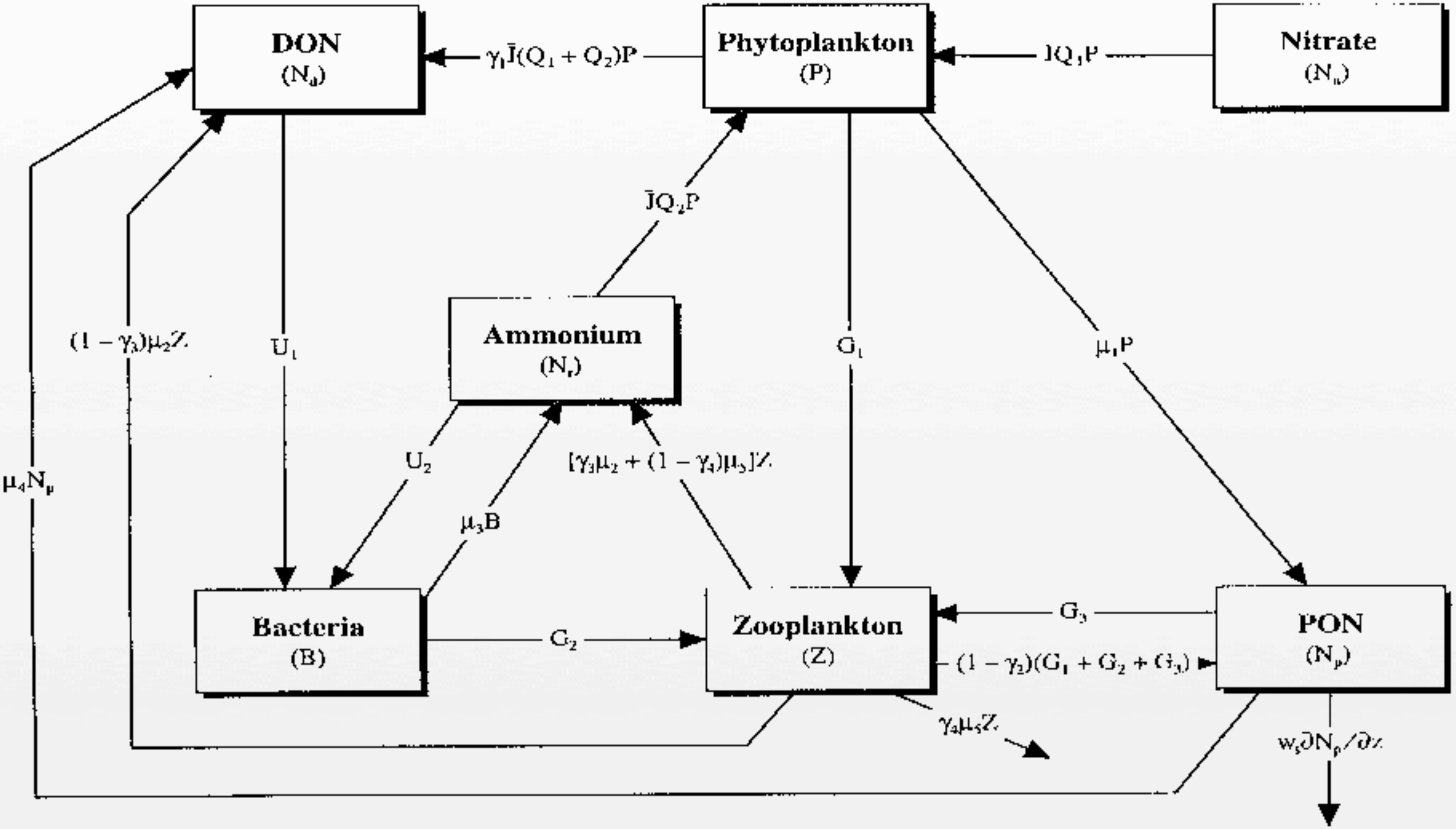
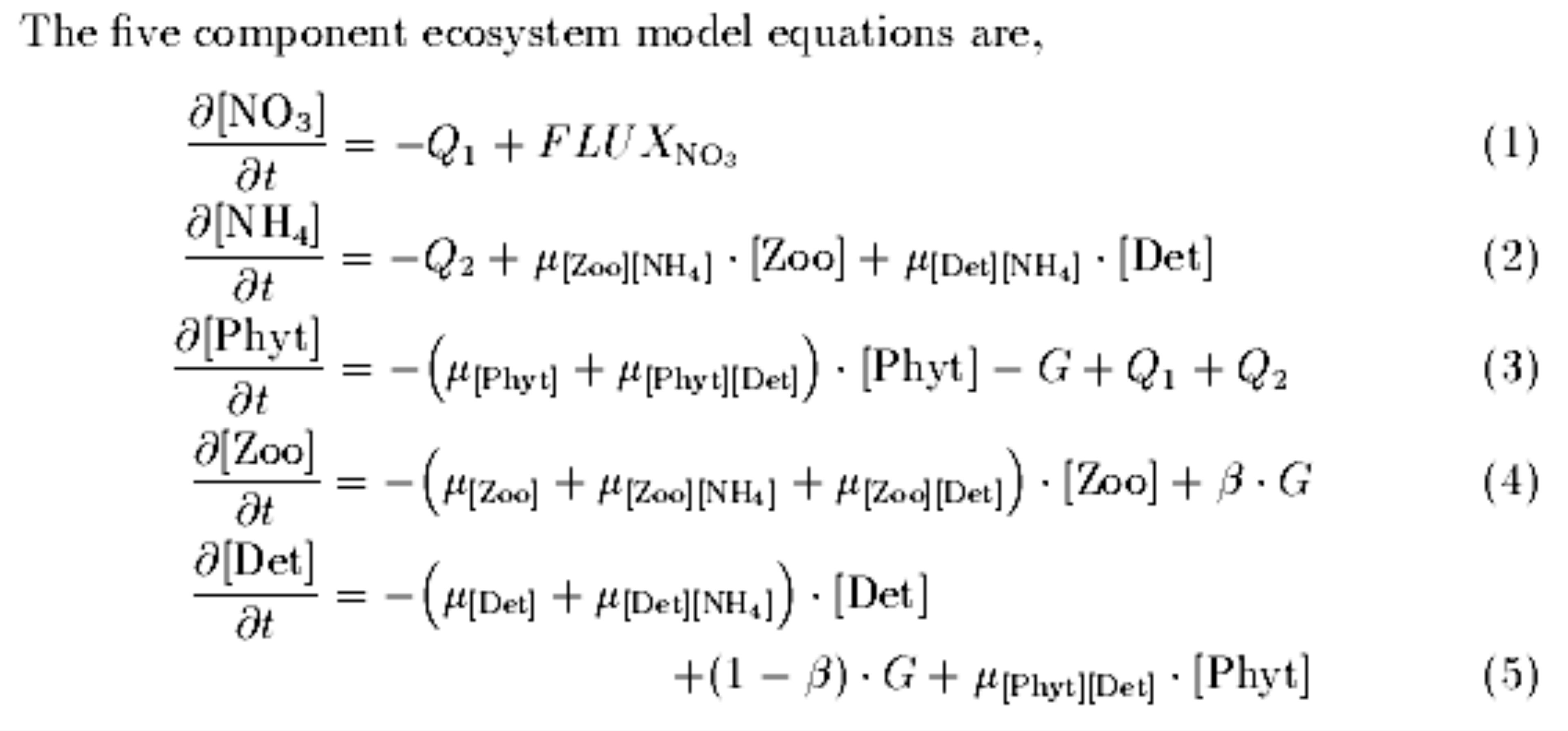
Fasham, Ducklow and McKelvie (1990)



Fasham, Ducklow and McKelvie (1990)



The five component ecosystem model equations are,

$$\frac{\partial[\mathrm{NO_3}]}{\partial t} = -Q_1 + FLUX_{\mathrm{NO_3}} \quad (1)$$

$$\frac{\partial[\mathrm{NH_4}]}{\partial t} = -Q_2 + \mu_{[\mathrm{Zoo}][\mathrm{NH_4}]} \cdot [\mathrm{Zoo}] + \mu_{[\mathrm{Det}][\mathrm{NH_4}]} \cdot [\mathrm{Det}] \quad (2)$$

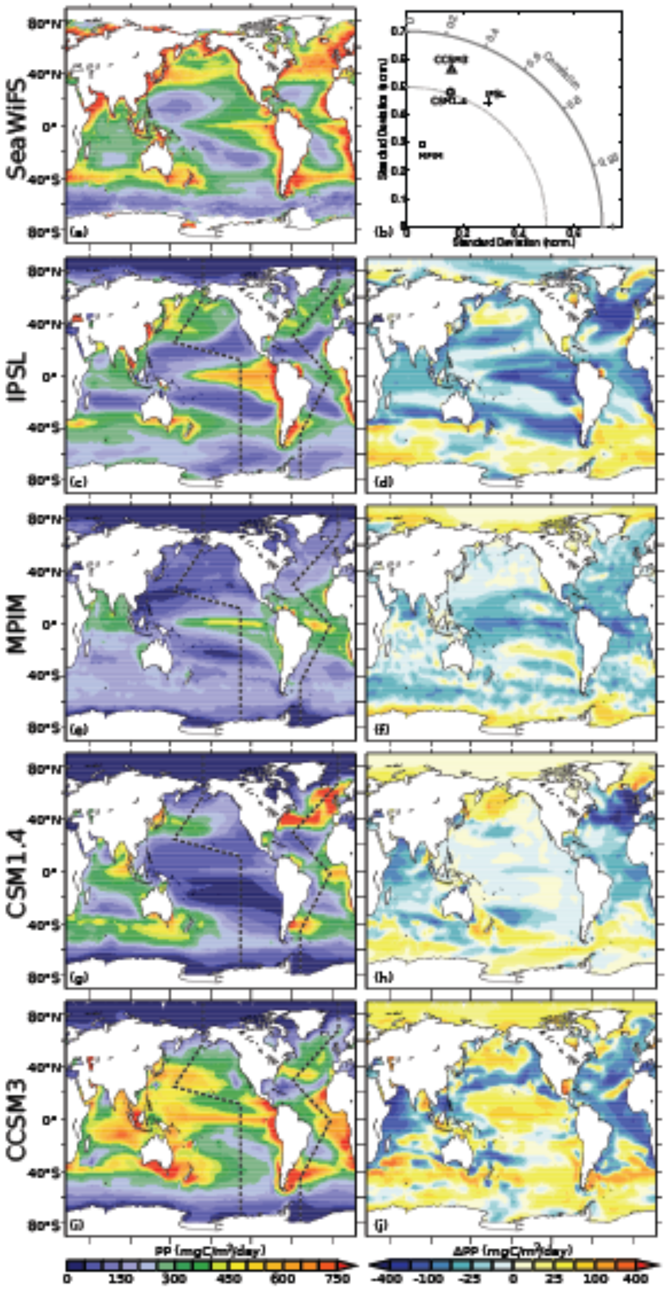
$$\frac{\partial[\mathrm{Phyt}]}{\partial t} = -\left(\mu_{[\mathrm{Phyt}]} + \mu_{[\mathrm{Phyt}][\mathrm{Det}]}\right) \cdot [\mathrm{Phyt}] - G + Q_1 + Q_2 \quad (3)$$

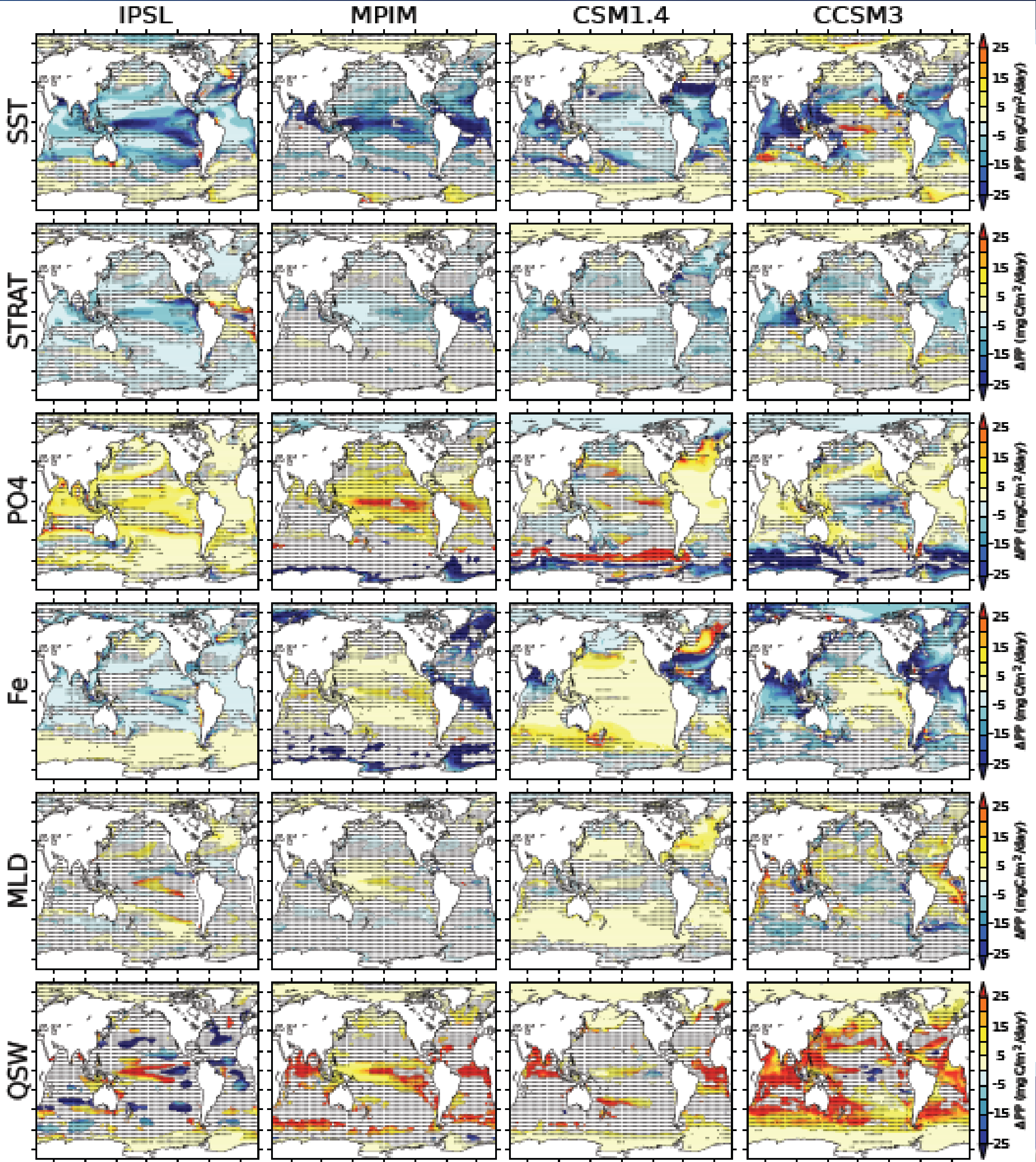
$$\frac{\partial[\mathrm{Zoo}]}{\partial t} = -\left(\mu_{[\mathrm{Zoo}]} + \mu_{[\mathrm{Zoo}][\mathrm{NH_4}]} + \mu_{[\mathrm{Zoo}][\mathrm{Det}]}\right) \cdot [\mathrm{Zoo}] + \beta \cdot G \quad (4)$$

$$\begin{aligned}\frac{\partial[\mathrm{Det}]}{\partial t} = &-\left(\mu_{[\mathrm{Det}]} + \mu_{[\mathrm{Det}][\mathrm{NH_4}]}\right) \cdot [\mathrm{Det}] \\ &+(1-\beta) \cdot G + \mu_{[\mathrm{Phyt}][\mathrm{Det}]} \cdot [\mathrm{Phyt}] \quad (5)\end{aligned}$$

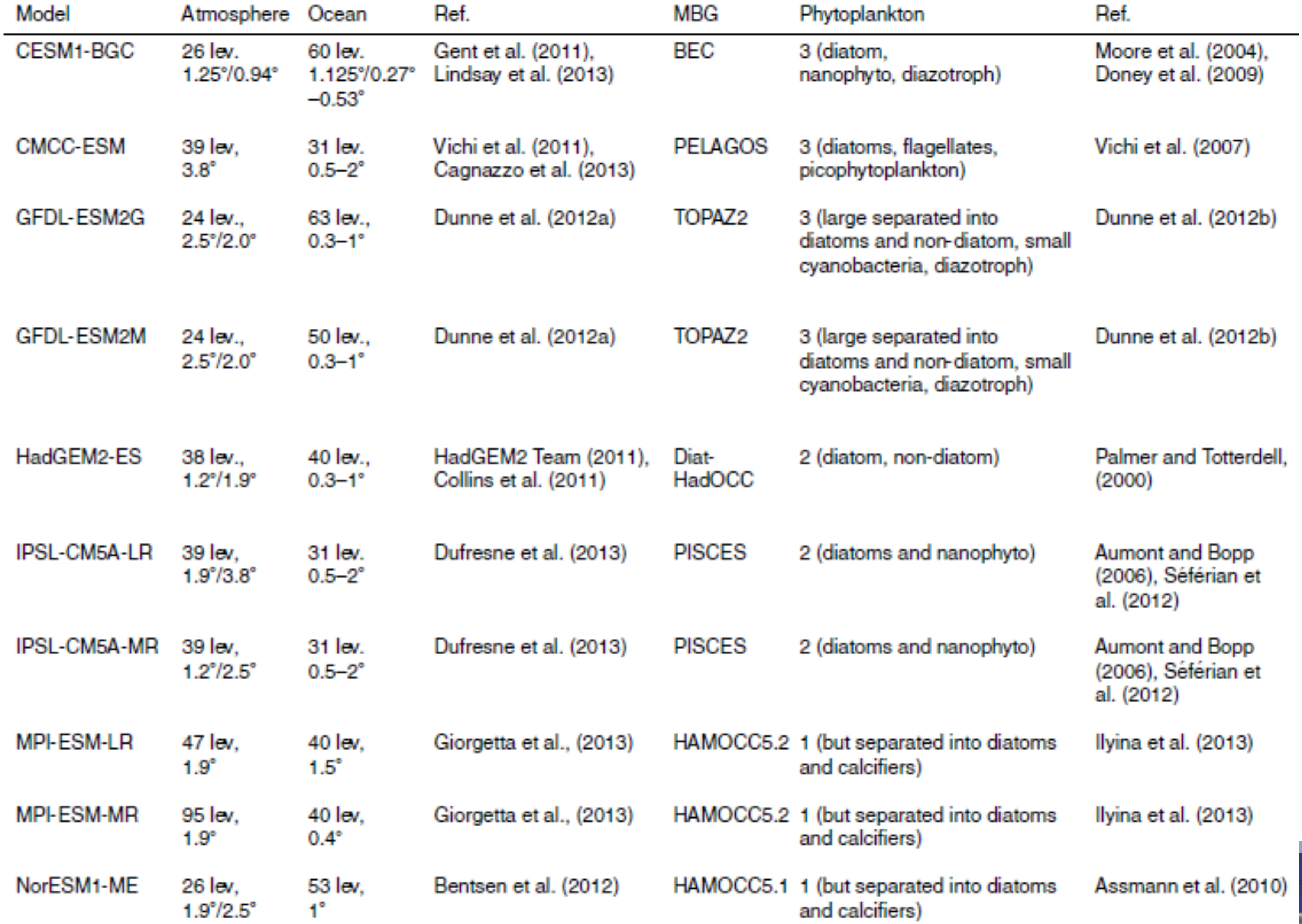
A variety of OBGCMs are now in use

Steinacher et al. (2010; Biogeosciences)





Diversity of Ocean BGC in CMIP5



Model	Atmosphere	Ocean	Ref.	MBG	Phytoplankton	Ref.
CESM1-BGC	26 lev. 1.25°/0.94°	60 lev. 1.125°/0.27° –0.53°	Gent et al. (2011), Lindsay et al. (2013)	BEC	3 (diatom, nanophyto, diazotroph)	Moore et al. (2004), Doney et al. (2009)
CMCC-ESM	39 lev, 3.8°	31 lev. 0.5–2°	Vichi et al. (2011), Cagnazzo et al. (2013)	PELAGOS	3 (diatoms, flagellates, picophytoplankton)	Vichi et al. (2007)
GFDL-ESM2G	24 lev., 2.5°/2.0°	63 lev., 0.3–1°	Dunne et al. (2012a)	TOPAZ2	3 (large separated into diatoms and non-diatom, small cyanobacteria, diazotroph)	Dunne et al. (2012b)
GFDL-ESM2M	24 lev., 2.5°/2.0°	50 lev., 0.3–1°	Dunne et al. (2012a)	TOPAZ2	3 (large separated into diatoms and non-diatom, small cyanobacteria, diazotroph)	Dunne et al. (2012b)
HadGEM2-ES	38 lev., 1.2°/1.9°	40 lev., 0.3–1°	HadGEM2 Team (2011), Collins et al. (2011)	Diat-HadOCC	2 (diatom, non-diatom)	Palmer and Totterdell, (2000)
IPSL-CM5A-LR	39 lev, 1.9°/3.8°	31 lev. 0.5–2°	Dufresne et al. (2013)	PISCES	2 (diatoms and nanophyto)	Aumont and Bopp (2006), Séférian et al. (2012)
IPSL-CM5A-MR	39 lev, 1.2°/2.5°	31 lev. 0.5–2°	Dufresne et al. (2013)	PISCES	2 (diatoms and nanophyto)	Aumont and Bopp (2006), Séférian et al. (2012)
MPI-ESM-LR	47 lev, 1.9°	40 lev, 1.5°	Giorgetta et al., (2013)	HAMOCC5.2	1 (but separated into diatoms and calcifiers)	Ilyina et al. (2013)
MPI-ESM-MR	95 lev, 1.9°	40 lev, 0.4°	Giorgetta et al., (2013)	HAMOCC5.2	1 (but separated into diatoms and calcifiers)	Ilyina et al. (2013)
NorESM1-ME	26 lev, 1.9°/2.5°	53 lev, 1°	Bentsen et al. (2012)	HAMOCC5.1	1 (but separated into diatoms and calcifiers)	Assmann et al. (2010)

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 N_2 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**

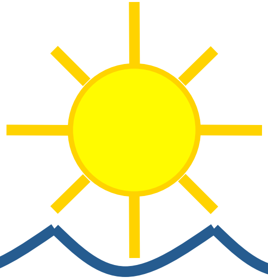
Philosophies for Ocean BGC Modeling

- 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:
    - Sentinal species (i.e. *Prochlorococcus, Trichodesmium, and T. weissflogii, E. huxleya*)
        - Calibration to best-known constraints, but leaves vast biogeochemical gaps
    - Phytoplankton functional groups (CO_2-fixers, N_2-fixers, silicifiers, calcifiers)
        - Calibration to particular functions, leaving other functions missing
    - Empirical biogeochemical function (CO_2-fxation, N_2-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.

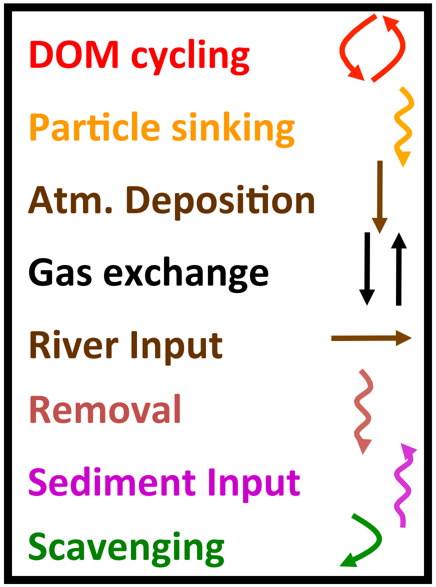
GFDL's Tracers of Phytoplankton with Allometric Zooplankton (TOPAZ)

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

30 Tracers

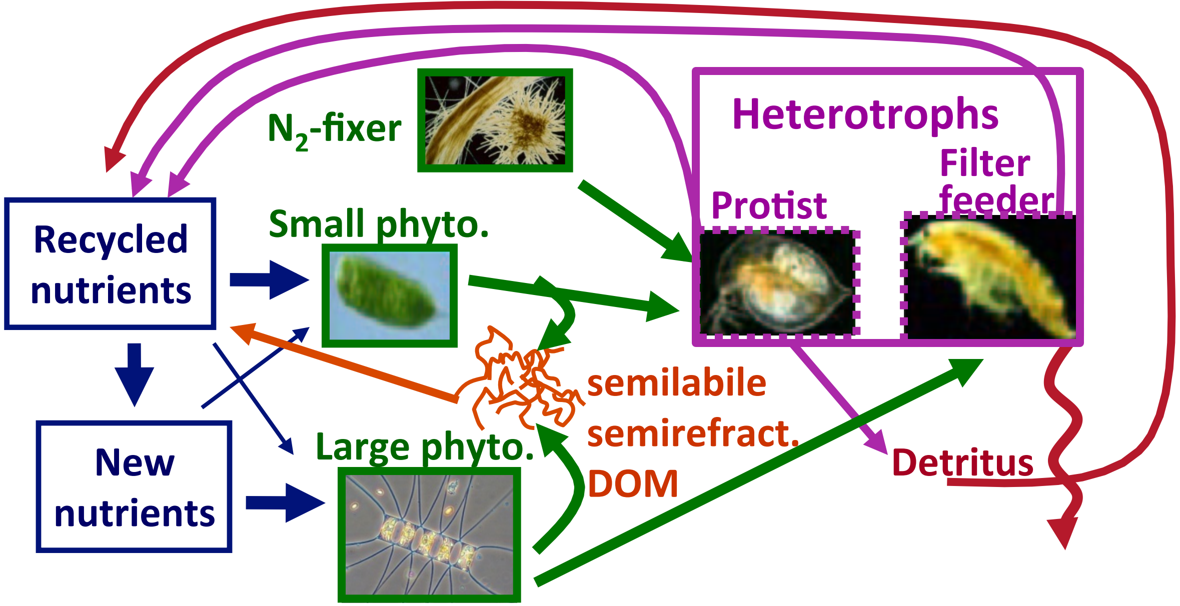


Biogeochemistry



- 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.

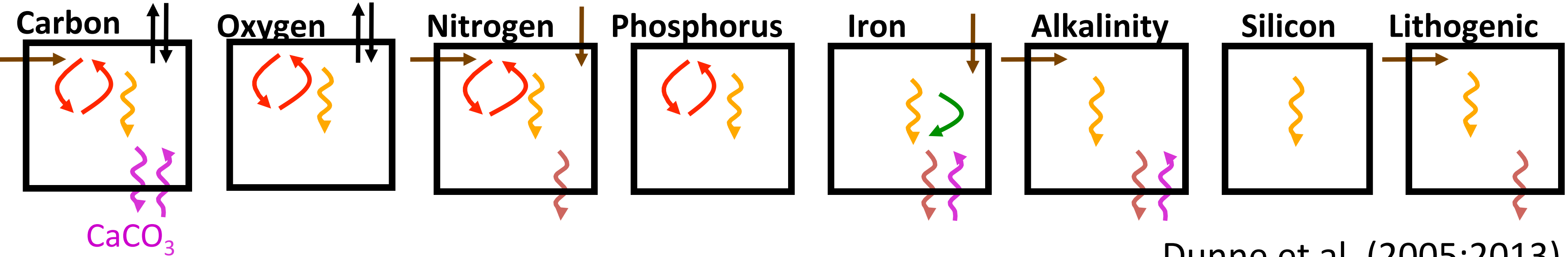
semilabile
semirefract.
DOM

Heterotrophs

Protist

Filter feeder

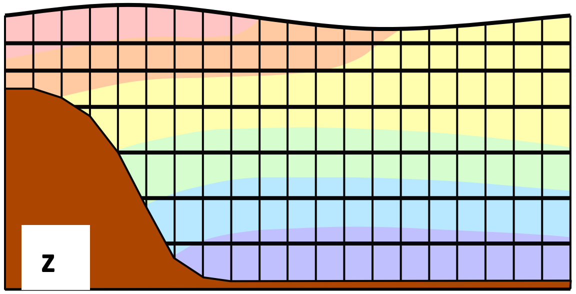
Detritus



Dunne et al. (2005;2013)

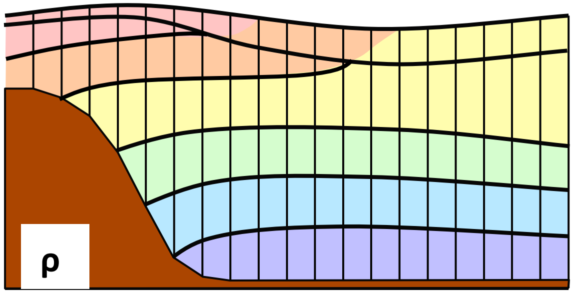
Many groups are exploring alternative vertical coordinates

z* (MOM4.1):

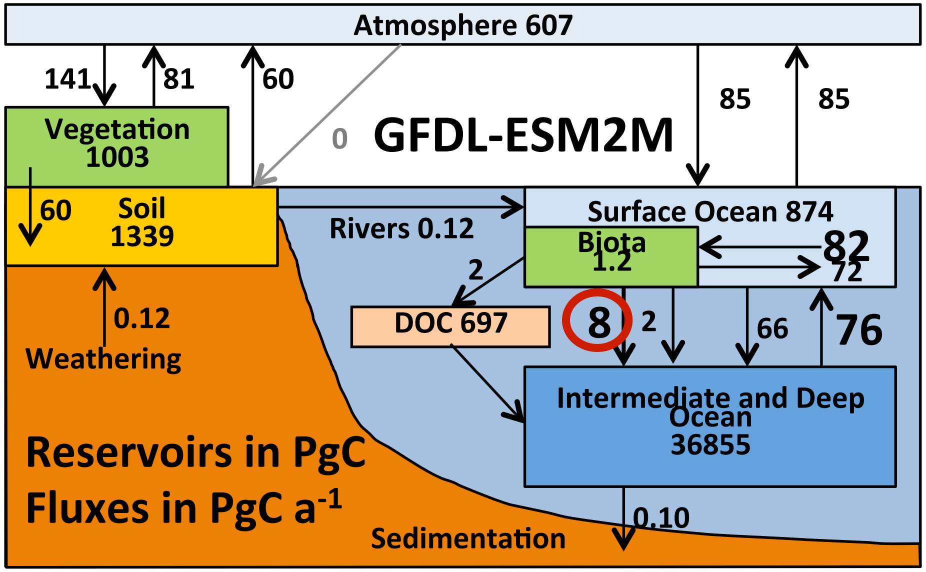


- Depth-based vertical coordinate
- Over 40 years of experience

ρ (GOLD):



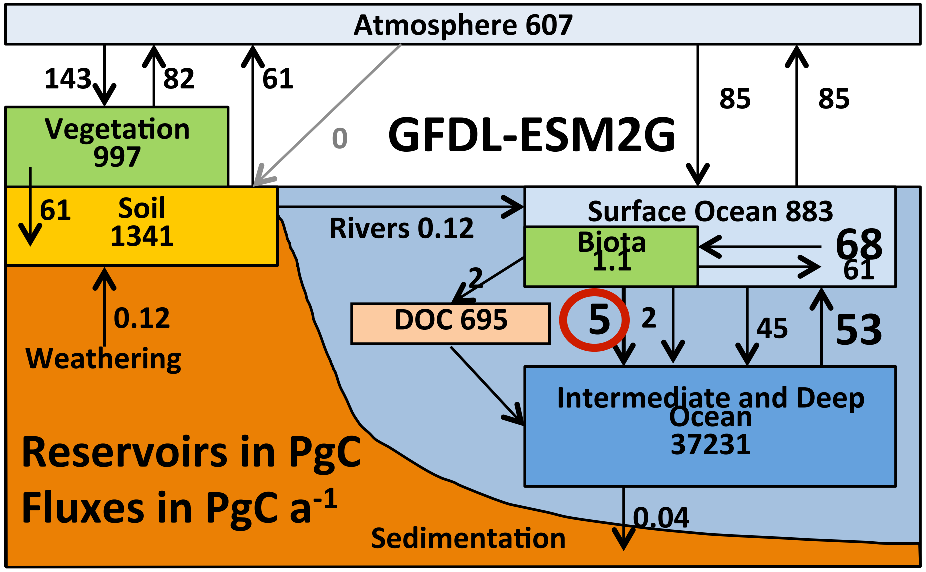
- Density-based vertical coordinate
- Easy to preserve water masses



GFDL-ESM2M

Atmosphere 607
141
81
60
0
85
85
Vegetation 1003
60
Soil 1339
Rivers 0.12
Surface Ocean 874
Biota 1.2
82
72
2
DOC 697
8
2
66
76
0.12
Weathering
Intermediate and Deep Ocean 36855
0.10
Sedimentation

Reservoirs in PgC
Fluxes in PgC a^{-1}



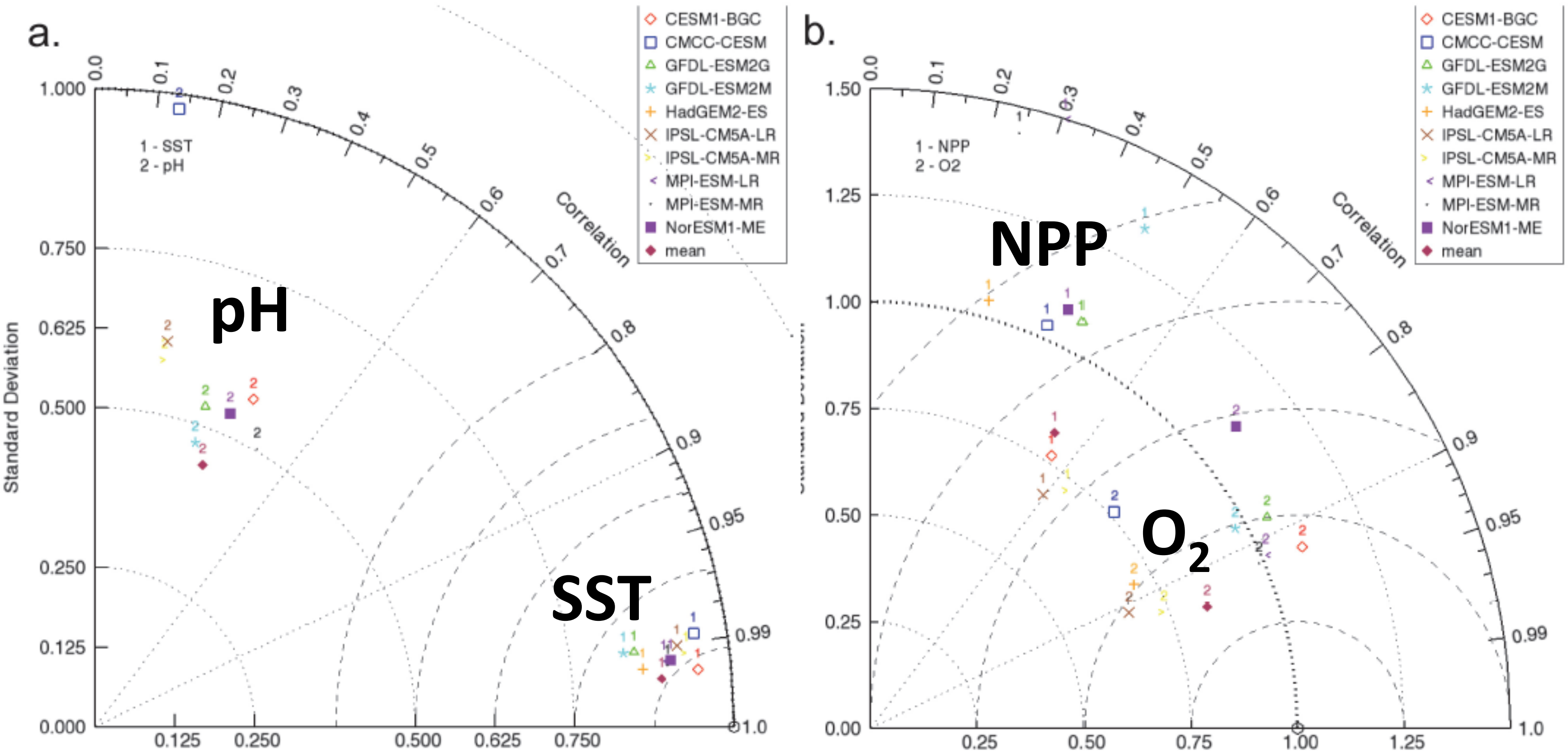
GFDL-ESM2G

Atmosphere 607
143
82
61
0
85
85
Vegetation 997
61
Soil 1341
Rivers 0.12
Surface Ocean 883
Biota 1.1
68
61
2
DOC 695
5
2
45
53
0.12
Weathering
Intermediate and Deep Ocean 37231
0.04
Sedimentation

Reservoirs in PgC
Fluxes in PgC a^{-1}

Dunne et al. (2012, 2013); Winton et al. (2013); Hallberg et al. (2013); Froelicher et al. (submitted)

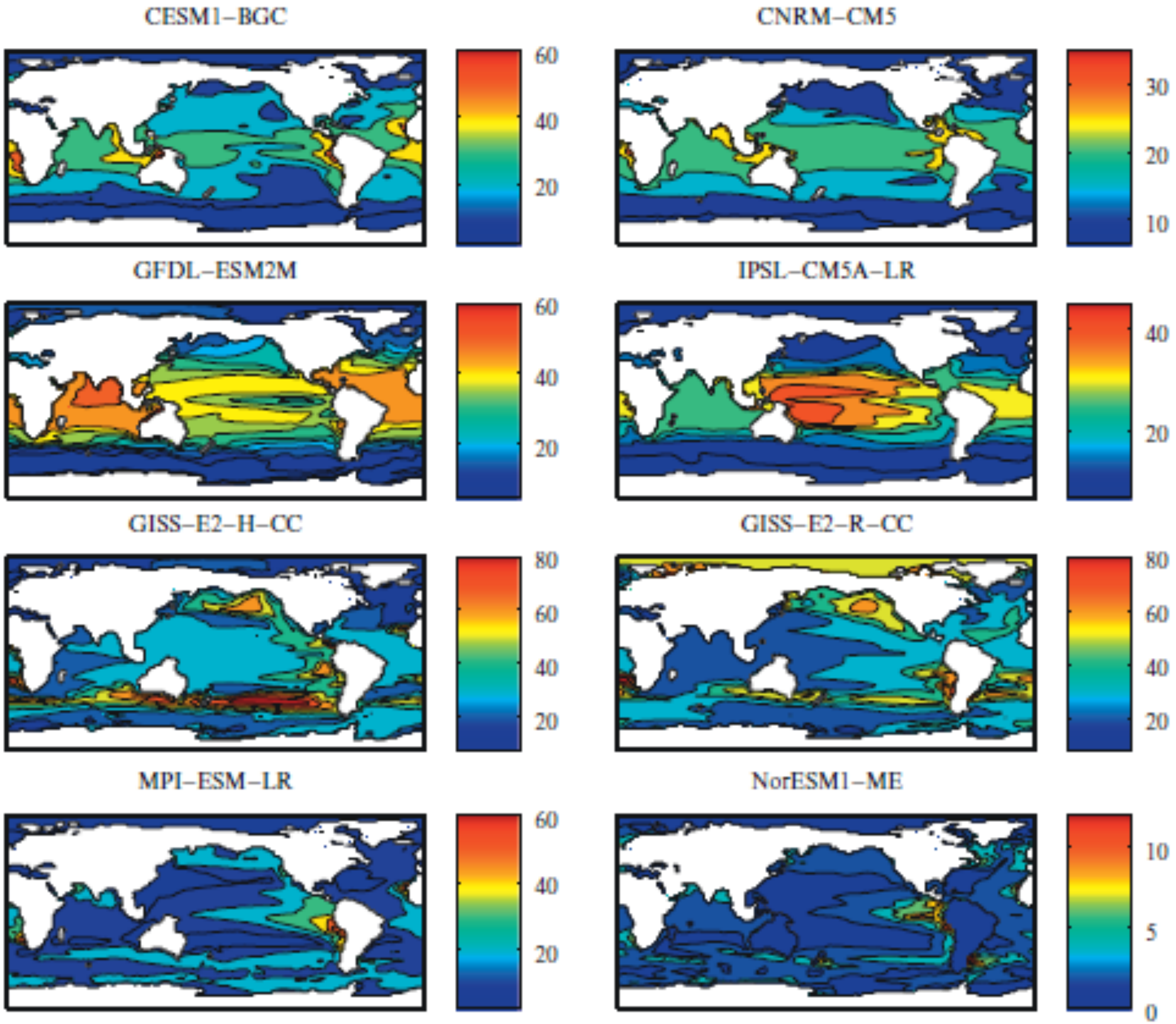
Taylor Diagrams of CMIP5 X-Y Patterns



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

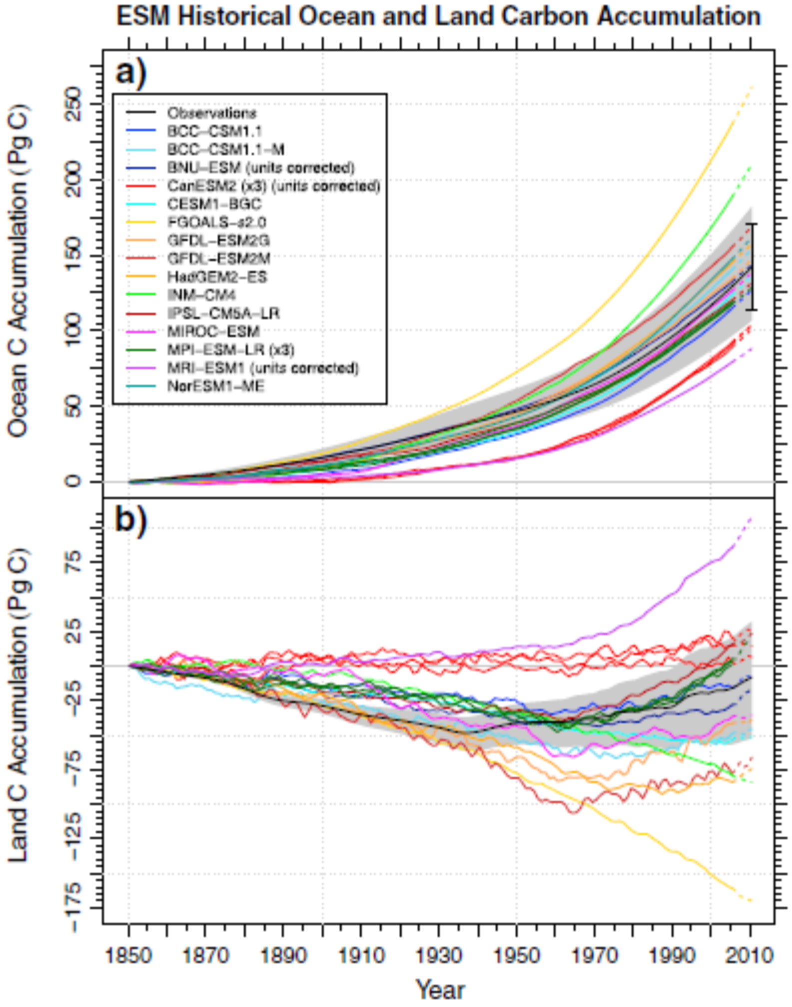
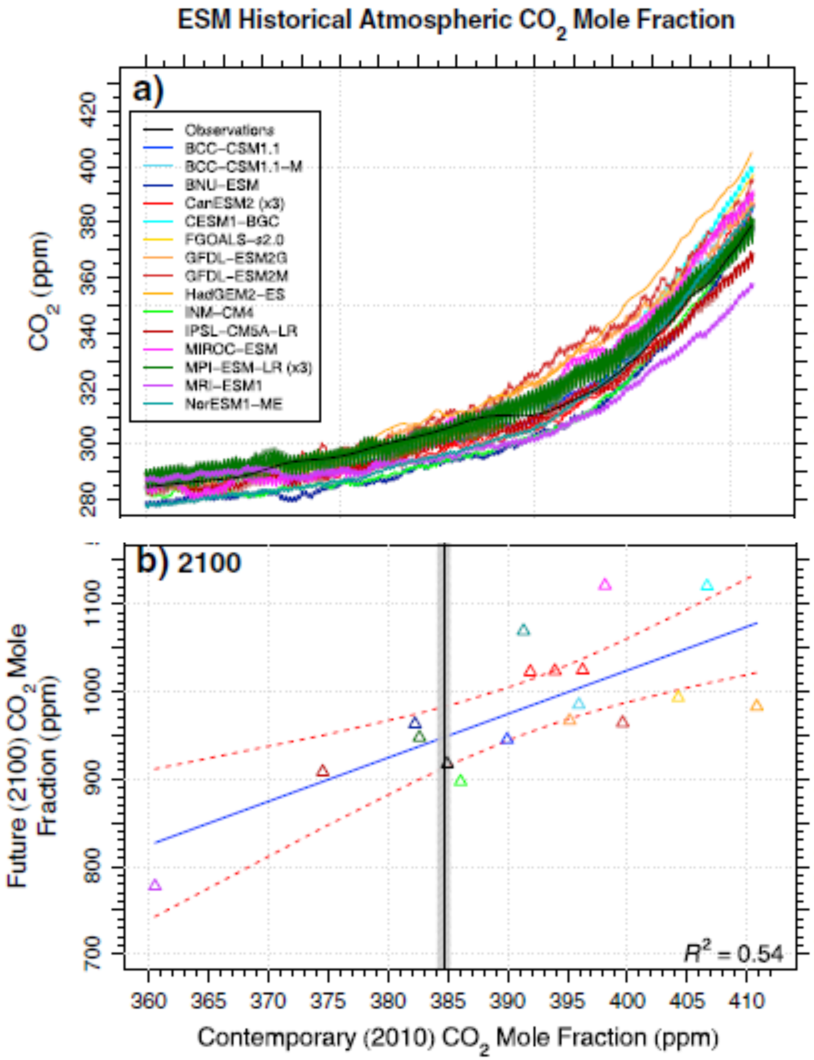
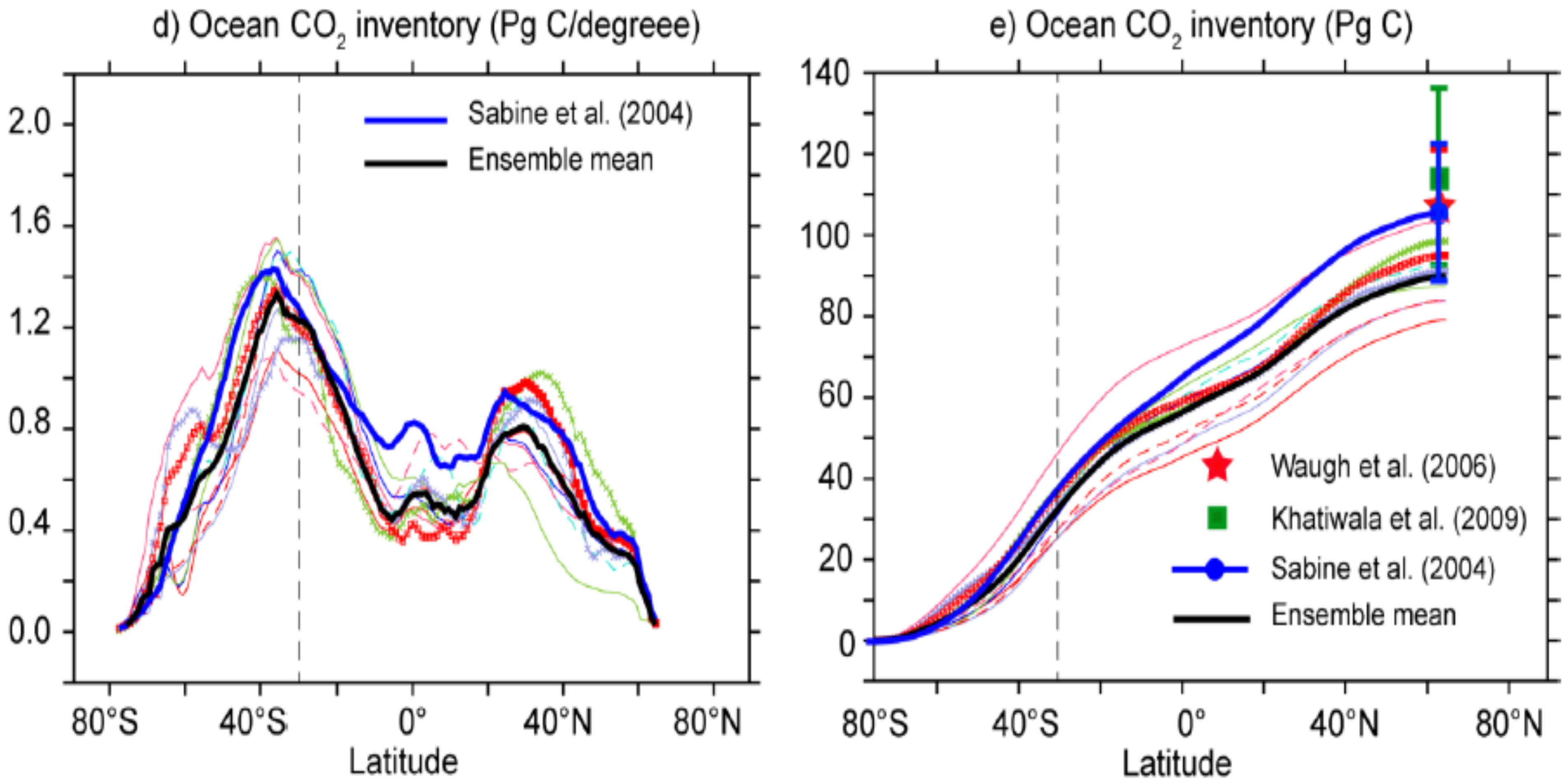


Figure 2. (a) Ocean and (b) land anthropogenic carbon inventories from



Hoffman et al., 2014

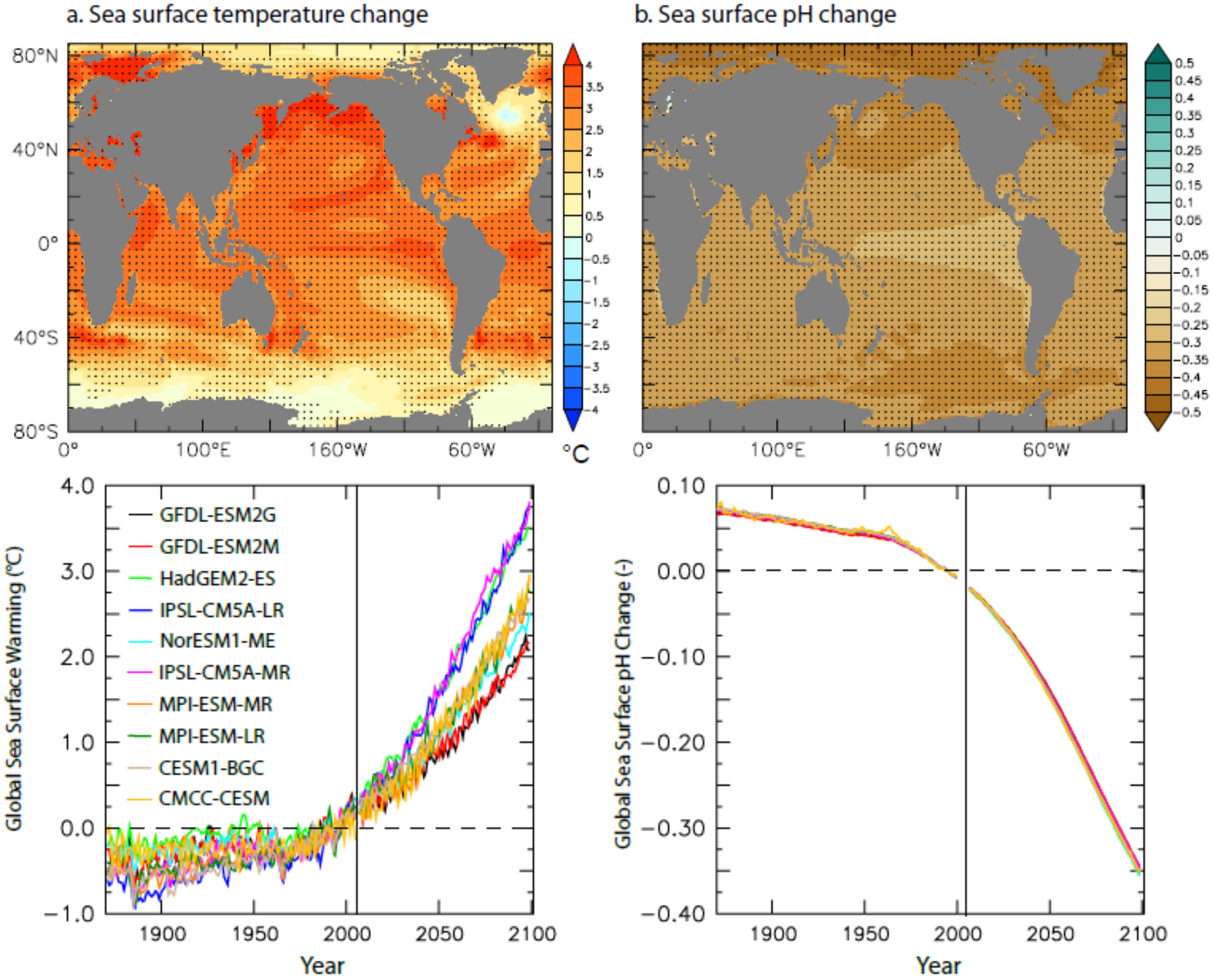
Southern Ocean Key to Carbon



Frölicher, T., J. Sarmiento, J. Dunne, D. Paynter, M. Winton, in press: Heat and carbon uptake in the CMIP5 models: The dominance of the Southern Ocean.

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

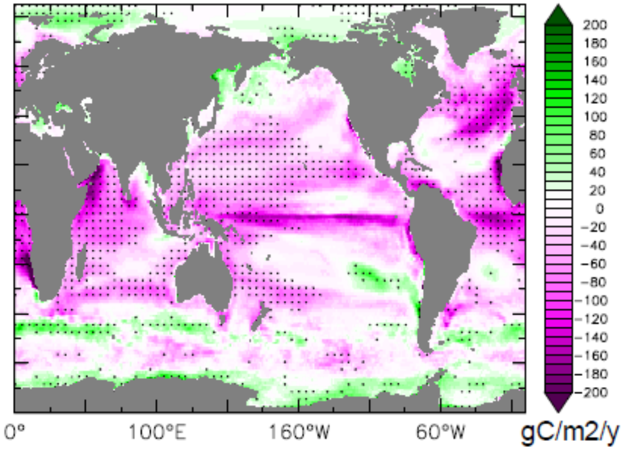


Bopp, L., L. Resplandy, J. C. Orr, S. C. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra, and M. Vichi, 2013: **Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models**, *Biogeosciences*, 10, 6225-6245, doi:10.5194/bg-10-6225-2013.

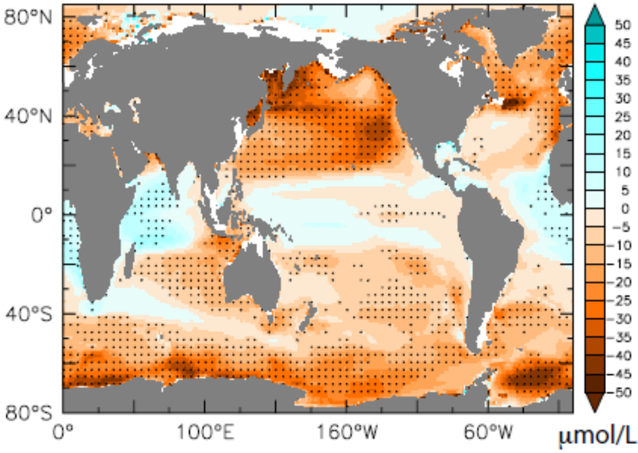
Major challenges remain in resolving areas where ESM's disagree

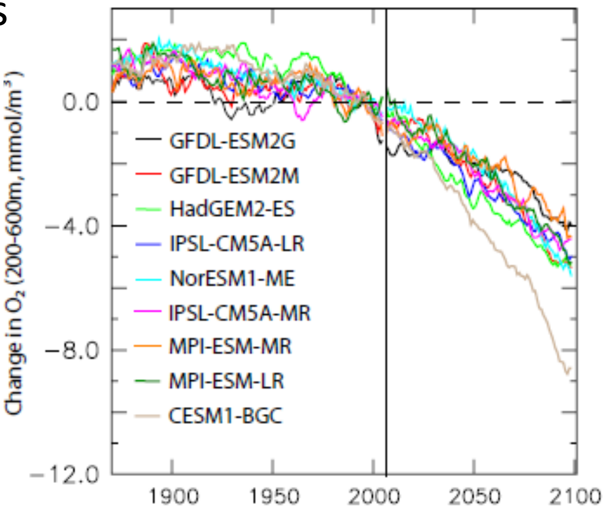
RCP8.5 at 2100 - Stippling indicates sign agreement among models

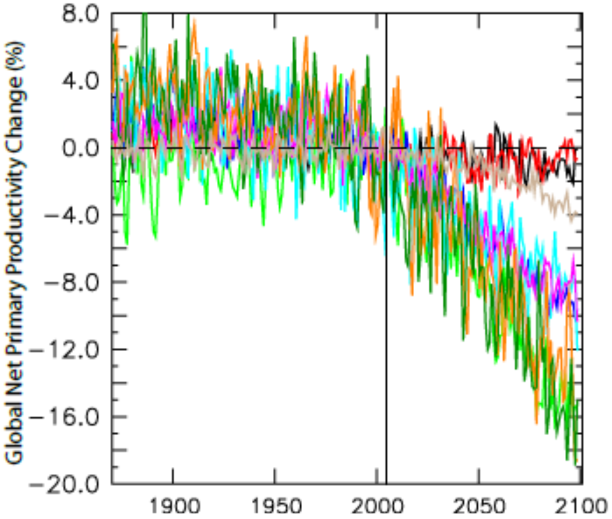
d. Integrated net primary productivity change

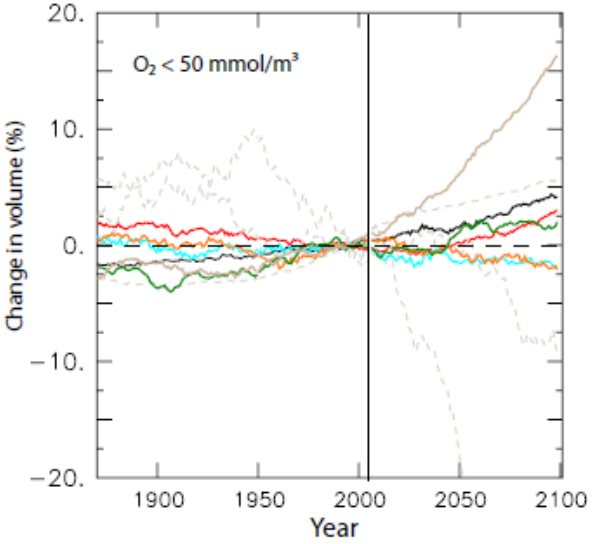


c. Oxygen concentration change at 200-600m





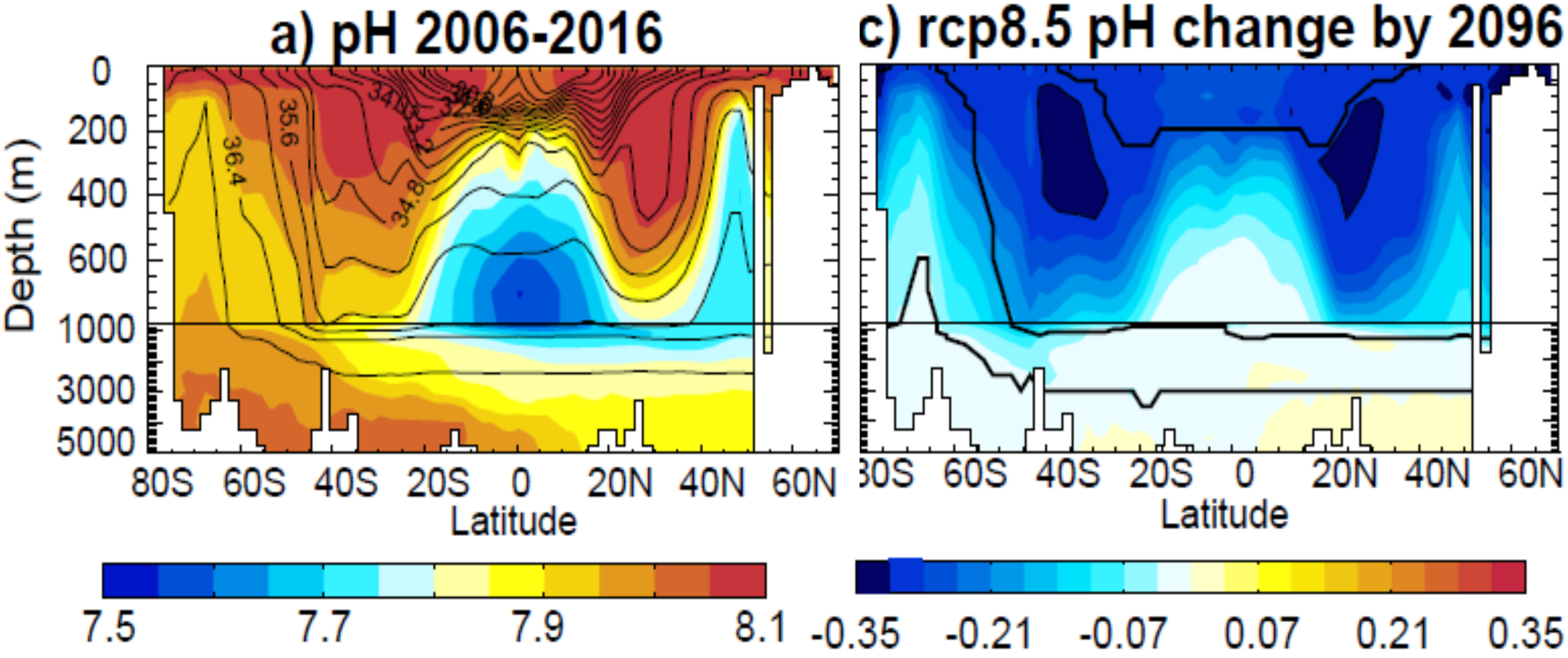




Bopp, L., L. Resplandy, J. C. Orr, S. C. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra, and M. Vichi, 2013: **Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models**, *Biogeosciences*, 10, 6225-6245, doi:10.5194/bg-10-6225-2013.

Largest Ocean Acidification in Tropical Mode Waters

ESM2M Pacific Section (190°E)



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

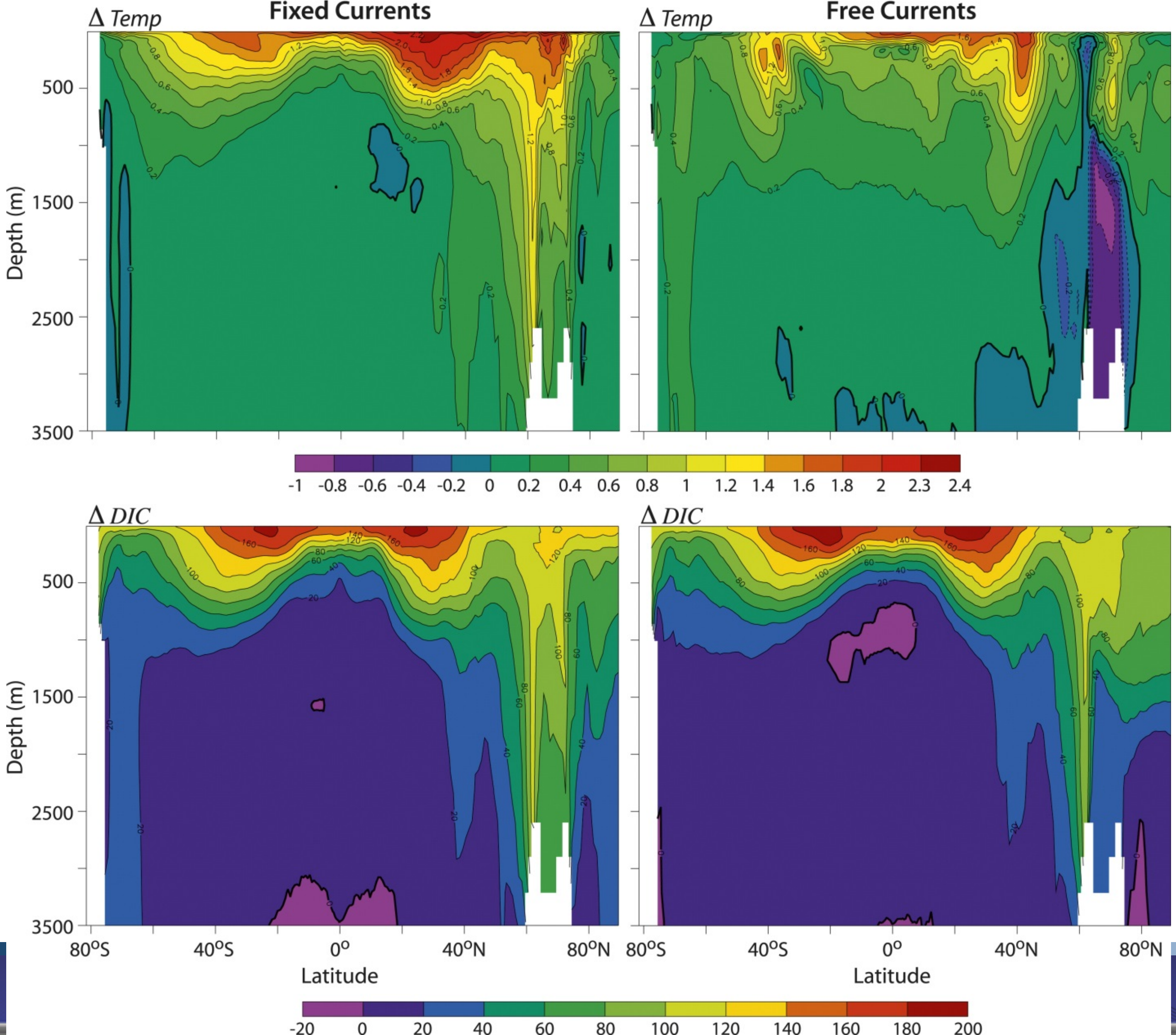
Resplandy, L. L. Bopp, J. Orr, and J. Dunne (2013)

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 biogeochemisty

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