Numerical modelling of the benthic-pelagic coupling (BPC) in coastal marine ecosystems at contrasting sites

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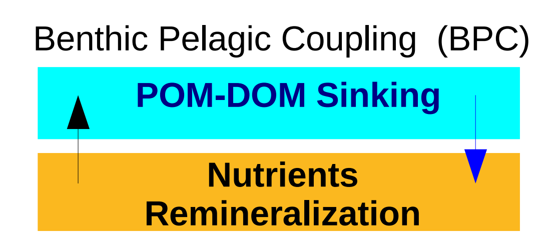
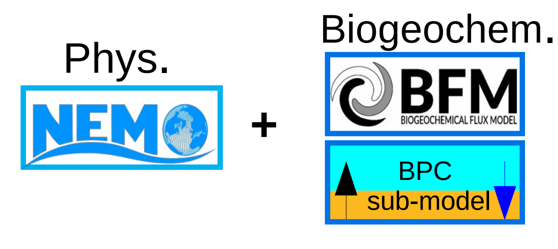
1. Scientific Goals

The Benthic and Pelagic fluxes play a crucial role in governing coastal waters dynamics.



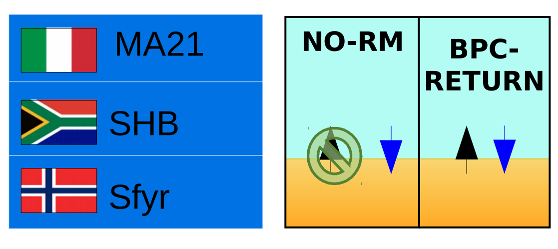
2. Model setup

NEMO – BFM 1D Configuration + embedded BPC submodel



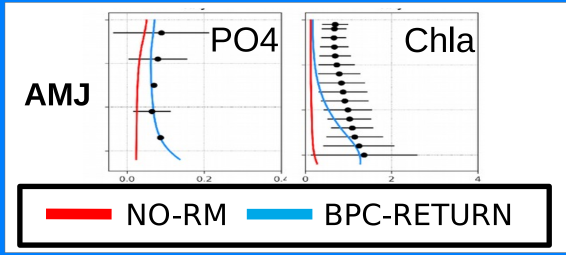
3. Implementation sites Experiments design

N. 3 implemented sites
N. 2 Experiments (Comparison)



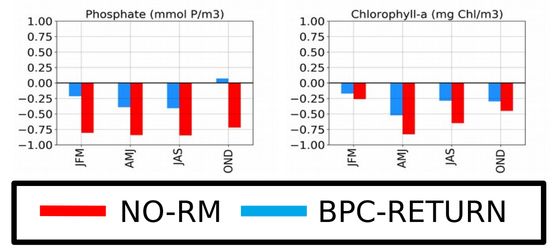
4. Gulf of Trieste (MA21)

Simulated Inorganic Nutrients affect Chl-a dynamic (mainly at depth, 78m).



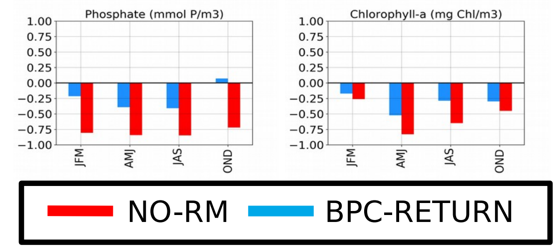
5. St.Helena Bay (SHB)

Inorganic Nutrients seasonal improvements positively affect Chl-a dynamic (Normalized Mean Seas. Bias)



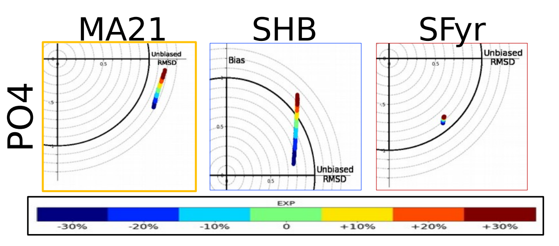
6. Svynøy Fyr (SFyr)

Chlorophyll dynamic is related to nutrients dynamic and light limitation (JFM). (Normalized Mean Seas. Bias)



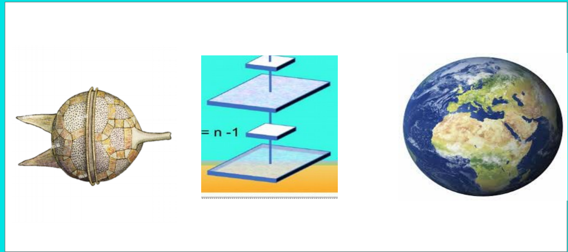
7. Sensitivity Analisys

Different degree of sensibility to the B-C fluxes (RMSE spread) and to site-specific characteristics.



8. Conclusions

- Model improvements in reproducing B-P fluxes;
- Different sedimentation-remineralization scenarios



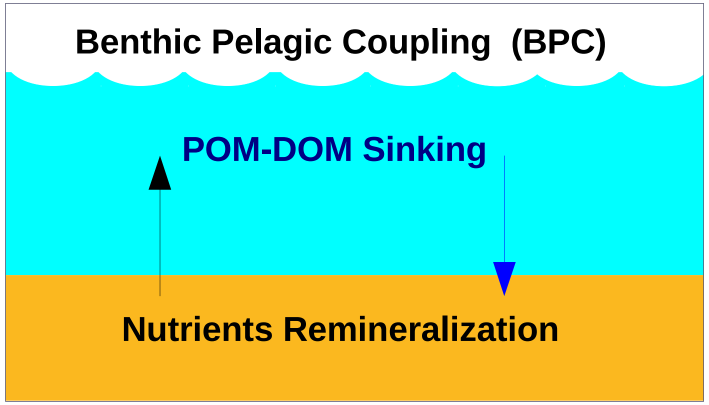
Scientific Framework

Coastal waters host the world's most productive ecosystems, providing:

- 30% of the global primary production;
- 80% of the organic matter burial;
- ~30% of atmospheric CO_2 sink (6% -11% anthropogenic CO_2 sink).

(Borges et al., 2011, Hardison et al., 2017)

Benthic activity play an important role in determining the pelagic biogeochemical characteristics of coastal waters (*Soetaert et al., 2000, Griffiths et al., 2017*).



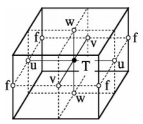
The physically mediated exchanges structuring the BPC are constituted by the sinking and resuspension fluxes of particulate organic matter and by the diffusion of inorganic nutrients

State of the art

- Limited knowledge about the exchange rates between the two habitats (*Griffiths et al., 2017*)
- Availability of data (*Soetaert et al., 2000, Griffiths et al., 2017*)
- Benthic-pelagic fluxes neglected or approximated to a simple closure term (*Soetaert et al., 2000*)

Scientific Goals

To implement and test a numerical model addressing benthic dynamics and BPC processes



To assess the skills of one-dimensional coupled physical-biogeochemical models in simulating the BPC

Evaluate ecosystem dynamics in three marine areas with different climatic and ecological characteristics

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Methodological approach

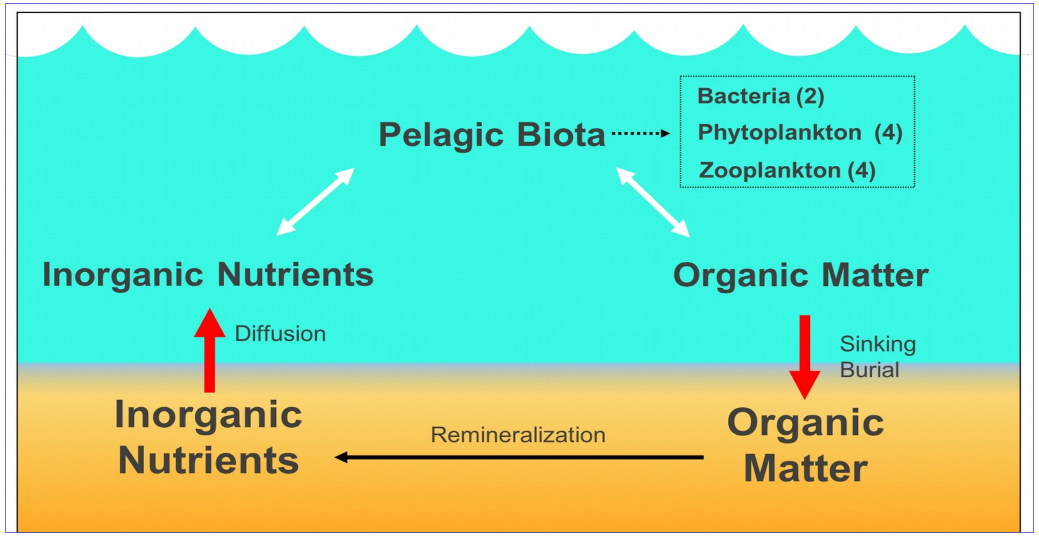
1-D configuration

NEMO + BFM BIOGEOCHEMICAL FLUX MODEL

$$\frac{\partial A}{\partial t} = \left.\frac{\partial A}{\partial t}\right|_{phys} + \left.\frac{\partial A}{\partial t}\right|_{bio}$$

A= generic state variable

Benthic-Pelagic Sub-model



$$\left.\frac{dQ_j^{(1,6)}}{dt}\right|^{rmn/diff} = \mu_{Q_j^{(1,6)}}\, Q_j^{(1,6)}\Big|_{z=zb}$$

$$\left.\frac{dQ_j^{(1,6)}}{dt}\right|^{sed}_{P_j^{(1,4)},R_j^{(1,6)}} = -\omega_{bur}\left[R_j^{(1,6)} + (\xi_j, 1-\xi_j)\sum_{i=1,4} P_{(j)}\right]_{z=z_b}$$

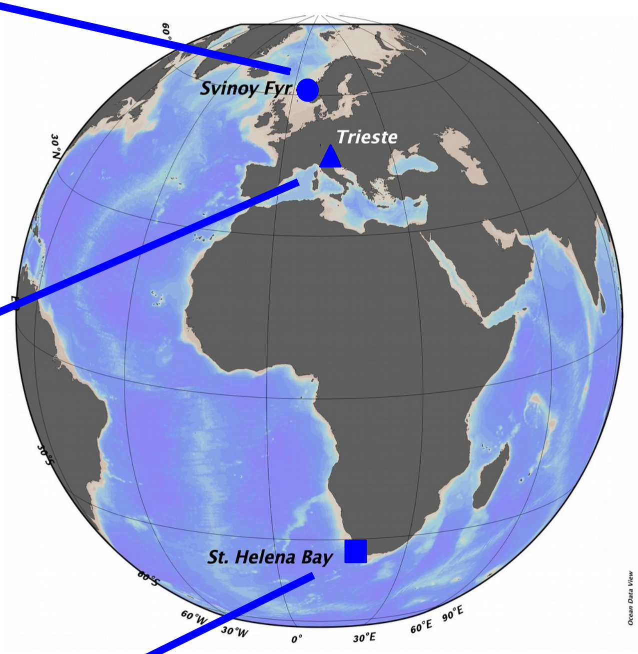
ω, μ	Burial and remineralization parameters	
ξ_j	Partitioning coefficient	
$R_j^{(1)}$	Pelagic dissolved organic matter	where j= C, N, P
$R_j^{(6)}$	Pelagic particulate organic matter	where j= C, N, P, S
P_j	Phytoplankton	where j= Diatoms, Large phytoplankton
$Q_j^{(1)}$	Benthic dissolved matter	where j= C, N, P

Implementation site

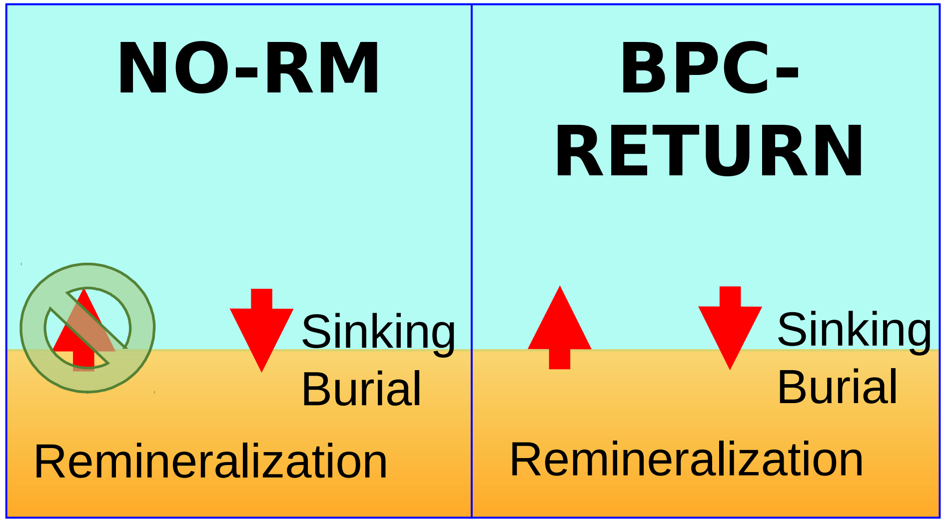
Site:	SFyr
Maximum Depth [m]	150
Atmospheric Forcing	ERA5
Observations	PO4; NO3; Chl-a; SiO4;

Site:	MA21
Maximum Depth [m]	16
Atmospheric Forcing	ERA-Interim
Observations	PO4; NO3; Chl-a; NH4; O2

Site	SHB
Maximum Depth [m]	78
Atmospheric Forcing	WRF model
Observations	PO4; NO3; Chl-a; SiO4; O2;



Experiments design



NO_RM: Remineralization flux nullified

BPC_RETURN: Both Sinking-Burial and Remineralization fluxes were considered

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Gulf of Trieste (MA21)

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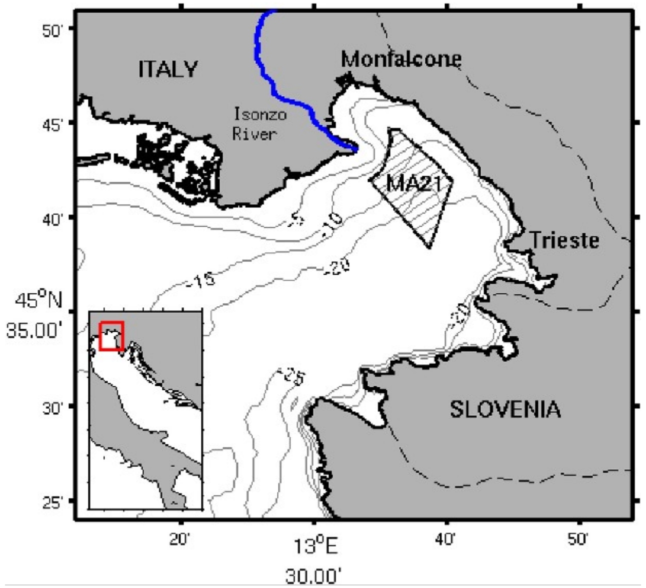
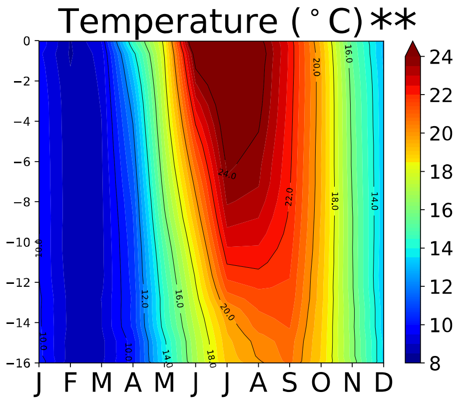
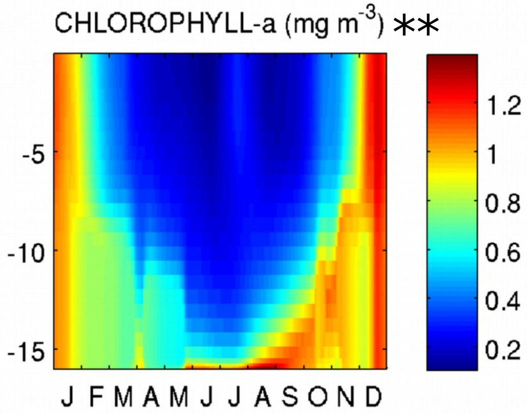
Study Area



http://dati.arpa.fvg.it

Physical and Biogeochemical dynamic





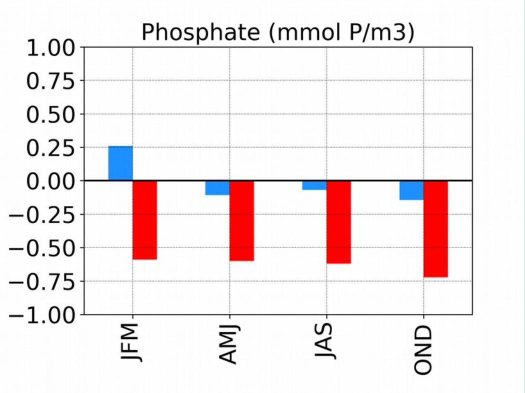
Benthic Sub-model Parameters	
Burial velocity [d^{-1}]	0.5
Remineralization (CNPS)[md^{-1}]	0.0025

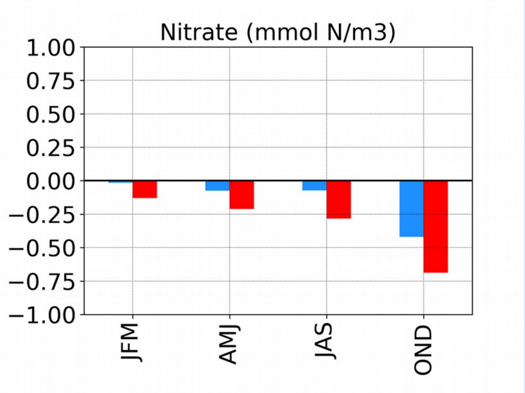
- **Well-mixed conditions** during winter and vertical thermal **stratification** in summer
- **Homogeneous** primary production condition in winter and **deep phytoplankton production** in summer

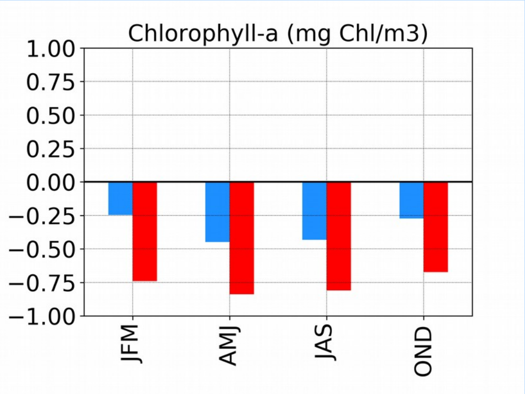
** Study Area figure and Chlorophyll Hovmöller from Mussap et al., 2016. Temperature monthly data from ARPA-FVG,OGS (2000-2011,2013)

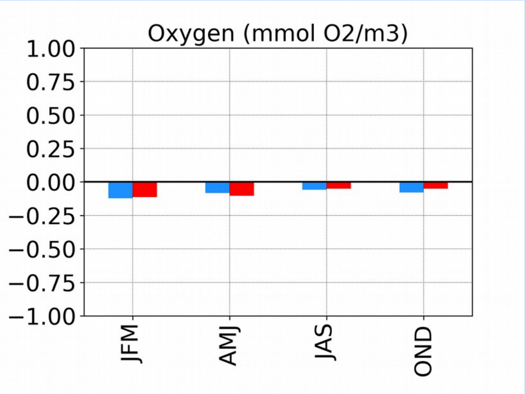
Gulf of Trieste (MA21)

Seasonal Normalized (in z) Mean Bias

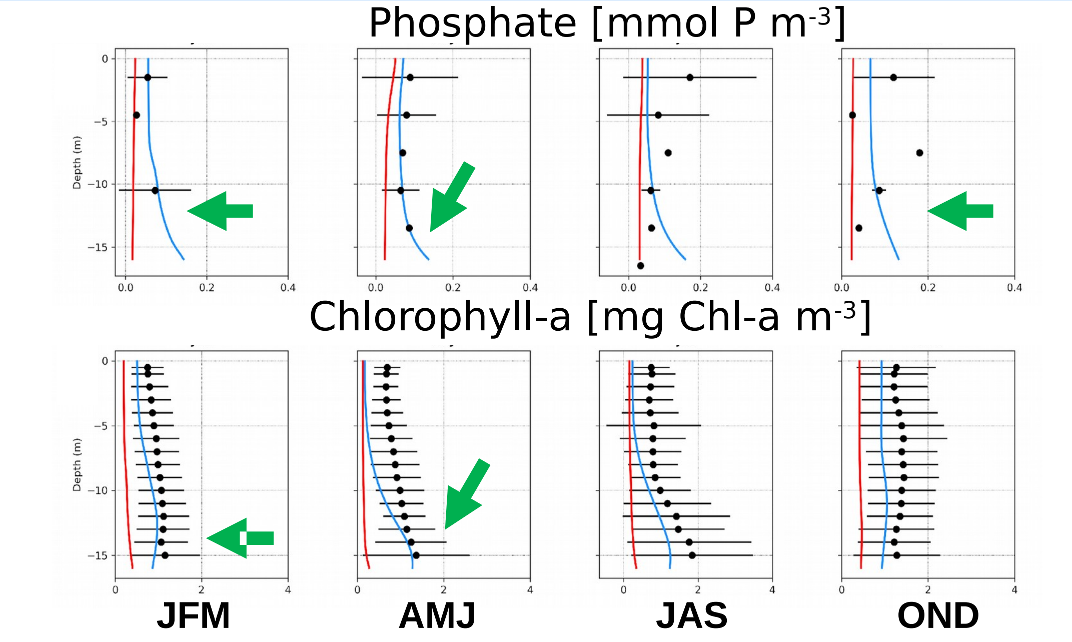








Mean Seasonal Vertical Profiles



- **NMB in NO-RM > NMB in BPC- RETURN** (exception of O_2)
- BPC-RETURN: **Inorganic nutrients** (at depth) **improvements** lead **amelioration of the simulated Chl-a dynamic** (green arrows).

NO-RM   BPC-RETURN

St.Helena Bay (SHB)

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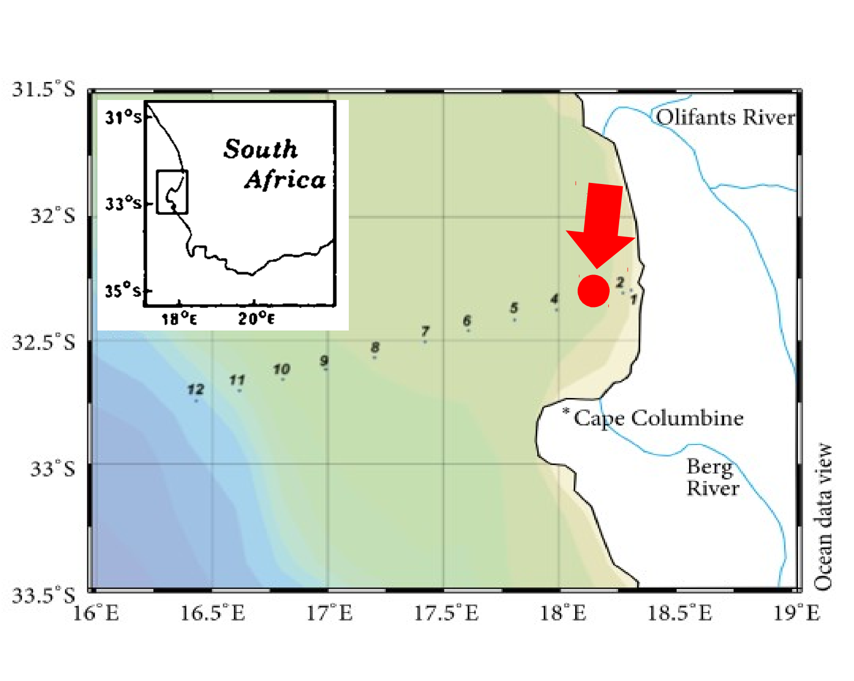
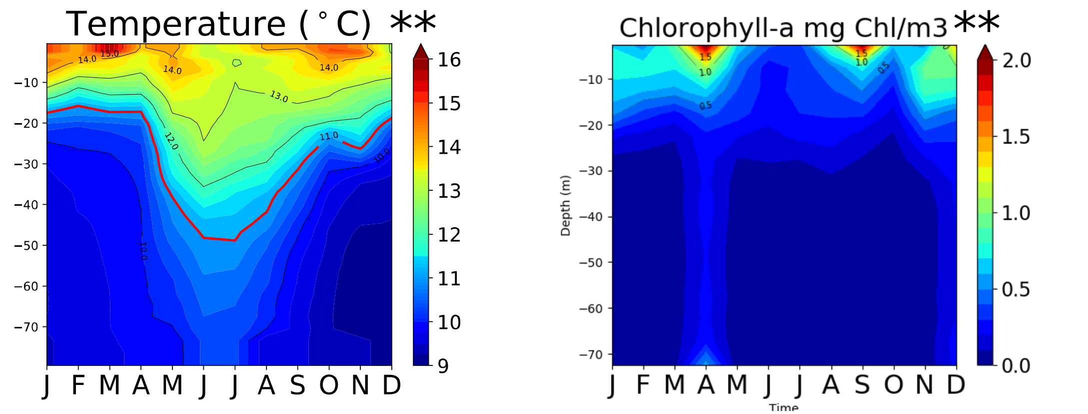
Study Area



Physical and Biogeochemical dynamic



Benthic Sub-model Parameters	
Burial velocity [d^{-1}]	1.0
Remineralization (CNP); (S) [md^{-1}]	0.0025 0.0015

- Embedded in the Benguela Current Large Marine Ecosystem
- South-easterly trade winds driven **upwelling between Sep.t-Apr.** (Vertical diffusivity [m^2s^{-1}] =5.0e-5)
- Peaks of primary production occurring during the upwelling period (maxima in April and September) *Shannon et al.,1996.*

** Monthly data (2000-2017) from BENEFIT (Benguela Environment and Fisheries Interactions and Training) program of the Department of Environmental Affairs of South Africa

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St.Helena Bay (SHB)

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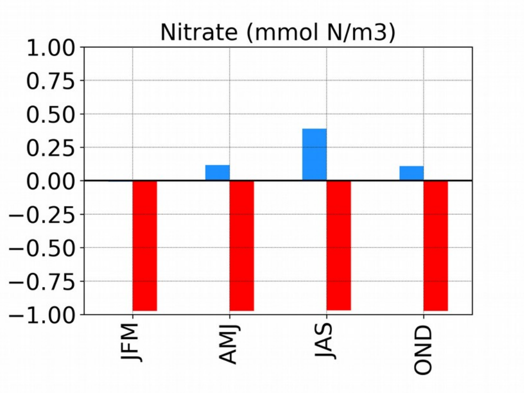
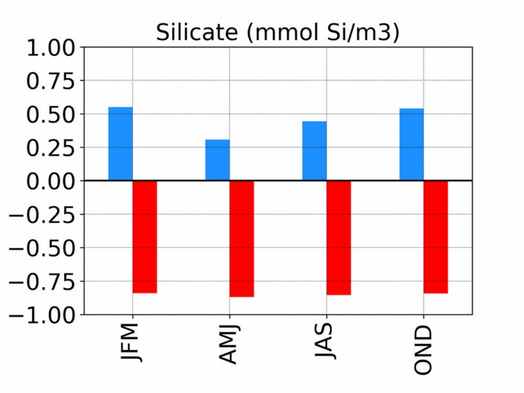
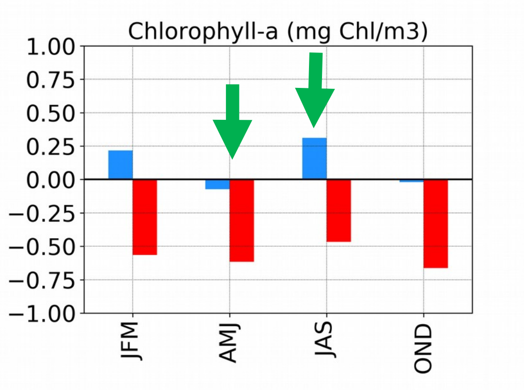
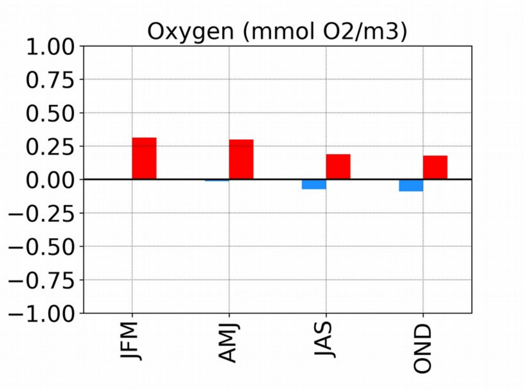
Seasonal Normalized (in z) Mean Bias

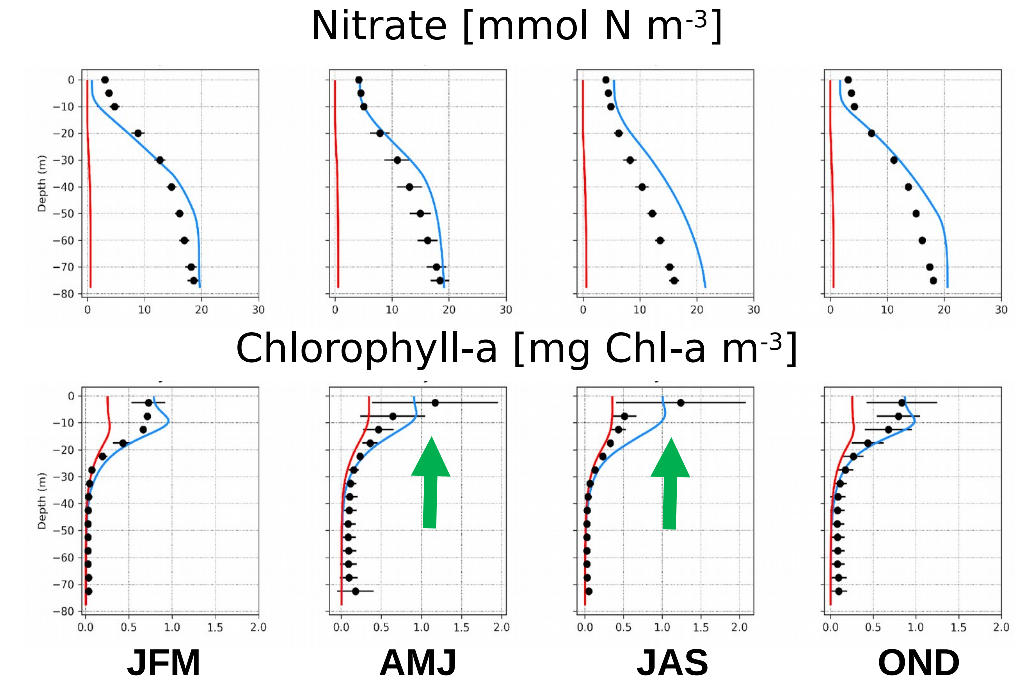








Mean Seasonal Vertical Profiles



- Bias NO-RM > BPC- RETURN
- Inorganic **Nutrients** seasonal **improvements positively affect Chl-a** dynamic seasonality (AMJ-JAS)

NO-RM BPC-RETURN

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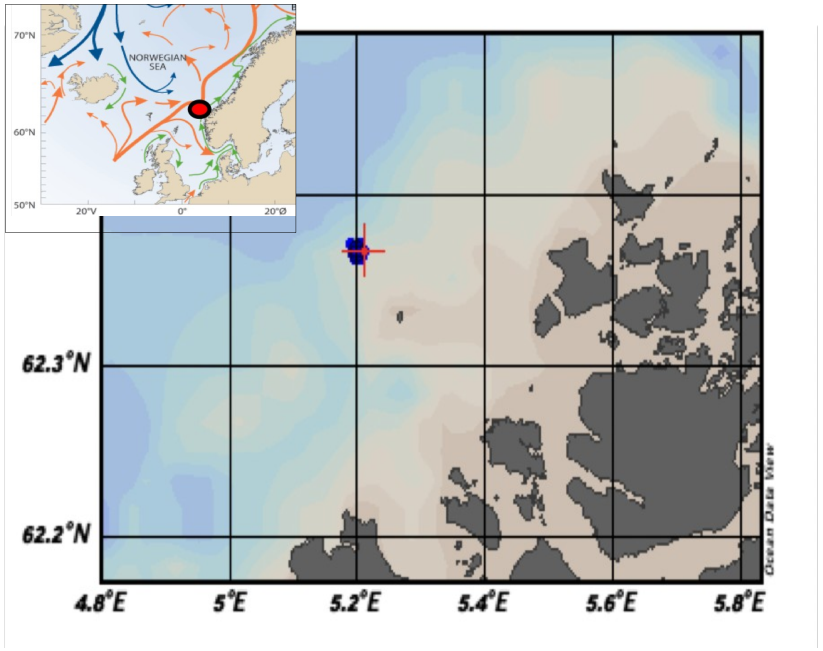
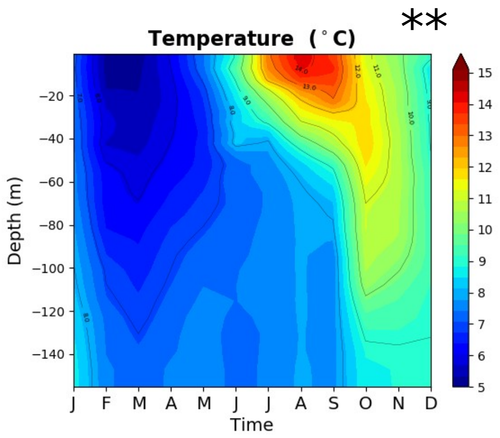
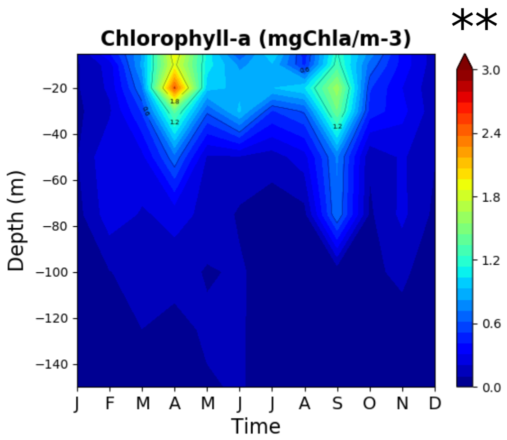
Svynøy Fyr (SFyr)

Study Area



Physical and Biogeochemical dynamic





Benthic Sub-model Parameters	
Burial velocity [d^{-1}]	1.0
Remineralization (CNP); (S) [md^{-1}]	0.0050

- Cold and deep mixed dynamic
- No Sea Ice formation (Norwegian Coastal Current)
- Phytoplankton peaks in no light limited seasons.

Ibrahim et al., 2014

** Monthly data from the Institute of Marine Research - Norwegian Marine Data Centre (INR- NMD) (1995-2015)

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Svynøy Fyr (SFyr)

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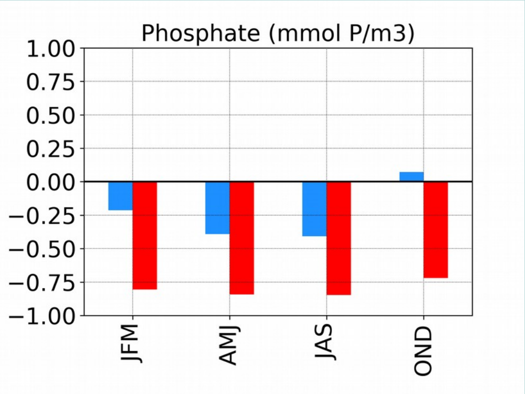
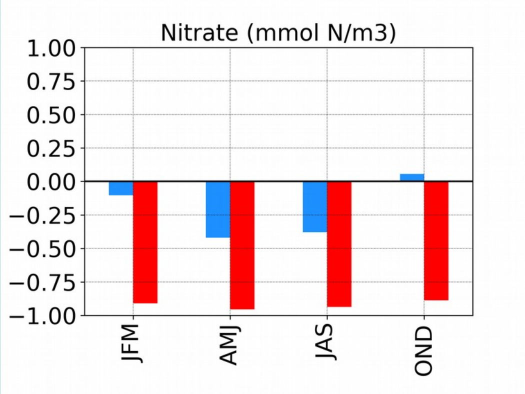
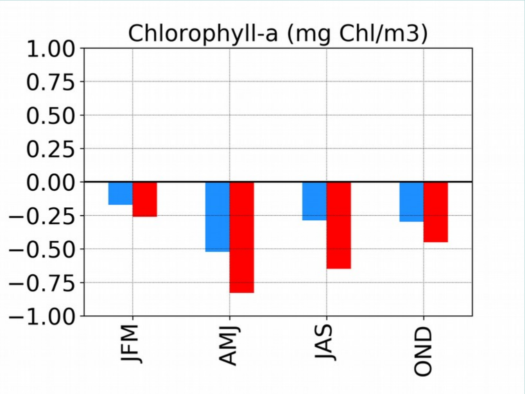
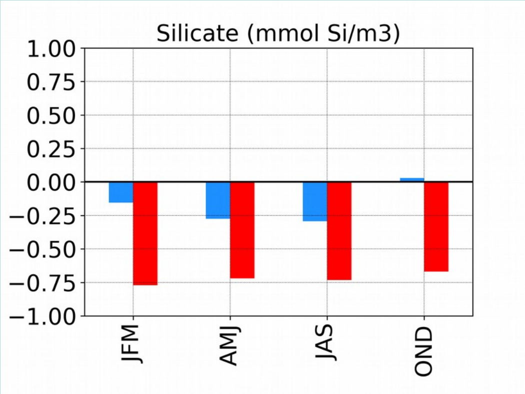
Seasonal Normalized (in z) Mean Bias

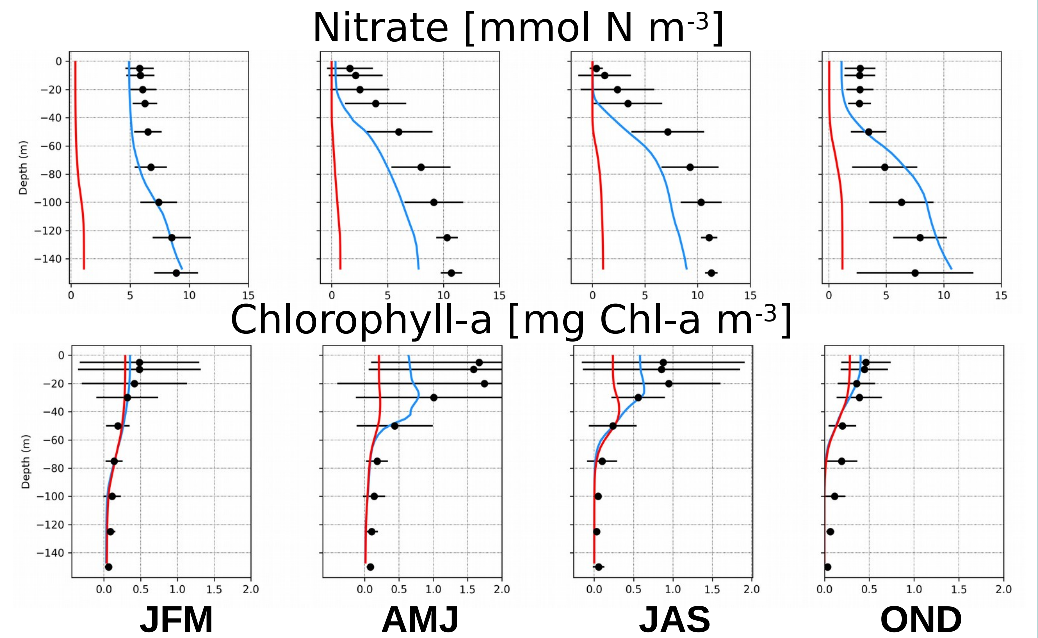








Mean Seasonal Vertical Profiles



- Bias **NO-RM > BPC- RETURN**
- **No sensible Chl-a growth** in **winter** (light limited primary production)
- Spring-summer **nutrients consumption** attributable to **Phytoplankton** dynamic

NO-RM   BPC-RETURN

Sensitivity Analysis (SA)

Overall goals

1. Find the 'best' setup of BPC parameterizations among a range of site specific values
2. Evaluate the role of BPC in determining the pelagic biogeochemical cycling

Analysis Procedure

Explore Remin and Burial ranges to find minimum error metric for PO_4, NO_3, Chla
(Annual mean vertical profile)

Summary Diagrams
(Taylor et al.,2001, Joliff et al., 2009)

Normalized Root Mean Square Error
(Mentaschi et al., 2013)

Site	Burial [m d^{-1}]	Remineralization [d^{-1}]
MA21	**ref = 0.5** (0.35 - 0.65)	**ref=0.0025** (0.00175-0.00325)
SHB	**ref=1.0** (0.60 - 1.20)	**ref=(0.0025)** (0.00175-0.00325)
SFyr	**ref=1.0** (0.10 - 1.50)	**ref= (0.0050)** 0.00350-0.00800

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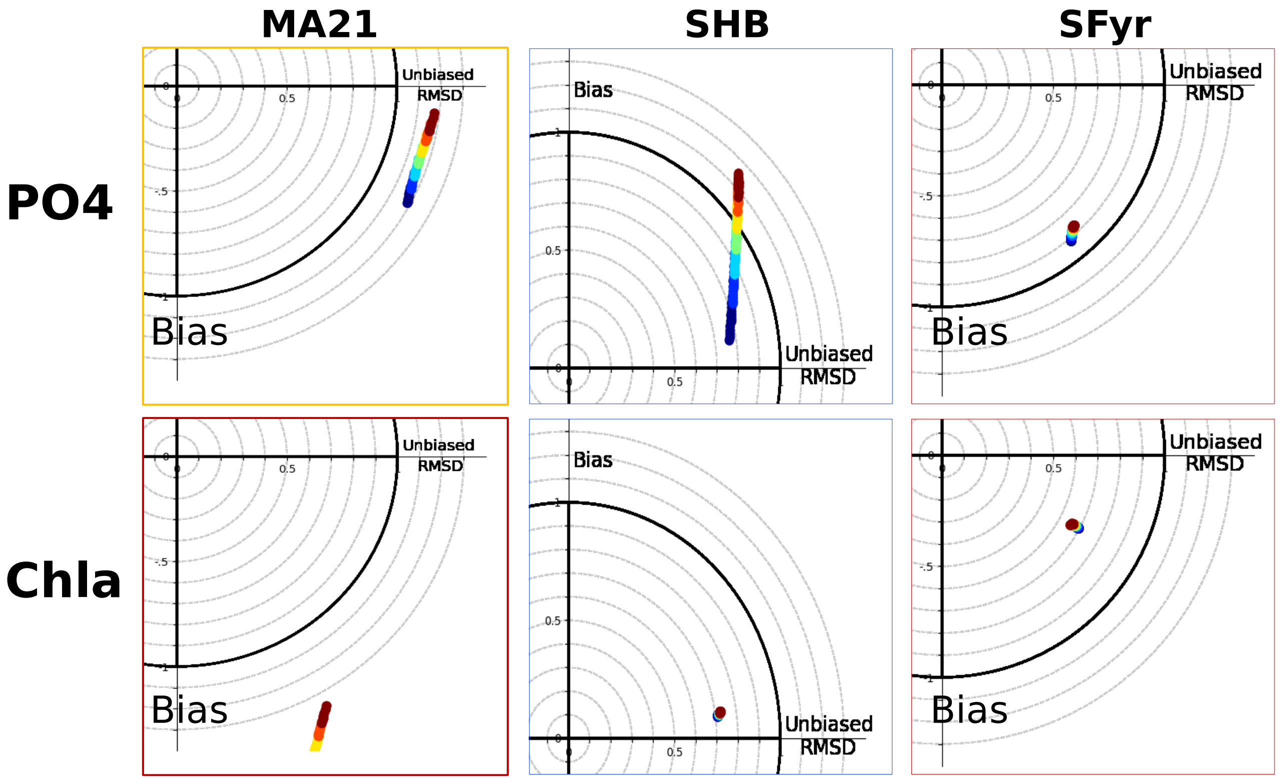
Outcomes of Sensitivity Analysis

Summary Diagrams

- **Identification of best model setup from FG**

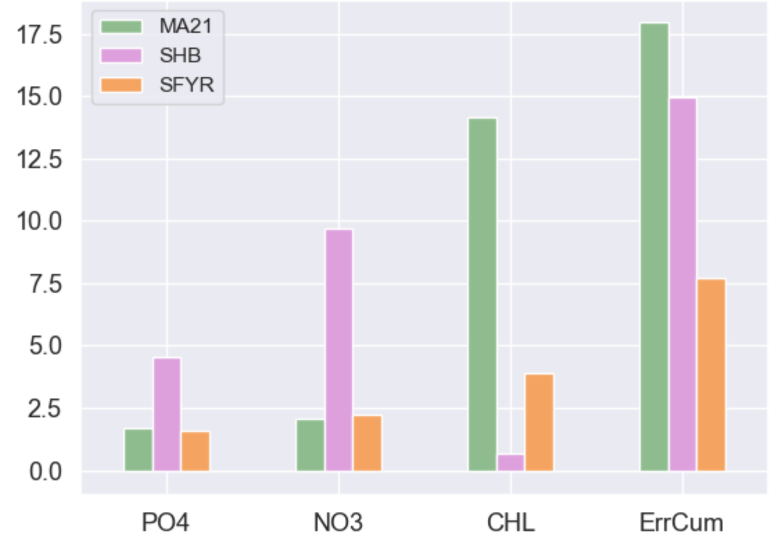


Remineralization-grouped

NRMSE

- **Effect of BPC processes on pelagic dynamics**

Max NRMSE spread (Worse – Best) Experiment



- MA21 and SFyr: small variations of inorganic nutrients affect primary production
- SHB: Nutrients variation does not affect primary production dynamic

Role of BPC processes on pelagic dynamics

Final setup of BPC parameters

Site	Depth [m]	Bur [m d^{-1}]	Remin [d^{-1}]
MA21	**16**	0.35	0.00 325
SHB	**78**	**0.60**	0.00 175
SFyr	**150**	0.10	**0.00 800**

Estimate of benthic-pelagic fluxes

Site	Depth [m]	POC-Burial [mg C m^{-2} d^{-1}]	N-Remin [mmol N m^{-3} d^{-1}]	P-Remin [mmol p m^{-3} d^{-1}]
MA21	**16**	**-0.1344**	**0.910**	**0.050**
SHB	**78**	-0.0021	**1.027**	**0.068**
SFyr	**150**	**-0.0636**	0.336	0.016

- **Dependency** between station **depth** and BP **fluxes** intensity

[Suess et al., 1980]

Qualitative analysis NRMSE based

Initial setup of BPC parameters (First Guess)

↓

Final setup of BPC parameters (Best Exp.)

Site	PO4	NO3	CHL-a	O2	SIL	NH4
MA21	-	+	+	+		+
SHB	+	+	+	+	+	
SFyr	+	+	+		+	

- SHB, SFyr widespread improvements
- MA21 improvements with exception of PO4

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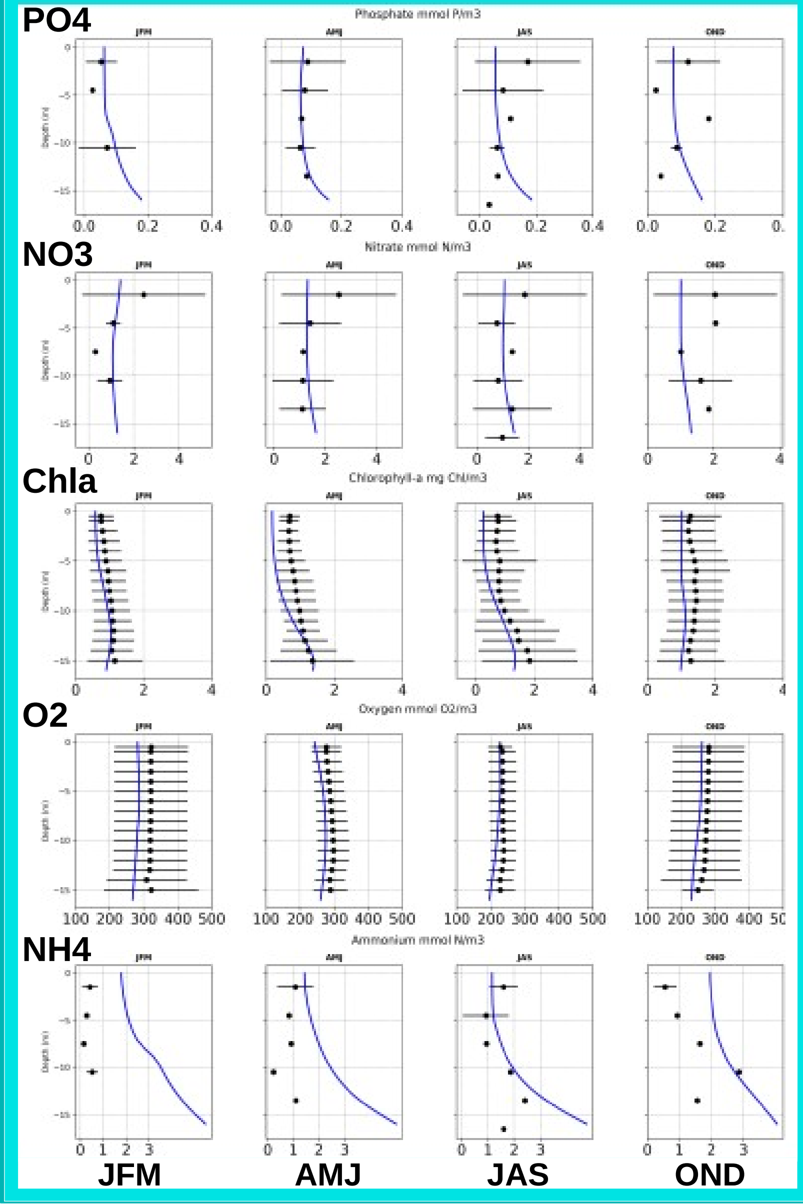
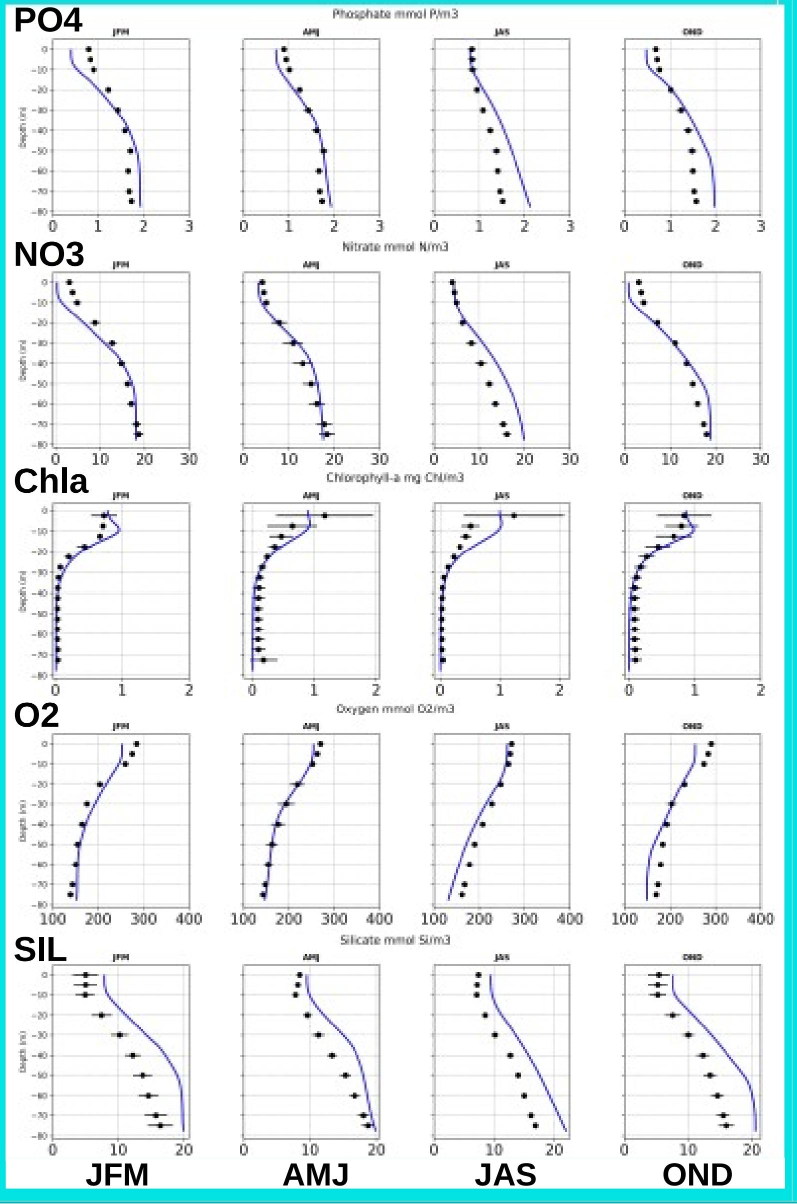
Results: Best Experiments

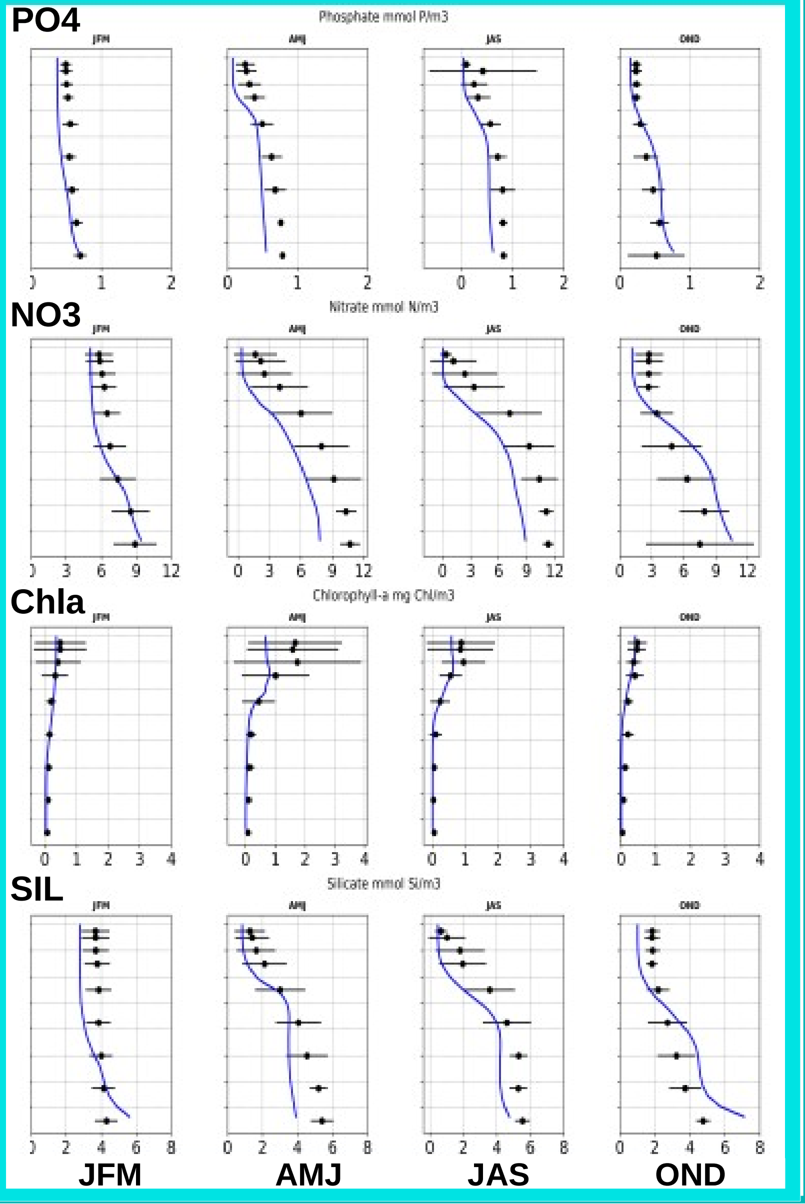
MA21



SHB



SFyr



Conclusions

- The **benthic-pelagic dynamic** processes were **successfully implemented** for the three different sites;

- The intercomparison between the **BPC-RETURN** and the **NO-RM** experiment allowed to asses the model **improvements in reproducing B-P fluxes**;

- The extensive **sensitivity analysis** showed different sedimentation-remineralization scenarios where the **shallower sites were more sensitive to the BPC parameterization**.

- MA21 and SHB areas were characterized by a more active benthic nutrients regeneration while SFyr and MA21 were characterized by the highest rates of deposition.

- The **agreement** between the used **pattern statistics successfully** allowed to individuate the **Best Experiments (Final setup)**.

Numerical modelling of the benthic-pelagic coupling (BPC) in coastal marine ecosystems at contrasting sites

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Università Ca'Foscari Venezia

Thank you

Citations

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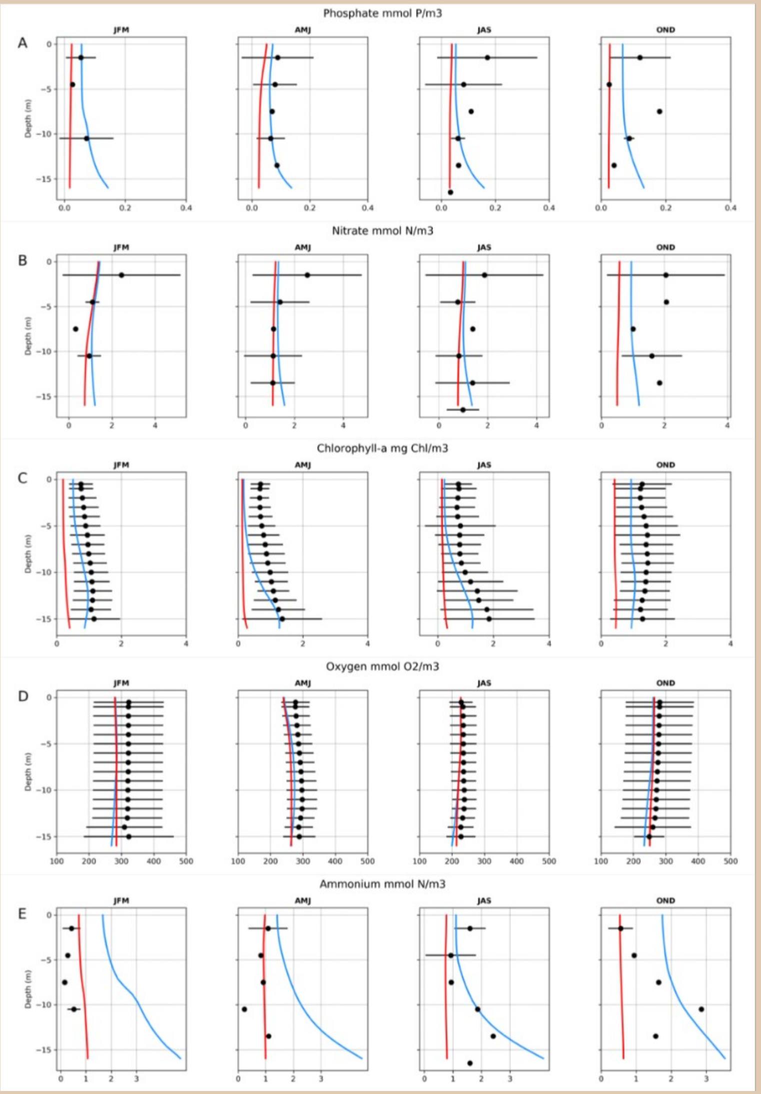
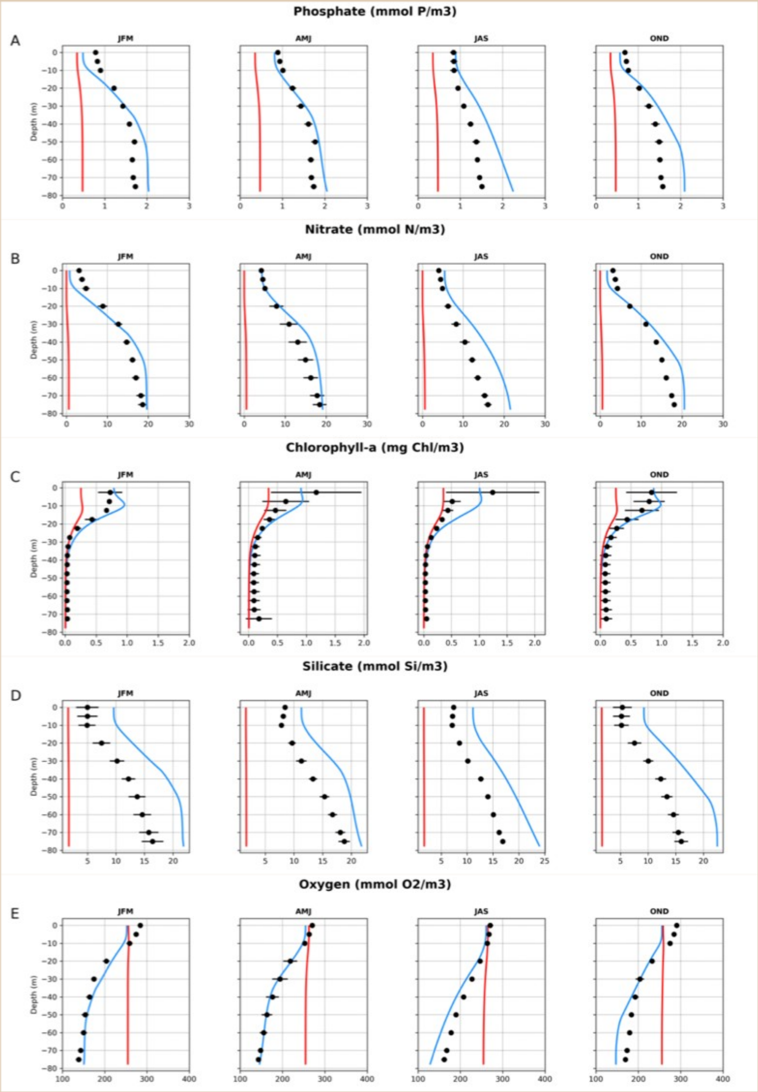
Supplementary slides

BPC Implementation
(NO-RM vs BPC_RETURN exps)

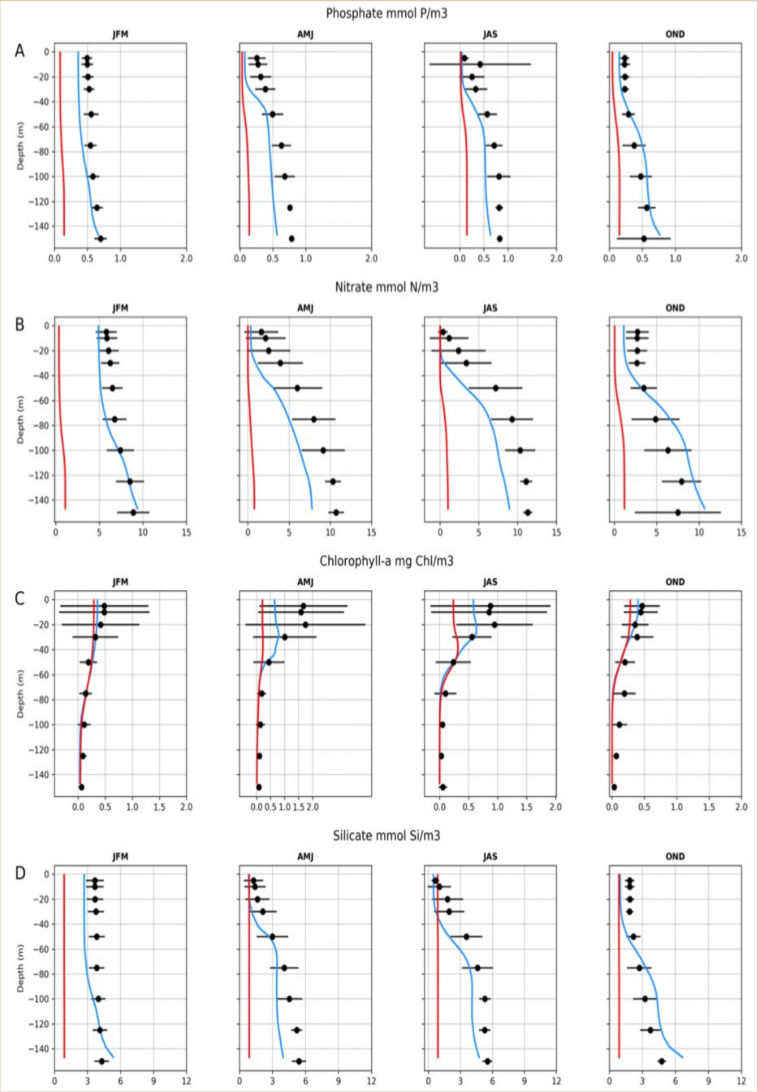
NO-RM vs BPC_RETURN Results



MA21



SHB



SFyr

Sensitivity Analysis Scheme

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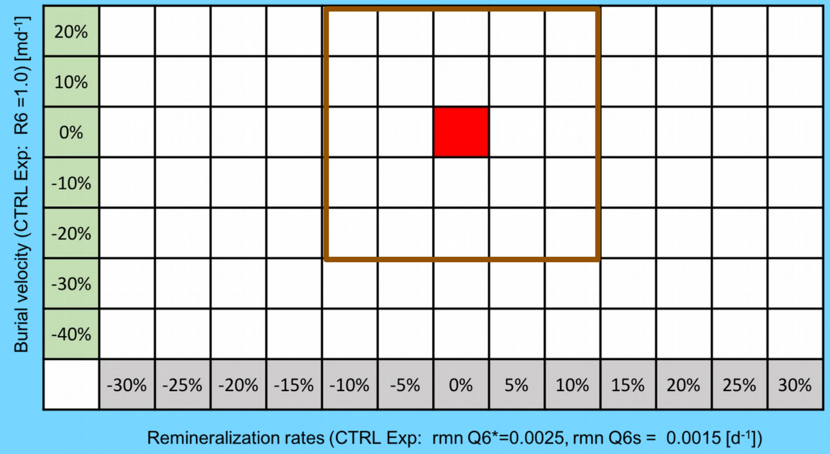
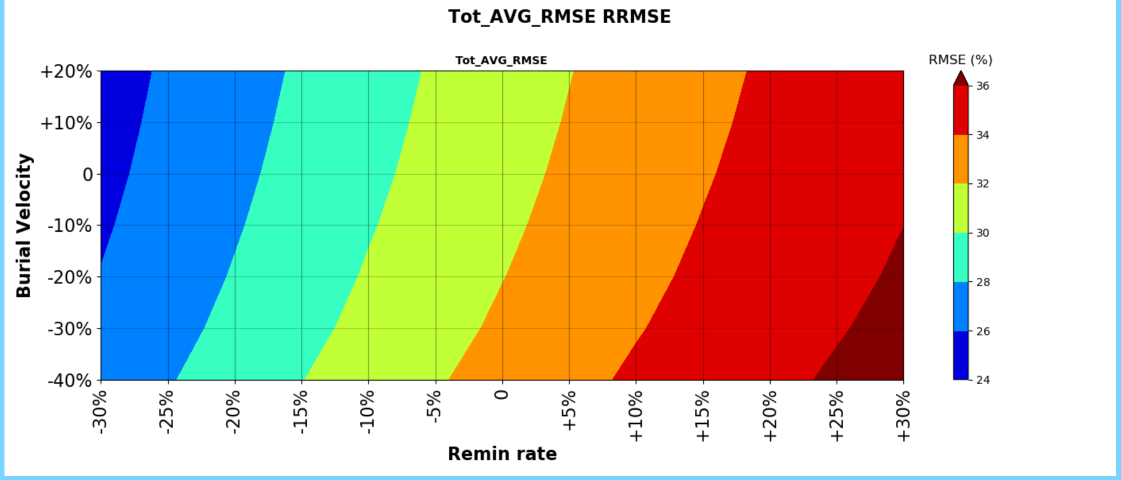
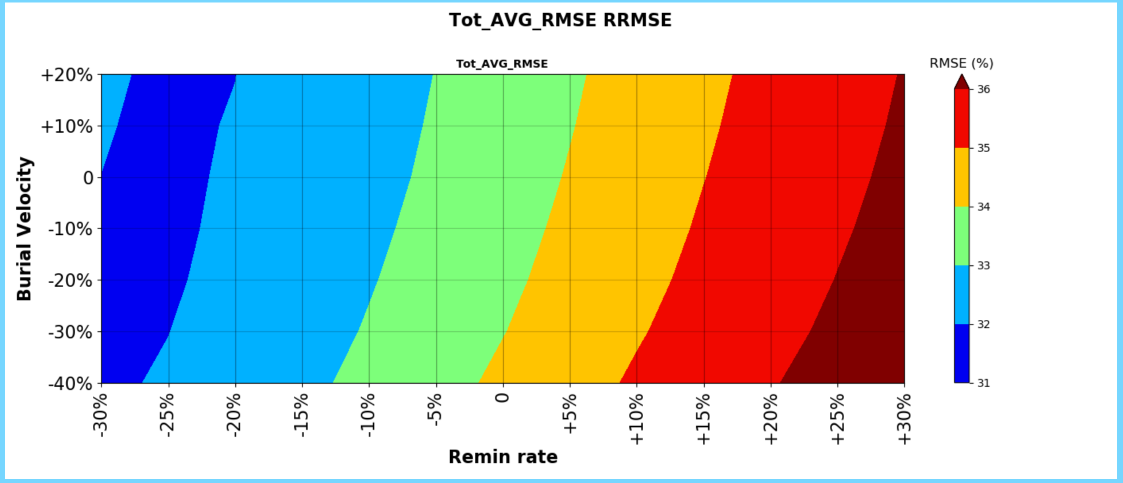
Sensitivity Experiment Matrix



Mean NRMSE (all variables)



Mean NRMSE (Sensitivity analysis variables)



Sensitivity Analysis
Best Exp Identification

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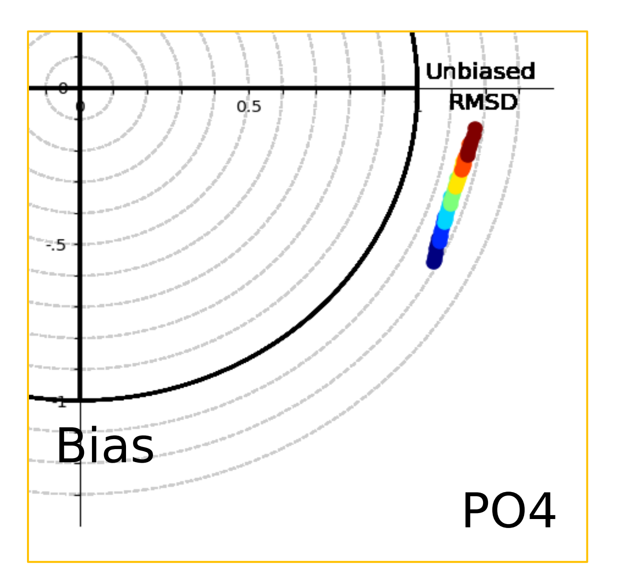
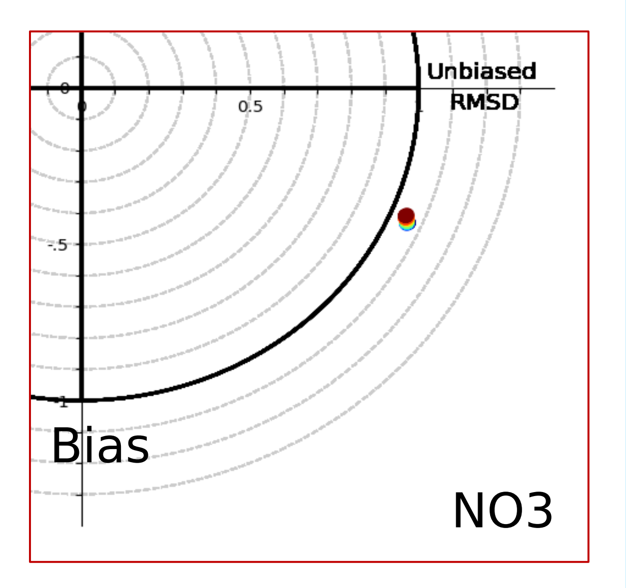
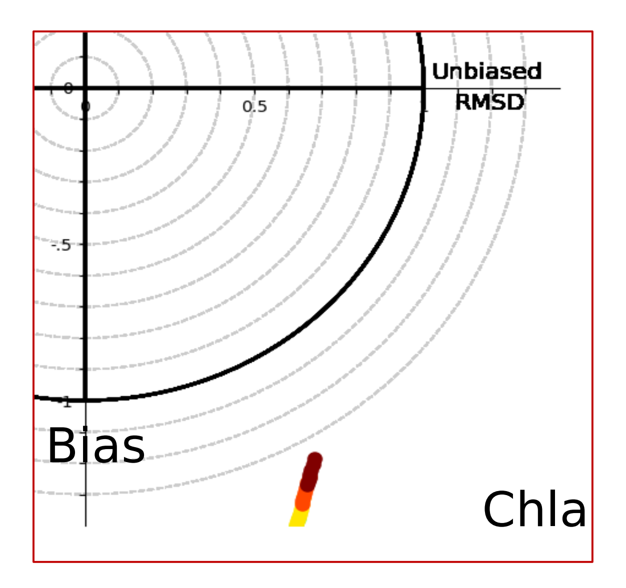
MA21: Identification of “Best Experiment”

Clouds of experiments grouped by Remineralization sets



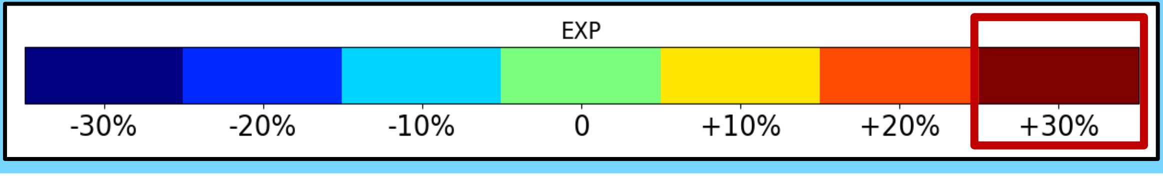




Best Exp: Remin +10%

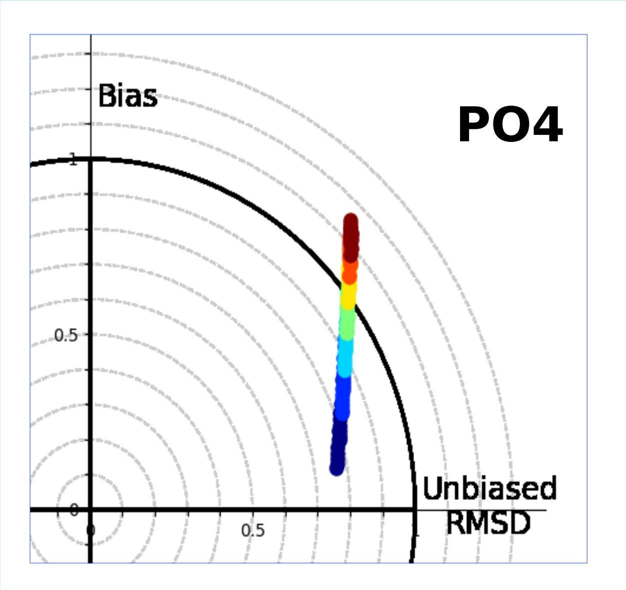
Best Exp: Remin +30%

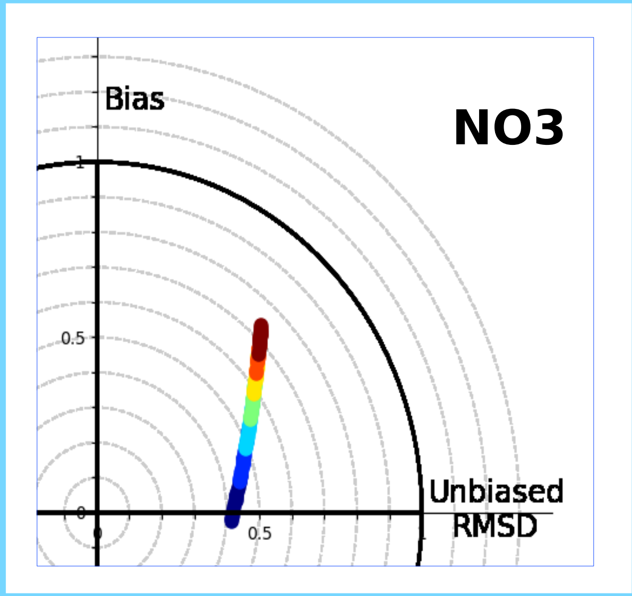
Best Exp: Remin +30%

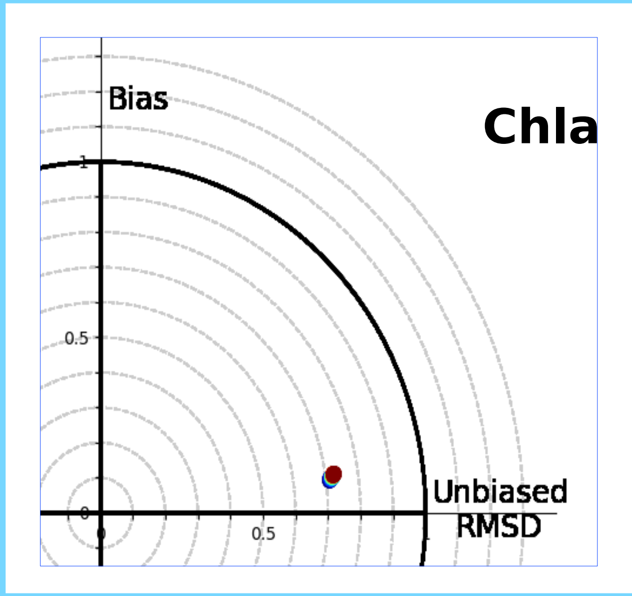


SHB Identification of “Best Experiment”

Clouds of experiments grouped by Remineralization sets



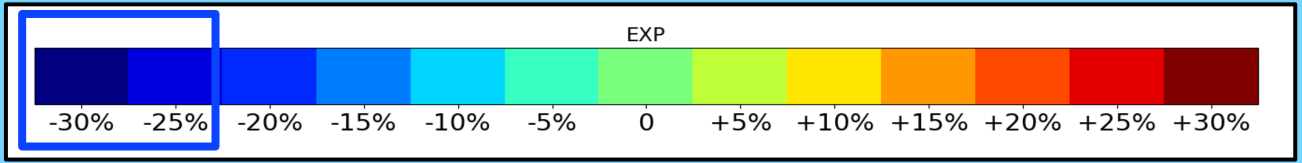




Best Exp: Remin -30%

Best Exp: Remin -25/-30%

Best Exp: Remin -30%



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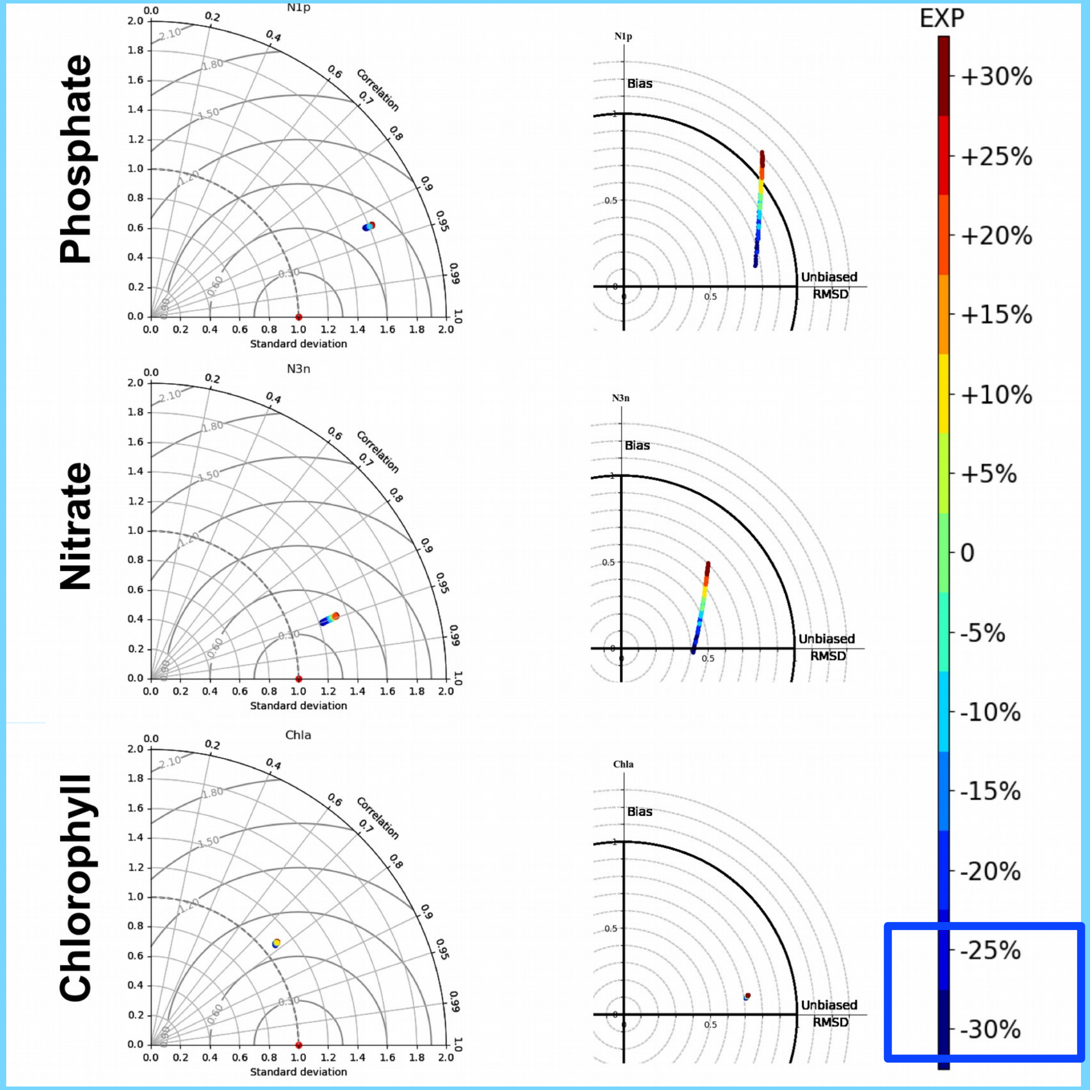
SHB Identification of “Best Experiment”

Best Exp: Remin -30%

Best Exp: Remin -30%

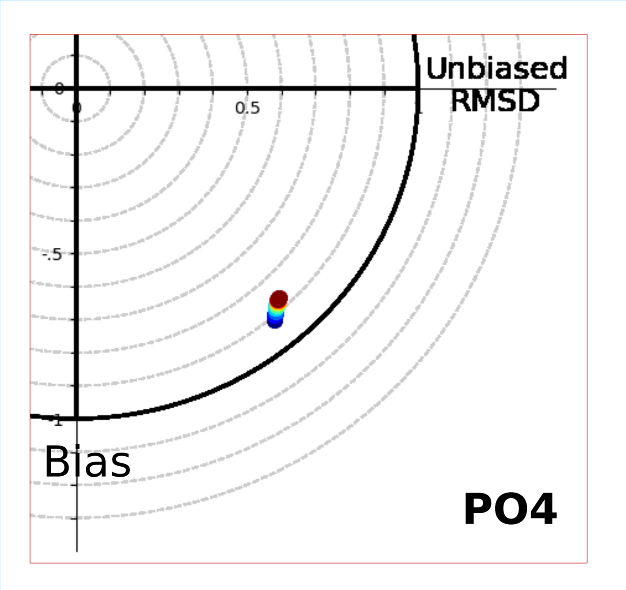
Best Exp: Remin -25/-30%

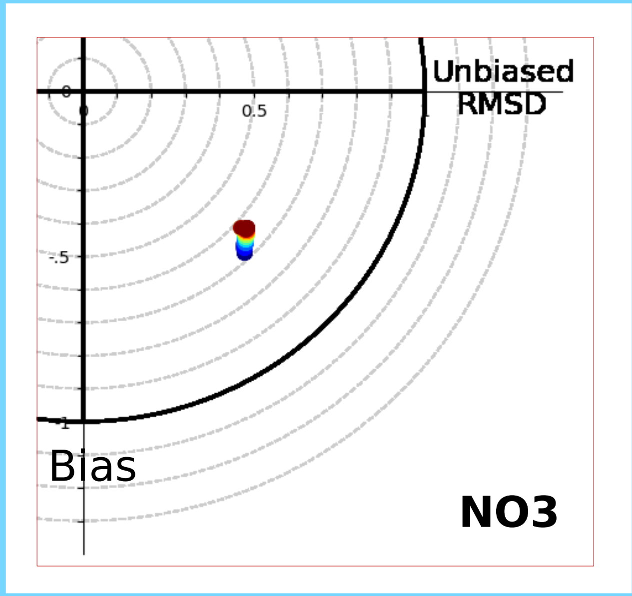


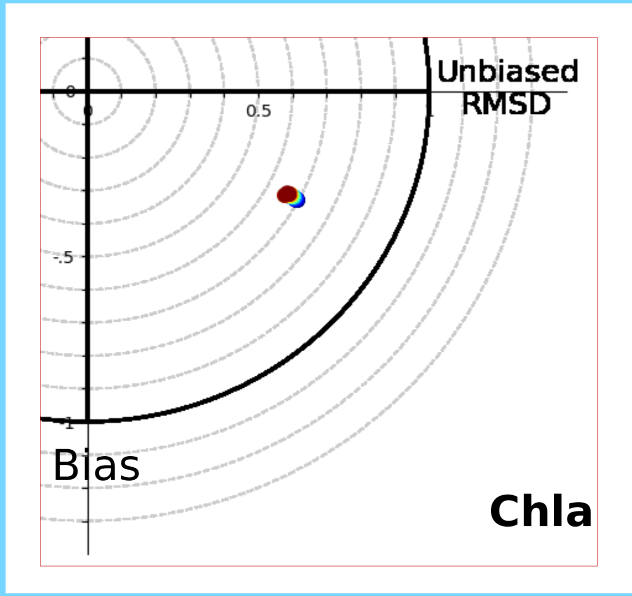
Clouds of experiments grouped by: Remineralization sets

SFyr Identification of “Best Experiment”

Clouds of experiments grouped by Remineralization sets



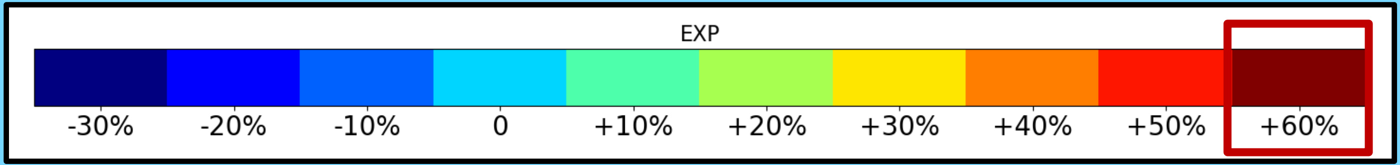




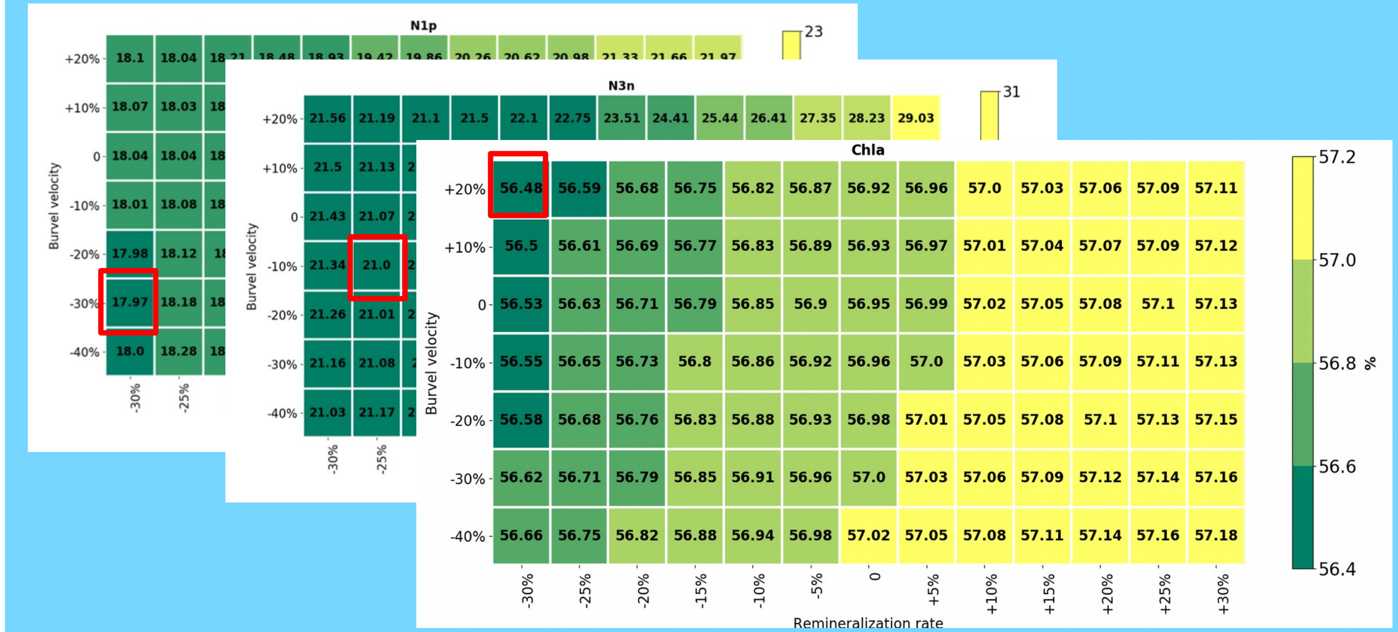
Best Exp: Remin +60%

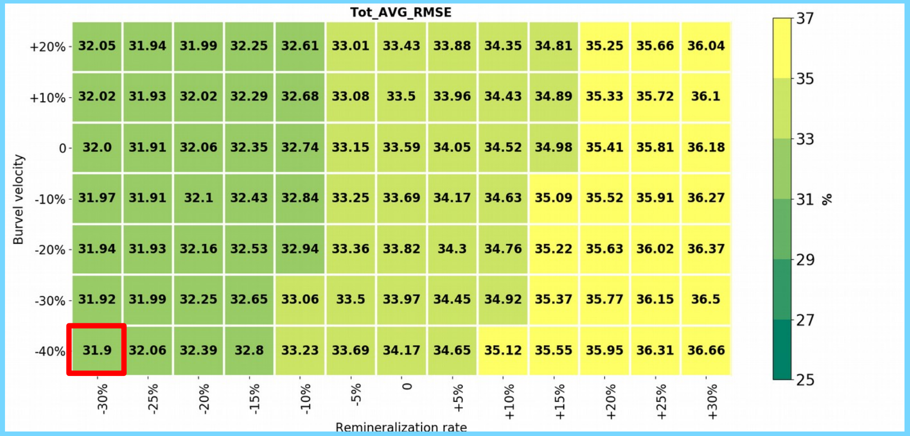
Best Exp: Remin +60%

Best Exp: Remin +60%



Agreement between used *pattern statistics*





SHB			
Variable	RMSD	Taylor diagram	Target diagram
Phosphate	B -30% R -30%	R -30%	R -30%
Nitrate	B -10% R -25%	R -30%	R -30% / R -25%
Chlorophyll	B +20% R -30%	R -30%	R -30%
Avg RMSD	B -40% R -30%	—	—
SFyr			
Variable	RMSD	Taylor diagram	Target diagram
Phosphate	B -90% R +60%	not clear	R +60%
Nitrate	B -90% R +60%	not clear	R +60%
Chlorophyll	B -90% R +60%	R +60%	R +60%
Avg RMSD	B -90% R +60%	—	—
MA21			
Variable	NRMSD	Taylor diagram	Target diagram
Phosphate	B -30% R -10%	R -30%	R -10%
Nitrate	B -30% R +30%	R +30%	R +30%
Chlorophyll	B -30% R +30%	R -30%/R -20%	R +30%
Avg RMSD	B -30% R +30%	—	—

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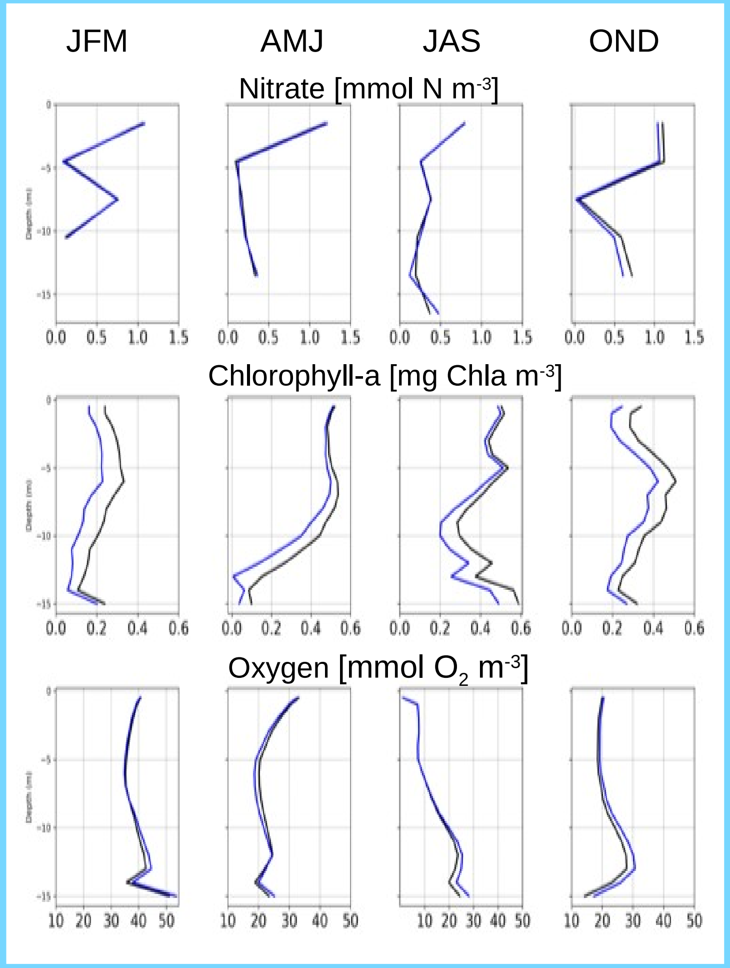
Sensitivity Analysis
Best Exp Vertical Profiles

Mean Absolute Error (MAE)

Best Guess-Obs vs **First Guess-Obs**

MA21



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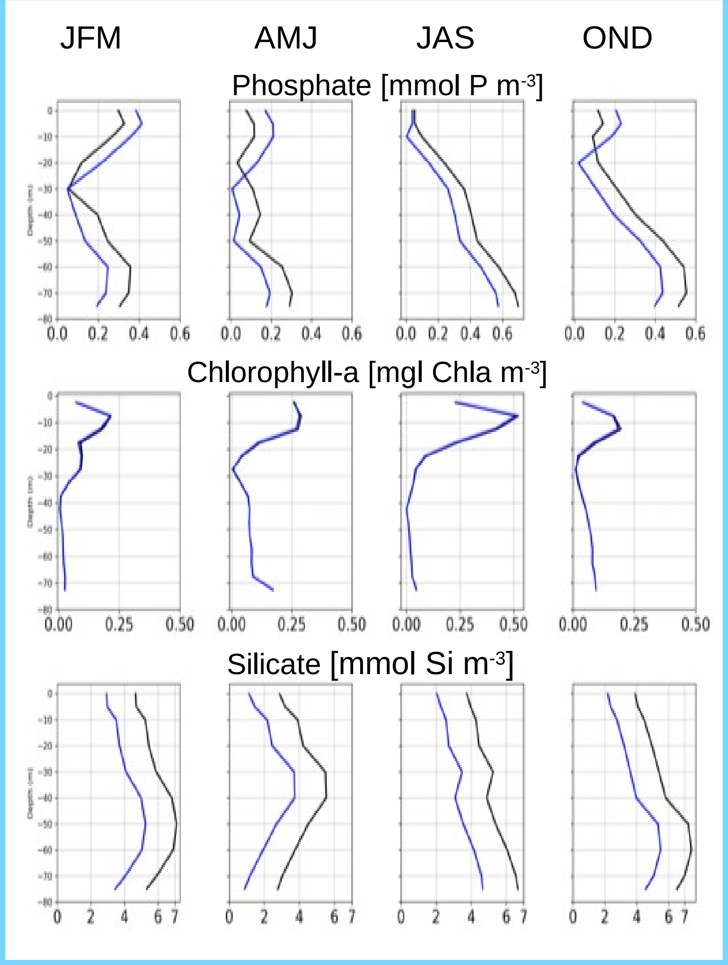
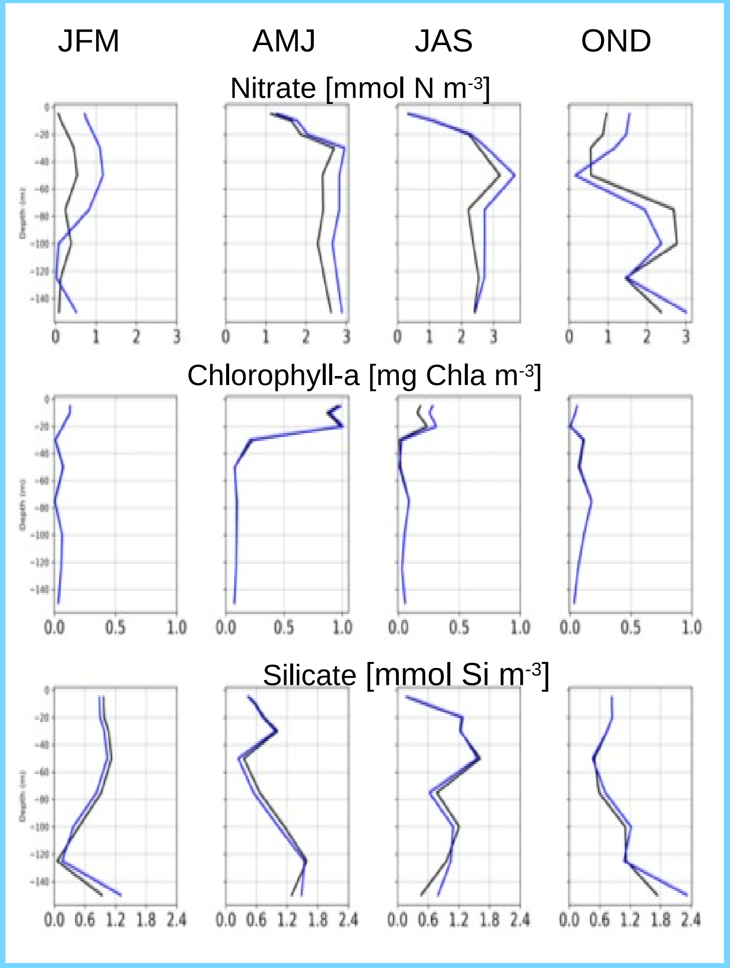


SFyr



First Guess — Best Guess