7th Euro-Argo Science Meeting. Athens 22-23 October 2019

Integration of novel optical observations in CMEMS–Biogeochemistry models to improve the CMEMS biogeochemical products **(BIOPTIMOD)**

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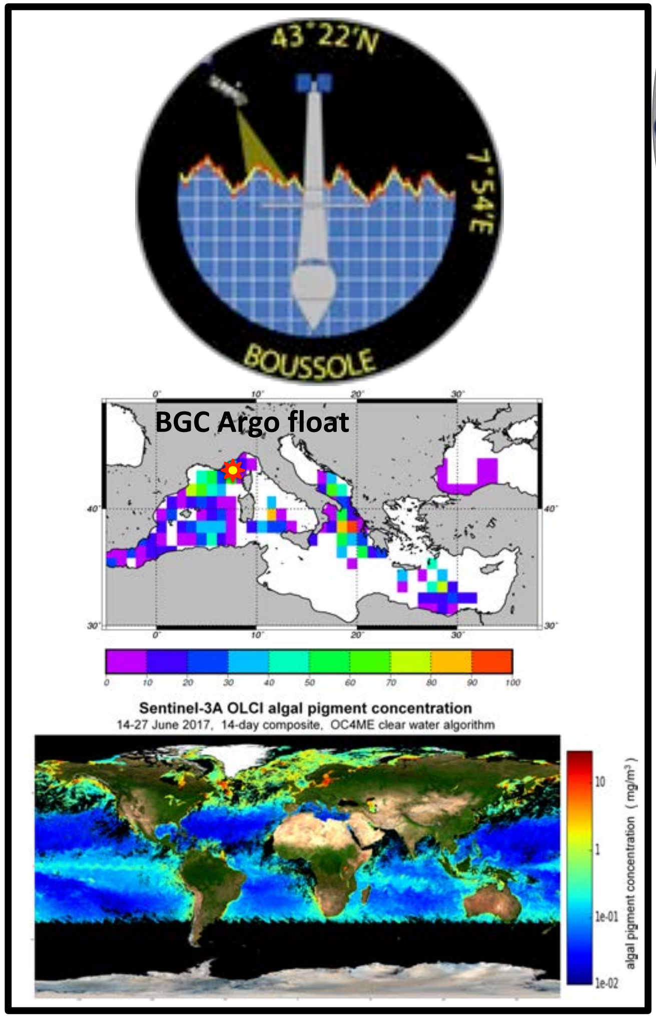
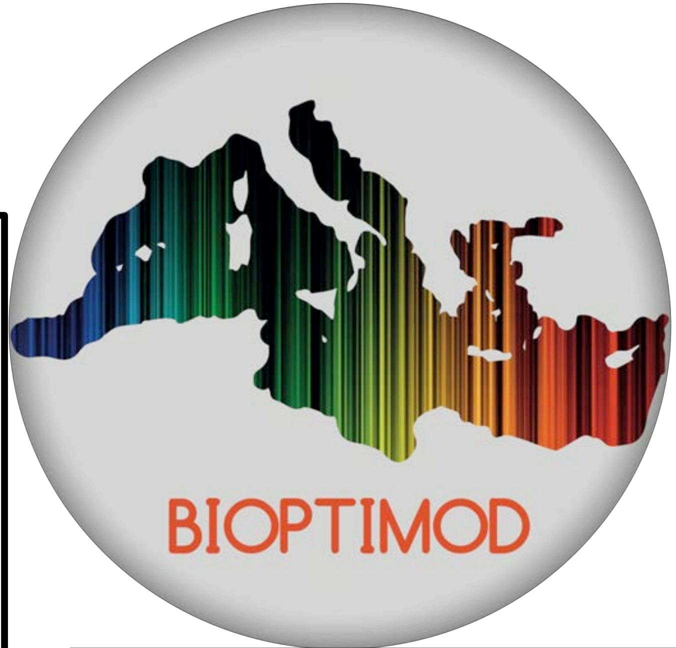
Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (Italy)

Laboratoire d'Océanographie de Villefranche-sur-Mer (France)

The major components:

1. BOUSSOLE, BGC-ARGO FLOAT and SENTINEL data in the Mediterranean Sea

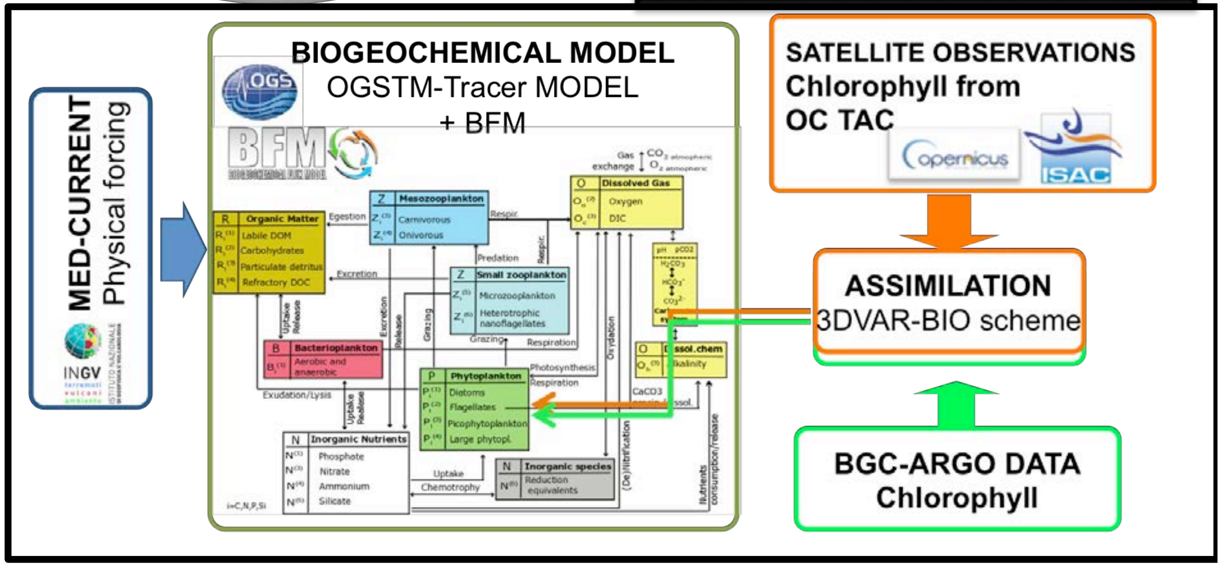




3. New bio-optical model

$$
\begin{aligned}
\frac{dE_d}{dz} &= -\frac{a+b}{\cos\theta_d}E_d \\
\frac{dE_s}{dz} &= -\frac{a+r_s b_b}{\overline{v}_s}E_s + \frac{r_u b_b}{\overline{v}_u}E_u + \frac{b-r_d b_b}{\cos\theta_d}E_d \\
-\frac{dE_u}{dz} &= -\frac{a+r_u b_b}{\overline{v}_u}E_u + \frac{r_s b_b}{\overline{v}_s}E_s + \frac{r_d b_b}{\cos\theta_d}E_d
\end{aligned}
$$

2. CMEMS–MED-MFC: Mediterranean Biogeochemistry model system (MedBFM)



BIOPTIMOD: some major scientific questions

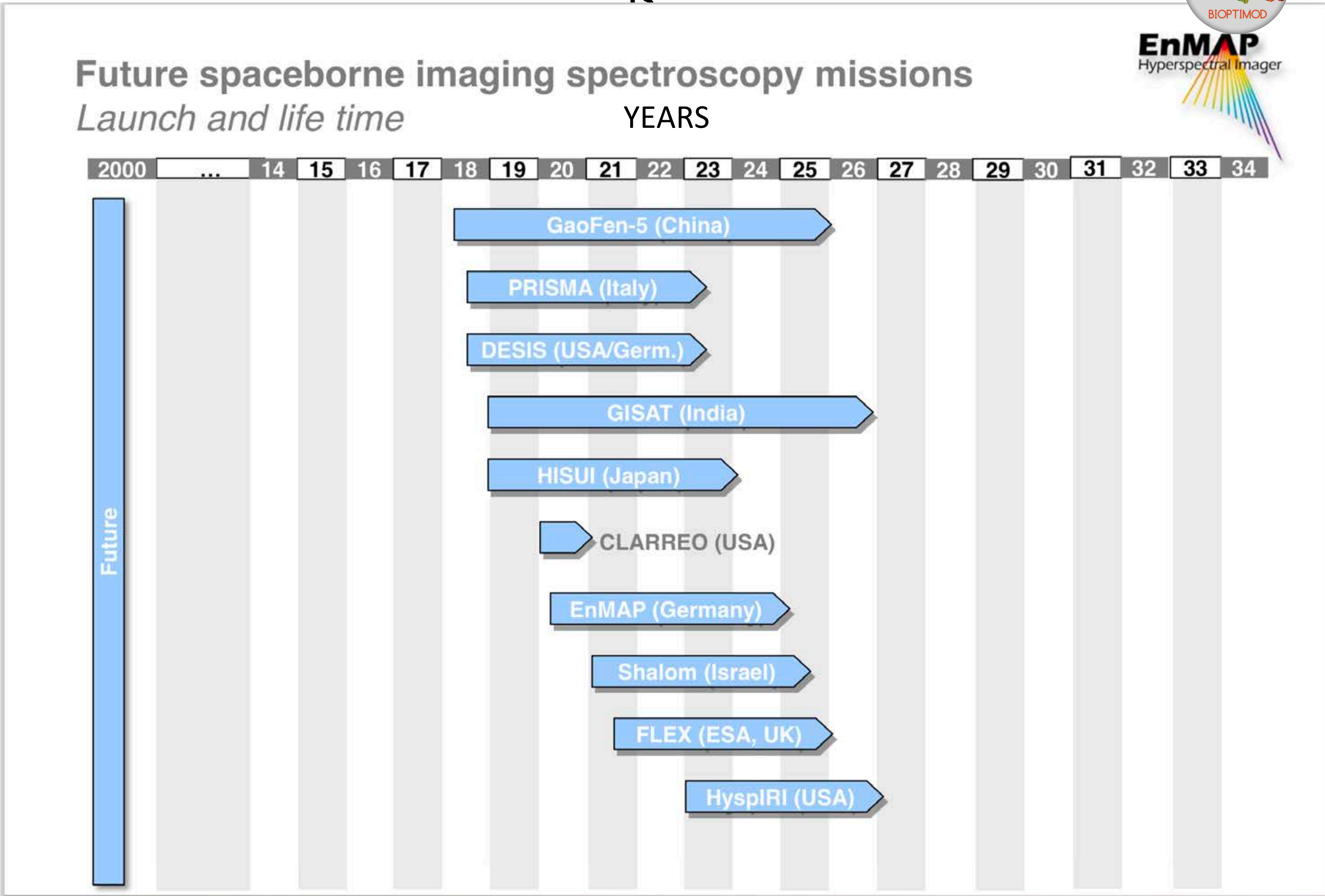
1) Impact of different bio-optical models - and parameterizations – on biogeochemical properties distributions

3) How the new multispectral information from satellite can be used to improve our understanding of the Med biogeochemistry?

2) Impact of CDOM **and PFT formulations** on Mediterranean Sea biogeochemistry, role of autochthonous and allochthonous CDOM (terrestrial origin)

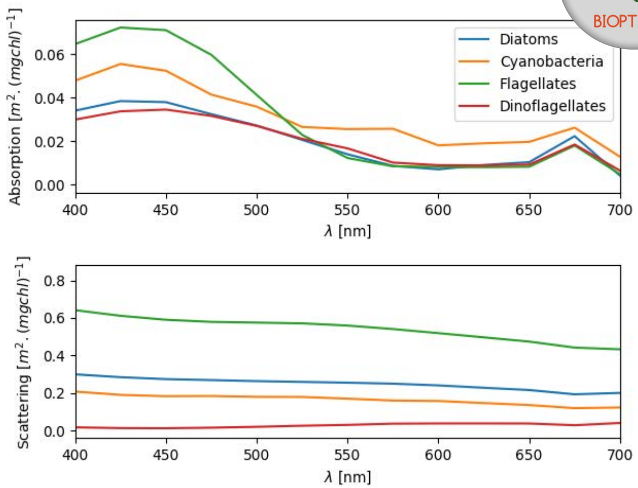
4) What are the benefits and best methodologies in assimilating the new radiometric information from SENTINEL satellite and BGC Argo floats in the model results?

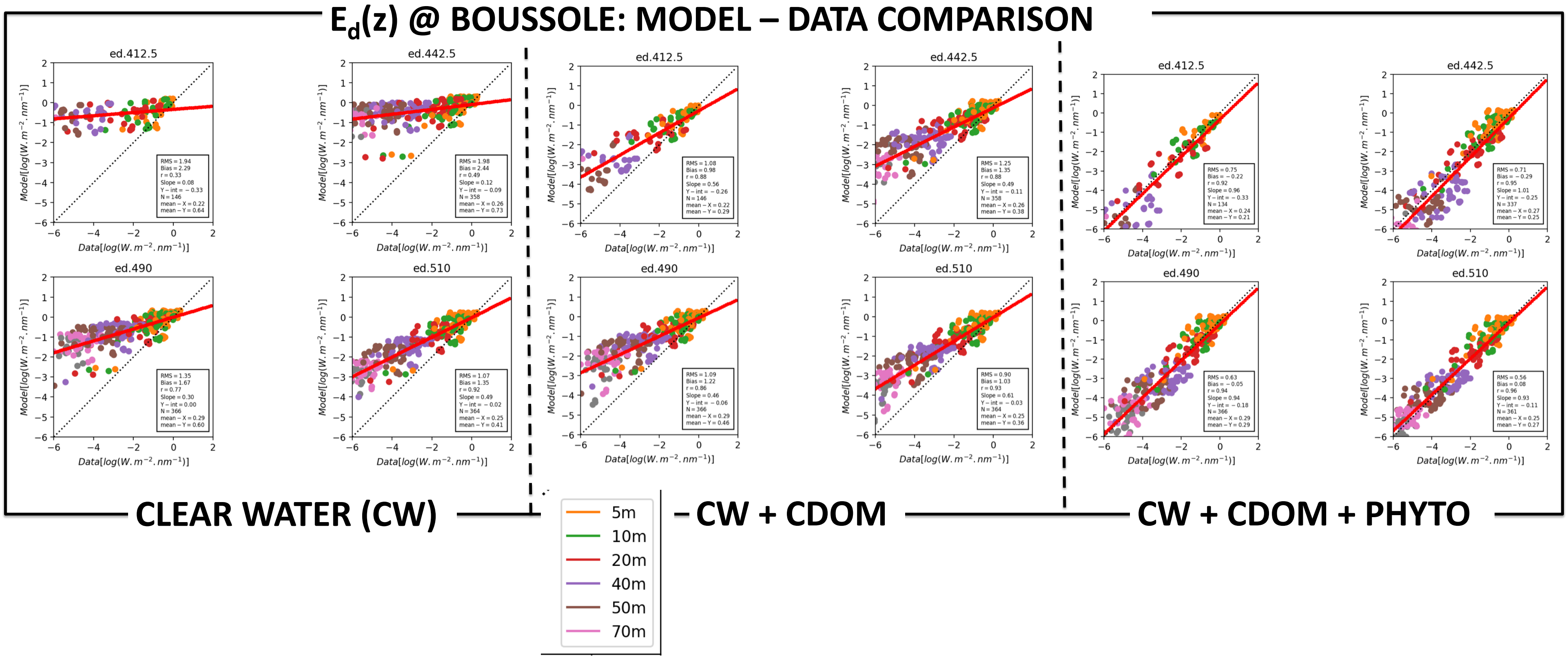
SATELLITE R_{rs} DATA STREAM



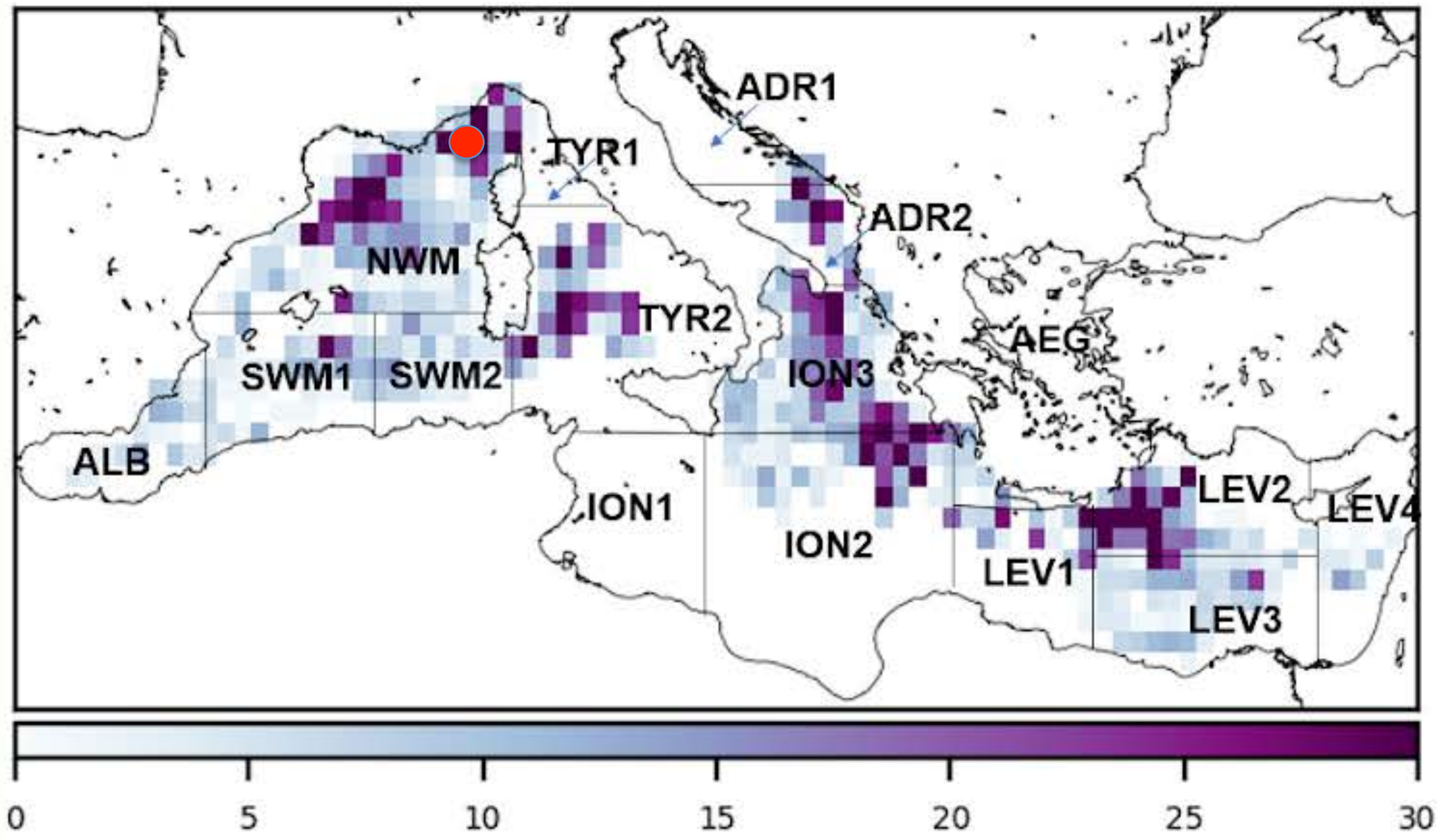
BOUSSOLE DATA STREAM

Period considered: 2011-2016
Input Data: Ed(0-),Es(0-) OASIM
CDOM: measured BOUSSOLE
Pigments: to derive absorption and scattering
Validation data: Ed(z)+Es(z) BOUSSOLE





BGC ARGO DATA STREAM



Unprecedented availability of data
~ 6000 profiles for radiometric measurements period (2012-2018)
Ed(380), Ed(412), Ed (490), PAR

BGC ARGO DATA STREAM

Data Direct insertion

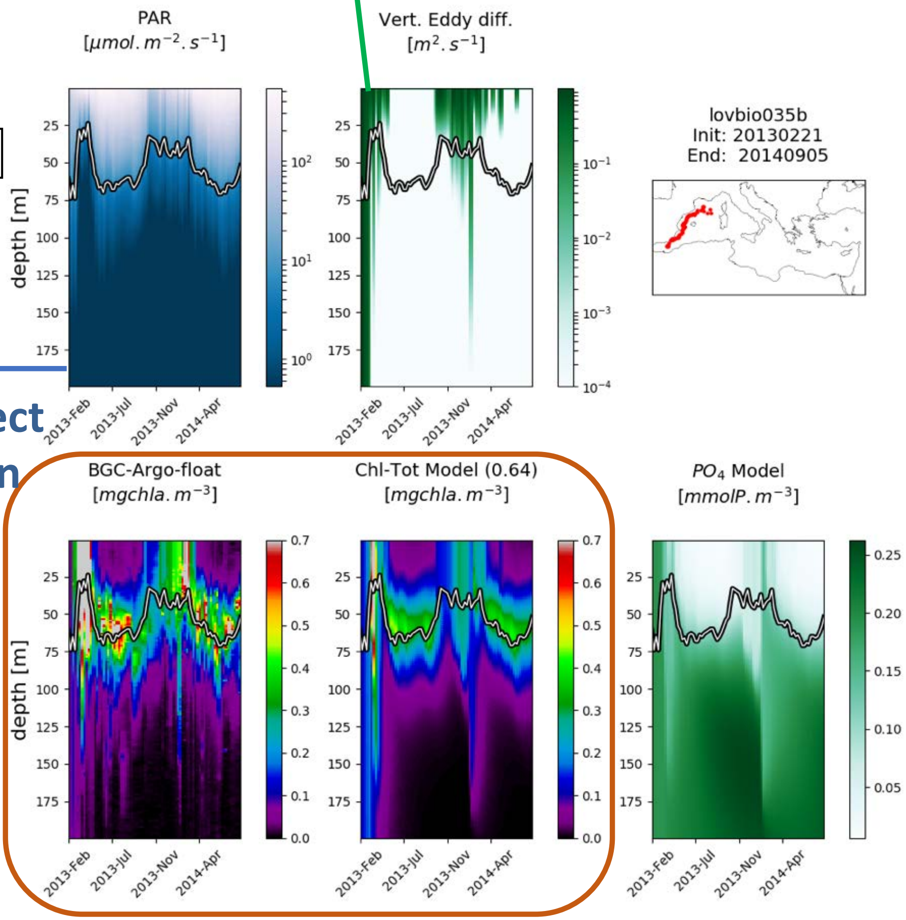
$$\begin{aligned}\partial_t C_i(z,t) &= \partial_z [\boxed{k_{V.E.D}(z,t)} \partial_z C_i(z,t)] \\ &+ v_{sink,i}\partial_z C_i(z,t) \\ &+ BFM_i(\boxed{T,S}, \boxed{Irr}, \overline{C}(z,t))\end{aligned}$$

BGC-Argo floats

Data Direct insertion

Chl-a comparison, data & model

Correlation of Hovmoeller (R →0.64)

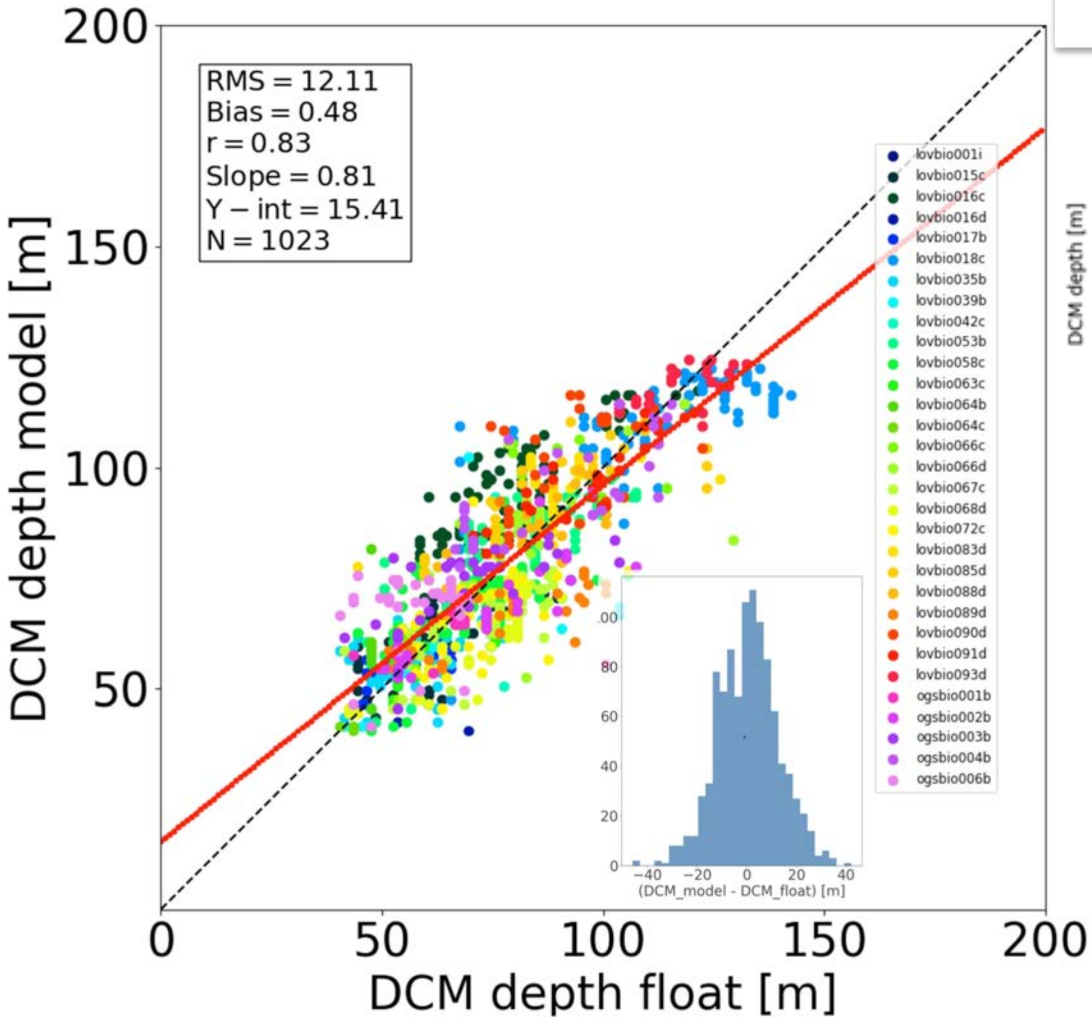


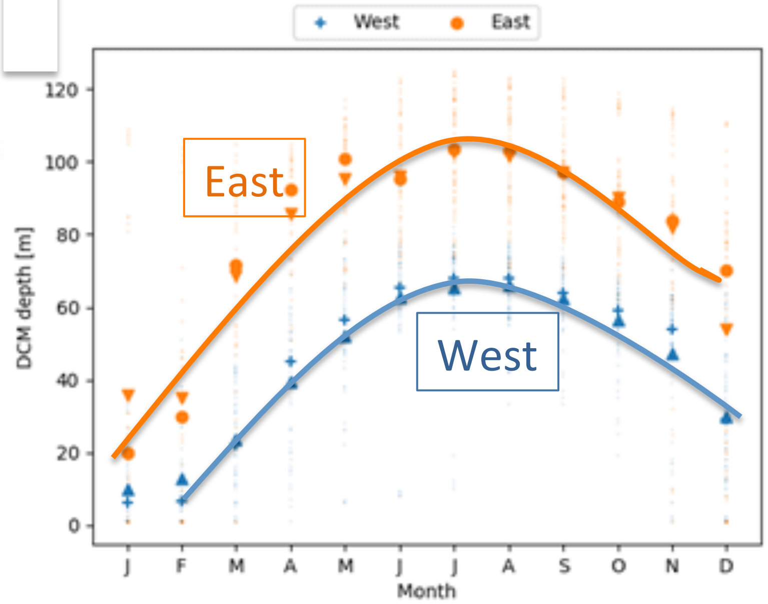
Additional OUTPUTs e.g. PO_4

Terzić et al, 2019 IRRADIANCE MEASUREMENTS→EXTREMELY IMPORTANT

BGC ARGO DATA STREAM

30 BGC Argo float for the period 2012, 2016: T,S, PAR, Chlorphyll





Terzić et al, 2019

<u>Process study</u>

Direct control by light in DCM

Secondary control by nutrients

MedBFM system: OGSTM-BFM model

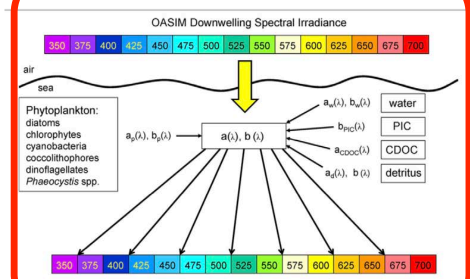
Mediterranean - MFC

Physical forcing
NEMO 3.6 daily at 1/16° and 72 z levels

Land & Atm. Forcings
high temporal resolution data for rivers and atm. forcing (toward operational)

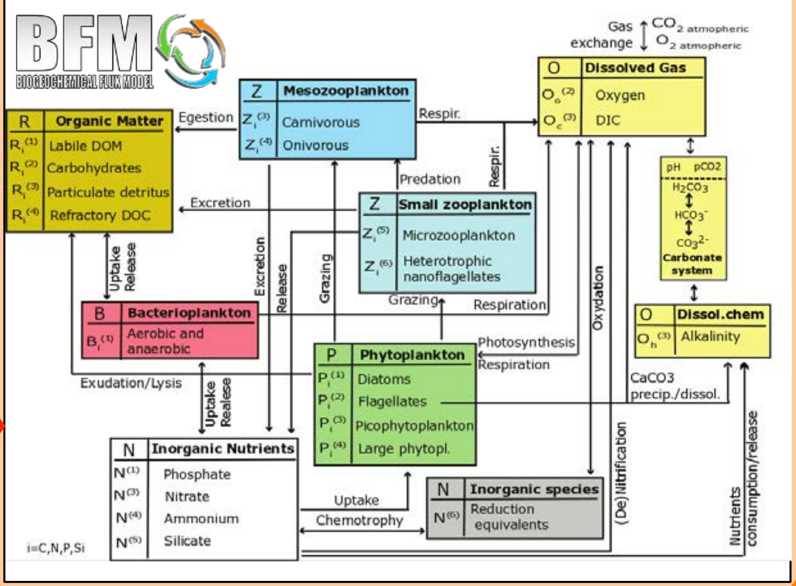
Boundary Conditions
coupling with CMEMS-GLOBAL and Dardanelles

Initial Conditions
MEDAR/MEDATLAS and 5-y hindcast spin-up



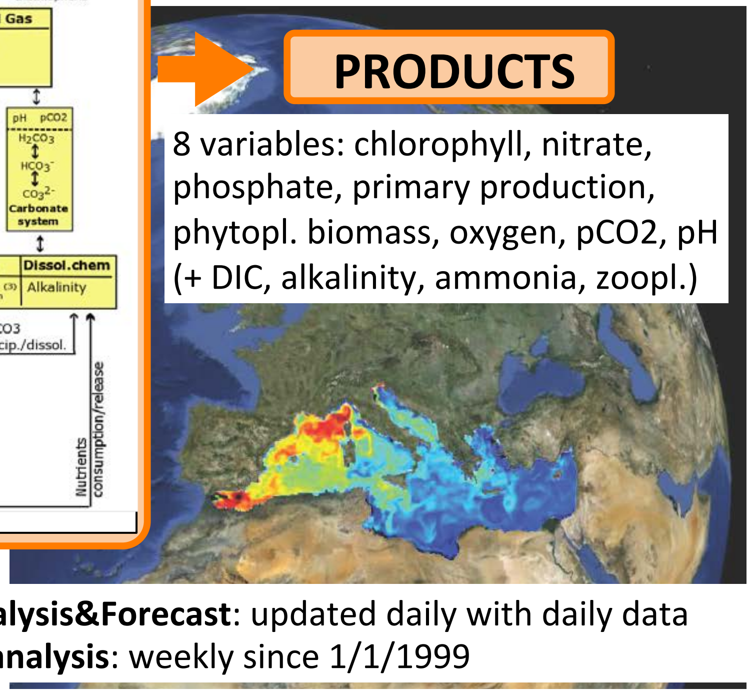
OGSTM - transport model
vvl formulation (non-linear free surface)

Biogeochemical Flux Model – BFM
51 variables; cycle of C, N, P, Si, O; carbonate system;



Observations:
Chlorophyll Satellite from CMEMS OC TAC

Assimilation
3DVAR-BIO
variational scheme; daily assimilation cycle

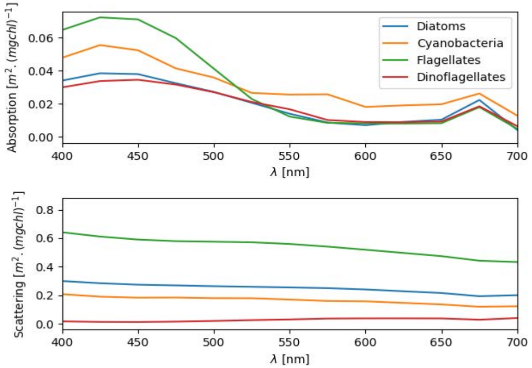


PRODUCTS

8 variables: chlorophyll, nitrate, phosphate, primary production, phytopl. biomass, oxygen, pCO2, pH (+ DIC, alkalinity, ammonia, zoopl.)

Analysis&Forecast: updated daily with daily data
Reanalysis: weekly since 1/1/1999

CDOM dynamics



Dutkiewicz et al., 2015, CDOM dynamics

Fraction DOM to CDOM	f_{cdom}	0.02	unitless
Bleaching rate for CDOM	ι_{cdom}	0.167	d^{-1}
Degradation rate for CDOM	d_{cdom}	0.003	d^{-1}
Light level for bleaching CDOM	I_{cdom}	60	$\mu\mathrm{E\,m^{-2}\,s^{-1}}$
CDOM absorption at λ_o	$c_{\mathrm{cdom}}(\lambda_o)$	0.18	$\mathrm{m^2\,(mmol\,C)^{-1}}$
Reference waveband	λ_o	450	nm
CDOM absorption spectral slope	s_{cdom}	0.021	$(\mathrm{nm})^{-1}$

~ 6 gg bleaching
~ 1 year other deg

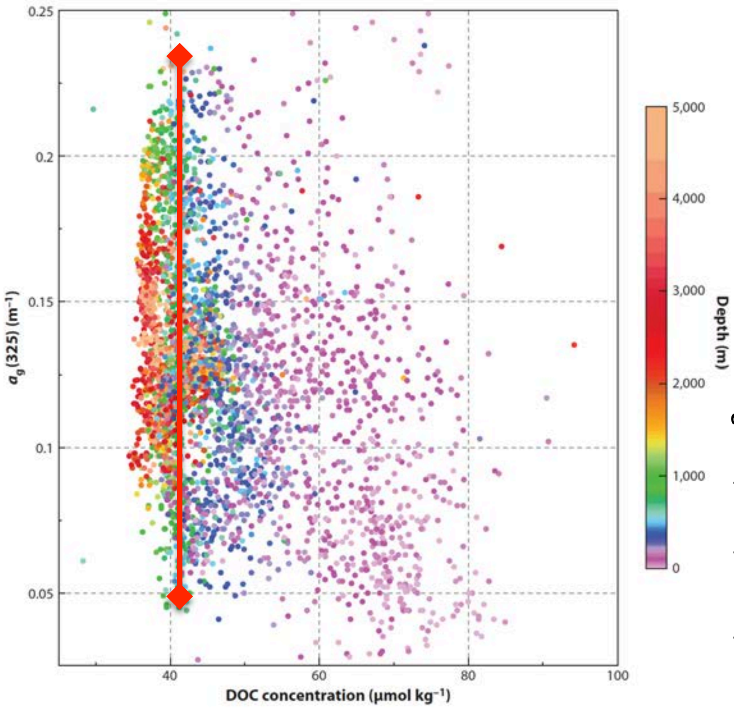
$$S_{\mathrm{CDOM}} = f_{\mathrm{cdom}} S_{\mathrm{DOM_S}} - \left[\gamma_{\mathrm{T}} d_{\mathrm{cdom}} + \iota_{\mathrm{cdom}} \min\left(\frac{\sum_{\lambda=400}^{\lambda=700} E_0(\lambda)}{I_{\mathrm{cdom}}}, 1\right)\right]\mathrm{CDOM},$$

$$a_{\mathrm{cdom}}(\lambda) = a_{\mathrm{cdom}}^{\mathrm{CDOM}}(\lambda)\mathrm{CDOM}$$

and

$$a_{\mathrm{cdom}}^{\mathrm{CDOM}}(\lambda) = c_{\mathrm{cdom}}(\lambda_o) e^{(-s_{\mathrm{cdom}}(\lambda-\lambda_o))},$$

CDOM ABSORPTION



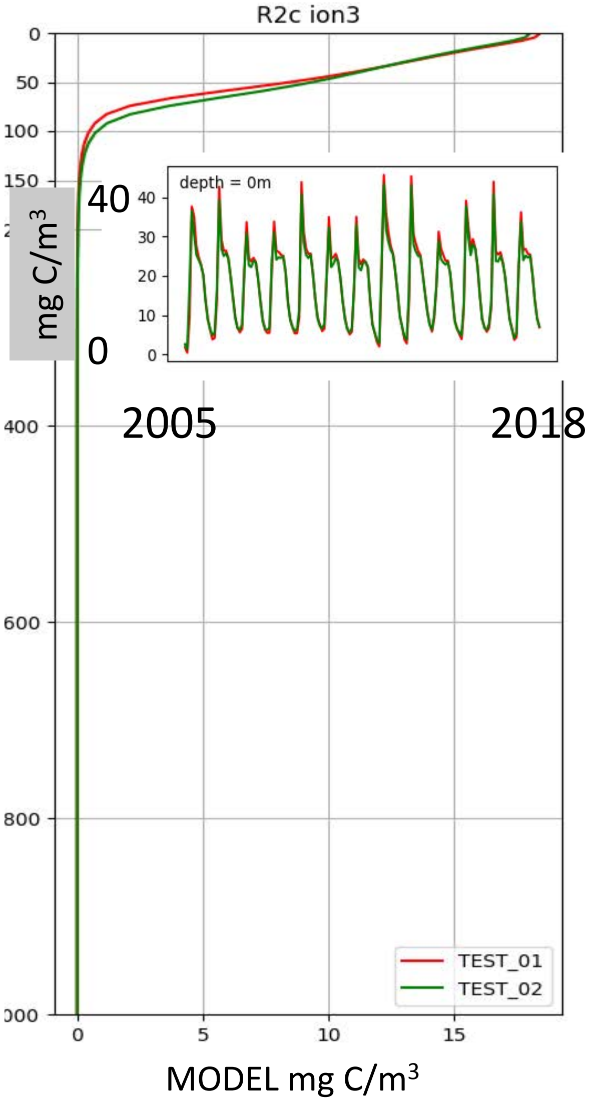
DOC CONCENTRATION

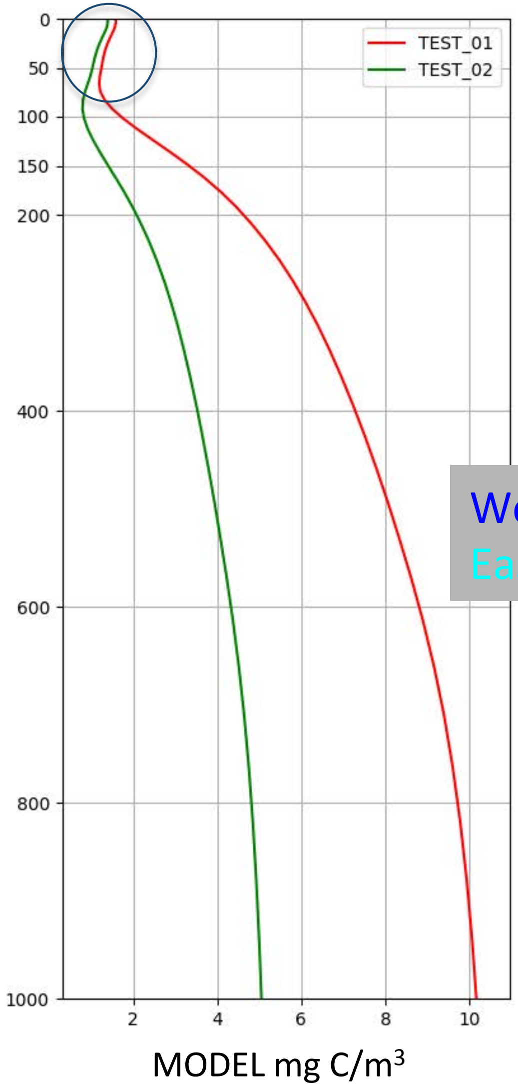
Nelson and Siegel, 2012

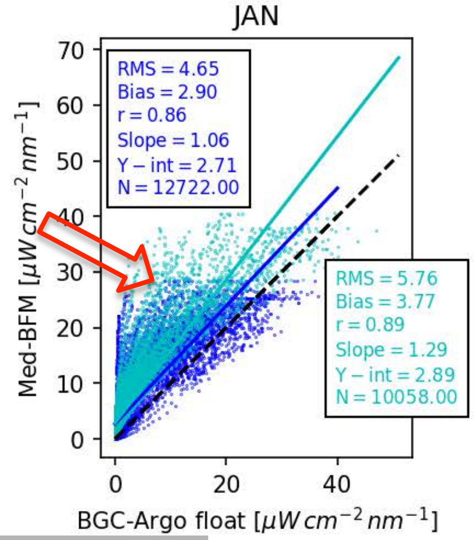
BGC-Argo DATA STREAM Ed (380 nm)

West: Slope 1.06
East : Slope 1.29

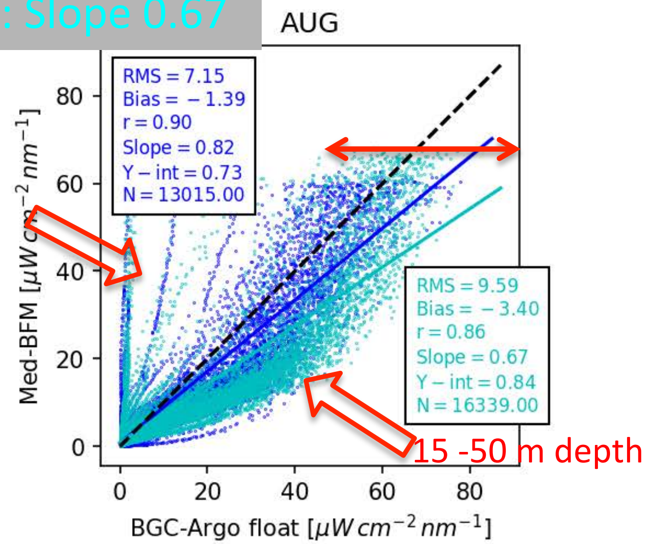
Semilabile DOC





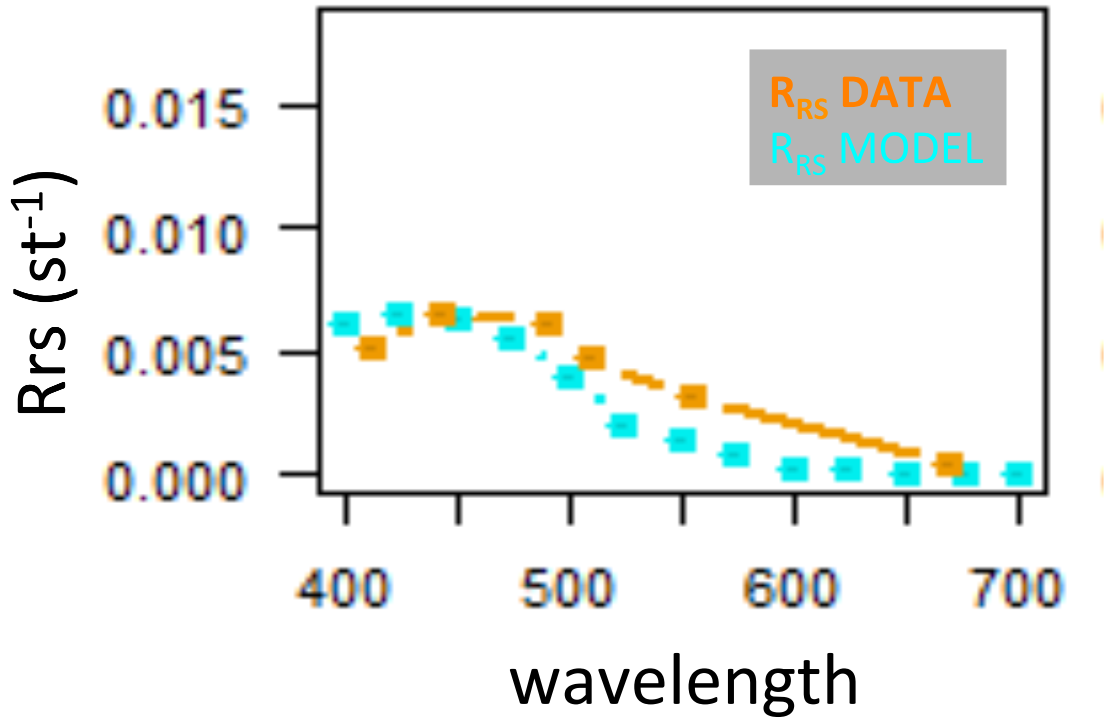


West: Slope 0.82
East : Slope 0.67



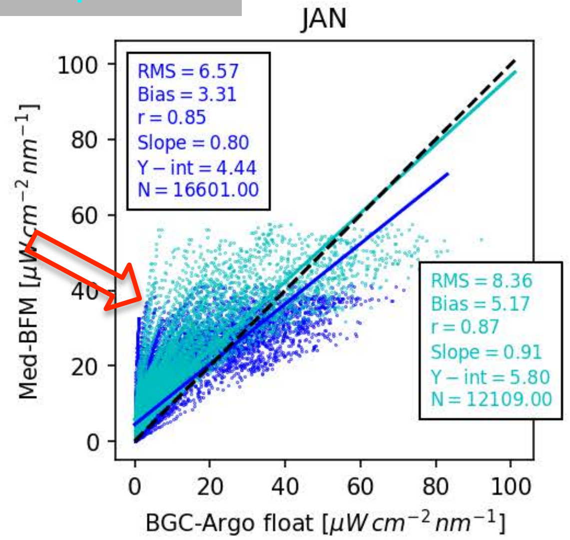
SATELLITE R_{rs} DATA STREAM

DATE: OC-CCI 4k monthly composite 2017 – August
MODEL: Med BFM system monthly average 2017 – August



BGC Argo DATA STREAM Ed (412 nm)

West: Slope 0.8
East : Slope 0.91



m

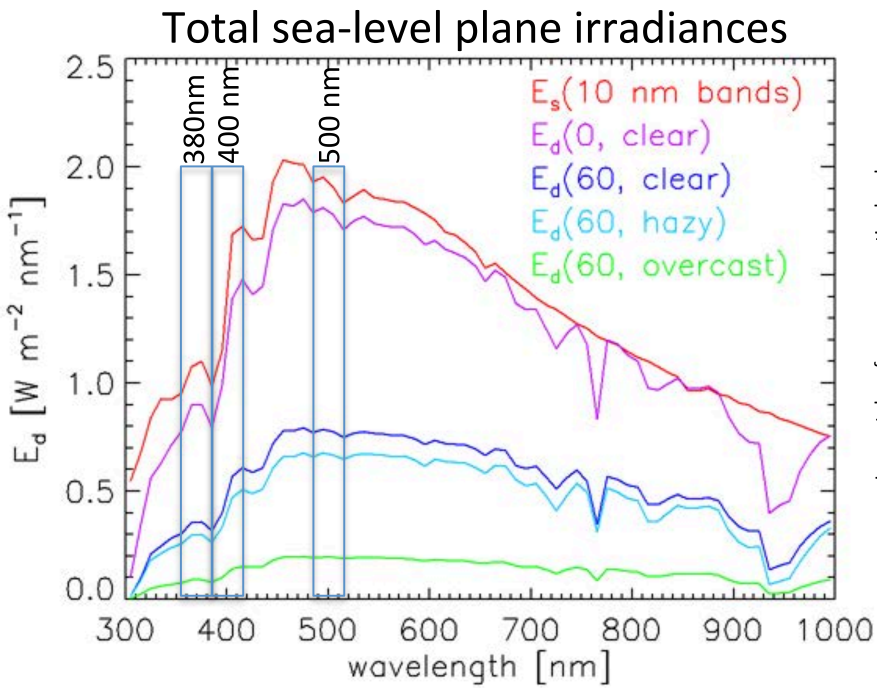
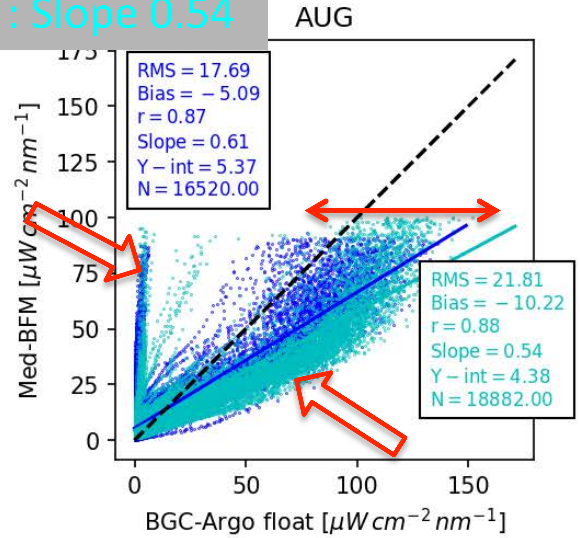


Image taken from ocean optics book
http://www.oceanopticsbook.info

West: Slope 0.61
East : Slope 0.54

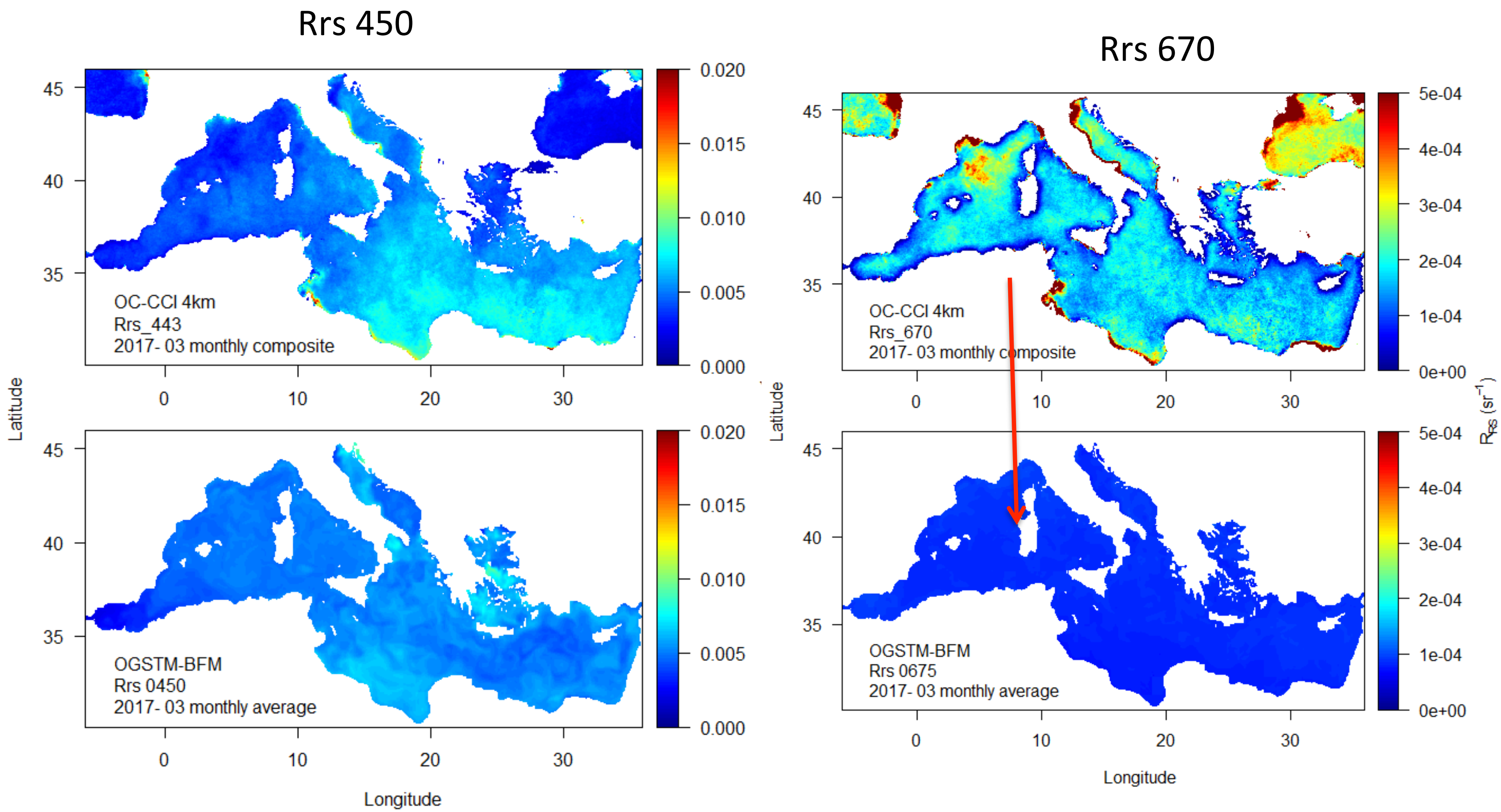


Increase the wavelength resolution of OASIM and in−water model to improve skill @ 412 nm

Error is compensated in Rrs (=Eu/(Ed+Es)/Q)

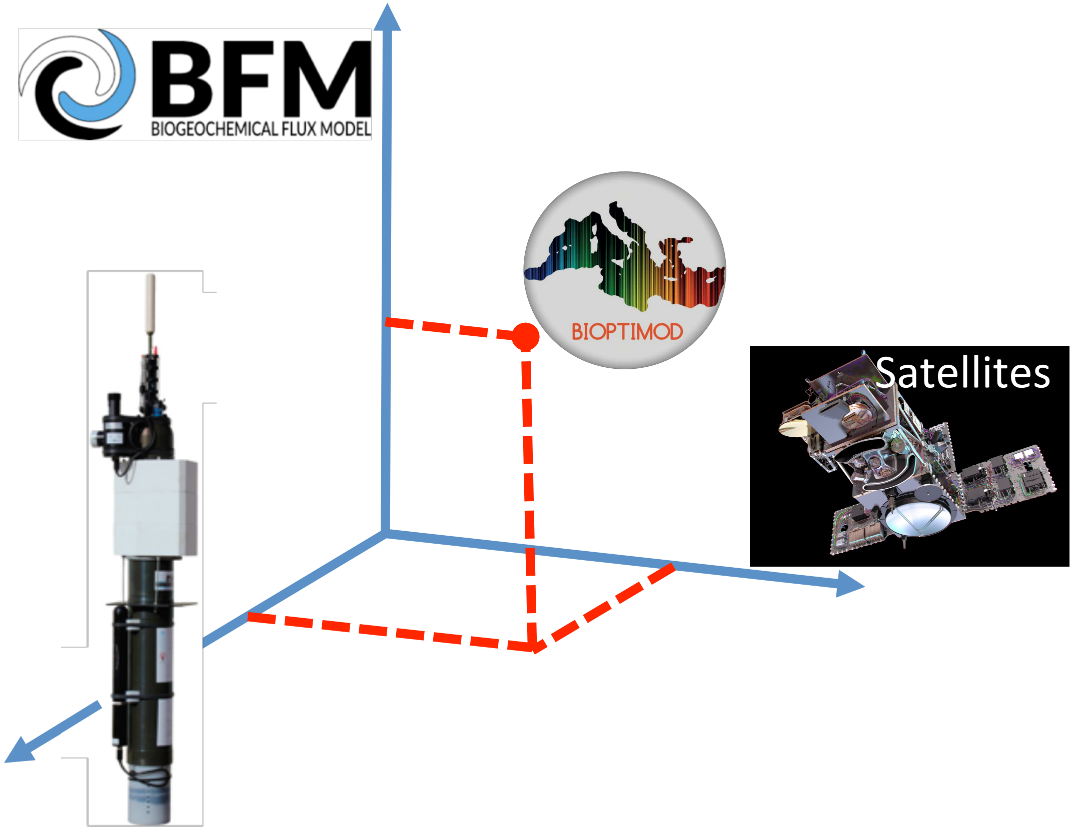
SATELLITE R_{rs} DATA STREAM

First example of simulated Rrs for the Mediterranean Sea



Additional information to be used for validation and assimilation in the model

BIOPTIMOD's strength:
Use and merging of data from different observational platforms



BGC-Argo floats

BIOPTIMOD's novelty:
Possibility of a ***3D comparison*** between:

BGC-Argo floats
MedBFM model
Satellite data

SUMMARY

Next generation BGC models will have as standard multispectral formulation of light propagation (Dutkiewicz et al. 2015; Gregg and Rousseaux, 2016)

In line with several remote sensing programs with multi or hyper spectral sensors (PRISMA, NASA Pace program).

Important to have radiometric measurements from BGC Argo float to cover the vertical dimension

Need to fill knowledge scientific gaps relation of CDOM to DOC to fully link radiometry with biogeochemical cycles

Thank you

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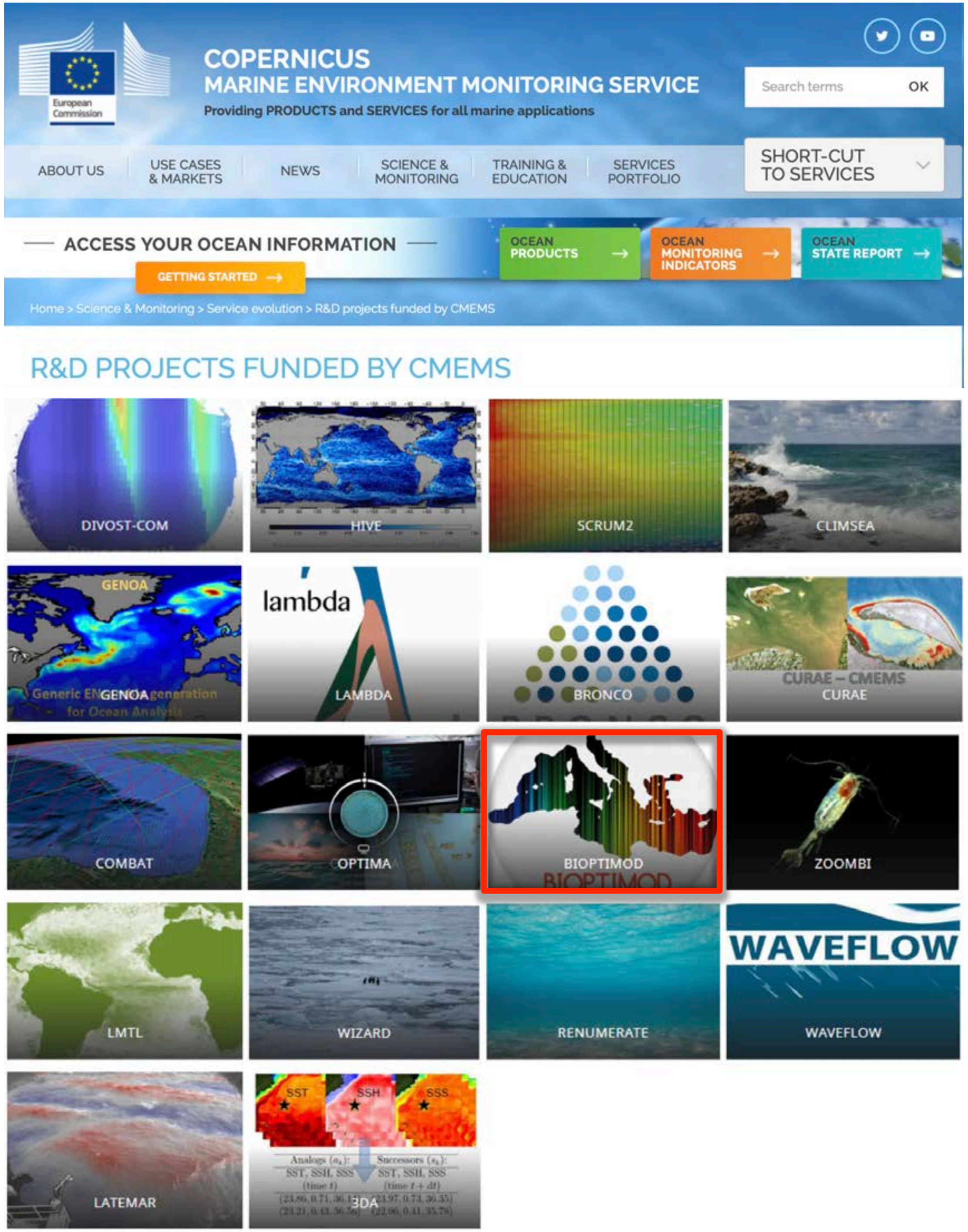
Service Evolution
Contract until
March 30, 2020



BIOPTIMOD

MedBFM system: OGSTM-BFM model + 3DVarBio

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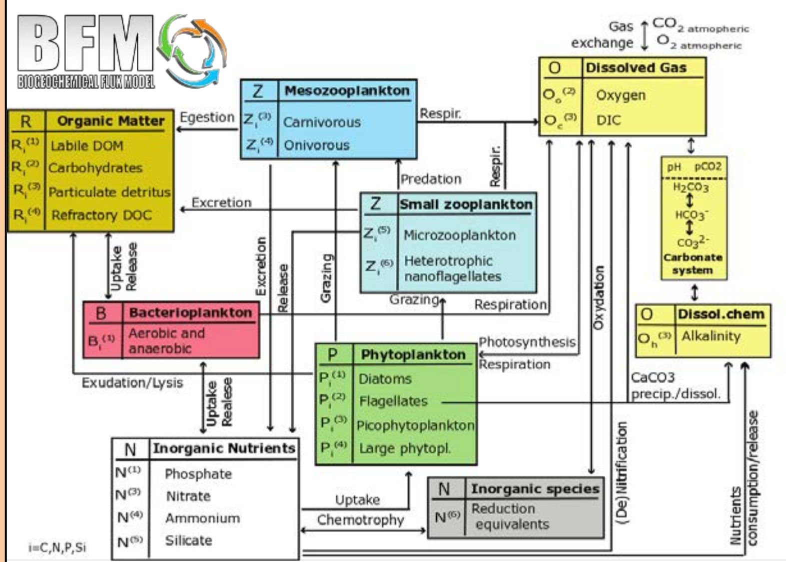

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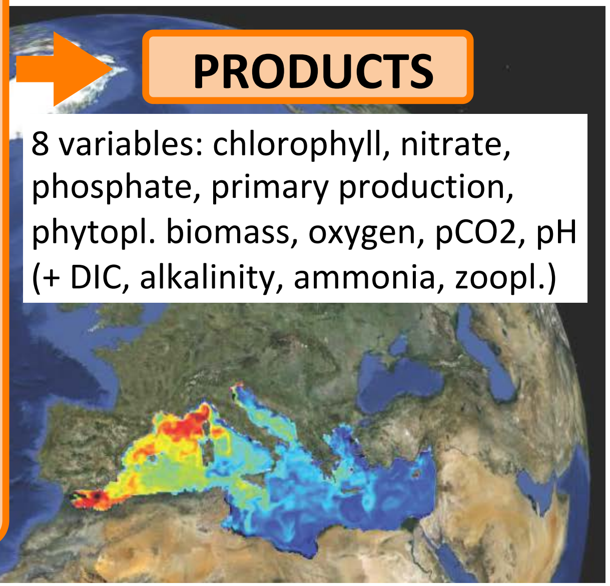
3DVAR-BIO
variational scheme; daily assimilation cycle



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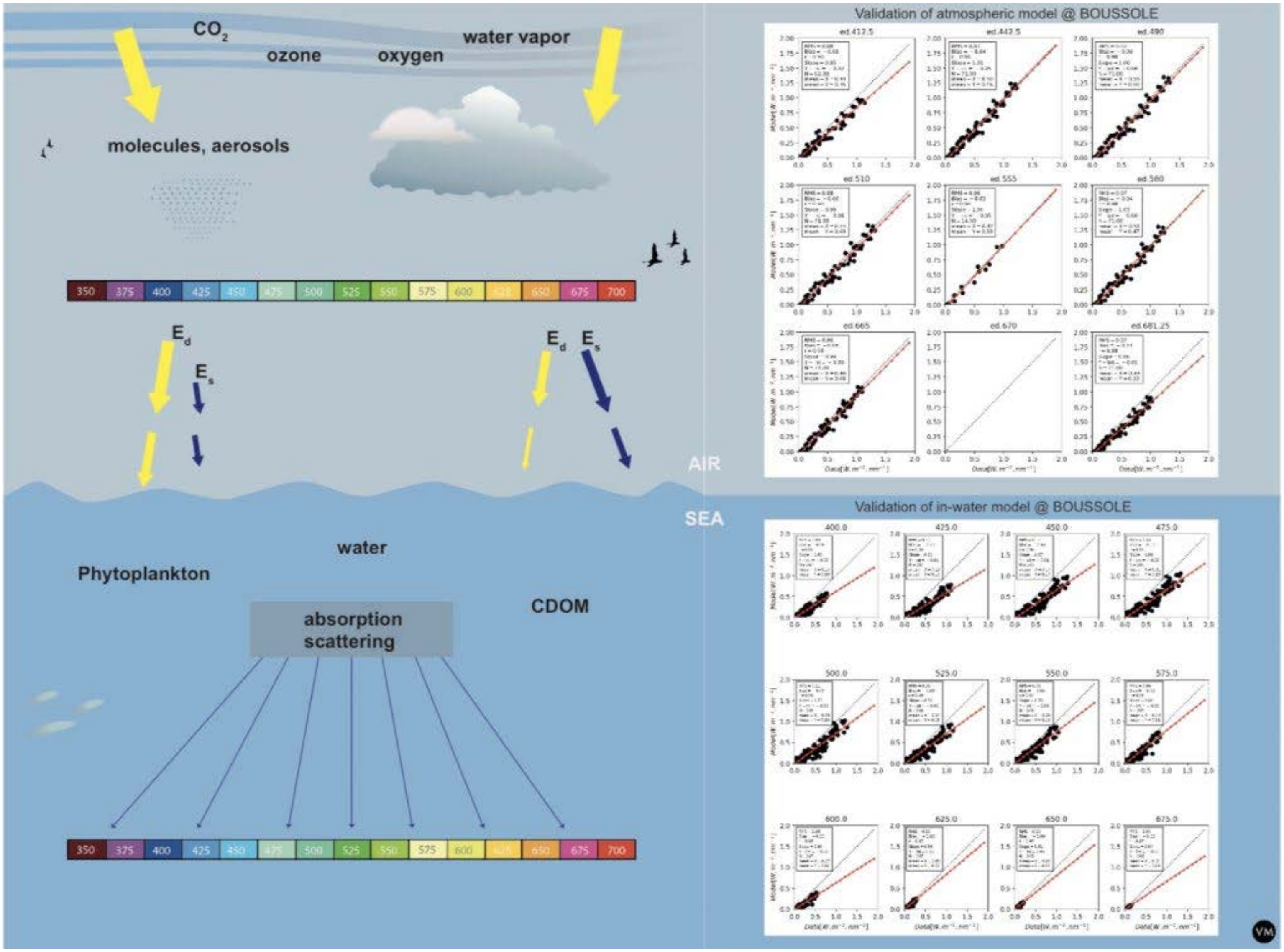
Reanalysis: weekly since 1/1/1999

THE COMPONENTS

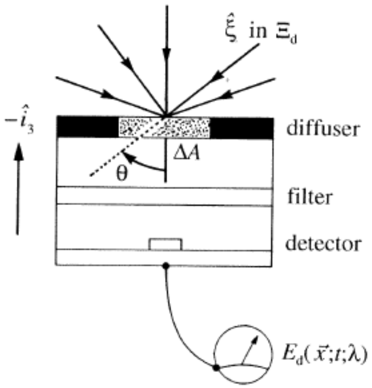


THE 3-STREAM RT

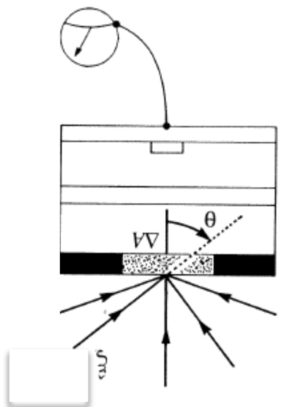
$$
\begin{aligned}
\frac{dE_d}{dz} &= -\frac{a+b}{\cos\theta_d}E_d \\
\frac{dE_s}{dz} &= -\frac{a+r_s b_b}{\overline{v}_s}E_s + \frac{r_u b_b}{\overline{v}_u}E_u + \frac{b-r_d b_b}{\cos\theta_d}E_d \\
-\frac{dE_u}{dz} &= -\frac{a+r_u b_b}{\overline{v}_u}E_u + \frac{r_s b_b}{\overline{v}_s}E_s + \frac{r_d b_b}{\cos\theta_d}E_d
\end{aligned}
$$

Gregg and Roisseaux, 2016
Dutkiewicz et al., 2015

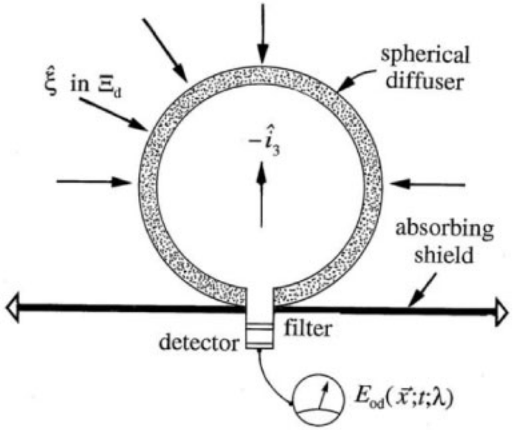
$E_d + E_s$



E_u



E_o



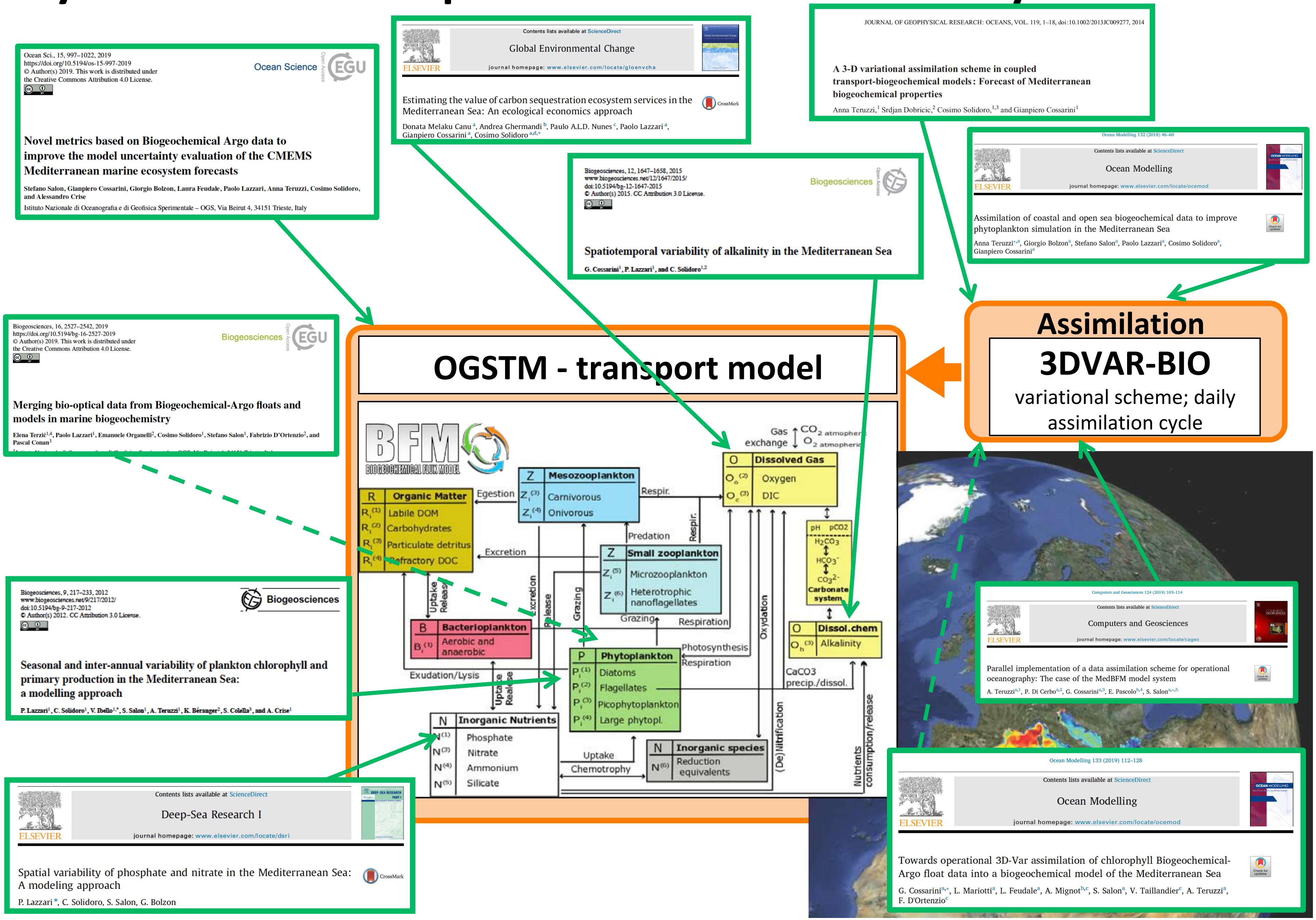
Ed, Es
BOUSSOLE
BGC ARGO FLOAT

Eu(0-)
[+ Ed(0-), Es(0-)]
Compute R_{rs}

E_0
Compute PAR
for BGC models

BOUNDARY VALUE PROBLEM

System evolution: improvement of the MedBFM system



OASIM INPUT DATA

Cloud properties (file modcld*.dat read by OASIM rdatopt.F subroutine)

OASIM variable	*Implementation in BIOPTIMOD*	*P*
cloud cover [%]	ERA-Interim: “Total cloud cover” [(0-1)]	(1)
cloud optical thickness [-]	computed within OASIM, Eq. (1)	-
cloud liquid water path [g m^{-2}]	ERA-Interim: “Total column cloud liquid water” [kg m^{-2}]	(2)
cloud droplet effective radius [μm]	based on MODIS climatology as in GC2009	-

ERA INTERIM ☺

ERA INTERIM ☺

Aerosols properties (file modaer*.dat read by OASIM rdatopt.F subroutine)

OASIM variable	*Implementation in BIOPTIMOD*	*P*
aerosol optical thickness [-]	based on MODIS data as in GC2009	-
aerosol asymmetry parameter [-]	based on MODIS data as in GC2009	-
aerosol single scattering albedo [-]	based on MODIS data as in GC2009	-

MODIS AEROSOL

MODIS AEROSOL

MODIS AEROSOL

Atmospheric properties (opt*.dat read by OASIM rdatopt.F subroutine)

OASIM variable	*Implementation in BIOPTIMOD*	*P*
surface pressure [mb]	ERA-Interim: “surface pressure” [Pa]	(3)
wind speed [m/s]	ERA-Interim: “10 metre wind speed” [m/s]	-
relative humidity [%]	computed from ERA-Interim data	(4)
ozone [DU]	ERA-interim: “Total column ozone” [kg m^{-2}]	(5)
precipitable water [cm]	computed from ERA-Interim data	(6)

ERAINTERIM ☺

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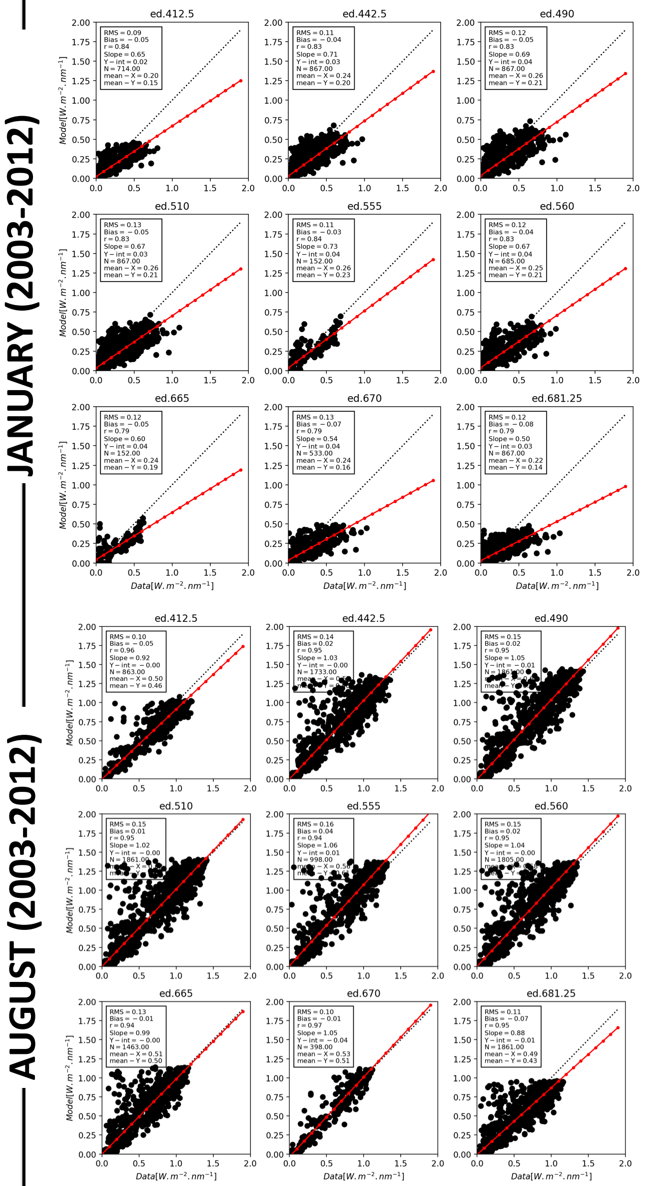
ERAINTERIM ☺

ERAINTERIM ☺

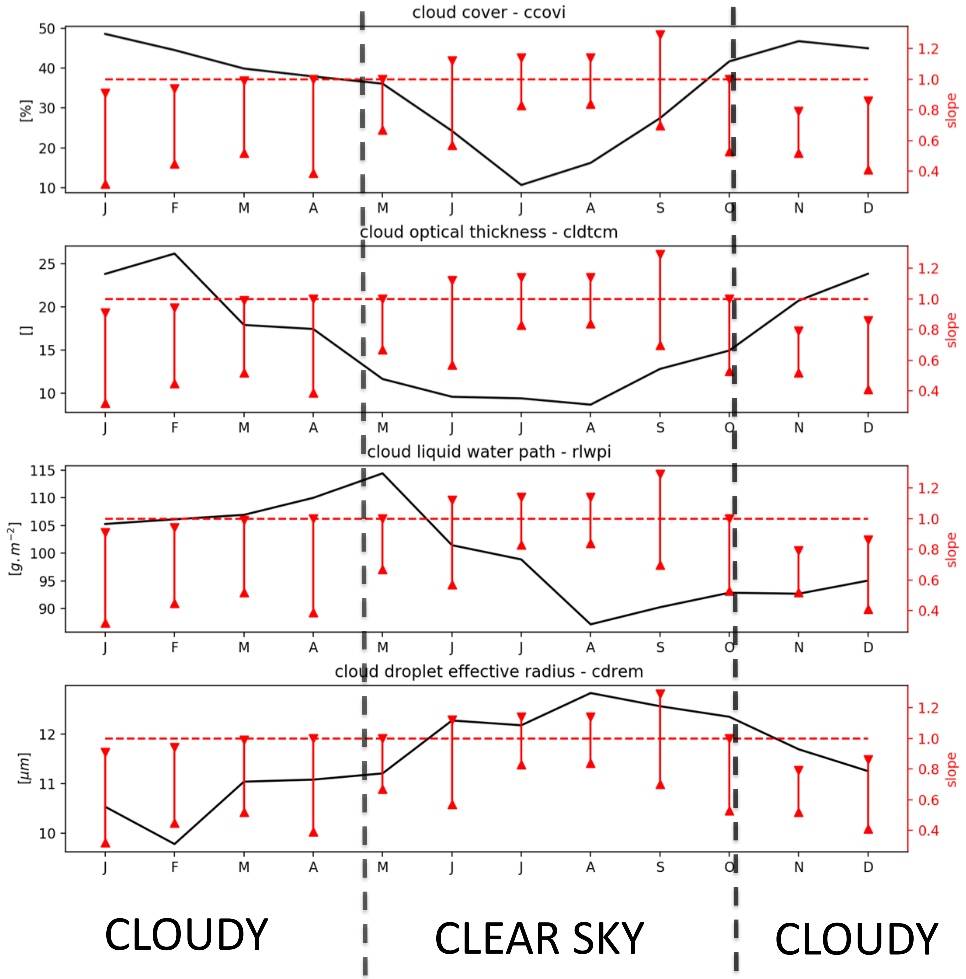
ERAINTERIM ☺

BOUSSOLE DATA STREAM

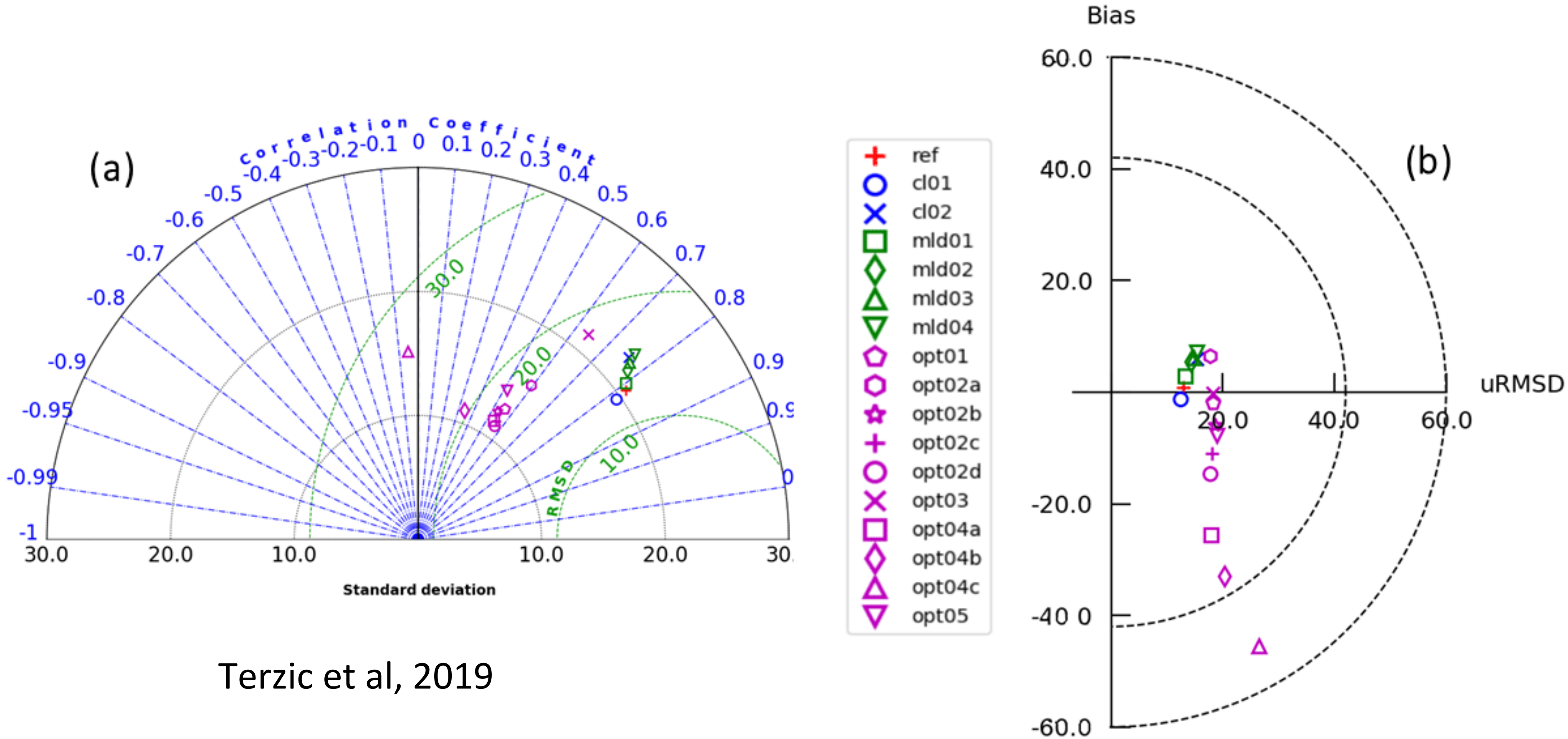
Downward Irradiance $E_d(0-)$ @ BOUSSOLE MODEL VS DATA



EFFECT OF CLOUDS ON E_d (0-)



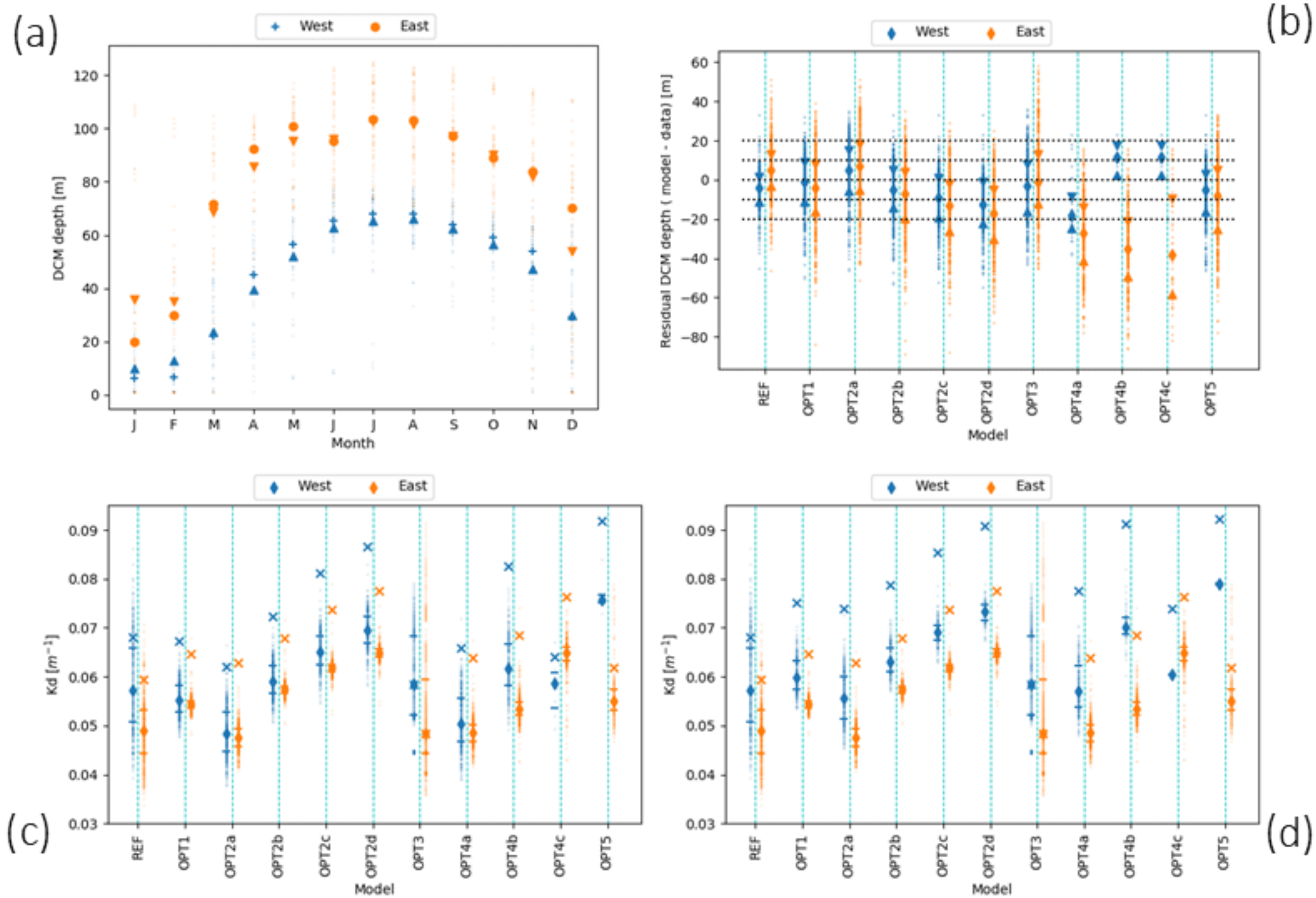
BGC ARGO DATA STREAM



Terzic et al, 2019

Task 2: Development of 1-D bio-optical model embedded in BFM

1) **DCM depth variability and water light attenuation**



Terzic et al, 2019

BIOPTIMOD

Task 2: Development of 1-D bio-optical model embedded in BFM

1) Developments performed by 1-D “virtual mooring” version of the Med-MFC model (@ Boussole and for BGC Argo float trajectories)

2**) Extension of the current bio-optical model used for BFM from mono to multi spectral formulation (wavelength resolution to be determined), new parameters → multi spectral absorbance and scattering for different components (PFT and CDOM)**

3) Computation of scattering components by means of parametric formulae (Baird, 2016; Kirk, 1991) and by direct solving of the scattering component (Aas, 1987; Ackelson et al., 1994; Gregg and Rousseaux, 2016)

4) New bio optical model integrated with photosynthesis module related to multi-spectral formulation for phytoplankton

5) **CDOM** formulation and interaction with **multi-spectral optical model** (e.g. Dutkiewicz et al., 2015).

BIOPTIMOD

Task 2: BIO-optical models: Three stream approach

$$\frac{dE_d(\lambda)}{dz} = -C_d(\lambda)E_d(\lambda)$$
$$\frac{dE_s(\lambda)}{dz} = -C_s(\lambda)E_s(\lambda) + B_u(\lambda)E_u(\lambda) + F_d(\lambda)E_d(\lambda)$$
$$\frac{dE_u(\lambda)}{dz} = +C_u(\lambda)E_u(\lambda) - B_s(\lambda)E_s(\lambda) - B_d(\lambda)E_d(\lambda)$$

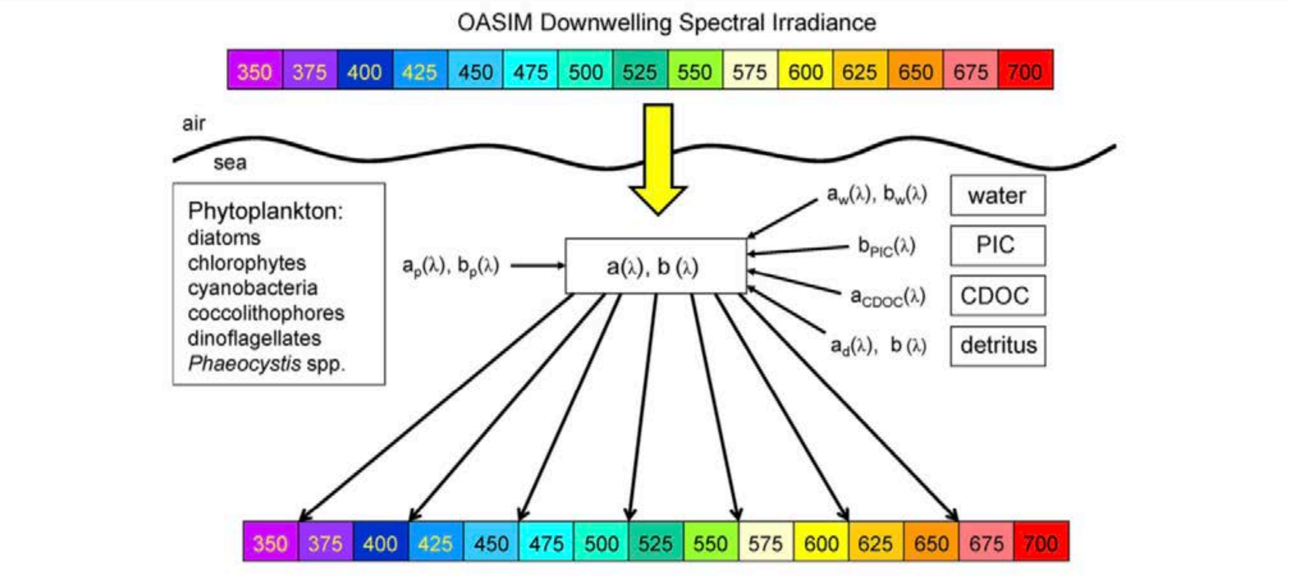


FIGURE 2 | OASIM spectral downwelling radiance and dependencies in the ocean. Shown are the visible bands. Inherent optical properties (spectral absorption coefficient a[λ], and spectral scattering coefficient b[λ]) are derived from spectral characteristics of water, phytoplankton groups, detritus, PIC, and CDOC. OASIM tracks spectral irradiance from the sun through the atmosphere into and through the oceans.

$$C_d(\lambda) = \frac{a(\lambda) + b(\lambda)}{< \mu_d >}$$
$$C_s(\lambda) = \frac{a(\lambda) + r_s b_b(\lambda)}{< \mu_s >}$$
$$C_u(\lambda) = \frac{a(\lambda) + r_u b_b(\lambda)}{< \mu_u >}$$
$$B_d(\lambda) = \frac{b_b(\lambda)}{< \mu_d >}$$
$$B_s(\lambda) = \frac{r_s b_b(\lambda)}{< \mu_s >}$$
$$B_u(\lambda) = \frac{r_u b_b(\lambda)}{< \mu_u >}$$
$$F_d(\lambda) = \frac{(1 - b_b')b(\lambda)}{< \mu_d >}$$

BIOPTIMOD

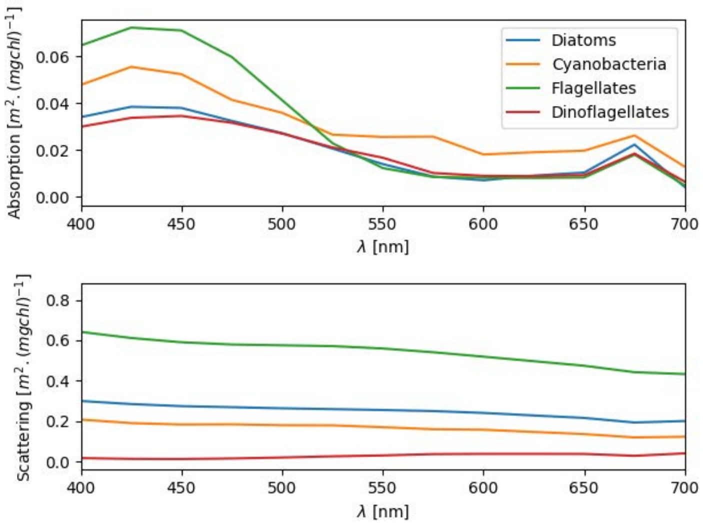
Task 2: BIO-optical models: Definition of the PFT

NASA NOBM

Diatoms (Diatoms)

Cyanobacteria Coccolithophores (Flagellates)

Dinoflagellates (DinoFlagellates)



DUTKIEWICZ

Diatoms

Large eukariotes

Trychodesmium

Coccolithophores

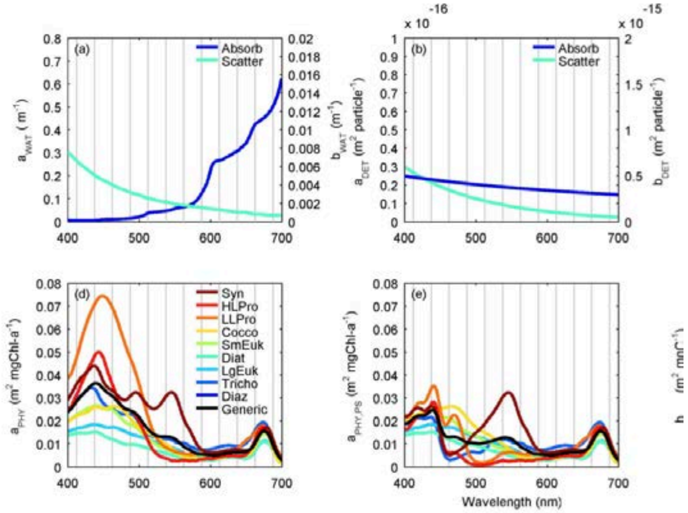
Unicellular diazotrophos

Picoeukariotes

Synechococcus

High-light Prochlorococcus

Low-ligh Prochlorococcus



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Task 2: Development of 1-D bio-optical model embedded in BFM

1) Developments performed by 1-D “virtual mooring” version of the Med-MFC model (@ Boussole and for BGC Argo float trajectories)

2) Extension of the current bio-optical model used for BFM from mono to **multi spectral** formulation (wavelength resolution to be determined), new parameters → multi spectral absorbance and scattering for different components (**phyto** and **CDOM**)

3) Computation of **scattering** components by means of parametric formulae (Baird, 2016; Kirk, 1991) and by direct solving of the scattering component (Aas, 1987; Ackelson et al., 1994; Gregg and Rousseaux, 2016)

4) New **bio optical** model integrated with photosynthesis module related to **multi-spectral** formulation for **phytoplankton**

5) CDOM formulation and interaction with multi-spectral optical model (e.g. Dutkiewicz et al., 2015).

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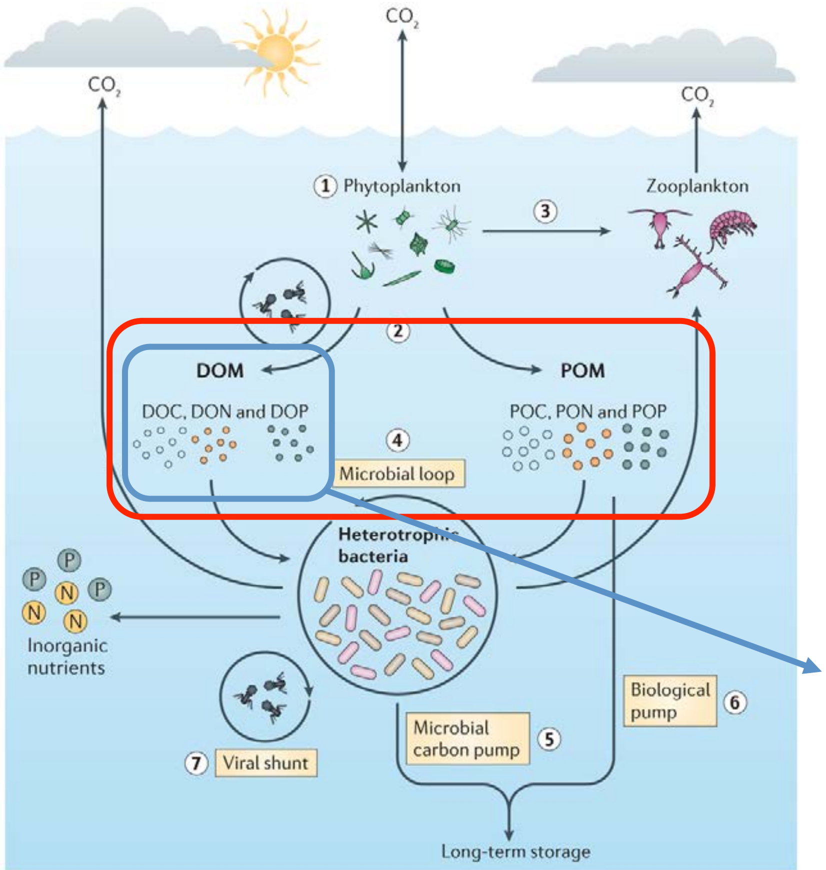
5) CDOM formulation and interaction with multi-spectral optical model (e.g. Dutkiewicz et al., 2015).



Nature Reviews | Microbiology

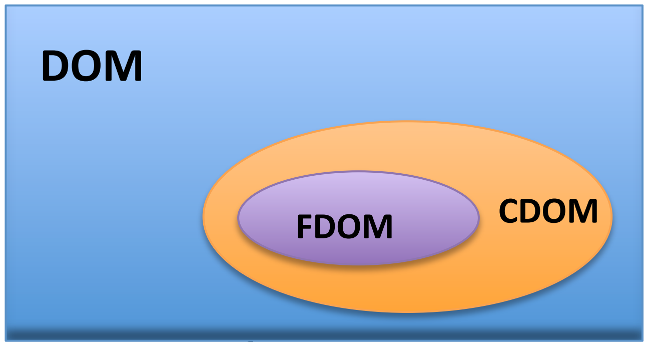
An upgraded description of DOM and its **photochemically active** fraction – **CDOM** (*chromophore* - part of an organic compound that can absorb light).

$$\mathrm{CDOM} = f_{CDOM}\ \mathrm{DOM} \quad \text{or} \quad \mathrm{DOM} = (1 - f_{CDOM})\ \mathrm{DOM} + f_{CDOM}\ \mathrm{DOM}$$

S_{CDOM} = f_{CDOM} [POM degradation + phyto- and zoo-plankton organic matter fraction (mortality + respiration + grazing)] **SOURCES**

–

CDOM degradation rate – CDOM bleaching rate **SINKS**



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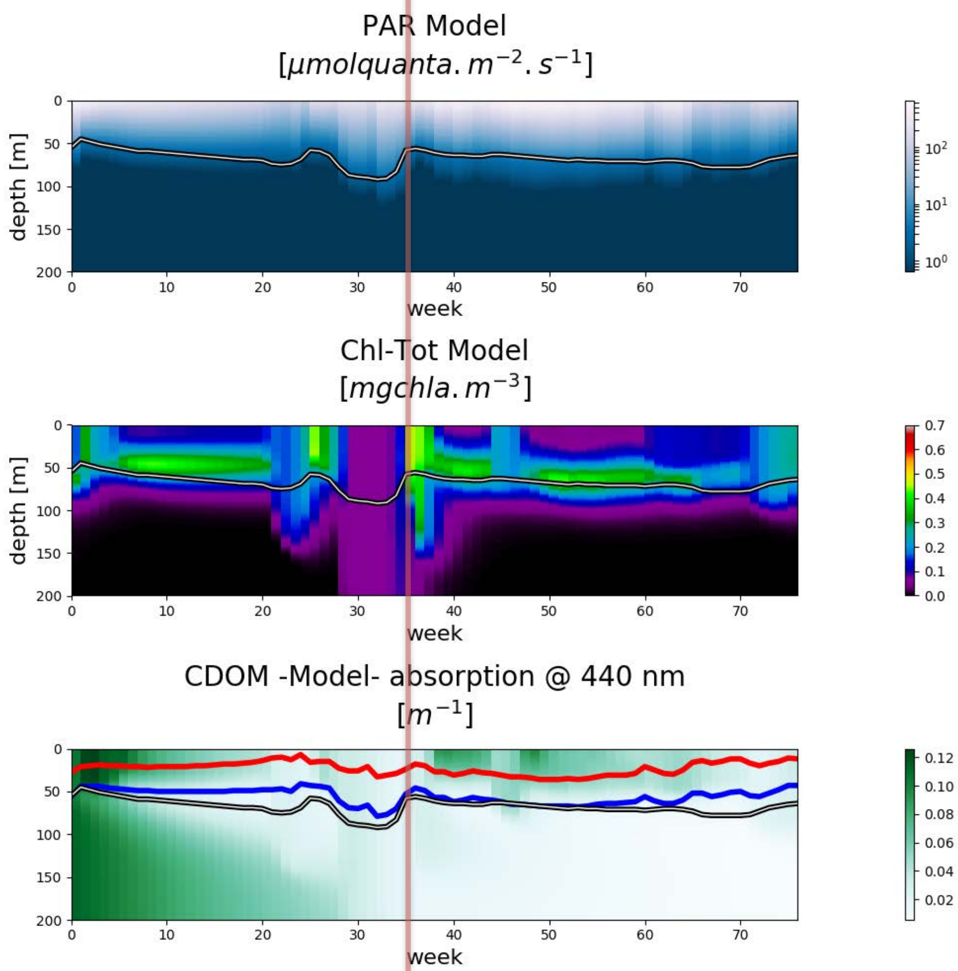
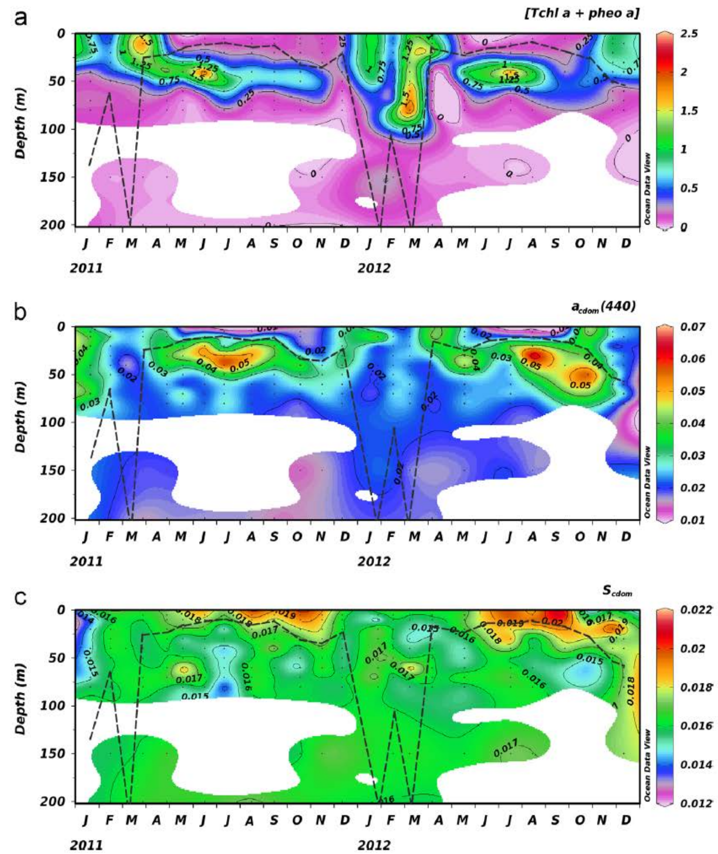
Task 2: Development of 1-D bio-optical model embedded in BFMv5 - CDOM module





Organelli et al., 2014

Terzić et al., 2019

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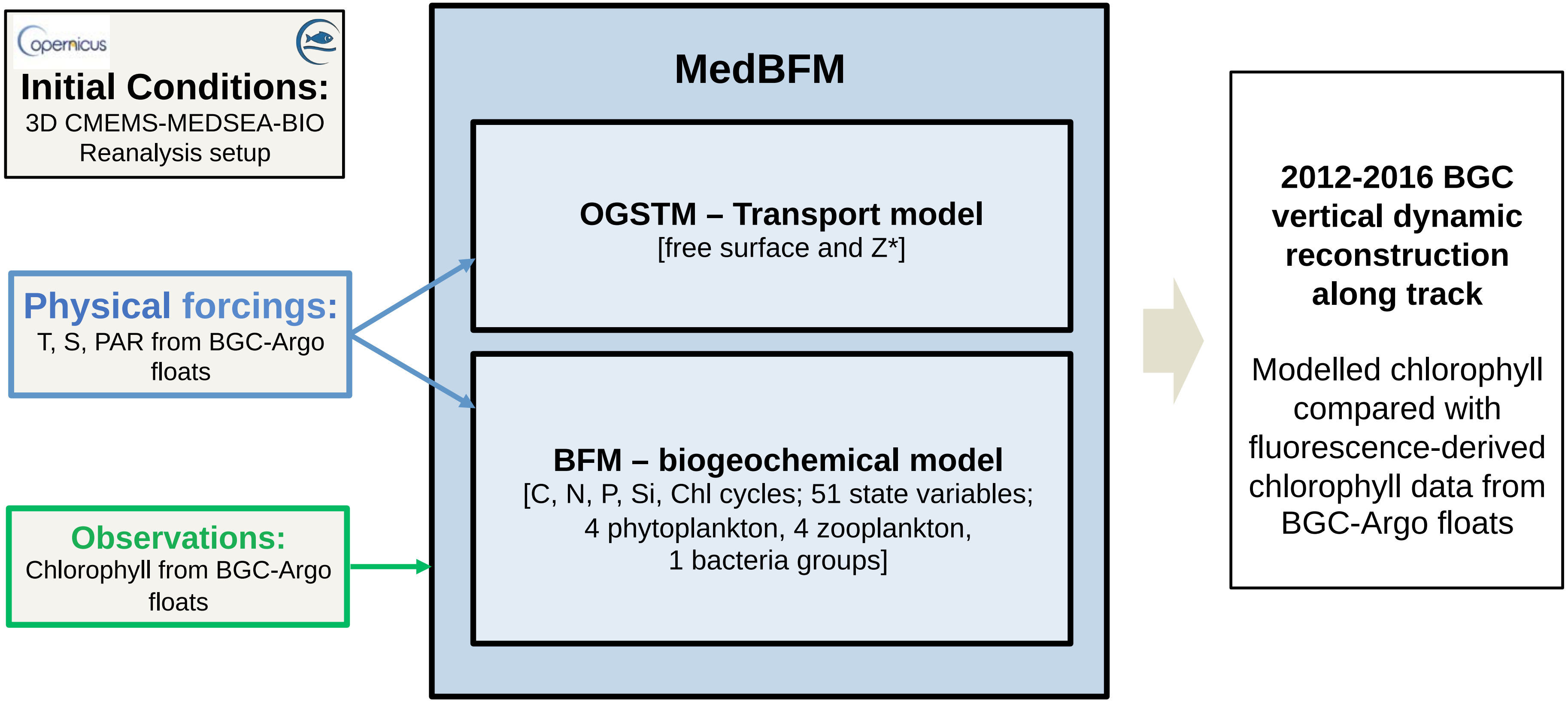
Task 2: Development of 1-D bio-optical model embedded in BFM



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Subtask 1.1: Results

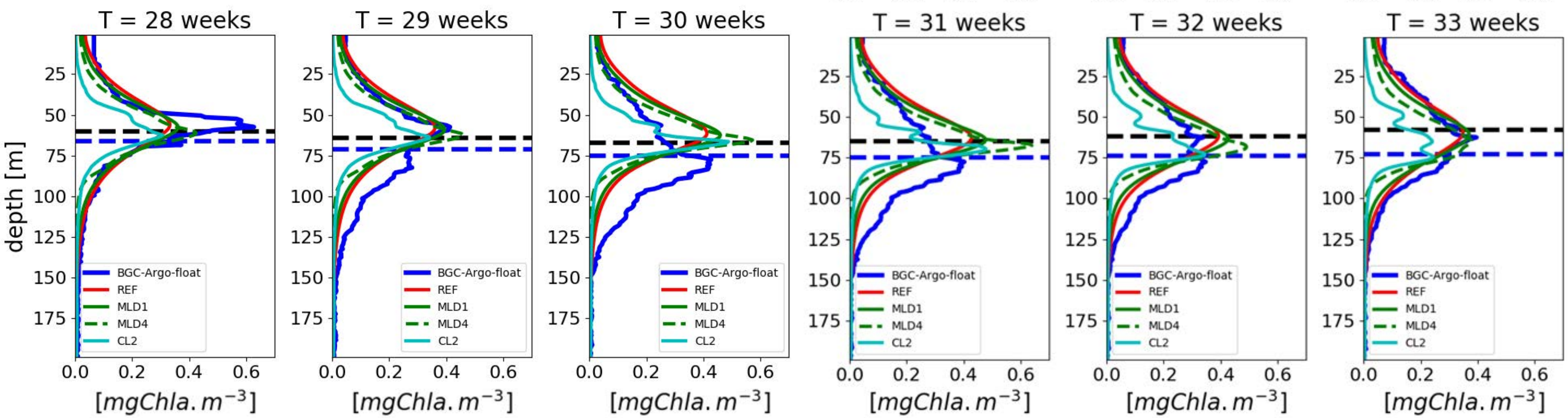
- ✓ Successfully selected the algorithm to compute the downward irradiance at sea surface.
- ✓ OASIM model coupled with ECMWF ERA INTERIM
- ✓ Model is corroborated with BOUSSOLE/BGC Argo float data with encouraging results
- ✓ Manuscript documenting the results in preparation
- ✓ Data shared with MED Black Sea 2012 daily freq., are you interested?

Next steps …

- Comparing OASIM results with ECMWF and MEDMFC short wave radiation products
- Reflectance data from Copernicus catalogue and water leaving radiance @ BOUSSOLE validation of the model developed in Task 2
- Comparing different PFT/PSC descriptions in terms of skill with data (Uitz et al. 2006; Dutkiewicz et al. 2015; Gregg and Rousseaux, 2016; Di Cicco et al., 2018)
- Test the feasibility of optical measurements direct assimilation (Remote sensing Rsr)

Task 2 Development of 1-D bio-optical model embedded in BFM

1) Developments performed by 1-D “virtual mooring” version of the Med-MFC model (@ Boussole and for BGC Argo float trajectories)



DCM plots of MLD1 and MLD4 mixing models ($D_v^{background} = 10^{-4}$ and 10^{-6} m^2/s respectively) + **REF** optical model with and without (continous light – CL2) the **diurnal variability**.

Increasing D_v → reduction of the profile‘s patchiness.

blue line: euphotic depth z_{eu} ;

black line: depth where measured PAR = 0.5 mol quanta m^{-2} day^{-1} (Mignot et al., 2014)

Combining daily-averaged irradiances with lowest diffusivity rates ($D_v^{background} = 10^{-6}$ m^2/s, simulation CL2) results in **additional relative chlorophyll maxima** at surface layers ("T = 33 weeks"), as well as in **increased patchiness** of the entire vertical profile.

lovbio035b float trajectory
Start: 21.02.2013
End: 05.09.2014

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Task 2: Development of 1-D bio-optical model embedded in BFM

1) Developments performed by 1-D "virtual mooring" version of the Med-MFC model (@ Boussole and for BGC Argo float trajectories)

Model Reference simulation present rather Gaussian smooth curve

BGC-Argo float show much irregular curves

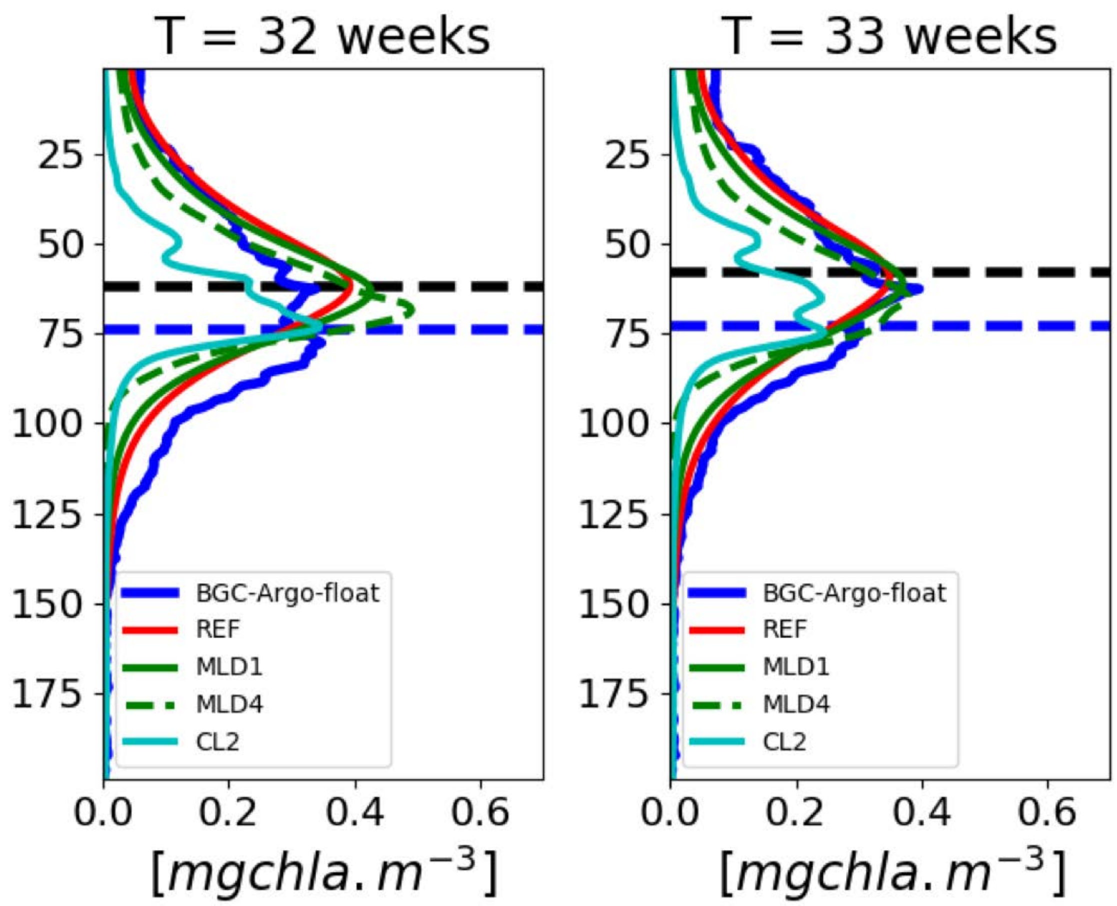
KISS simplified model predicts that

$$L_c \propto \sqrt{\frac{D}{\mu}}$$

Diffusion

Growth rate

Lowering backgorund diffusion to $10^{-6}\ m^2.s^{-1}$ profile increases it's complexity but only if diel cycle variability is removed !!



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Task 2: Development of 1-D bio-optical model embedded in BFM

Sensitivity analysis of different parameterizations

SIM	MODEL DESCRIPTION
REF	PAR from BGC-Argo floats ; $D_v^{background} = 10^{-4} m^2 s^{-1}$
CL1	as REF with continuous daily light
CL2	as REF with continuous daily light and $D_v^{background} = 10^{-6} m^2 s^{-1}$
MLD1	as REF with $D_v^{background} = 5\,10^{-5} m^2 s^{-1}$
MLD2	as REF with $D_v^{background} = 10^{-5} m^2 s^{-1}$
MLD3	as REF with $D_v^{background} = 5\,10^{-6} m^2 s^{-1}$
MLD4	as REF with $D_v^{background} = 10^{-6} m^2 s^{-1}$
OPT1	Riley: $K_d(PAR) = 0.04 + 0.054\,Chl^{\frac{2}{3}} + 0.0088$ Chl
OPT2a	$K_d(PAR) = \mathrm{a}\,Chl^b + \mathrm{c}$
OPT2b	
OPT2c	
OPT2d	
OPT3	$K_d(PAR)$ for the first optical depth $z_{od} = z_{eu}/4.6$
OPT4a	as OPT2a + Chl degradation to CDOM - time scale 1 day
OPT4b	as OPT2a + Chl degradation to CDOM - time scale 1 week
OPT4c	as OPT2a + Chl degradation to CDOM - time scale 1 month
OPT5	as OPT2a + CDOM following Dutkiewicz et al. (2015)

REF model with light data from floats

Continous daily light experiments CL1 and CL2 – other models include **diurnal variability**

Different **mixing** models with optical (PAR) data from BGC-Argo floats (**REF)**

Optical models, where K_d(PAR) is described as a function of chlorophyll concentration

Kd calculated as the local slope of ln(Ed) for layers of 15 m thickness for the euphotic depth range

Impact of CDOM on light propagation

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