MODELING OF BIOGEOCHEMICAL CYCLES: CURRENT STATE, RECENT ADVANCES AND REMAINING CHALLENGES

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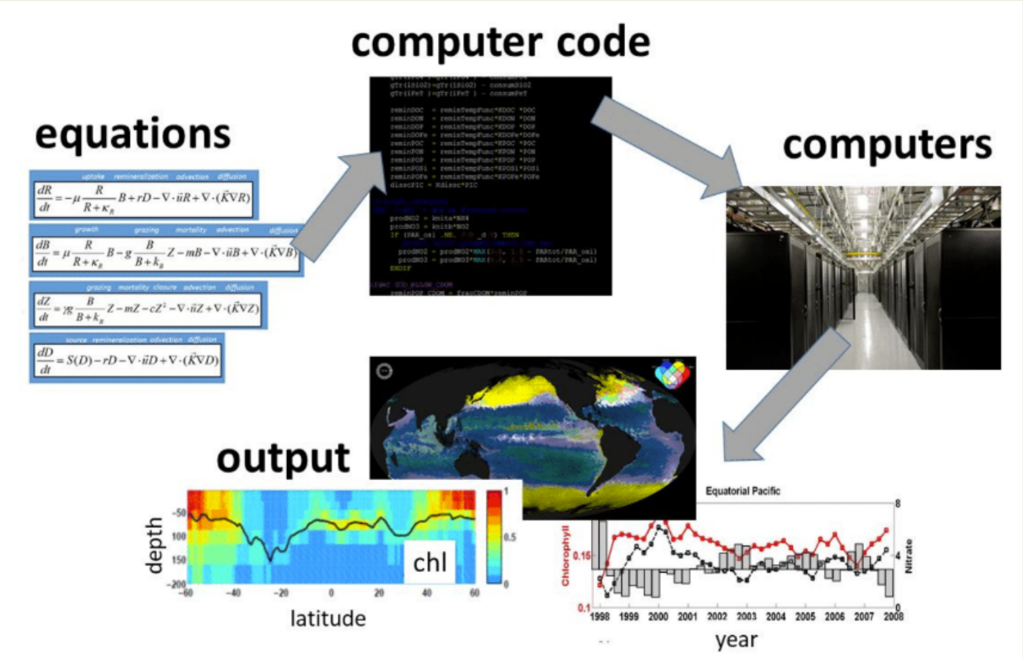
1. Biogeochemical models: current states

- Biogeochemical models used for hindcast or reanalysis, forecast
- Models differ in their degree of complexity and the processes their represent
- Representations of biogeochemical processes in models are associated with some degree of uncertainties



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- Highly empirical, attempt to describe non-linear processes such as photosynthesis, zoo grazing etc through idealized formulations
- Even most observable parameters (e.g. phyto grow rate) include substantial uncertainty
- Identification of the best parameters to use in the model usually requires a lengthy process of fine-tuning carried out manually or occasionally in an automated fashion

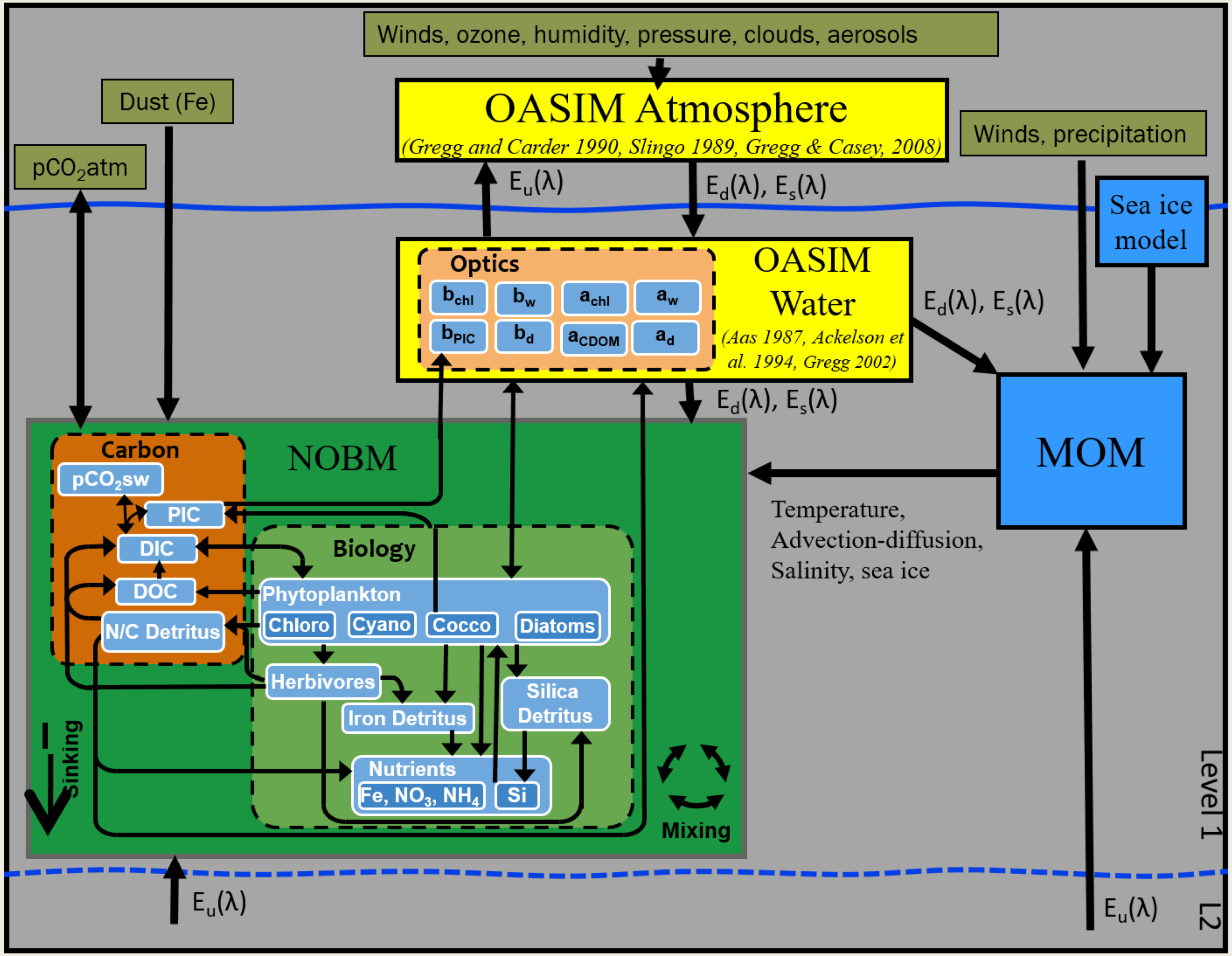

Winds, ozone, humidity, pressure, clouds, aerosols
OASIM Atmosphere
(Gregg and Carder 1990, Slingo 1989, Gregg & Casey, 2008)
Dust (Fe)
pCO_2atm
Winds, precipitation
$E_u(\lambda)$
$E_d(\lambda)$, $E_s(\lambda)$
Sea ice model
Optics
b_{chl} b_w a_{chl} a_w
b_{PIC} b_d a_{CDOM} a_d
OASIM Water
(Aas 1987, Ackelson et al. 1994, Gregg 2002)
$E_d(\lambda)$, $E_s(\lambda)$
$E_d(\lambda)$, $E_s(\lambda)$
MOM
NOBM
Carbon
pCO_2sw
PIC
DIC
DOC
N/C Detritus
Biology
Phytoplankton
Chloro
Cyano
Cocco
Diatoms
Herbivores
Iron Detritus
Silica Detritus
Nutrients
Fe, NO_3, NH_4
Si
Sinking
Mixing
Temperature, Advection-diffusion, Salinity, sea ice
Level 1
L2
$E_u(\lambda)$
$E_u(\lambda)$

TABLE 1 | Examples of analysis and prediction tools for ocean biogeochemistry and ecosystems.

Model acronym, reference	Region[1]	Mode[2]	Product class[3]	Type of DA (if any)	Data used for DA	Data used validation	Link to products
NEMO-PISCES[a]	Global	O, PO, RD	P, R, S	NA	No assimilation of biogeochemical data	Ocean color; *In situ* nutrients, chlorophyll, oxygen, pCO_2, pH	marine.copernicus.eu
NEMO-ERSEM[b]	NWS	O, PO	P, R, S	3D-Var	Ocean color total chlorophyll and PFT chlorophyll; DA for spectral PFT absorption and glider and float data is under development	Ocean color; *In situ* nutrients, chlorophyll, oxygen, fCO_2, pH	marine.copernicus.eu
POLCOMS-ERSEM[c]	NWS	RD	R	EnKF	Ocean color: total chlorophyll; PFT chlorophyll; spectral diffuse light attenuation coefficient	Ocean color; *In situ* nutrients, chlorophyll, oxygen, fCO_2, pH	portal.ecosystem-modelling.pml.ac.uk
ROMS-NEMURO[d]	CCS	PO, RD	P, R	4D-Var	Satellite chlorophyll, physical data	*In situ* chlorophyll, nutrients, oxygen, rates	oceanmodeling.ucsc.edu
eReefs[e]	GBR	PO, RD	R	EnKF	Spectral ocean color	Chlorophyll fluorescence from	www.ereefs.info
ROMS-ECB[f]	CB	PO, RD	P, R	none			
ROMS-DO[g]	GoMex	PO	P	none			
ROMS-Fennel[h]	GoMex	RD	R, S	none			
OGSTM-BFM[i]	Med	O	R, P	3D-Var			
MITgcm-BFM[k]	NAdr	PO, RD	P	none			
GHER-BAMHBI[j]	Black Sea	O	R, P	SEEK filter			

[1]*Regional acronyms: NWS, northwest European Shelf Seas; CCS, California Current S*
Med, Mediterranean Sea; NAdr, Northern Adriatic Sea; [2]*Mode refers to research-driven*
prediction (P), scenarios (S); [a]*Aumont et al., 2015; Lellouche et al., 2018;* [b]*Edwards et*
2018; [d]*Song et al., 2016a,b,c; Mattern et al., 2017;* [e]*Baird et al., 2016, 2018; Jones et*
2019; [g]*Hetland and DiMarco, 2008; Yu et al., 2015;* [h]*Fennel et al., 2011; Laurent et al., 2012;* [i]*Lazzari et al., 2016; Teruzzi et al., 2018; Cossarini et al., 2019;* [j]*Grégoire et al., 2008; Capet et al., 2016;* [k]*Cossarini et al., 2019.*

Fennel et al. 2019

Gehlen et al. 2015

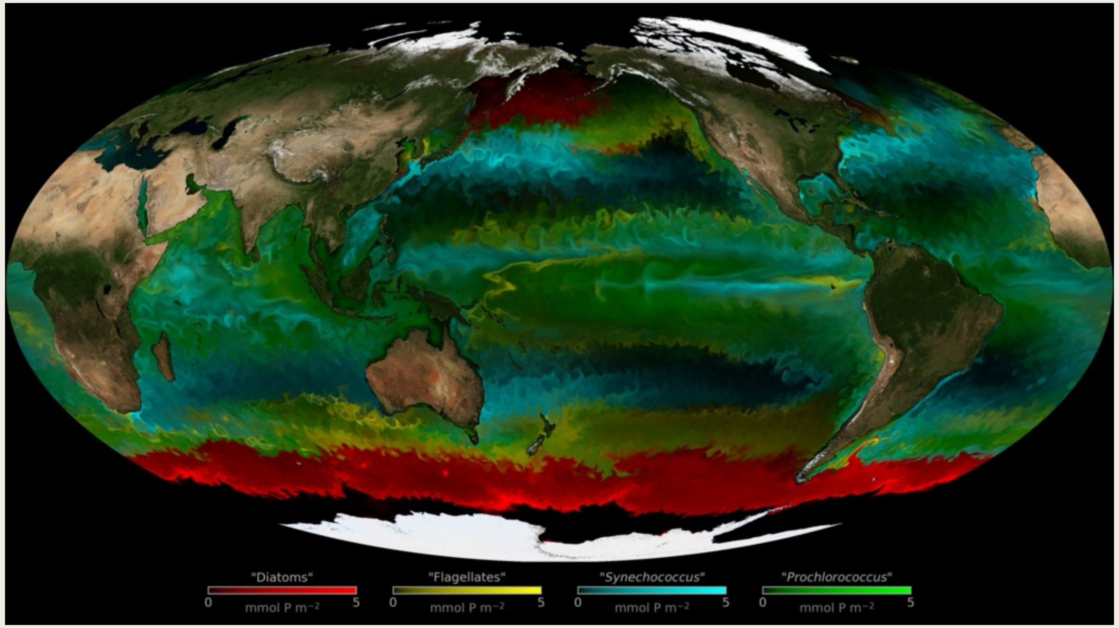
Table 1. Overview of biogeochemical models included in (pre-)operational systems.

	HadOCC	ERSEM	NORWECOM	PISCES	BFM	GSBM
Biogeochemical cycles	N (NO_3, NH_4), C[a]	N (NO_3, NH_4), Si, O_2, P	N (NO_3), Si, O_2, P	N (NO_3, NH_4), Si, Fe, P, C[a], O_2	N (NO_3, NH_4), Si, Fe, P, C[a], O_2	N (NO_3, NH_4), C[a], O_2
autotrophic PFTs	Phytoplankton	Picophytoplankton, flagellates, diatoms, dinoflagellates	Flagellates, diatoms	Nanophytoplankton, diatoms	Picophyto-, nanophyto-plankton, diatoms	Flagellates, diatoms
Heterotrophic PFTs	Zooplankton	Microzoo-, mesozoo-plankton, heterotrophic nanoflagellates, bacterioplankton	Microzoo-, mesozoo-plankton	Microzoo-, mesozoo-plankton	Nanozoo-, microzoo-, mesozoo-, bacterioplankton	Microzoo-, mesozoo-plankton
BGC functions included without explicit PFT	$CaCO_3$ production			$CaCO_3$ production/dissolution, N_2-fixation/denitrification	Biogenic Si dissolution, biogenic Fe dissolution	
External inputs		River nutrients, sediments, terrestrial sediments	River nutrients	River carbon and nutrients, aeolian Fe, Si and N, sedimentary Fe source	Aeolian Fe	River carbon and nutrients
References	b	c	d	e	f	g

[a]Dissolved and particulate, prognostic alkalinity, $CaCO_3$ production and dissolution, CO_2 chemistry fully resolved.
[b]HadOCC (Hadley Centre Ocean Carbon Cycle Model): Palmer and Totterdell (2001); Geider et al. (1997); Eppley (1972); Anderson (1993); Hemmings et al. (2008).
[c]ERSEM (European Regional Seas Ecosystem Model): Edwards et al. (2012); Blackford et al. (2004); Artioli et al. (2012); Sykes and Barciela (2012).
[d]NORWECOM (Norwegian Ecological Model): Skogen et al. (1995); Skogen et al. (2007); Hansen and Samuelsen (2009); Moll and Stegert (2007); Pätsch et al. (2009); Stegert et al. (2009); Samuelsen et al. (2009).
[e]PISCES (Pelagic Iteraction Scheme for Carbon and Ecosystem Studies): Aumont and Bopp (2006); Aumont et al. (2008); Ludwig et al. (1996); Johnson et al. (1999); de Baar and de Jong (2001).
[f]BFM (Biogeochemical Flux Model): Lazzari et al. (2010); Vichi et al. (2007a); Vichi et al. (2007b); Baretta et al. (1995); Orr (1999); Geider et al. (1998).
[g]GSBM (Gulf of St Lawrence Biogeochemical Model): Le Fouest et al. (2005); Le Fouest et al. (2006); Martin et al. (1987); Jin et al. (2007); Signorini et al. (2001); Dickson et al. (2007).

2. Biogeochemical models: recent advances

- Improved spatial resolution
- Assimilation of data
    - Satellite data: chlorophyll as well as new products/hyperspectral data
    - Data from glider/Argo/Bio-Argo



http://darwinproject.mit.edu

- Intercomparison of modeling approaches (and/or modeling versus satellite)
- Increasing number of models and increasing complexity, identification of optimal complexity has become an active area of research

Example point: IOCCG Report 19

- Improved communication between model and satellite ocean color community
- Both approaches have their own needs and uncertainties
- Highlights some of the challenges:
    - Uncertainties
    - Variables and units
    - Skill assessment
    - Using satellite in models and vice versa

Reports and Monographs of the International Ocean Colour Coordinating Group

An Affiliated Programme of the Scientific Committee on Oceanic Research (SCOR)
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IOCCG Report Number 19, 2019

Synergy between Ocean Colour and Biogeochemical/Ecosystem Models

Edited by:
Stephanie Dutkiewicz

Report of the IOCCG working group on the Role of Ocean Colour in Biogeochemical, Ecosystem and Climate Modelling, chaired by Stephanie Dutkiewicz, and based on contributions from (in alphabetical order):

- Report conclude by suggesting a continued open discussion through mechanisms such as:

  - Breakout or working group with representation of modeler and ocean color scientists at OC/modeler conferences
  - Facilitate early-career cross-discipline collaboration through summer schools designed to attract scientists from both communities
  - Integrate ocean color and models at the project level and by including both communities in large projects (EXPORTS, Climate Modeling User Group-ESA)
  - Involve modelers in the development of ocean color products and mission planning (e.g. OSSEs) and involve satellite expert in model development

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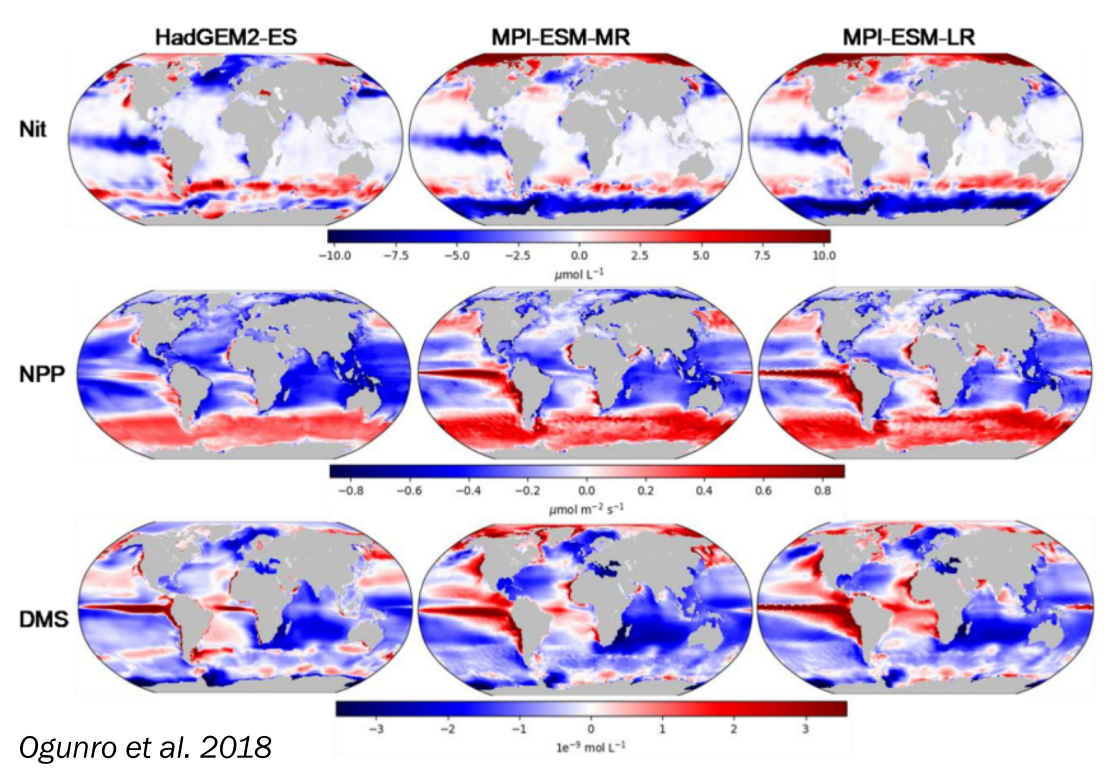
Example: How well do Earth System Models represent the ocean biogeochemistry?

International Ocean Model Benchmarking (IOMB) effort



Ogunro et al. 2018

An overview of several models with respect to each of the variables, using absolute (left) and relative (right) scores to determine the degree of uncertainty in relation to referenced datasets.

- *Physical variables* are among the more realistic (CESM and E3SM are for a calendar year from uncoupled simulations)
- *Nutrients*: intermediate
- *Biogeochemical products*: mid to low scores

Note that some of these biogeochemical variables are secondary derivatives of the experiments which makes them susceptible to compound uncertainties.

Lower uncertainty as we progress through a list of biogeochemical processes

3. Biogeochemical models: remaining challenges

- Using **in situ data** to parametrize, provide initial conditions and/or characterize uncertainties in biogeochemical models BUT:

- Lots of models still don’t validate their output-lack of data

- Lack of uncertainties of observational dataset and mismatch:

    - Extrapolation of data from in situ bottle to model grid cell -> scalability challenge

    - Mismatch in type of information (measuring pigments but modelling biomass)

    - Temporal and/or spatial variability in parameter values due to natural variability in phytoplankton species of unrepresented ambient conditions

3. Biogeochemical models: remaining challenges (part 2)

- **Assimilation of data:**

  a) Information on data to validate/assimilate

  - Currently mostly satellite data, i.e. chlorophyll + surface only. Progress being made to assimilate spectral bands and various water constituents
  - Uncertainties associated with the data

  b) Discrepancies in units/variables we are measuring and what's represented by models (as well as misunderstanding by each of the communities of what is actually represented)

  c) Coupling of radiation model to BGCs in combination with assimilation of hyperspectral data

4. Conclusions and perspectives

- Biogeochemical models are becoming more complex and detailed in the process their represent
- The improvements that this increased complexity and diversity brings needs to be quantified (either through validation or intercomparison)
- Biogeochemical models represent a great platform to integrate several datasets, provide information on variables that cannot be derived from satellite/in situ data at the global scale, and can provide forecast
- 3 majors areas of future development:

  (a) Data and processes resolved/assimilated in BGCs,

  (b) Validation/characterization of uncertainties and

  (c) Communication with satellite and stakeholders communities (working groups, summer schools, etc)

Questions for discussion:

- *What are the current gaps of our understanding of BGC?* Interactions between carbon cycle, community composition at the global scale. Mismatch between in situ, satellite and model data
- *What are the current efforts being done in improving the interactions/integrated use of in situ, model and satellite data.* Modeling effort, community reports (e.g. IOCCG) and workshops
- *Are there particular areas/variables that are lagging behind in terms of our understanding/observations or modeling of them?* We are still lagging on the assimilation processes and number of variables assimilated, processes represented (carbon fluxes, light representation, sinking of particles)
- *What does the next 5 years look like for the in situ/satellite and modeling of BGC?* The representation of water constituents (both in number and the processes influencing the composition) will improve (including representation of light and other processes), so will the assimilation of hyperspectral water leaving radiances and or water constituents as hyperspectral sensors become more common (e.g. PACE)