Ocean biogeochemistry

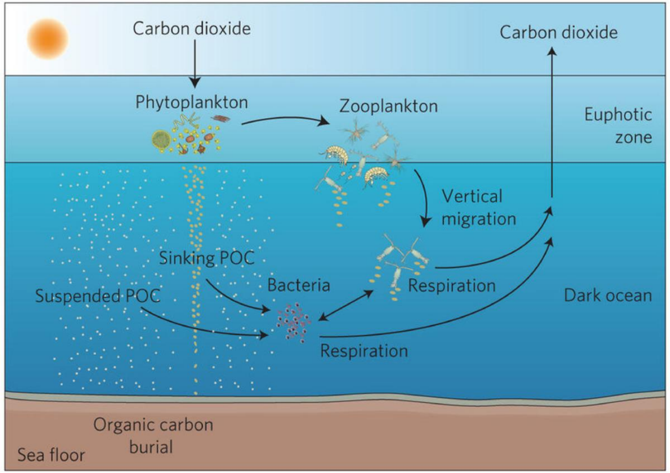
tomas.torsvik@uib.no, joeran.maerz@uib.no

Ocean biogeochemistry

Ocean biogeochemistry involves the study of the oceans' biological, geological and chemical processes.

Ocean chemistry – dissolved inorganic nutrients (nitrogen, phosphorus, carbon, iron,...) that play a role in biological cycles.

Ocean biology – all living organisms from phytoplankton and zooplankton at the base of the food web, to fish and marine mammals.



Herndl & Reinthaler 2013

NOTE: Following should not substitute lectures/in-depth studies - just a teaser

Scope of ocean biogeochemistry (OBGC) models in ESMs

Prognostic modeling of climate-relevant ocean biogeochemistry processes with a focus on the carbon cycle and linked nutrient cycles.

OBGC models are not ecosystem models, while the line between them is blurred.

Process representation is often constrained
i) by spatio-temporal resolution of the driving circulation model, and
ii) by computational limitations.

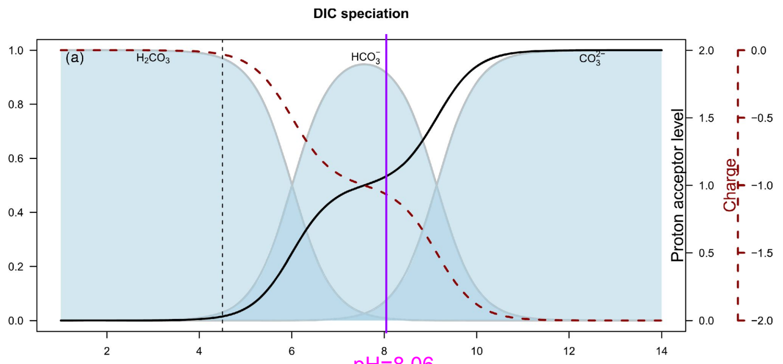
Seawater carbon chemistry

Carbon dioxide reacts with water to bicarbonate ions that dissociates to carbonate ions producing protons, making CO_2 an acid.

$$CO_2^{*} + H_2O \rightleftarrows HCO_3^{-} + H^{+}$$
$$HCO_3^{-} \rightleftarrows CO_3^{2-} + H^{+}$$

Dissolved inorganic carbon (**DIC**) is thus:
$DIC = [CO_2^{*}] + [HCO_3^{-}] + [CO_3^{2-}]$

Bjerrum plot



pH=8.06 (surface ocean)

Middelburg et al. 2020

Alkalinity defined as net charge contribution of conserved ions (not taking part in the weak acid-base reactions) relative to *zero level of protons*, where proton donors balance proton acceptors (typically pH=4.5 for sea water by definition of Dickson, 1981).

Carbonate alkalinity $A_C = [HCO_3^{-}] + 2[CO_3^{2-}]$

Total alkalinity

$A_C \lesssim$ Total alkalinity $A_T([HCO_3^-],[CO_3^{2-}],[B(OH)_4^-],...)$ altered by physical and biological processes.

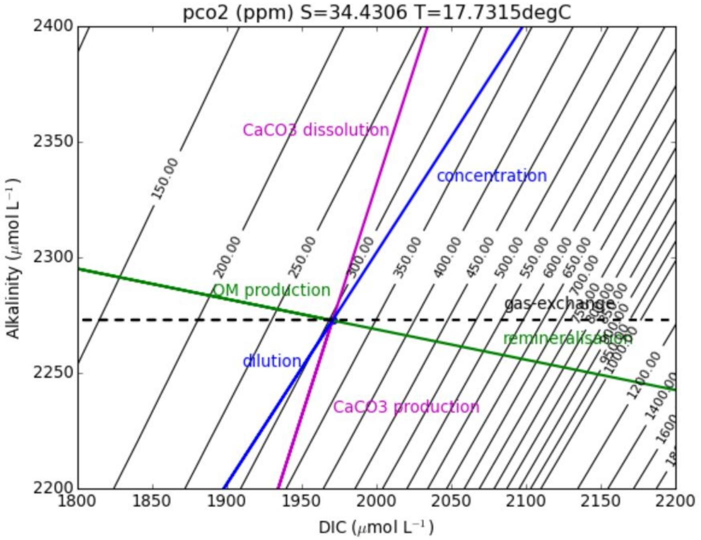
Surface DIC negatively correlates with temperature due to solubility.

Surface alkalinity correlates with salinity due to precipitation and evaporation patterns.

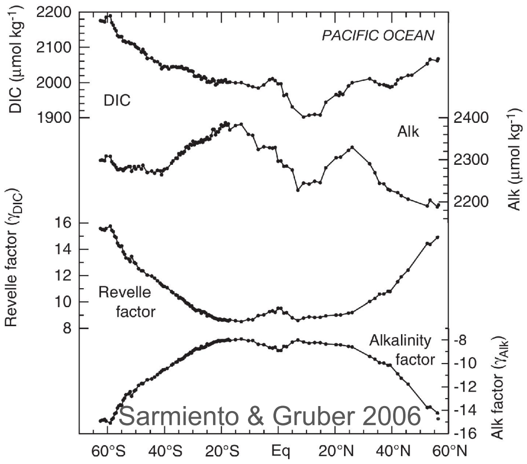
Revelle factor: sensitivity of partial pressure ($pCO_2=CO_2^*$/solubility) to changes in DIC:

$$\gamma_{DIC}=\partial \ln(pCO_2)/\partial \ln(DIC) \quad \text{“Buffering factor”}$$

For further reading on pCO_2, alkalinity, please refer to: Takahashi et al. 2002, Wolf-Gladrow et al. 2007, Middelburg et al. 2020



Irene Stemmler (pers. communication)



Sarmiento & Gruber 2006

Primary production and heterotrophic growth

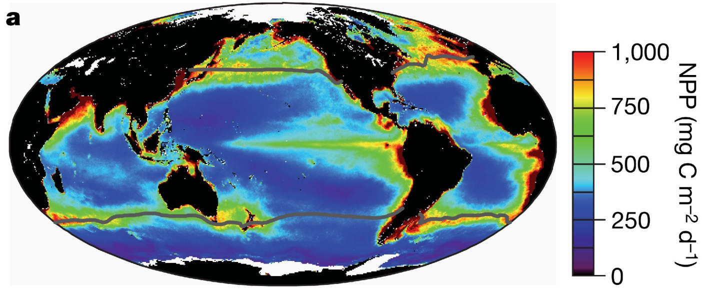
In the sunlit surface ocean, light serves as energy source for phytoplankton as primary producers to fix CO_2 and nutrients to grow organic matter.

Primary production forms the basis of the marine foodweb.

During decay and grazing through zooplankton, detritus and dissolved organic matter (DOM) is formed which gets remineralized to inorganic nutrients and CO_2.

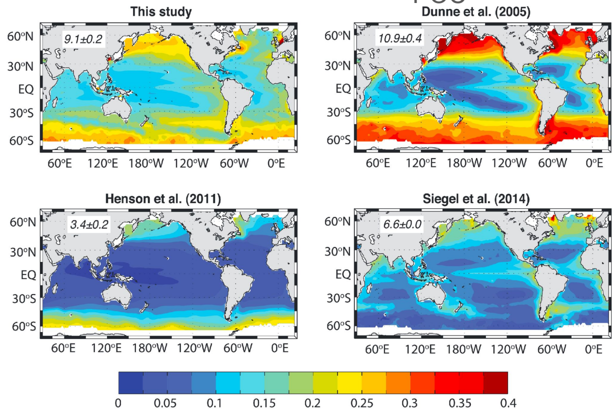
Current estimates: net primary production: $53\pm7 PgCyr^{-1}$ Johnson and Bif (2021)
Export fluxes at about 100 m depth: $7.36 \pm2.12 PgCyr^{-1}$ Yamaguchi et al. (2024)

Net primary production



Behrenfeld et al. 2006

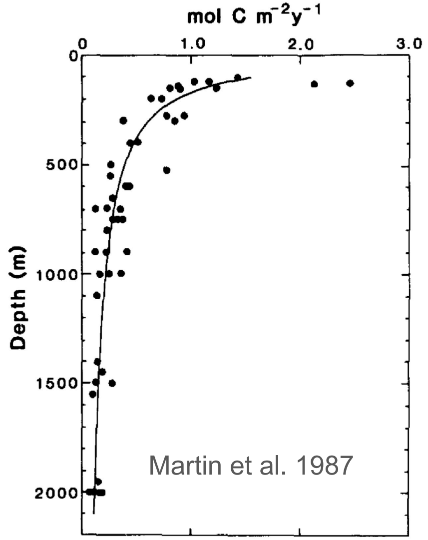
Export ratio: ep=F_{POC}/NPP



DeVries & Weber 2017

Carbon pumps (classical view)

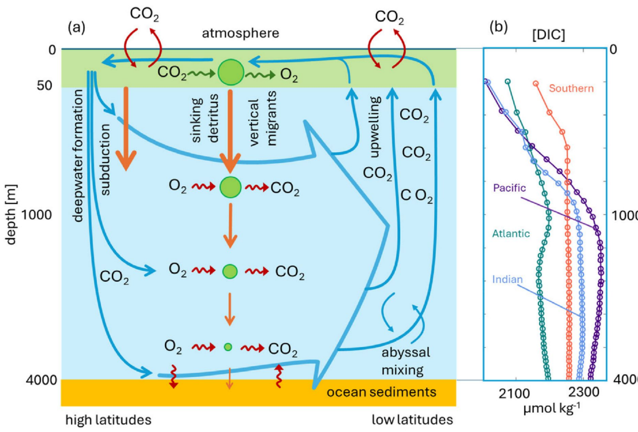
Soft tissue pump
Particulate organic carbon (POC) can sink.
Vertical POC fluxes follow classically a Martin power law curve (Martin et al. 1987) and transport biologically fixed CO_2 to deeper ocean regions, where it can be stored for longer time scales.



Martin et al. 1987

Carbonate pump
Some phyto- and zooplankton produce biogenic $CaCO_3$ structures (reducing alkalinity), which sink and dissolve.

Together with circulation, the physicochemical **solubility pump** and **CO_2 counter pump**, these processes set the dissolved inorganic carbon (DIC) gradients and oceanic CO_2 storage.



Visser 2025

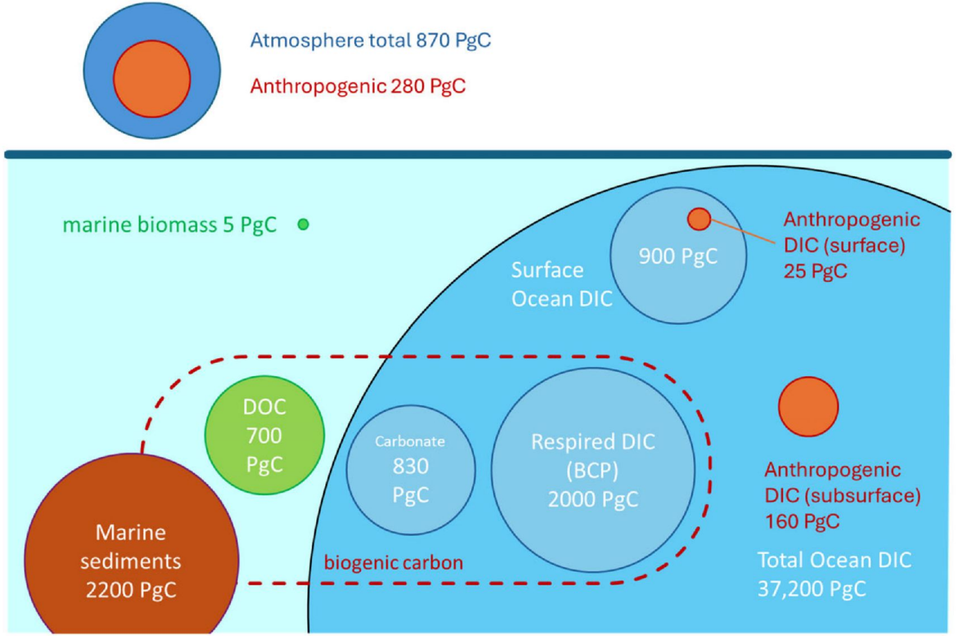
Oceanic CO_2 storage

Vertical DIC gradients driven to about ~21% / ~17% / ~62% by solubility/carbonate/soft tissue pump (Bacastow & Maier-Reimer 1990).

The biological carbon pumps (BCP) mainly **maintain** vertical DIC gradients.

Max. 10% of current **anthropogenic** carbon uptake is driven by biological pumps, the remaining 90% by the solubility pump (Broecker 1991).

➡ Only large changes in the BCP and circulation changes can alter oceanic CO_2 storage.



Visser 2025

Changing circulation and decreasing export fluxes lead to a **net** effect of 20-50 PgC **more respired** DIC by the end of the century at the cost of declining oxygen (Koeve et al. 2020, Wilson et al. 2022).

ODZs & remineralization in hypoxic/suboxic/anoxic waters

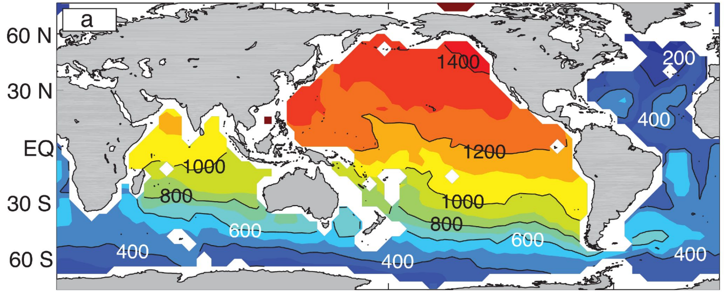
Along the meridional overturning circulation (MOC; Time scale of about 1000 years), deep-water mass age increases and imprints on deep ocean nutrient concentrations and oxygen ventilation.

Old water masses combined with high primary production atop through upwelling processes, lead to oxygen depletion and thus oxygen deficit zones (ODZs) with impacts on higher organisms (Heinze et al. 2021).

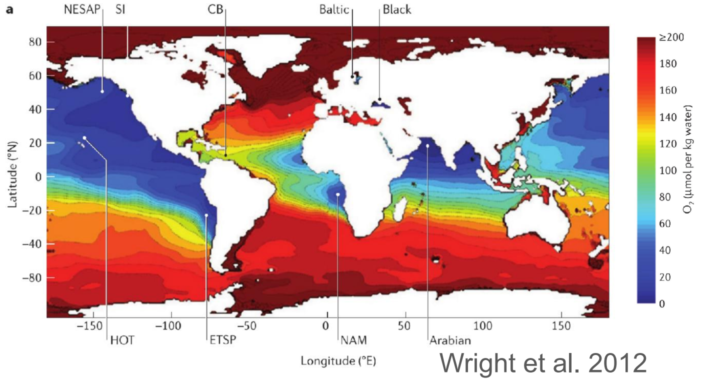
ODZs are hotspots of anaerobic processes such as the nitrogen cycle leading to N_2 loss and production of the highly potent non-CO_2 GHG N_2O.

ODZs pose long-term feedbacks on upper ocean primary production processes through altering the stoichiometry of available nutrients.

Mean water mass age for depths >2000m



De Vries & Primeau 2011

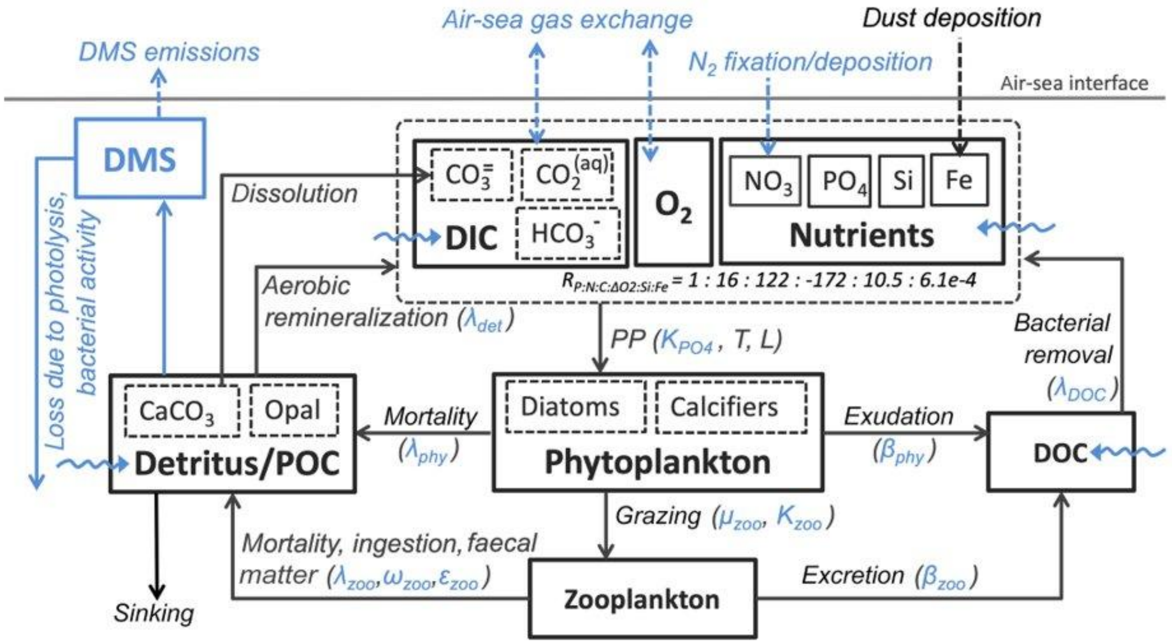


Wright et al. 2012

iHAMOCC - NorESM ocean biogeochemistry component

iHAMOCC features:

- Air-sea gas exchange
- Full inorganic seawater carbon chemistry
- NPZD-type P-based ecosystem representation with fixed, Fe-extended Takahashi (1985) Redfieldian stoichiometry
- Vertical fluxes of dust, biogenic minerals (opal and $CaCO_3$) and POM
- Simplified sediment pore water & particulate biogeochemistry and burial



Tjiputra et al. 2020

Additional tracers & processes:

- Alkalinity
- Riverine inputs
- N_2O, N_2
- Dust

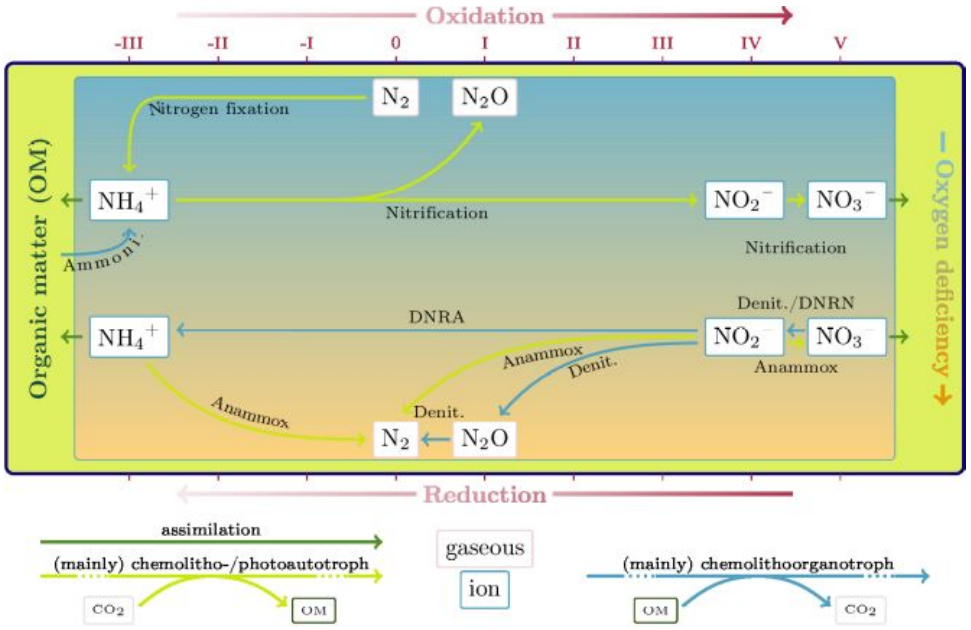
Changes and new processes represented in NorESM2.3

NOTE: iHAMOCC and some new processes in NorESM2.3 not scientifically supported/documented/tuned - can be perceived as testbed towards NorESM3.X

- Bugfixes (dust fluxes and sediment alkalinity)
- Additional pre-formed tracers (now pre-formed O_2, PO_4^{3-}, Si, A_T, DIC)
- Temperature(Q_{10})- & O_2-dependency of aerobic remineralization
- Online sediment spin-up scheme to accelerate sediment towards steady state
- Extended N-cycle (with emission-driven, coupling capabilities for N_2O, NH_3 and N-deposition; non-standard NorESM configuration)

Extended nitrogen cycle in iHAMOCC

- Introducing new tracers NH_4^+ and NO_2^- allow for the explicit representation of the major N-cycle pathways
- Temperature dependence of processes
- Dark carbon fixation through chemolithoautotrophic processes
- Implemented in both the water column and the sediment



Maerz et al. (in prep.)

Optional processes and representations

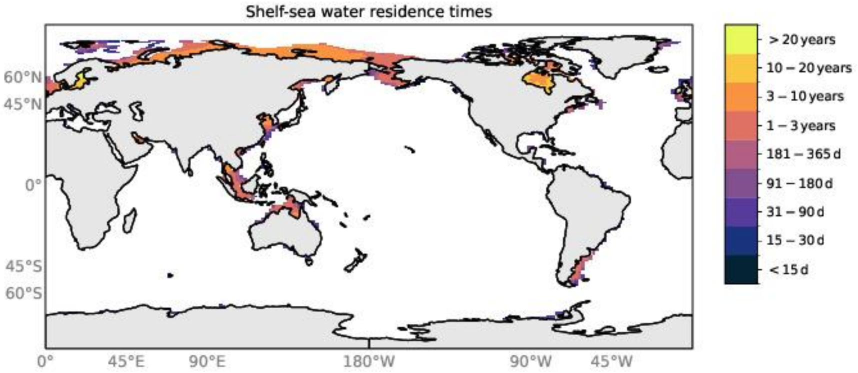
- Potential to break up separation between mixed layer and deeper ocean process (useful in the hybrid coordinates)
- CFCs
- C-isotopes (not compatible with all optional processes)
- DOM classes representing labile, semi-labile, semi-refractory and refractory DOM
- Phytoplankton feedback on physics through light absorption
- River2OMIP: new riverine input and low- and high-C terrestrial DOM representation
- Sediment-features (under testing/development):
    - POM quality- and sediment age-dependent remineralization
    - Extendable sediment depth from fixed (default ~15cm) to variable depth
    - Capability to define variable sediment porosity via external file
- Aggregation scheme (Kriest et al. 2001)
- Shelf sea water age tracer for coastal and shelf sea studies
- M^4AGO sinking scheme (Maerz et al. 2020,2025) optional to current default Martin curve-like POC flux representation

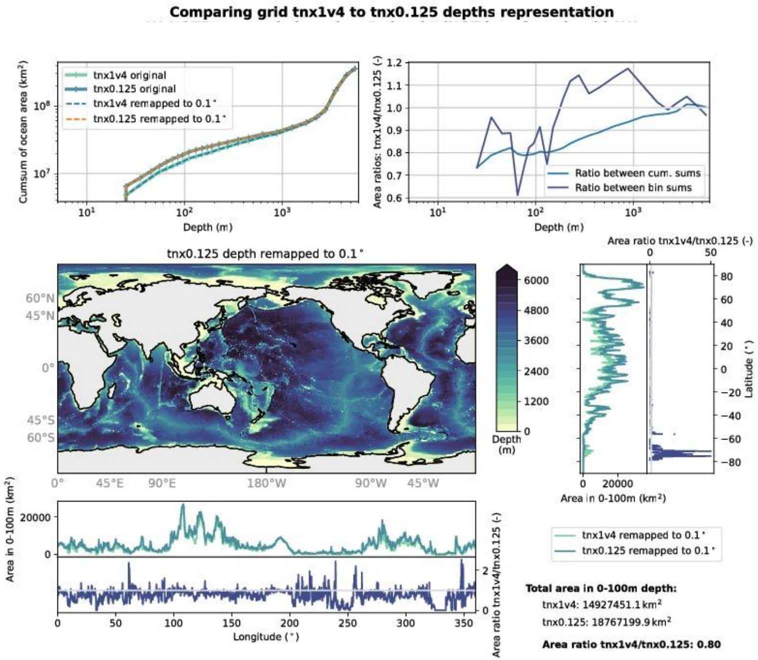
Shelf sea water age tracer

Introduced following Liu et al. (2019):

- Shelf sea water age enables to calculate residence times
- Useful for studying coastal & shelf sea-open ocean exchange processes on the land-ocean continuum

Note the horizontal grid resolution dependence of coastal and shelf sea representation and residence times.



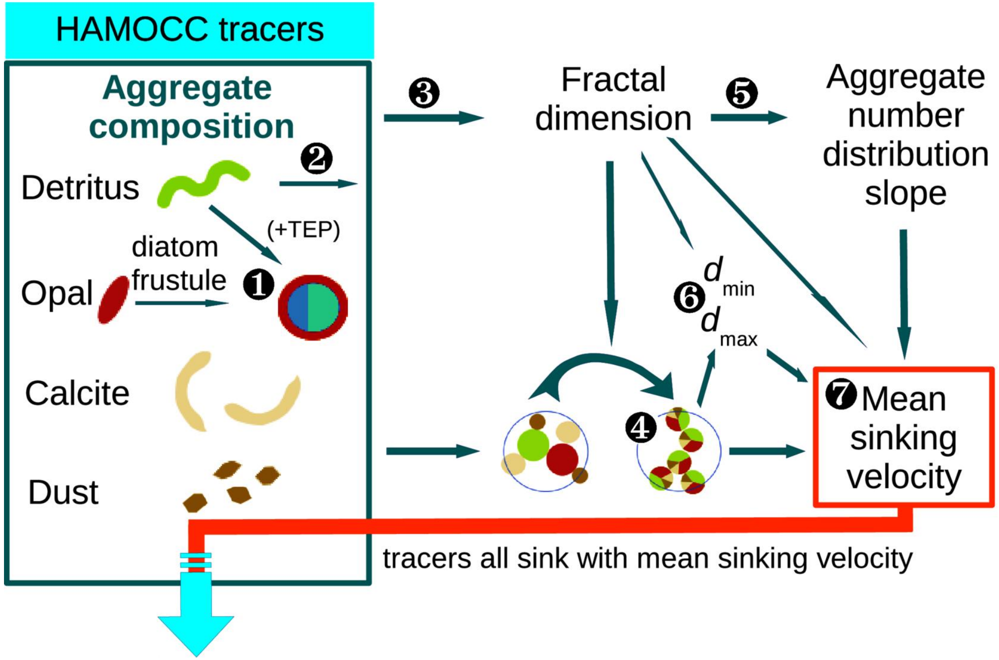


M^{4}AGO sinking scheme

Explicit representation of spatio-temporally variable, heterogeneously composed marine particles, featuring

- Power law size spectrum
- Microstructure
- Variable size and density

→ Local mean sinking velocity of all particulate tracers



Maerz et al. 2020, 2025

Interaction between BLOM and iHAMOCC

The iHAMOCC model is fully encapsulated in BLOM, i.e. all communication with NorESM coupler goes through BLOM, and are passed between BLOM and iHAMOCC through an interface module **`mo_hamocc4bcm`**, with the aid of two transfer subroutines **`blom2hamocc`** and **`hamocc2blom`**.

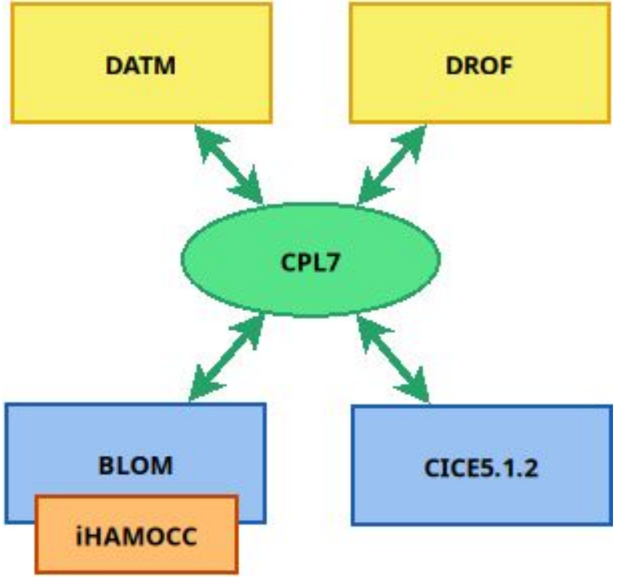
Internally, iHAMOCC is a (0-D / 1-D) box model, with partial representation of vertical transport through sinking of particulate matter in the water column, sedimentation, pore water diffusion and burial in sediments.

BLOM is responsible for transporting/mixing all BGC fields, as passive tracers. Temporal and spatial resolution is determined by BLOM.

By default, iHAMOCC has no direct feedback to ocean physics (only indirectly via air-sea fluxes and atmosphere response to coupled climate-active gases)

iHAMOCC (and other tracer fields) is updated once per 3-D BLOM time step.

Run ocean/sea-ice stand-alone setup



- Active ocean physics, sea ice and optionally biogeochemistry
- Use data atmosphere and data river runoff

Data available under shared folder on Betzy:
`/cluster/shared/noresm/inputdata/ocn/`

- Ocean/sea-ice compsets defined in `<BLOM_SRC>/cime_config/config_compsets.xml`
- Data components defined in `<NORESM_SRC>/cime/src/components/data_comps/`
  - `datm/cime_config/namelist_definition_datm.xml`
  - `drof/cime_config/namelist_definition_drof.xml`

Available DATM/DROF datasets

- **`IAF`** : OMIP-1/CORE-II : Ocean forced through use of interannual atmospheric state of Large and Yeager (2009), and river runoff data based on Dai et al. (2009), covers the period from 1948 to 2009.
  - Pre-OMIP protocol defined by the Coordinated Ocean-ice Reference Experiments (CORE)
  - 6 hour temporal frequency, 1.875° horizontal resolution (**T62 grid**)
  - Data available from `/cluster/shared/noresm/inputdata/ocn/iaf`
- **`NYF`** : OMIP-1/CORE-II : Normal year forcing, similar to **`IAF`**
  - Data available from `/cluster/shared/noresm/inputdata/atm/datm7/NYF`
- **`JRA`** : OMIP-2/JRA55-do : Based on Japanese 55-year atmospheric reanalysis (JRA-55; Kobayashi et al., 2015), currently covers the period from 1958 to 2018.
  - 3 hour temporal frequency, 0.5625° horizontal resolution (**TL319 grid**)
  - Data available from `/cluster/shared/noresm/inputdata/ocn/jra55/v1.3_noleap/`

OMIP-style compsets

Ocean physics (BLOM) and sea ice (CICE) are always active components.

Ocean biogeochemistry is enabled with component modifier BLOM%ECO.

Data atmosphere (DATM) and runoff (DROF) must be from consistent sets of external forcing files (e.g. NYF, JRA) or files created by NorESM spinup (CPLHIST).

Stub components defined for land (SLND), land ice (SGLC) and waves (SWAV).

NOINY : OMIP-1 forcing, ocean physics and sea ice

`2000_DATM%NYF_SLND_CICE%NORESM-CMIP6_BLOM_DROF%NYF_SGLC_SWAV`

NOIIAJRAOC : OMIP-2 forcing, ocean physics, biogeochemistry and sea ice

`2000_DATM%JRA_SLND_CICE%NORESM-CMIP6_BLOM%ECO_DROF%JRA_SGLC_SWAV`

NOICPLHISTOC : NorESM spinup forcing, ocean physics, biogeochemistry and sea ice

`2000_DATM%CPLHIST_SLND_CICE%NORESM-CMIP6_BLOM%ECO_DROF%CPLHIST_SGLC_SWAV`

iHAMOCC settings: enabled with “./xmlchange”

Run `./xmlquery --listall | less` and look for BLOM and CICE settings.

Settings in “build_component_blom” (set before running “case.build”)

- BLOM_TRACER_MODULES = [iage; iage ecosys] : Optional ocean traces (only ideal age tracer by default). BLOM%ECO compset enables “iage ecosys”.
- BLOM_CMIP6 = [TRUE; **FALSE**] : Build with parameter settings for CMIP6-like BLOM circulation (requires: BLOM_UNIT=cgs, BLOM_VCOORD=isopyc_bulkml)
- BLOM_VCOORD = [**isopyc_bulkml**; cntiso_hybrid] : Vertical coordinate type, default isopycnic layers

Settings in “run_component_blom” (set before running “case.submit”)

- OCN_CO2_TYPE = [**constant**; prognostic; diagnostic] : Usually set by compset
- HAMOCC_SINKING_SCHEME = [**wlin**; m4ago; agg; const] : Sinking scheme for iHAMOCC
- HAMOCC_SEDBYPASS = [TRUE; **FALSE**] : Do not include sediment deposition
- HAMOCC_SEDSPINUP = [**TRUE**; FALSE] : Use accelerated sediment spinup option (see also HAMOCC_SEDSPINUP_NCYCLE and HAMOCC_SEDSPINUP_YR_START and HAMOCC_SEDSPINUP_YR_END)
- HAMOCC_PREF_TRACERS = [**TRUE**; FALSE] : Activate optional tracking of preformed tracers
- HAMOCC_CICO = [TRUE; **FALSE**] : Activate optional tracking of carbon isotopes
- HAMOCC_OUTPUT_SIZE = [**default**; spinup] : Pre-set options for amount of output

iHAMOCC: some namelist settings in `user_nl_blom`

Set some parameter values

```
drempoc = 0.026                    !Reset remineralization rate (as an example)
```

Specify **files for boundary** conditions, different from default settings

```
fedepfile=/mypath/myfile    !File name for iron (dust) deposition
ndepfile =/mypath/myfile    !File name for atmospheric nitrogen deposition data
riverinfile=/mypath/myfile  !File name for riverine input data
```

Logical switches that are not available through **`xmlchange`** options

```
with_dmsph = true/false          !Turn on/off pH dependency of DMS production
use_river2omip = true/false      !Turn on/off riverine carbon and nutrient inputs
use_domclasses = true/false      !Turn on/off DOM code with labile & refractory classes
```

iHAMOCC settings: namelist settings in `user_nl_blom`

Set output frequency and precision for output variables

Output is written at daily, monthly and yearly intervals by default, with precision determined by integer value (0=no output, 2=int2+scale factor; 4=real4; 8=real8)

```
srf_phosph    = 0,2,2     !Surface phosphorus field
lvl_phosph    = 0,2,2     !3D (constant level) phosphorus field
lyr_phyto     = 0,0,2     !3D (grid layer) phytoplancton
int_bromopro  = 4,2,2     !Vertically integrated bromoform production
flx_ndepnoy   = 0,2,2     !NOy nitrogen deposition flux
```