# Global Carbon Budget 2023: Protocol Ocean Models

**FINAL 30 May 2023**

Contact: Judith Hauck (Judith.hauck@awi.de), Nicolas Mayot (N.Mayot@uea.ac.uk) and Pierre Friedlingstein (P.Friedlingstein@exeter.ac.uk)

## Deadline for submission of simulations: 07 July 2023



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# Goal

To calculate the annual ocean $CO_2$ uptake for the Global Carbon Budget 2023

We invite groups that can commit to update their model results annually to contribute to this effort.

Your input will be used to estimate the global ocean $CO_2$ sink and the regional distribution in the Global Carbon Budget 2023, which we will submit as a living update of Friedlingstein et al. ESSD 2022. We invite one person per model to co-author the paper.

# Model sharing

Your annual mean model output for the globe and for the North, Tropics, and South will be part of an open-access database available with the ESSD paper. The gridded fields of $fCO_2$ and $CO_2$ flux will be made *open access*. The additional model output will be made available on the Exeter server, on request.

# Instructions for Output

Please upload your data to the Exeter ftp server via
sftp GCBocean2023@trendy.ex.ac.uk
password: ocean-provide

On the ftp-server please create one folder for your model and deposit all data (see naming convention below) in this folder without subfolders. When ready, please send an email to Nicolas Mayot (N.Mayot@uea.ac.uk) and Judith Hauck (judith.hauck@awi.de) with cc to Pierre Friedlingstein (P.Friedlingstein@exeter.ac.uk ).

**PLEASE update model description tables and nominate author**

Please report any new info (for new models) or changes from Table 4 and A2 in the current ESSD paper. For each model, nominate an author for the ESSD Global Carbon Budget 2023, and provide their full address and relevant acknowledgements on the Google Drive:

**Table 4:** GCB2023_Table4ocean

**Table A2:** GCB2023_TableA2_GOBM_processes_setup.xlsx

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# Model Simulation and output for the Global Carbon Budget 2023

**We strongly encourage a multi centennial preindustrial spin-up simulation. This will be enforced in the future, foreseen for 2025 (likely not yet for 2024 in light of JRA forcing discontinuation in 2023)**.
We require **four** model simulations covering at least 1959-2022:

**simulation A:** with varying climate forcing conditions and varying atmospheric $CO_2$
**simulation B:** with constant climate forcing conditions and constant atmospheric $CO_2$.
**simulation C:** with constant climate forcing conditions and varying atmospheric $CO_2$.
**simulation D:** with varying climate forcing conditions and constant atmospheric $CO_2$

The simulation A should reproduce the interannual variability and trend in the ocean carbon uptake in response to changes in both atmospheric $CO_2$ and climate. Thus, models should be forced by observed climate (e.g., from reanalysis products) and observed atmospheric $CO_2$ throughout the entire time period. While there are no specified products recommended, we require continuity in forcing, i.e., only one forcing data should be used for the full time-series. Available forcing data sets for the full time-series are for example NCEP/NCAR R1 and JRA55 or JRA55-do (latest updates).

The simulations with constant climate forcing (B and C) should be consistent with the variable climate simulations (A and D), for example by using a climatology calculated from the variable forcing or looping over a single year.

We provide atmospheric $CO_2$ but you can use your own estimation as long as it is based on observations. In the simulations with constant atmospheric $CO_2$, the $CO_2$ should be kept constant at preindustrial levels (278 ppm, equivalent to year 1765 in Meinshausen et al 2011; note though that in GCB provided atm xCO2 varies between 276.6 and 277.6 ppm between 1700 and 1777) and it should be started from the spin-up or from another simulation with constant $CO_2$ at 278 ppm and not from a simulation with increasing atmospheric $CO_2$. **The atmospheric xCO2 value of 278 ppm will be strictly enforced from GCB2024 onwards.**

We will assume that no drift correction and other post-processing (e.g., adjustment for riverine outgassing) has been applied unless you let us know otherwise.

In addition to providing the globally-integrated air-sea $CO_2$ flux time-series calculated on the native model grid, we request that the raw output of the models is regridded by each group to a standard 1x1 latitude longitude grid (see below for grid convention), and that the resulting regridded data are provided at the indicated frequency for the following fields.

# Required output

1. Annual mean air-sea $CO_2$ flux time-series in PgC/yr for 1959-2022. **Please provide one file in netcdf format per simulation** which includes the four time-series (Globe, South (<30°S), Tropics (30°S-30°N), North (>30°N)).
2. Gridded monthly output in netcdf format on a regular grid. Please submit the gridded fields on a monthly 1x1 degree grid (0.5 to 359.5°E longitude, -89.5 to 89.5°N latitude), one file for full time-series per variable. Please make sure that your submitted time-series and 3d fields are consistent. For required variables, see below.
3. **We require the following information for model evaluation, all as one dimensional time-series 1959-2022: AMOC, Southern Ocean surface salinity, Southern Ocean stratification index, Surface ocean Revelle factor (see Table, and further info further down)**

## Output requirement tables

Here, we define three tiers and one case study:

- Tier 1: The minimum request (with ancillary data) is mandatory for participation in GCB. Data for tier 1 are requested to be on a **regular 1x1 degree grid**.
- Tier 2: Full RECCAP2 request on a **regular 1x1 degree grid** will be made available for groups seeking to investigate specific research questions on the ocean carbon cycle under its own data policy (see below).
- Tier 3: Global and regional $CO_2$ flux time-series since 1850
- Case study (voluntarily): provide two members of simulations B and C:
    - with one repeated year forcing (member 1, e.g., year 1961)

- with repeated cycling over the first 10 years of the (JRA55) forcing data set (member 2)

Note minor changes compared to last year's request (in red: sea surface height).

Time period tier 1 and tier 2: 1959 – 2022.

## Tier 1: Minimum request

| Variable Name | Units | Output frequency | Shape | Long name |
|---|---|---|---|---|
| | | ***Surface ocean or 2D properties*** | | |
| fgco2_glob | Pg C $yr^{-1}$ | monthly | T | Globally integrated air-sea $CO_2$ flux (**positive downward**) |
| fgco2_reg | Pg C $yr^{-1}$ | monthly | iT | Regionally integrated air-sea $CO_2$ flux (**positive downward**) (using regional bounds), i: number of regions |
| intDIC_1994_glob | PgC | | | Globally integrated DIC inventory in the year 1994 (average over 1994) |
| intDIC_1994_reg | PgC | | i | Regionally integrated DIC inventory in the year 1994 (average over 1994) |
| intDIC_2007_glob | PgC | | | Globally integrated DIC inventory in the year 2007 (average over 2007) |
| intDIC_2007_reg | PgC | | i | Regionally integrated DIC inventory in the year 2007 (average over 2007) |
| fgco2 | mol $m^{-2}$ $s^{-1}$ | monthly | XYT | Flux density of the total air-sea $CO_2$ exchange (**positive downward**) |
| sfco2 | µatm | monthly | XYT | Surface ocean $CO_2$ fugacity ($fCO_2$) |
| fice | - | monthly | XYT | fractional ice-cover (=sea-ice concentration) used for the computation of the air-sea exchange flux [0-1] |
| dissicos | mol $m^{-3}$ | monthly | XYT | sea-surface DIC |
| talkos | mol $m^{-3}$ | monthly | XYT | sea-surface Alkalinity |
| tos | degC | monthly | XYT | sea-surface temp |
| sos | - | monthly | XYT | sea-surface salinity (PSS-78) |
| intdic | mol $m^{-2}$ | monthly | XYT | vertically-integrated DIC |
| AMOC | Sv | monthly | T | maximum of the Atlantic meridional overturning streamfunction at 26°N |
| SO_SSS | | monthly | T | Mean Southern Ocean salinity (psu) in the SPSS biome, see RECCAP mask in google folder (variable name 'southern', value=2) |
| SO_SI | kg $m^{-3}$ | monthly | T | Southern Ocean stratification index, following Bourgeois et al. 2022 |
| Revelle | - | monthly | XYT | Surface ocean Revelle factor |

Ancillary data for tier 1:

| Variable Name | Units | Shape | Long name |
| --- | --- | --- | --- |
| area | $m^2$ | XY | Total surface area of each grid cell (regridded) |
| volume | $m^3$ | XYZ | Total volume of each grid cell (regridded) |
| mask_sfc | - | XY | Field indicating the fraction of presence of ocean in a grid cell [0-1]; fraction of surface area |
| mask_vol | - | XYZ | Field indicating the fraction of presence of ocean in a grid cell [0-1] fraction of volume |
| Area_tot_native | $m^2$ | ireg | Total surface ocean area covered by native grid, for global, T, S, N |
| Vol_tot_native | $m^3$ | | Total ocean volume covered by native grid (global) |
| Atm_$CO_2$ | ppm | T | Time-series of atmospheric $CO_2$ used to drive the model. |
| RivCin | PgC $yr^{-1}$ | | River carbon inflow into the ocean, time-average |
| Burial | PgC $yr^{-1}$ | | Net C flux into the sediment, time-average |

## Tier 2: Full RECCAP request

These data are also requested on the regular 1x1 grid.

| Variable Name | Units | Output frequency | Shape | Long name |
| --- | --- | --- | --- | --- |
| | | ***Surface ocean or 2D properties*** | | |
| fgo2 | mol m-2 s-1 | monthly | XYT | Gas exchange flux of $O_2$ (positive into ocean) |
| intpp | mol $m^{-2}$ $s^{-1}$ | monthly | XYT | vertically-integrated net primary production |
| epc100 | mol $m^{-2}$ $s^{-1}$ | monthly | XYT | Particle flux of POC at 100 m |
| epc1000 | mol $m^{-2}$ $s^{-1}$ | monthly | XYT | Particle flux POC at 1000 m |
| epc100*type* / epc1000*type* | mol $m^{-2}$ $s^{-1}$ | monthly | XYT | particle fluxes at 100 and 1000 m for different particle types (e.g., slow, fast or small, large) |
| epcalc100 | mol $m^{-2}$ $s^{-1}$ | monthly | XYT | Export flux of $CaCO_3$ at 100 m |
| Kw | m $s^{-1}$ | monthly | XYT | Air-sea piston velocity |
| pco2atm | µatm | monthly | XYT | Atmospheric pCO2 ('pco2atm' [uatm] will vary spatially, as opposed to the spatially uniform 'xco2atm' [ppm] atm CO2 forcing due to corrections for atm pressure and vapor pressure) |
| alpha | mol $kg^{-1}$ $atm^{-1}$ | monthly | XYT | CO2 solubility |
| no3os | mol $m^{-3}$ | monthly | XYT | Surface Dissolved Nitrate Concentration |

| | | | | |
|---|---|---|---|---|
| po4os | mol $m^{-3}$ | monthly | XYT | Surface Total Dissolved Inorganic Phosphorus Concentration |
| sios | mol $m^{-3}$ | monthly | XYT | Surface Total Dissolved Inorganic Silicic acid Concentration |
| dfeos | mol $m^{-3}$ | monthly | XYT | Surface Dissolved Iron Concentration |
| o2os | mol $m^{-3}$ | monthly | XYT | Surface Dissolved Oxygen Concentration |
| intphyc | mol C $m^{-2}$ | monthly | XYT | Vertically-integrated Concentration of total phytoplankton expressed in carbon units |
| intphynd | mol C $m^{-2}$ | monthly | XYT | Vertically-integrated concentration of non-diatom phytoplankton expressed in carbon units (if available) |
| intdiac | mol C $m^{-2}$ | monthly | XYT | Vertically-integrated Concentration of diatom Phytoplankton expressed in carbon units (if available) |
| intzooc | mol C $m^{-2}$ | monthly | XYT | Vertically-integrated concentration of total zooplankton expressed in carbon units |
| chlos | kg $m^{-3}$ | monthly | XYT | Surface Mass Concentration of Total Phytoplankton expressed as Chlorophyll in Sea Water |
| mld | m | monthly | XYT | user-defined mixed layer depth |
| zeu | m | monthly | XYT | user-defined euphotic zone depth |
| **zos** | m | Monthly | XYT | Dynamic sea level |
| **Interior ocean or 3D properties** | | | | |
| dissic | mol $m^{-3}$ | monthly | XYZT | Dissolved inorganic carbon |
| talk | mol $m^{-3}$ | monthly | XYZT | Total Alkalinity |
| thetao | degC | monthly | XYZT | seawater potential temperature |
| so | - | monthly | XYZT | Salinity (PSS-78) |
| epc | mol $m^{-2}$ $s^{-1}$ | monthly | XYZT | 3D field of particle flux of POC |
| no3 | mol $m^{-3}$ | monthly | XYZT | Dissolved Nitrate Concentration |
| po4 | mol $m^{-3}$ | monthly | XYZT | Total Dissolved Inorganic Phosphorus Concentration |
| si | mol $m^{-3}$ | monthly | XYZT | Total Dissolved Inorganic Silicic Concentration |
| o2 | mol $m^{-3}$ | monthly | XYZT | Dissolved Oxygen Concentration |

## Tier 3: Extension to 1850

Time period: 1850 - 2021

| Variable Name | Units | Output frequency | Shape | Long name |
|---|---|---|---|---|
| | | ***Surface ocean or 2D properties*** | | |
| fgco2_glob | Pg C $yr^{-1}$ | monthly | T | Globally integrated air-sea $CO_2$ flux (**positive downward**) |

| | | | | |
|---|---|---|---|---|
| fgco2_reg | Pg C $yr^{-1}$ | monthly | iT | Regionally integrated air-sea $CO_2$ flux (**positive downward**) (using regional bounds), i: number of regions |

## Naming convention

Please generate one file per variable (do not merge different variables into one file). This file should contain full time-series for 2-D-variable. For 3-D variables, split in chunks as need be.

**File names:** Groups are encouraged to follow the CMIP naming convention for file names (see this link), the file name can be constructed consistent with the following template

> **file name = <variable_id>_<model_id>_<experiment_id>_<member_id>_<grid_label>_<time_range>_<version_id>.nc**
>
> Example file name = fgco2_CESM-ETHZ_A_1_gr_1980-2018_v20200101.nc

**version _id**: We suggest to use version numbering of your files, indicating the date of creation as vYYYYMMDD.

**member _id**: Will be "1" in most of the cases, but can be used to distinguish variants of the same model, such as runs with different forcings. Variant 1 should be considered the standard case used in the analysis.

## Evaluation metrics, additional info

1. **Atlantic Meridional Overturning Circulation, AMOC: here defined as maximum of the Atlantic meridional overturning streamfunction at 26°N**
2. **Mean Southern Ocean salinity in the SPSS biome, see RECCAP mask in google folder (variable name 'southern', value=2)**
3. **Southern Ocean density criterion (simplified from Bourgeois et al., 2022):**
    a. **Calculate average in situ density at surface between 30-55S**
    b. **Calculate average in situ density at 1000 m depth between 30-55S**
    c. **Calculate stratification index as SI = rho(1000m) - rho(surf)**
4. **Surface ocean Revelle factor, XYT**

# Data policy

The global annual average of the ocean sink data are available with the Global Carbon Budget publication. Ocean model simulation results are available under the CC-BY-NC license (https://creativecommons.org/licenses/by-nc/4.0/). Gridded data of $CO_2$ flux and surface ocean fugacity of $CO_2$ ($fCO_2$) are available open access.

Additional model output (tier 1 and tier2) is available upon request. For the current and last year global carbon budget, the full ocean model gridded data are available on request (judith.hauck@awi.de). The GCB-ocean modelling groups have identified studies they will conduct with these data over the coming year. If an external study does not conflict with these studies, the data will be made available. Co-authorship of GCB-ocean modelers depends on the importance of the GCB-ocean data in the study and should be discussed with the GCB-ocean coordinator (J. Hauck) early on in the process. All studies should be circulated to the modelling groups prior to submission.

GCB-ocean data from previous global carbon budget are freely available, with no request for GCB-ocean modelers co-authorship.

# References

Bourgeois et al., 2022: https://doi.org/10.1038/s41467-022-27979-5
Friedlingstein et al., 2022: https://essd.copernicus.org/articles/14/4811/2022/
Meinshausen et al. 2011: http://link.springer.com/10.1007/s10584-011-0156-z