Chemistry, Carbon, Ecosystems, and Climate:

Coupled Carbon-Climate Earth System Modeling

Presented by

John Dunne

On behalf of Collaborators at GFDL, Princeton University, and Beyond.

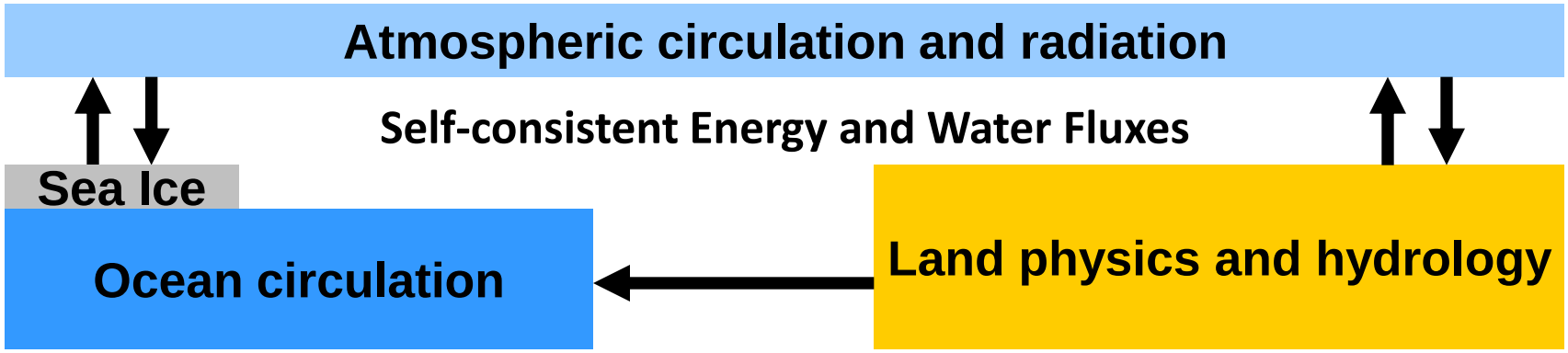
Geophysical Fluid Dynamics Laboratory Review

May 20 – May 22, 2014

Roadmap

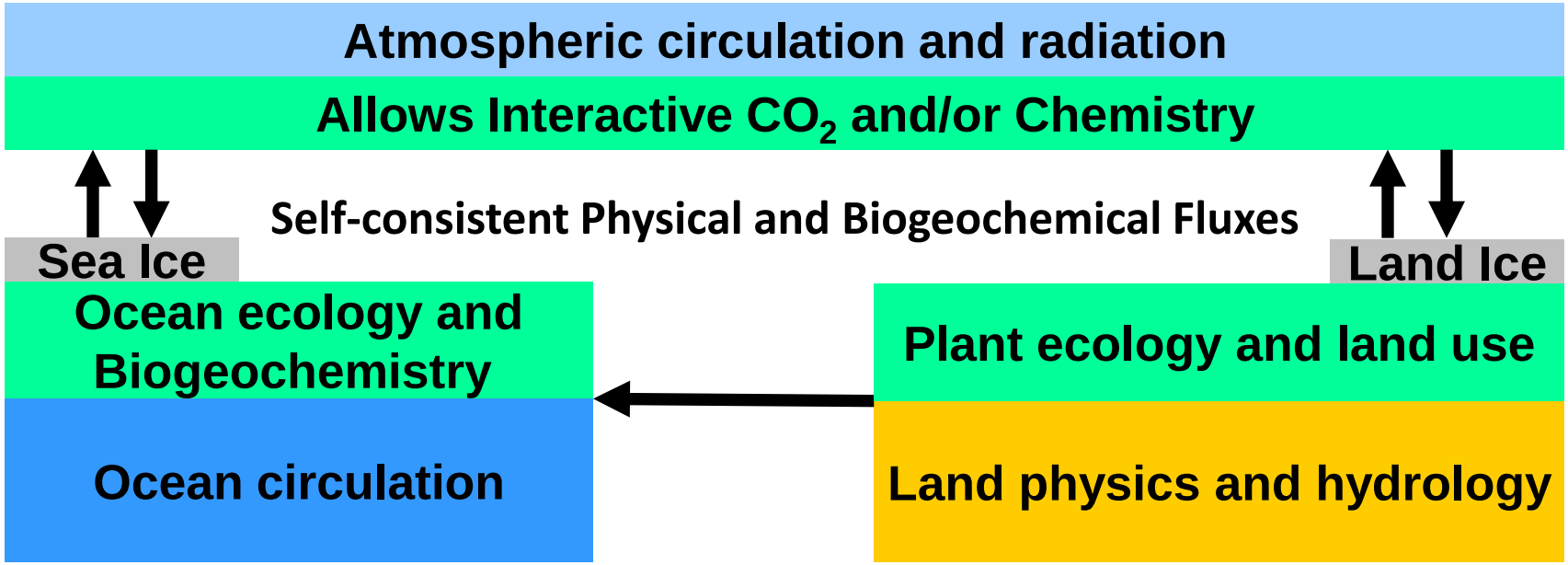
- Introducing Earth System Models (ESMs)
- GFDL Coupled Carbon-Climate ESMs in CMIP5
- Ocean Biogeochemical Mechanisms under Climate Warming and Acidification
- Pushing the Envelope: 1° -> 0.1° Ocean Biogeochemistry
- 3 Broad Examples of GFDL ESMs Informing Decisions
- Introducing the Rest of the Session

GFDL's Traditional Climate Modeling Focus



- Comprehensive atmospheric and ocean physics and dynamics
- Forced by solar, atmospheric concentrations of gases and aerosols.

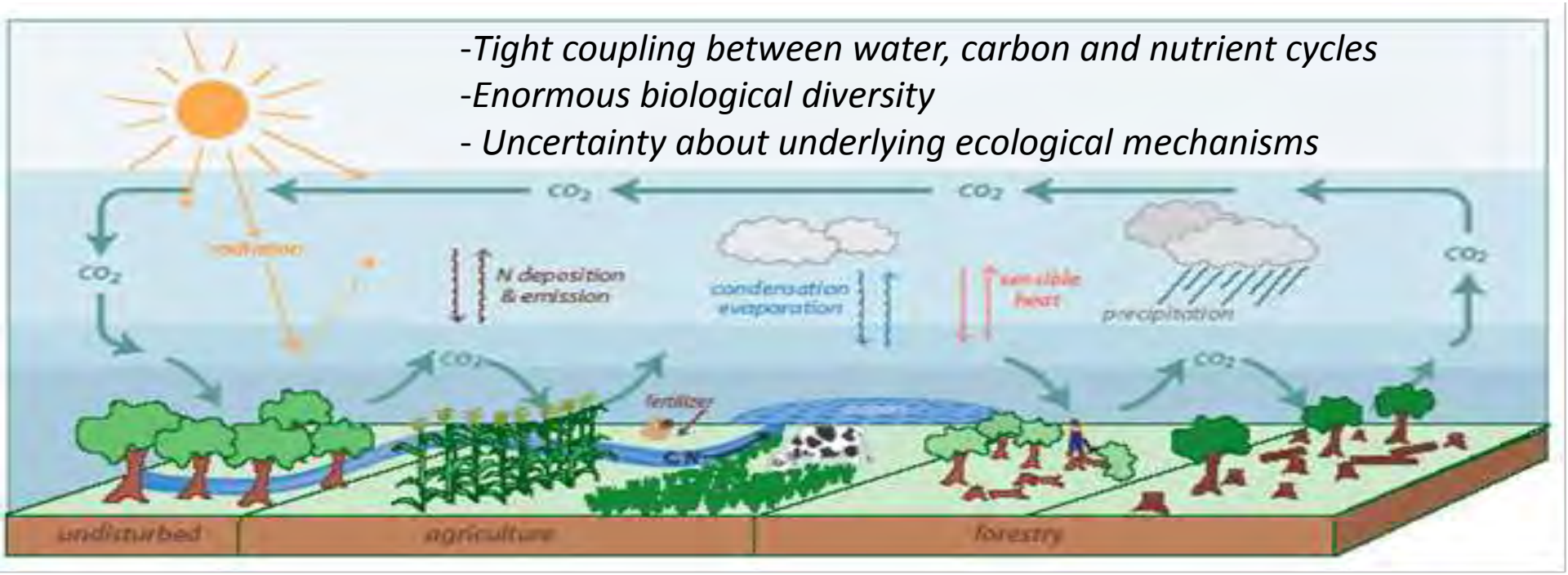
GFDL ESMs for Coupled Carbon-Climate and Chemistry



- Comprehensive land and ocean carbon dynamics
- Interactive/prognostic CO_2
- Forced by either concentrations or anthropogenic fluxes
- Allows investigation of feedbacks
- Amenable to inter-disciplinary impacts studies

Land Coupled Carbon-Climate (Shevliakova this session)

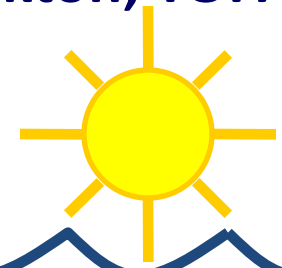
- How changes in land ecosystem structure and functioning effect global biogeochemical cycles and climate?
- How direct human activities and climate influence land ecosystems?



Unparalleled Biogeochemical Comprehensiveness in GFDLs CMIP5 ESMs (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

N_2-fixer
Heterotrophs
Protist
Filter feeder
Recycled nutrients
Small phyto.
New nutrients
Large phyto.
semilabile
semirefract.
DOM
Detritus

Carbon
Oxygen
Nitrogen
Phosphorus
Iron
Alkalinity
Silicon
Lithogenic
$CaCO_3$

Dunne et al. (2005;2013)

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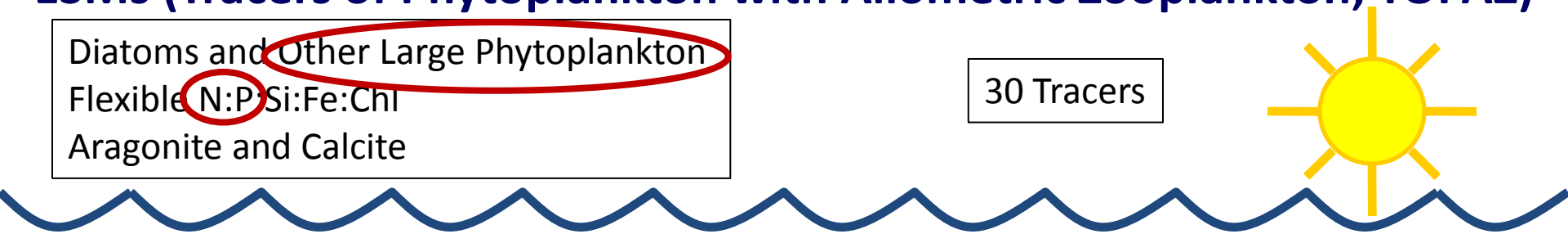

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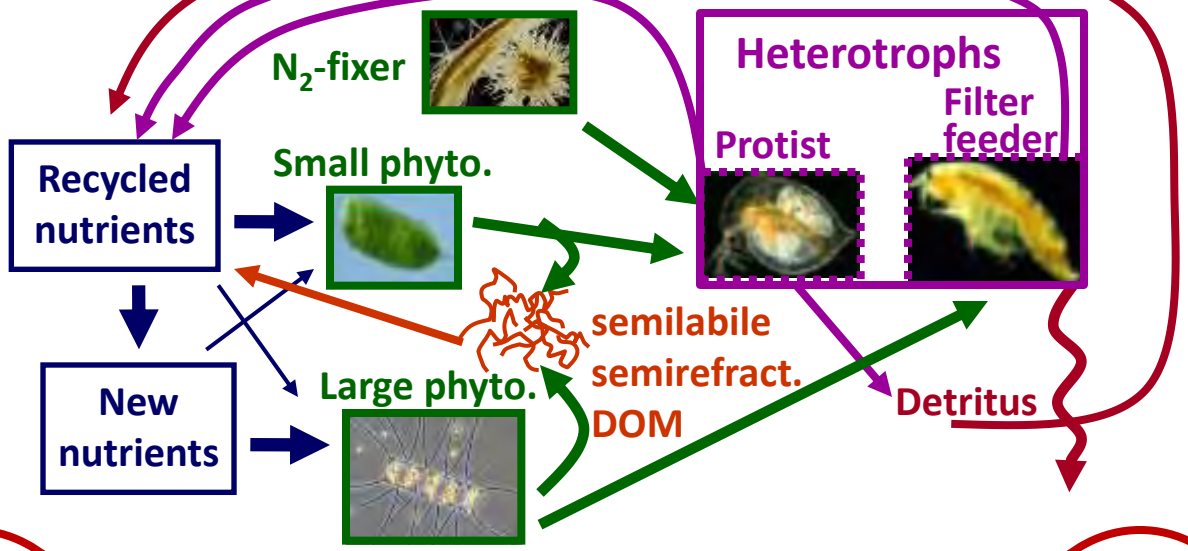
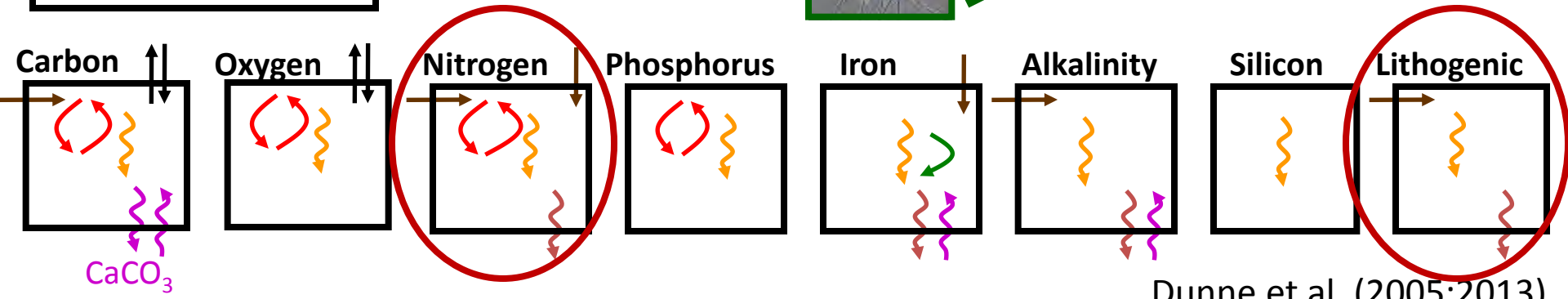
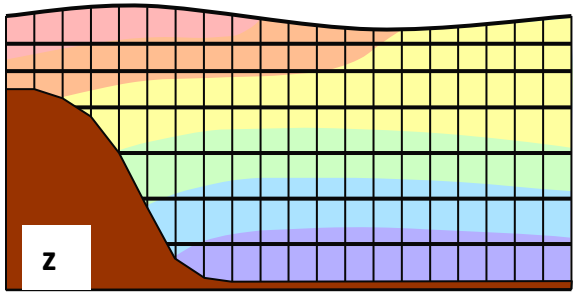




Dunne et al. (2005;2013)

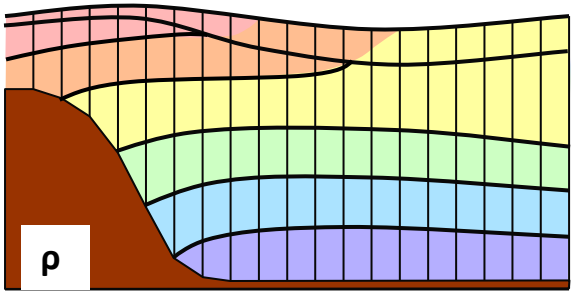
NOAA's First Earth System Models reduce uncertainty in heat and carbon uptake under climate warming

z* (MOM4.1):

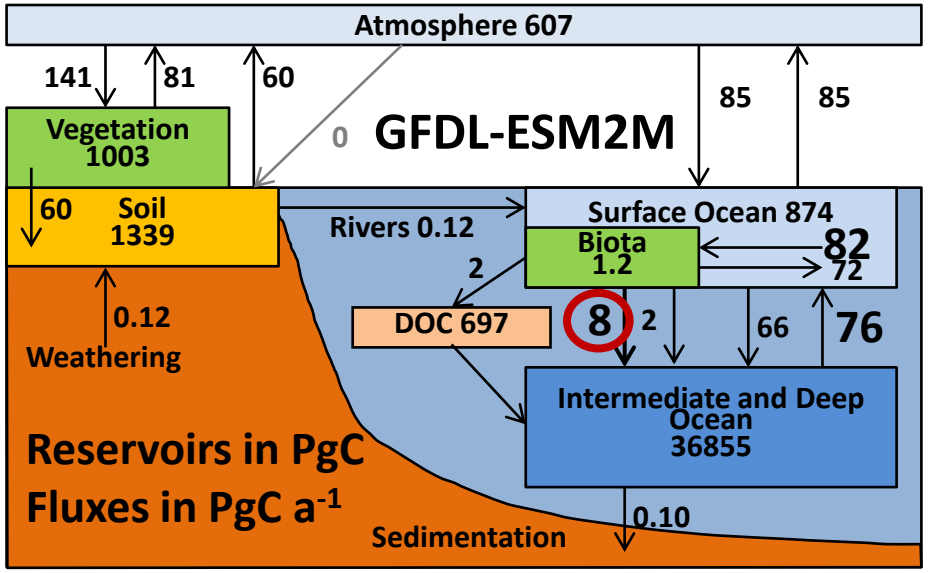


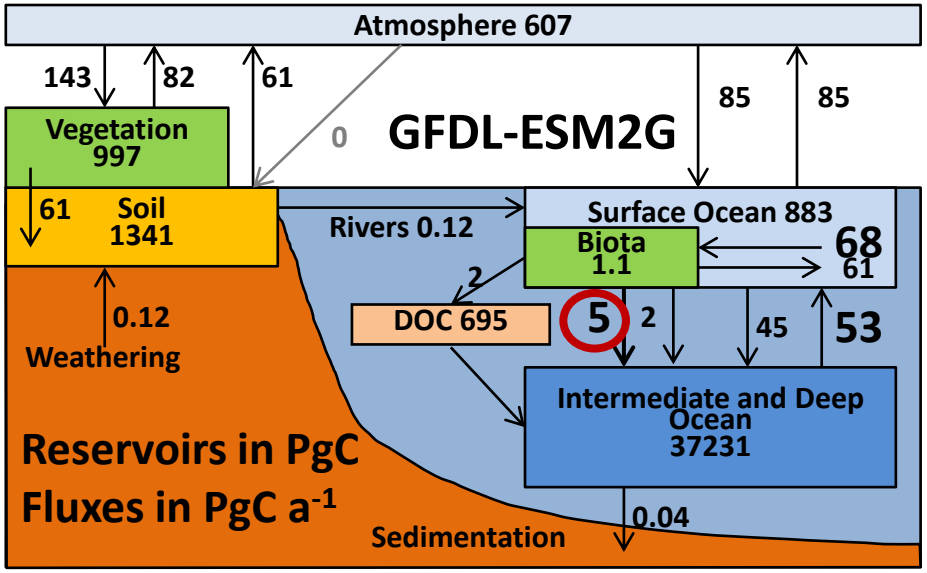
- Depth-based vertical coordinate
- Over 40 years of experience

ρ (GOLD):



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



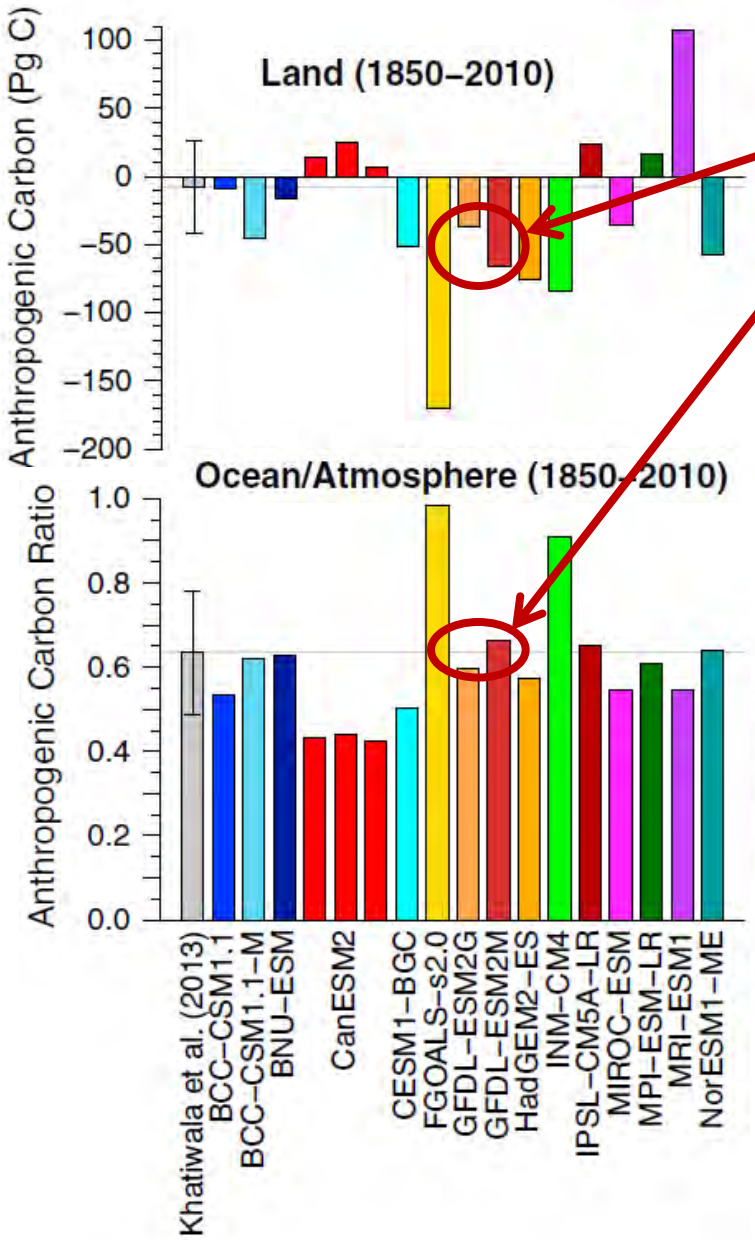


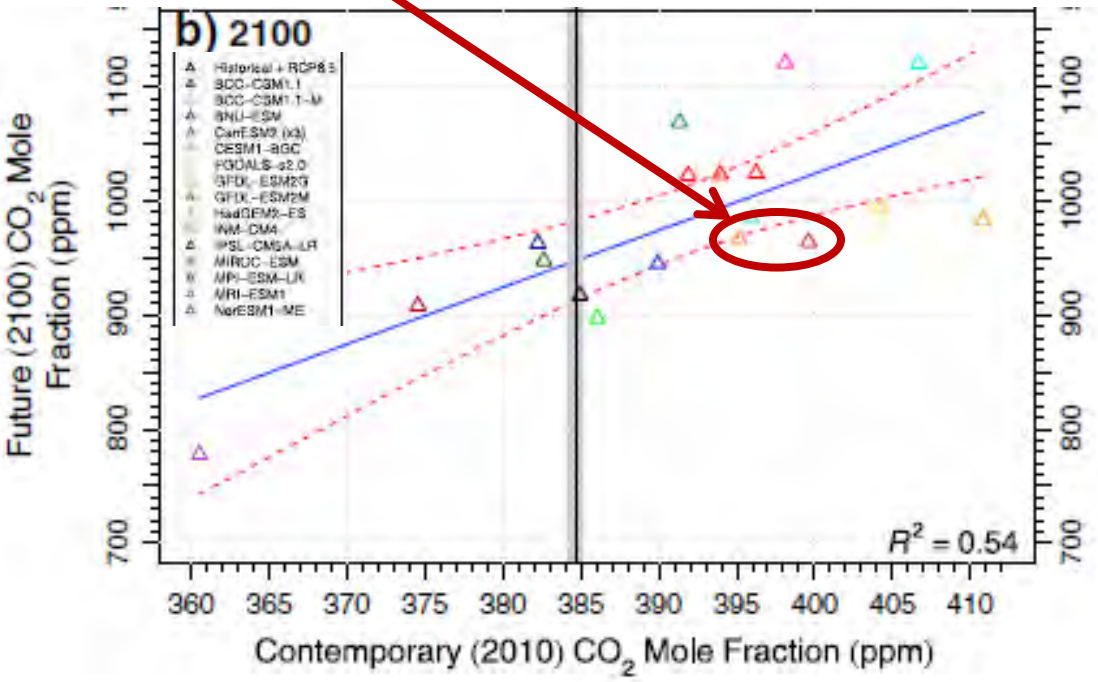
Dunne et al. (2012, 2013); Winton et al. (2013); Hallberg et al. (2013); Froelicher et al. (submitted)

GFDL ESMs Key CMIP5 Contribution

Hoffman et al., 2014

- Land competitive even including both dynamic vegetation and land use with secondary forests
- Ocean-atmospheric partitioning among the best
- While overestimating contemporary CO_2 (not enough land uptake), they give median uptake at 2100.



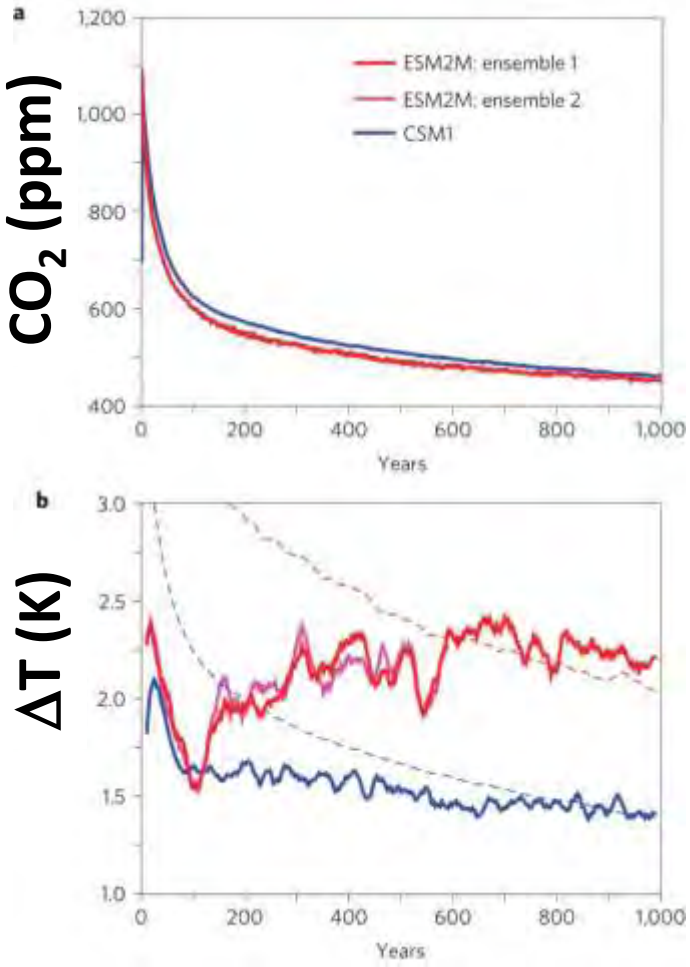


Putting the Puzzle Pieces Together: Coupled Carbon-Climate in CMIP5 ESMs

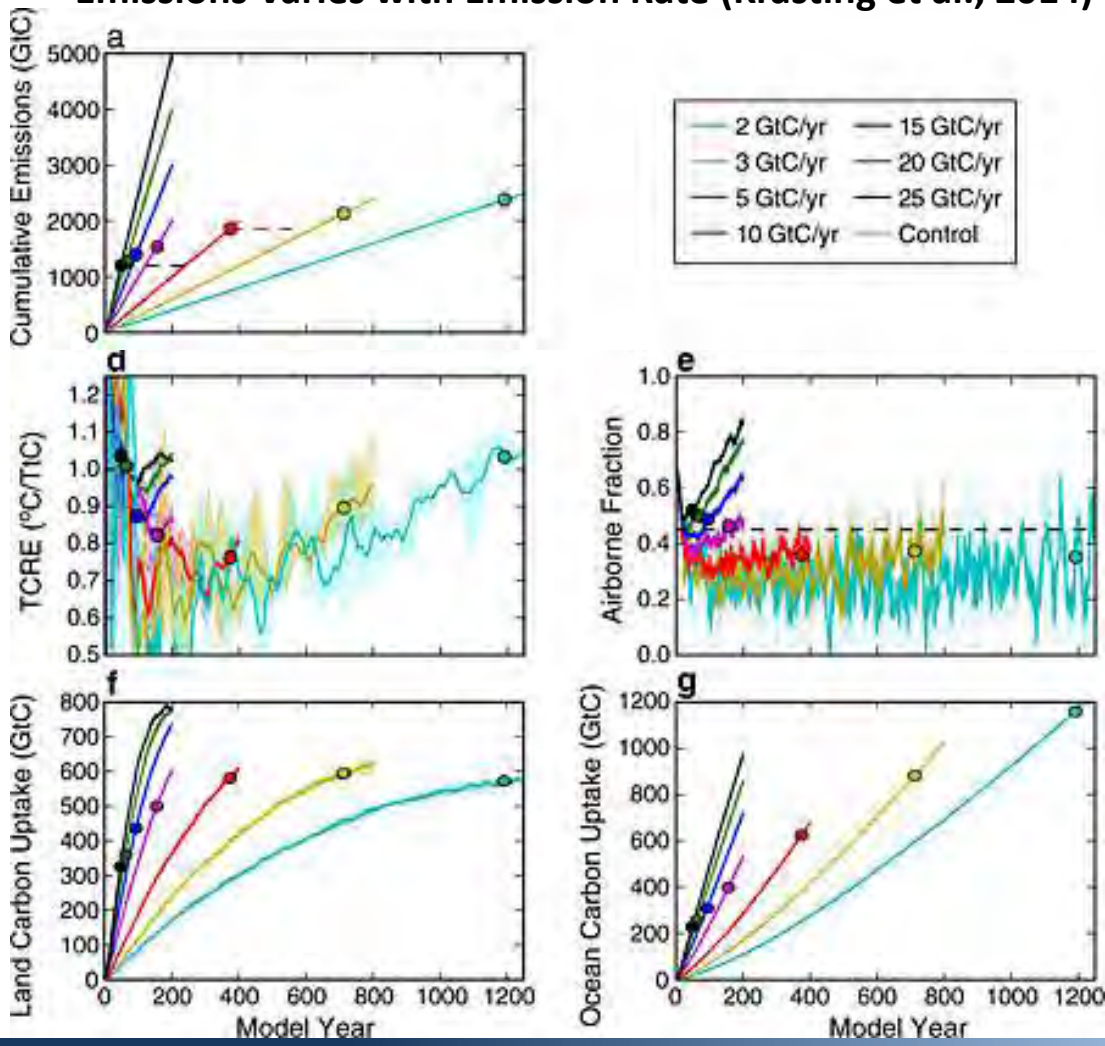
- ESMs can simulate atmospheric CO_2 from emissions!
- Ocean Carbon (and Heat)Uptake uncertainty strongly reduced from C4MIP to CMIP5
- ESMs support use of Transient Climate Response to Cumulative Carbon Emissions (TCRE) metric
- Land Carbon System Uncertainty now main driver and focus of broad study (Shevliakova this session)

Digging into Mechanisms: GFDL ESMs Demonstrate Tight Linkage Between Total Emissions and Climate Response

After an Abrupt 4xCO_2 Increase, Carbon Uptake Timescales Modulate the Climate Response (Froelicher et al., 2013)



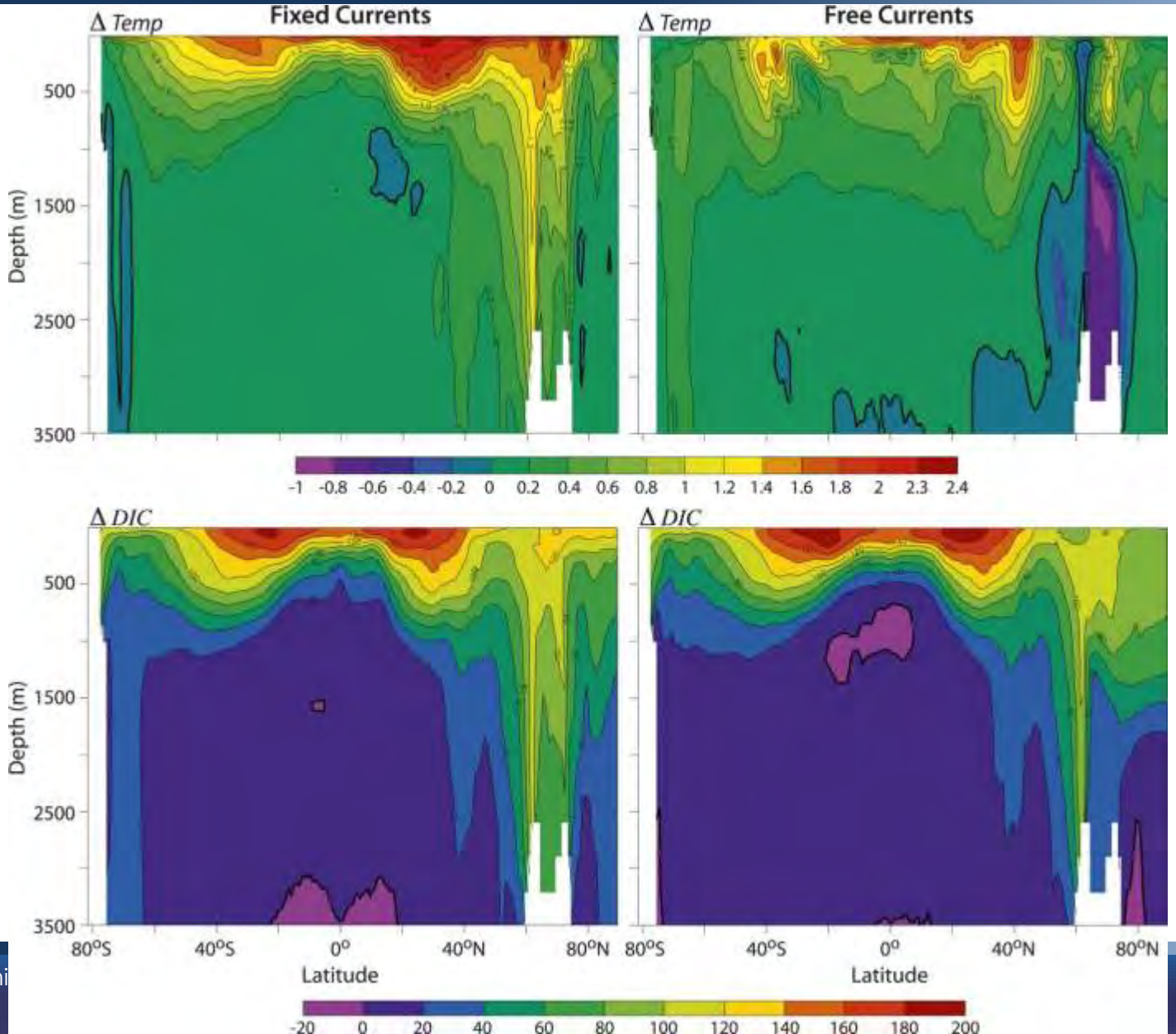
The Transient Climate Response to Cumulative Carbon Emissions Varies with Emission Rate (Krasting et al., 2014)



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

ΔTemp

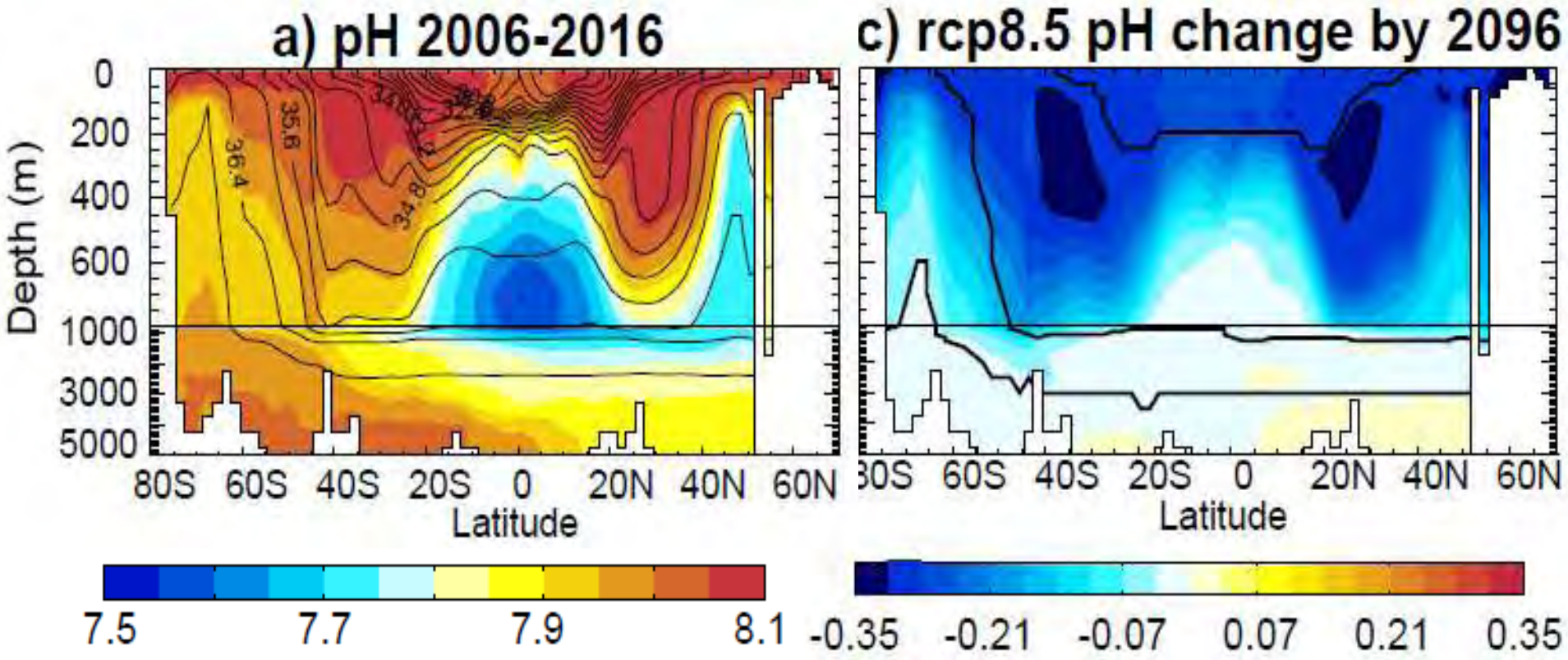
ΔDIC



Winton et al., 2013

ESM2M Superior Mode Water pH Allows Detection of Largest Ocean Acidification in Tropical Mode Waters, not the Surface

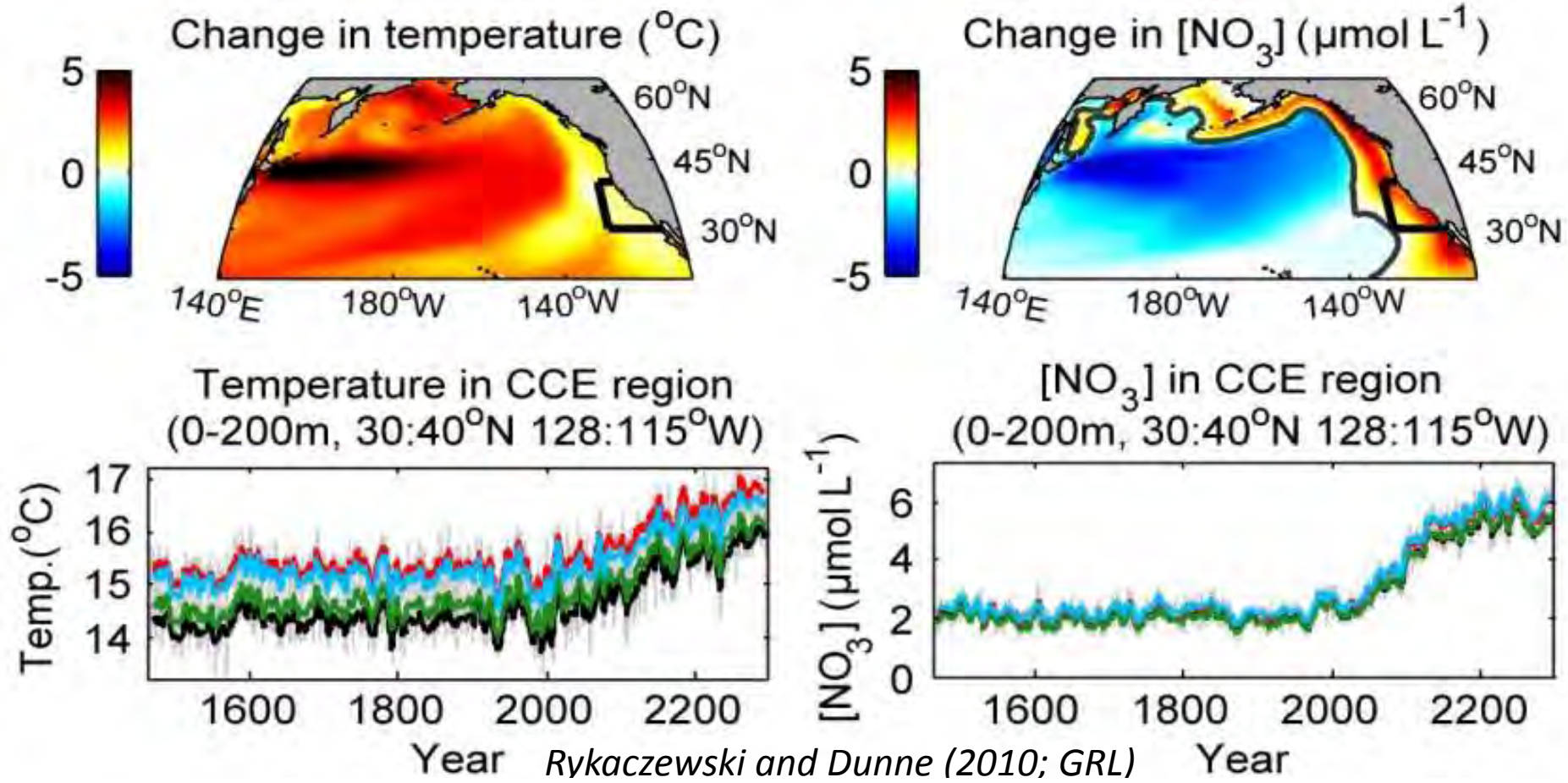
ESM2M Pacific Section (190°E)



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)

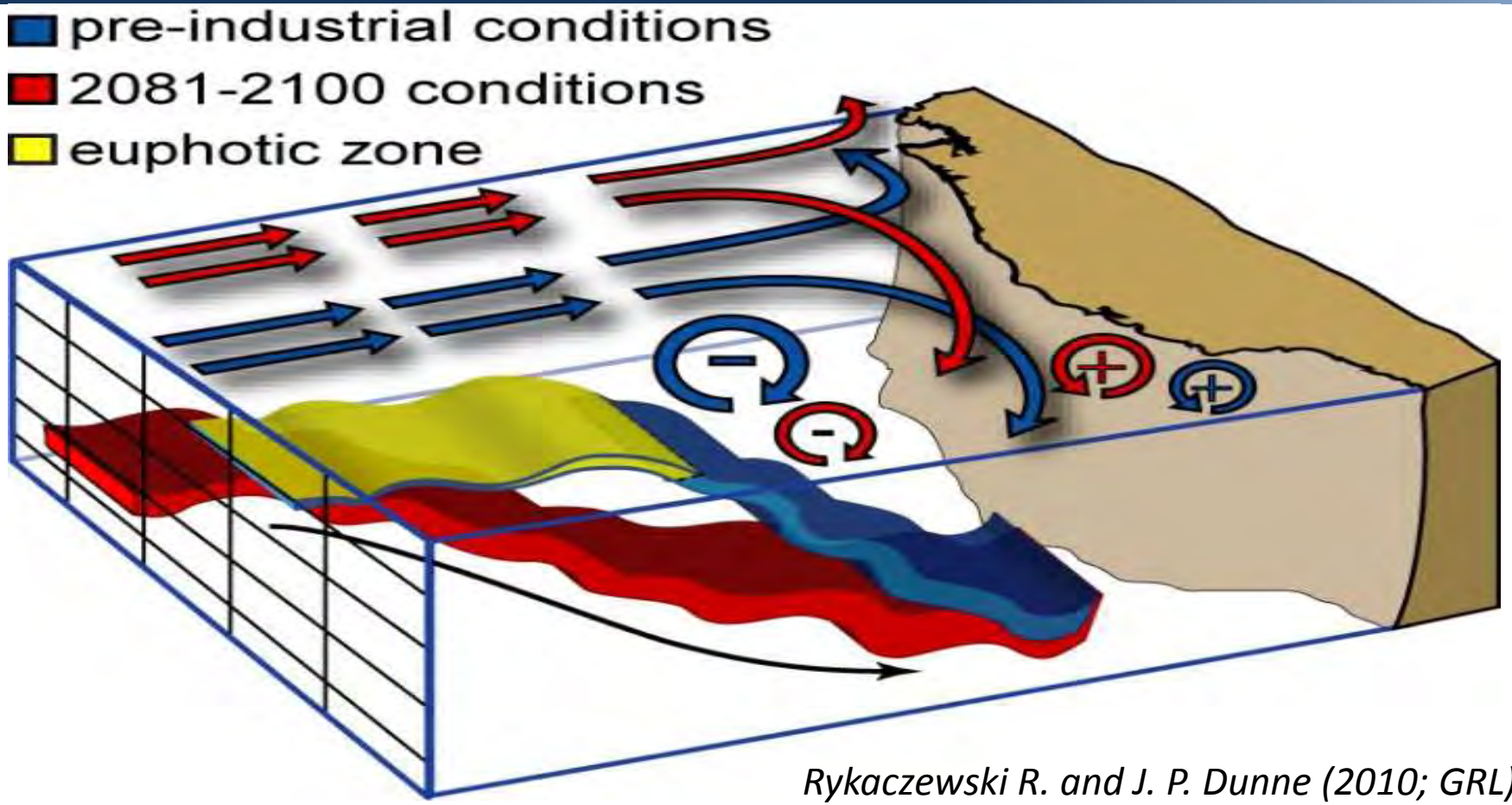
Large and Complex Regional changes: Example of the California Current Large Marine Ecosystem



Rykaczewski and Dunne (2010; GRL)

- **GFDL ESMs 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**

Complex Interplay of Mechanisms in the California Current Large Marine Ecosystem

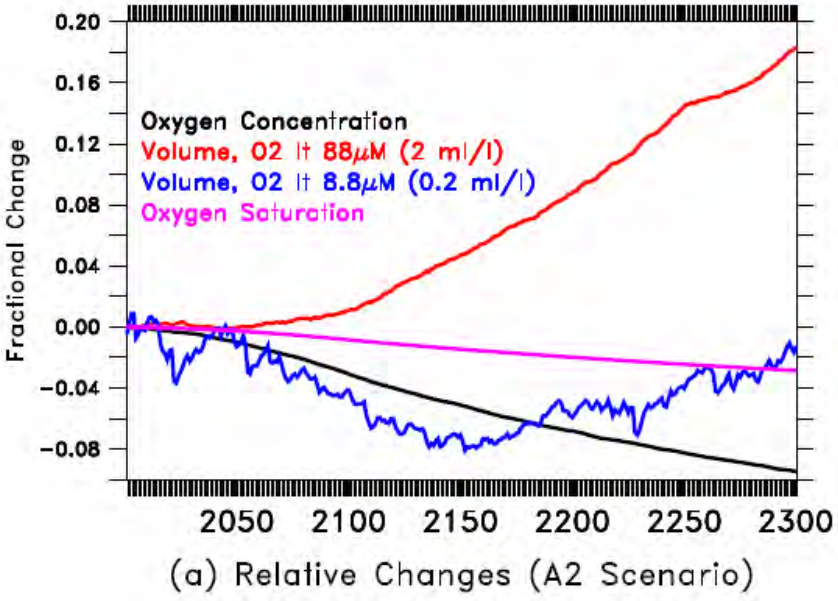


Rykaczewski R. and J. P. Dunne (2010; GRL)

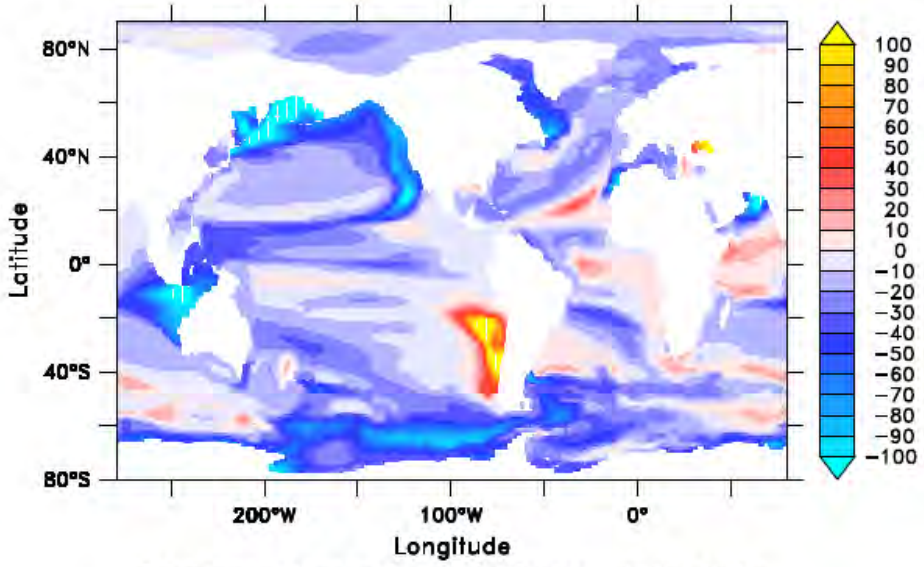
- **Dominance of remote forcing on regional California Current changes**
- **Interplay of atmospheric winds, heat fluxes, stratification, ventilation, and watermass pathways modulating overall biogeochemical response**

GFDL ESMs Bring New Insight into Ocean Biogeochemical Change: Rebalancing of Oxygen Ventilation Pathways

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/m^3) 2281–2300, 300m

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

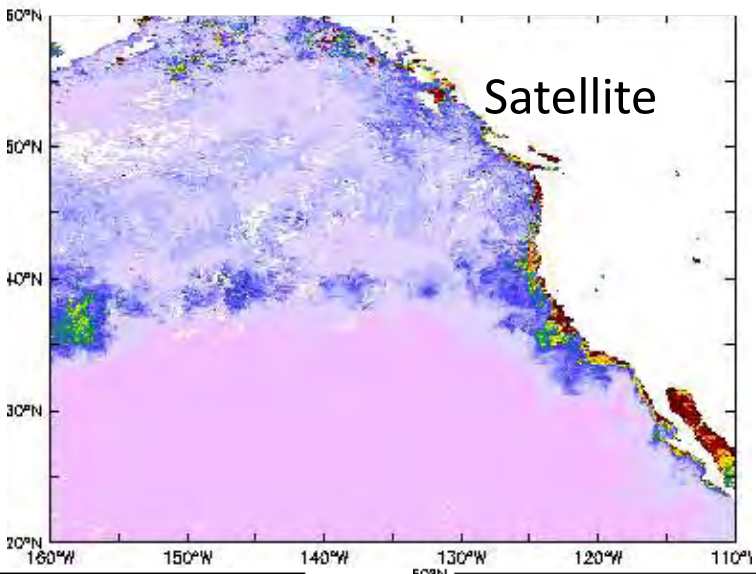
Gnanadesikan, Dunne, and John, 2012: Understanding why the volume of suboxic waters does not increase over centuries of global warming in an Earth System Model

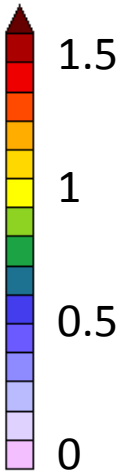
Putting the puzzle pieces together: Mechanisms of Ocean Biogeochemical Change in GFDL ESMs

- **Warming increases stratification**
  - *Ventilation and nutrient supply decreases globally*
  - *Increase in maximum rates, shift to microbial loop (not shown)*
- **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*
- **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.**

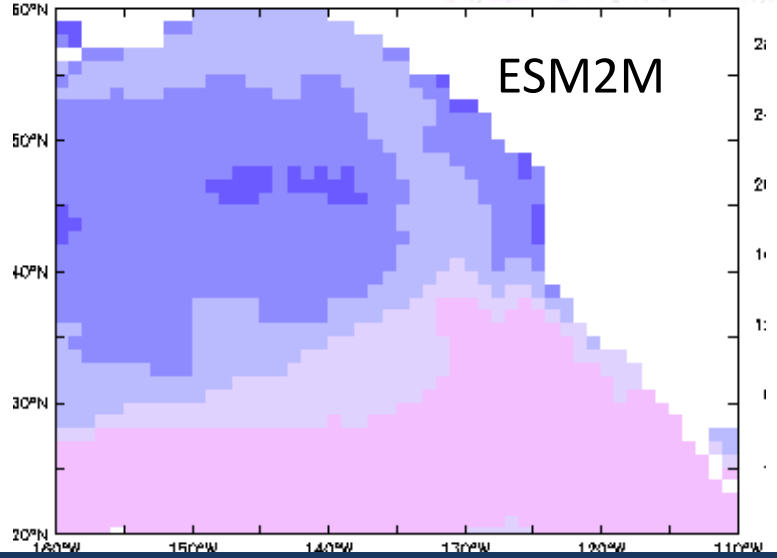
Pushing the envelope: Decadal high resolution prototype with next generation biogeochemisty

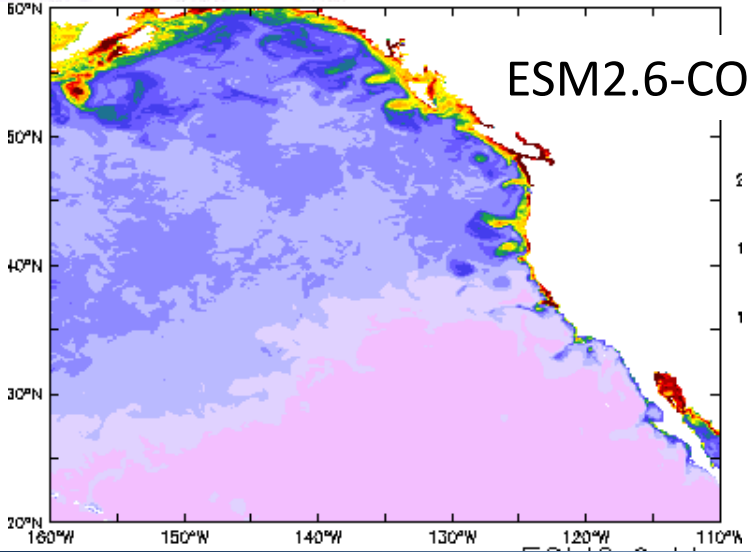
California Current Upwelling Signature vastly improved from 1° to 1/10° Resolution





Chlorophyll (mg Chl m^{-3})

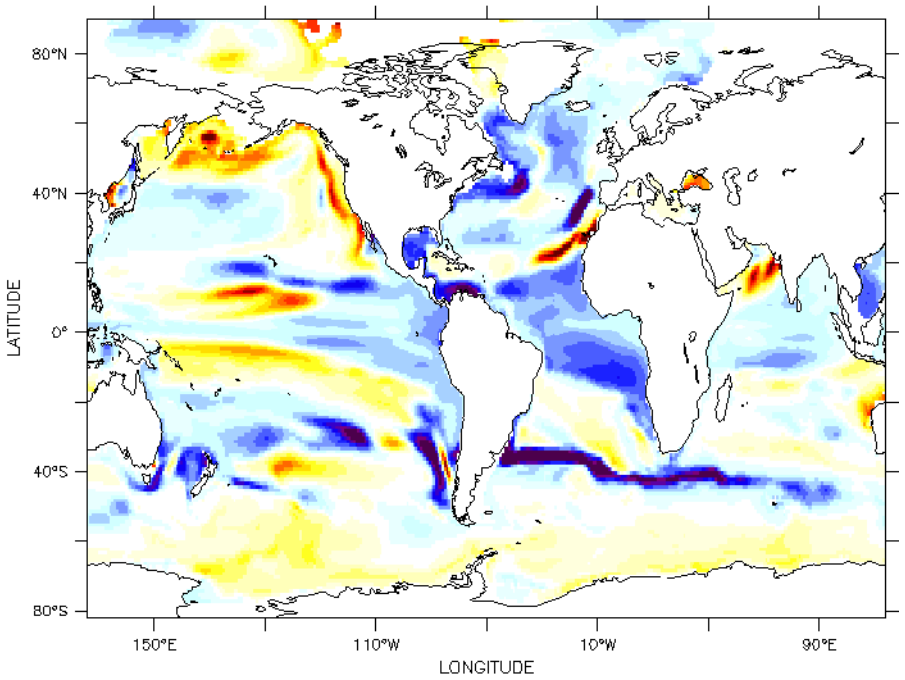




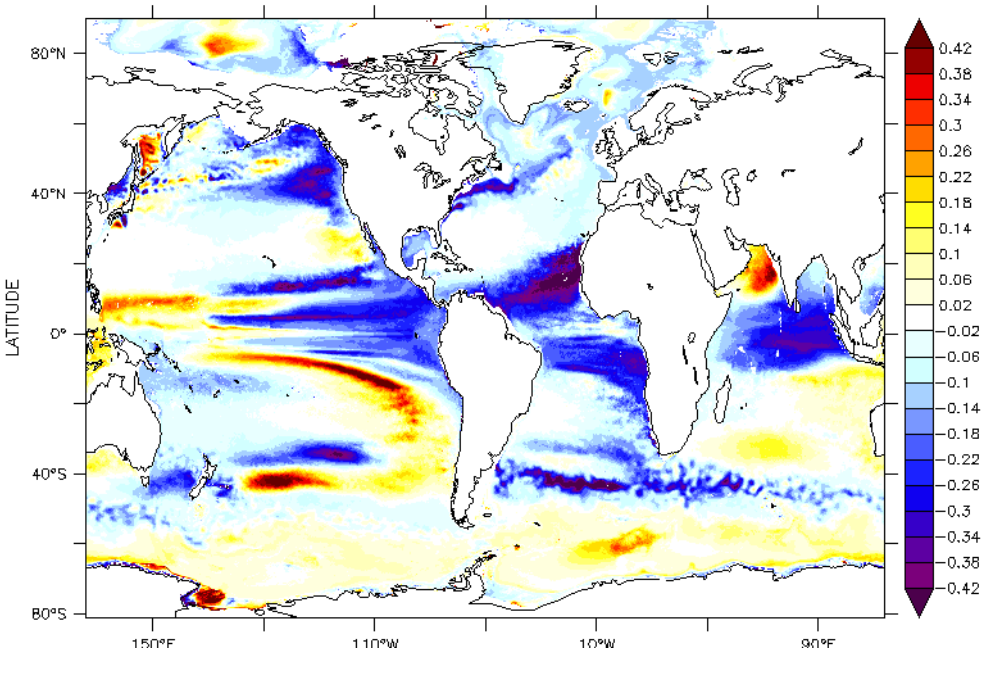
Pushing the Envelope: Centennial high resolution prototype with simplified 3-tracer biogeochemistry (MiniBLING)

ΔPO_4 at 200m for CO_2 doubling minus Control

ESM2M-miniBLING



CM2.6-miniBLING



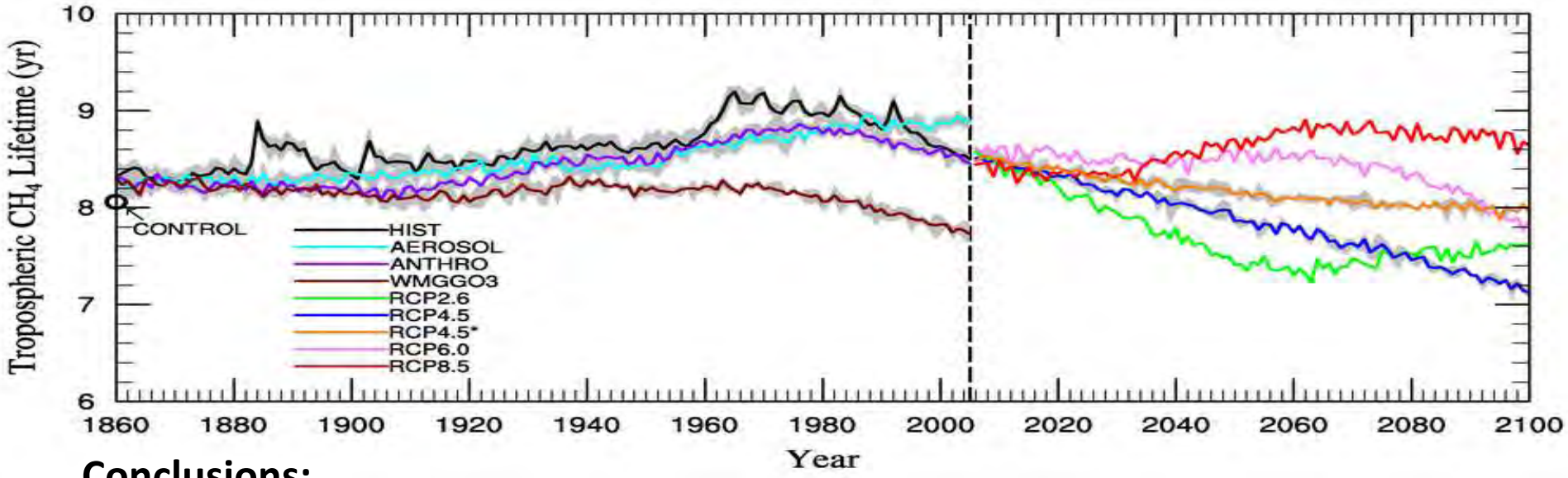
Tropical pattern appears robust to model resolution, but North Pacific and Eastern Boundary Current Patterns differ… interpretation is ongoing.

Dunne et al. (In Preparation)

GFDL's multidisciplinary ESMs inform decisions: Nonlinearity and Drivers of CH_4 Lifetime

Motivation:

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



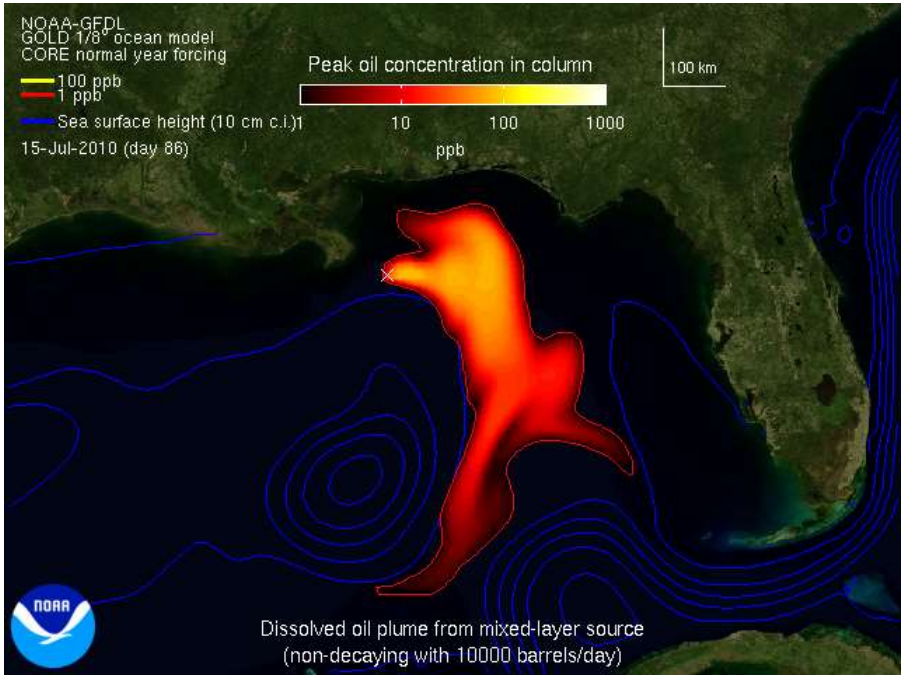
Conclusions:

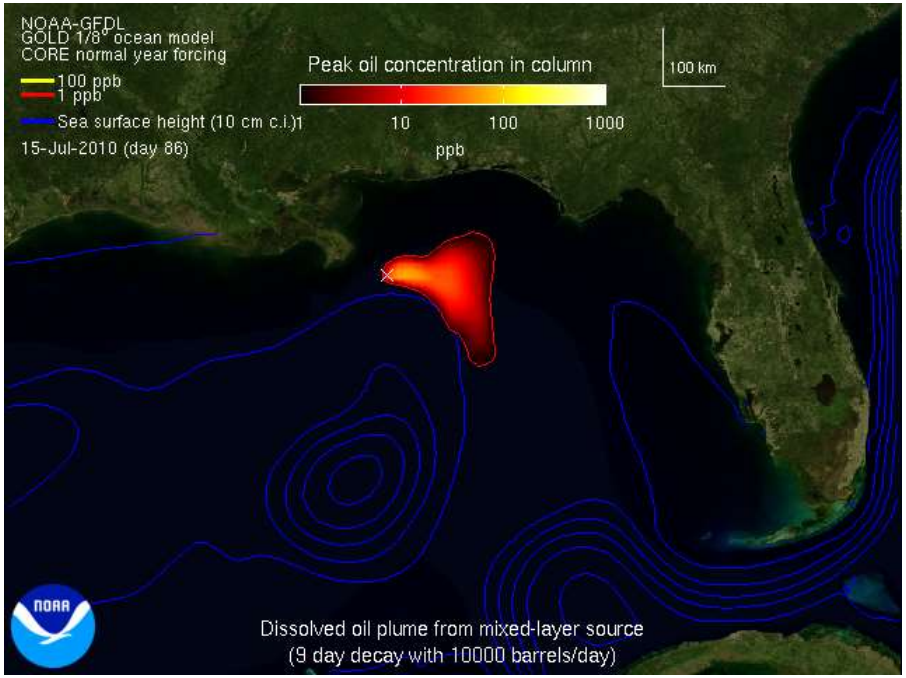
- **5% historical variation in τ_{CH4} driven mainly by anthropogenic emissions**
- **CM3 projects reduced τ_{CH4} except in RCP8.5**

John et al. (2012 and Poster!!!)

GFDL's multidisciplinary ESMs inform decisions: Biogeochemical Consequences of Deepwater Horizon

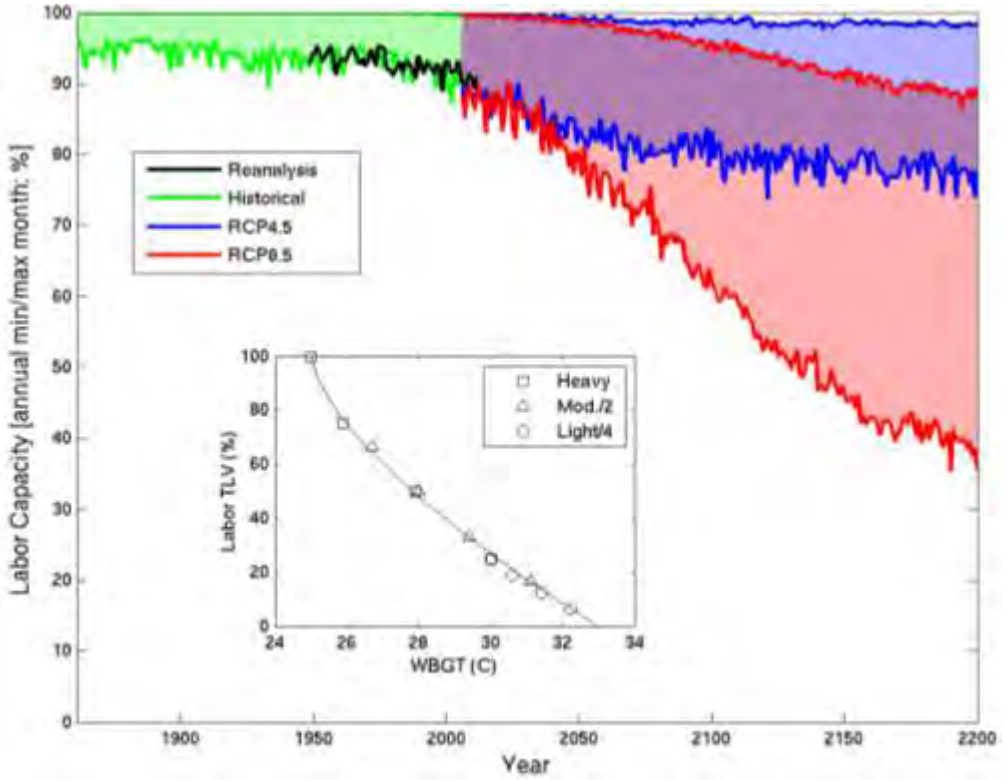
- Case study of ocean transport and microbial decay of Deepwater Horizon oil spill with a 1/8° global ocean model (collaboration with NOAA/OR&R)
- Demonstrated importance of incorporating our biogeochemical understanding in predictions of the fate of the oil



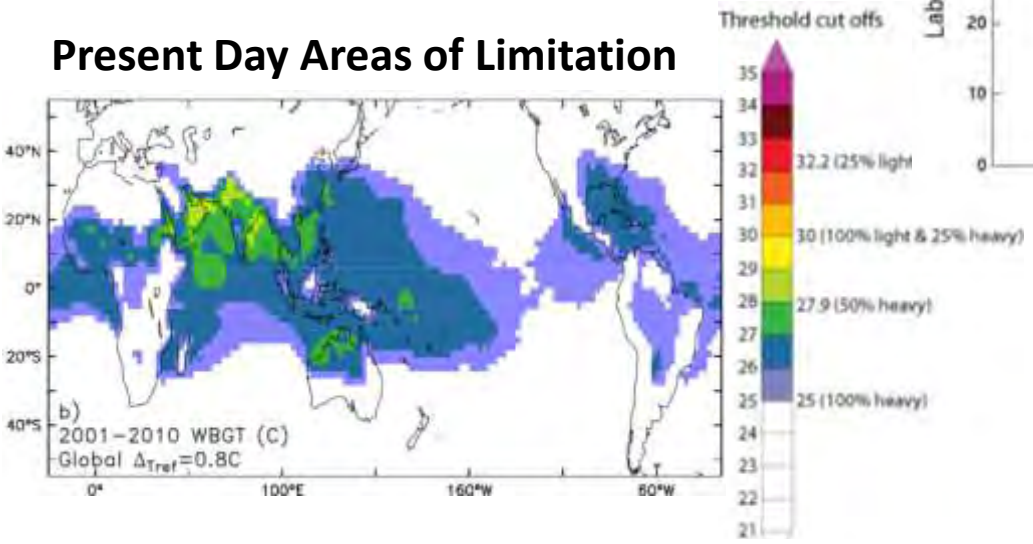


Reference: A. Adcroft, R. Hallberg, J.P. Dunne, B.L. Samuels, J.A. Galt, C.H. Barker and D.Payton (2010): Simulations of underwater plumes of dissolved oil in the Gulf of Mexico, Geophys. Res. Lett., doi:10.1029/2010GL044689.

GFDL's multidisciplinary ESMs inform decisions: Human Limits to Safe Labor Lnder Heat Stress



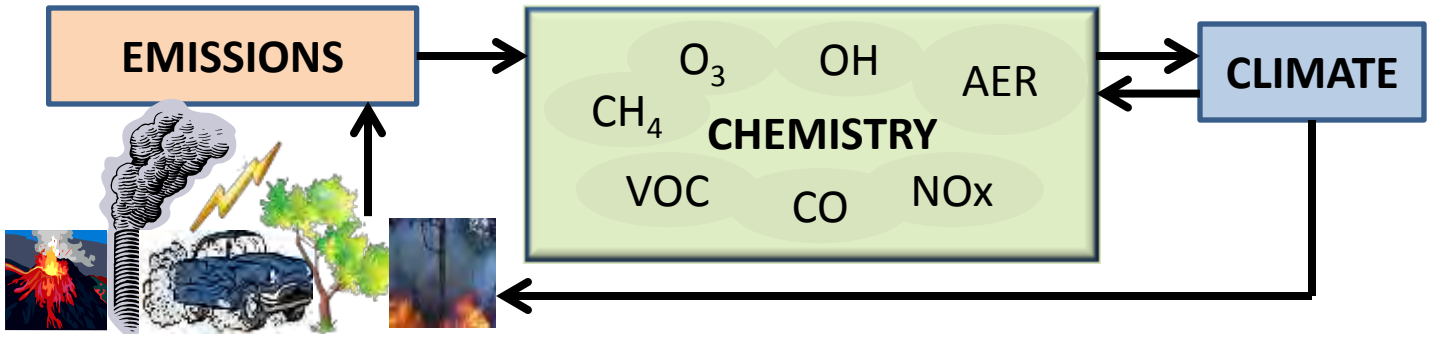
Present Day Areas of Limitation

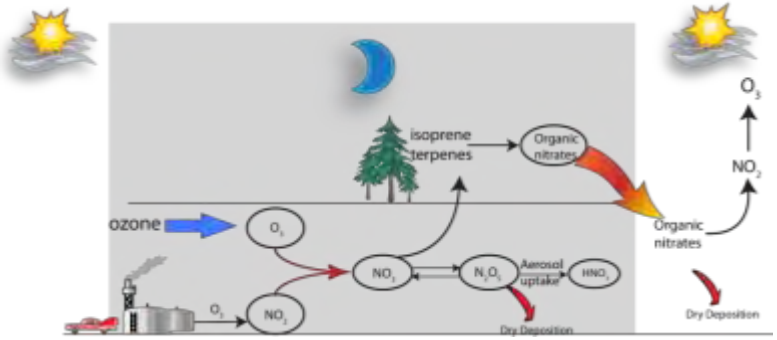


Dunne, J. P., Stouffer, R. J., and John, J. G. Labor capacity reduction from heat stress under climate warming. Nat. Clim. Change (2013).

This Session: GFDL's Chemistry Applications to NOAA's Missions in Climate and Air Quality

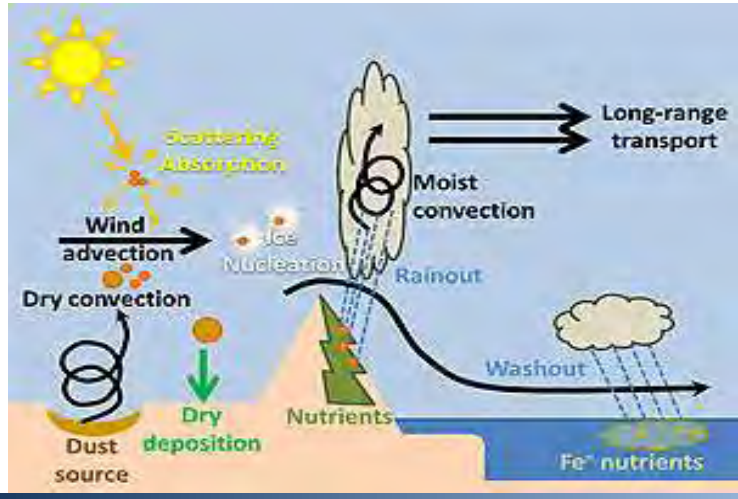
Vaishali Naik: GFDL's ongoing leadership role in chemistry- climate coupling with CM3





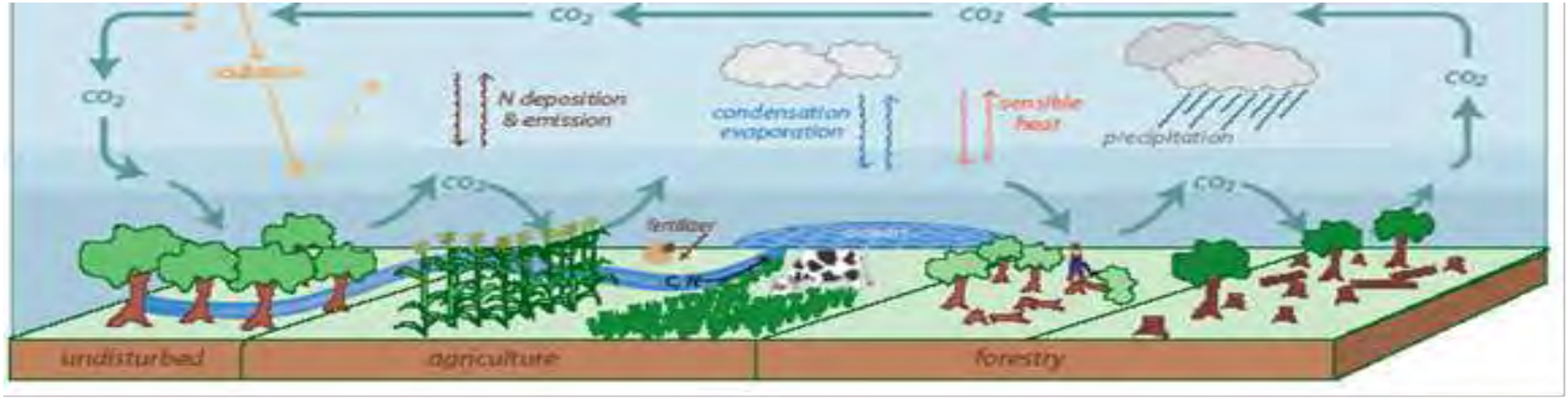
Jingqiu Mao: Using the CM3 framework to understand the mechanisms driving air pollution

Paul Ginoux: Next generation Land-Atmosphere Interactions linking dust generation processes and atmospheric aerosols



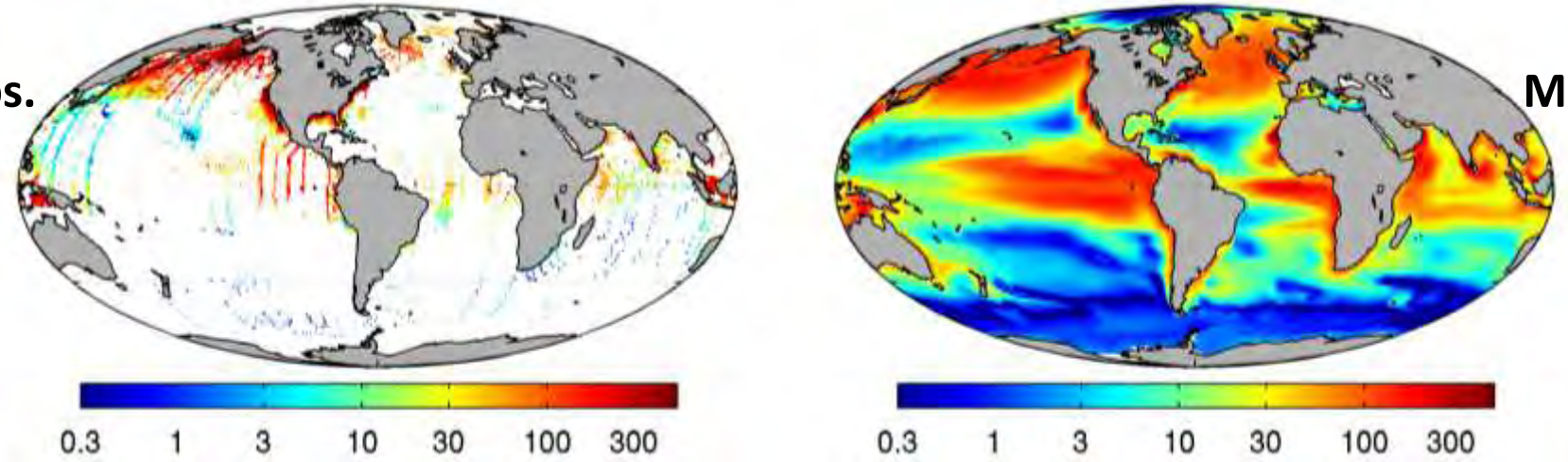
This Session: ESM Applications Bringing Life to GFDL

Elena Shevliakova: Putting land ecosystems and their human drivers into a comprehensive earth system context



Charles Stock: GFDL's impacts projection and next generation marine ecosystem modeling in Support of NOAA's stewardship of Living Marine Resources

Obs. **Model**



Overall Coupled Chemistry, Carbon-Climate and Ecosystems Achievements

- Improved understanding of processes determining biogeochemical distributions, change and impacts:
  - Led or co-authored over 200 scientific papers on atmospheric chemistry (>100), marine biogeochemistry (>40) and ecosystems (>40) and land ecosystems (>20) since 2009
- Key contributor to CMIP5:
  - Reduced uncertainty in past and future chemistry-climate, ocean and land carbon uptake and biogeochemical feedbacks