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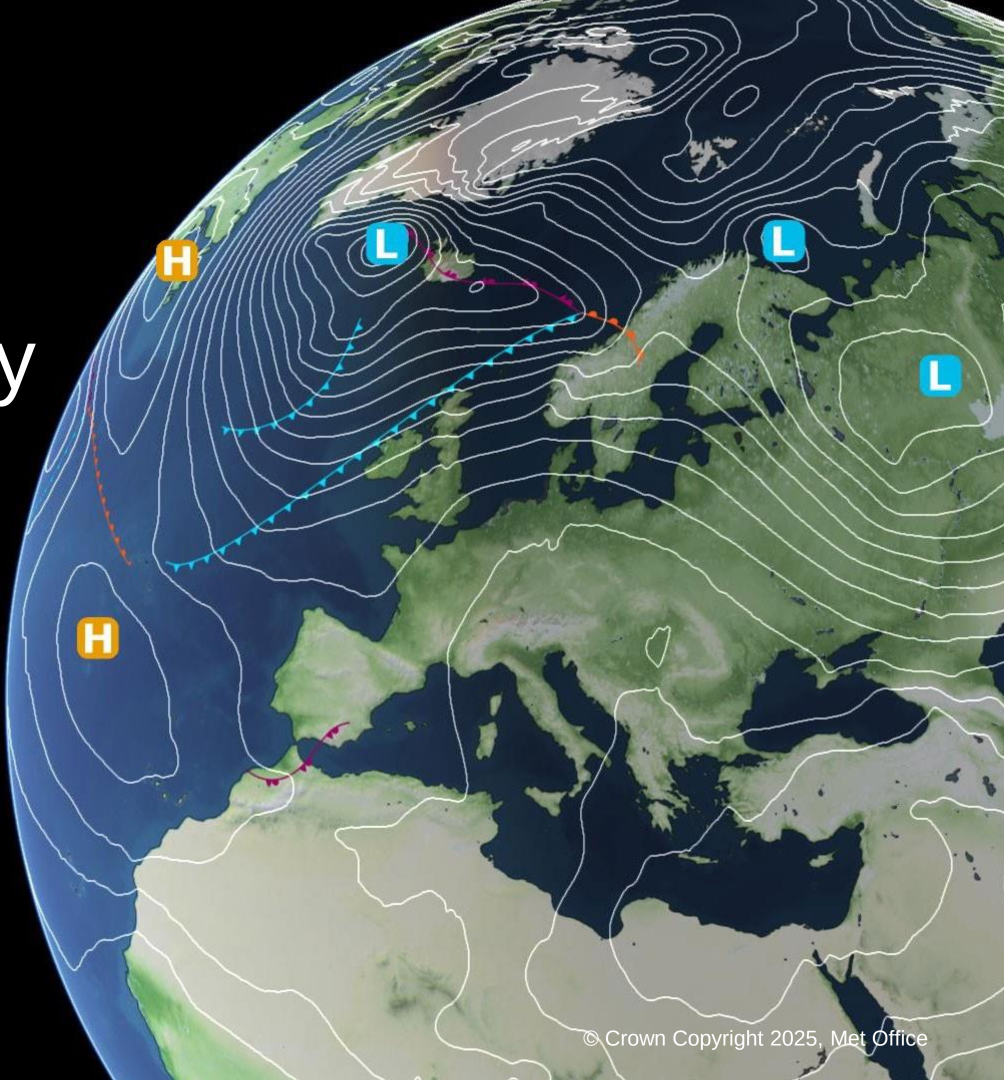
Data assimilation for marine biogeochemistry

David Ford

NERC/NCEO/DARC Training course on data assimilation, 10th June 2025

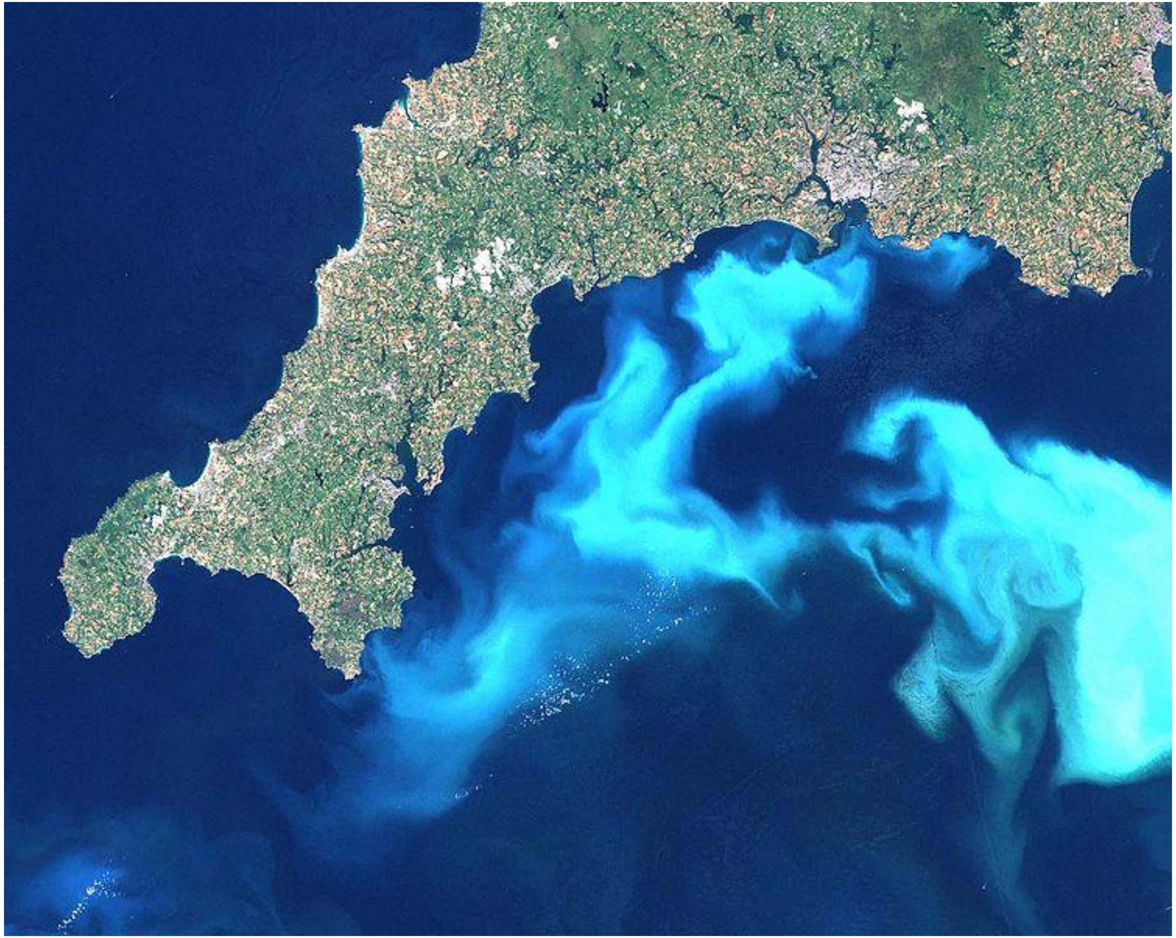


Contents

- Marine biogeochemistry applications
- Models
- Observations
- DA examples
- Challenges
- Coupling

Marine biogeochemistry applications
Forecast and reanalysis

Algal blooms



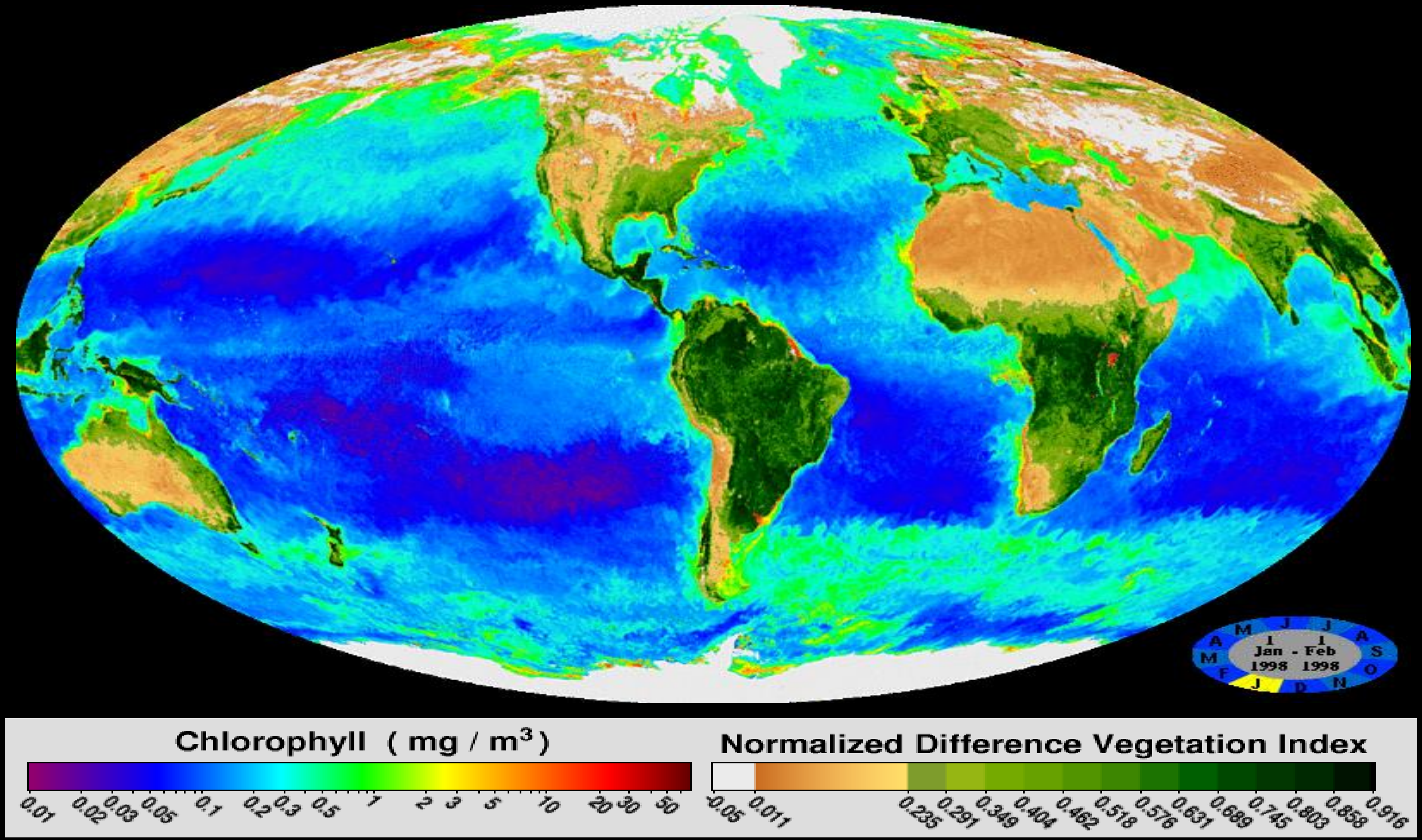
http://en.wikipedia.org/wiki/File:Cwall99_lg.jpg

Fisheries and aquaculture

https://unsplash.com/photos/silver-fishes-underwater-YV593oyMKmo

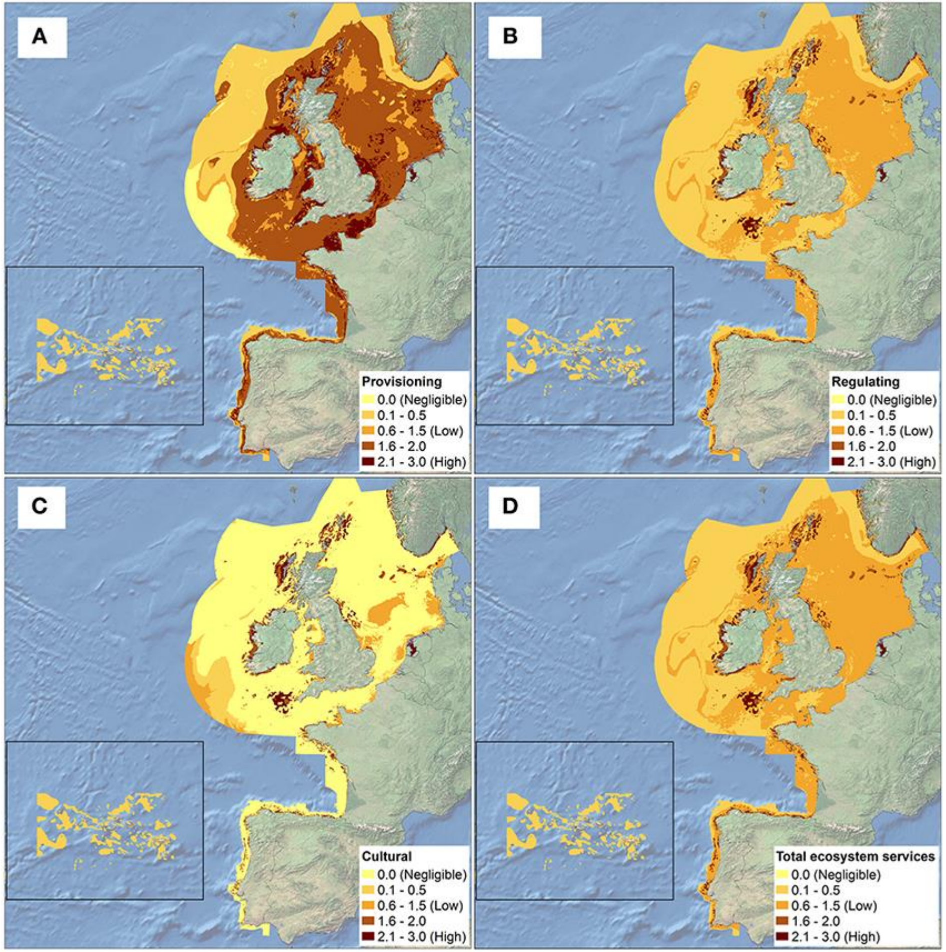
Visibility

https://visibleearth.nasa.gov/images/69721/sediment-in-the-north-sea



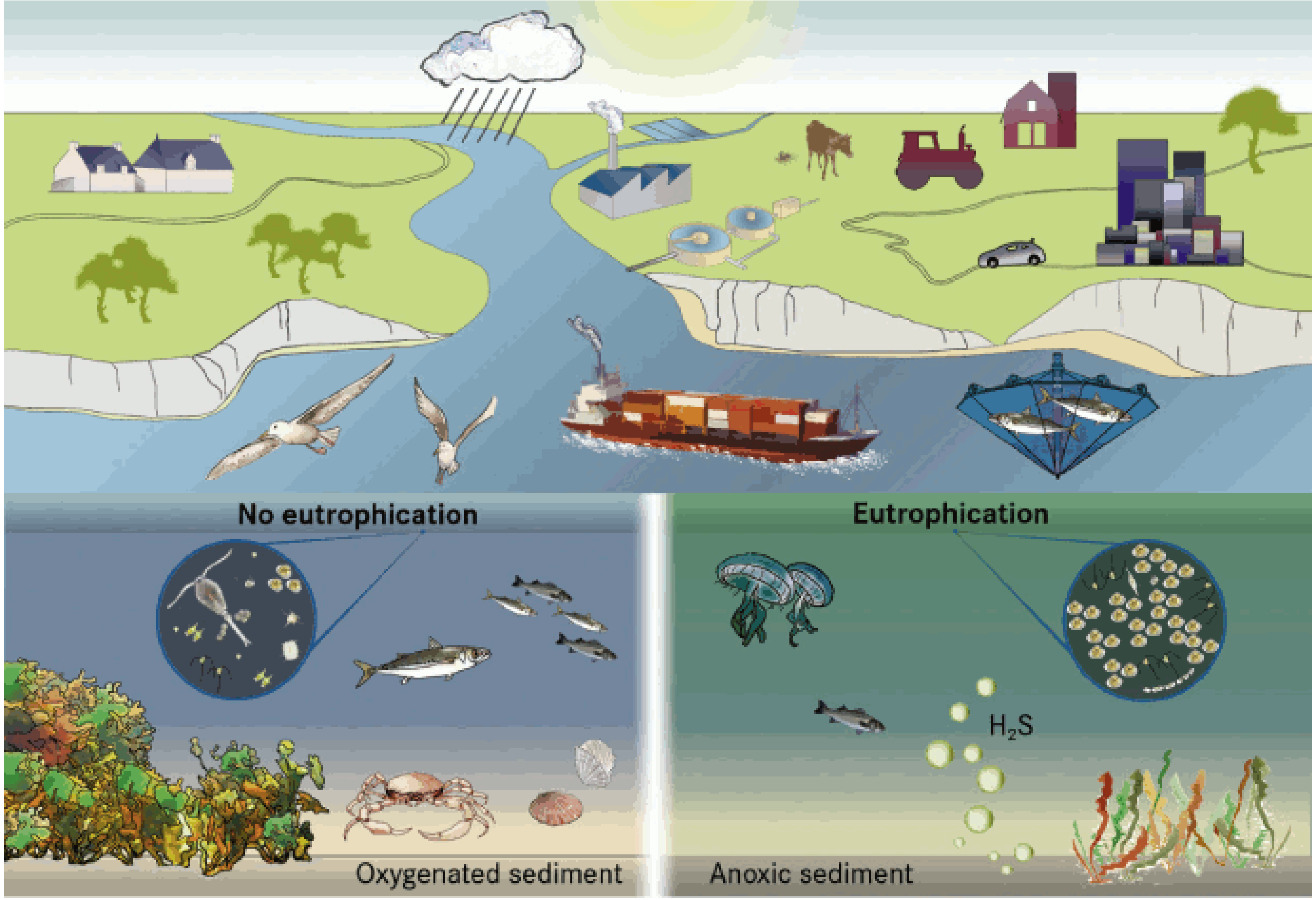
http://oceancolor.gsfc.nasa.gov/SeaWiFS/HTML/SeaWiFS.BiosphereAnimation.70W.html

Habitat mapping



Galparsoro et al., 2014, Front. Mar. Sci.

Eutrophication and hypoxia



https://qsr2010.ospar.org/en/media/content_img/ch04/Fig_4_1_EN.gif

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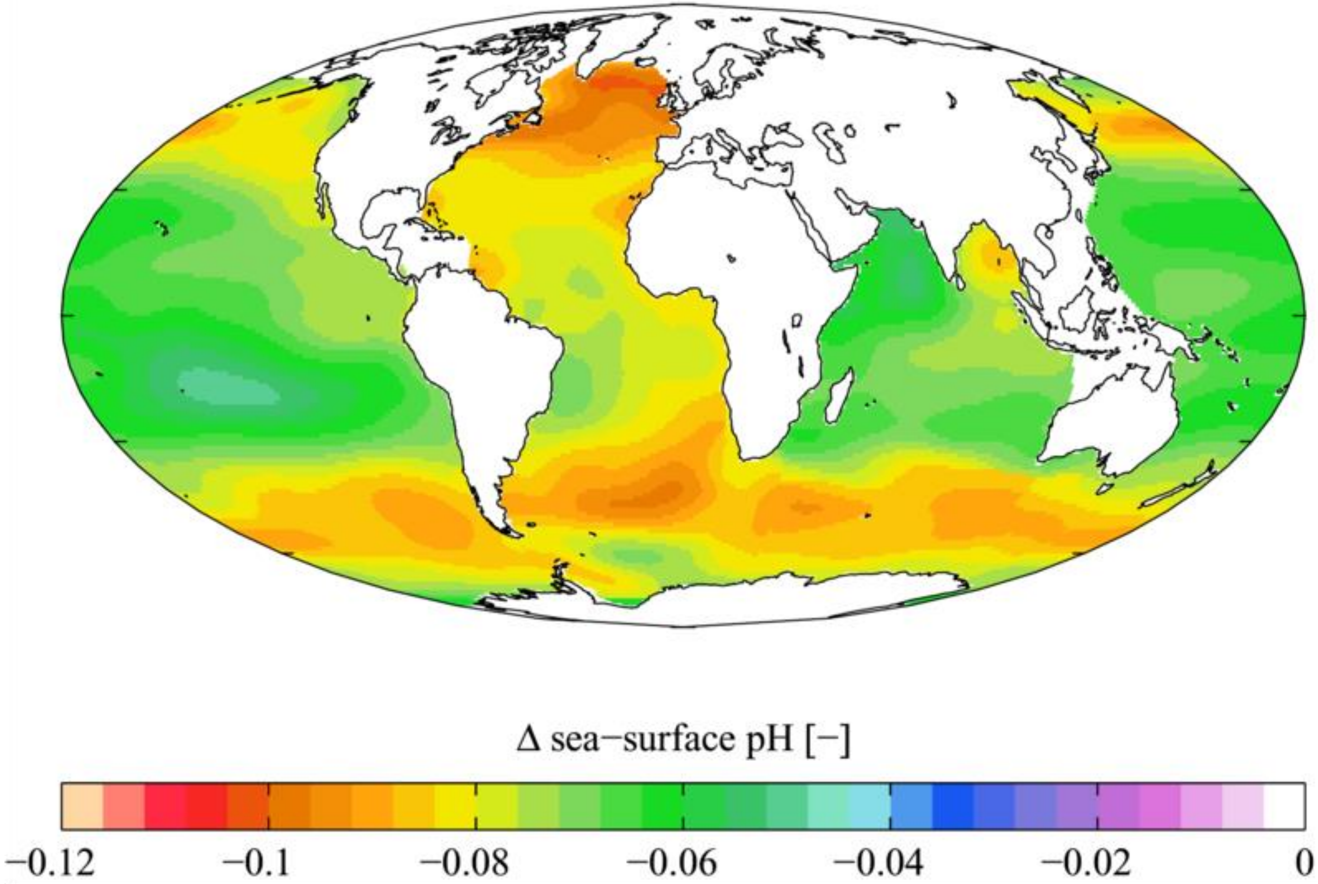
Policy and legislation

http://msfd.eu/site/wp-content/uploads/2016/12/cropped-w-questions.png

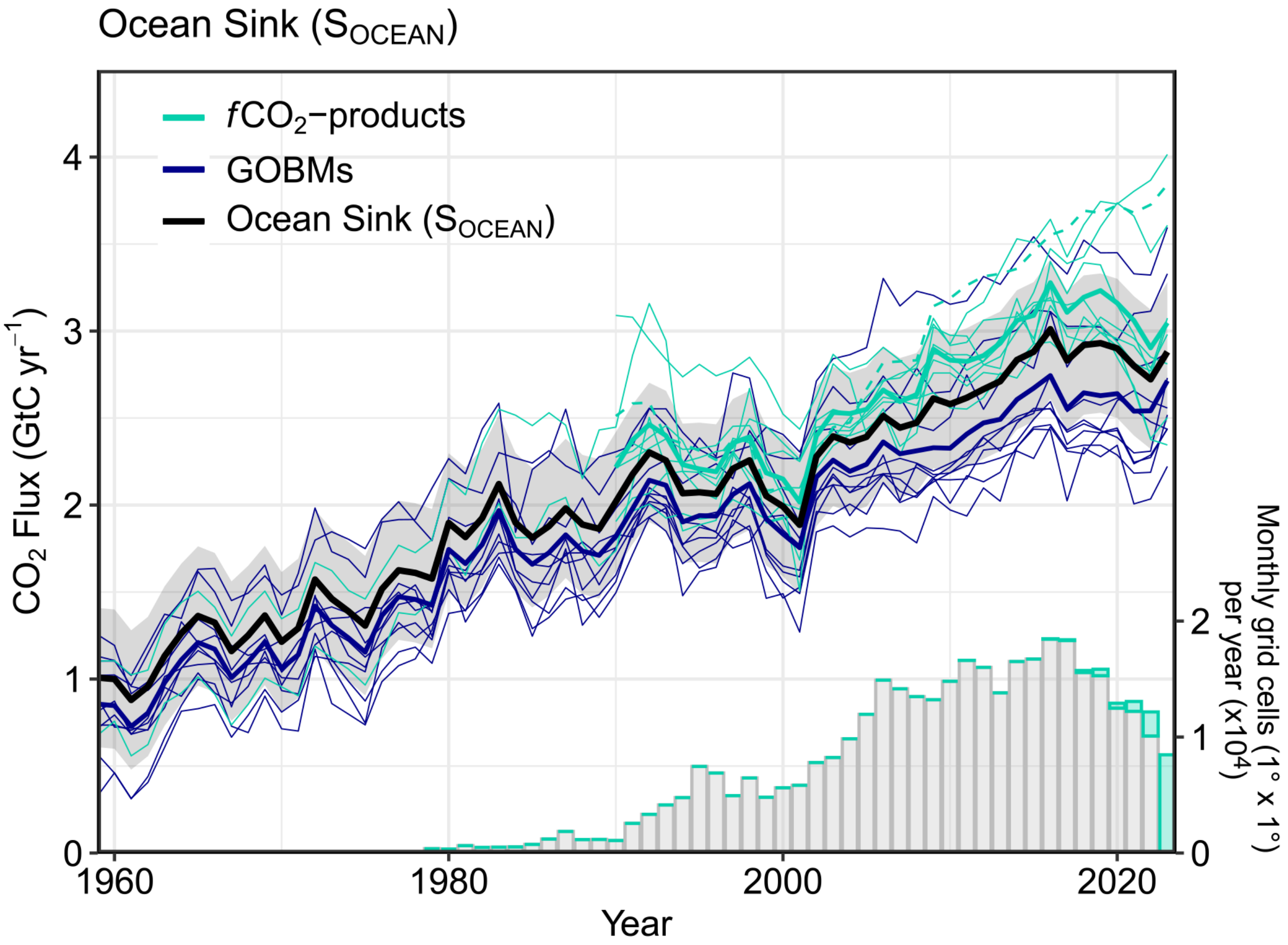
Ocean acidification



Estimated change in sea water pH between the 1700s and the 1990s, from GLODAP and WOA

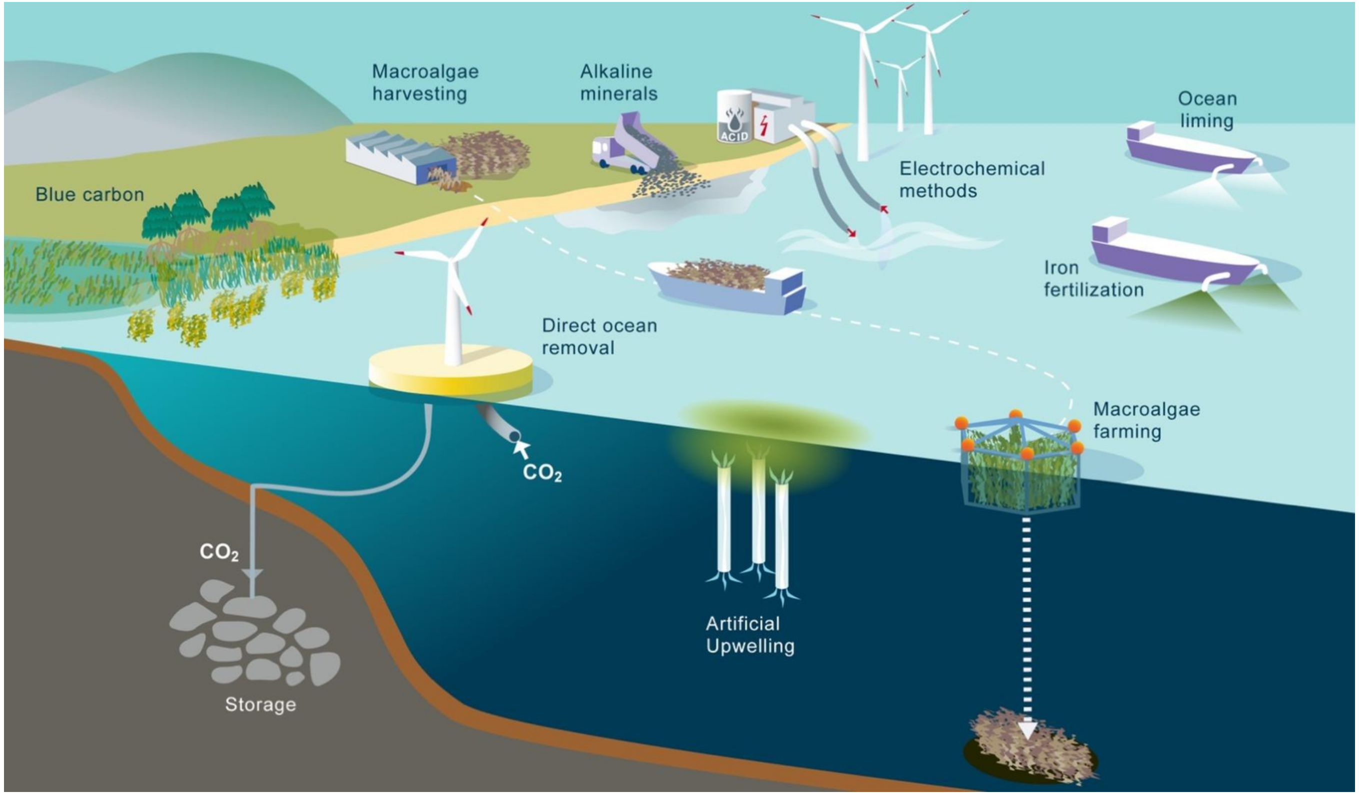
https://en.wikipedia.org/wiki/File:WOA05_GLODAP_del_pH_AYool.png

Ocean carbon uptake



Global Carbon Budget 2024, Friedlingstein et al. (2025), https://doi.org/10.5194/essd-17-965-2025

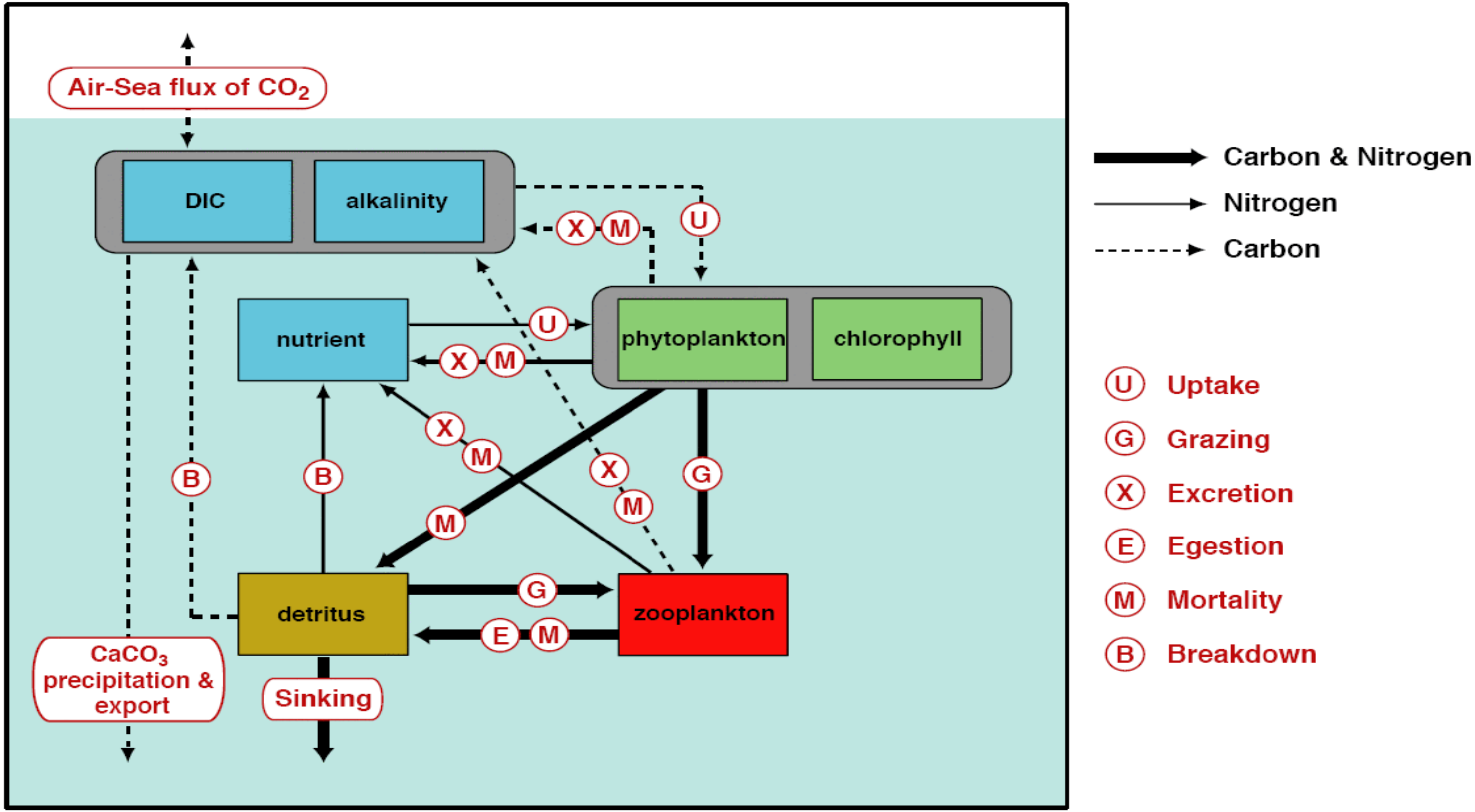
Marine carbon dioxide removal (MCDR) monitoring



Oschlies et al. (2025), https://doi.org/10.3389/fclim.2024.1506181

Marine biogeochemical models

Hadley Centre **O**cean **C**arbon **C**ycle (**HadOCC**)



Palmer and Totterdell, 2001, Deep-Sea Research I

Biogeochemical models

- Have one or more "currencies", e.g. nitrogen, carbon, phosphorus, silicon, iron, chlorophyll
- State variables modelled as dissolved concentrations of these currencies (passive tracers)
- Equations for each state variable (T) take the form:

$$\frac{\partial T}{\partial t} = advection(T) + diffusion(T) + sms(T)$$

- sms = "source minus sink", i.e. the biogeochemical model

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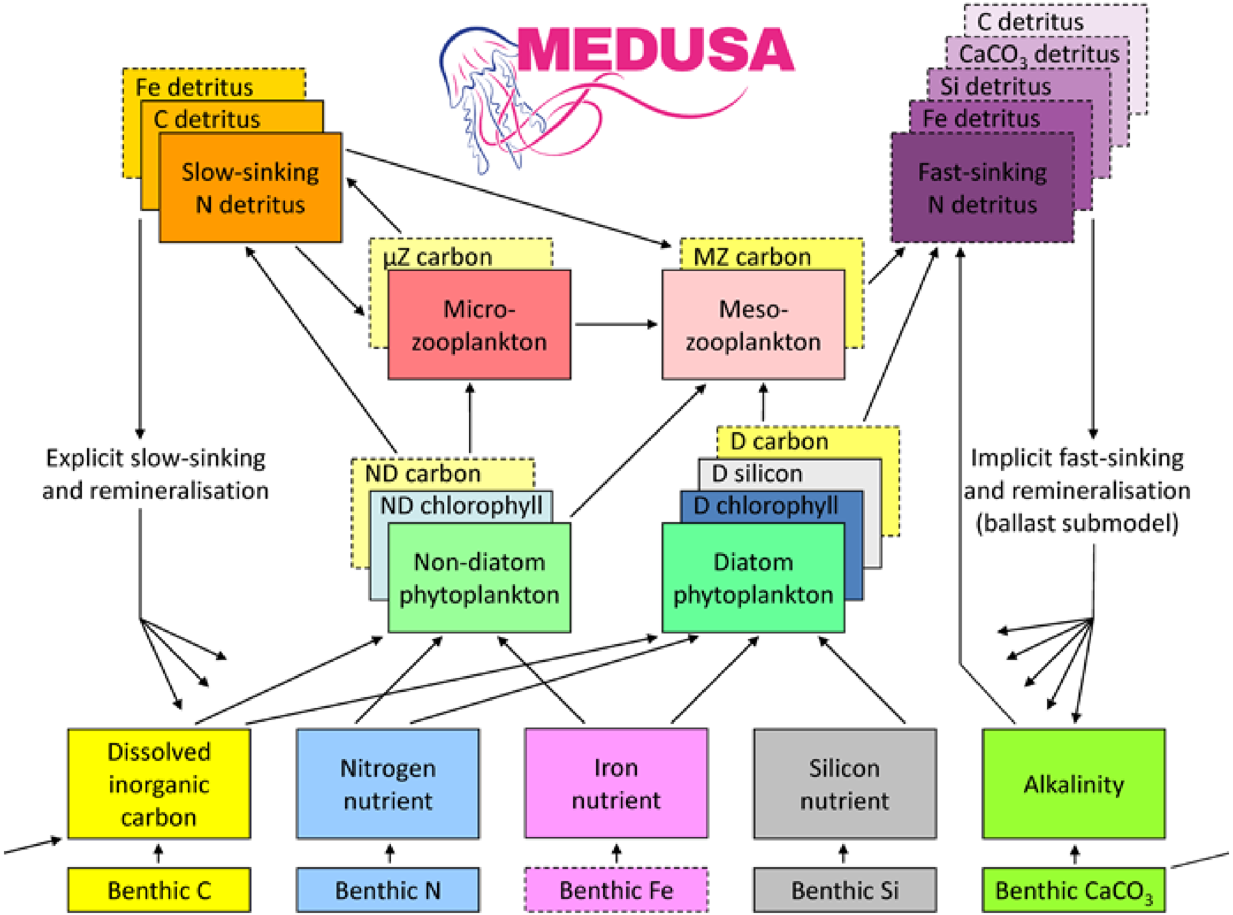
Model of **E**cosystem **D**ynamics, nutrient **U**tilisation, **S**equestration, and **A**cidification (**MEDUSA**)



https://projects.noc.ac.uk/medusa/

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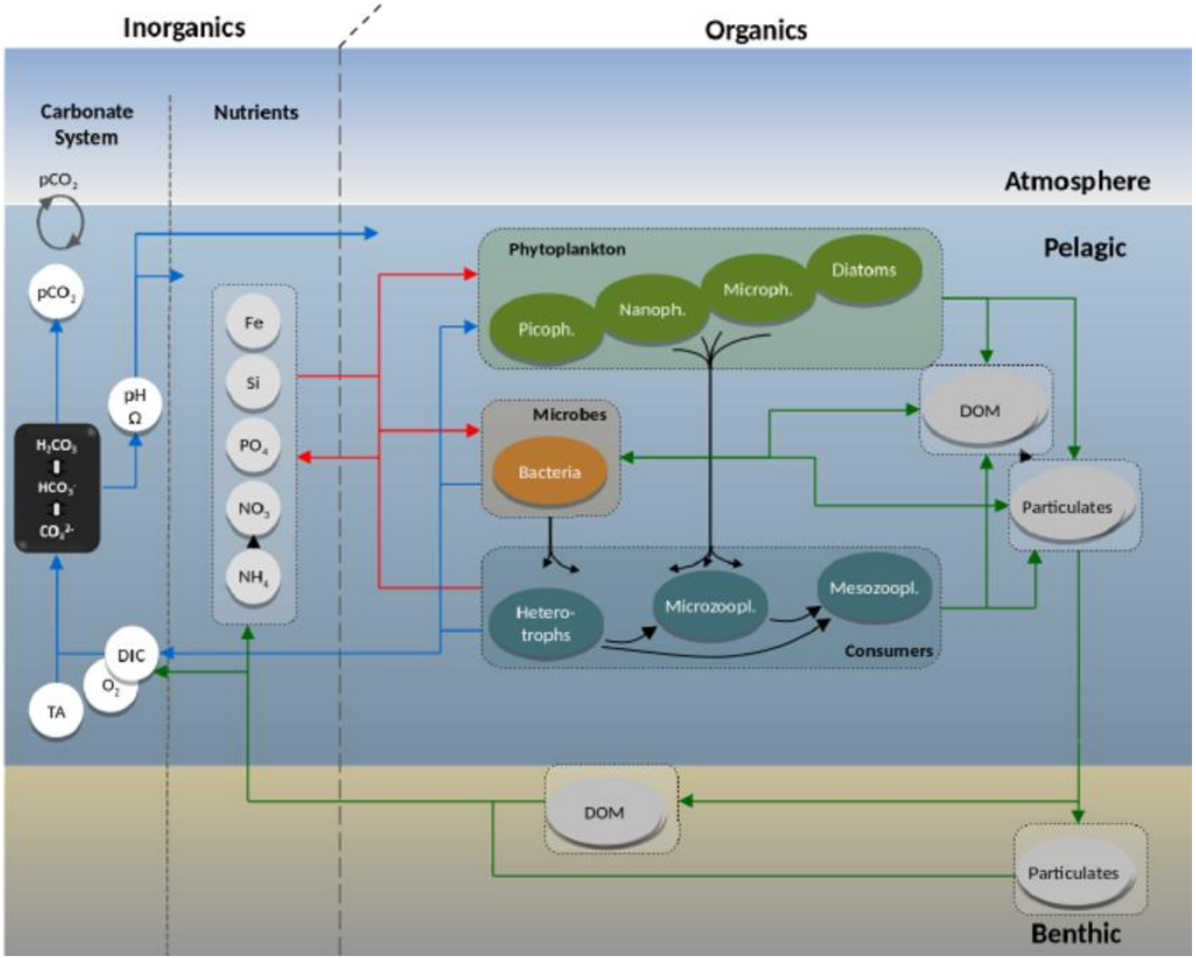
European
Regional
Seas
Ecosystem
Model
(**ERSEM**)

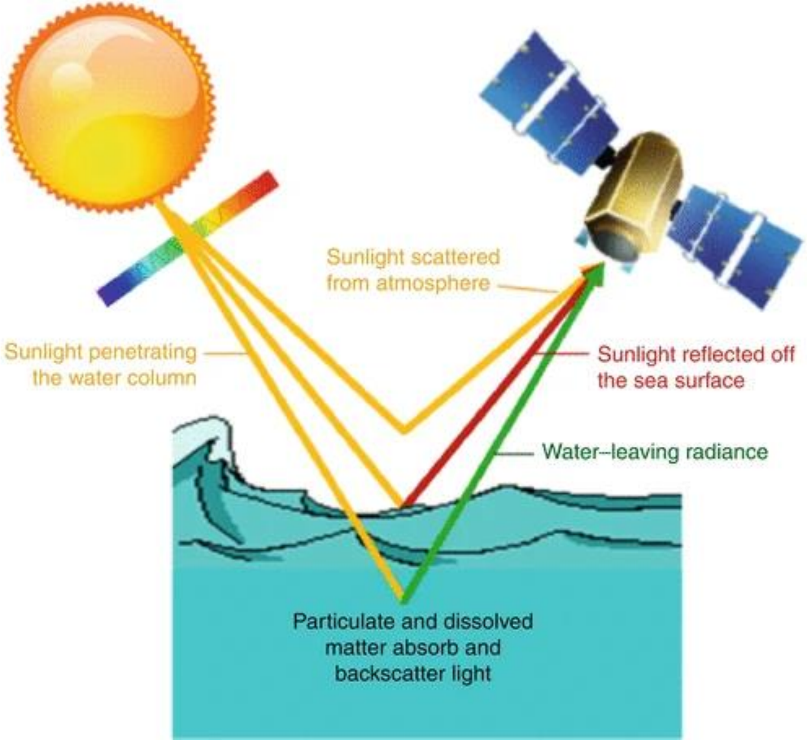
up to
59 pelagic
36 benthic
state variables

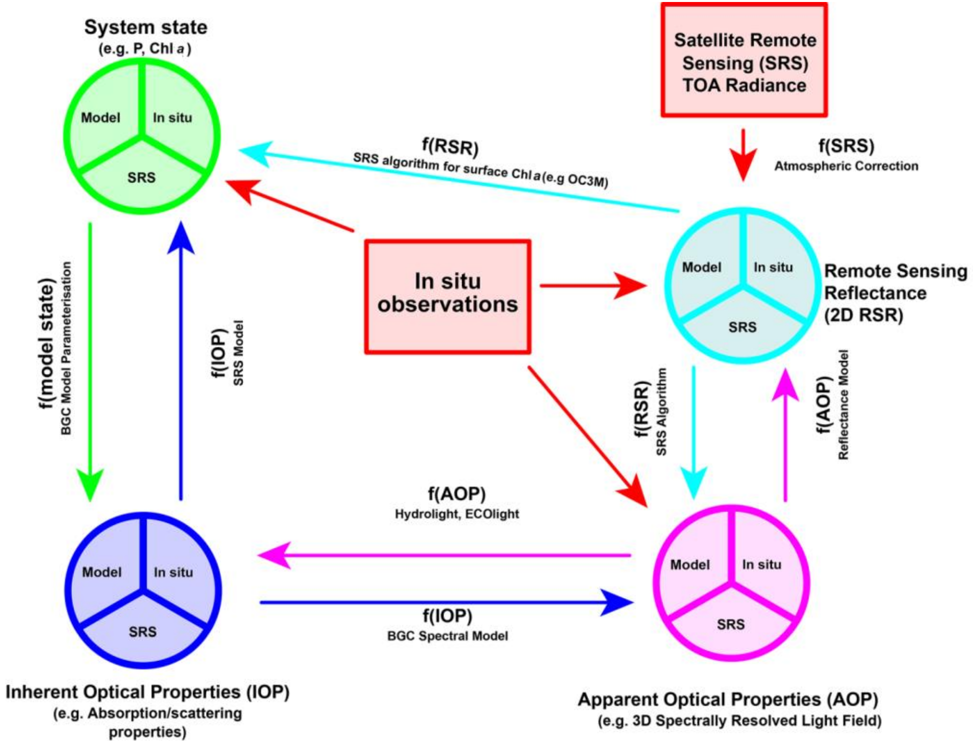


Butenschön et al., 2016, GMD

Observations

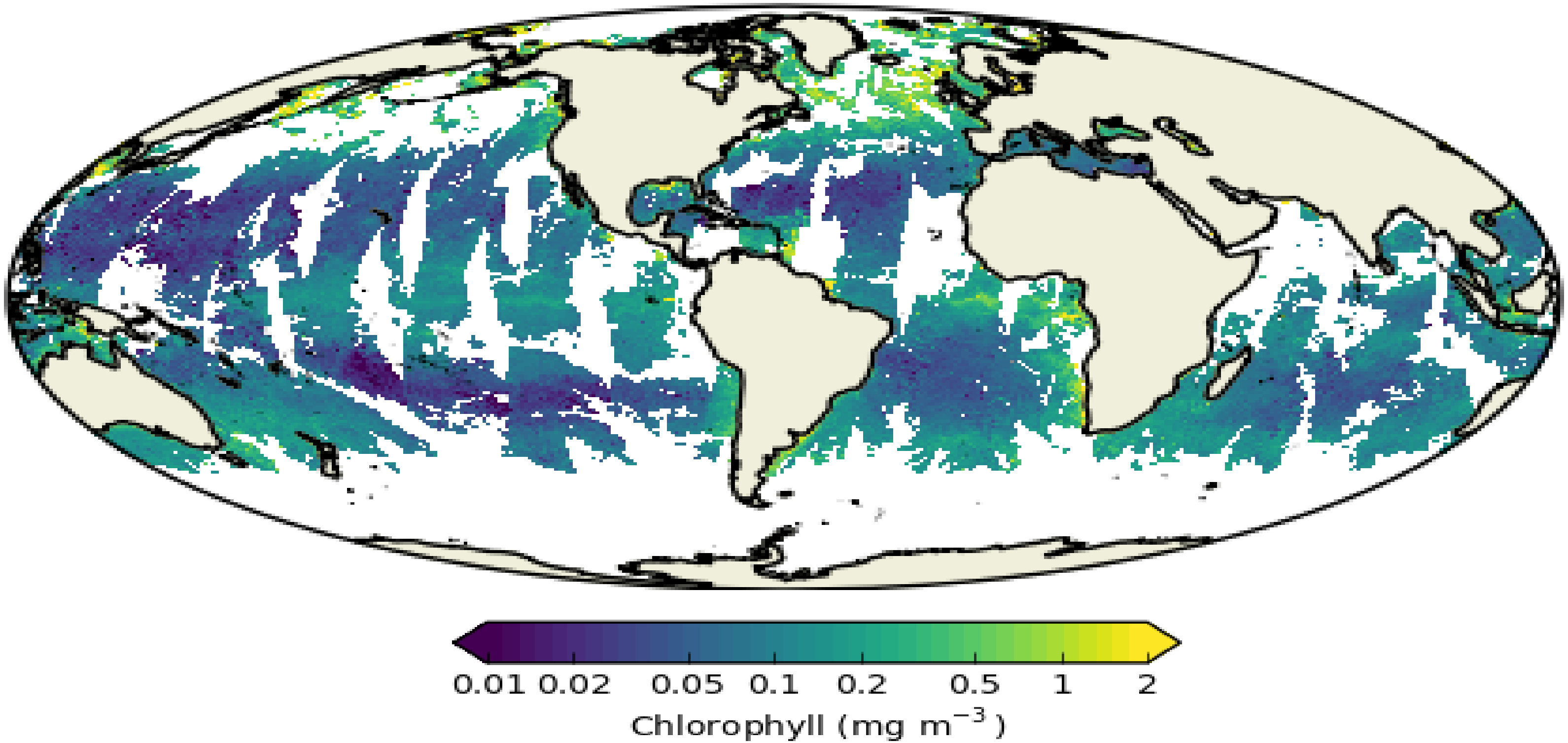
Ocean colour





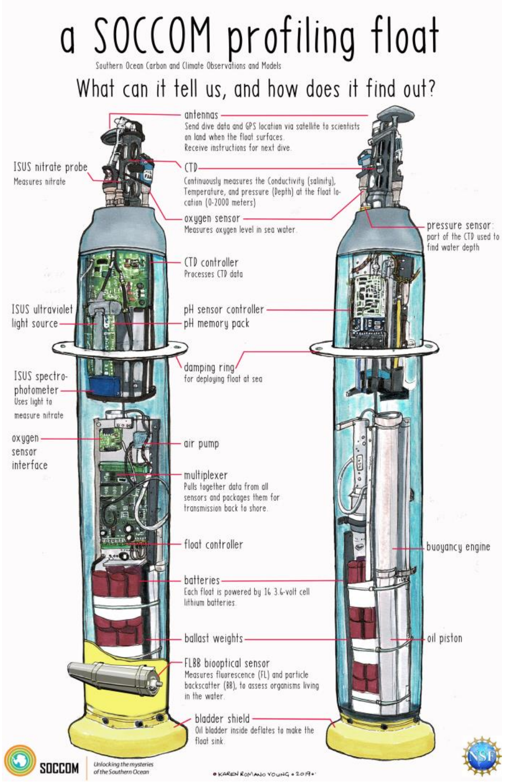
Dierssen, H.M., Randolph, K. (2012). Remote Sensing of Ocean Color . In: Meyers, R.A. (eds) Encyclopedia of Sustainability Science and Technology
Jones et al., 2016, Biogeosciences

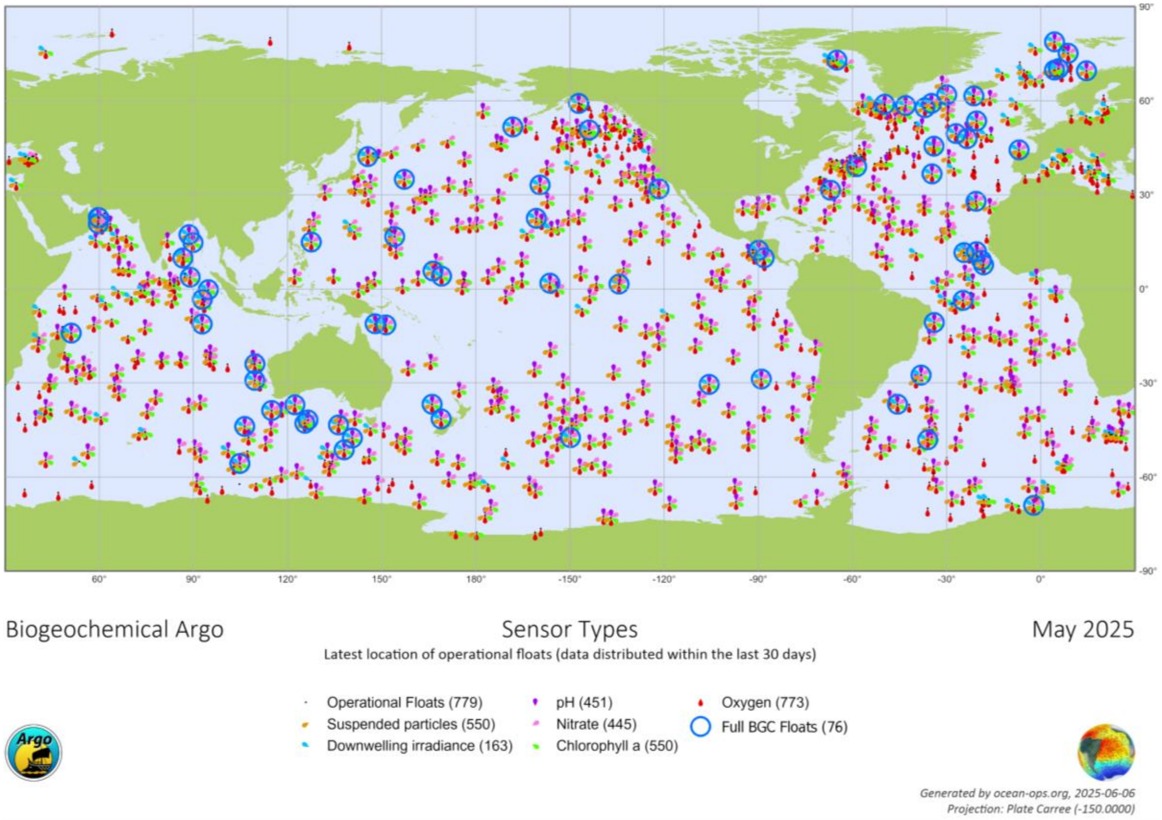
Chlorophyll



Example of daily coverage

Biogeochemical Argo





https://argo.ucsd.edu/outreach/media/schematics/
https://biogeochemical-argo.org/float-map-network-status-maps.php

Gliders, ships, moored buoys

https://en.wikipedia.org/wiki/Underwater_glider#/media/File:RU02_flying_in_Sargasso_Sea.jpg
https://en.wikipedia.org/wiki/RRS_Sir_David_Attenborough#/media/File:RRS_Sir_David_Attenborough_moored_at_Punta_Arenas.jpg
https://www.westernchannelobservatory.org.uk/buoys_E1.php

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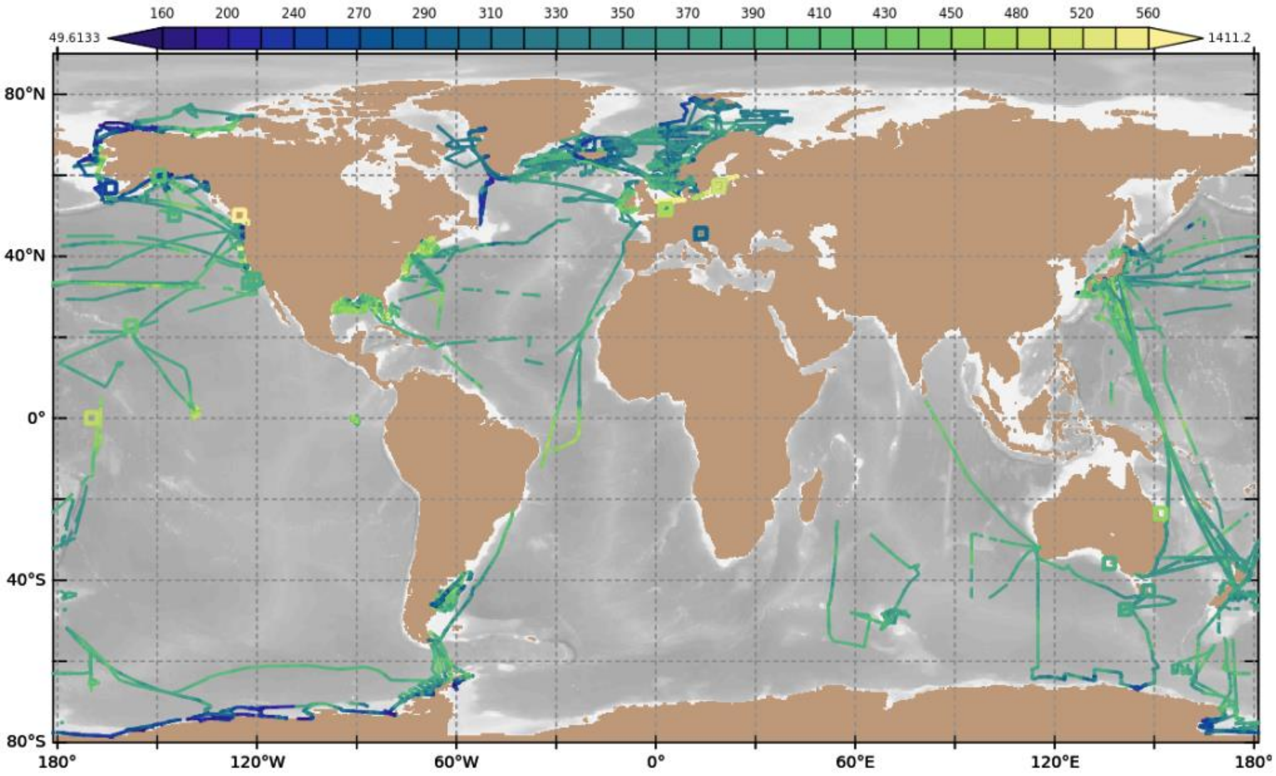

All (currently available) pCO_2 observations for 2024

https://socat.info/v2025-las-datasets

Data assimilation examples

Satellite chlorophyll – global

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JOURNAL OF GEOPHYSICAL RESEARCH
Oceans
AN AGU JOURNAL

JGR

Explore this journal >

The lognormal distribution as a model for bio-optical variability in the sea

Janet W. Campbell

First published: 15 July 1995 Full publication history

DOI: 10.1029/95JC00458 View/save citation

View issue TOC
Volume 100, Issue C7
15 July 1995
Pages 13237–13254
or
Browse Virtual Issue

Chlorophyll errors are non-Gaussian

- Assimilate log(chlorophyll) [most common]
- Assimilate chlorophyll [e.g. Teruzzi et al., 2014]
- Perform anamorphic transform [e.g. Brankart et al., 2012]
- Use a different assimilation method, e.g.
  - Particle filter [e.g. Mattern et al., 2013]
  - Extended 3D/4D-Var [e.g. Song et al., 2012]
  - GIGG-EnKF [Bishop, 2016]

How to update the multivariate state?

- Ocean colour just tells us about surface chlorophyll
- Need to control nutrients and other variables
- Need to control sub-surface
- Not straightforward!

Inherently multivariate assimilation

- Techniques such as Ensemble Kalman Filter (EnKF) and Singular Evolutive Extended Kalman (SEEK) filter evolve covariances to produce multivariate increments

- Commonly used, with some success

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Balancing increments

- Calculate chlorophyll increments and apply balances
- Simplest is to adjust nutrients proportionally (e.g. Rousseaux and Gregg, 2012)
- Or, something less simple...

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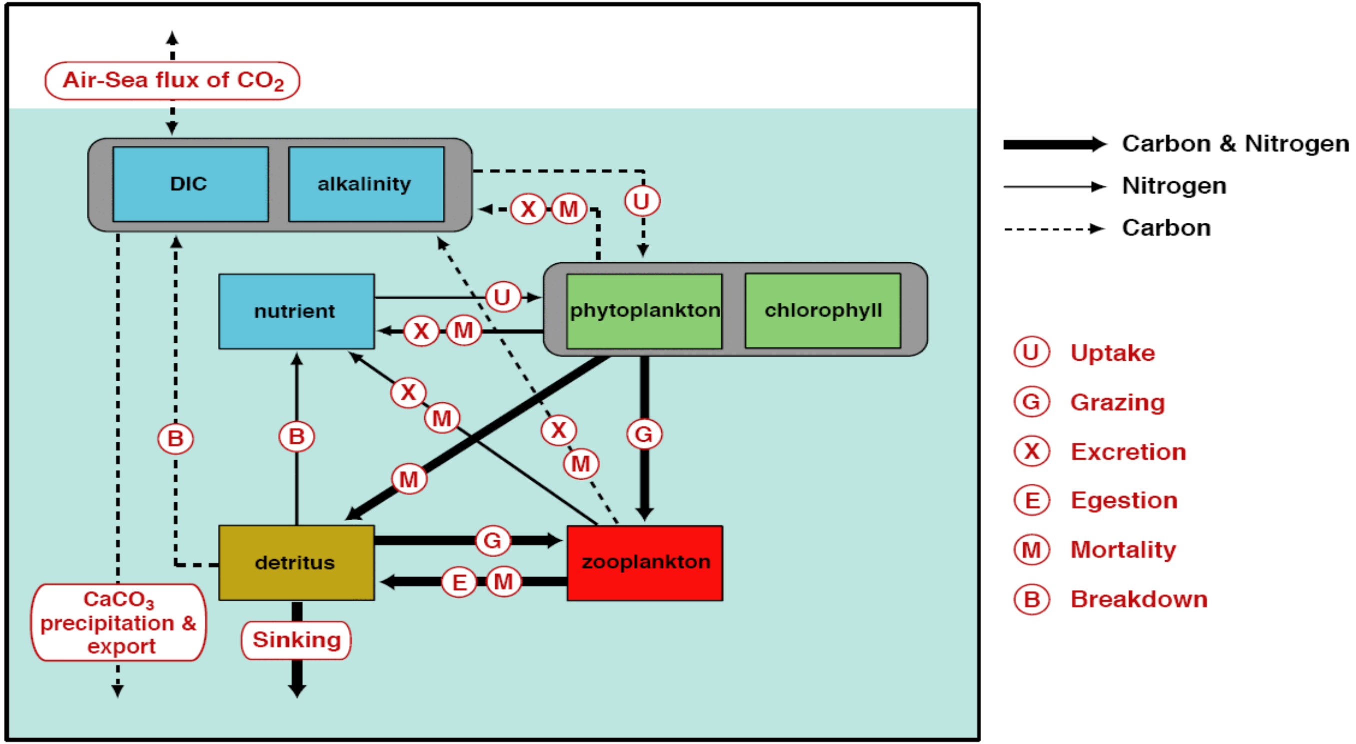
+

Hadley
Centre
Ocean
Carbon
Cycle
(**HadOCC**)



Palmer and Totterdell, 2001, Deep-Sea Research I

NEMOVAR (3D-Var)

Find model state **x** that minimises:

$$J(\mathbf{x}) = (\mathbf{x} - \mathbf{x}_b)^{\mathrm{T}} \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + (\mathbf{y} - H(\mathbf{x}))^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{y} - H(\mathbf{x}))$$

where:

$\mathbf{x}_b$ = background model state

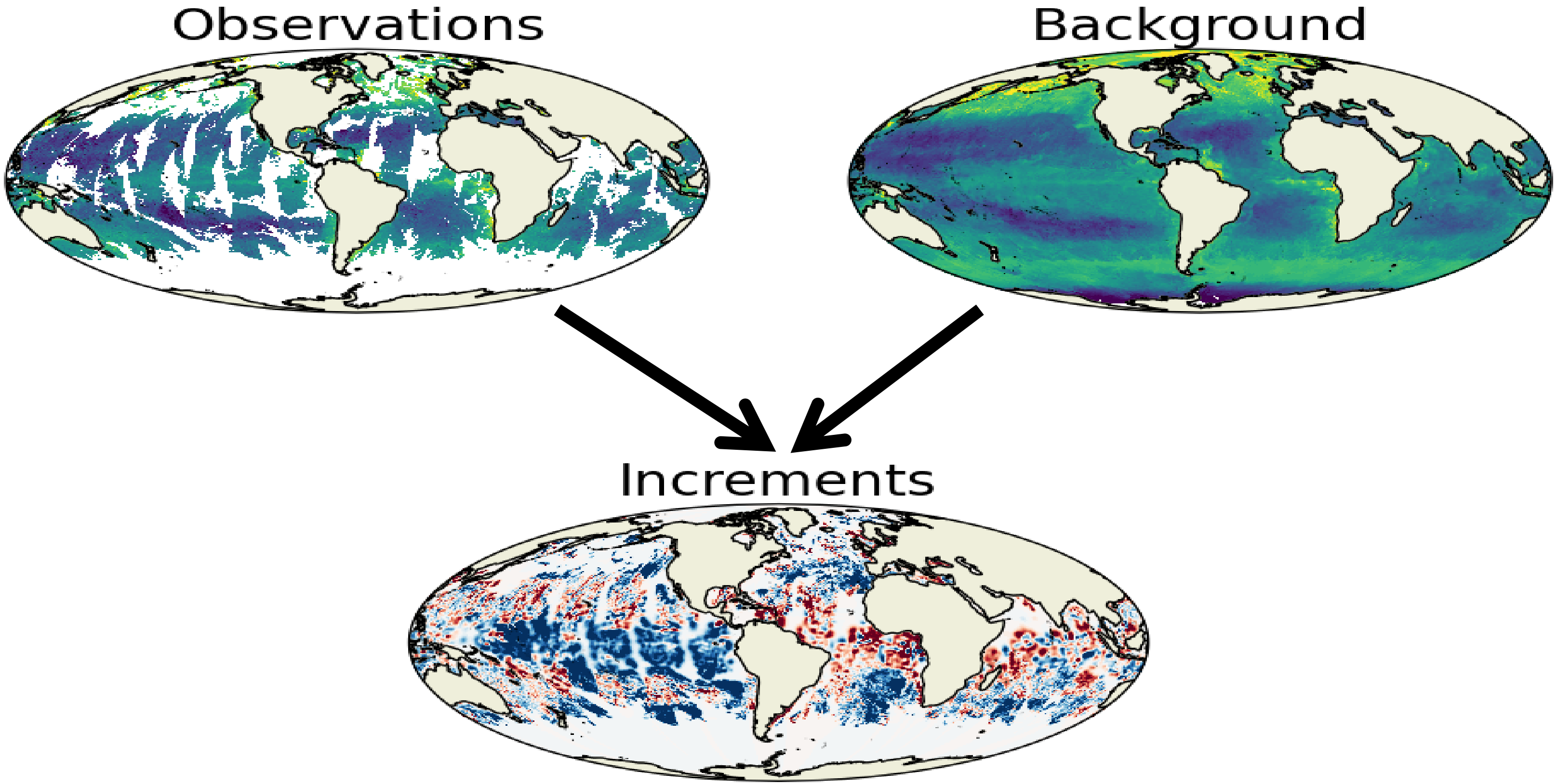
$\mathbf{y}$ = observations

$\mathbf{B}$ = background error covariances

$\mathbf{R}$ = observation error covariances

$H(\mathbf{x})$ = observation operator

$\log_{10}$(chlorophyll) increments



Nitrogen balancing

Home / Journal of Marine Research, Volume 66, Number 1

F Ocean color data assimilation with material conservation for improving model estimates of air-sea CO_2 flux

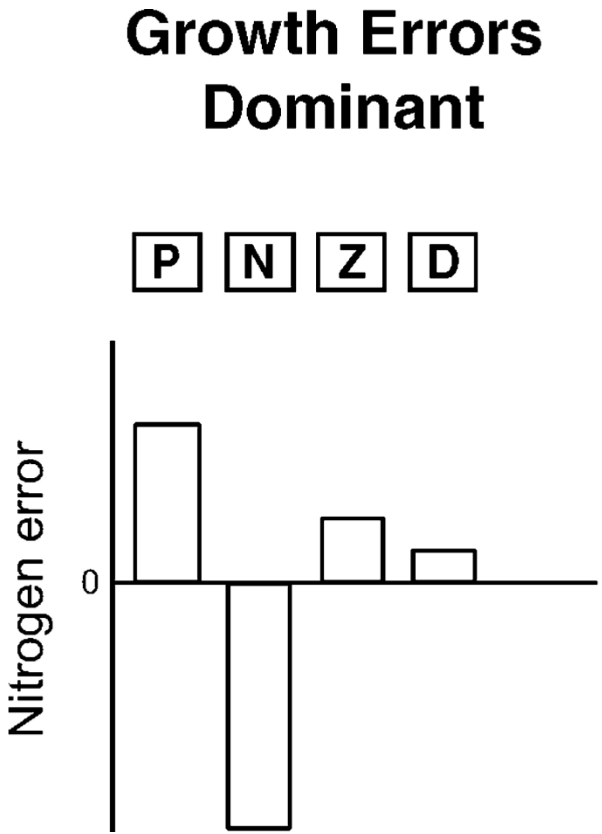
Authors: Hemmings, John C. P.; Barciela, Rosa M.; Bell, Michael J.

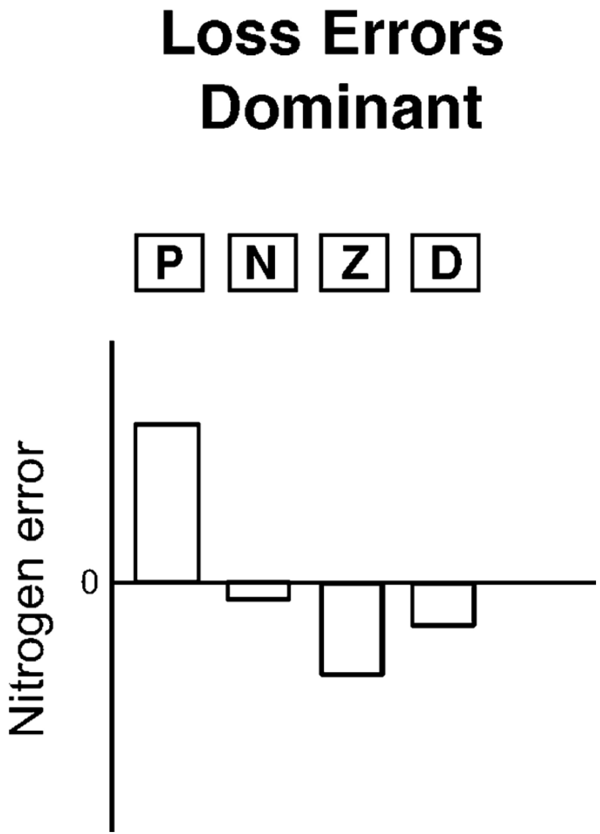
Source: Journal of Marine Research, Volume 66, Number 1, January 2008, pp. 87-126(40)

Publisher: Sears Foundation for Marine Research

DOI: https://doi.org/10.1357/002224008784815739

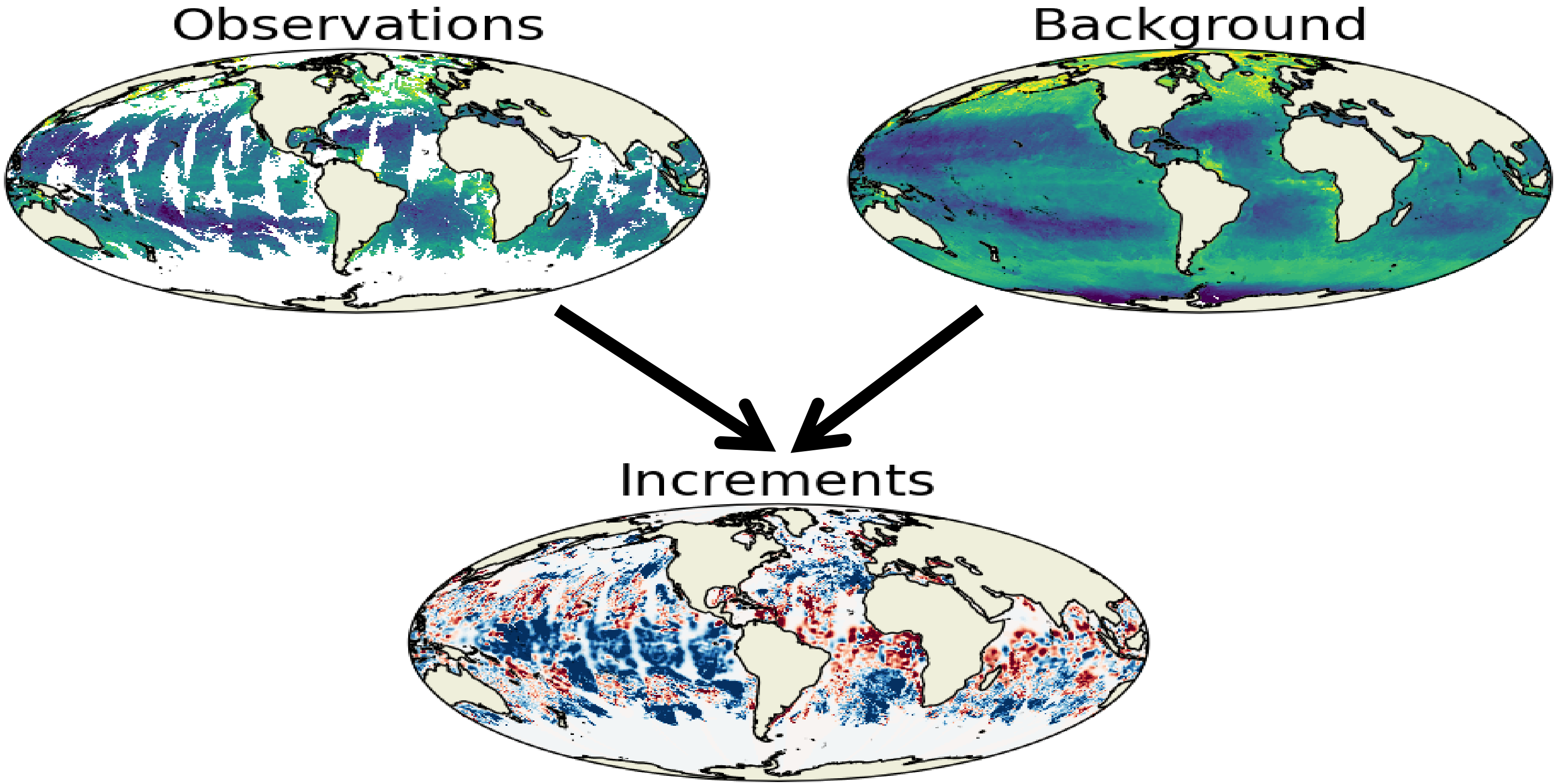
Nitrogen balancing





Hemmings et al., 2008, J. Mar. Res.

$\log_{10}$(chlorophyll) increments



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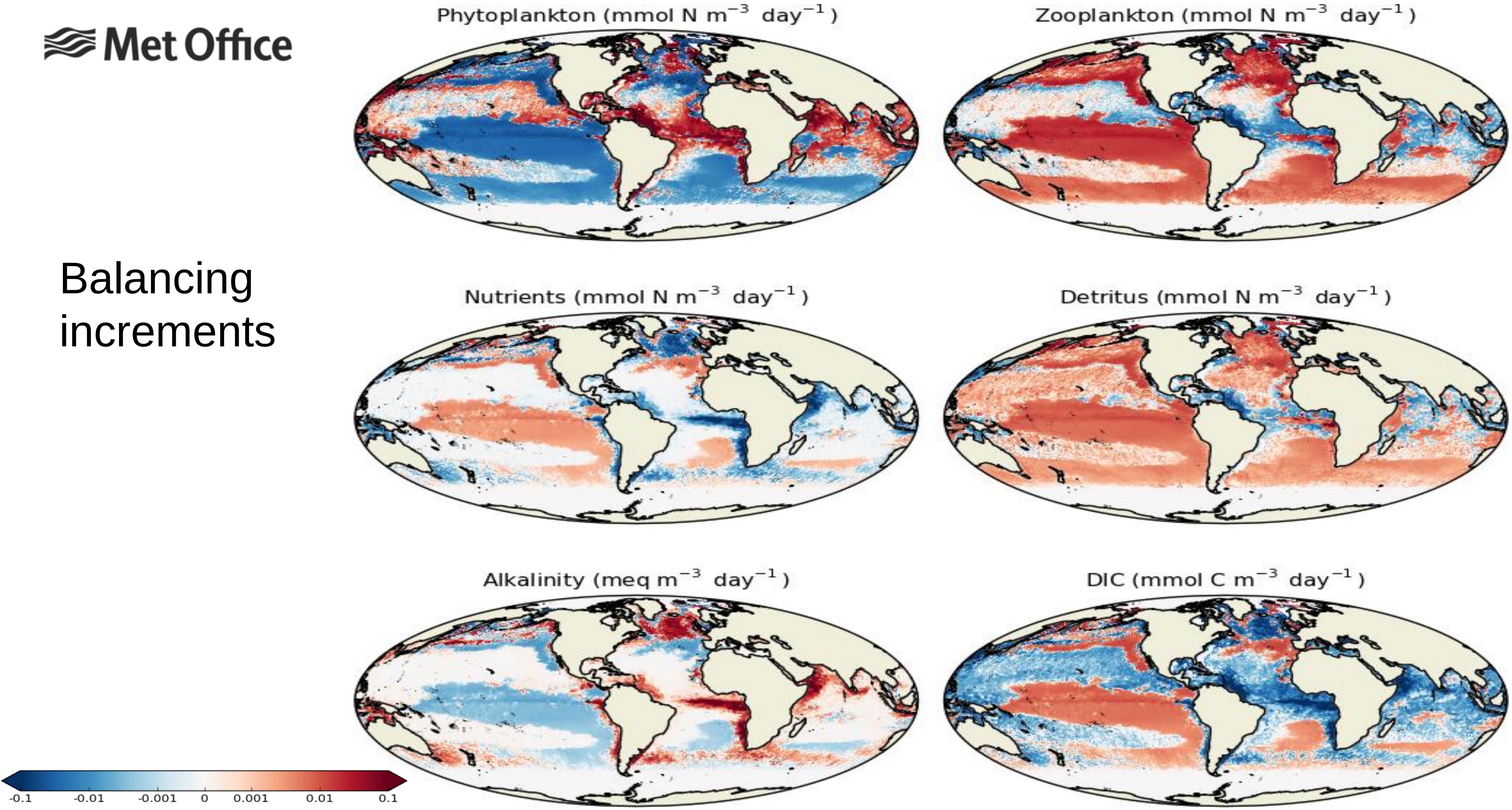
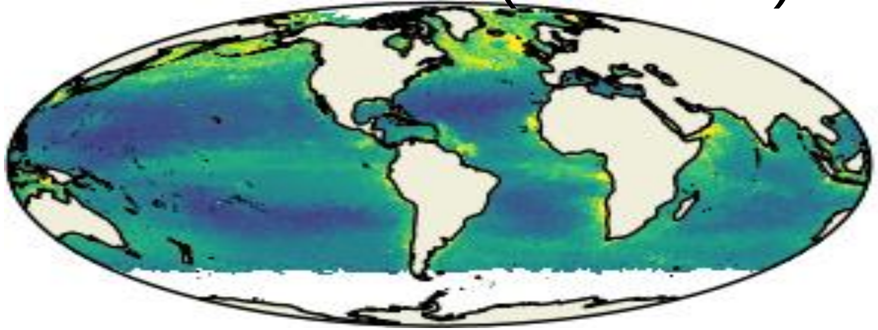
Balancing increments

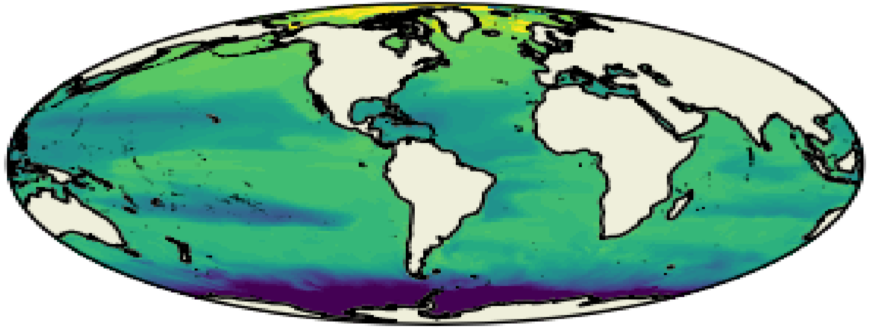


Surface chlorophyll (July 2002)

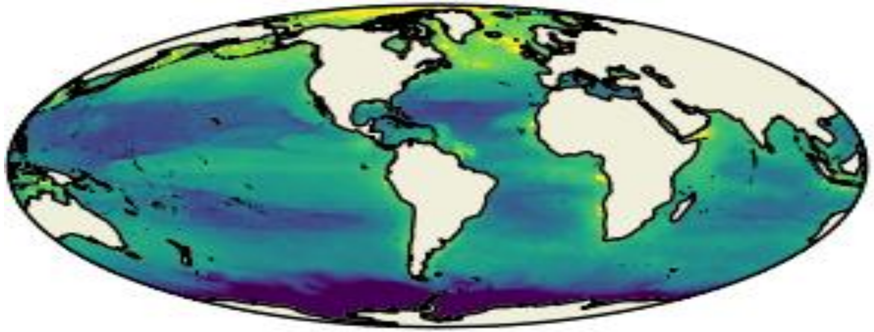
Observations (ESA CCI)



Free run

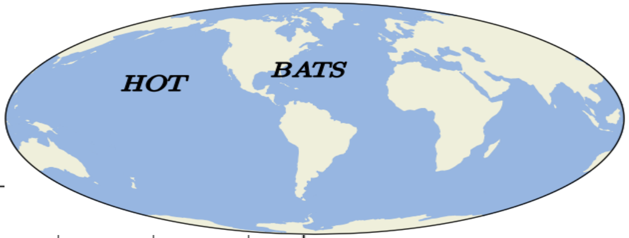


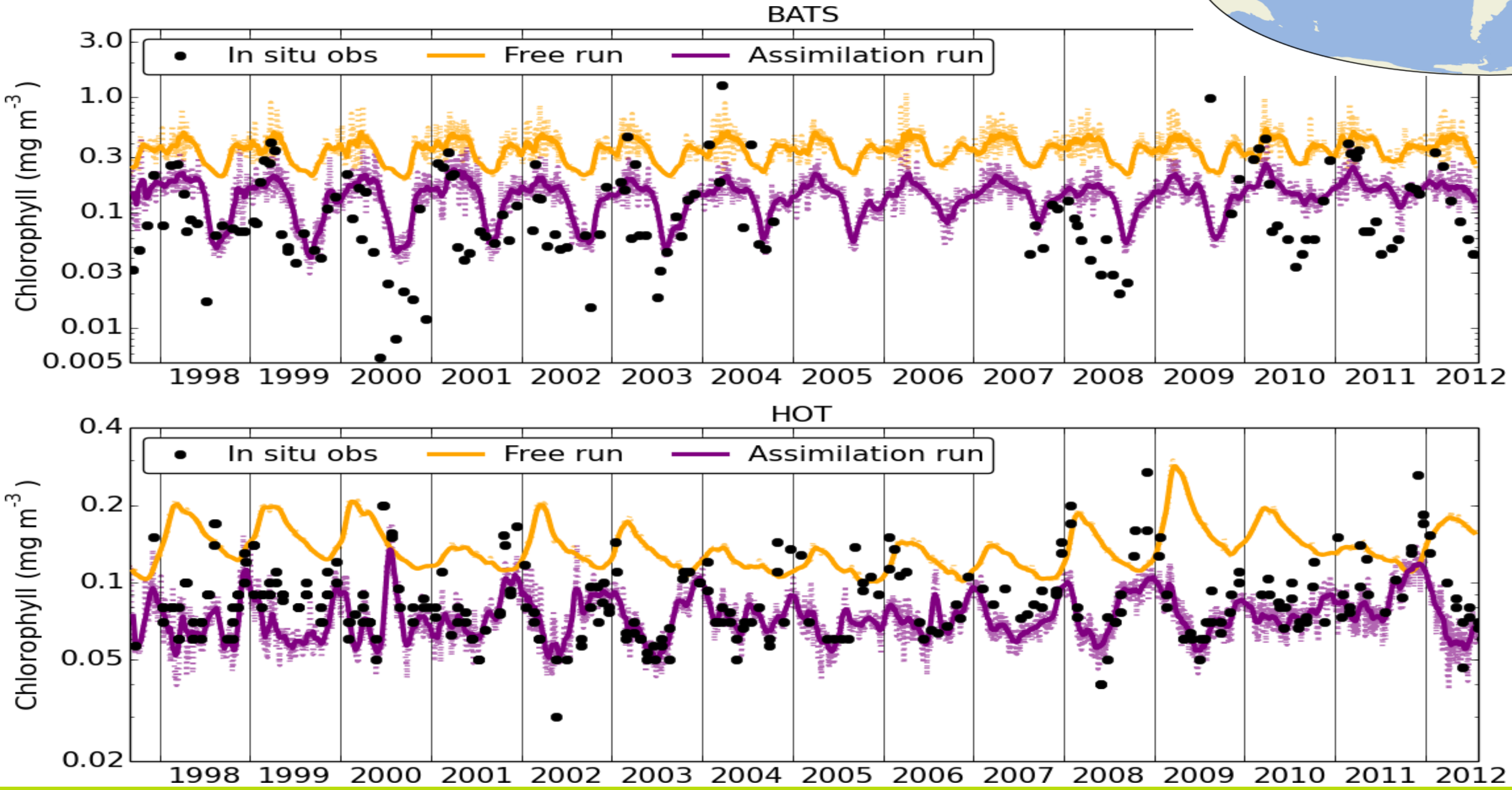
Assimilation run



Ford and Barciela, 2017, Remote Sensing of Environment

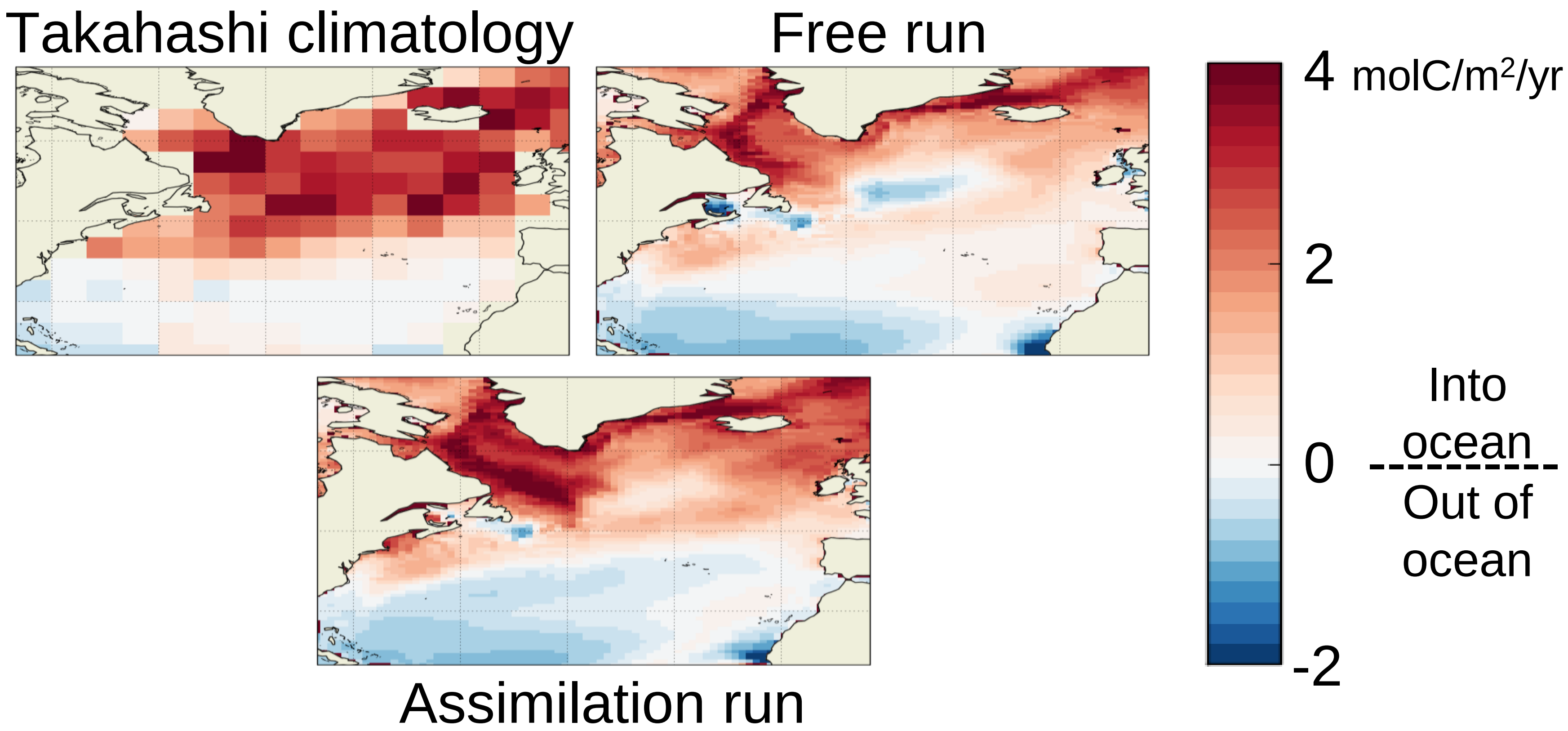
Surface chlorophyll





Ford and Barciela, 2017, Remote Sensing of Environment

Air-sea CO_2 flux (June mean)



Gehlen et al., 2015, Journal of Operational Oceanography

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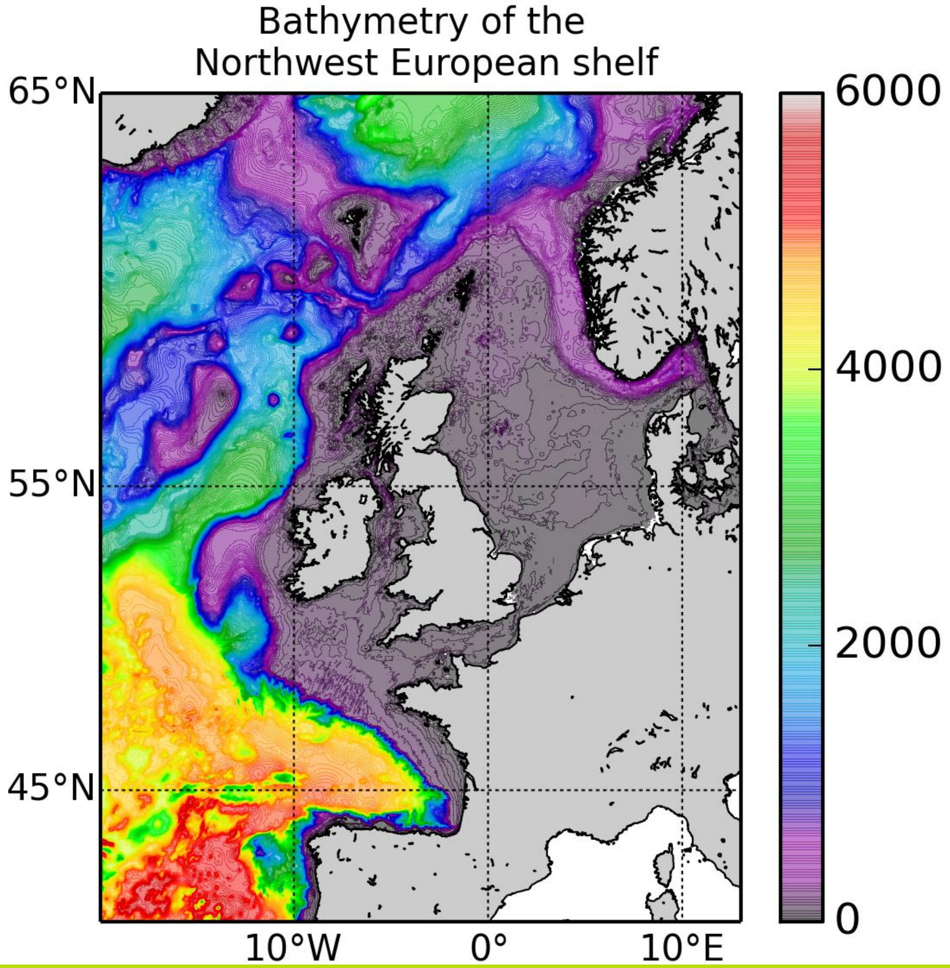
Satellite chlorophyll – regional

Northwest European Shelf (NWS)

a.k.a.

Atlantic Margin Model (AMM) domain



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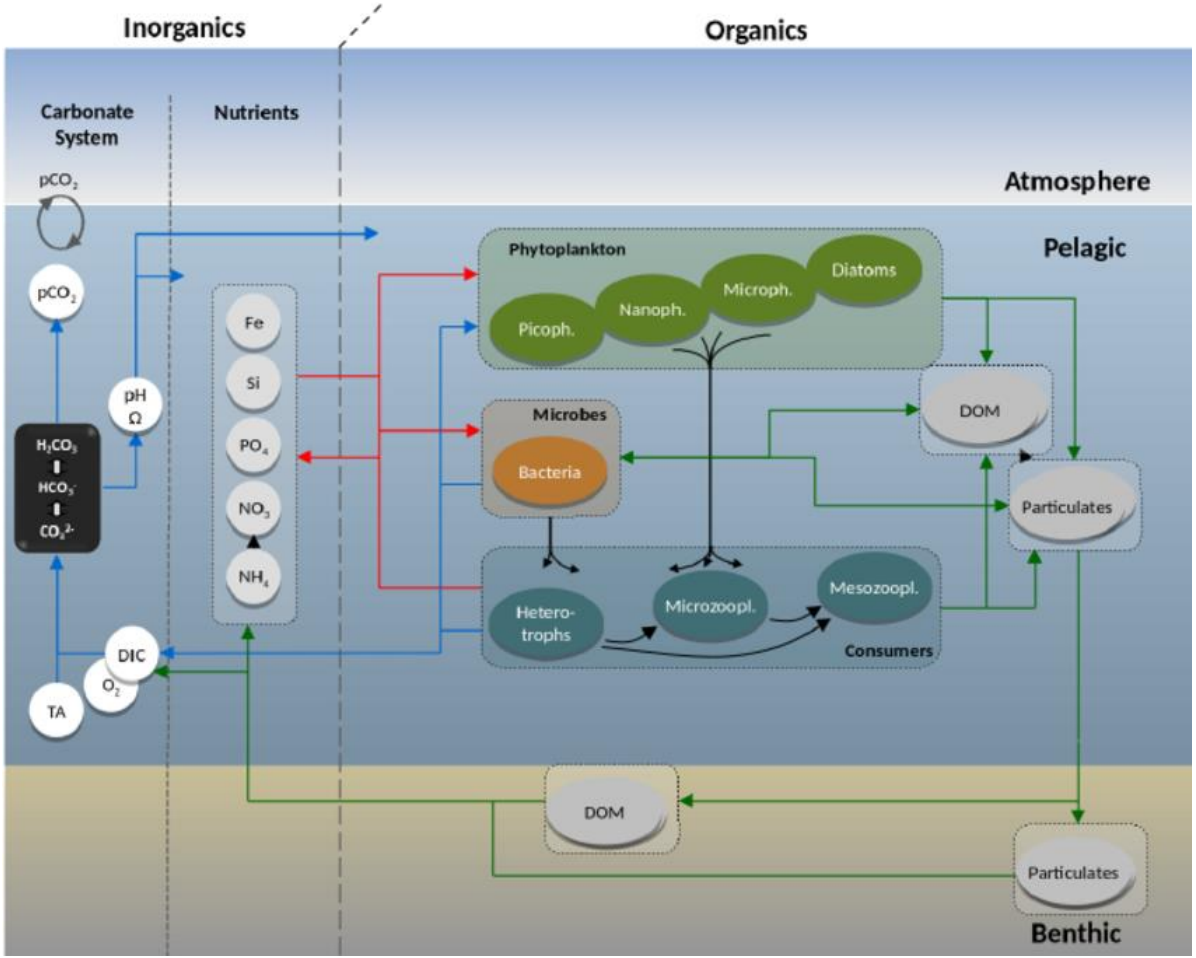
NEMO

+

European **R**egional **S**eas **E**cosystem **M**odel (**ERSEM**)

+

NEMOVAR (3D-Var assimilation)

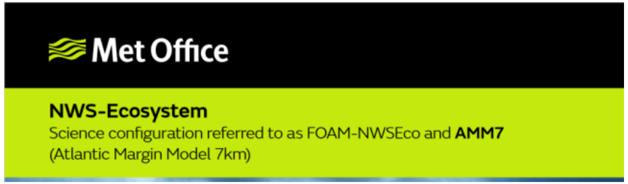


7km resolution

- Operational forecasts
  - Analysis and six-day forecast available from Met Office
  - Updated daily

- Physics assimilation:
  - Satellite and in situ SST
  - In situ temperature and salinity
  - Satellite altimetry

- Biogeochemistry assimilation:
  - Chlorophyll from satellite ocean colour



https://www.metoffice.gov.uk/services/data/met-office-marine-data-service

Returning soon to Copernicus Marine Service

Chlorophyll assimilation

- Model has four phytoplankton classes, each with state variables for nitrogen, carbon, phosphorus, chlorophyll (and silicon for diatoms)

- Ocean colour products give total chlorophyll (currently used) or chlorophyll for each phytoplankton class (future upgrade, used for reanalysis)

- Calculate increments to remaining phytoplankton state variables which maintain existing modelled ratios between them at each grid point

- Still working on effective way to update non-phytoplankton variables

In situ observations
(one of an increasing number of examples)

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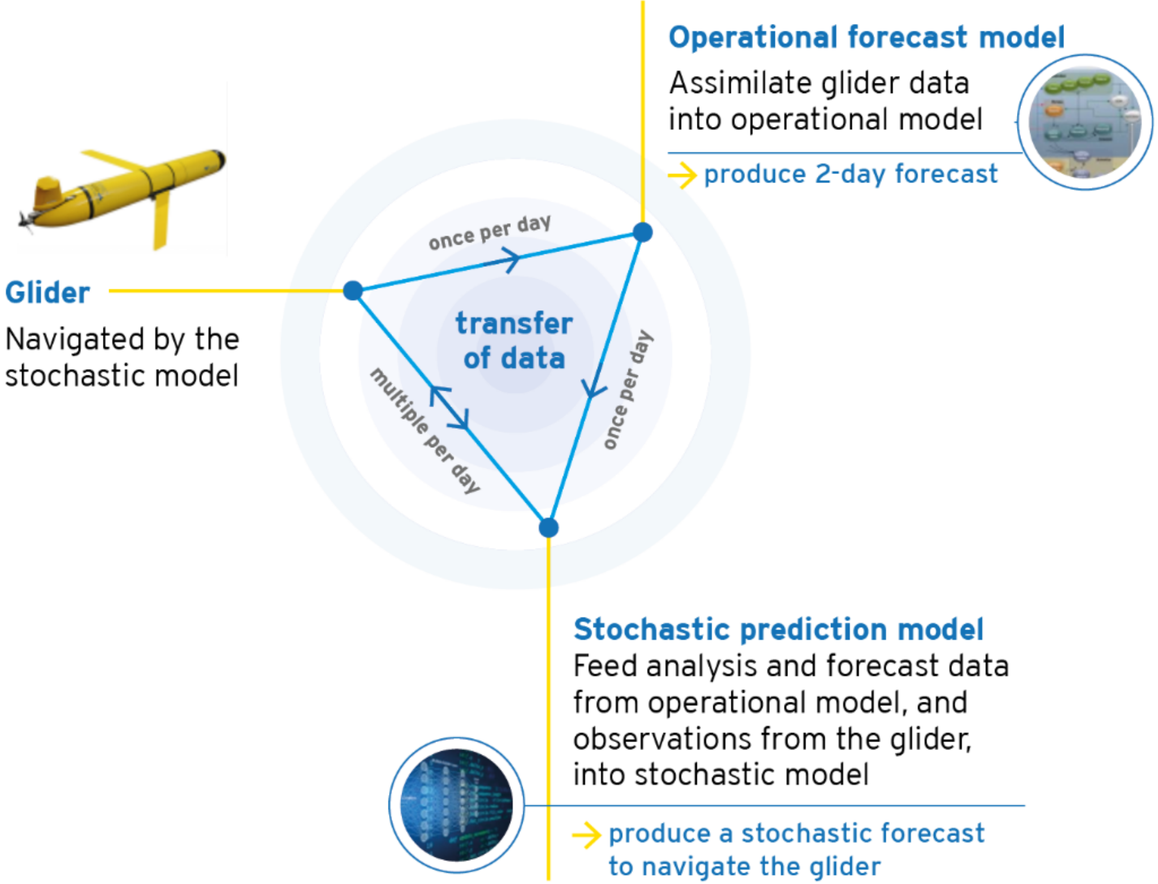
Operational forecast model
Assimilate glider data into operational model
produce 2-day forecast
Glider
Navigated by the stochastic model
once per day
transfer of data
multiple per day
once per day
Stochastic prediction model
Feed analysis and forecast data from operational model, and observations from the glider, into stochastic model
produce a stochastic forecast to navigate the glider

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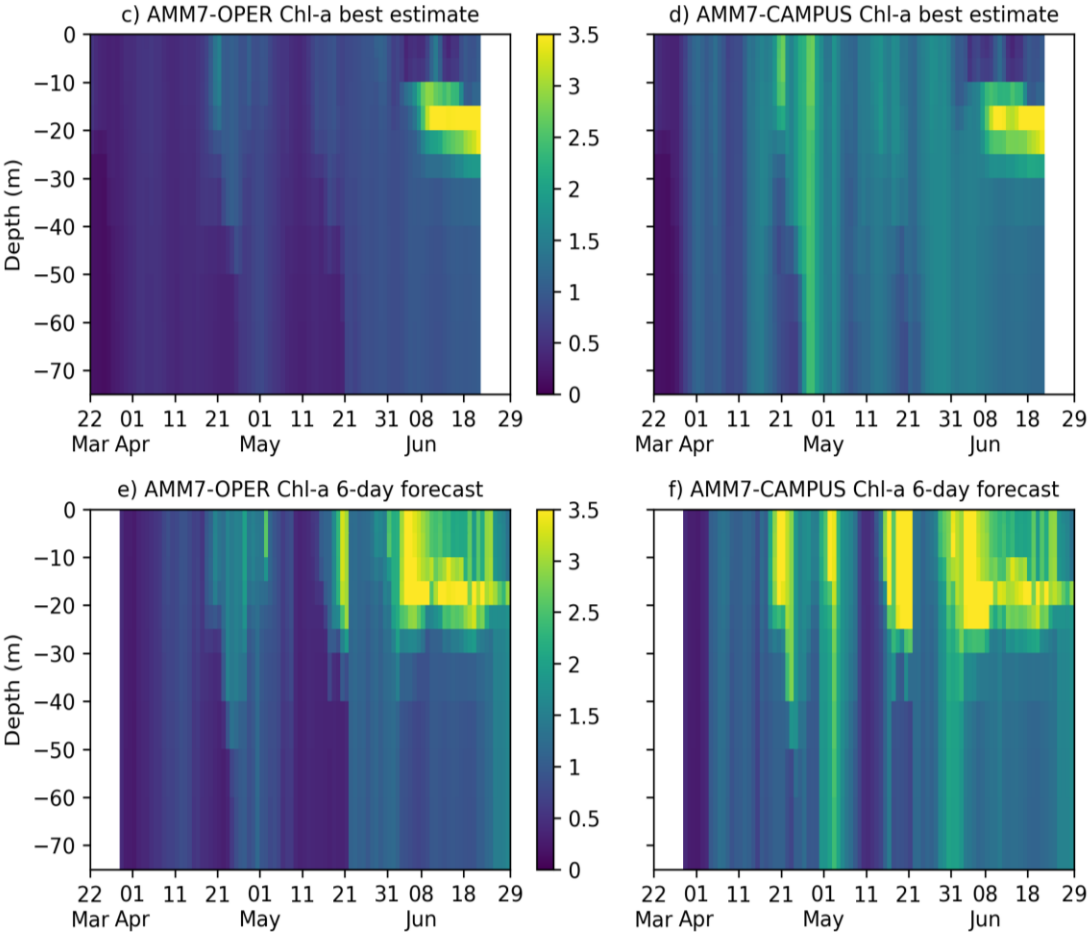
Chl-a analysis
without
glider assimilation

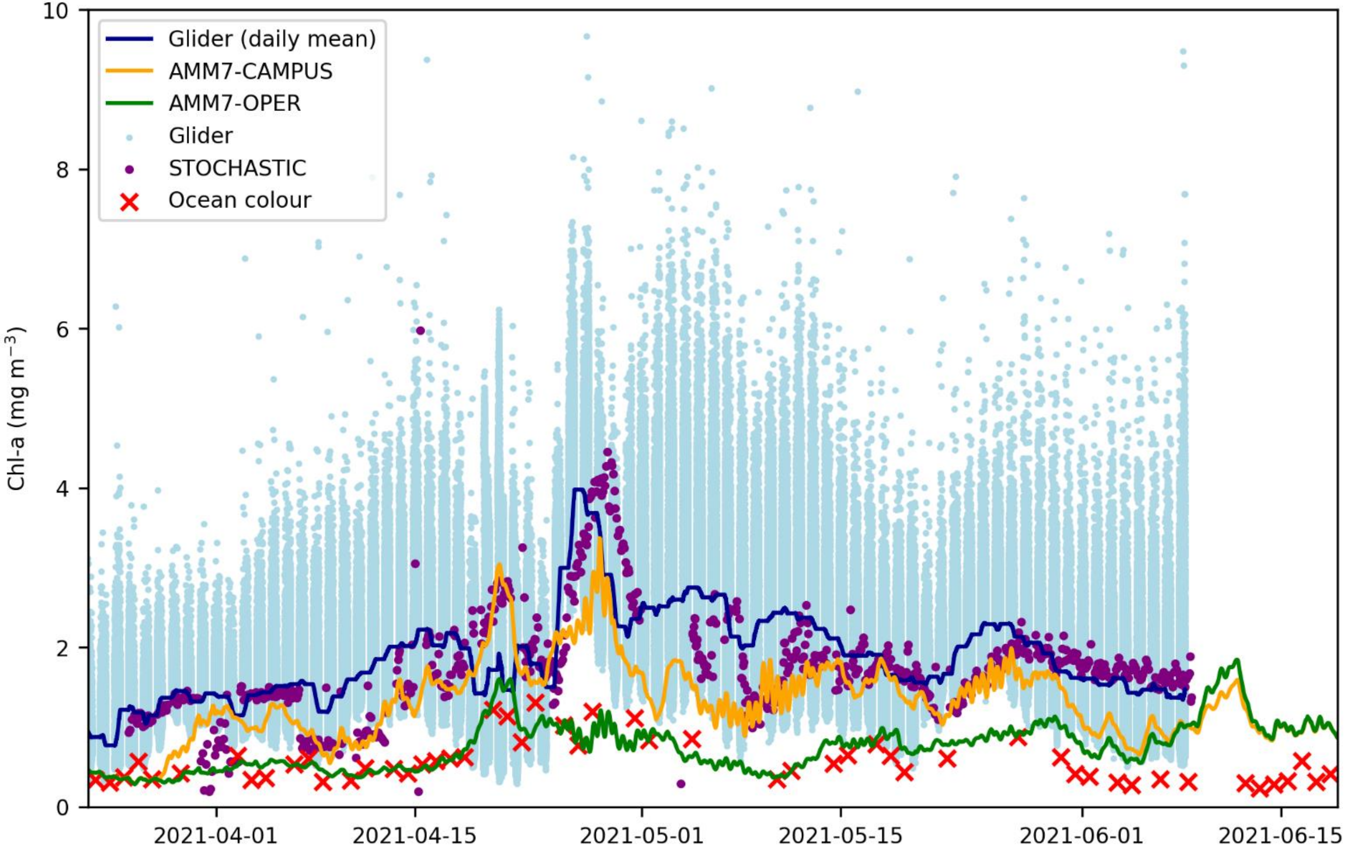


Chl-a analysis
with
glider assimilation

6-day forecast
without
glider assimilation

6-day forecast
with
glider assimilation

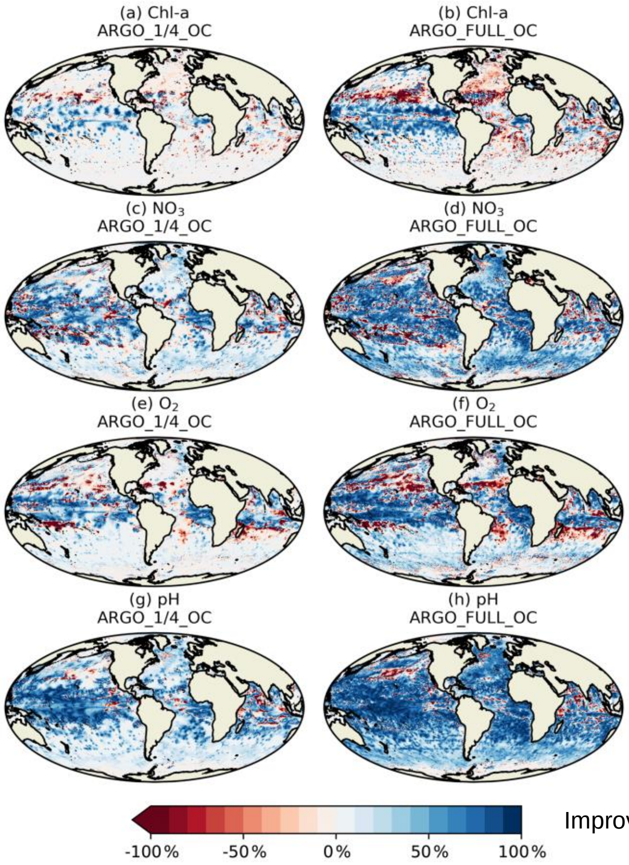
(Near-)surface chlorophyll



In situ observations (a synthetic example)

Biogeochemical-Argo

- Observing system simulation experiments (OSSEs)
- Test potential impact of having
  - BGC sensors on all Argo floats
  - BGC sensors on ¼ of Argo floats
- More floats the better
- Positive impact in both cases
- More could be done to improve use of sparse observations in DA



Improvement vs truth

Ford, 2021, https://doi.org/10.5194/bg-18-509-2021

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Challenges

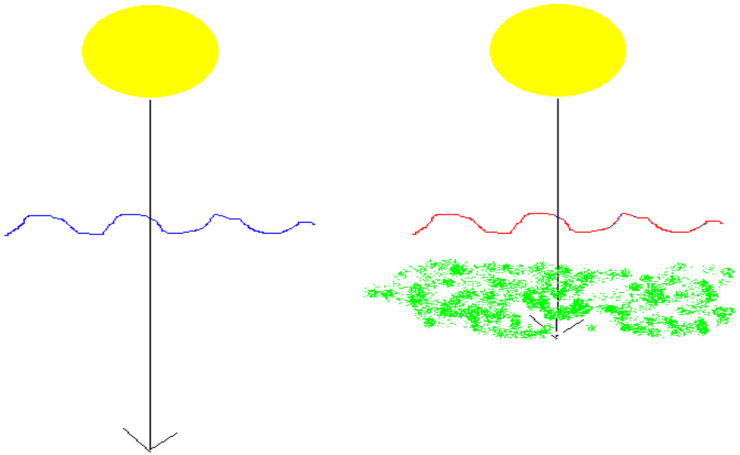
Challenges

- Lack of observations
- Variables are non-Gaussian
- Potentially large model biases
- Potentially large observation uncertainties
- Combining satellite and in situ
- Updating multivariate state
- How best to use ocean colour
  - Less derived products like radiances?
  - More derived products like phytoplankton functional types?
- Combined state-parameter estimation
- Two-way coupling with ocean physics

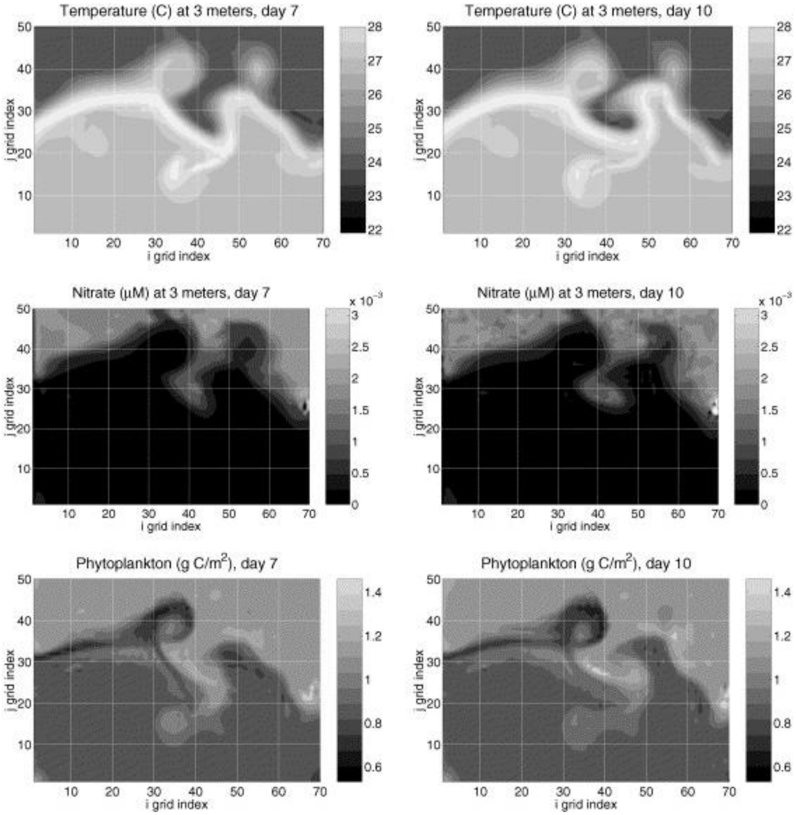
Ocean physics-biogeochemistry coupling

Light absorption

- Longwave radiation absorbed in upper few cm
- Shortwave radiation penetrates more deeply
- Phytoplankton, sediments and gelbstoff alter depth of penetration [and therefore ocean physics]



Alignment of fronts and vertical features



Anderson et al., 2000, https://doi.org/10.1016/S0967-0637(00)00019-4

Questions?