Ensemble-based parameter estimation for improving ocean biogeochemistry in an Earth system model

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Introduction

- Ocean **BGC** models utilise a large number of **poorly-constrained parameters** to mimic unresolved processes, which contributes the significant error in the model simulation.

- BGC parameters are often **manually estimated** in small-scale laboratory experiments, which becomes **complicated and inefficient** when the number of parameters increases.

- We proposed an efficient and flexible data assimilation framework to tune model parameters in an ESMs using Iterative Ensemble Smoother (IES).

Norwegian Climate Prediction Model (NorCPM)

Norwegian Earth System model (NorESM)
chemistry/aerosols
CAM
CICE CISM CLM
MICOM
HAMOCC
RTM
30 members

Data assimilation (EnKF)
correction
Propagation
Member1
Member2
......
Member29
Member30

Selected BGC parameters

(1) Half-saturation constant for nutrient uptake (**BKPHY**)
(2) Maximum zooplankton grazing rate (**GRAZRA**)
(3) Sinking speed for particulate organic carbon (**WPOC**)
(4) Half-saturation constant for silicate uptake (**BKOPAL**)
(5) Deep ocean remineralization constant of particulate organic carbon. (**DREMPOC**)

Observations:
WOA18 monthly climatology
Physics: TEM, SAL Profile
BGC: PO_4, NO_3, O_2 Profile

Iterative Ensemble Smoother for BGC Parameter Estimation

2 years spinup DA | 1 year for PE | 10 years for verification

NorESM 10 years model spin up run using perturbed parameters. 30-members

Online monthly ocean reanalysis with TEM+SAL obs. assimilation. Without BGC state estimation

Monthly BGC (Model - Obs.)

Offline PE Assim. 12-months obs. jointly

Updated Param / Iterative assimilation

1. Parameter values are perturbed and spin up for 10 years free run
2. Run 2-years spinup + 1-year reanalysis that assimilates WOA18 ocean TEM, SAL monthly observations.
   → BGC error grows with a near-perfect ocean state
3. Estimate BGC parameters (global value) from last one reanalysis by assimilating monthly PO4, NO3, O2 WOA18 clim. obs. offline.

Experiment Details: *TimePeriod 2015-2026*

FREE_DP   : NorESM Model free run with BGC default parameters
REANA_DP. : Ocean Reanalysis (TEM+SAL monthly clim. obs. assim.) with BGC default parameters
REANA_GP : Repeat REANA_DefParam but with global estimated parameters from Iteraion-1.
REANA_SP : Repeat REANA_DefParam but with Spatially varying estimated parameters Iteraion-1.

Global RMSE Profile

(a) Phosphate (b) Nitrate (c) Oxygen (d) Silicate (e) Dissolved Inorganic Carbon (f) Total Alkalinity

FREE_DP, REANA_DP, REANA_GP, REANA_SP

Benefits of multi-iteration

REANA_GP2 : Repeat REANA_GP but with global estimated parameters from **Iteraion-2**.

Phosphate, Nitrate, Oxygen, Dissolved Inorganic Carbon

FREE_DP, REANA_GP, REANA_DP, REANA_GP2

Results

Default Parameters
(a) FREE_DP — Temperature RMSE
(b) REANA_DP — Temperature RMSE

Parameter estimation (PE)
Phosphate RMSE: FREE_DP, REANA_DP, REANA_GP, REANA_SP

RMSE Diff.

Phosphate | Nitrate | Dissolved Inorganic Carbon
FREE_DP minus REANA_DP
REANA_DP minus REANA_GP
REANA_DP minus REANA_SP

Degradation — Improvement

Table: Global error Reduction

Variables (0-800m)	% error reduction w.r.t REANA_DP		% error reduction w.r.t FREE_DP	
	REANA_GP	REANA_SP	REANA_GP	REANA_SP
Phosphate	12.2%	9.3%	15.6%	12.9%
Nitrate	14.4%	10.3%	16.4%	12.3%
Oxygen	6.7%	4.9%	7.9%	6.1%
Silicate	-3.1%	-4.3%	-7.3%	-8.4%
Dissolved Inorganic Carbon	17.5%	15.8%	7.7%	5.8%
Total Alkalinity	7.8%	7.6%	1.9	1.6%

Zonally averaged seasonal cycle

Observation | FREE_DP | REANA_DP | REANA_GP | REANA_SP | RMSE

Net Primary Production [mol C m-2 year-1]
(a) (b) (c) Corr. = 0.36 (d) Corr. = 0.39 (e) Corr. = 0.42 Corr. = 0.48 (f)
NorESM_DP, REANA_DP, REANA_GP, REANA_SP

Sea-air CO2 fluxes [mol C m-2 year-1]
(g) (h) (i) Corr. = 0.68 (j) Corr. = 0.53 (k) Corr. = 0.72 Corr. = 0.71 (l)

30-years NorCPM ocean reanalysis with improved BGC Parameters

The NorCPM ocean reanalysis has been generated from 1993-2022 using BGC **global estimated parameters** in the model and monthly assimilation of EN4 TS profile + NOAA SST observations.

Phosphate, Nitrate, Oxygen, Silicate, Dissolved Inorganic Carbon, Total Alkalinity

NorESM model free run
NorCPM coupled reanalysis of BGC

- Our exercise reveals that ocean BGC parameters in ESMs are likely tuned toward the wrong physics.
- The parameter estimation converges quickly — 10-year ensemble spin-up and the calibration converges within a 1-year cycle.
- Globally estimate parameter perform best but spatially estimated parameter are superior in some regions.
- Iterative minimisation further refine the results.
- The result are robust and verified on a 30-years reanalysis simulation.
- The list of parameters may be adjusted to mitigate the degradation identified for silicate
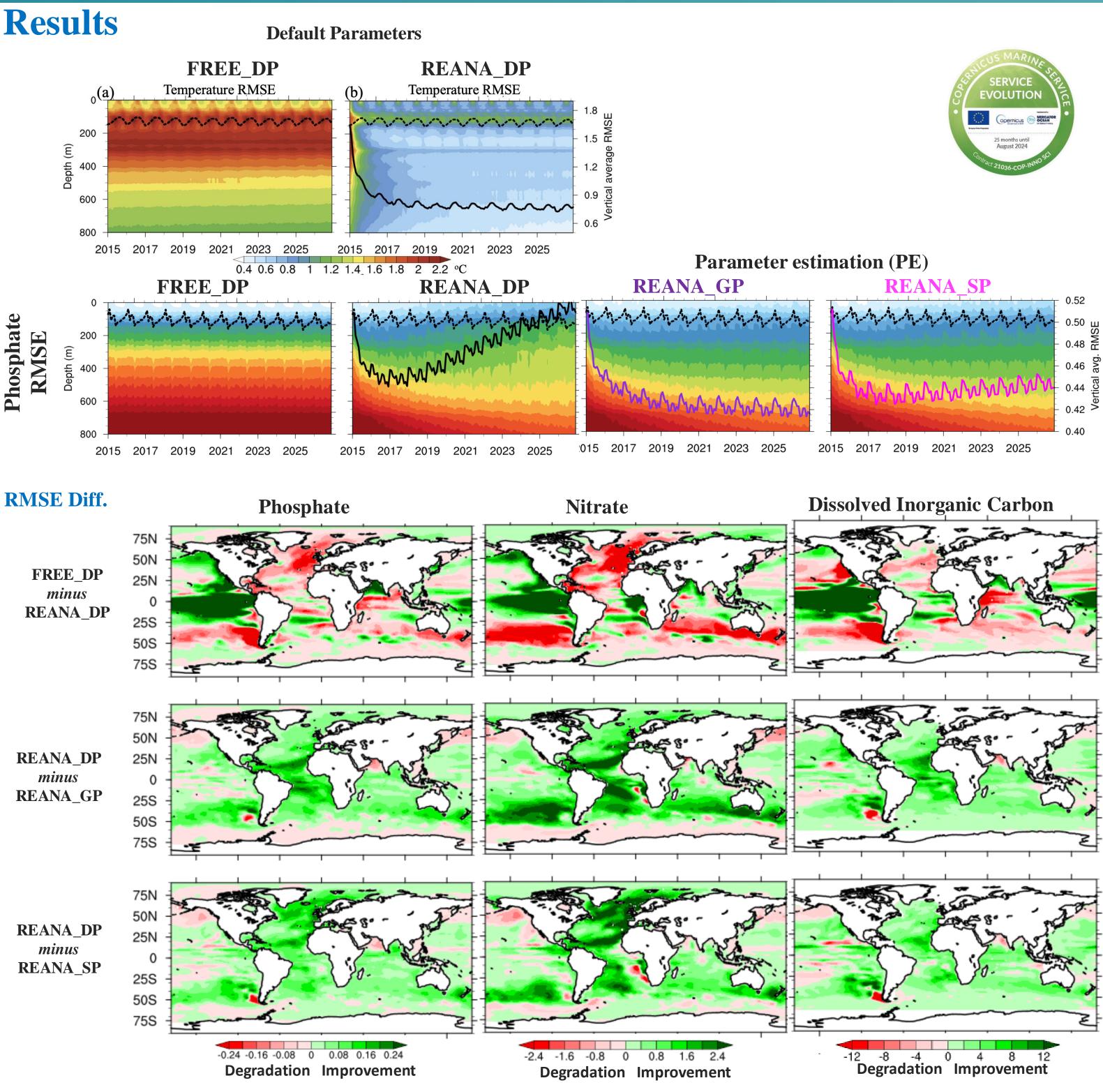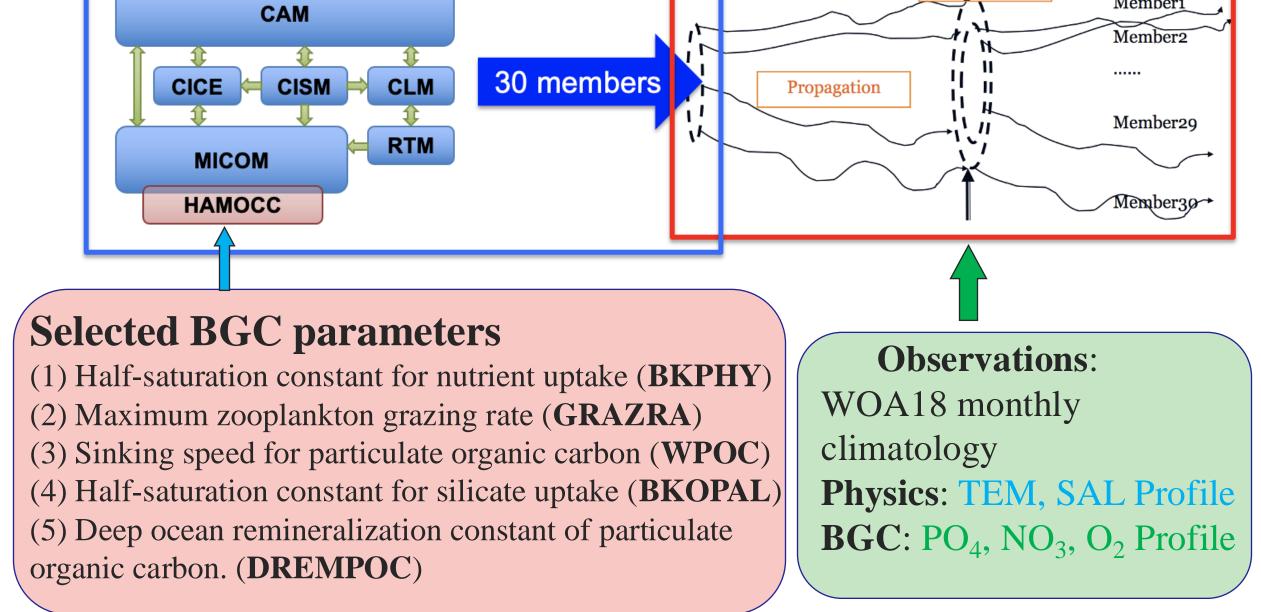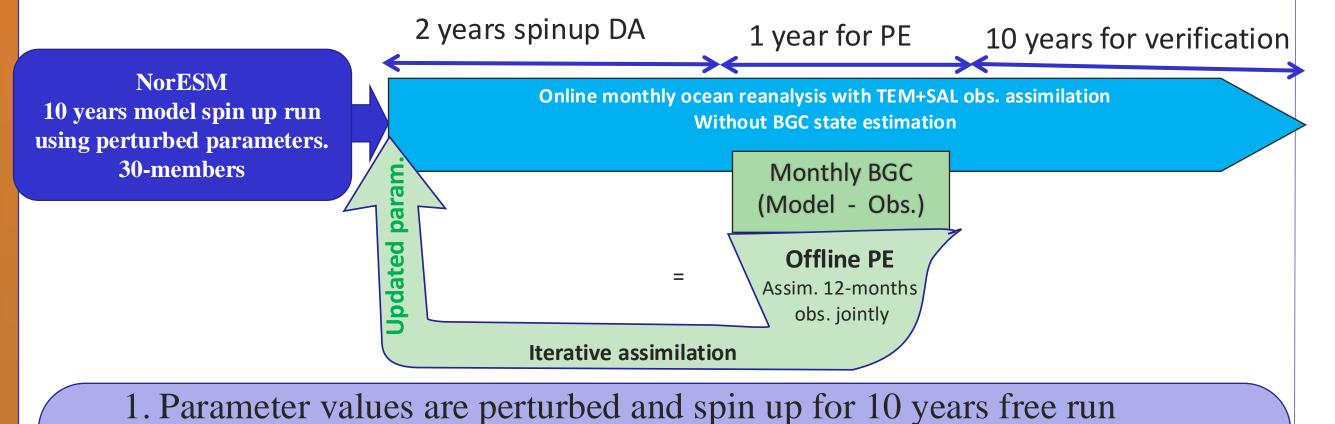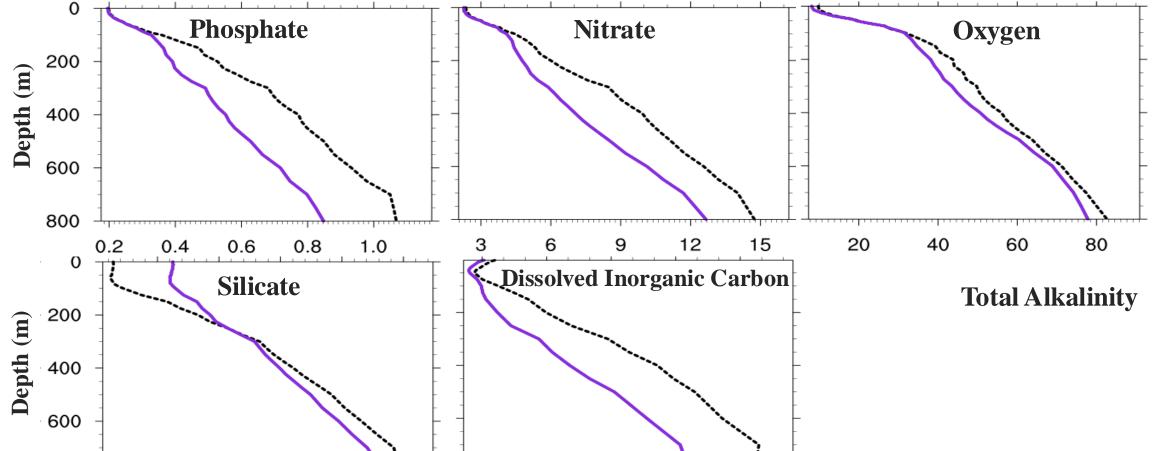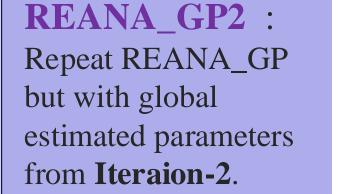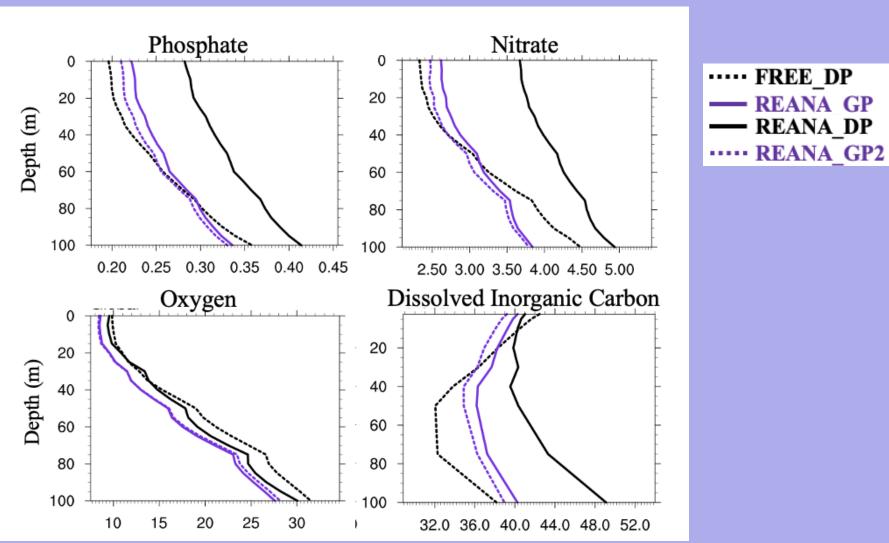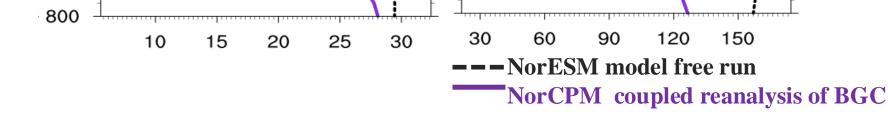
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