Frauke Bunsen, Judith Hauck, Lars Nerger et al.

ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

2.7.2025 at MEAP-TT

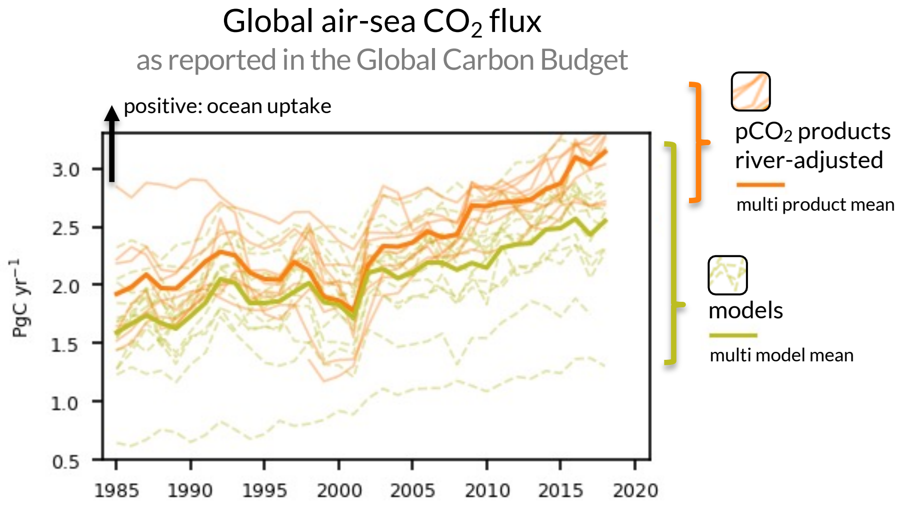
Estimating the recent global ocean CO_2 uptake with data assimilation

FESOM Finite volumE Sea ice-Ocean Model
REcoM Regulated Ecosystem Model
PDAF Parallel Data Assimilation Framework

Motivation

Estimating the recent global ocean carbon uptake

- Ocean: Sink for ~30% of CO_2 emissions
- Sparse observations of partial pressure of CO_2 (pCO_2): ~2% of ocean surface sampled (~2% of monthly 1° × 1° ocean cells)
- Variability of air-sea CO_2 flux in time + by region
- Discrepancy between ocean biogeochemical model and observation-based pCO_2 product estimates
- Data assimilation used to study air-sea CO_2 flux



Outline

- Methods: Ocean model and data assimilation
- Studies:

I.
Assimilating temperature and salinity

Articles / Volume 21, issue 1 / OS, 21, 437–471, 2025

Ocean Science

Article | Assets | Pe

https://doi.org/10.5194/os-21-437-2025
© Author(s) 2025. This work is distributed under the Creative Commons Attribution 4.0 License.

Research article | 13 Feb 2025

Ocean carbon sink assessment via temperature and salinity data assimilation into a global ocean biogeochemistry model

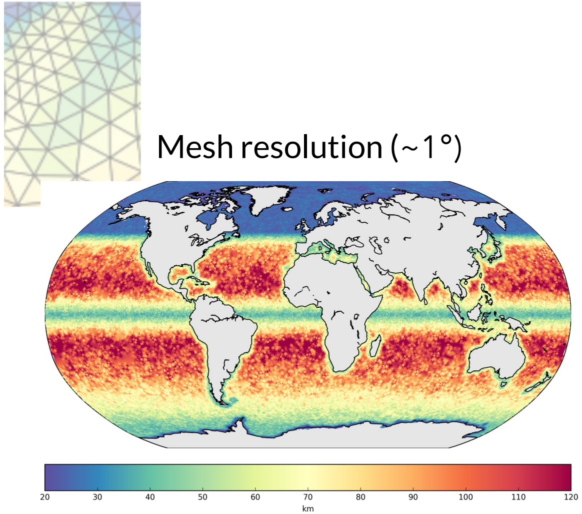
Frauke Bunsen, Judith Hauck, Sinhué Torres-Valdés, and Lars Nerger

https://os.copernicus.org/articles/21/437/2025/

II.
Assimilating biogeochemical observations

Method: Model and state variables

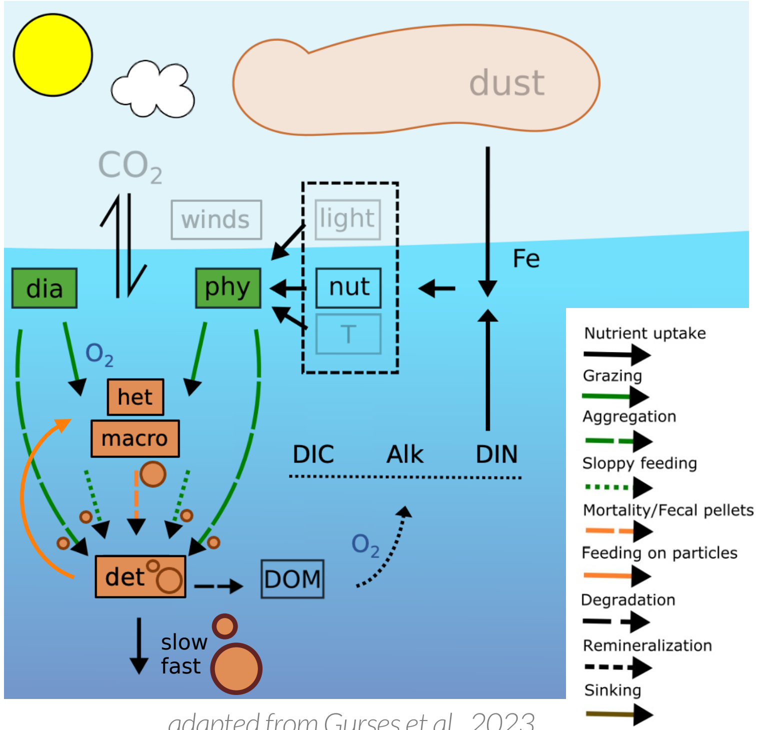
Ocean circulation model FESOM



Ocean biogeochemistry model REcoM

variable stoichiometry

diatoms N:C:Chl:Si
nano phyto N:C:Chl:Calc



adapted from Gurses et al., 2023

Method: Set-up

I.
Assimilating temperature and salinity

- Time period 2010 – 2020
- Experiments with different observation types:

FREE

ASML
physics

- Temperature and salinity profiles
  EN4
- Sea surface temperature
  OSTIA
- Sea surface salinity
  ESA CCI

Method: Set-up

- Time period 2010 – 2020
- Experiments with different observation types:

FREE

ASML
physics

- Temperature and salinity profiles
  EN4
- Sea surface temperature
  OSTIA
- Sea surface salinity
  ESA CCI

Method: Data assimilation

- PDAF implementation of Ensemble Kalman Filter variant (LESTKF)
  - useful to track a changing state over time: ocean pCO_2 2010 – 2020
  - extendable to the most recent annual estimate

https://pdaf.awi.de/trac/wiki

Assimilation of temperature and salinity observations into ocean circulation model → Variables incremented during assimilation step:

temperature, salinity, horizontal velocities, sea surface height

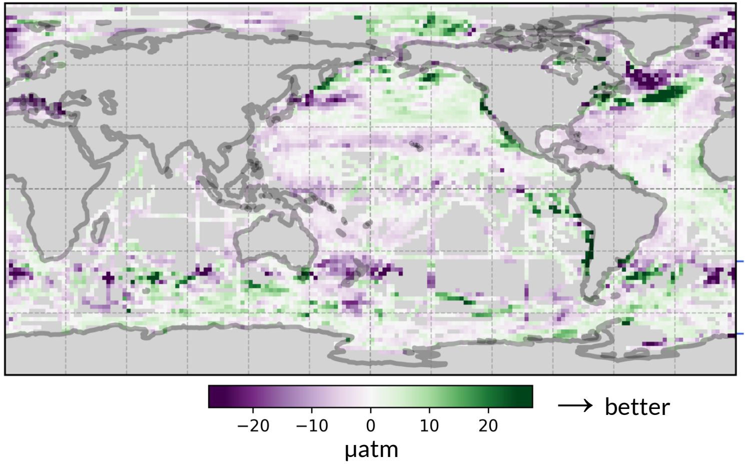
- Model uncertainty represented through ensemble (size 40) with perturbations of
  - initial physical state
  - atmospheric forcing

Results: Validation

- Improvement of physical model
  - Sea surface temperature and salinity: model-observation differences reduced by ~50%
  - Mixed layer: differences reduced by ~30% compared to climatology

- Mixed effect on biogeochemistry
  - Regional improvements and degradation compared to observations (pCO$_2$, DIC, Alk and surface chlorophyll)
  - not always consistent across different evaluated variables

pCO$_2$ improvement of model-observation agreement

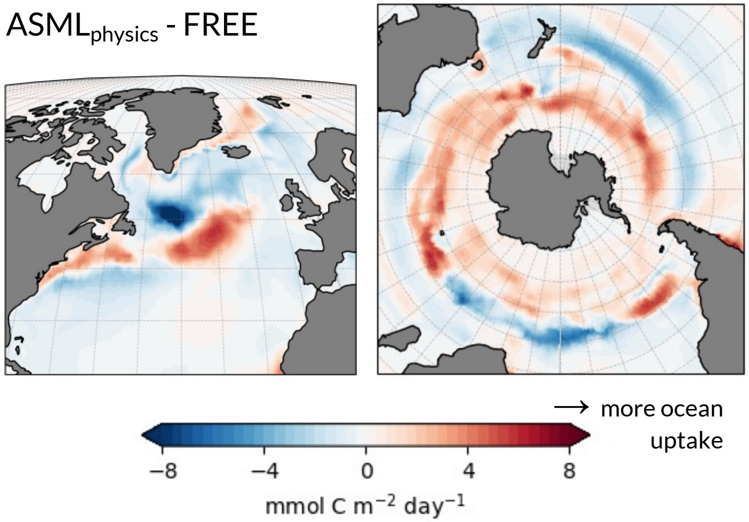


Results: CO_2 flux

- Local effects on air-sea CO_2 flux
  - North Atlantic Current and Subantarctic Front
  - Regional shifts following sea surface temperature
- Basin-scale effect in Southern Ocean: reduced winter outgassing (-0.2 PgC yr^{-1})
- More stable stratification and less DIC at 0 – 200 m
- Regional shifts in balance without altering the global ocean carbon uptake (-0.05 PgC yr^{-1})

CO_2 flux difference

$ASML_{physics}$ - FREE



Method: Set-up

- Experiments with different observation types:

FREE

ASML
physics

- Temperature and salinity profiles
  EN4
- Sea surface temperature
  OSTIA
- Sea surface salinity
  ESA CCI

Method: Set-up

- Experiments with different observation types:

FREE

ASML
physics

- Temperature and salinity profiles
  EN4
- Sea surface temperature
  OSTIA
- Sea surface salinity
  ESA CCI

Method: Set-up

- Experiments with different observation types:

FREE

ASML
physics

- Temperature and salinity profiles
  EN4
- Sea surface temperature
  OSTIA
- Sea surface salinity
  ESA CCI

ASML
carbs

- pCO_2
  SOCAT
- DIC and alkalinity profiles
  GLODAP

Method: Set-up

- Experiments with different observation types:

FREE

ASML
physics

- Temperature and salinity profiles
  EN4
- Sea surface temperature
  OSTIA
- Sea surface salinity
  ESA CCI

ASML
carbs

- pCO_2
  SOCAT
- DIC and alkalinity profiles
  GLODAP

ASML
carbs plus

- O_2 and nitrate profiles
  WOD, COMFORT, BGC Argo
- Surface chlorophyll anomalies
  OC CCI

Method: Data assimilation

Assimilation of temperature and salinity observations into ocean circulation model → Variables incremented during assimilation step:

temperature, salinity, horizontal velocities, sea surface height

+ Assimilation of biogeochemical (BGC) observation types into BGC model → 26 variables incremented during assimilation step:

- carbon, calcite, nitrogen and silicate in plankton and detritus and / or as dissolved (in)organic matter
- alkalinity and O_2

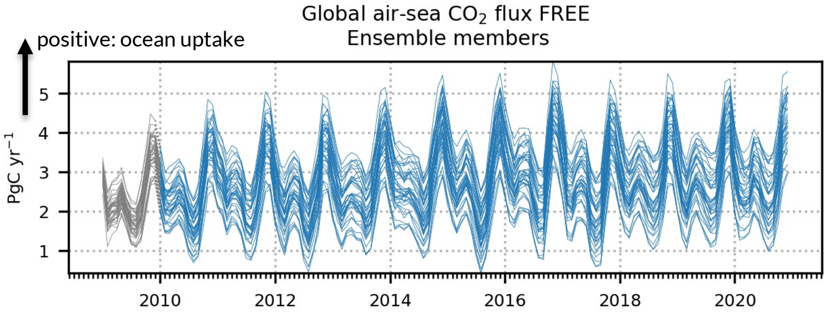
Method: Model uncertainty

- Model uncertainty represented through ensemble (size 40) with perturbations of
  - initial physical state
  - atmospheric forcing

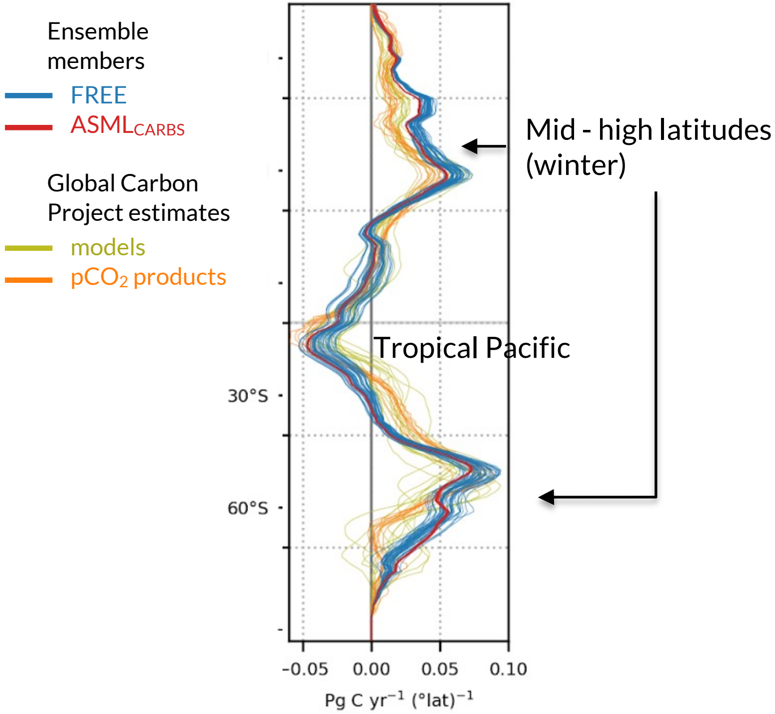
- Perturbations of
  - 33 biogeochemical parameters → plankton dynamics
  - initial state of inorganic tracer concentrations:
    dissolved inorganic carbon (DIC) and nitrogen (DIN), alkalinity (Alk) and O_2
  - background diffusivity coefficient

Method: Model uncertainty

- Uncertainty from the biogeochemical model larger than from physics (not shown)
- Different parameters increase ensemble spread over time

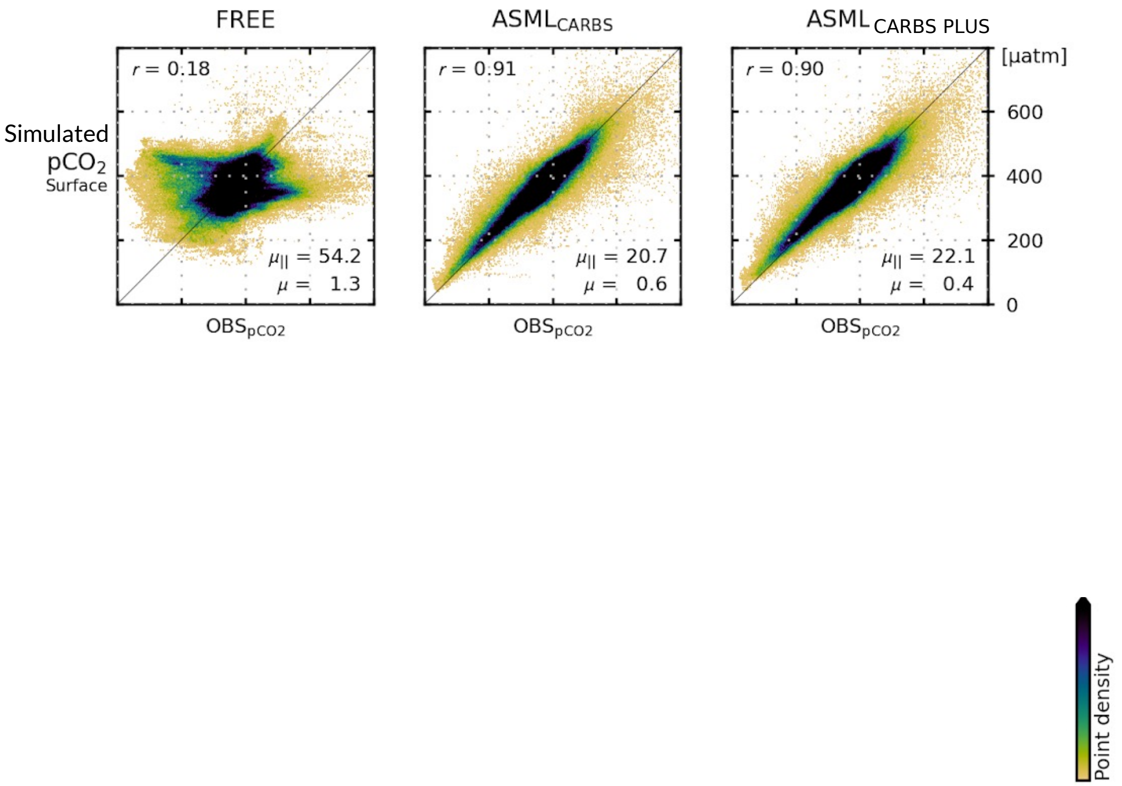


Zonal sum of air-sea CO_2 flux



Results: Evaluation

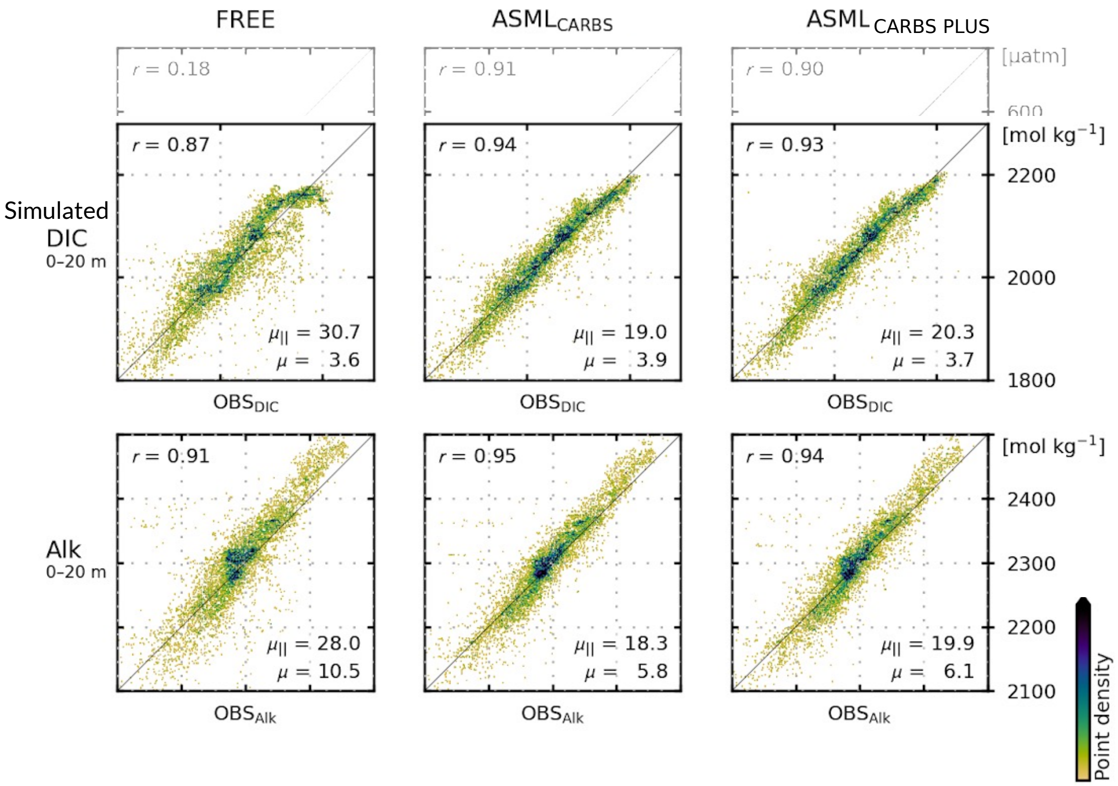
- Improved agreement with **pCO_2** observations:
  Absolute differences ($\mu_{||}$) reduced by more than ~50%



Results: Evaluation

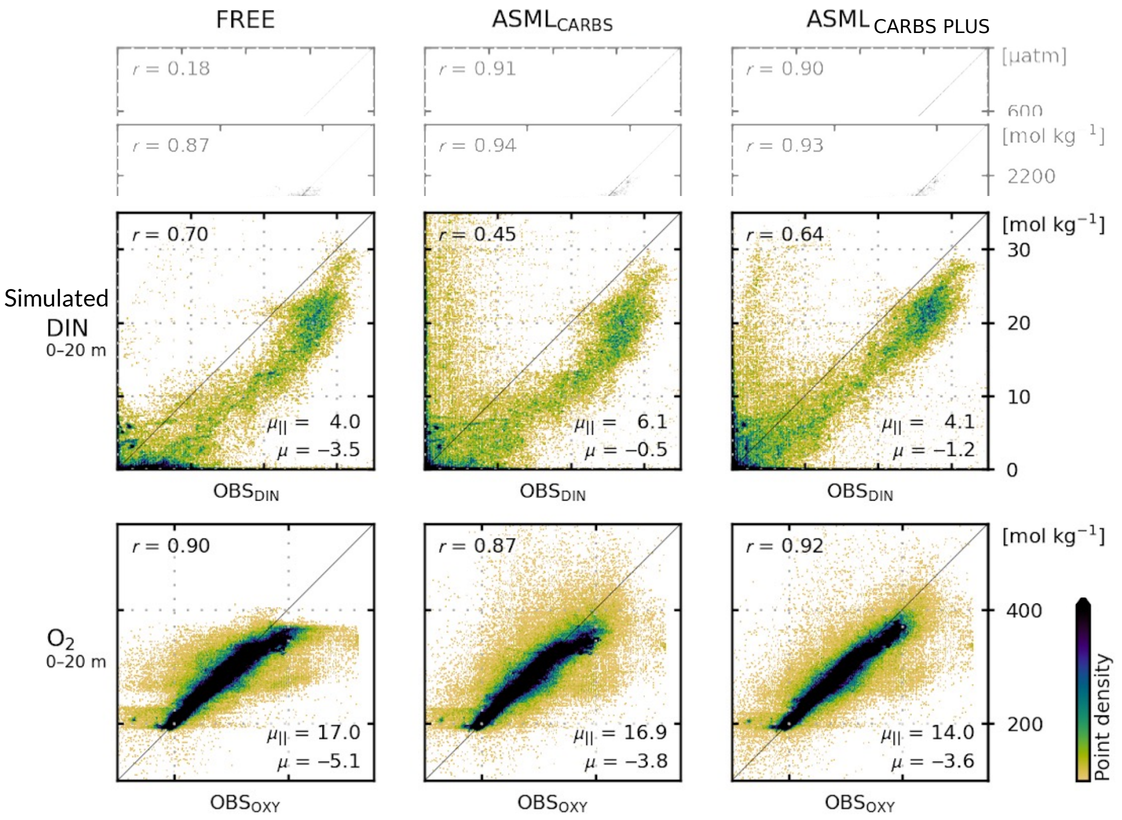
- Improved agreement with **pCO_2** observations: Absolute differences ($\mu_{||}$) reduced by more than ~50%

- Already good agreement for **DIC and alkalinity**: Differences reduced by ~20 % at ~0-400 m



Results: Evaluation

- Improved agreement with pCO_2 observations:
  Absolute differences ($\mu_{||}$) reduced by more than ~50%
- Already good agreement for **DIC** and **alkalinity**:
  Differences reduced by ~20 % at ~0-400 m
- Assumed high uncertainty of **nitrate** and **O_2** observations (otherwise degrading pCO_2)
- Agreement with assimilated **nitrate** and **O_2** observations improves despite high observation error



FESOM Finite volumE Sea ice-Ocean Model
REcoM Regulated Ecosystem Model
PDAF Parallel Data Assimilation Framework

Results: Evaluation

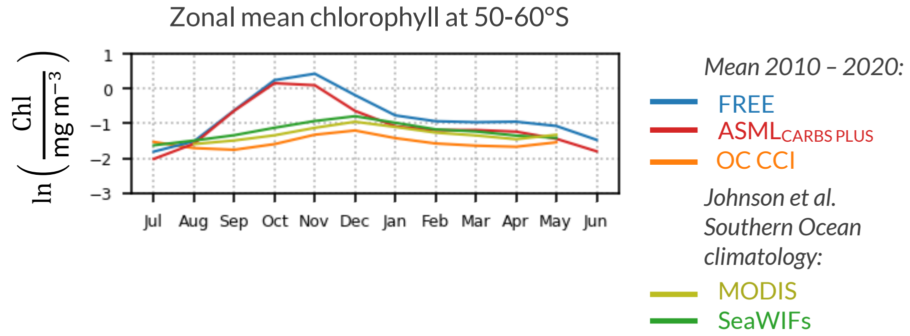
- Improved agreement with pCO_2 observations:
  Absolute differences ($\mu_{||}$) reduced by more than ~50%

- Already good agreement for **DIC** and **alkalinity**:
  Differences reduced by ~20 % at ~0-400 m

- Assumed high uncertainty of **nitrate** and **O_2** observations (otherwise degrading pCO_2)

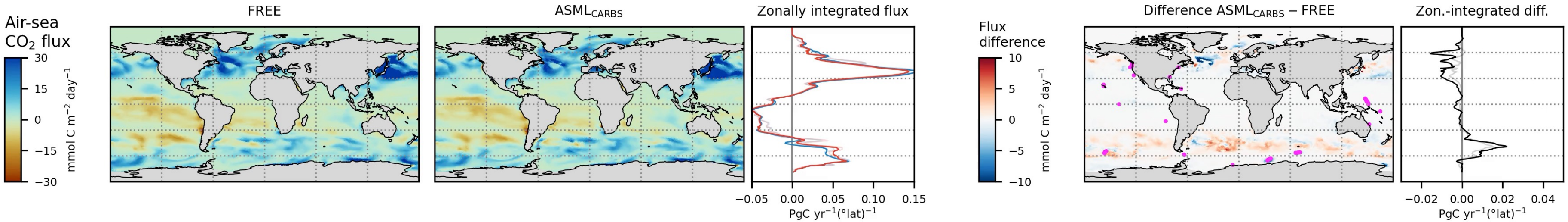
- Agreement with assimilated **nitrate** and **O_2** observations improves despite high observation error

- **Chlorophyll-a:**
  Systematic model observation difference in timing and extent of bloom.
  Use anomalies.



next slide if video doesn't play

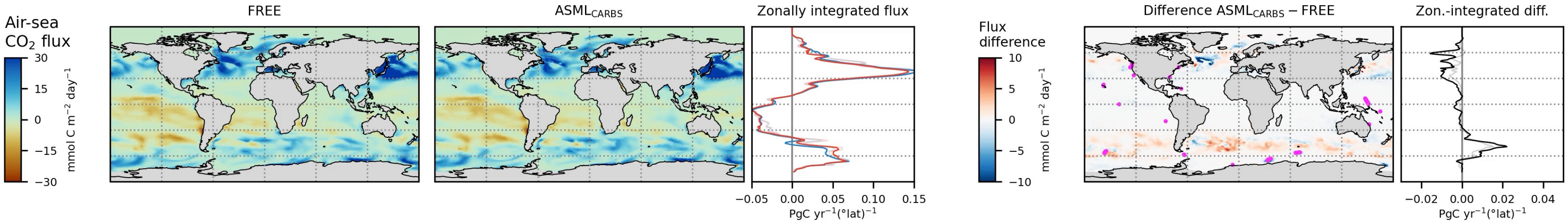
Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)



- Daily wind-driven flux variability
- Outgassing in (sub)tropics and Antarctic
- Oceanic uptake at mid / high latitudes

next slide
if video doesn't play

Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)



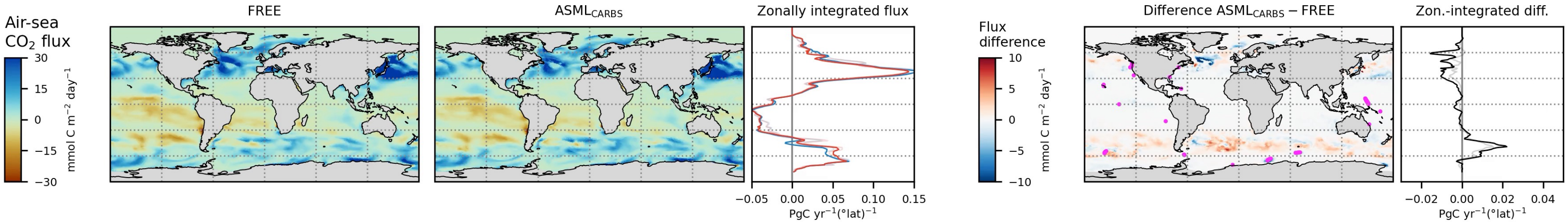
Jun Jul May Aug Apr Sep Mar 2010 Oct Feb Nov Jan Dec

Maximum uptake (→)
during winter
in each hemisphere

FREE
ASML

next slide
if video doesn't play

Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)



Daily observation locations

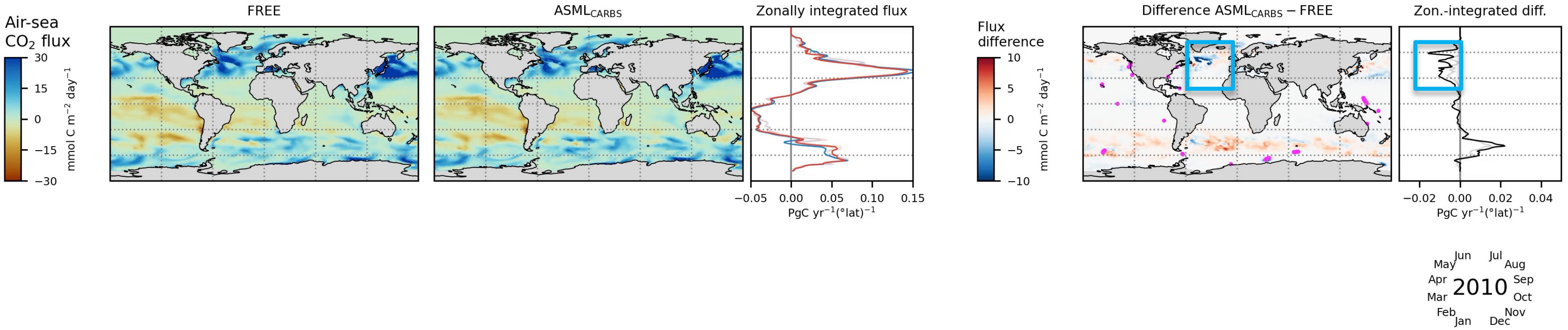
- pCO_2
- DIC
  Alk

next slide if video doesn't play

Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)

Differences in $ASML_{CARBS}$

- Less uptake in North Atlantic in DJF

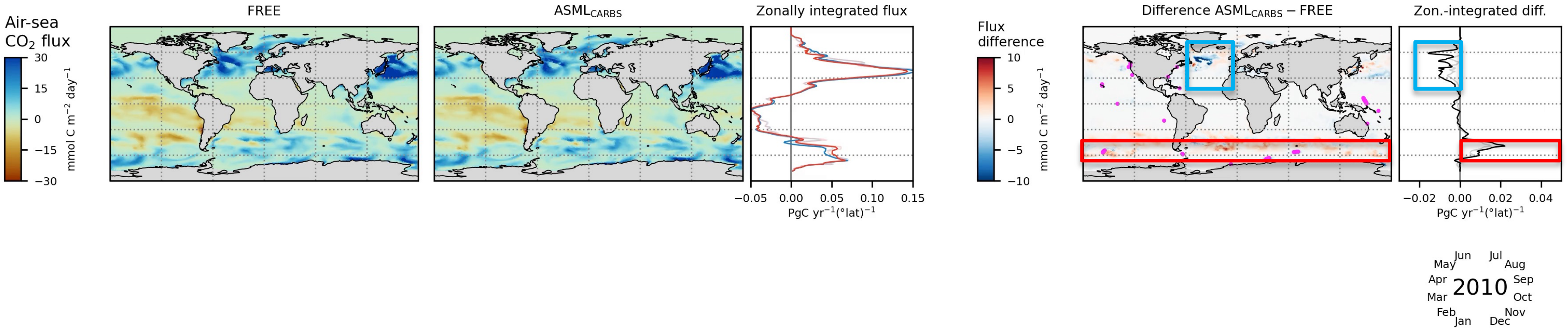


next slide if video doesn't play

Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)

Differences in $ASML_{CARBS}$

- Less uptake in North Atlantic in DJF
- More uptake in Southern Ocean in SON



FESOM Finite volumE Sea ice-Ocean Model
REcoM Regulated Ecosystem Model
PDAF Parallel Data Assimilation Framework

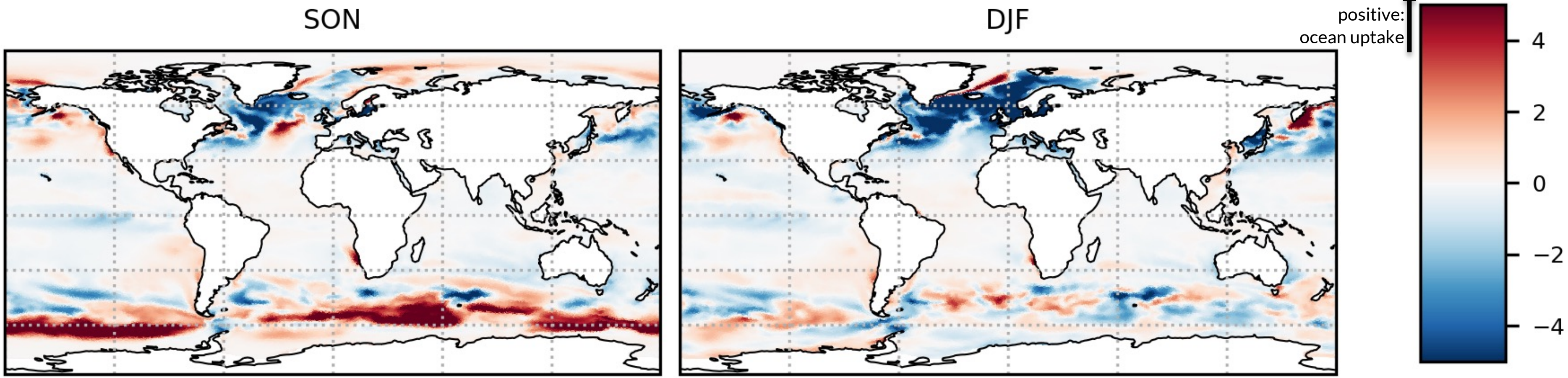
alternative slide

Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)

Southern Ocean spring (SON):
more uptake

North Atlantic winter (DJF):
less uptake

Air-sea CO_2 flux differences $ASML_{CARBS}$ - FREE

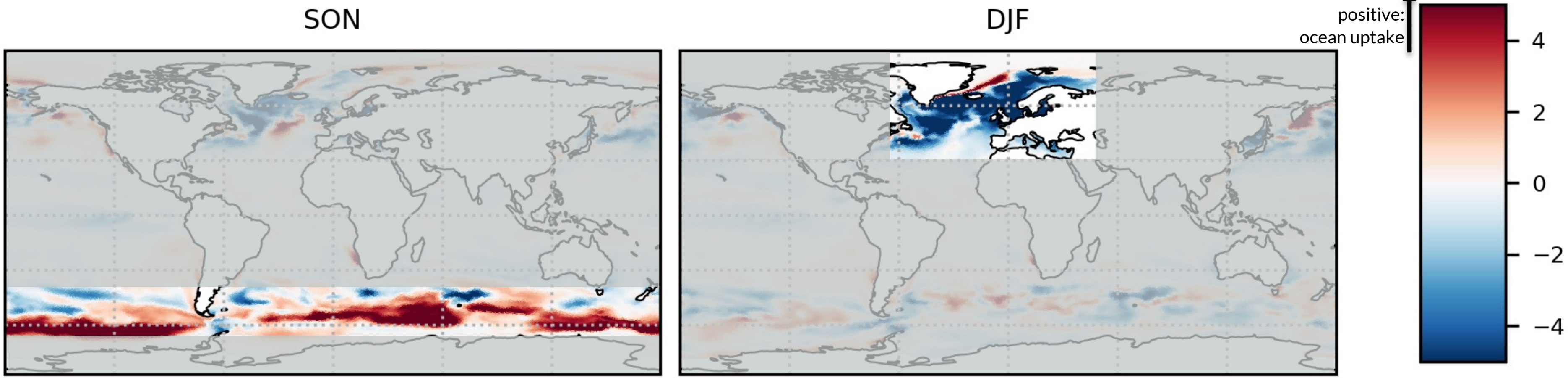


Results: Regional air-sea CO_2 fluxes ($ASML_{CARBS}$)

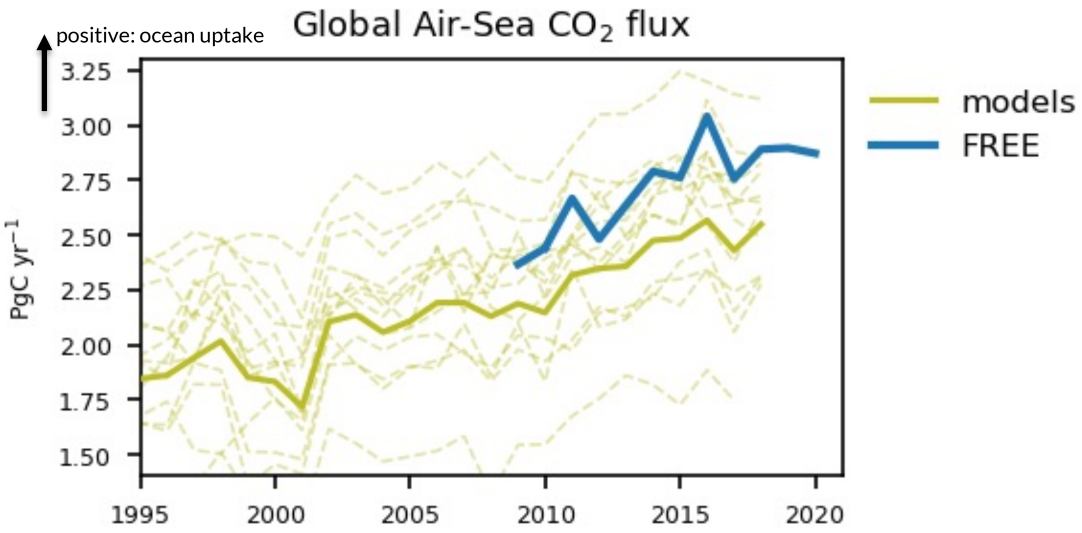
Southern Ocean spring (SON):
more uptake

North Atlantic winter (DJF):
less uptake

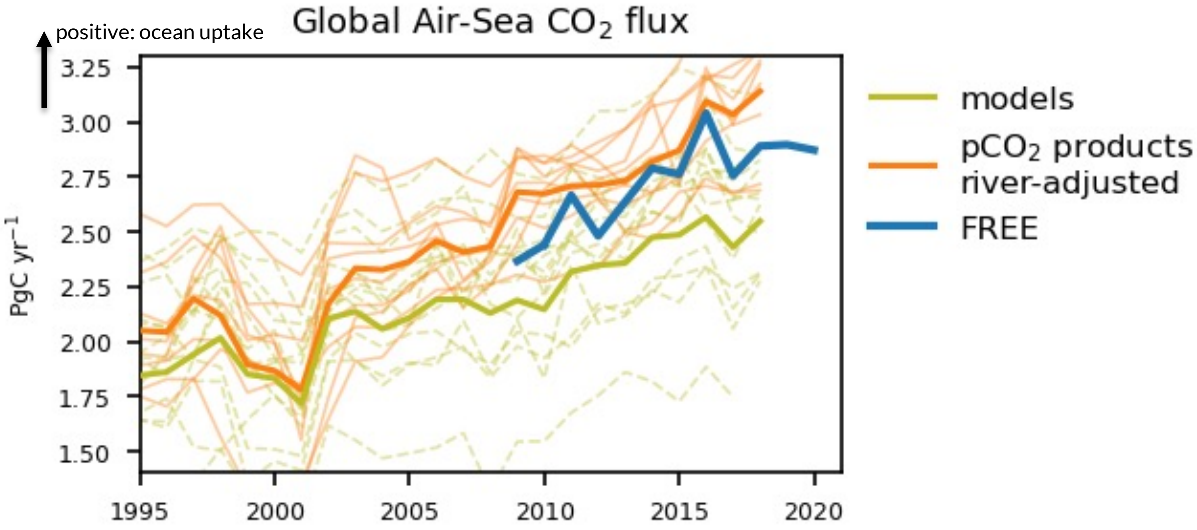
Air-sea CO_2 flux differences $ASML_{CARBS}$ - FREE



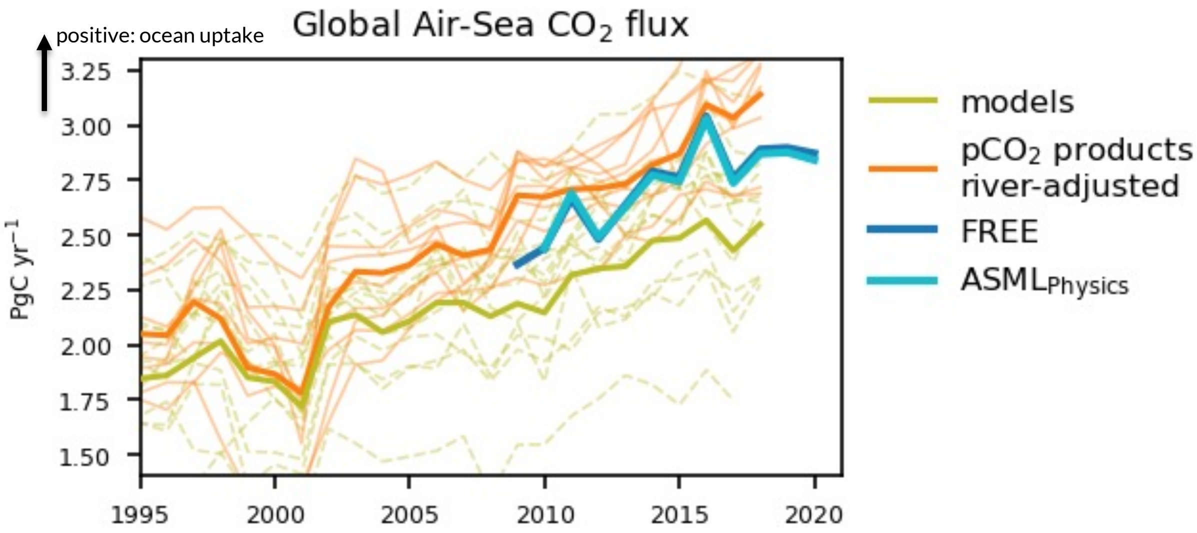
Results: Global ocean carbon uptake



Results: Global ocean carbon uptake

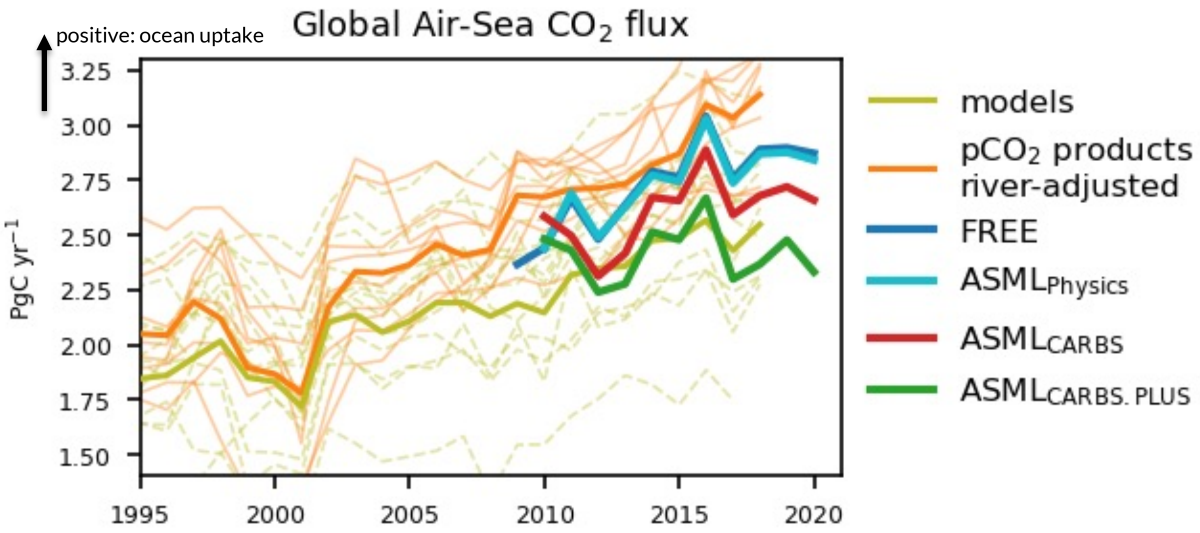


Results: Global ocean carbon uptake



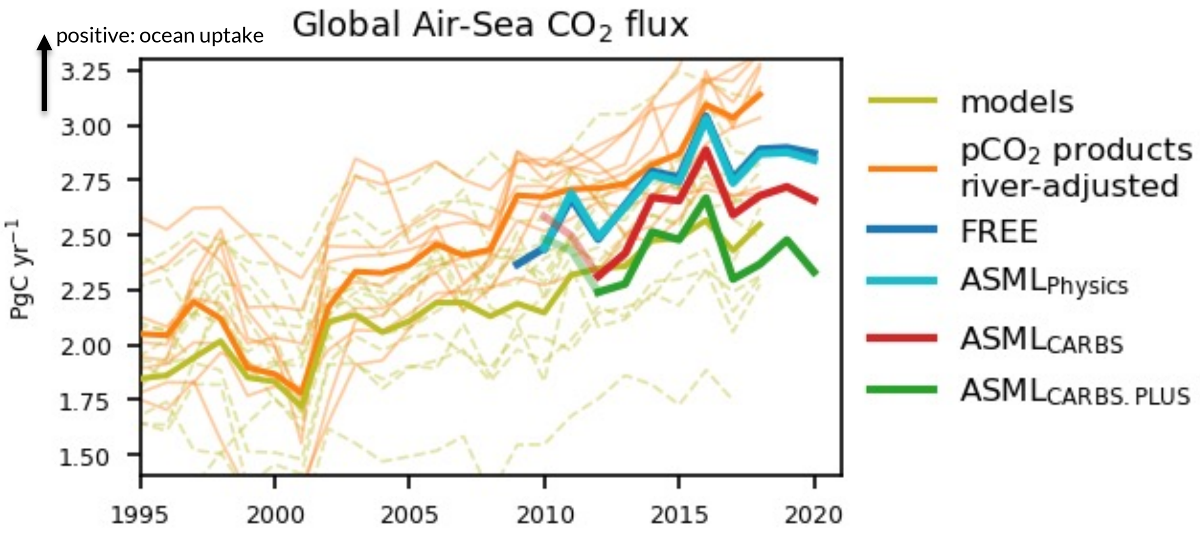
Results: Global ocean carbon uptake

- $ASML_{CARBS}$
  - Less global ocean uptake and similar trend compared to FREE
- $ASML_{CARBS\ PLUS}$
  - Less uptake



Results: Global ocean carbon uptake

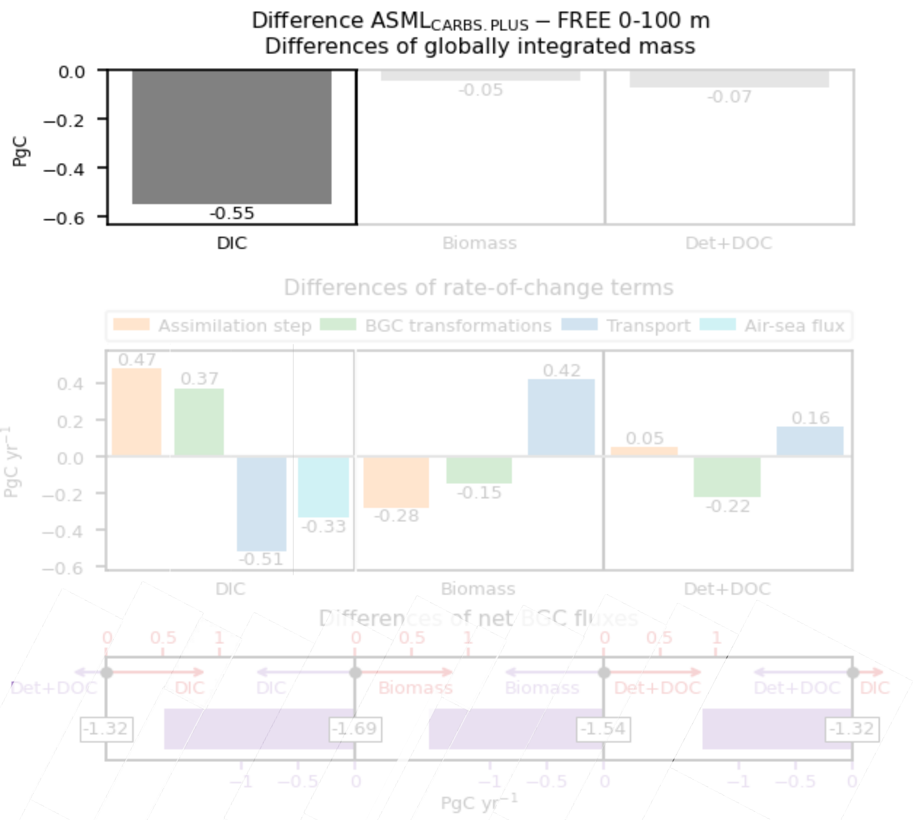
- ASML$_{CARBS}$
  - Less global ocean uptake and similar trend compared to FREE
- ASML$_{CARBS\ PLUS}$
  - Less uptake



- Difference after ~1-2 years: Vertical gradients of DIC and alkalinity and the ocean reservoir of natural carbon adjusting to strength of vertical transport (biological pumps) in model

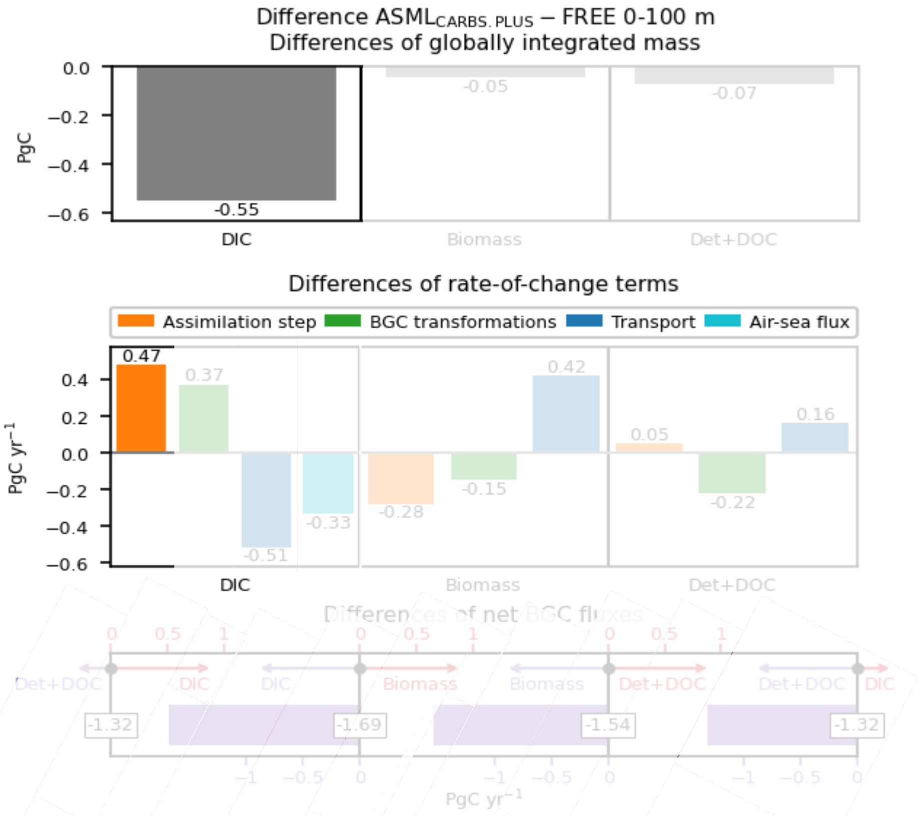
FESOM Finite volumE Sea ice-Ocean Model REcoM Regulated Ecosystem Model PDAF Parallel Data Assimilation Framework

Discussion: Model response to tracer updates



DIC 0 – 100 m smaller (↓) in ASML

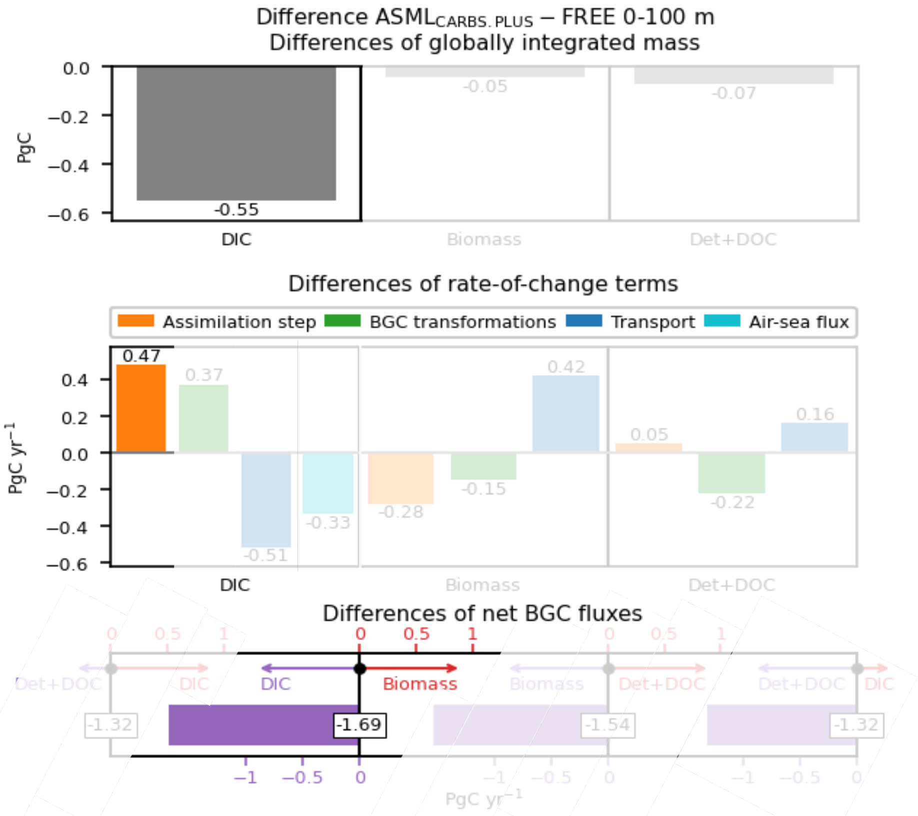
Discussion: Model response to tracer updates



DIC 0 – 100 m smaller (↓) in ASML

- Assimilation increment of DIC: DIC↑

Discussion: Model response to tracer updates



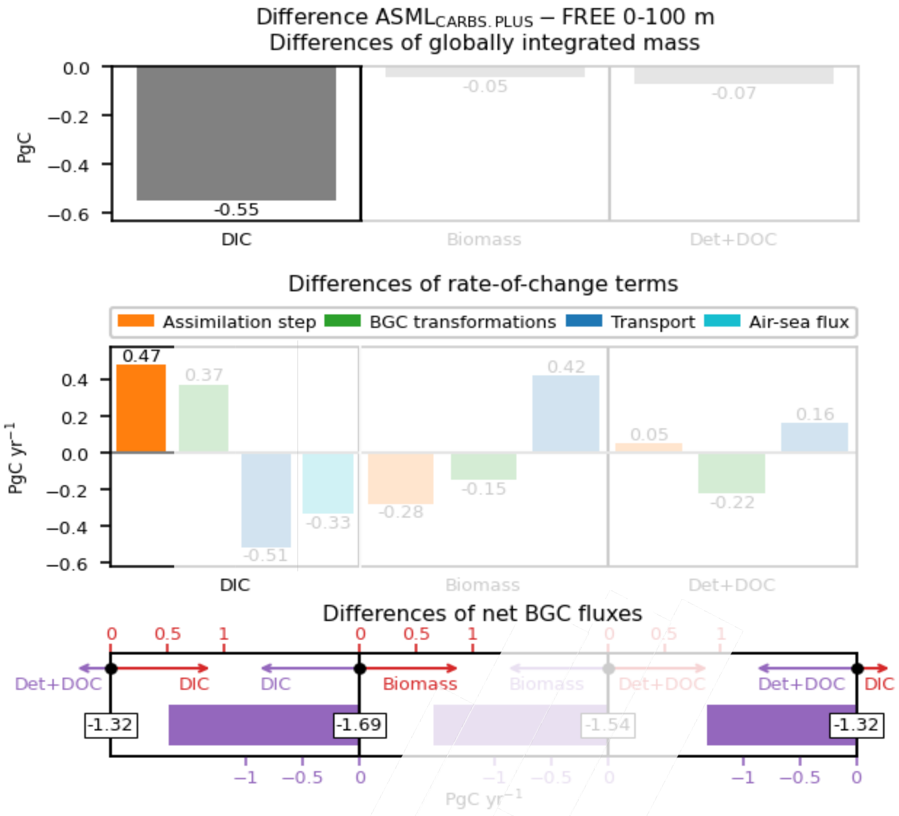
DIC 0 – 100 m smaller (↓) in ASML

- Assimilation increment of DIC: DIC↑
- Response of biogeochemical model:
  - Net flux* from DIC to biomass is smaller in ASML (DIC↑)

  ** = sum of photosynthesis, respiration, …*

FESOM Finite volumE Sea ice-Ocean Model REcoM Regulated Ecosystem Model PDAF Parallel Data Assimilation Framework

Discussion: Model response to tracer updates



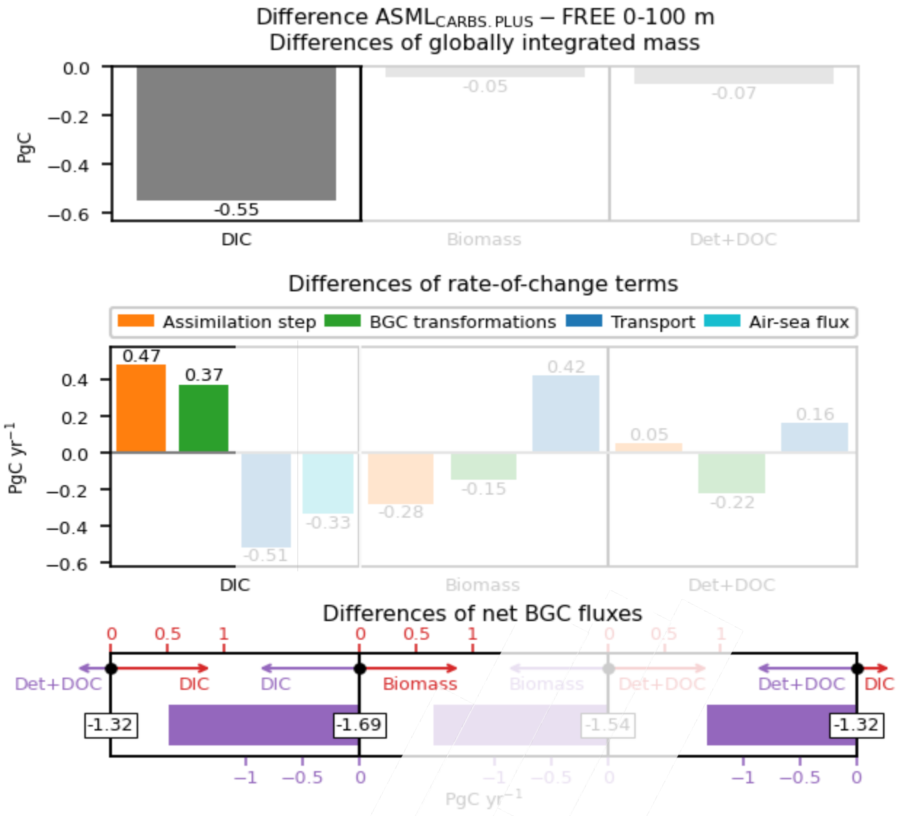
DIC 0 – 100 m smaller (↓) in ASML

- Assimilation increment of DIC: DIC↑
- Response of biogeochemical model:
  - Net flux* from DIC to biomass is smaller in ASML (DIC↑)

    ** = sum of photosynthesis, respiration, …*
  - Net flux* from Detritus+DOC to DIC is also smaller (DIC↓) but to a lesser extent

    ** = sum of remineralization, …*

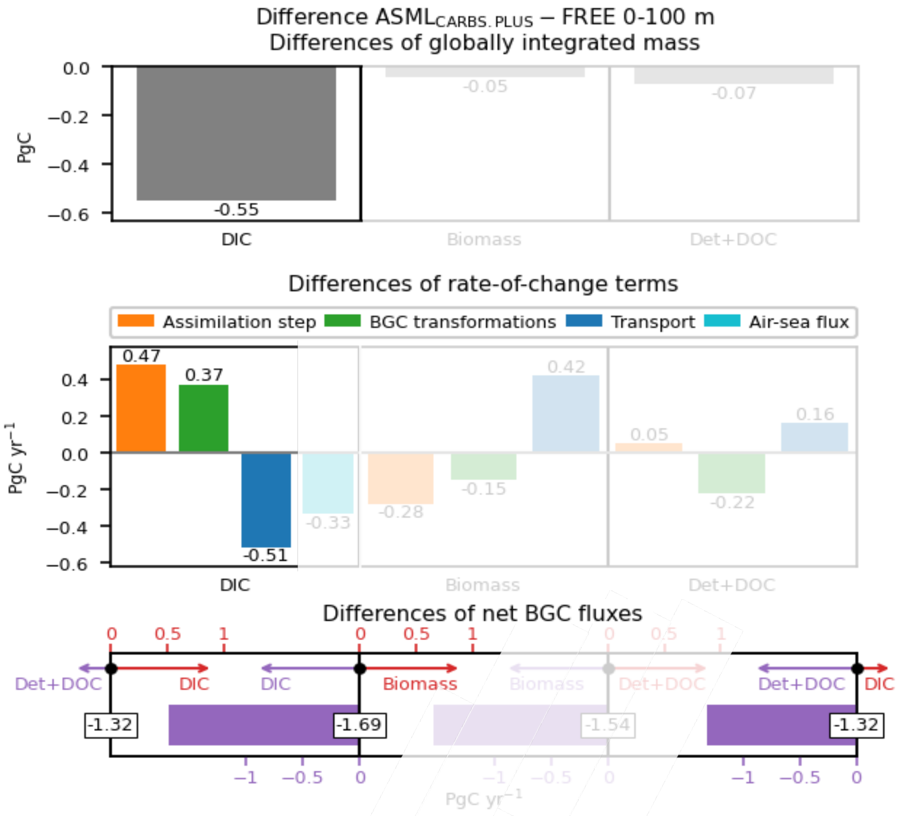
Discussion: Model response to tracer updates



DIC 0 – 100 m smaller (↓) in ASML

- Assimilation increment of DIC: DIC↑
- Response of biogeochemical model:
  - Net flux* from DIC to biomass is smaller in ASML (DIC↑)
    ** = sum of photosynthesis, respiration, …*
  - Net flux* from Detritus+DOC to DIC is also smaller (DIC↓) but to a lesser extent
    ** = sum of remineralization, …*
- In sum, biogeochemical model reinforces increment (DIC↑)

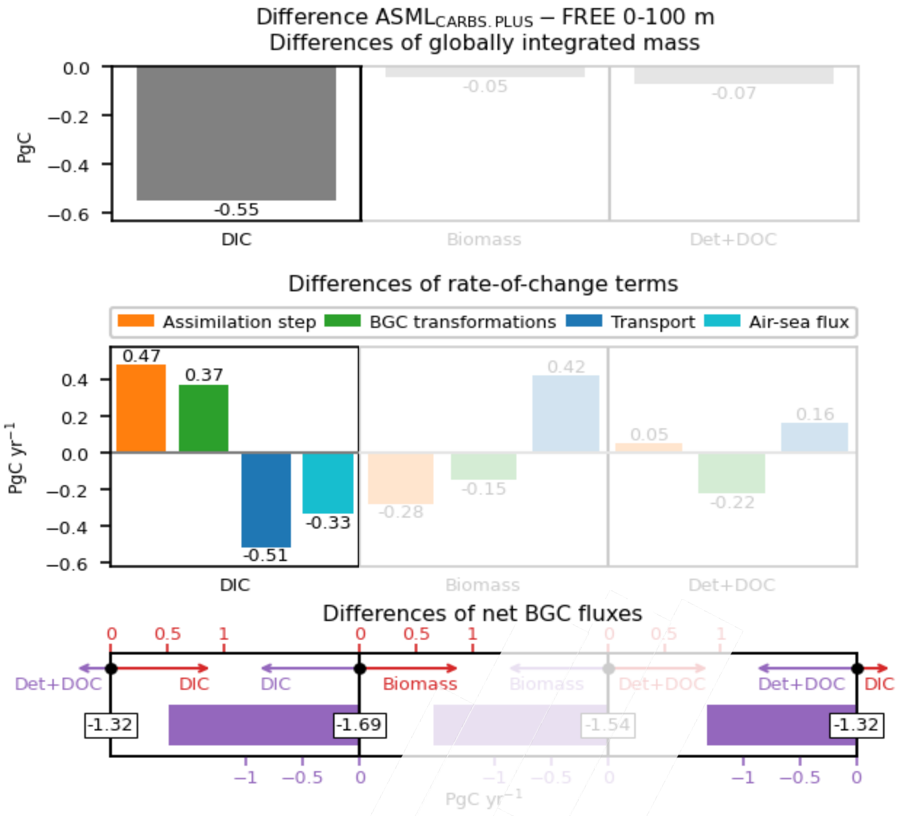
Discussion: Model response to tracer updates



DIC 0 – 100 m smaller (↓) in ASML

- Assimilation increment of DIC: DIC↑
- Response of biogeochemical model:
  - Net flux* from DIC to biomass is smaller in ASML (DIC↑)
    ** = sum of photosynthesis, respiration, …*
  - Net flux* from Detritus+DOC to DIC is also smaller (DIC↓) but to a lesser extent
    ** = sum of remineralization, …*
- In sum, biogeochemical model reinforces increment (DIC↑)
- Response of circulation model*: DIC↓
  ** = transport across 100 m depth*

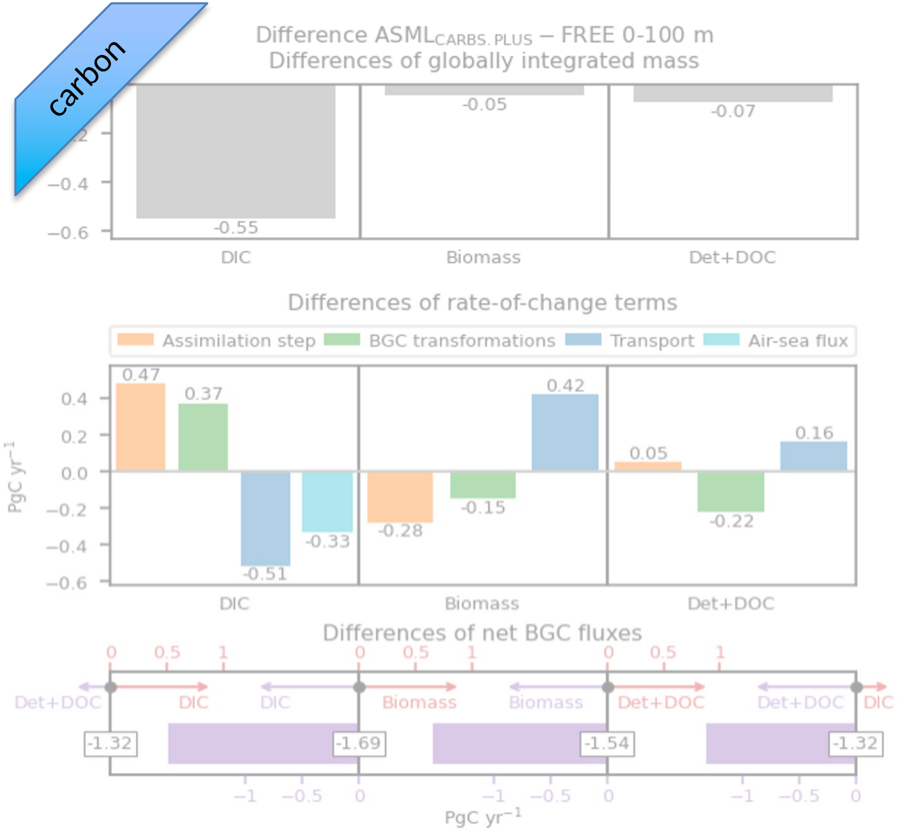
Discussion: Model response to tracer updates



DIC 0 – 100 m smaller (↓) in ASML

- Assimilation increment of DIC: DIC↑
- Response of biogeochemical model:
  - Net flux* from DIC to biomass is smaller in ASML (DIC↑)
    ** = sum of photosynthesis, respiration, …*
  - Net flux* from Detritus+DOC to DIC is also smaller (DIC↓) but to a lesser extent
    ** = sum of remineralization, …*
- In sum, biogeochemical model reinforces increment (DIC↑)
- Response of circulation model*: DIC↓
  ** = transport across 100 m depth*
- Ocean CO_2 uptake from atmosphere smaller (DIC↓)

Discussion: Model response to tracer updates

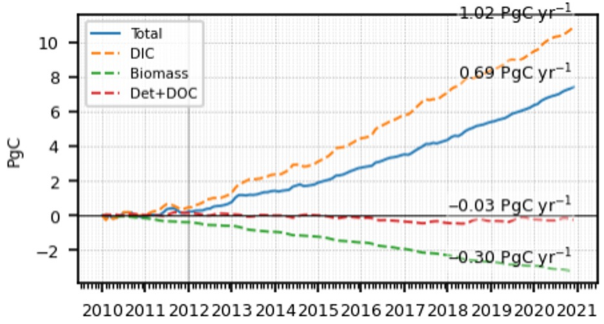


To large extent,
state is determined by
biogeochemical model fluxes,
which amplify, dissipate, or
compensate for
direct data-assimilation-induced
changes of tracers

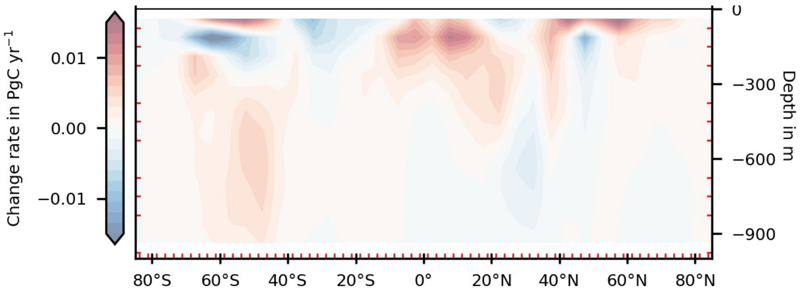
Discussion: Incremental carbon increase

- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$

Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020



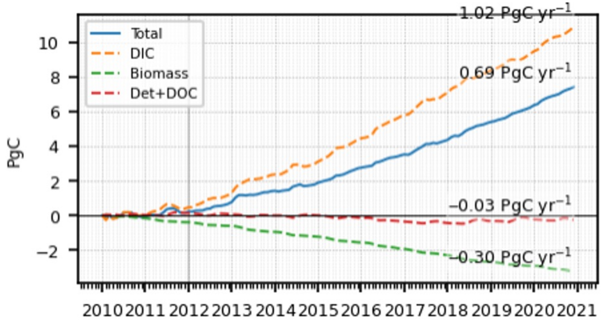
Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020



Discussion: Incremental carbon increase

- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$

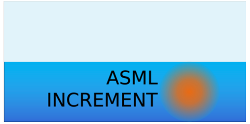
Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020



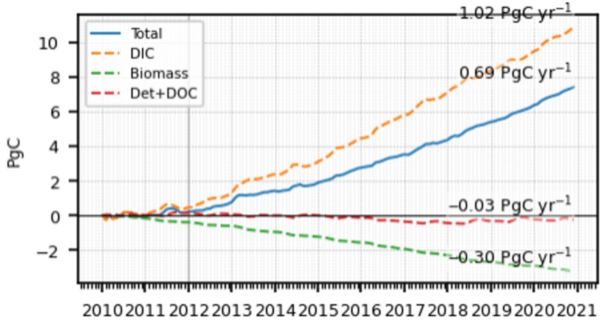
Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020

Discussion: Incremental carbon increase

- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in ASML$_{CARBS}$ and 0.7 ASML$_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state



Cumulative increments of global ocean carbon content in ASML$_{CARBS\ PLUS}$ 2010-2020

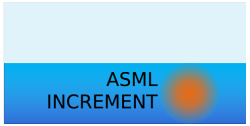


Increment of total carbon during assimilation step in ASML$_{CARBS\ PLUS}$ 2010-2020

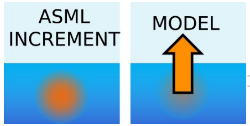
FESOM Finite volumE Sea ice-Ocean Model REcoM Regulated Ecosystem Model PDAF Parallel Data Assimilation Framework

Discussion: Incremental carbon increase

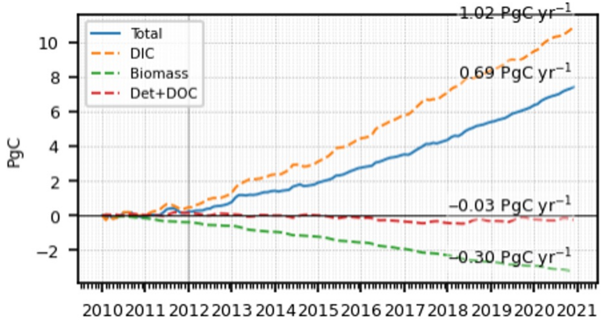
- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state



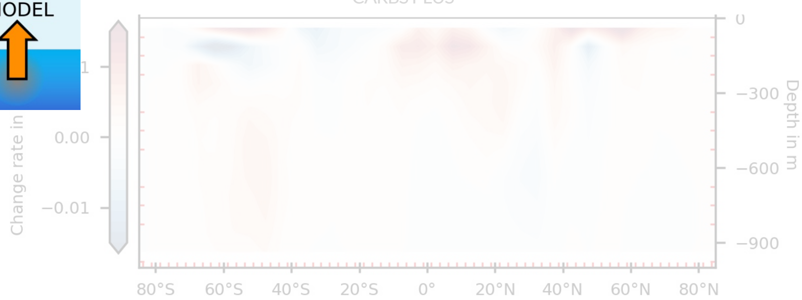
    - Compensation for a counteracting model response



Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020

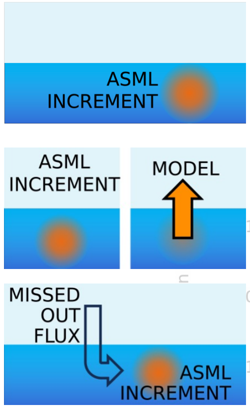


Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020

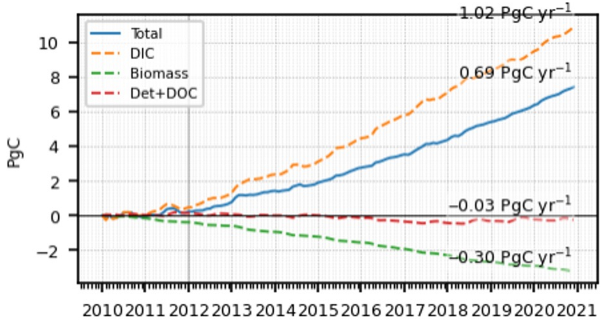


Discussion: Incremental carbon increase

- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state
    - Compensation for a counteracting model response
    - Compensation for deficiencies in surface flux without correcting the surface flux



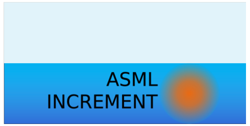
Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020



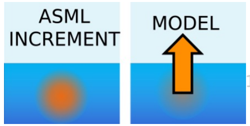
Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020

Discussion: Incremental carbon increase

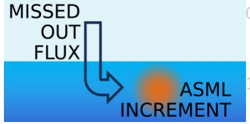
- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state



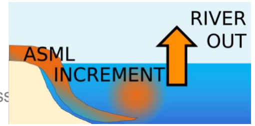
    - Compensation for a counteracting model response



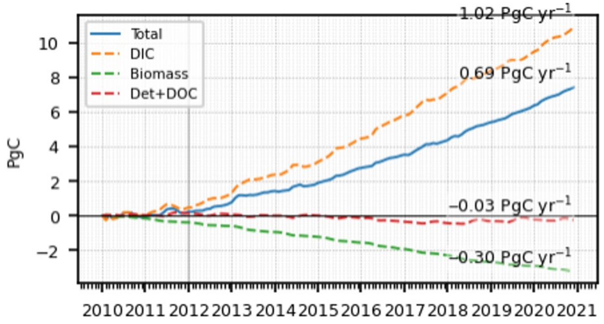
    - Compensation for deficiencies in surface flux without correcting the surface flux



    - Replacement for a missing term: rivers?



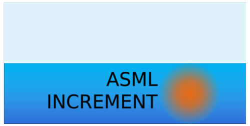
Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020



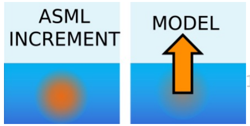
Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020

Discussion: Incremental carbon increase

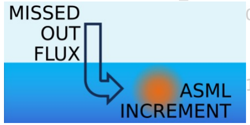
- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state



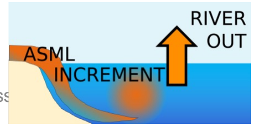
    - Compensation for a counteracting model response



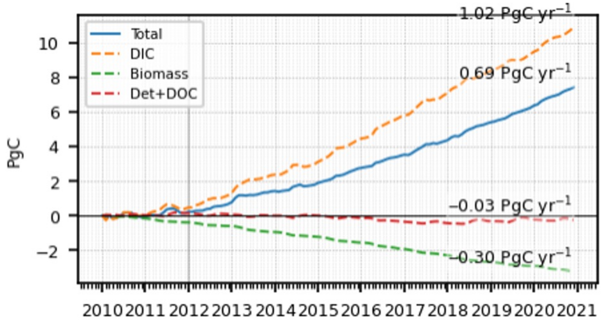
    - Compensation for deficiencies in surface flux without correcting the surface flux



    - Replacement for a missing term: rivers?



Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020

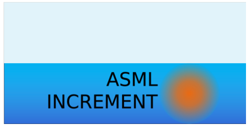


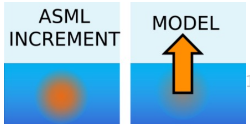
Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020

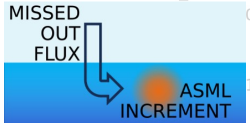
FESOM Finite volumE Sea ice-Ocean Model
REcoM Regulated Ecosystem Model
PDAF Parallel Data Assimilation Framework

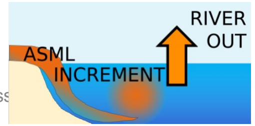
Discussion: Incremental carbon increase

- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon 0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state
    - Compensation for a counteracting model response
    - Compensation for deficiencies in surface flux without correcting the surface flux
    - Replacement for a missing term: rivers?

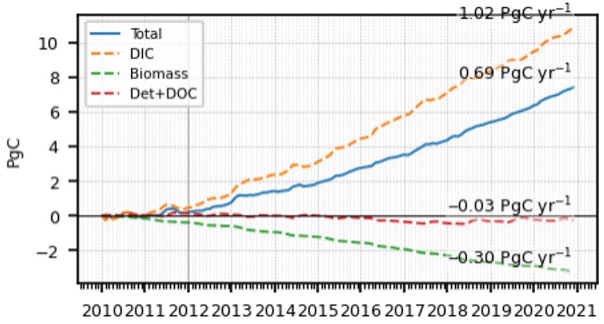




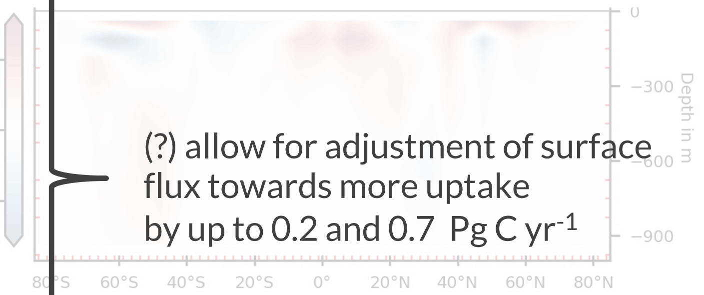




Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020



Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020

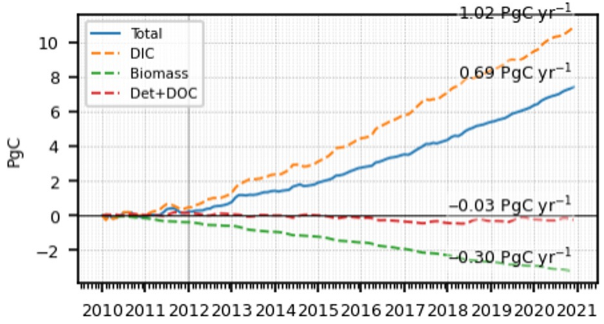


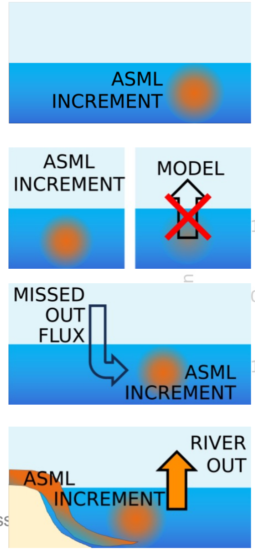
(?) allow for adjustment of surface flux towards more uptake by up to 0.2 and 0.7 Pg C yr^{-1}

Discussion: Incremental carbon increase

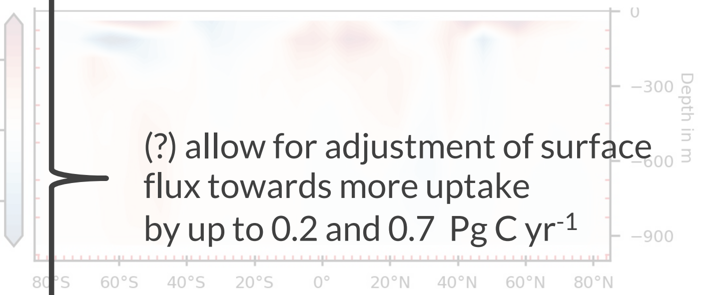
- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in ASML$_{CARBS}$ and 0.7 ASML$_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state
    - Compensation for a counteracting model response
    - Compensation for deficiencies in surface flux without correcting the surface flux
    - Replacement for a missing term: rivers?

Cumulative increments of global ocean carbon content in ASML$_{CARBS\ PLUS}$ 2010-2020





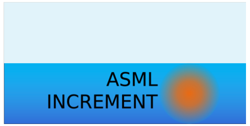
Increment of total carbon during assimilation step in ASML$_{CARBS\ PLUS}$ 2010-2020

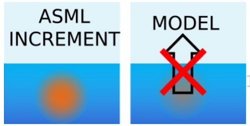


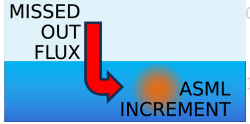
(?) allow for adjustment of surface flux towards more uptake by up to 0.2 and 0.7 Pg C yr^{-1}

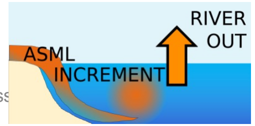
Discussion: Incremental carbon increase

- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon 0.2 Pg C yr^{-1} in ASML$_{\text{CARBS}}$ and 0.7 ASML$_{\text{CARBS PLUS}}$
    - Correction of natural ocean carbon content towards observed state
    - Compensation for a counteracting model response
    - Compensation for deficiencies in surface flux without correcting the surface flux
    - Replacement for a missing term: rivers?

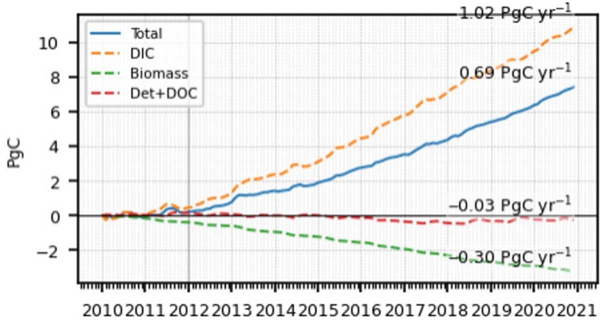




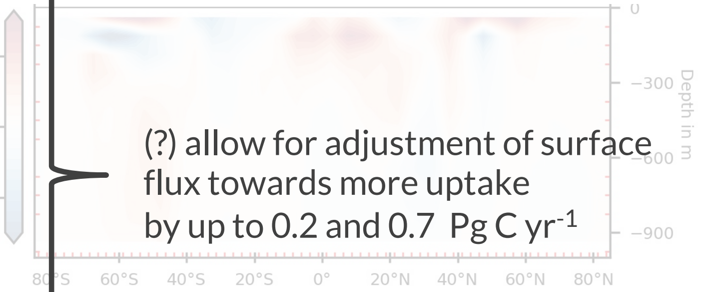




Cumulative increments of global ocean carbon content in ASML$_{\text{CARBS PLUS}}$ 2010-2020



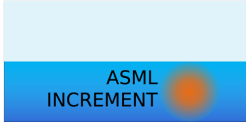
Increment of total carbon during assimilation step in ASML$_{\text{CARBS PLUS}}$ 2010-2020



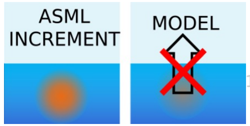
(?) allow for adjustment of surface flux towards more uptake by up to 0.2 and 0.7 Pg C yr^{-1}

Discussion: Incremental carbon increase

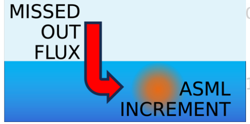
- Assimilation increment:
  - Ocean carbon content shifted regionally
  - Net global decrease of biomass and increase of DIC
  - Net global increase of total carbon
    0.2 Pg C yr^{-1} in $ASML_{CARBS}$ and 0.7 $ASML_{CARBS\ PLUS}$
    - Correction of natural ocean carbon content towards observed state



    - Compensation for a counteracting model response

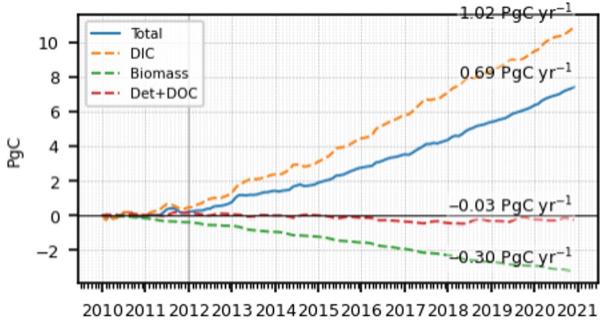


    - Compensation for deficiencies in surface flux without correcting the surface flux

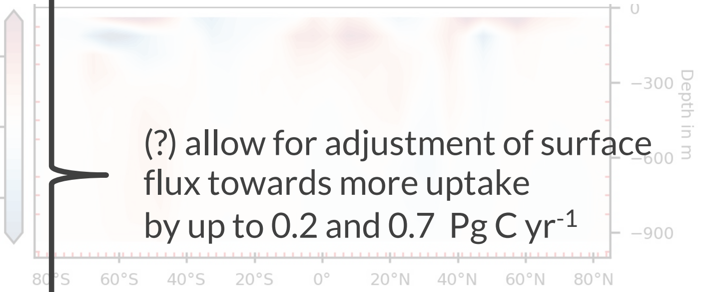


    - Replacement for a missing term: rivers?

Cumulative increments of global ocean carbon content in $ASML_{CARBS\ PLUS}$ 2010-2020



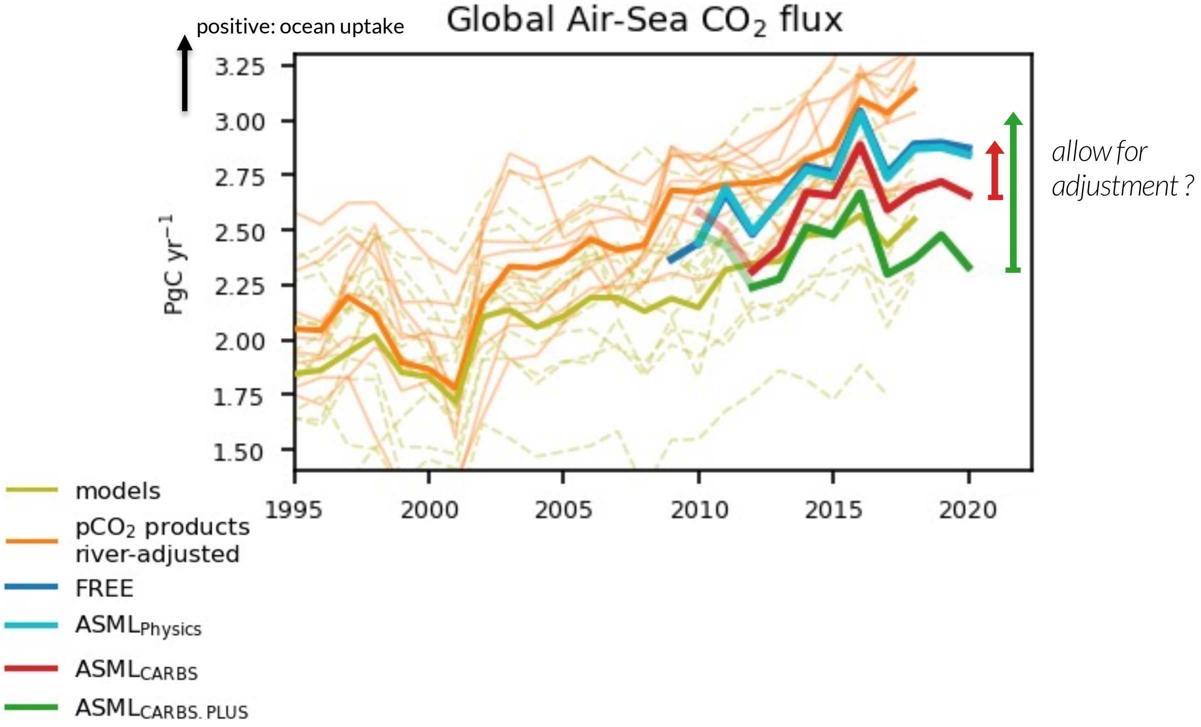
Increment of total carbon during assimilation step in $ASML_{CARBS\ PLUS}$ 2010-2020



(?) allow for adjustment of surface flux towards more uptake by up to 0.2 and 0.7 Pg C yr^{-1}

Conclusions

- ASML$_{CARBS\ PLUS}$
  - Peculiar: Effect of additional observations
- ASML$_{CARBS}$
  - Higher confidence as pCO_2, DIC, alkalinity and sea surface temperature are directly affected



Take-home

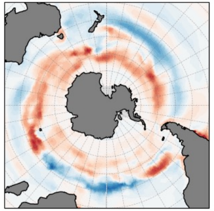
Estimates of global ocean CO_2 uptake (2010 – 2020)

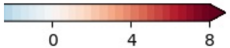
1. Data assimilation of physical ocean observations:
   Regional shifts in air-sea CO_2 fluxes

2. Simulation tailored to agree with the observed ocean carbonate system by adding pCO_2, DIC and alkalinity observations:
   Less global CO_2 uptake

3. Adding further biogeochemical ocean observations raises questions

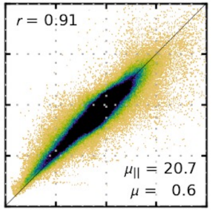
CO_2 flux difference
$ASML_{physics}$ - FREE





→ more ocean uptake

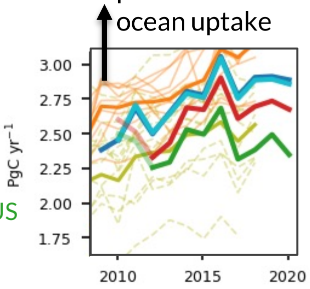
pCO_2 in $ASML_{CARBS}$



pCO_2 in SOCAT

positive:
ocean uptake

FREE
ASML PHYSICS
ASML CARBS
ASML CARBS PLUS



Thank you!

FESOM Finite volumE Sea ice-Ocean Model
REcoM Regulated Ecosystem Model
PDAF Parallel Data Assimilation Framework