Intro to Biogeochemical Modeling
Ocean & Coupled

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Lecture Outline

1) Large Scale Ocean Biogeochemical Features
2) Techniques for Modeling Biological Productivity
3) Skill Assessment
4) Global Carbon Cycle
5) Summary
NO$_3$ (a nutrient), O$_2$ (dissolved gas) 
Along Pacific Transect
DIC (~CO$_2$) Along Same Pacific Transect
Takahashi Air-Sea CO$_2$ Gas Flux
Primary Processes Governing Distribution of Nutrients, O$_2$, Carbon, etc.

- Biological Productivity in Euphotic Zone
  - Consumes Nutrients & Inorganic Carbon
  - Produces Organic Matter & O$_2$

- Export of Organic Matter out of Euphotic Zone
  - Sinking Particles (e.g. detritus, CaCO$_3$ shells, ...)
  - Circulation of Suspended Matter

- Remineralization of Organic Matter
  - ‘reverse’ of productivity, consumes O$_2$

- General Circulation
  - Advective Transport
  - Lateral & Vertical Mixing

- Temperature Dependent Air-Sea Gas Exchange
Other Processes, Smaller Global Impact, Regionally Significant

• Atmospheric Nutrient Deposition
  – Fe, N, P, ...

• Sedimentary Burial

• Riverine Inputs

• Nitrogen Fixation
  – Conversion of dissolved $N_2$ gas into $NH_4$

• Denitrification
  – Consumption of $NO_3$ during remineralization
What is an NPZD model?

N  Nutrient
   nitrate, ammonium, phosphate, silicate, iron, etc.

P  Phytoplankton
   photosynthesizers

Z  Zooplankton
   grazers

D  Detritus

Canonical Example

Many more variations are used...

Fasham model diagram from www.gotm.net
Simple NPZ Model

\[ \frac{dP}{dt} = \mu_0 \left( \frac{N}{k_N + N} \right) \left( 1 - e^{\alpha / \mu_0} \right) P - g \left( \frac{P}{k_p + P} \right) Z - m_P P \]

Nutrient limitation  Light limitation  Grazing  Mortality

\[ \frac{dZ}{dt} = a g \left( \frac{P}{k_p + P} \right) Z - m_Z Z \]

\[ \frac{dN}{dt} = -\mu_0 \left( \frac{N}{k_N + N} \right) \left( 1 - e^{\alpha / \mu_0} \right) P + (1 - a) g \left( \frac{P}{k_p + P} \right) Z + m_P P + m_Z Z \]

• Three coupled ordinary differential equations
• Mass conservation
How do you estimate parameters and functional forms?

• Laboratory & field incubations
  – P-I curves
  – Nutrient uptake curves
• Tune/Optimize against field data
• Previous Models
Plankton Functional Types (PFTs)

• Categorize plankton species by how they function and use representative types/groups
  – Explicit biogeochemical role
  – Biomass and productivity controlled by distinct physiological, environmental, or nutrient requirements
  – Behavior has distinct effect on other PFTs
  – Quantitative importance in some region of the ocean
Skill & Portability in 12 Different NPZD models
Friedrichs et al., JGR-Oceans, 2007.

(b) Simple models do just as well as more complex models when tuned for specific sites.
(c) More complex models do better at multiple sites with single parameter sets.
(d) More complex models perform better at different sites when tuned for one site.
CCSM BEC model

Inorganic Tracers
- NO₃, NH₄, PO₄,
- Si(OH)₃, Fe, O₂,
- DIC & Alkalinity

Growth
- N₂ Fixation
- Calcification

Phytoplankton
- pico/nano diatoms
diazotrophs

Excretion
- Mortality & Aggregation

Detritus
- suspended/DOM
- large (POM, silica, CaCO₃, dust)

Remineralization & Dissolution

Sinking

Grazing

Chlorophyll pico/nano diatoms diazotrophs

Photoadaptation

Mortality & Sloppy Feeding

Doney et al.
(J. Mar. Systems, 2009)

Moore, Doney, Lindsay, Global Biogeochemical Cycles, 2004.
Moore et al., J Climate, 2013.
Primary Features of CESM BEC Model

• Nutrients: N, P, Si, Fe
• 4 Plankton Functional Groups
  – 3 Autotrophs, 1 Grazer
  – Implicit coccolithophores
  – 32 tracers in CESM 2.0
    • 27 in CESM 1.2 and 24 in CESM 1.0/1.1
• Fixed C:N ratios in plankton
• Variable P:C, Fe:C, Si:C, Chl:C ratios
  – P:C was fixed in CESM 1.2 and previous versions
• Fe model has prognostic Fe-binding ligand
  – as of CESM 2.0
Known Gaps in Ocean BGC in CESM1

• Calcification & open ocean CaCO$_3$ dissolution rates are independent of CO$_3$ saturation state
• Riverine inputs of BGC tracers are prescribed
• C, N, P, Si, CaCO$_3$ buried in sediments are lost from the system
• No treatment of BGC in sea-ice

• Focus in on lower trophic levels
Model Validation: Examples of Data Sets

- Macronutrients (PO$_4$, NO$_3$, SiO$_3$) and O$_2$ from World Ocean Atlas
- DIC, ALK from GLODAP Analysis
- pCO$_2$ and CO$_2$ Flux assembled by Takahashi
- Surface Chl measured by satellite
- Productivity estimated from satellite
- JGOFS study sites
- HOTS & BATS timeseries
Air-sea CO$_2$ Flux

Doney et al. (Deep-Sea Res. II, 2009)
Known Challenges

• Optimize BGC model parameters
  – Functional group approach increases uncertainty of parameters (i.e. multiple species, with different characteristics, are clumped together)
  – Don’t want to overtune too much to compensate for biases in physical model

• Given BGC model parameters and physical circulation, generate balanced BGC state
  – Need to deal w/ diurnal to millenial timescales
  – Using Newton-Krylov for this is a work in progress
Large Scale Global Carbon Cycle

Figure courtesy PMEL
20th Century CO2 Fluxes into Atmosphere in CESM1(BGC)

(a) Total
(b) Fossil Fuels
(c) Sea-to-Air
(d) Land-to-Air

Lindsay et al., 2014, J Clim
20th Century CO₂ Fluxes into Atmosphere in CESM1.2+(BGC)

(a) Total
(b) Fossil Fuels
(c) Sea-to-Air
(d) Land-to-Air
Seasonal Cycle of CO$_2$, CESM1(BGC)

Lindsay et al., 2014, J Clim
Seasonal Cycle of CO$_2$, CESM1.2+(BGC)

Point Barrow, Alaska

Mauna Loa, Hawaii

Palmer Station, Antarctica

South Pole
Atmospheric CO$_2$ in CMIP5 Earth System Models

Hoffmann et al, JGR-BGS, 2013
Ocean and Land Carbon Accumulation in CMIP5 Earth System Models

Hoffmann et al, JGR-BGS, 2013
Subset of Literature on Carbon Cycle in Earth System Models

• C4MIP
  – Friedlingstein et al., J Clim, 2006

• Carbon Cycle Model Evaluation
  – Randerson et al., Global Change Biology, 2009
  – Cadule et al., GBC, 2010
  – Anav et al., J Clim, 2013
  – Hoffmann et al., JGR-BGS, 2013

• Emissions Compatible w/ Prescribed CO$_2$ Concentrations
  – Jones et al., J Clim, 2013

• Feedbacks in 1% CO$_2$ ramping CMIP5 experiments
  – Arora et al., J Clim, 2013
  – Schwinger et al., J Clim, 2014

• Emergent constraints
  – Cox et al., Nature, 2013
  – Wang et al., GRL, 2014
  – Wenzel et al., JGR-BGS, 2014
Summary

• Large scale ocean biogeochemical features are determined by handful of processes
• ‘Perfect’ ecosystem model doesn’t exist, many simplifications need to be made. Improving models is ongoing research. Scientific questions and observational constraints guide this process.

• Global carbon cycle is now present in numerous CMIP class models (ESMs). Observations of atmospheric CO$_2$, on multiple timescales, are valuable constraint on models.
• Land & ocean uptake of anthropogenic CO$_2$, particularly sensitivity to climate change is ongoing research.
• Literature on the global carbon cycle in ESMs (e.g. CMIP5) is growing rapidly.

• Practical Notes for activating the carbon cycle in CESM are available and will be presented in Land/BGC breakout.