

Supplementary Material for Irreversible loss in marine ecosystem habitability after a temperature overshoot

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Earth system models description

ACCESS-ESM1-5

The Australian Community Climate and Earth System Simulator (ACCESS-ESM1-5¹) is comprised of a number of component models. The atmospheric component is the UK Met Office Unified Model at version 7.3^{2,3} with their land surface model replaced with the Community Atmosphere Biosphere Land Exchange (CABLE) model⁴. The ocean component is the NOAA/GFDL Modular Ocean Model (MOM) at version 5⁵ using a nominal 1° horizontal resolution. Latitudinal resolution is higher near the equator (0.33°) and over the Southern Ocean (~0.4° at 70°S). The vertical ocean grid has 50 levels, top levels are nominally 10 m thick to 200 m. The maximum depth is 6000 m where resolution is ~300 m. Sea ice is simulated using the LANL CICE4.1 model⁶. The carbon cycle is included in ACCESS-ESM1-5 through the CABLE land surface model and its biogeochemistry module, CASA-CNP⁷ with nitrogen and phosphorus limitation enabled^{8,9}, and through the World Ocean Model of Biogeochemistry and Trophic-dynamics (WOMBAT¹⁰).

CNRM-ESM2-1

The CNRM-CERFACS climate group have designed the standard resolution (i.e., $\sim 1^\circ$) Earth System Models of second generation (CNRM-ESM2-1¹¹) as a contribution to the sixth phase of the Coupled Model Intercomparison Project¹² (CMIP6). It uses the physical-dynamical core of the ocean-atmosphere coupled climate model CNRM-CM6-1¹³, and accounts for several Earth system feed-backs enabled by interactive atmospheric chemistry and aerosols, as well as interactive land and ocean carbon cycles. The ocean component is NEMOV3.6¹⁴, which resolves ocean dynamics on an eORCA1 grid¹⁵ with 75 vertical z-coordinate levels. This grid offers a horizontal resolution of about 1° with a grid refinement up to 0.3° in the tropics.

GFDL ESM2M

The global coupled carbon-climate model GFDL ESM2M developed at the National Oceanic and Atmospheric Administration (NOAA)'s Geophysical Fluid Dynamics Laboratory (GFDL)^{16,17} consists of an ocean model (MOM4p1¹⁸), an atmosphere model (AM2¹⁹), a land model (LM3.0²⁰), a sea ice model²¹, and also includes iceberg dynamics²². The ocean model MOM4p1 uses a tripolar horizontal grid with a nominal resolution of 1° increasing zonally to $1/3^\circ$ near the equator. Its vertical grid has 50 levels with a time-dependent resolution of about 10m in the upper 230m of the water column. The ocean biogeochemical and ecological component is version two of the Tracers of Ocean Productivity with Allometric Zooplankton (TOPAZv2) module that parametrizes the cycling of carbon, nitrogen, phosphorus, silicon, iron, oxygen, alkalinity, and lithogenic material as well as surface sediment calcite¹⁷.

GFDL ESM4.1

GFDL ESM4.1 is the CMIP6 generation fully coupled carbon-chemistry-climate Earth System Model developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL)²³. It consists of an atmospheric component, GFDL-AM4.1²⁴, a land component (GFDL-LM4.1, Shevliakova et al., in revision), the Modular Ocean Model Version 6 (MOM6²⁵) and a Sea Ice Simulator (SIS2²⁵). The ocean biogeochemical component of ESM4.1 is Version 2 of the Carbon, Ocean Biogeochemistry, and Lower Trophics (COBALTv2) model^{26,27}. The ocean and sea-ice models are on a nominal 0.5° tripolar horizontal grid with 75 vertical hybrid depth-isopycnal layers.

MIROC-ES2L

The Model for Interdisciplinary Research on Climate, Earth System version 2 for Long-term simulations (MIROC-ES2L²⁸) ESM developed for CMIP6 uses the physical core of the ocean-atmosphere coupled climate model MIROC5.2²⁹. The land and ocean biogeochemical components are represented by VISIT-e²⁹ and OECO2, respectively. The ocean general circulation model

COCO³¹ has a horizontal tripolar coordinate system. To the south of 63°N, where a spherical coordinate system is adopted, the longitudinal grid spacing is 1°, while the meridional grid spacing varies from approximately 0.5° near the equator to 1° in mid-latitude regions. There are 62 vertical layers in a hybrid sigma-z coordinate.

NorESM2-LM

The Norwegian Earth System Model version 2 (NorESM2^{32,33}) is an updated version of the first generation NorESM1^{34,35}. The variant used in this study (NorESM2-LM) is configured on approximately 2° and 1° horizontal grid resolution in the atmosphere and ocean, respectively. The atmospheric (CAM6), land (CLM5), and sea-ice (CICE5) components are based on the Community Earth System Model version 2 (CESM2³⁶). The aerosol chemistry in the atmosphere has been modified in its life cycle of particulate aerosols and the representation of aerosol-radiation-cloud interactions. The ocean biogeochemistry is coupled to an isopycnal coordinate ocean general circulation model (iHAMOCC-BLOM), comprising 53 vertical density layers, and a bulk mixed layer depth (top 2 layers).

UKESM1-0-LL

The United Kingdom Community Earth System Model, UKESM1-0-LL^{37,38} is based upon the HadGEM3-GC3.1³⁹ general circulation model which includes coupled ocean, atmosphere, land, and sea ice components. The atmosphere component has a resolution of 1.875° by 1.25° with 85 vertical levels and the ocean component uses the NEMO dynamical ocean at 1° resolution with 75 vertical levels⁴⁰. The land component uses the JULES land surface model with interactive carbon and nitrogen cycles⁴¹. Ocean biogeochemistry is represented by MEDUSA-2⁴², which resolves a dual size-structured ecosystem and the biogeochemical cycles of nitrogen, silicon, and iron nutrients as well as the cycles of carbon, alkalinity, and dissolved oxygen. The ocean's oxygen cycle exchanges oxygen with the atmosphere, and dissolved oxygen is additionally created by primary production and depleted by remineralization.

References

1. Ziehn, T. *et al.* The Australian Earth System Model: ACCESS-ESM1.5. *J. South. Hemisph. Earth Syst. Sci.* **70**, 193 (2020).
2. Martin, G. M. *et al.* Analysis and Reduction of Systematic Errors through a Seamless Approach to Modeling Weather and Climate. *J. Clim.* **23**, 5933–5957 (2010).
3. Bellouin, N. *et al.* The HadGEM2 family of Met Office Unified Model climate configurations. *Geosci. Model Dev.* **4**, 723–757 (2011).
4. Kowalczyk, E. A., *et al.* The land surface model component of ACCESS: description and impact on the simulated surface climatology. *Aust. Meteorol. Ocean. J.* **63**, 65–82 (2013).

5. Griffies, S. *Elements of the Modular Ocean Model (MOM) 5:(2012 release with updates)*. GFDL Ocean Group Tech. Rep. 7. (2014).
6. Hunke, E. C. & Lipscombe, W. H. *CICE: The Los Alamos sea ice model: Documentation and software user's manual, version 4.1. T-3 Fluid Dynamics Group Rep.* (2010).
7. Wang, Y. P., Law, R. M. & Pak, B. A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere. *Biogeosciences* **7**, 2261–2282 (2010).
8. Law, R. M. *et al.* The carbon cycle in the Australian Community Climate and Earth System Simulator (ACCESS-ESM1) – Part 1: Model description and pre-industrial simulation. *Geosci. Model Dev.* **10**, 2567–2590 (2017).
9. Ziehn, T., Lenton, A., Law, R. M., Matear, R. J. & Chamberlain, M. A. The carbon cycle in the Australian Community Climate and Earth System Simulator (ACCESS-ESM1) – Part 2: Historical simulations. *Geosci. Model Dev.* **10**, 2591–2614 (2017).
10. Oke, P. R. *et al.* Evaluation of a near-global eddy-resolving ocean model. *Geosci. Model Dev.* **6**, 591–615 (2013).
11. Séférian, R. *et al.* Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth System Processes in Present-Day and Future Climate. *J. Adv. Model. Earth Syst.* **11**, 4182–4227 (2019).
12. Eyring, V. *et al.* Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
13. Voldoire, A. *et al.* Evaluation of CMIP6 DECK Experiments With CNRM-CM6-1. *J. Adv. Model. Earth Syst.* **11**, 2177–2213 (2019).
14. Madec, G. *et al.* *NEMO ocean engine*. <https://www.earth-prints.org/handle/2122/13309> (2017) doi:10.5281/zenodo.3248739.
15. Mathiot, P., Jenkins, A., Harris, C. & Madec, G. Explicit representation and parametrised impacts of under ice shelf seas in the z * - coordinate ocean model NEMO 3.6. *Geosci. Model Dev.* **10**, 2849–2874 (2017).
16. Dunne, J. P. *et al.* GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part I: Physical Formulation and Baseline Simulation Characteristics. *J. Clim.* **25**, 6646–6665 (2012).
17. Dunne, J. P. *et al.* GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics*. *J. Clim.* **26**, 2247–2267 (2013).
18. Griffies, S. M., Schmidt, M. A. R. T. I. N., & Herzfeld, M. I. K. E. *Elements of mom4p1*. GFDL Ocean Group Tech. Rep. (2009).
19. Anderson, J. L., Stouffer, R. J., Broccoli, A. J. & Al., E. The New GFDL Global Atmosphere and Land Model AM2–LM2: Evaluation with Prescribed SST Simulations. *J. Clim.* 4641–4671 (2004) doi:10.1175/JCLI3632.1.
20. Milly, P. C. D. *et al.* An Enhanced Model of Land Water and Energy for Global Hydrologic and Earth-System Studies. *J. Hydrometeorol.* **15**, 1739–1761 (2014).

21. Winton, M. A Reformulated Three-Layer Sea Ice Model. *J. Atmos. Ocean. Technol.* **17**, 525–531 (2000).
22. Martin, T. & Adcroft, A. Parameterizing the fresh-water flux from land ice to ocean with interactive icebergs in a coupled climate model. *Ocean Model.* **34**, 111–124 (2010).
23. Dunne, J. P. *et al.* The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics. *J. Adv. Model. Earth Syst.* **12**, (2020).
24. Horowitz, L. W. *et al.* The GFDL Global Atmospheric Chemistry-Climate Model AM4.1: Model Description and Simulation Characteristics. *J. Adv. Model. Earth Syst.* **12**, (2020).
25. Adcroft, A. *et al.* The GFDL Global Ocean and Sea Ice Model OM4.0: Model Description and Simulation Features. *J. Adv. Model. Earth Syst.* **11**, 3167–3211 (2019).
26. Stock, C. A., Dunne, J. P. & John, J. G. Global-scale carbon and energy flows through the marine planktonic food web: An analysis with a coupled physical–biological model. *Prog. Oceanogr.* **120**, 1–28 (2014).
27. Stock, C. A. *et al.* Ocean Biogeochemistry in GFDL’s Earth System Model 4.1 and Its Response to Increasing Atmospheric CO₂. *J. Adv. Model. Earth Syst.* **12**, (2020).
28. Hajima, T. *et al.* Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks. *Geosci. Model Dev.* **13**, 2197–2244 (2020).
29. Tatebe, H., Tanaka, Y., Komuro, Y. & Hasumi, H. Impact of deep ocean mixing on the climatic mean state in the Southern Ocean. *Sci. Rep.* **8**, 14479 (2018).
30. Ito, A. & Inatomi, M. Water-Use Efficiency of the Terrestrial Biosphere: A Model Analysis Focusing on Interactions between the Global Carbon and Water Cycles. *J. Hydrometeorol.* **13**, 681–694 (2012).
31. Hasumi, H. *CCSR Ocean Component Model (COCO)*. (2015).
32. Seland, Ø. *et al.* Overview of the Norwegian Earth System Model (NorESM2) and key climate response of CMIP6 DECK, historical, and scenario simulations. *Geosci. Model Dev.* **13**, 6165–6200 (2020).
33. Tjiputra, J. F. *et al.* Ocean biogeochemistry in the Norwegian Earth System Model version 2 (NorESM2). *Geosci. Model Dev.* **13**, 2393–2431 (2020).
34. Bentsen, M. *et al.* The Norwegian Earth System Model, NorESM1-M – Part 1: Description and basic evaluation of the physical climate. *Geosci. Model Dev.* **6**, 687–720 (2013).
35. Tjiputra, J. F. *et al.* Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM). *Geosci. Model Dev.* **6**, 301–325 (2013).
36. Danabasoglu, G. *et al.* The Community Earth System Model Version 2 (CESM2). *J. Adv. Model. Earth Syst.* **12**, (2020).
37. Sellar, A. A. *et al.* UKESM1: Description and Evaluation of the U.K. Earth System Model. *J. Adv. Model. Earth Syst.* **11**, 4513–4558 (2019).
38. Sellar, A. A. *et al.* Implementation of U.K. Earth System Models for CMIP6. *J. Adv. Model. Earth Syst.* **12**, (2020).

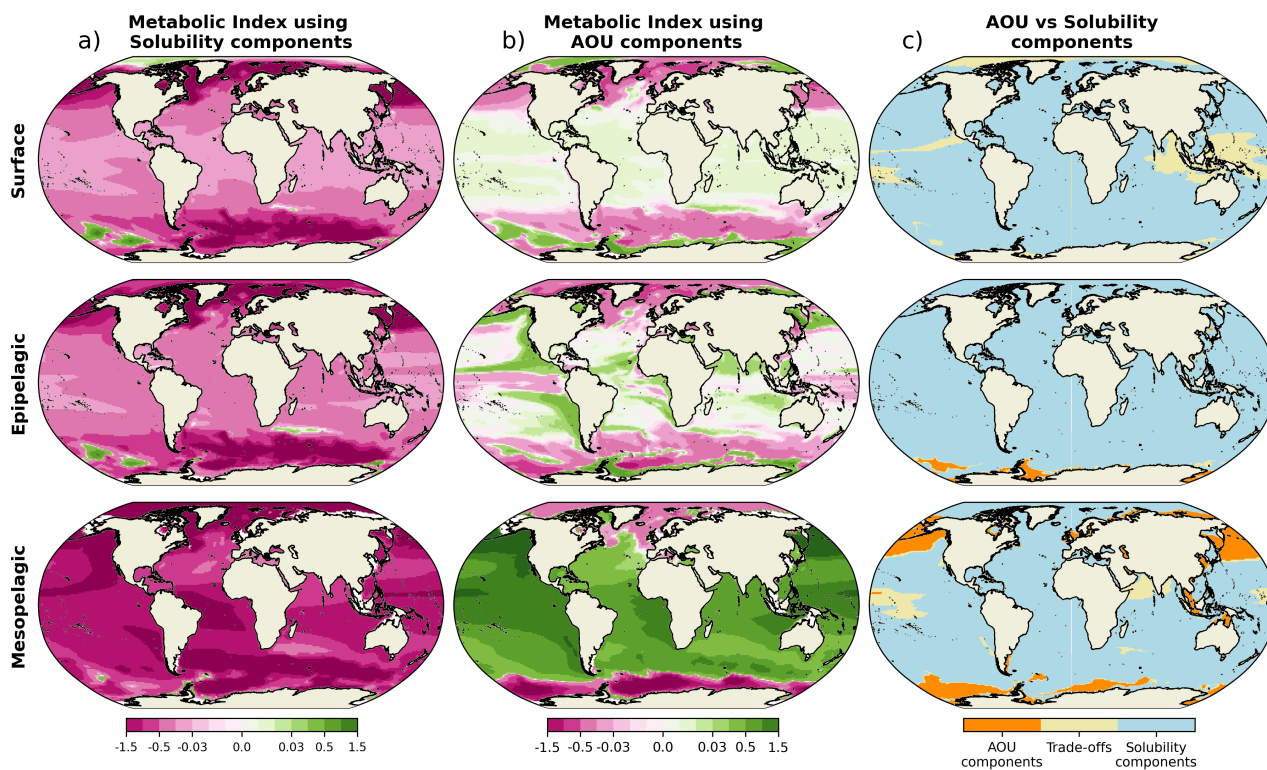
39. Williams, K. D. *et al.* The Met Office Global Coupled Model 3.0 and 3.1 (GC3.0 and GC3.1) Configurations. *J. Adv. Model. Earth Syst.* **10**, 357–380 (2018).
40. Storkey, D. *et al.* UK Global Ocean GO6 and GO7: a traceable hierarchy of model resolutions. *Geosci. Model Dev.* **11**, 3187–3213 (2018).
41. Wiltshire, A. J. *et al.* JULES-CN: a coupled terrestrial carbon–nitrogen scheme (JULES vn5.1). *Geosci. Model Dev.* **14**, 2161–2186 (2021).
42. Yool, A., Popova, E. E. & Anderson, T. R. MEDUSA-2.0: an intermediate complexity biogeochemical model of the marine carbon cycle for climate change and ocean acidification studies. *Geosci. Model Dev.* **6**, 1767–1811 (2013).

Supplementary Table

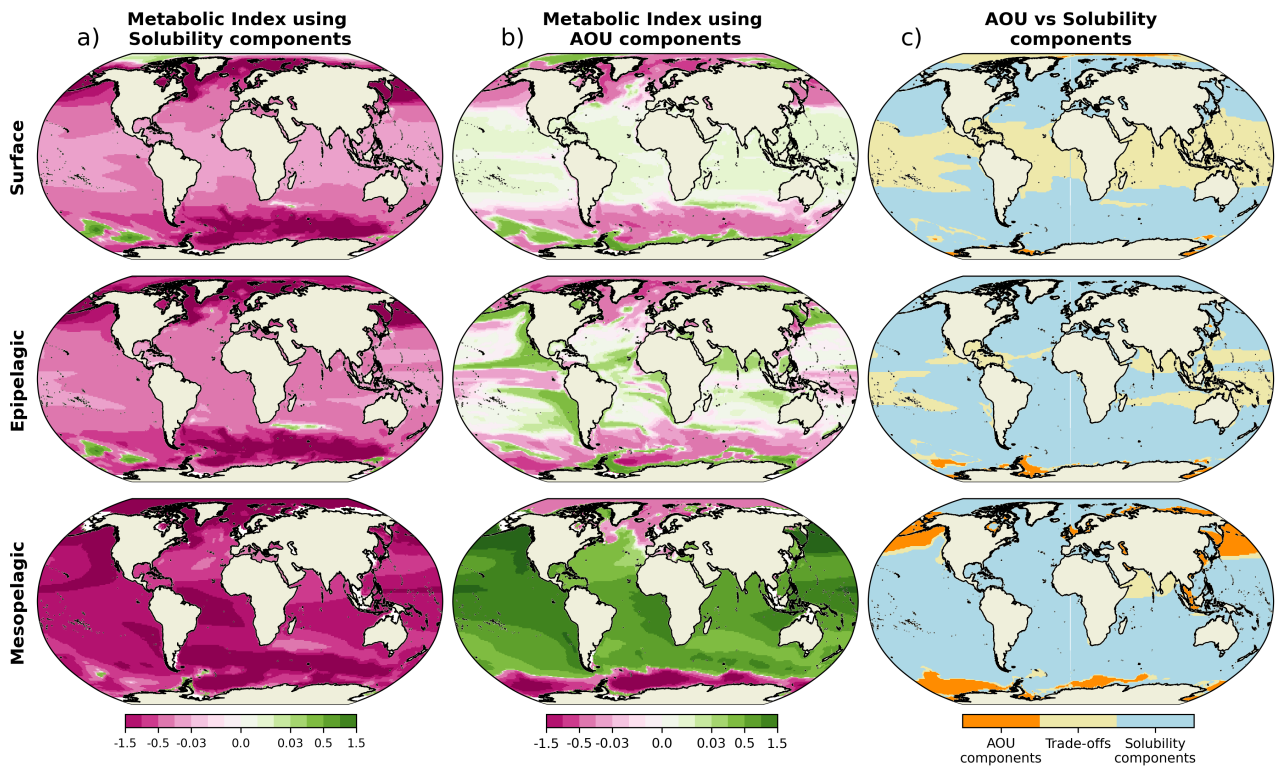
Model	CMIP generation	Institution / Country	Ocean Model
ACCESS-ESM1-5	CMIP6	CSIRO / Australia	MOM5
CNRM-ESM2-1	CMIP6	CNRM-CERFACS / France	NEMOv3.6
GFDL-ESM2M	CMIP5	GFDL-NOAA / USA	MOM4p1
GFDL-ESM4.1	CMIP6	GFDL-NOAA / USA	MOM6
MIROC-ES2L	CMIP6	MIROC / Japan	MIROC5.2
NorESM2-LM	CMIP6	Norway Climate Consortium / Norway	iHAMOCC-BLOM
UKESM1-0-LL	CMIP6	UKESM / UK	NEMO

Supplementary Table 1: Summary of the six CMIP6 and one CMIP5 models used in this study

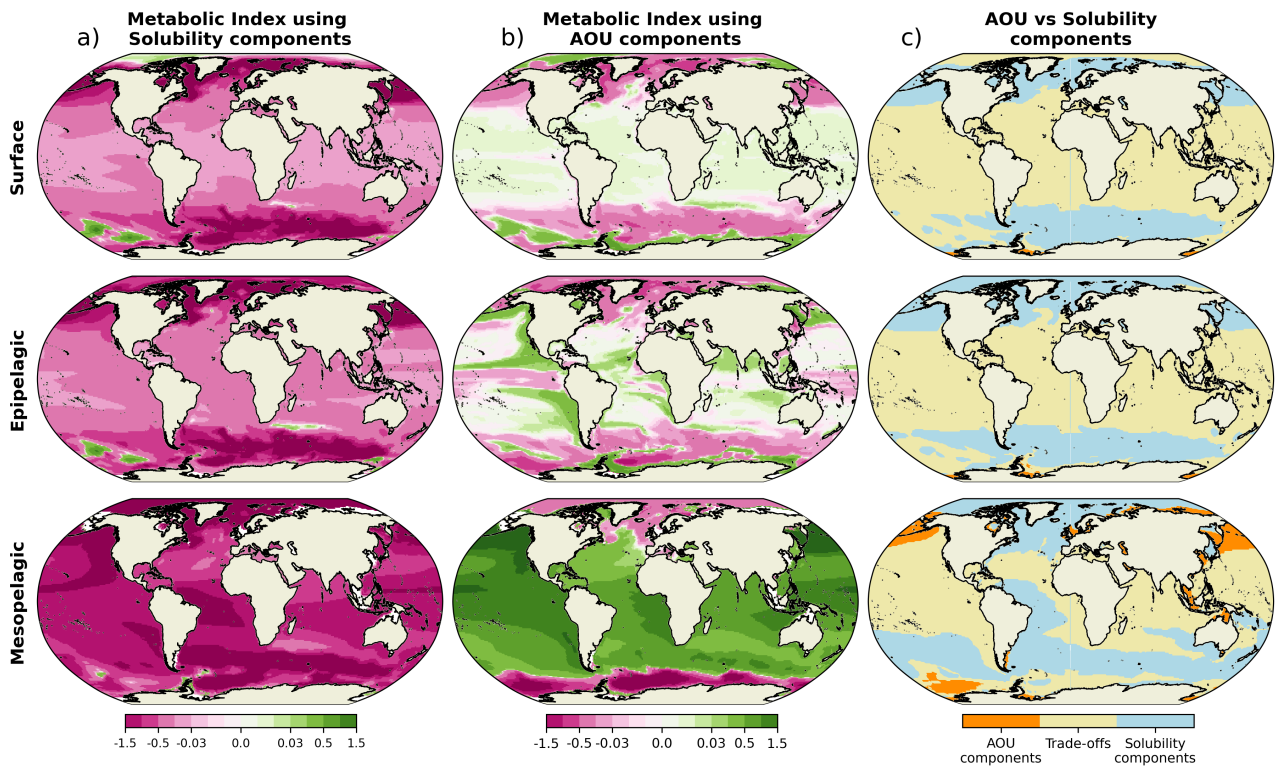
Supplementary Figures



Supplementary Figure 1: Changes in years 311-340 relative to *piControl* on the solubility and AOU components of the metabolic index. Multi-model mean differences of the metabolic index at the ocean surface (top panels), epipelagic (0 – 200 m; middle panels) and mesopelagic (200 – 1000 m; bottom panels) depth levels. Metabolic index is decomposed into solubility (a) and AOU components (b). Magenta/green indicates lower/higher metabolic indexes at the end of the experiment. A map on the absolute dominant effect of both components is included (c). Blue colours indicate dominance of solubility components. Orange colours indicate dominance of AOU components. Lighter colours ([-0.05,0.05]) indicate the absolute contribution of both components are similar. Metabolic Index corresponds to the averaged over 72 species considered in the study.



Supplementary Figure 2: Changes in years 311-340 relative to *piControl* on the solubility and AOU components of the metabolic index. Multi-model mean differences of the metabolic index at the ocean surface (top panels), epipelagic (0 – 200 m; middle panels) and mesopelagic (200 – 1000 m; bottom panels) depth levels. Metabolic index is decomposed into solubility (a) and AOU components (b). Magenta/green indicates lower/higher metabolic indexes at the end of the experiment. A map on the absolute dominant effect of both components is included (c). Blue colours indicate dominance of solubility components. Orange colours indicate dominance of AOU components. Lighter colours ([-0.1,0.1]) indicate the absolute contribution of both components are similar. Metabolic Index corresponds to the averaged over 72 species considered in the study.



Supplementary Figure 3: Changes in years 311-340 relative to *piControl* on the solubility and AOU components of the metabolic index. Multi-model mean differences of the metabolic index at the ocean surface (top panels), epipelagic (0 – 200 m; middle panels) and mesopelagic (200 – 1000 m; bottom panels) depth levels. Metabolic index is decomposed into solubility (a) and AOU components (b). Magenta/green indicates lower/higher metabolic indexes at the end of the experiment. A map on the absolute dominant effect of both components is included (c). Blue colours indicate dominance of solubility components. Orange colours indicate dominance of AOU components. Lighter colours ([-0.5,0.5]) indicate the absolute contribution of both components are similar. Metabolic Index corresponds to the averaged over 72 species considered in the study.