Climate, Carbon, and Ecosystem Interactions

Presented by John Dunne and Charles Stock on behalf of GFDL, Princeton University CICS, and external collaborators

Frontiers in Climate and Earth System Modeling: Advancing the Science

Geophysical Fluid Dynamics Laboratory

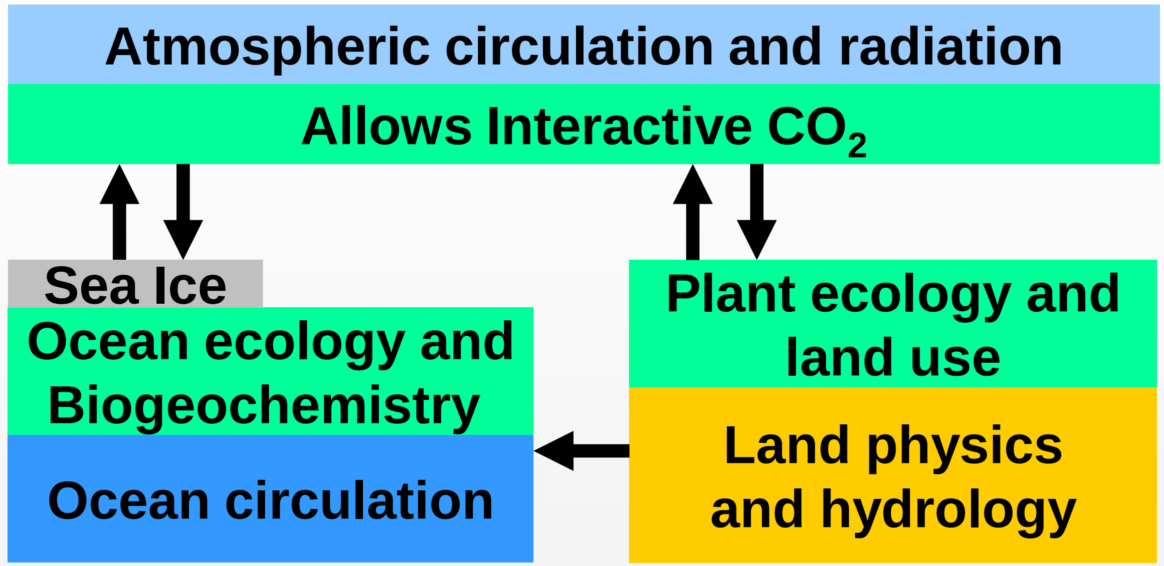
May 20, 2013

Recent Coupled Carbon-Climate Activities

- Led or co-authored >25 papers on interactions between climate and biogeochemistry since 2009
- Improved understanding of processes determining biogeochemical distributions and change
- Reduced uncertainty in future ocean and land carbon uptake and biogeochemical feedbacks

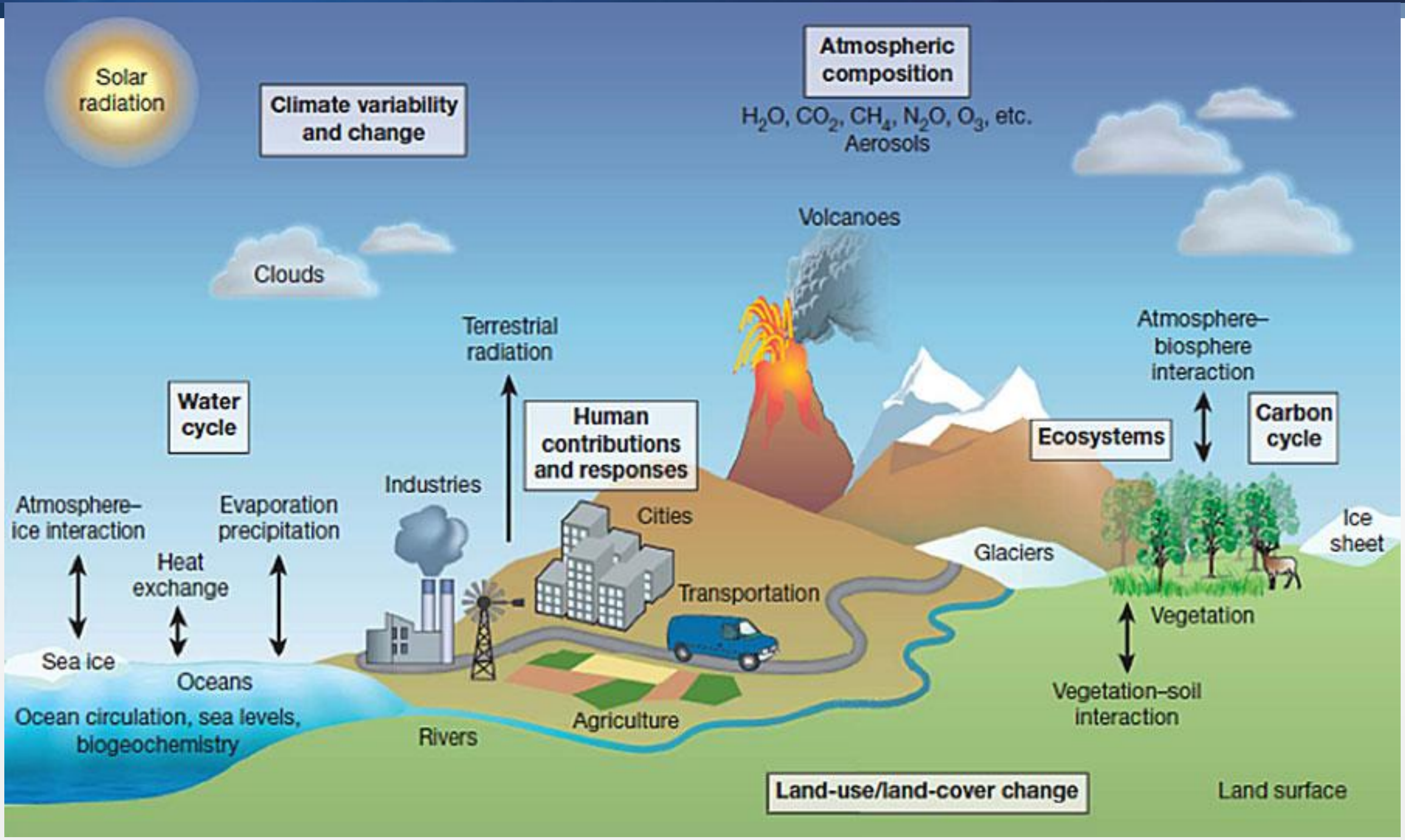
GFDL's earth system model (ESM) for coupled carbon-climate

Earth System Model



- Comprehensive land and ocean carbon dynamics
- Interactive/Prognostic CO_2
- Allows investigation of feedbacks.

Earth System Modeling for Coupled Carbon-Climate



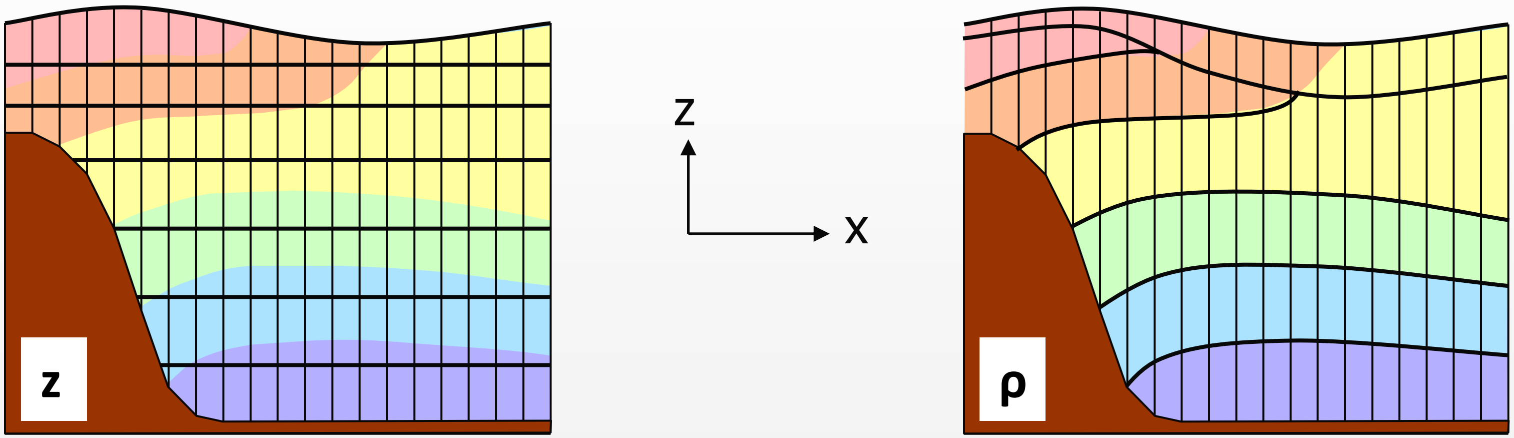
How much CO_2 will the land and ocean continue to take up?

What are the biogeochemical feedbacks?

What are the biogeochemical and ecological impacts?

ESM2M and ESM2G differ only in ocean physics

Goal: Comparison of implications of ocean vertical coordinate choice



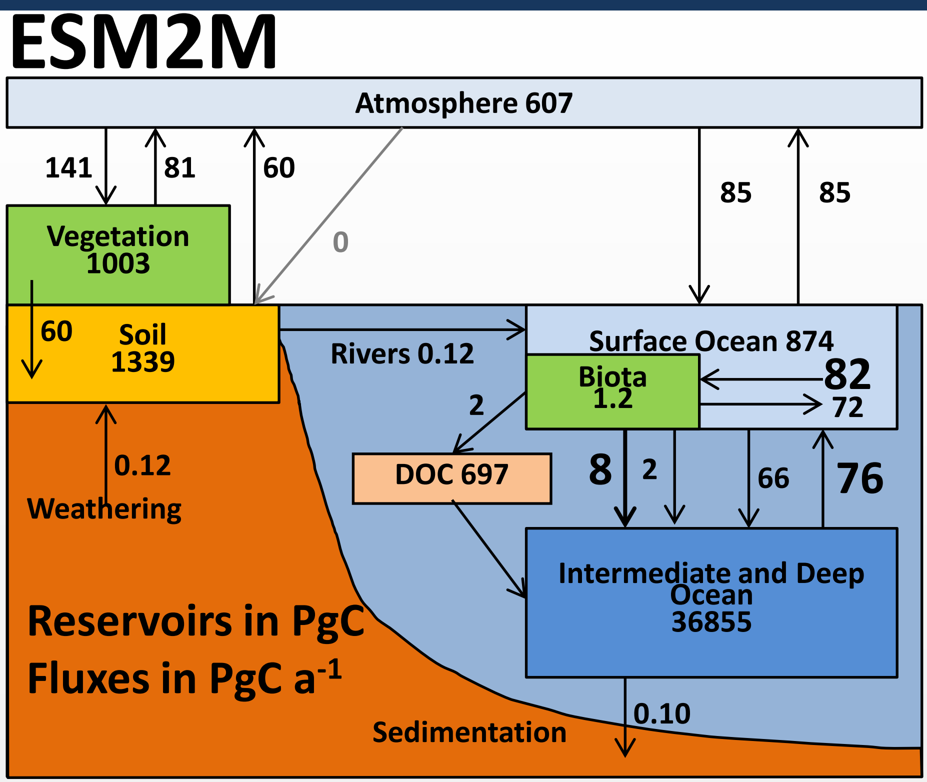
z* (MOM4.1):

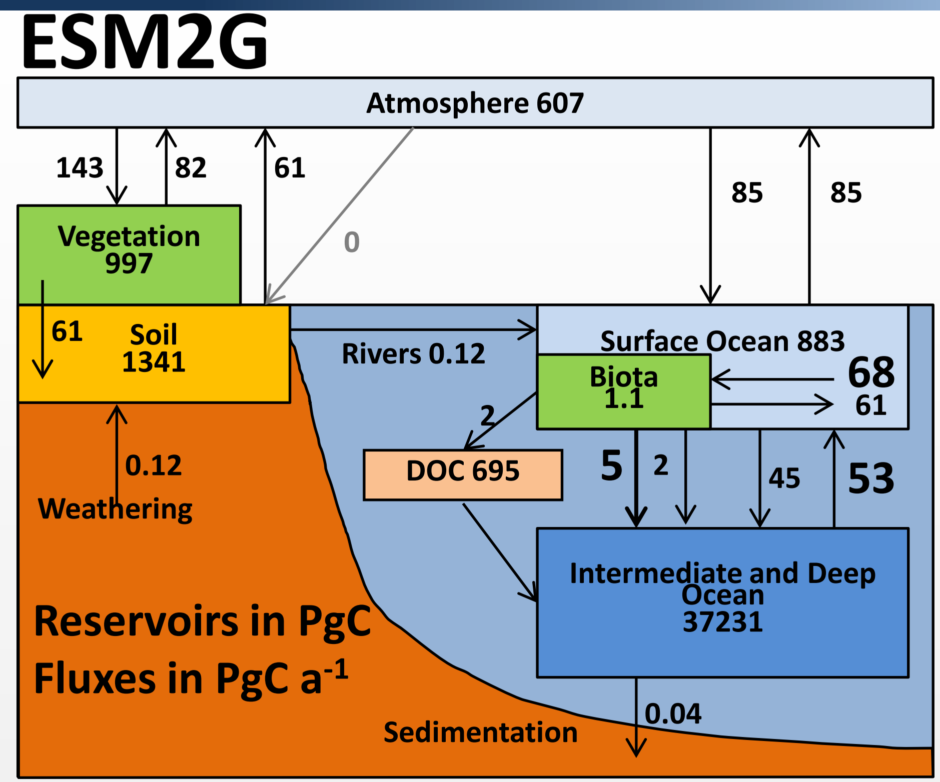
- **Depth-based vertical coordinate**
- **Over 40 years of experience**

ρ (GOLD):

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

Both ESMs represent Carbon Cycles in addition to Climate





2 PgC ≈ 1 ppm CO2

- **Though similarly credible, large differences exist.**
- **ESM2M has 43% more surface ventilation and 21% more ocean primary production than ESM2G.**

Dunne et al., 2013: J. Climate.

Robustness of Climate Change Response to Differing ESM2M and ESM2G Circulation

While large mean state differences exist …

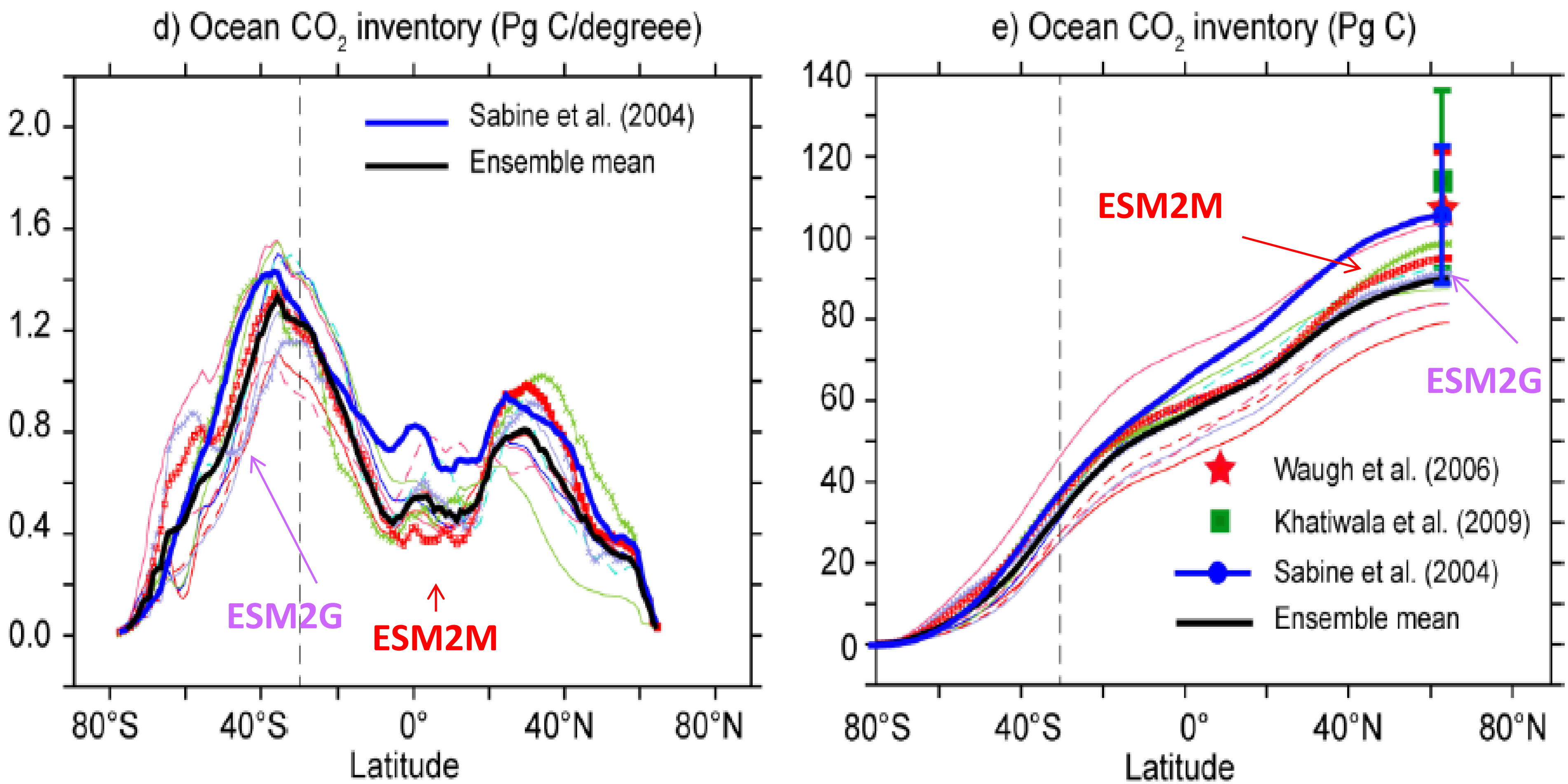
- **ESM2G has a shallower thermocline, more Antarctic Bottom Water formation, and tropical upwelling**
- **ESM2M has more Southern Ocean upwelling and downwelling and thermocline ventilation**

… Their climate change response is very similar.

- **Both oceans respond similarly to similar atmospheric forcing.**
- **Slow-down in Atlantic Overturning and speed-up of Southern Ocean Overturning results in tropical and subantarctic downwelling anomalies in ocean tracers.**

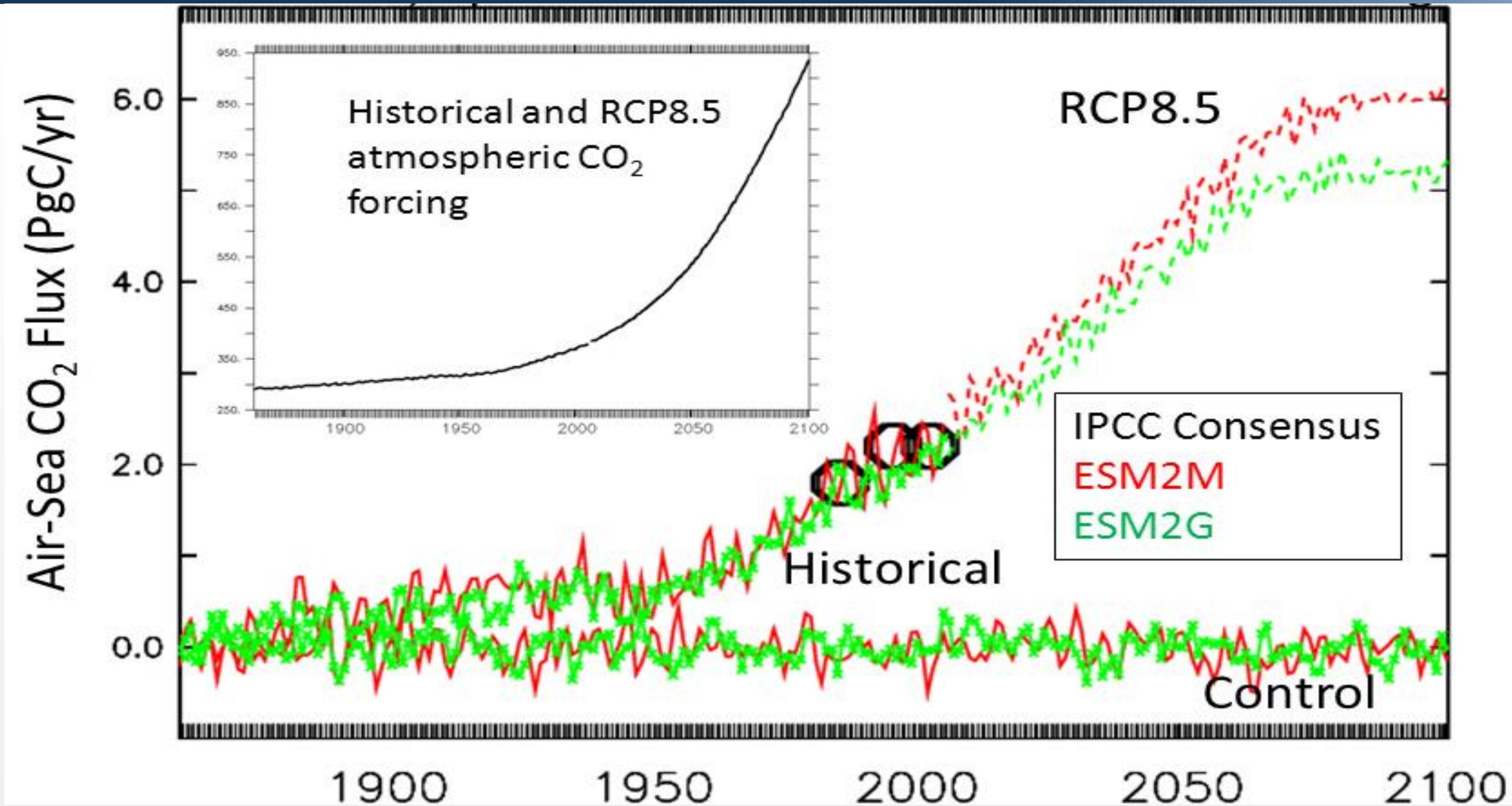
Winton et al., 2012; Dunne et al., in preparation

GFDL ESMs major contributors to CMIP5



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

Reducing Uncertainty in Ocean CO_2 uptake

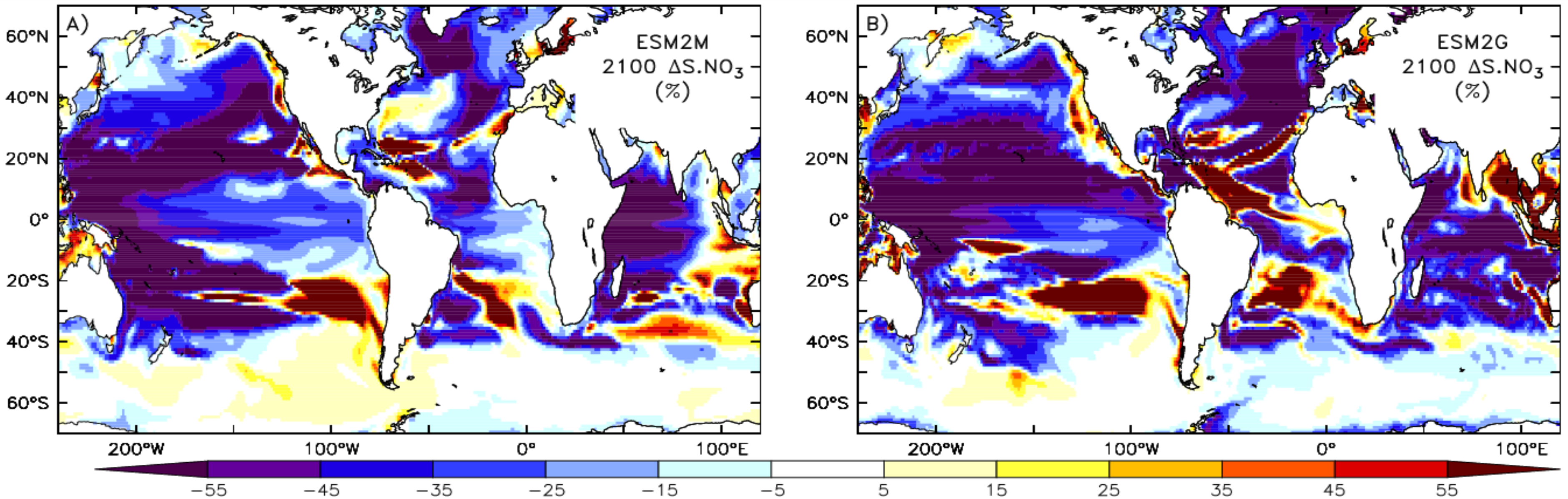


- **Both models have stable controls**
- **ESM2M takes up 10% more CO_2 than ESM2G**
- **Both models saturate uptake rate by ~2080 (~700 ppm)**

Rich structure in projected surface nutrient changes, largely similar between models

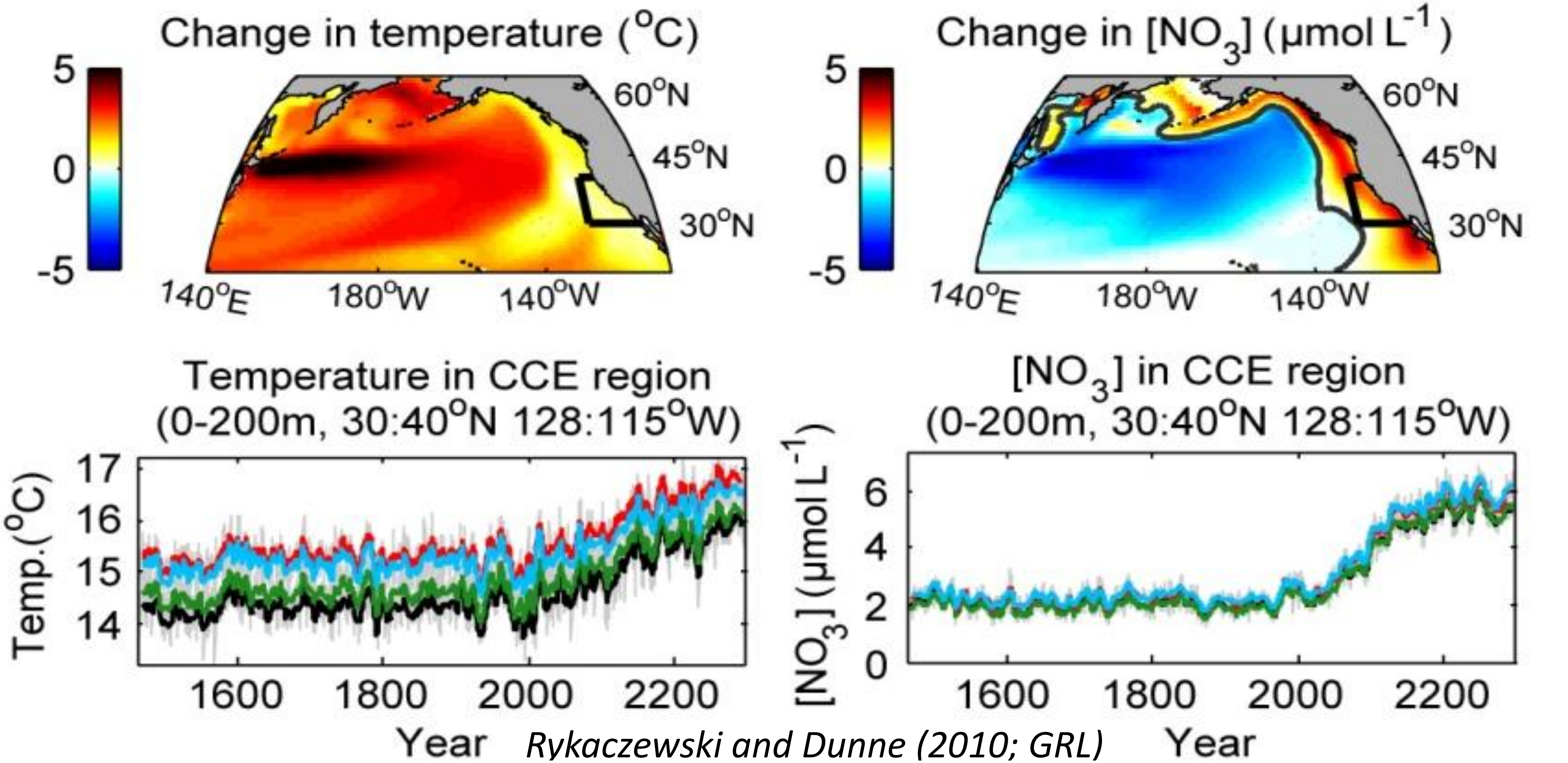
ΔSurface NO_3 under RCP8.5

ESM2M **ESM2G**



- **Increased stratification and decreased nutrient supply leads to 6% decrease in surface NO_3 globally**
- **5% decrease in large phytoplankton production, but negligible change in total production with enhanced microbial loop at higher temperature**

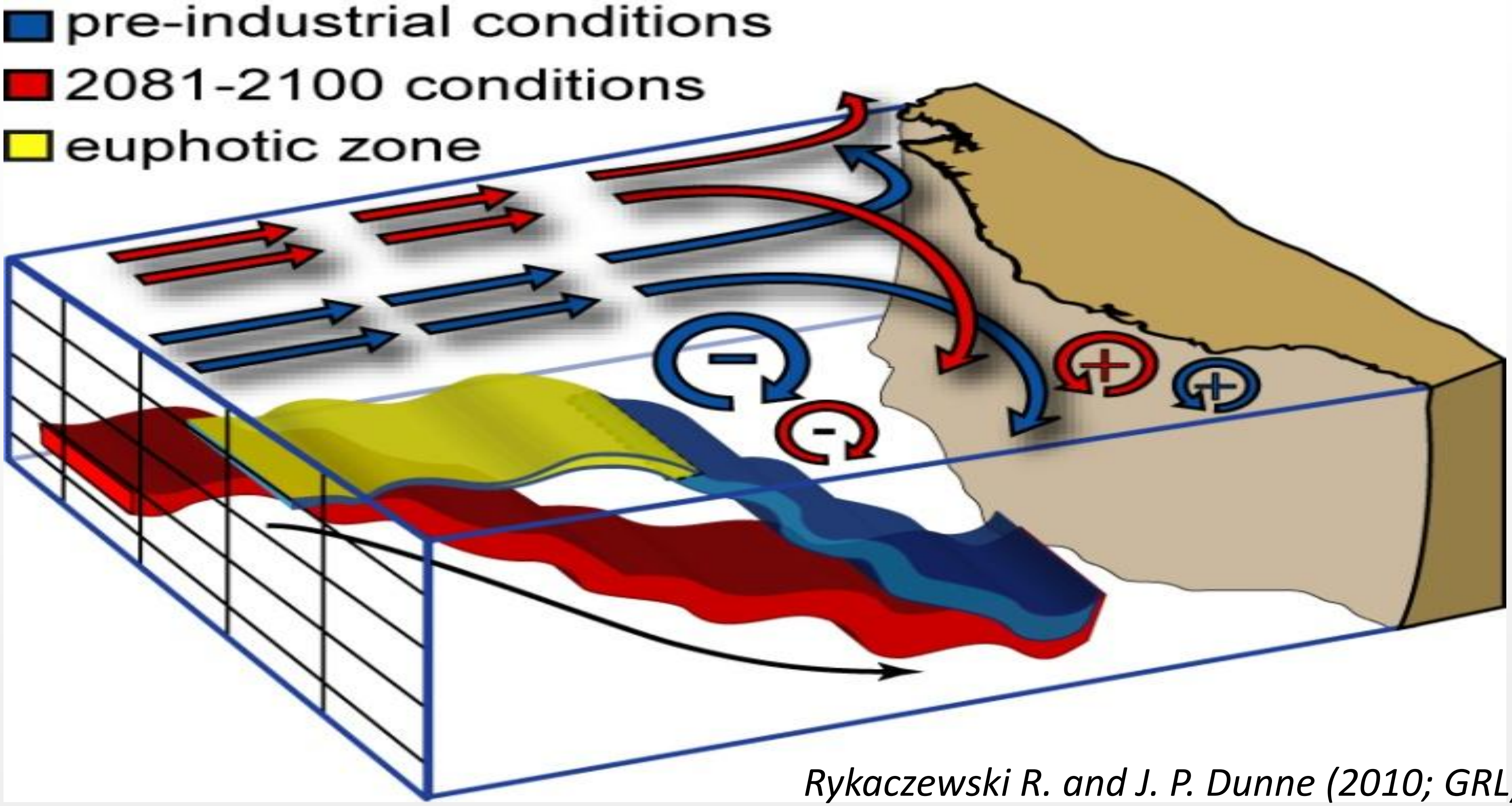
Relating large scale changes to the California Current



Rykaczewski and Dunne (2010; GRL)

- **GFDL ESM's increase NO_3 in the California Current**
- **While T and NO_3 are negatively correlated seasonally and interannually, they are positively correlated under climate change**

Relating large-scale changes to the California Current

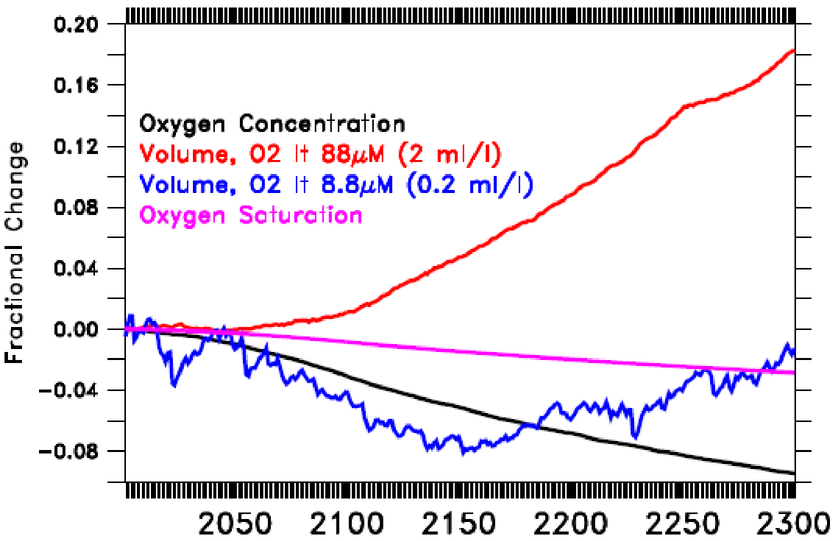


Rykaczewski R. and J. P. Dunne (2010; GRL)

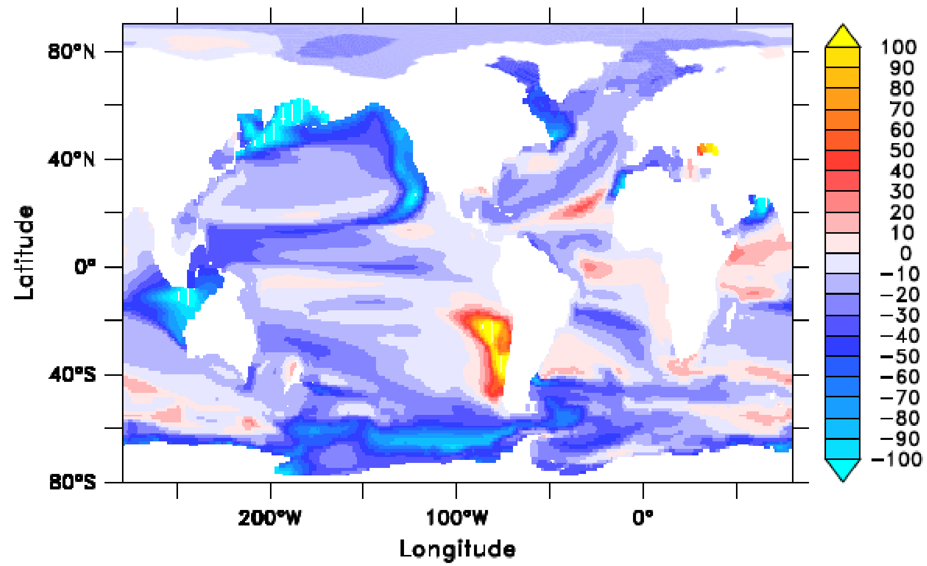
- **Dominance of remote forcing on local California Current changes**
- **Interplay of changes in atmospheric winds and heat fluxes, stratification, ventilation, and watermass pathways modulating biogeochemical response**

Oxygen ventilation mechanisms rebalance in importance under climate change

Motivation: Observational records suggest decreasing interior O_2 leading to concerns about increasing volume of low O_2 waters (hypoxia).



(a) Relative Changes (A2 Scenario)

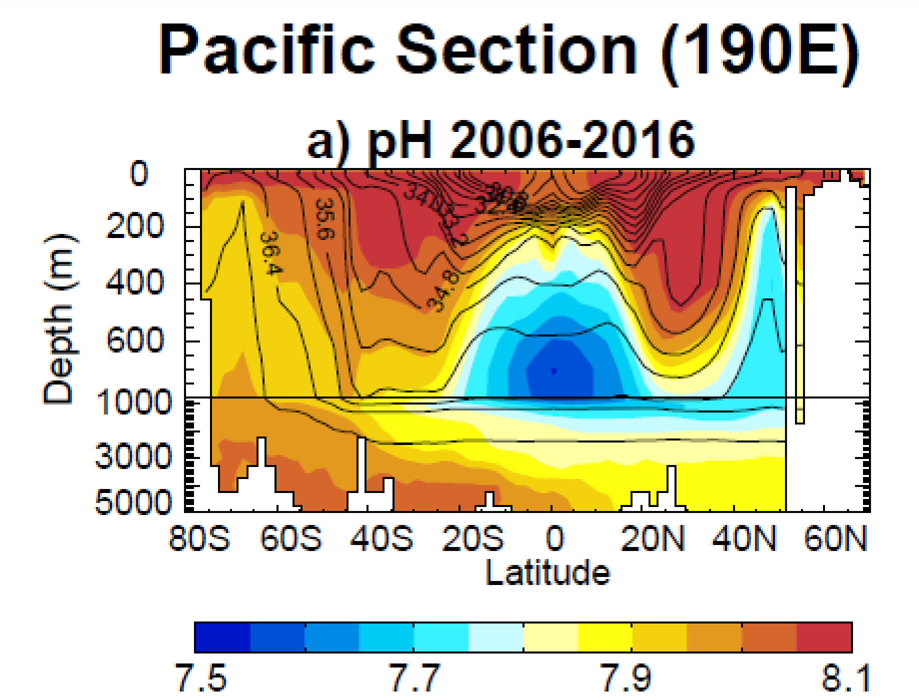


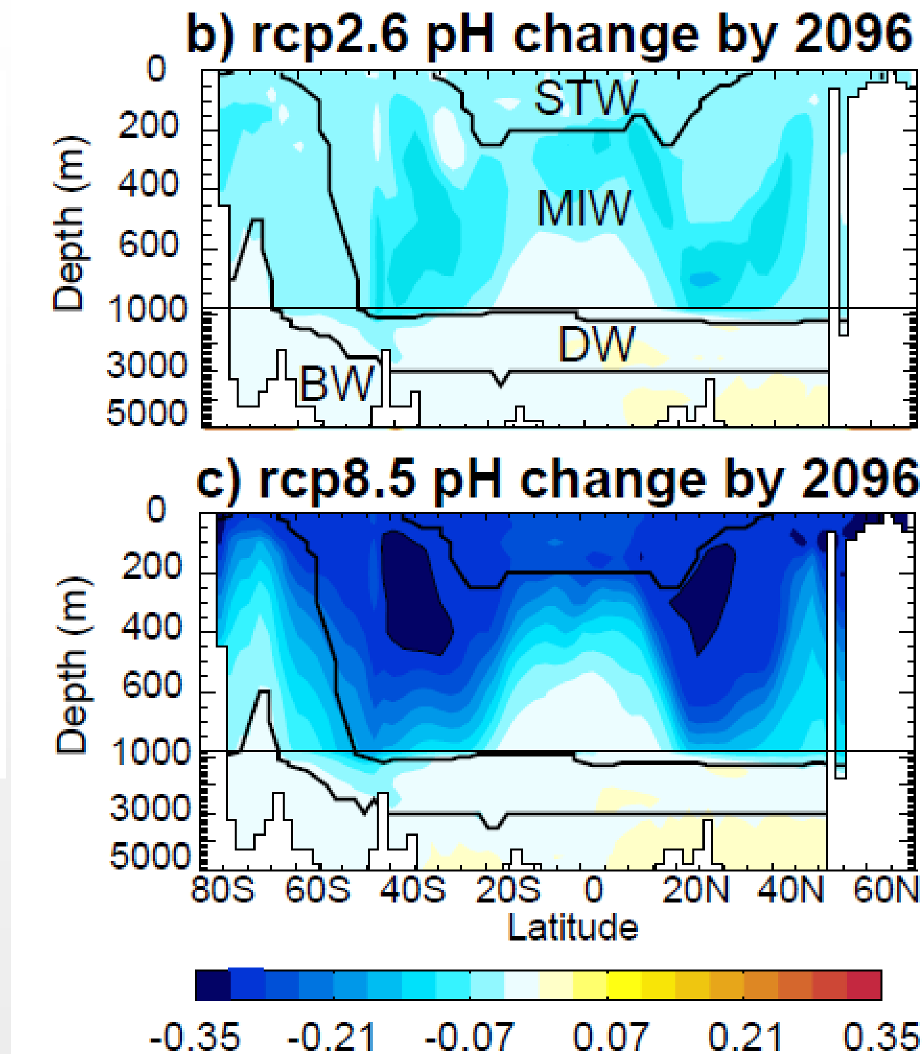
(b) Oxygen Change (mmol/m³) 2281–2300, 300m

Conclusions: GFDL ESMs increase weak hypoxia volume, but decrease most hypoxic volume as winter convection off of Chile becomes more robust.

Gnanadesikan, Dunne, and John, 2012: Understanding why the volume of suboxic waters does not increase over centuries of global warming in an Earth System Model

ESM2M





Illustrates the importance of including dynamical, chemical and biogeochemical interactions

Resplandy, L. L. Bopp, J. Orr, and J. Dunne (in press)

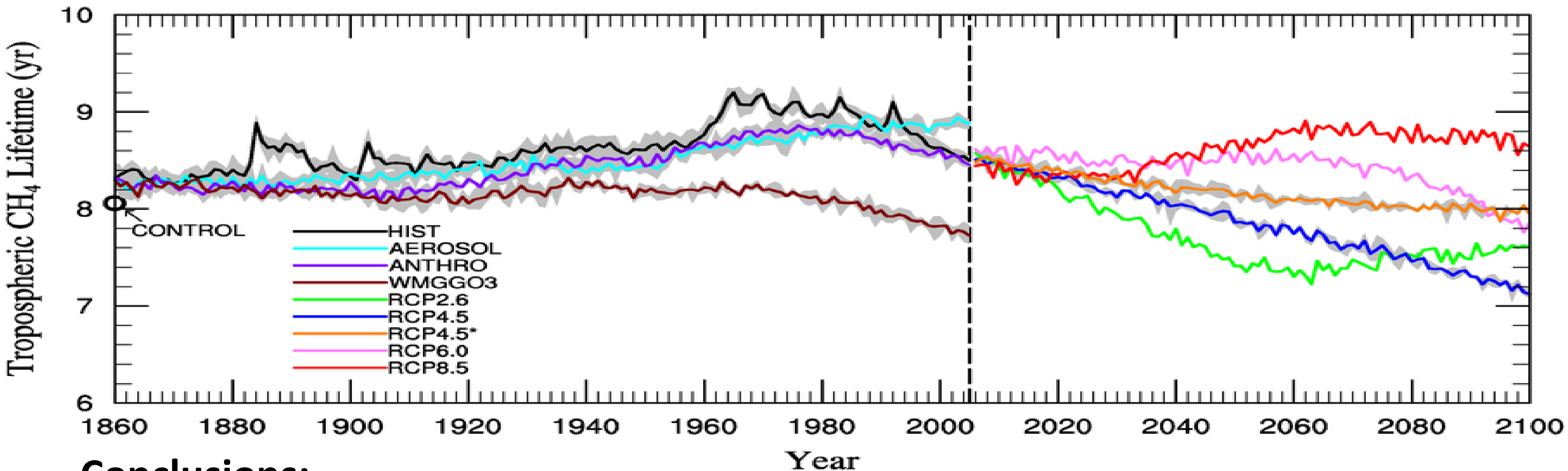
Putting the puzzle pieces together: Mechanisms of Ocean Change in GFDL ESMs

- **Warming increases stratification**
  - *Ventilation and nutrient supply decreases globally*
  - *Shift to microbial loop with little total productivity change*
- **Poleward expansion and slow-down of subtropical gyres**
  - *Shoaling nutricline in the subtropical gyres*
  - *Enhanced nutrients, hypoxia and acidification in some areas*
  - *Beginning convection off Chile ventilating Pacific low O_2 region*
- **Intensified hydrological cycle reduces North Atlantic overturning**
  - *Shoaling Northern Subpolar Atlantic and deepening tropical physical and biogeochemical properties*
- **and many more pieces…. Overall, a changing balance of processes creates intense regional structure in the net biogeochemical change.**

Beyond CO_2: Investigating CH_4 Lifetime Drivers

Motivation:

- **2^{nd} most important anthropogenic greenhouse gas**
- **Precursor to O_3**
- **Concern about positive CH_4-climate feedback under exhaustion of OH**



Conclusions:

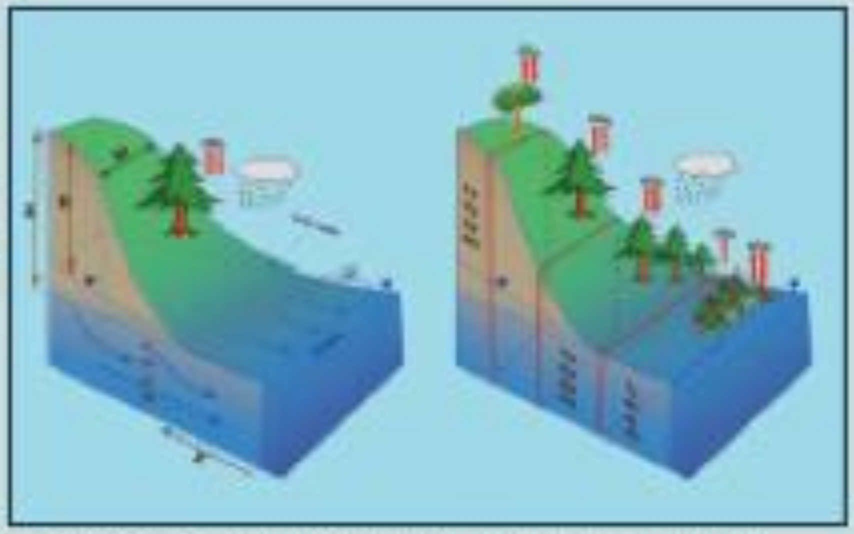
- **5% historical variation in τ_{CH4} driven mainly by anthropogenic emissions**
- **CM3 projects reduced τ_{CH4} except in RCP8.5**

John et al, 2012: Atmos. Chem. Phys.

Arctic-Boreal Land BGC and Climate

- 500-700 PgC in peatlands - source of CO_2, CH_4, and N_2O
- Involves interactions between vegetation, soil, biogeochemistry, and hydrology on a landscape scale, including permafrost.
- Requires new land capabilities

Topographic variation drives peatland development and carbon cycling
Photo: Aber et al 2001



GFDL ESM framework: landscape heterogeneity simulated using hydrological tiling

Moving forward with GFDL's ESMs

- Multi-member ensembles for detection/attribution
- Centennial-millennial scale carbon-climate coupling
- Idealized climate and carbon sensitivity
- **Comprehensiveness:** beyond CO_2 to aerosol, Fe, CH_4 and N cycles, including improved hydrology and ecosystems
- **Resolution:** Resolving the ocean mesoscale for carbon uptake and marine ecosystem applications

Understanding the impact of climate on ecosystems

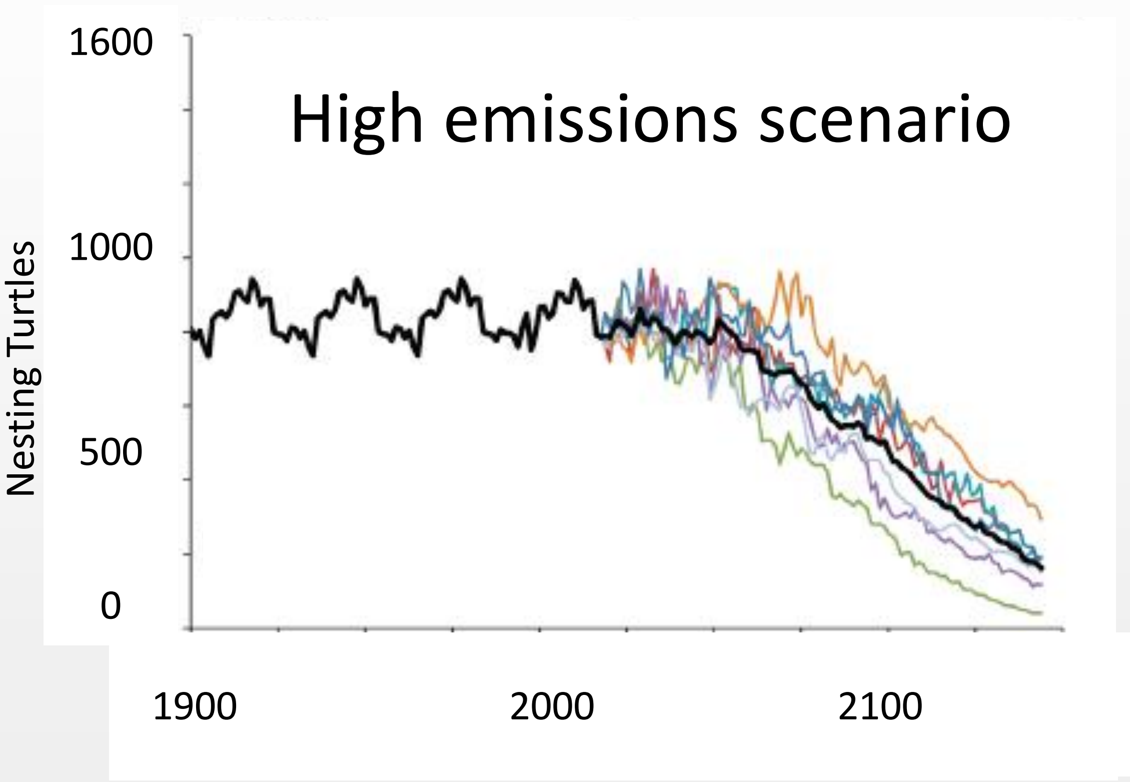
- Led or co-authored over 25 published studies of climate impacts on marine resources since 2009
- Led comprehensive synthesis on the use of IPCC-class models to assess the impact of climate on living marine resources
- Developed and applied innovative earth system models to improve ecosystem impacts assessment.

Negative impacts on endangered leatherback turtles

- Hatch and emergence success depend on temperature and precipitation
- Sex ratio depends on precipitation levels
- Returns to land for nesting depend on ocean productivity (cold, La-Nina conditions indicate more productive ecosystem)

Saba, V. S., C. A. Stock, et al., 2012: Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*.

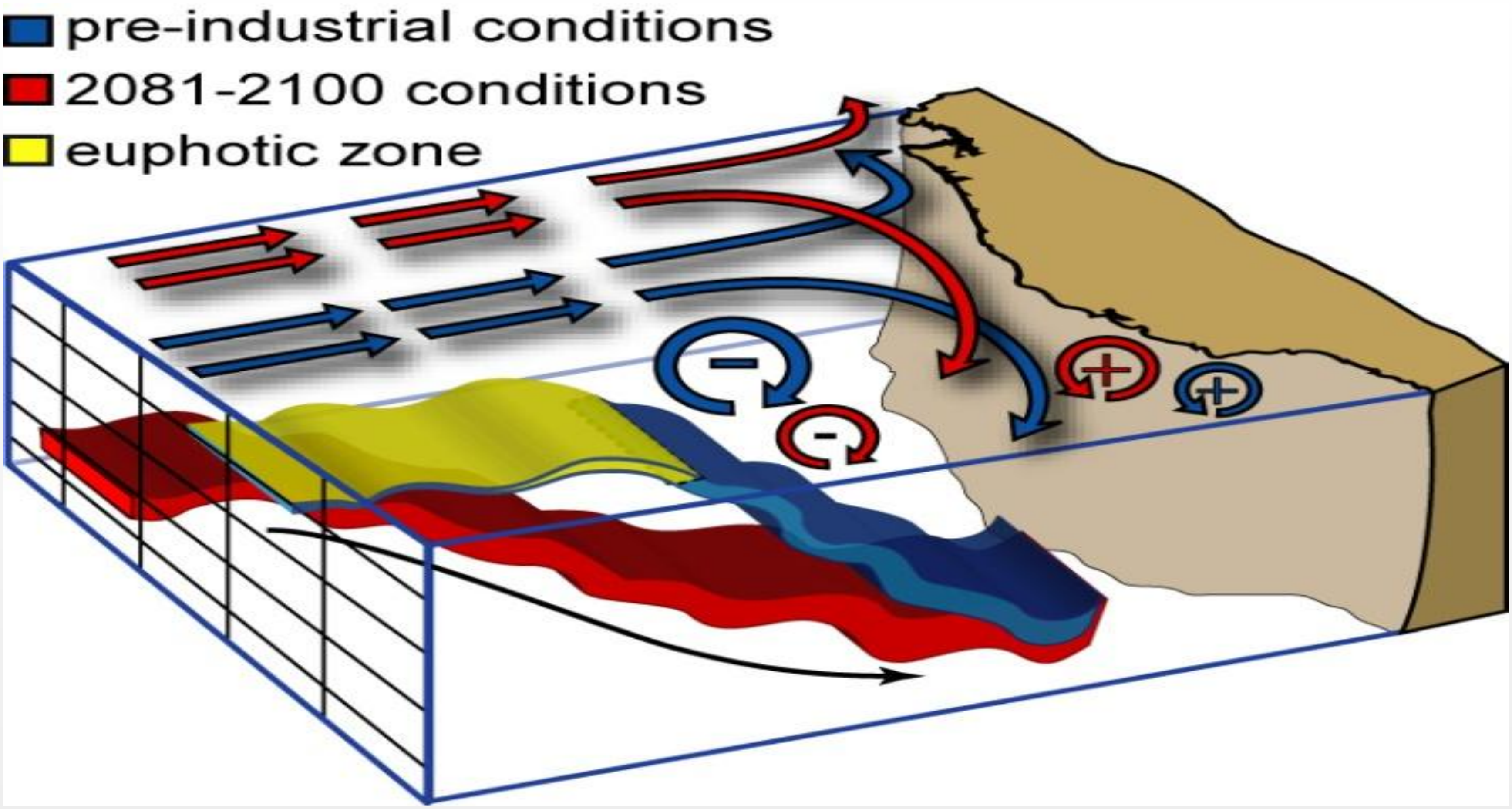
Negative impacts on endangered leatherback turtles



- Project declining numbers due to lower hatching/emergence with increasing temperature
- Nesting further north unlikely due to extremely dry conditions in sub-tropics
- Potential to maintain population through irrigation and shading if projected impacts begin to manifest.

Saba, V. S., C. A. Stock, et al., 2012: Projected response of an endangered marine turtle population to climate change. *Nature Climate Change*.

Potential increase in nutrients to California Current



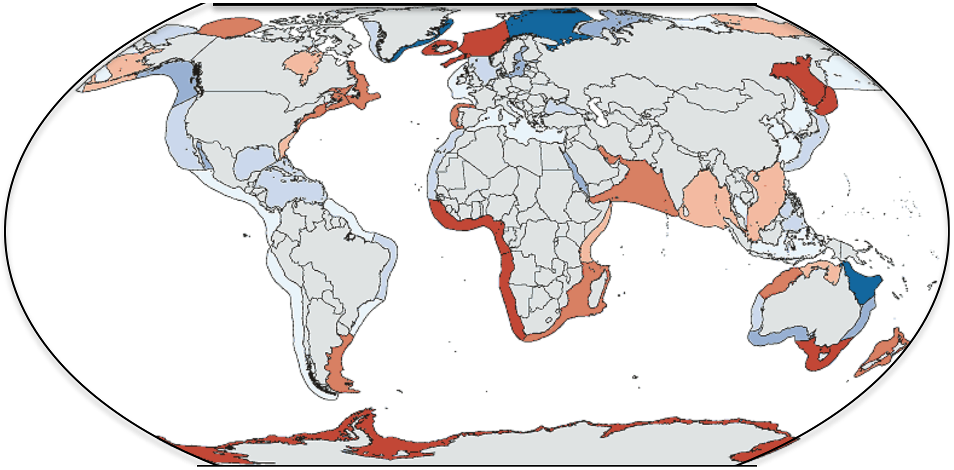
Rykaczewski, R. and J. P. Dunne, 2010, GRL, 37

Progress and Challenges

- Present assessments: magnitude, direction, and first-order drivers of climate-change impacts
- Priority developments:
  - Strengthen mechanistic and quantitative connections between climate drivers and ecosystem responses
  - Consider responses to multiple stressors
  - Improve resolution of local/regional impacts
  - Provide predictions and projections on time-scales from seasons to centuries.

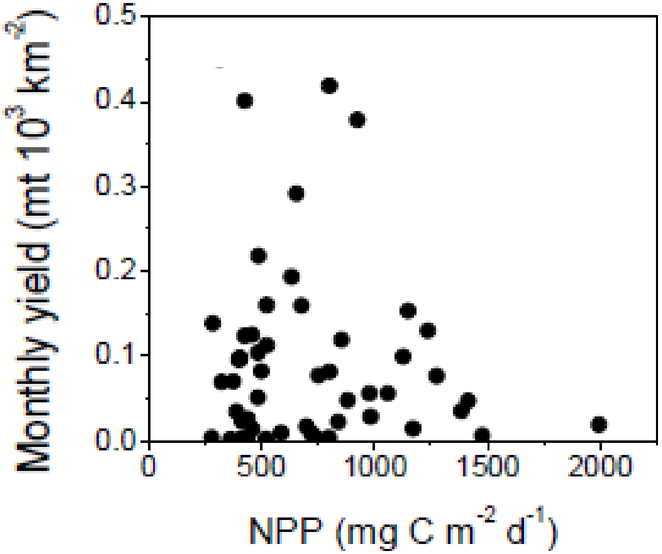
Connecting climate and global fisheries yields

Primary production alone is not a good indicator of fisheries yields



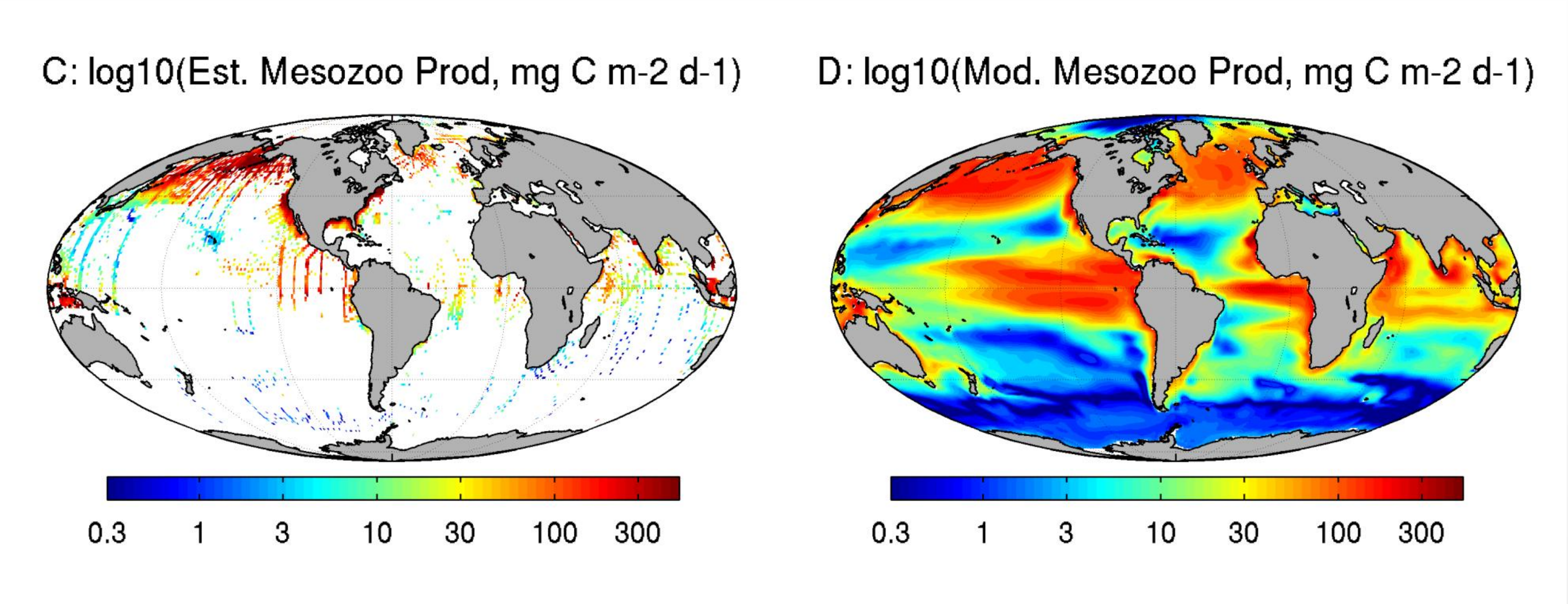
Large Marine Ecosystems

Ken Sherman (NOAA/NMFS)



Friedland, K. D., C. A. Stock, et al., 2012: Pathways between Primary Production and Fisheries Yields of Large Marine Ecosystems. PLoS ONE

Connecting climate and global fisheries



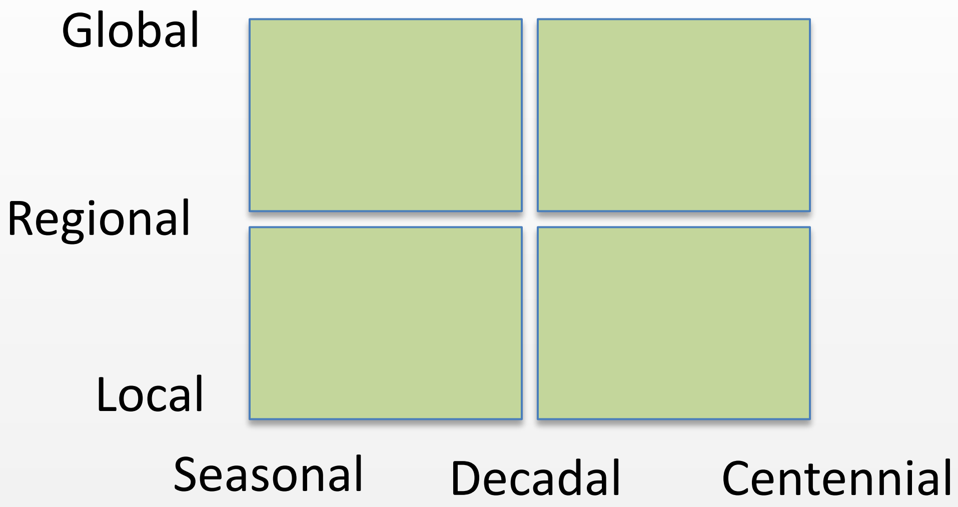
Observation-based estimates of mesozooplankton production

(NOAA Copepod database, O'Brien, 2005; Hirst and Bunker, 2003; SeaWiFS)

Mesozooplankton production in GFDL's COBALT ecosystem model

(Stock et al., 2010; Stock et al., submitted)

Impacts predictions for diverse space/time scales

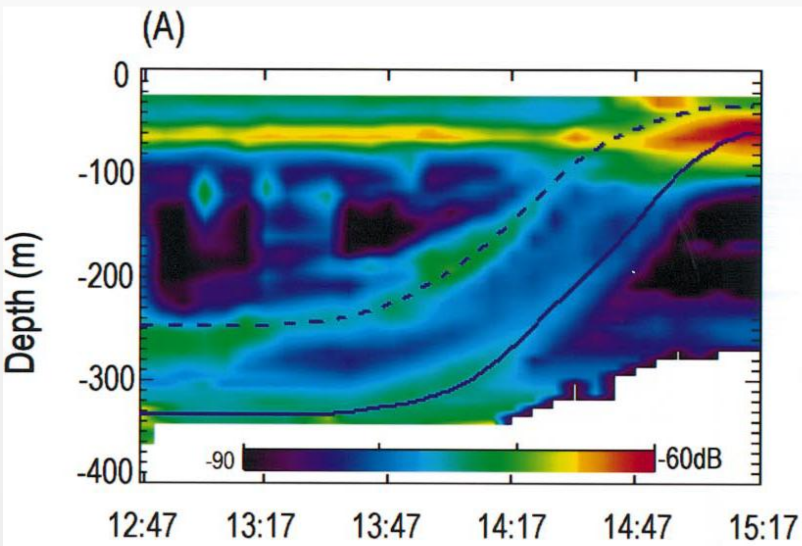


Pursuing ecosystem applications and integration of ecosystem dynamics with GFDL models making physical climate predictions over the full range of these spatial and temporal scales

Improving ecosystem models to improve carbon projections

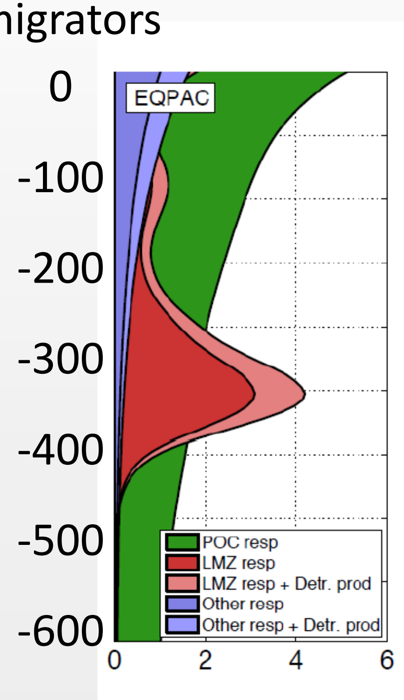
Migrating mesozooplankton support “active” carbon fluxes from the euphotic zone, contributing ~15-40% of flux due to sinking particles.

Migration detected with ADCP



Luo et al., DSR2, 2000

Modeled carbon remineralization by migrators



Bianchi, D. C. A. Stock, et al., GBC, 2013

Contributions to NOAA's Next Generation Strategic Plan

Climate Adaptation and Mitigation:

- Improved understanding of the changing climate system through coupled climate-carbon models
- Assessments of climate change impacts to inform science, service and stewardship decisions

Healthy Oceans:

- Improved understanding of ecosystems to inform resource management decisions

Resilient coastal communities and economies:

- Resilient coastal communities that can adapt to the impacts of hazards and climate change