Fasham, Ducklow and McKelvie (1990)
The five component ecosystem model equations are,

\[
\frac{\partial [\text{NO}_3]}{\partial t} = -Q_1 + FLUX_{\text{NO}_3}
\]  \hspace{1cm} (1)

\[
\frac{\partial [\text{NH}_4]}{\partial t} = -Q_2 + \mu_{\text{Zoo}}[\text{NH}_4] \cdot [\text{Zoo}] + \mu_{\text{Det}}[\text{NH}_4] \cdot [\text{Det}]
\]  \hspace{1cm} (2)

\[
\frac{\partial [\text{Phyt}]}{\partial t} = -\left(\mu_{\text{Phyt}} + \mu_{\text{Phyt}}[\text{Det}]\right) \cdot [\text{Phyt}] - G + Q_1 + Q_2
\]  \hspace{1cm} (3)

\[
\frac{\partial [\text{Zoo}]}{\partial t} = -\left(\mu_{\text{Zoo}} + \mu_{\text{Zoo}}[\text{NH}_4] + \mu_{\text{Zoo}}[\text{Det}]\right) \cdot [\text{Zoo}] + \beta \cdot G
\]  \hspace{1cm} (4)

\[
\frac{\partial [\text{Det}]}{\partial t} = -\left(\mu_{\text{Det}} + \mu_{\text{Det}}[\text{NH}_4]\right) \cdot [\text{Det}]
\]  
\[+ (1 - \beta) \cdot G + \mu_{\text{Phyt}}[\text{Det}] \cdot [\text{Phyt}]
\]  \hspace{1cm} (5)
A variety of OBGCMs are now in use

Steinacher et al. (2010; Biogeosciences)
Diversity of Ocean BGC in CMIP5

<table>
<thead>
<tr>
<th>Model</th>
<th>Atmosphere</th>
<th>Ocean</th>
<th>Ref.</th>
<th>MBG</th>
<th>Phytoplankton</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CESM1-BGC</td>
<td>26 lev.</td>
<td>60 lev.</td>
<td>Gent et al. (2011), Lindsay et al. (2013)</td>
<td>BEC</td>
<td>3 (diatom, nanophyto, diazotroph)</td>
<td>Moore et al. (2004), Doney et al. (2009)</td>
</tr>
<tr>
<td>GFDL-ESM2G</td>
<td>24 lev.,</td>
<td>63 lev.</td>
<td>Dunne et al. (2012a)</td>
<td>TOPAZ2</td>
<td>3 (large separated into diatoms and non-diatom, small cyanobacteria, diazotroph)</td>
<td>Dunne et al. (2012b)</td>
</tr>
<tr>
<td>GFDL-ESM2M</td>
<td>24 lev.,</td>
<td>50 lev.</td>
<td>Dunne et al. (2012a)</td>
<td>TOPAZ2</td>
<td>3 (large separated into diatoms and non-diatom, small cyanobacteria, diazotroph)</td>
<td>Dunne et al. (2012b)</td>
</tr>
<tr>
<td>MPI-ESM-LR</td>
<td>47 lev.</td>
<td>40 lev.</td>
<td>Giorgetta et al., (2013)</td>
<td>HAMOCC5.2</td>
<td>1 (but separated into diatoms and calcifiers)</td>
<td>Ilyina et al. (2013)</td>
</tr>
<tr>
<td>MPI-ESM-MR</td>
<td>95 lev.</td>
<td>40 lev.</td>
<td>Giorgetta et al., (2013)</td>
<td>HAMOCC5.2</td>
<td>1 (but separated into diatoms and calcifiers)</td>
<td>Ilyina et al. (2013)</td>
</tr>
<tr>
<td>NorESM1-ME</td>
<td>26 lev.</td>
<td>53 lev.</td>
<td>Bentsen et al. (2012)</td>
<td>HAMOCC5.1</td>
<td>1 (but separated into diatoms and calcifiers)</td>
<td>Assmann et al. (2010)</td>
</tr>
</tbody>
</table>

Bopp et al. (2013)
What’s happened since 1990?

- Global application
- Incorporation of other elemental cycles
  - Carbon Cycle (OCMIP2)
  - Oxygen cycle
  - Iron cycle (HNLC)
  - Silicic Acid (diatoms)
  - Calcification (forams, coccoliths)
  - Nitrogen-Phosphorus interactions
    - River, atmosphere and N₂ fixation supply
    - Water Column and sediment denitrification
- Improved processes
  - Phytoplankton K/R strategies and size structure
  - Mechanistically motivated sinking
  - Dissolved organic matter
Typical OBGCMs applications

1. How much anthropogenic carbon uptake has occurred?
2. How will anthropogenic carbon uptake change under climate change?
3. How will the natural carbon cycle change under climate change?
4. How will ecosystems change under climate change?

...limiting uncertainties representing ocean circulation and sensitivity to change.

Biogeochemical uncertainties include mechanistic controls on:

- Euphotic zone nutrient consumption and degree of residual nutrient
- Controls on POM/DOM passive and active transport
- Deviations in stoichiometry from Redfield (e.g. N$_2$ fixation)
- Remineralization scales through the twilight zone

Ecological uncertainties include:

- Physiology (general controls, functional traits, adaptation limits)
- Biodiversity (predictability, phenology, niche gaps, etc)
- Ecological interactions
Philosophies for Ocean BGC Modeling

- Challenge: the vast complexity of natural systems versus the limited, imperfect ability to mathematically represent those processes.
  - Seek fundamental rules and constraints of energy, mass, and biogeochemistry
- Representation of phytoplankton via:
  - Sentinel species (i.e. *Prochlorococcus*, *Trichodesmium*, and *T. weissflogii*, *E. huxleya*)
    - Calibration to best-known constraints, but leaves vast biogeochemical gaps
  - Phytoplankton functional groups (CO₂-fixers, N₂-fixers, silicifiers, calcifiers)
    - Calibration to particular functions, leaving other functions missing
  - Empirical biogeochemical function (CO₂-fxation, N₂-fixation, silicification, calcification)
    - Calibration to overall biogeochemical impact
- Assessment and attribution of biases
  - Prioritization of process study sites, field observations, vs satellite estimates for ‘truth’
  - Attribution to deficiencies in ocean physics? Atmospheric physics?
  - If attribution to biology, is it external inputs, physiology, ecology, or biogeochemistry?
  - Depending on attribution, decision-making on possibilities to change assumptions.
GFDL’s Tracers of Phytoplankton with Allometric Zooplankton (TOPAZ)

Diatoms and Other Large Phytoplankton
Flexible N:P:Si:Fe:Chl
Aragonite and Calcite

Biogeochemistry
- DOM cycling
- Particle sinking
- Atm. Deposition
- Gas exchange
- River Input
- Removal
- Sediment Input
- Scavenging

Phytoplankton ecology
- Recycled nutrients
- New nutrients
- N$_2$-fixer
- Small phyto.
- Large phyto.
- Semi-labile
- Semirefract.
- DOM
- Heterotrophs
- Protist
- Filter feeder
- Detritus

Carbon
Oxygen
Nitrogen
Phosphorus
Iron
Alkalinity
Silicon
Lithogenic

Dunne et al. (2005;2013)
Many groups are exploring alternative vertical coordinates

- Depth-based vertical coordinate
- Over 40 years of experience

- Density-based vertical coordinate
- Easy to preserve water masses

Dunne et al. (2012, 2013); Winton et al. (2013); Hallberg et al. (2013); Froelicher et al. (submitted)
Taylor Diagrams of CMIP5 X-Y Patterns

Models get SST, under estimate pH variability, and vary widely on NPP

Bopp et al. (2013)
‘Labile’ DOC in CMIP5 (Anderson et al 2015)
Carbon a Key CMIP5 Contribution

Figure 2. (a) Ocean and (b) land anthropogenic carbon inventories from

Hoffman et al., 2014
Southern Ocean Key to Carbon

ESM ensembling and inter-comparison provide powerful constraints insofar as the models agree (i.e. SST and pH changes)

RCP8.5 at 2100 - Stippling indicates sign agreement among models

Major challenges remain in resolving areas where ESM’s disagree

RCP8.5 at 2100 - Stippling indicates sign agreement among models

The achievement in GFDL’s ESMs illustrates the importance of including dynamical, chemical and biogeochemical interactions

Digging into Mechanisms: Without Circulation Change, Heat Uptake Would Look Much Like Carbon Uptake

**ΔTemp**

**ΔDIC**

Winton et al., 2013
Putting the puzzle pieces together: Mechanisms of Ocean Biogeochemical Change in CMIP5 ESMs

- Warming increases stratification
  - Ventilation and nutrient supply decreases globally
  - Increase in maximum rates, shift to microbial loop

- Poleward expansion and slow-down of subtropical gyres
  - Shoaling nutricline in the subtropical gyres
  - Enhanced nutrients, hypoxia and acidification in some areas

- Intensified hydrological cycle reduces North Atlantic overturning
  - Shoaling Northern Subpolar Atlantic and deepening tropics

- and many more pieces... Overall, a changing balance of processes creates intense regional structure.
Moving forward with GFDL’s ESMs

• **Application:** Multi-member ensembles for detection and attribution, centennial-millennial scales, idealized sensitivity, diverse impacts application.

• **Comprehensiveness:** beyond closing the CO$_2$ cycle to fully comprehensive and self consistent representation of aerosol, Fe, CH$_4$ and N cycles, and ecosystems

• **Resolution:** Resolving regional atmosphere-land interactions and the ocean mesoscale for improved base state and change, and the human and marine applications

• **Prediction:** Integration with seasonal-decadal climate prediction effort, exploring opportunities for experimental biogeochemistry prediction
Pushing the envelope: Decadal high resolution prototype with next generation biogeochemistry.

California Current Upwelling Signature vastly improved from 1° to 1/10° Resolution.