, 3-7.0, 5-8.5	United Kingdom Earth System Model	Met Office and Natural Environment Research Council (NERC), United Kingdom	Sellar et al., 2019

③ Temporal trends

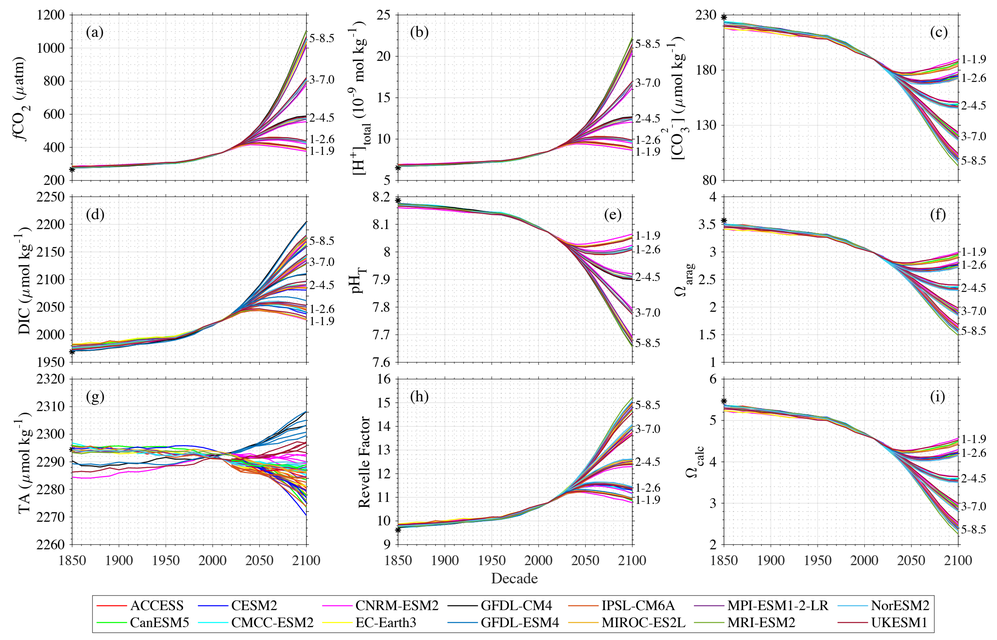

Figure 1. Temporal changes of global surface ocean OA indicators (area-averaged globally) from 14 CMIP6 Earth System Models after applying adjustments with observational data.

④ Spatial distributions

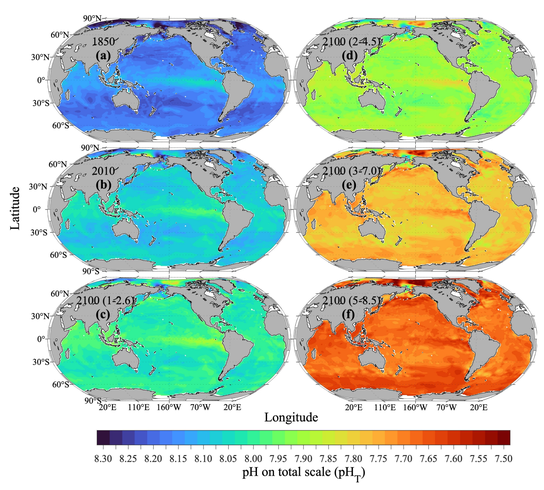

Figure 2. Surface ocean pH on total scale (inter-model median)

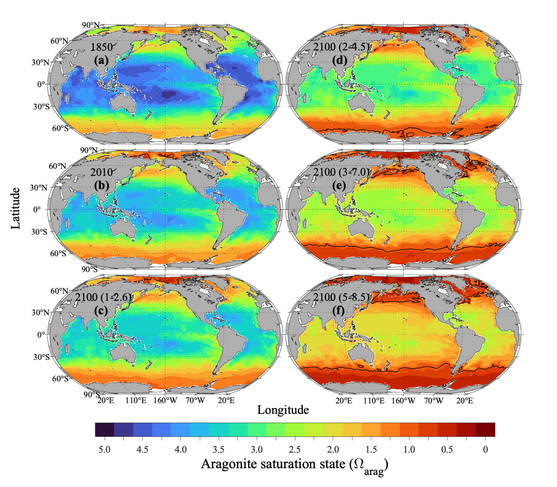

Figure 3. Surface ocean aragonite saturation state (inter-model median)

⑤ Summary

Compared to Jiang et al., 2019, this product:

1. Utilizes an ensemble of 14 distinct Earth System Models, instead of relying on just one model, i.e., the GFDL-ESM2M.
2. Eliminates model biases using observational data, and model drift using pre-Industrial controls.
3. Covers 10 OA indicators, as opposed to just pH, acidity, and buffer capacity.
4. Incorporates the new Shared Socioeconomic Pathways (SSPs).

The generated data product offers a state-of-the-art research and management tool for the 21st century under the combined stressors of global climate change and ocean acidification.

Acknowledgements

Funding for L-QJ was from NOAA Ocean Acidification Program (OAP, Project ID: 21047) and NOAA National Centers for Environmental Information (NCEI) through a NOAA Cooperative Institute for Satellite Earth System Studies (CISESS) grant (NA19NES4320002) at the Earth System Science Interdisciplinary Center (ESSIC), University of Maryland.

How to cite: Jiang, L.-Q., Dunne, J., Carter, B. R., Tjiputra, J. F., Terhaar, J., Sharp, J. D., et al. (2023). Global surface ocean acidification indicators from 1750 to 2100. *Journal of Advances in Modeling Earth Systems*, 15, e2022MS003563. https://doi.org/10.1029/2022MS003563.