GFDL's Carbon Cycle Modeling

John Dunne

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Early Mixed Model work with Manabe

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A CO_2-climate sensitivity study with a mathematical model of the global climate

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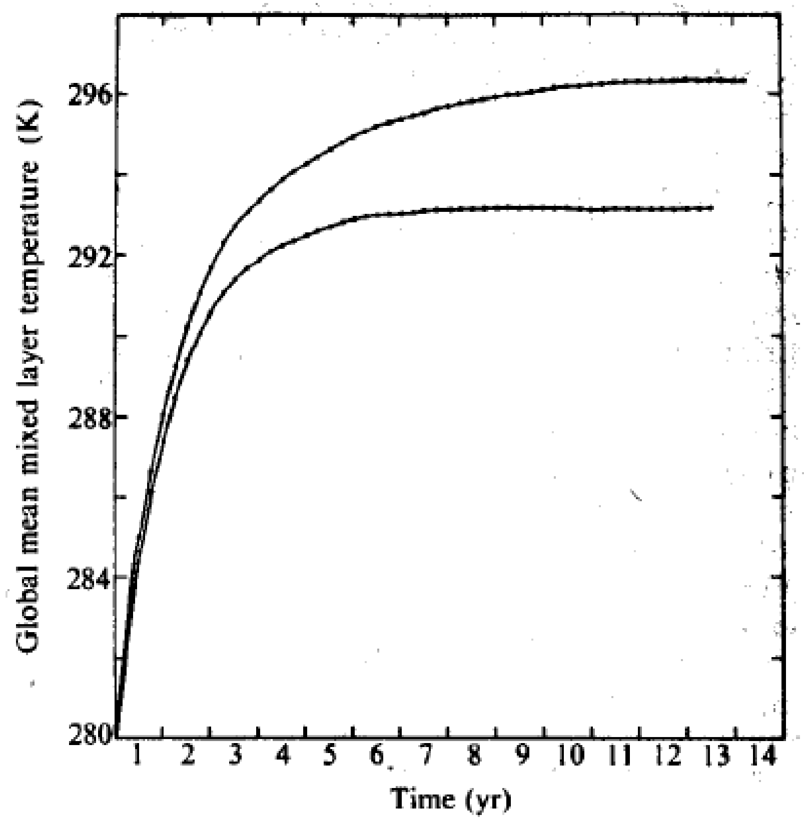
An increase in the CO_2-content of the atmosphere resulting from man's activity could have a significant effect on the climate in the near future[1]. We describe here some new results from a study of the response of a mathematical model of the climate to an increase in the CO_2-content of the air.

The mathematical model consists of (1) a general circulation model of the atmosphere and (2) a simple mixed layer ocean model with uniform thickness. The atmospheric model predicts the changes of the vertical component of vorticity, divergence,



Early Climate Model work with Manabe

Transient Responses of a Coupled Ocean–Atmosphere Model to Gradual Changes of Atmospheric CO_2. Part I: Annual Mean Response

S. MANABE, R. J. STOUFFER, M. J. SPELMAN AND K. BRYAN

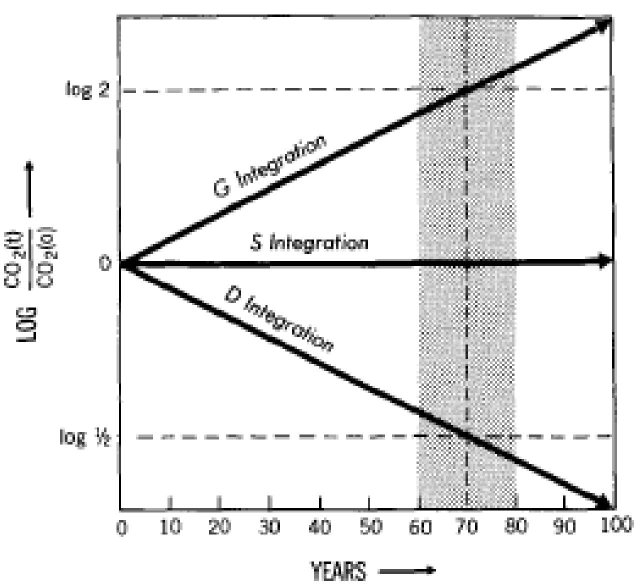


FIG. 1. Schematic diagram of the G, S, and D integrations. The abscissa denotes time in years and the ordinate is the logarithm of the ratio of atmospheric carbon dioxide at time t to its initial value. The period chosen for detailed analysis is indicated by shading.

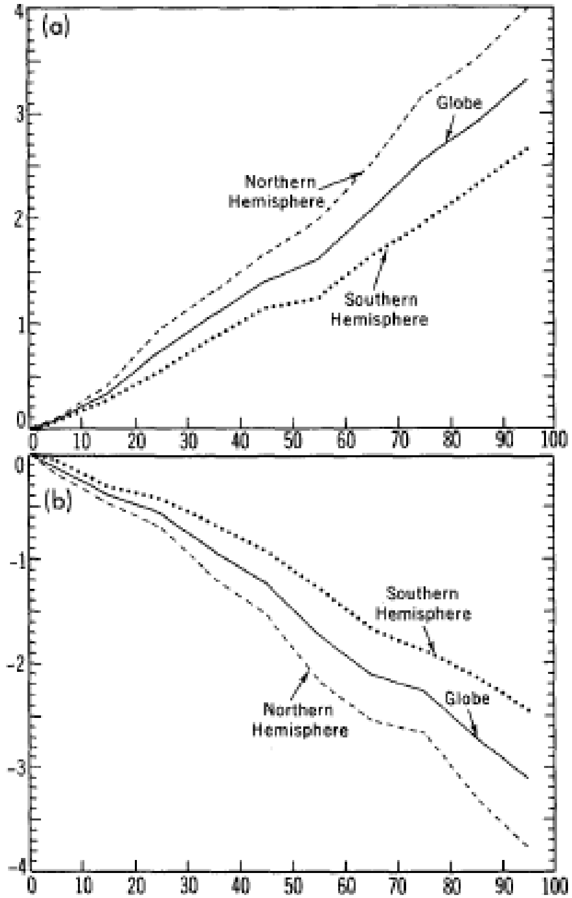


FIG. 8. The temporal variation of the differences in area-averaged, decadal-mean surface air temperature (°C) between the integrations (a) G and S, and (b) D and S. Solid, dashed, and dotted lines indicate the differences over the globe, and Northern and Southern Hemispheres, respectively.

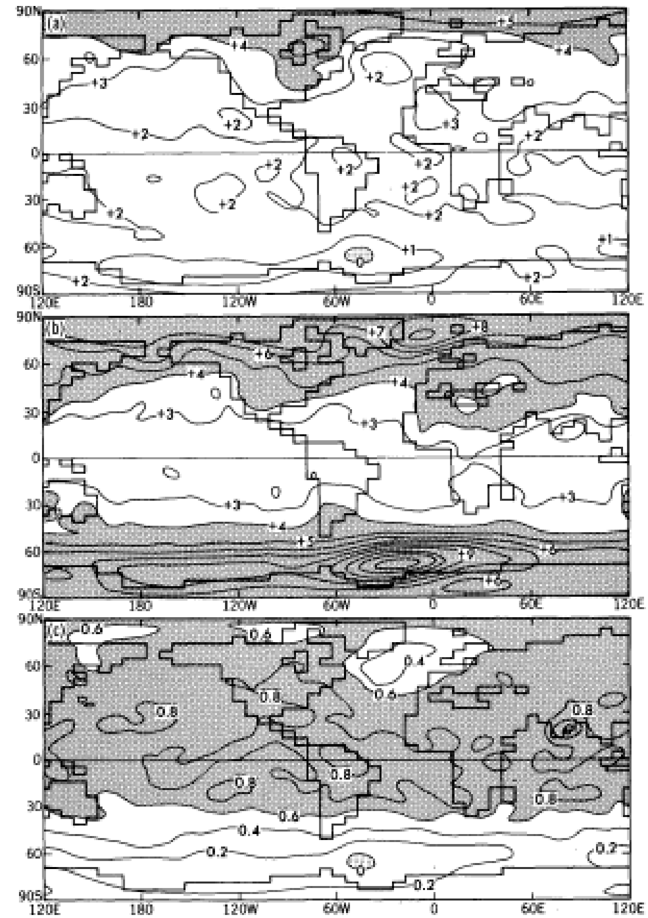


FIG. 12. (a) The transient response of the surface air temperature of the coupled ocean–atmosphere model to the 1%/year increase of atmospheric carbon dioxide. The response (°C) is the difference between the 20-year (60th to 80th year) mean surface air temperature from the G integration and 100-year mean temperature from the S integration. (b) The equilibrium response of surface air temperature to the doubling of atmospheric carbon dioxide. The response is the difference between the two 10-year mean states of the E2X and ES integrations. (c) The ratio of the transient to equilibrium responses.

How is this ‘Carbon Cycle’ work?

How is this ‘Carbon Cycle’ work?

1. The focus is climate sensitivity to changing CO_2

2. Reasonable so long as the experimental design approximates the net carbon cycle response to plausible fossil fuel projections.

… but is it?

Basin in Carbon Cycle Box Models

Bolin, B. and Eriksson, E. (1959) **Changes of the carbon dioxide content of the atmosphere and sea due to fossil fuel combustion**. In: Bolin, B. (Ed.) Atmosphere and Sea in Motion, 130-142. Rockefeller Institute Press.

Machta, L. (1973) **Prediction of CO_2 in the atmosphere**. In Woodwell, G.M. and Pecan, E.V. (Eds.) Carbon in the Biosphere. AEC Symposium Series 30, 21-31, NTIS US DoC.

Bacastow, R. and Keeling, C.D. (1973) **Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle: Changes from A.D. 1700 to 2070 as deduced from a geochemical model**. In Woodwell, G.M. and Pecan, E.V. (Eds.) Carbon and the Biosphere. AEC Symposium Series 30, 86-135, NTIS US DoC.

Keeling, C.D. and Bacastow, R.B. (1977) **Impact of industrial gases on climate**. In: Energy and Climate. Stud. Geophys., 72-95. Nat. Acad. of Sciences, Washington, D.C.

Siegenthaler, U. & Oeschger, H. (1978) **Predicting future atmospheric carbon dioxide levels**. Science 199: 388-395.

Broecker, W.S., Takahashi, T., Simpson, H.J., Peng, T.-H. (1979) **Fate of fossil fuel carbon dioxide and the global carbon budget**. Science, 206,409-418.

Bolin, B. (1981) **Carbon cycle modelling**. SCOPE 16.

Early GFDL Ocean BGC and Coupled Carbon-Climate

Sarmiento, J L., J R Toggweiler, and R G Najjar, 1988: **Ocean carbon-cycle dynamics and atmospheric pCO2**. Philosophical Transactions of the Royal Society of London, A, 325, 3-21.

Toggweiler, J R., K W Dixon, and W Broecker, 1991: **The Peru upwelling and the ventilation of the South Pacific thermocline**. Journal of Geophysical Research, 96(C11), 20,467-20,497.

Najjar, R G., J L Sarmiento, and J R Toggweiler, 1992: **Downward transport and fate of organic matter in the ocean: Simulations with a general circulation model.** Global Biogeochemical Cycles, 6(1), 45-76.

Sarmiento, J L., R D Slater, M J Fasham, H W Ducklow, J R Toggweiler, and G T Evans, 1993: **A seasonal three-dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone.** Global Biogeochemical Cycles, 7(2), 417-450.

Toggweiler, J R., and S Carson, 1995: **What are upwelling systems contributing to the ocean's carbon and nutrient budgets?** In Upwelling in the Ocean: Modern Processes and Ancient Records, Chichester, UK, John Wiley & Sons, 337-360.

Sarmiento, J L., T M C Hughes, R J Stouffer, and S Manabe, 1998: **Simulated response of the ocean carbon cycle to anthropogenic climate warming**. Nature, 393(6682), 245-249.

Carbon Sensitivity to Climate with Sarmiento

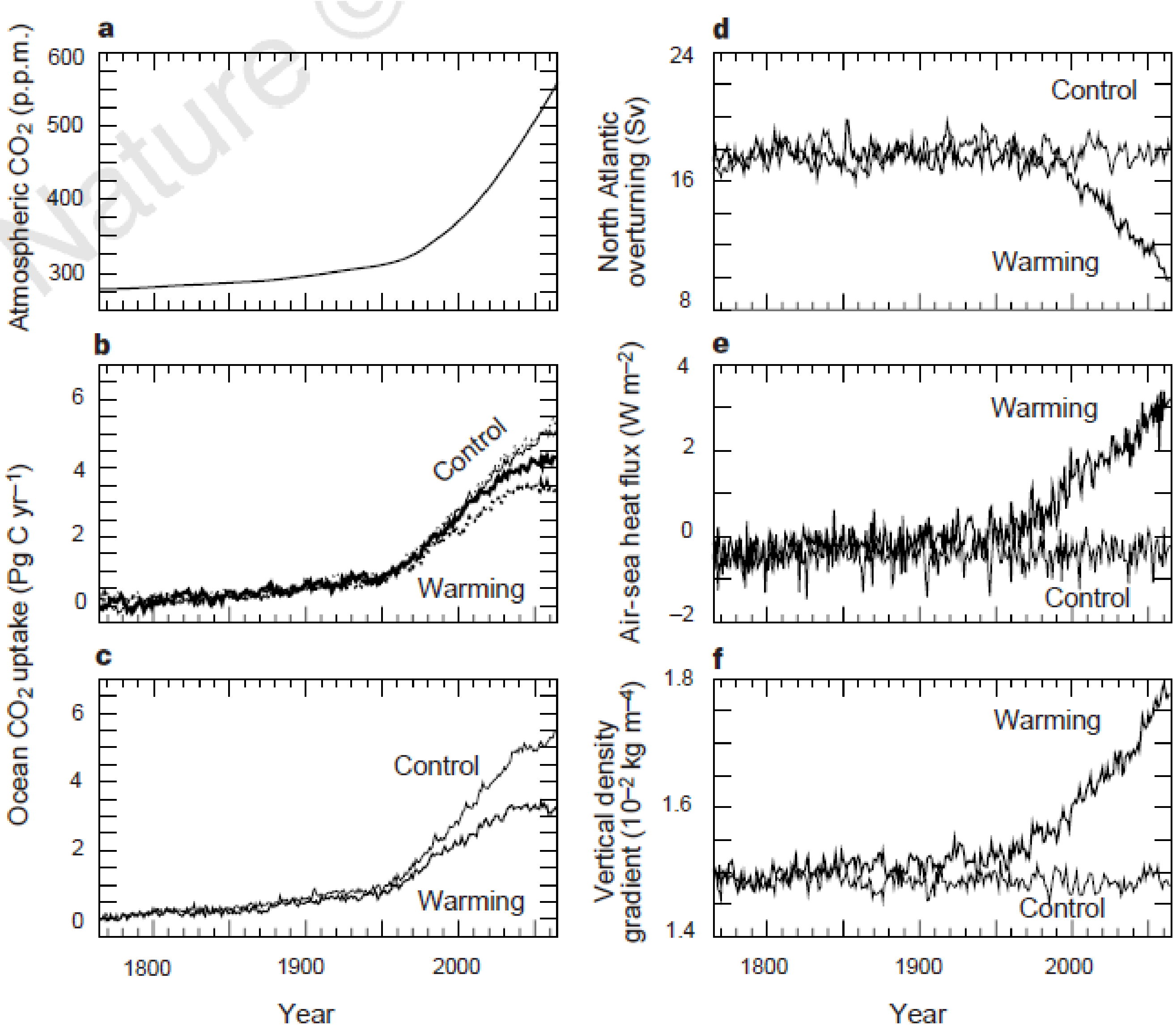


Figure 1 Time series of model boundary conditions and predictions. **a**, Atmospheric CO_2 based on observations before 1990 and the IPCC IS92a model[23] thereafter. **b**, Annual ocean uptake of carbon by the biology model. Four simulations are shown: the constant-biota control model (thin solid line), the constant-biota GW model (thick solid line), the constant-phosphate control model (thin dotted line) and the constant-phosphate GW model (thick dotted line). **c**, Annual ocean uptake of carbon by the 'solubility' model. **d**, Maximum value of overturning in the thermohaline cell of the North Atlantic in units of Sverdrups (1 Sv = 10^6 m^3 s^{-1}). **e**, Global mean of the air–sea heat flux. **f**, Global mean vertical density gradient at the base of the first layer of the model (50.9 m) for latitudes polewards of 30° in both hemispheres.

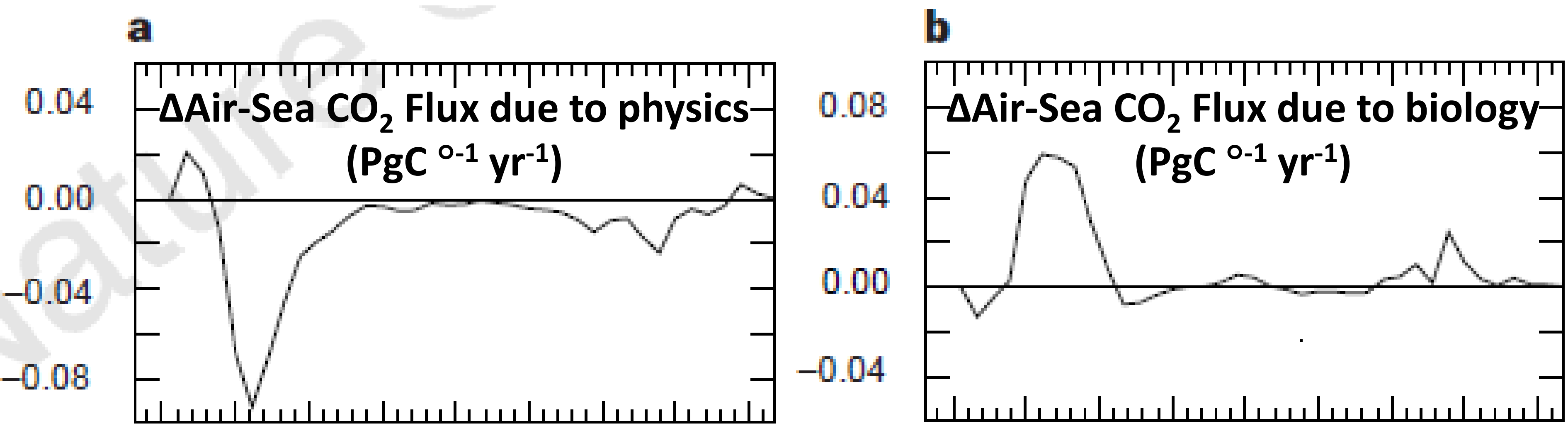
Simulated response of the ocean carbon cycle to anthropogenic climate warming

Jorge L. Sarmiento*, Tertia M. C. Hughes*, Ronald J. Stouffer† & Syukuro Manabe†‡

Carbon Sensitivity to Climate with Sarmiento

Table 1 Oceanic uptake of anthropogenic CO_2 in constant-biota model

	Cumulative uptake (Pg C)	
	1765–1990	1990–2065
A. Constant-biota baseline	112	289
B. Change due to variation in transport processes in absence of biological pump*	−5	−63
C. Change due to warming in absence of biological pump†	−23	−33
D. Change due to biological pump‡	+39	+69
E. Global warming constant-biota model	123	262



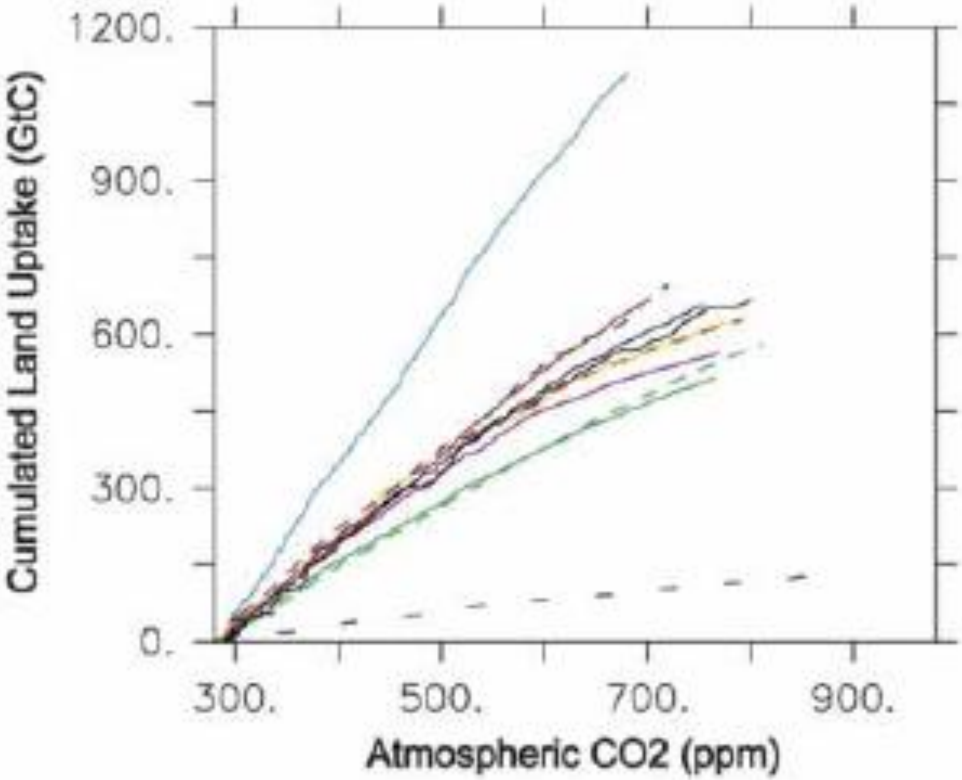
Sarmiento, J. L., T. Hughes, R. J. Stouffer, and S. Manabe (Nature, 1998)

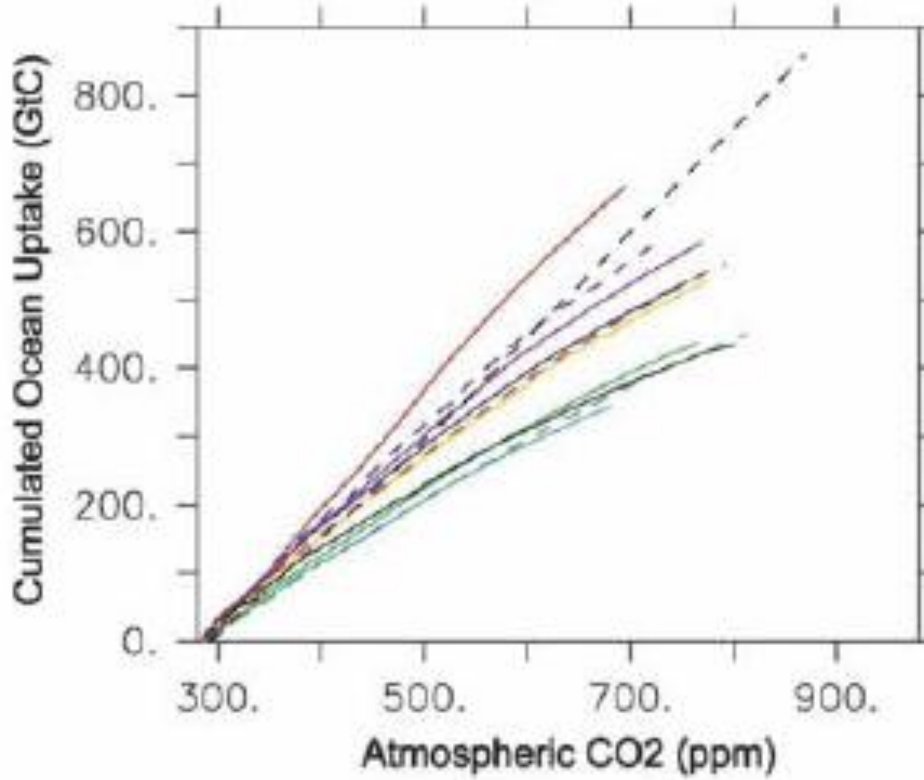
…Meanwhile, other groups were building coupled carbon-climate models, e.g.:

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A., & Totterdell, I. J. (2000). Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature, 408(6809), 184-187.

… and GFDL struggled to define how to contribute.

Coupled Carbon Cycle Climate Model Inter-comparison (C^4MIP) Project showed large uncertainties in land and ocean uptake under SRES-A2

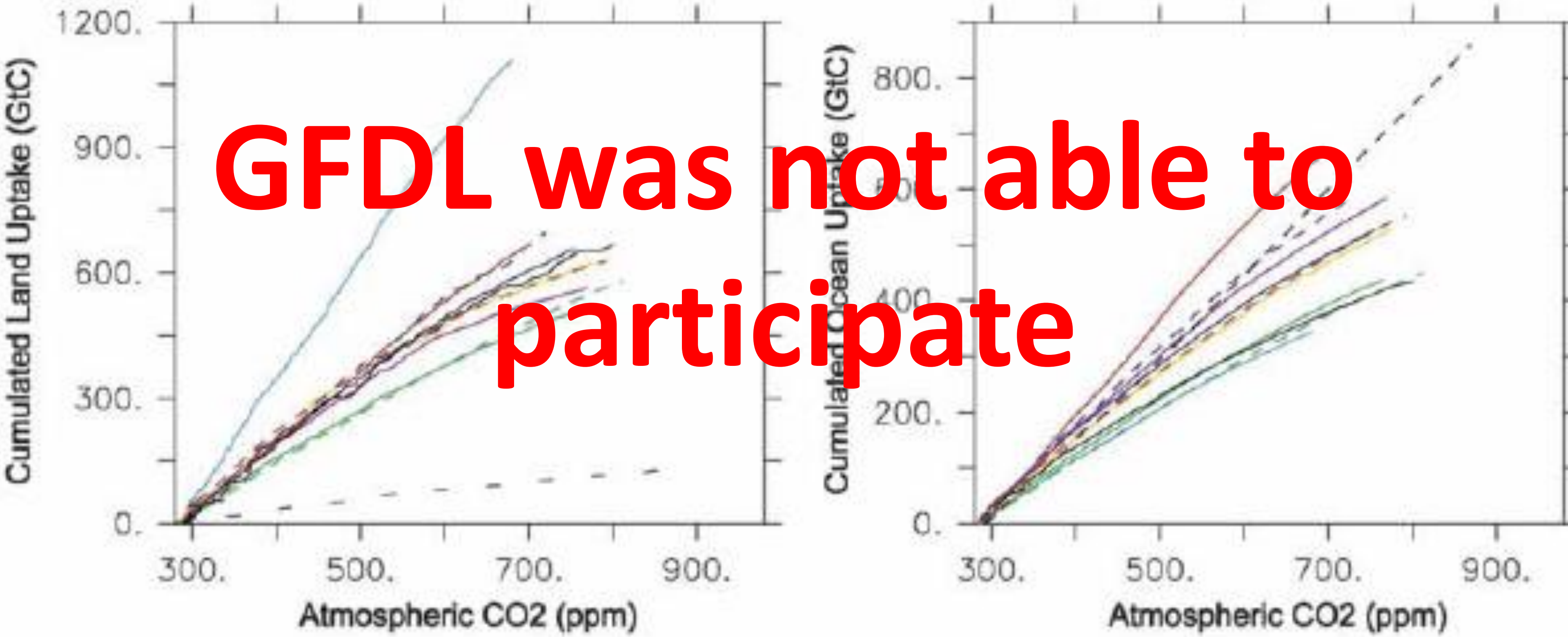




- 200-400 PgC (100-200 ppm CO_2) feedbacks in both land and ocean
- Coarse/simple climate models
- Rudimentary ecosystem models

Source: Friedlingstein et al. (2006; J. Climate)

Coupled Carbon Cycle Climate Model Inter-comparison (C^4MIP) Project showed large uncertainties in land and ocean uptake under SRES-A2



- $\bullet$200-400 PgC (100-200 ppm CO_2) feedbacks in both land and ocean
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Source: Friedlingstein et al. (2006; J. Climate)

Creation of GFDL’s ESMDT (04/22/2004)

Recommendations of the Earth System Modeling Task Force

Challenge: How can we produce a decadal-centennial scale Earth System Model for GFDL?

Gross

Stouffer

Gnanadesikan

Dunne

Shevliakova

Levy

Creation of GFDL's ESMDT (04/22/2004)

Status of Component Models

Climate Model

- ESM2 (1000 yrs in 500 days; 180pe; 130K cpu·hrs/mo)
  - Currently minimally acceptable for Dec-Cen
  - Intensive efforts to improve both speed and realism
- ESM1p5 (1000 yrs in 120 days; 40pe; 29K cpu·hrs/mo)
  - Unacceptable for Dec-Cen
  - No support for development

Dynamic Land Biogeochemistry Model

- Preliminary LM3vp1-AM2p12 runs (code and FRE in 2 mo)
- Coupled Carbon code is in testing
- Continuing development on N45 grid

Prognostic Ocean Biogeochemistry Model

- Prototype available in FRE
- Coupled version in a matter of weeks
- Continuing development on OM1p5 grid

Atmospheric Transport Model – prototype available

Component Integration Steps

- Code to pass CO_2 between model components is ongoing
- Propose to develop individual components:
  - Land dynamics and BGC at N45 resolution in stand-alone, AM2 and CM2 (within LMDT in collaboration with AMDT and CMDT)
  - Ocean BGC in OMIP configurations
- Propose to develop ESM through:
  - Including ESM components in Khartoum city release
  - Developing prototype ESM1p5
  - Incorporating ESM into Regression Test Suite as soon as components are ready for long spin-up
  - Switching resolution to ESM2p1 if/when available

Example Spin-up Strategy

- CO_2 roles: Atm. tracer, land/ocean BGC, radiative forcing
- Reminder: Carbon inventory adjusts to climate
- Spin-up Goal: find CO_2 in equilibrium with climate
- Challenge: fickle models and climate

Land BGC spin-up with atm clim. or active atm $O(10^2)$y

Ocean BGC spin-up with active ocean $O(10^3)$y

$CO_{2Tracer}$=prog CO_{2BGC}=280 CO_{2Rad}=280	$CO_{2Tracer}$=prog CO_{2BGC}=prog CO_{2Rad}=280	$CO_{2Tracer}$=prog CO_{2BGC}=prog CO_{2Rad}=prog
coupled phys. Lnd/Ocn BGC adjustment	coupled phys. Lnd/Ocn/Atm BGC adjustment	coupled phys. fully coupled carbon-climate
100 yr	100 yr	~600 yr

…for a mimimum 1800 yr integration in ESM1p5 taking 4 months

Roles of collaborators

Sarmiento Lab. (AOS) - Contributed ocean tracer infrastructure, C system components, preliminary prognostic BGC code and plans to evaluate and apply ESM for C cycle studies.

Pacala Lab. (EEB) - Implemented LM3v and are evaluating biophysical feedbacks, vegetation dynamics and terrestrial carbon cycle

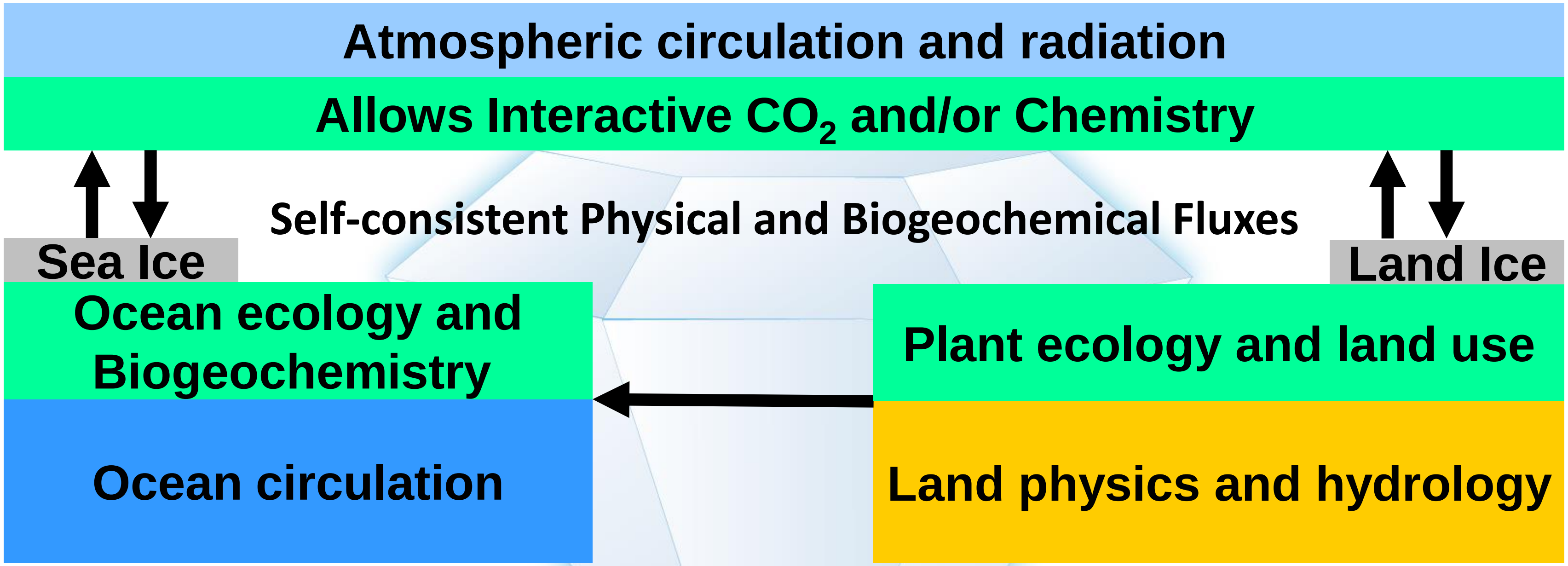
UNH - Contributed historical land use forcing and may contribute C and N river transport and water management models

Hedin Lab. (EEB; with Pacala Lab) - Plans to develop land N model

USGS - Plans to evaluate hydrology in ESM

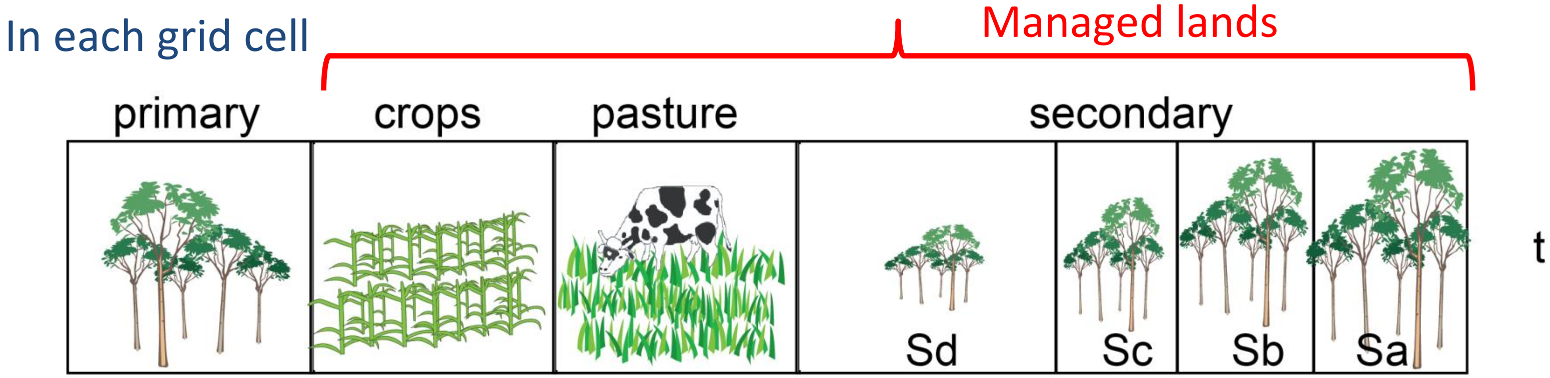
Wood Lab. (CEE) - Plans to contribute to evaluation of LM3 hydrology

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 use and surface heterogeneity

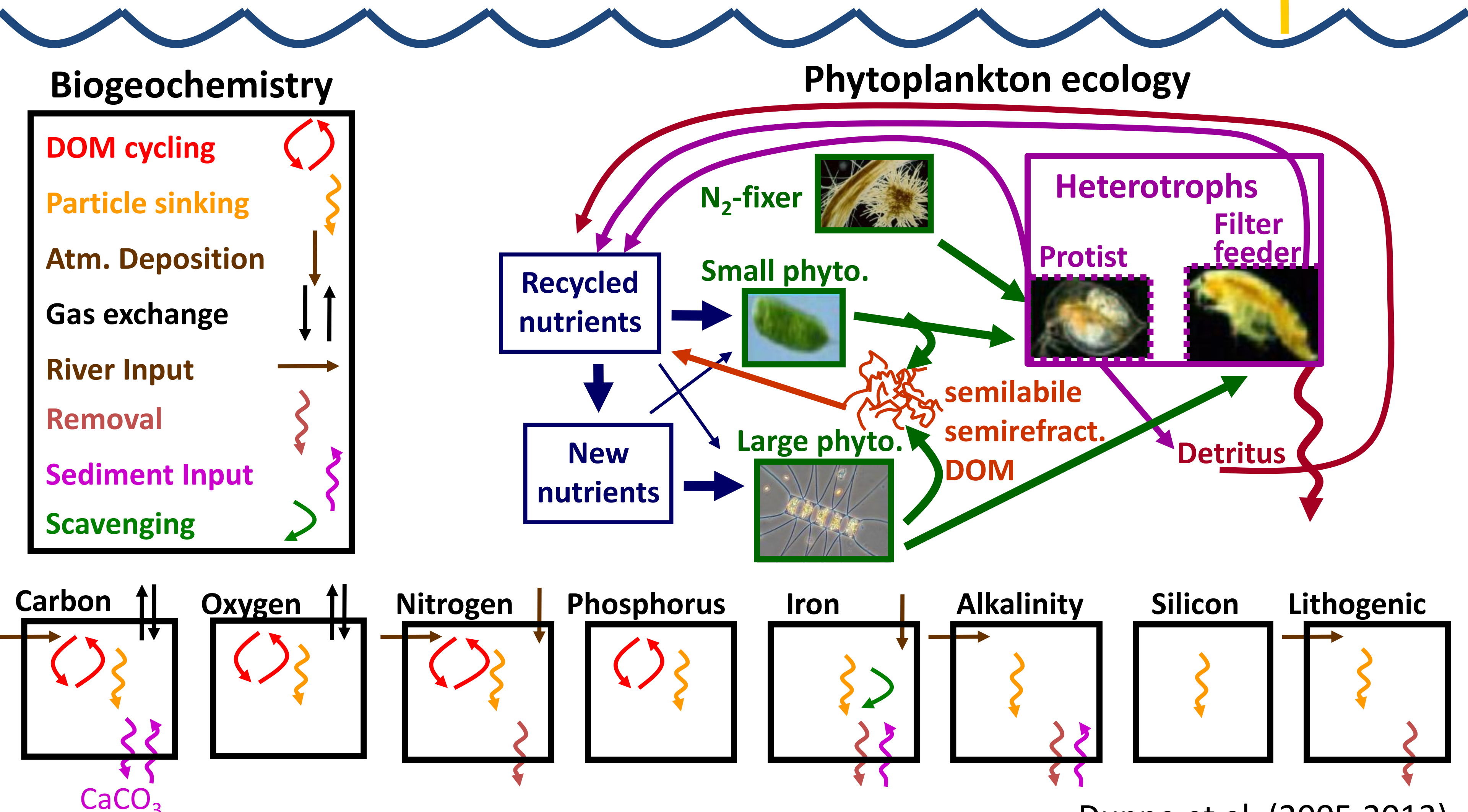


- CMIP5 scenarios of land use change (Hurtt et al 2011)
- Unique features of GFDL land model:
  - wood harvesting of primary *and* secondary forests
  - secondary forests re-growth and shifting cultivation
  - explicit treatment of above and below ground physical and biogeochemical states for LU categories
  - vegetation and soil fluxes as well as harvests for all land use types
  - for LM4: improving croplands phenology and diversity
  - Management: fertilizer seasonality, products management

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

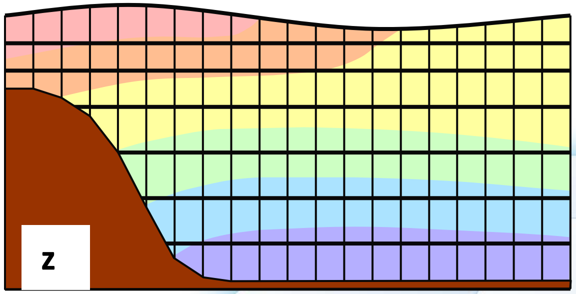
30 Tracers



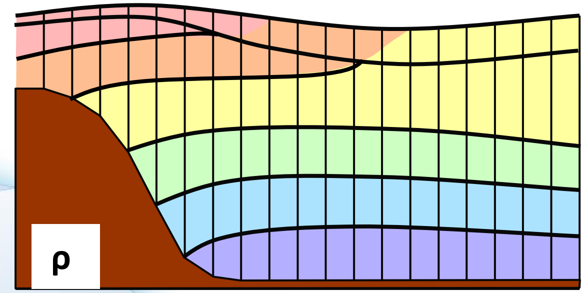
Dunne et al. (2005;2013)

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

z* (MOM4.1):

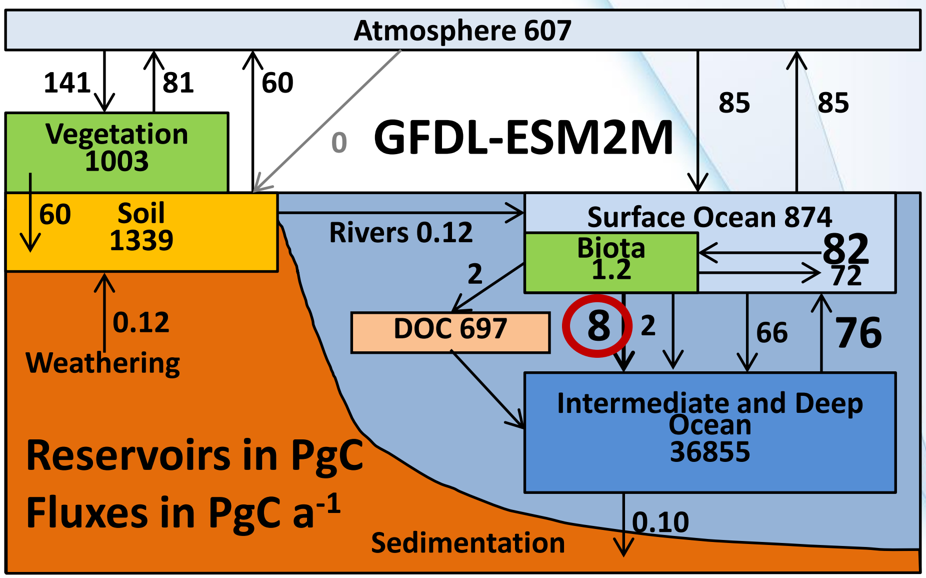


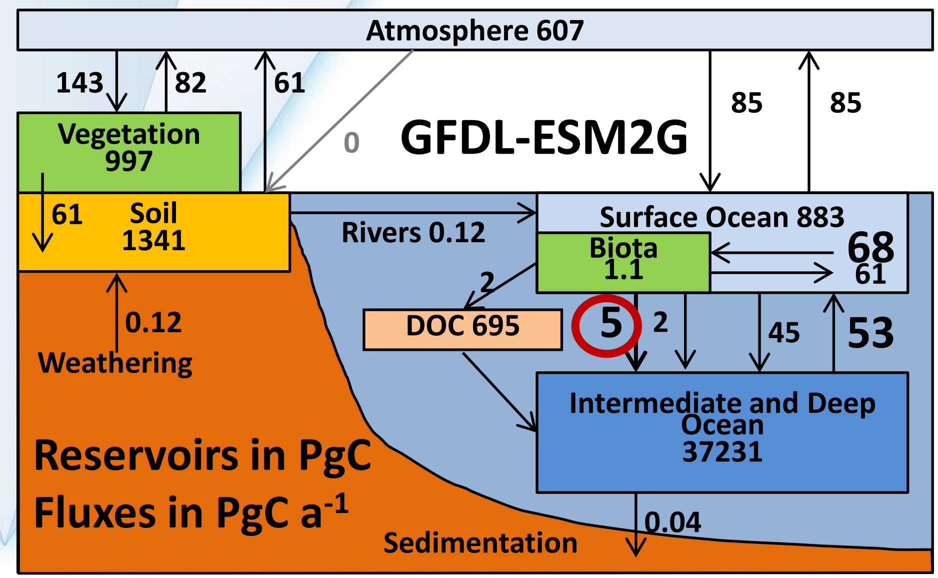
ρ (GOLD):



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

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

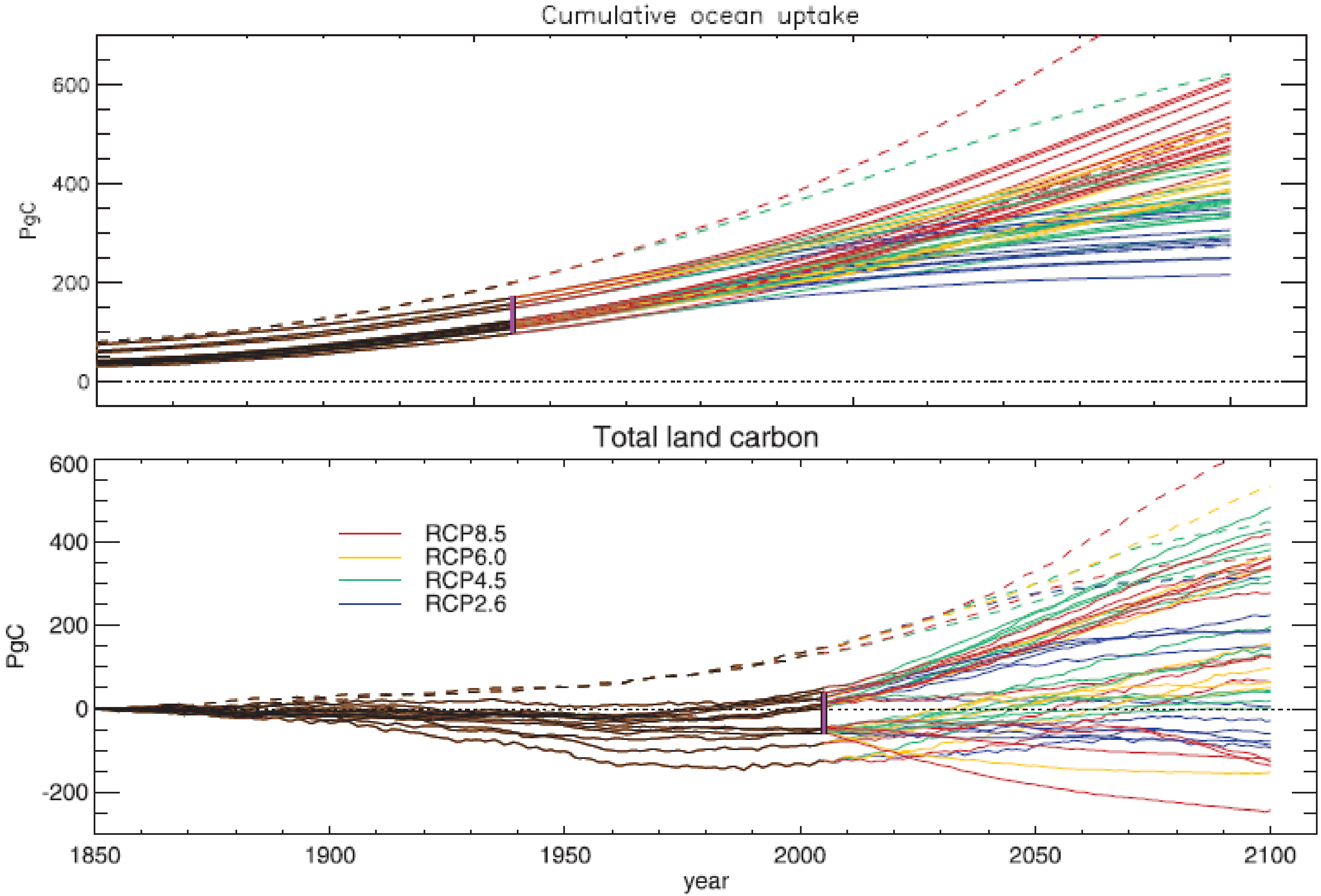




Dunne et al. (2012, 2013); Winton et al. (2013); Hallberg et al. (2013)

Twenty-First-Century Compatible CO_2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways

CHRIS JONES,[a] EDDY ROBERTSON,[a] VIVEK ARORA,[b] PIERRE FRIEDLINGSTEIN,[c] ELENA SHEVLIAKOVA,[d] LAURENT BOPP,[e] VICTOR BROVKIN,[f] TOMOHIRO HAJIMA,[g] ETSUSHI KATO,[h] MICHIO KAWAMIYA,[g] SPENCER LIDDICOAT,[a] KEITH LINDSAY,[i] CHRISTIAN H. REICK,[f] CAROLINE ROELANDT,[j] JOACHIM SEGSCHNEIDER,[f] AND JERRY TJIPUTRA[j]



Scenario Uncertainty Dominance

Structural Uncertainty Dominance

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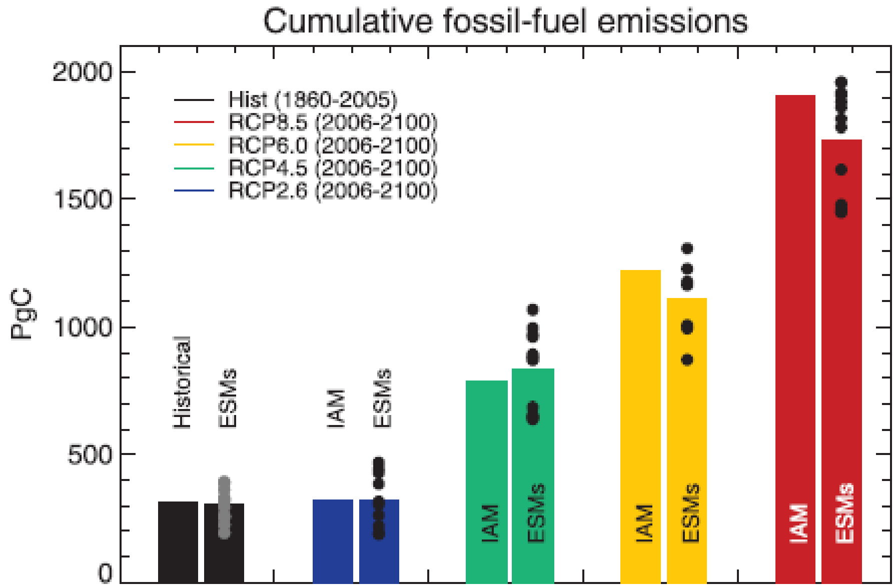
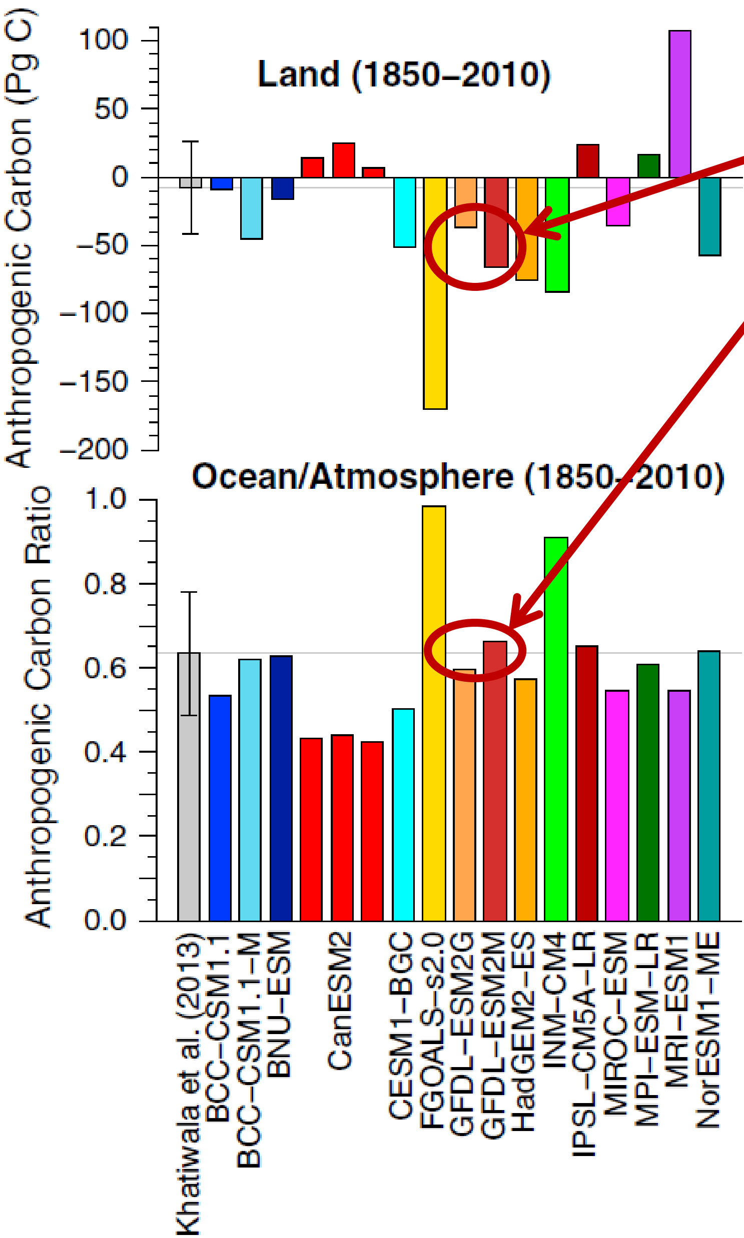


FIG. 5. Compatible fossil-fuel emissions from CMIP5 models for the historical period (black) and the four RCP scenarios for the twenty-first century (colors). (top) Time series of annual emissions: the thick solid lines denote the multimodel mean and the thick dashed lines the historical and RCP scenarios. Individual model estimates are shown in the thin lines. (bottom) Cumulative emissions for historical (1850–2005) and twenty-first century (2006–2100). The left-hand bars in each pair show the cumulative emissions from the historical reconstruction or from the RCP scenario as generated by IAM models, and the right-hand bars the CMIP5 multimodel mean. Black/gray circles show individual model values.

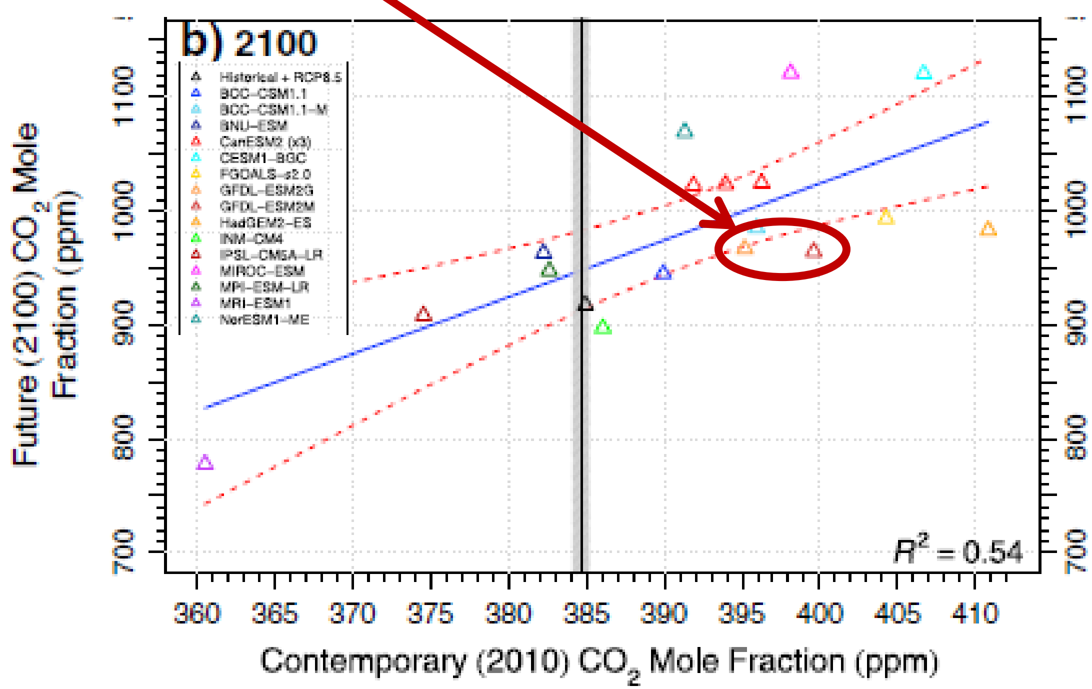
Overall good agreement between IAMs and ESMs in Compatible CO_2 Emissions for each Scenario

GFDL ESMs Key CMIP5 Contribution

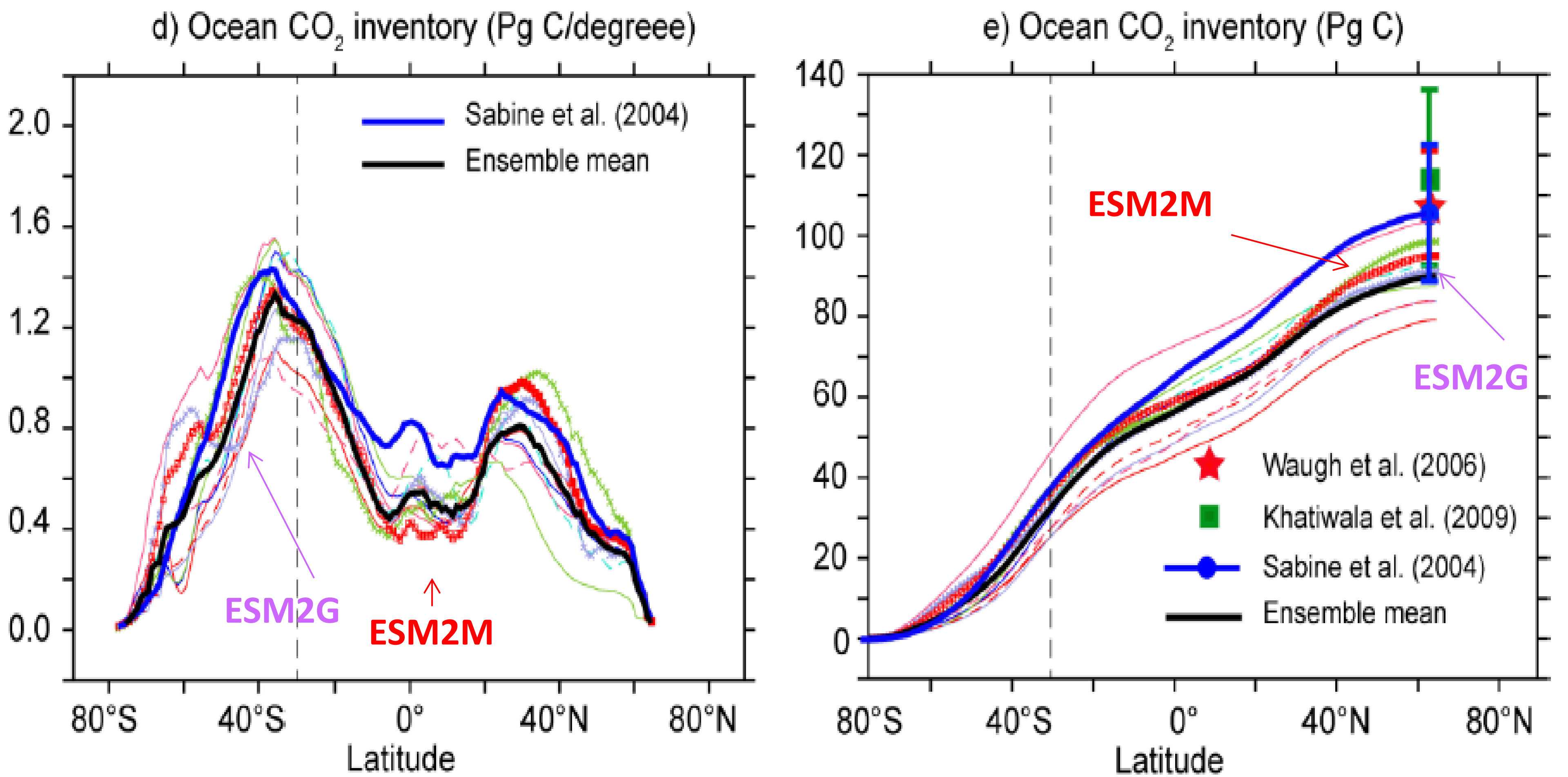


Hoffman et al., 2014

- 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.

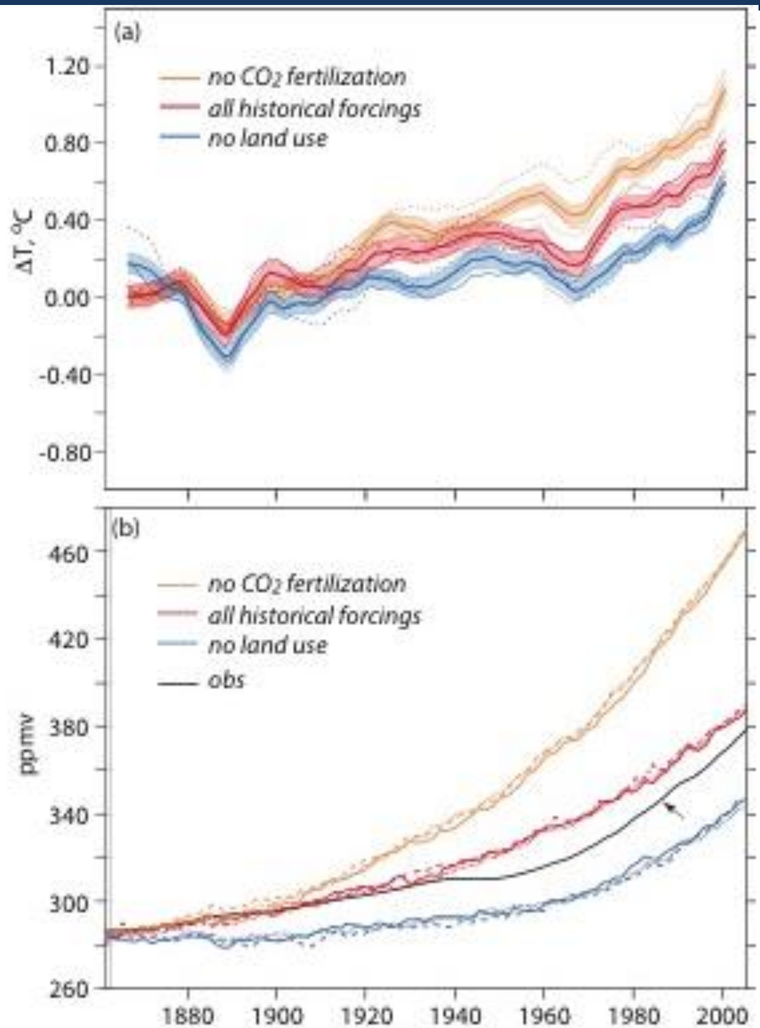


GFDL ESMs key CMIP5 Contribution

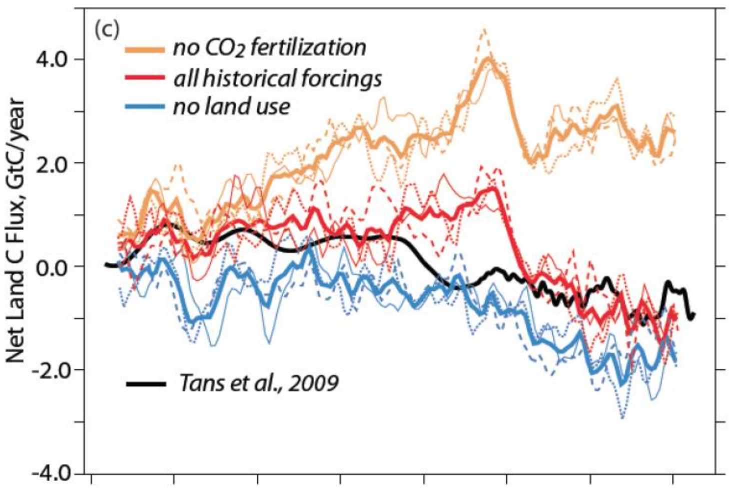


Frölicher, T., J. Sarmiento, J. Dunne, D. Paynter, M. Winton, 2015: Heat and carbon uptake in the CMIP5 models: The dominance of the Southern Ocean, J. Climate, DOI:10.1175/JCLI-D-14-00353.1..

LULCC affects atmospheric CO_2 and thus climate

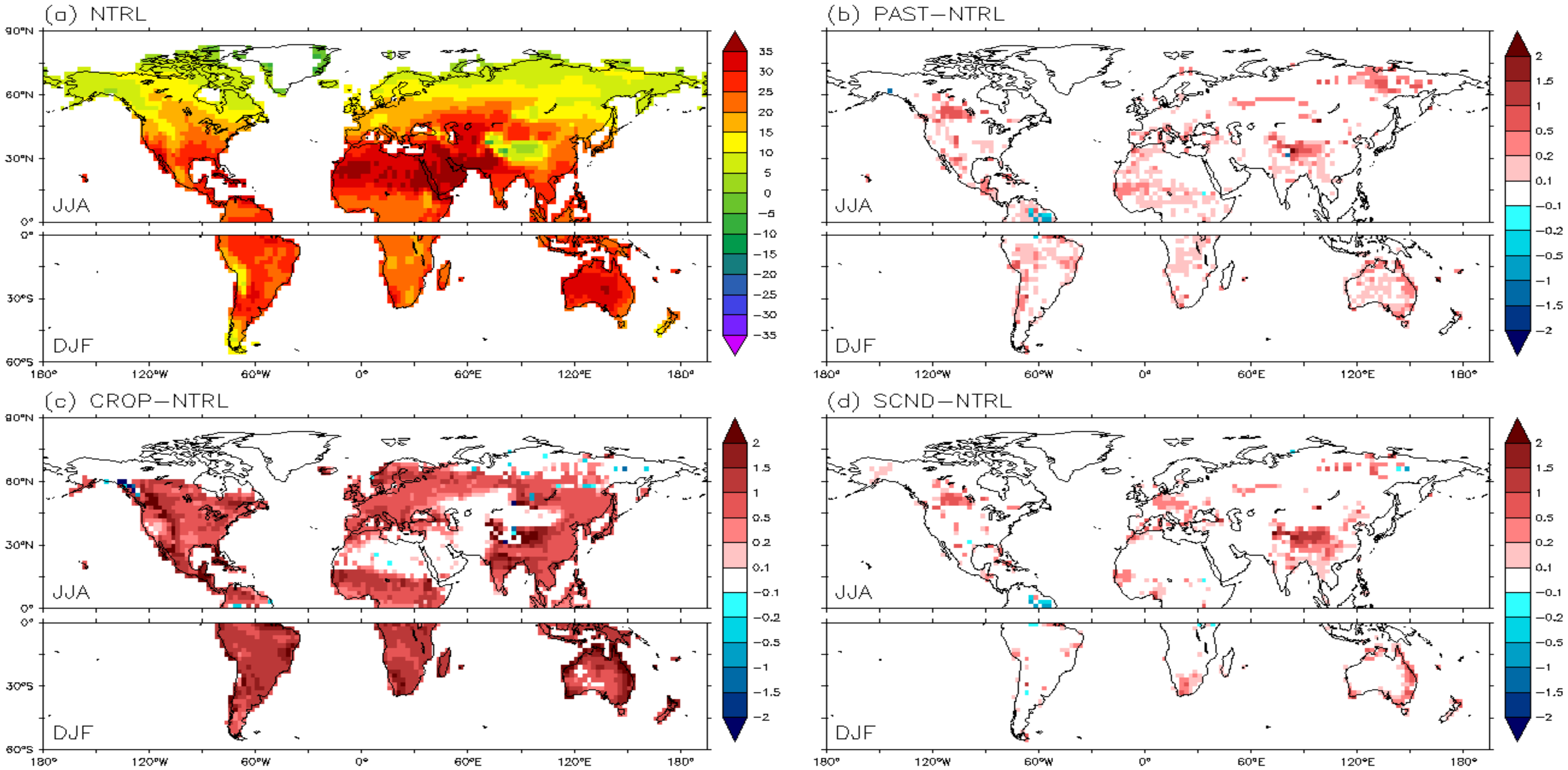


- Land-use (in blue) emissions contributed ~30 ppm to the 2005 atmospheric CO_2 increase ;
- Without land use over historical period
  - global surface temperature would be 0.16±0.06°C lower (similar to other ESMs) ;
  - Land would be a sink of C;
- Larger LU source requires a larger enhanced sink



Simulations with NOAA/GFDL FF-emissions forced ESM2G model, Shevliakova et al. 2013

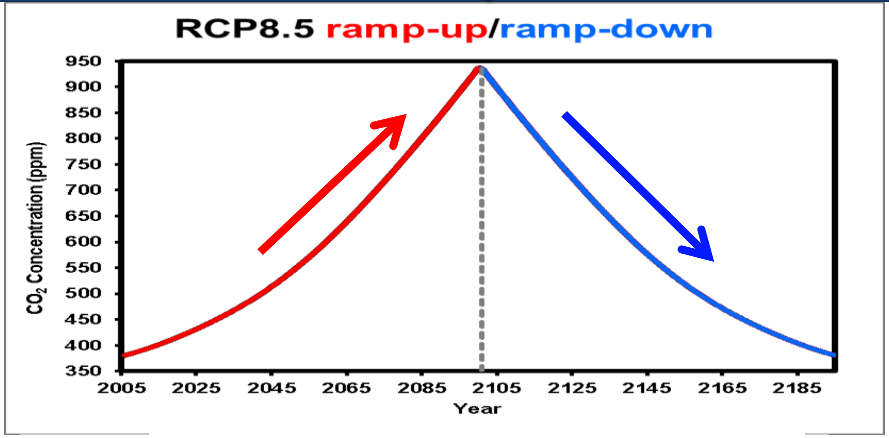
Difference in summer climate from LU



1986-2005, surface air temperature

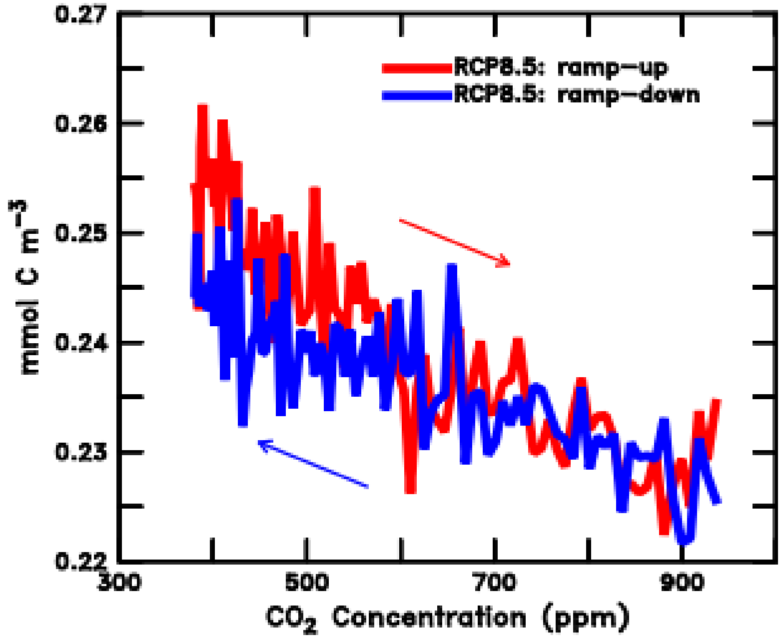
Malyshev et al 2015

Global reversibility of Community Composition (John et al., GRL, 2015)

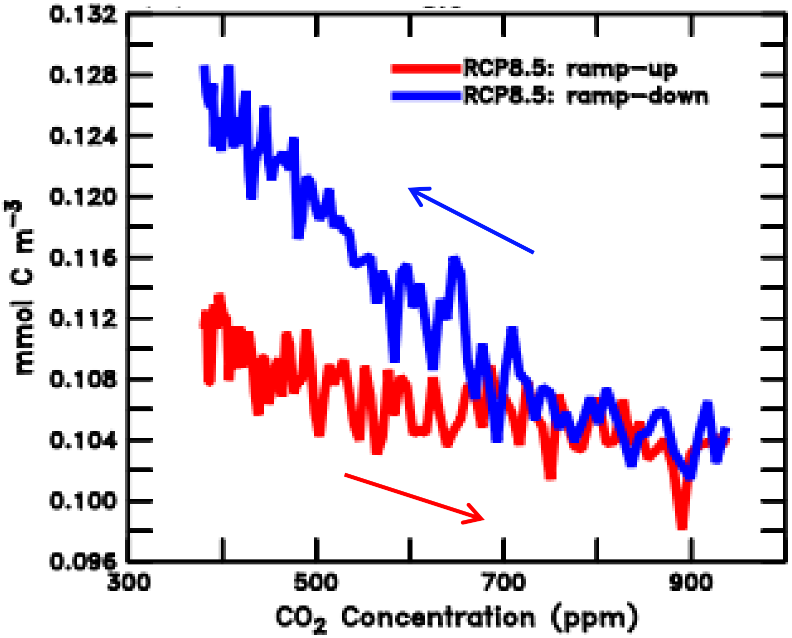


Scenario:
Ramp-up/Ramp-down
RCP8.5 2006-2100 (Riahi et al., 2007), followed by reversal of RCP8.5 from 2101-2195.

Surface large diatoms

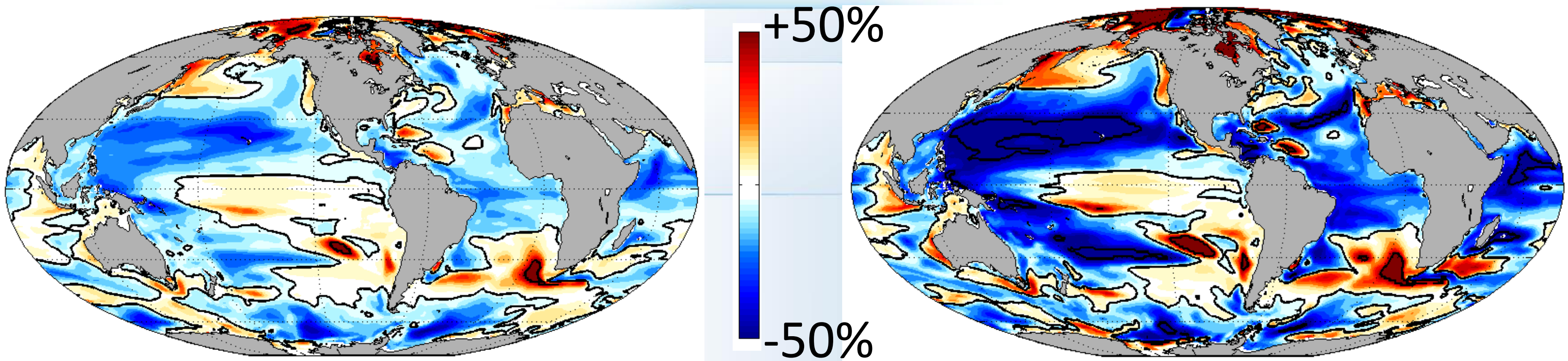


Surface large non-diatoms



Amplification of ocean productivity changes

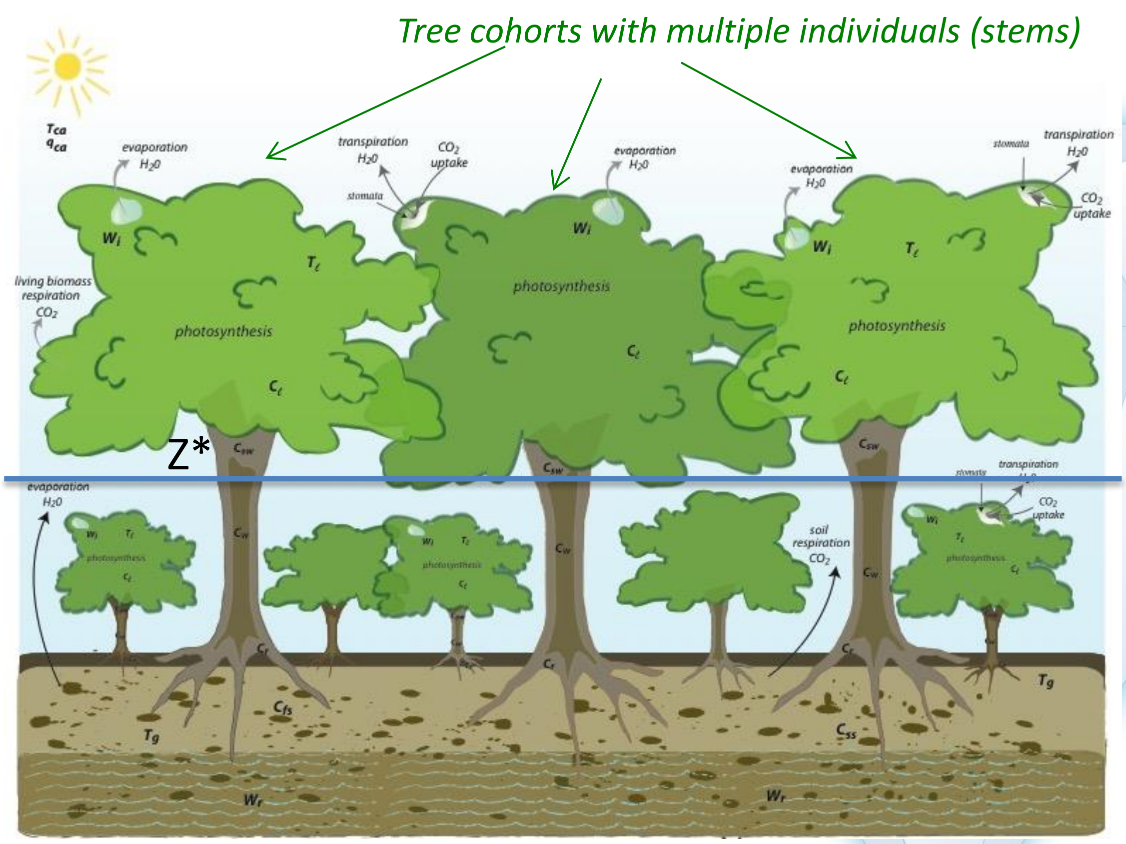
% change, primary prod | % change, mesozoo prod



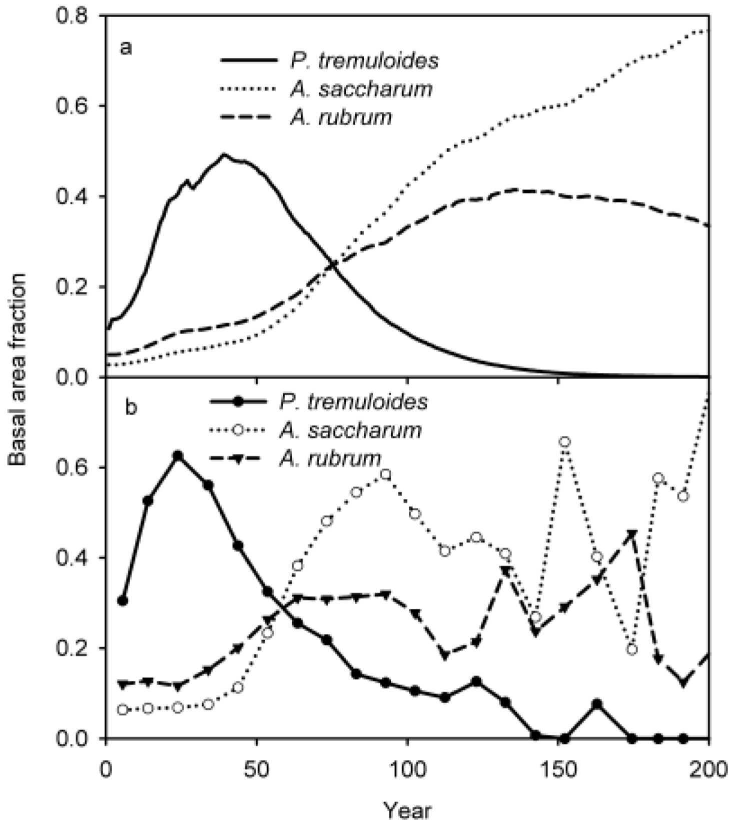
- Projected percent changes in mesozooplankton productivity are 2X primary productivity changes
- Large regional changes
- Quantitative attribution to the same planktonic food web characteristics that drive spatial gradients

Stock, C.A., J. P. Dunne, and J.G. John, submitted: *Understanding trophic amplification of ocean productivity trends in a changing climate.*

Perfect Plasticity Approximation (PPA) Vegetation Dynamics



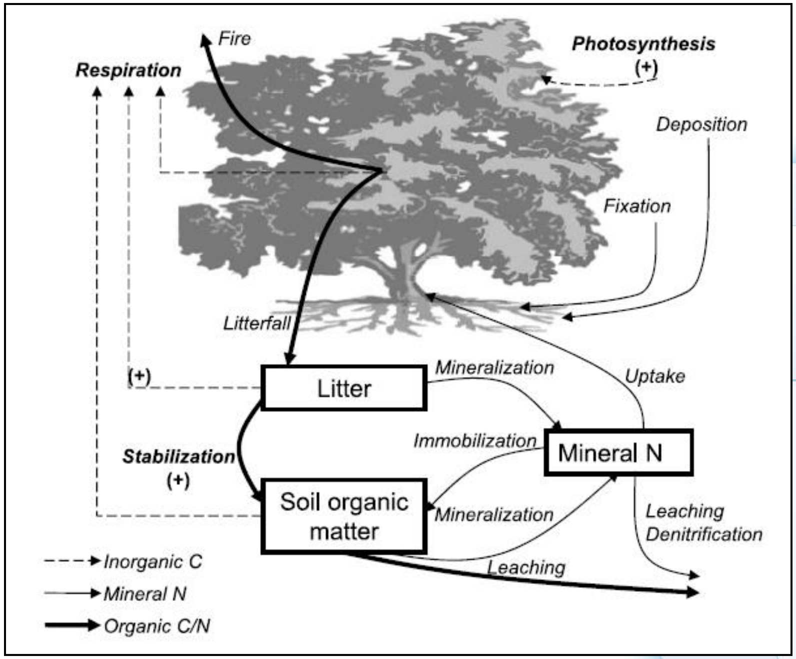
Willow Creek, WI

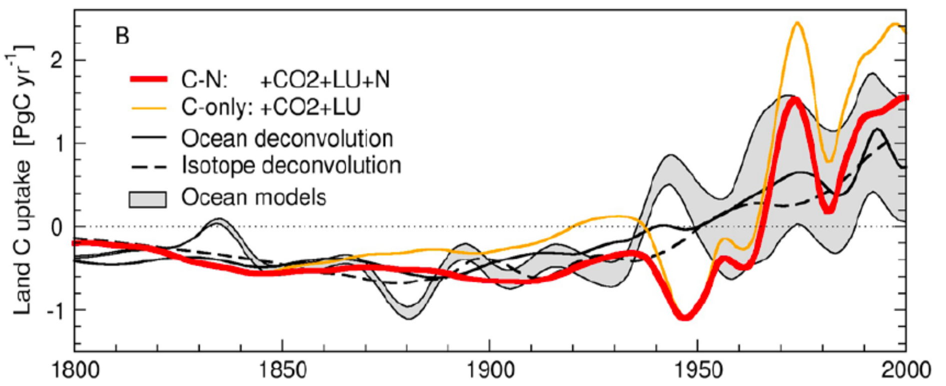


Weng et al. , 2015
Strigul et al. 2008

- *Challenges for global PPA*
  - *capturing plant diversity*
  - *phenology and mortality*
  - *evaluating succession*

Nitrogen Biogeochemistry

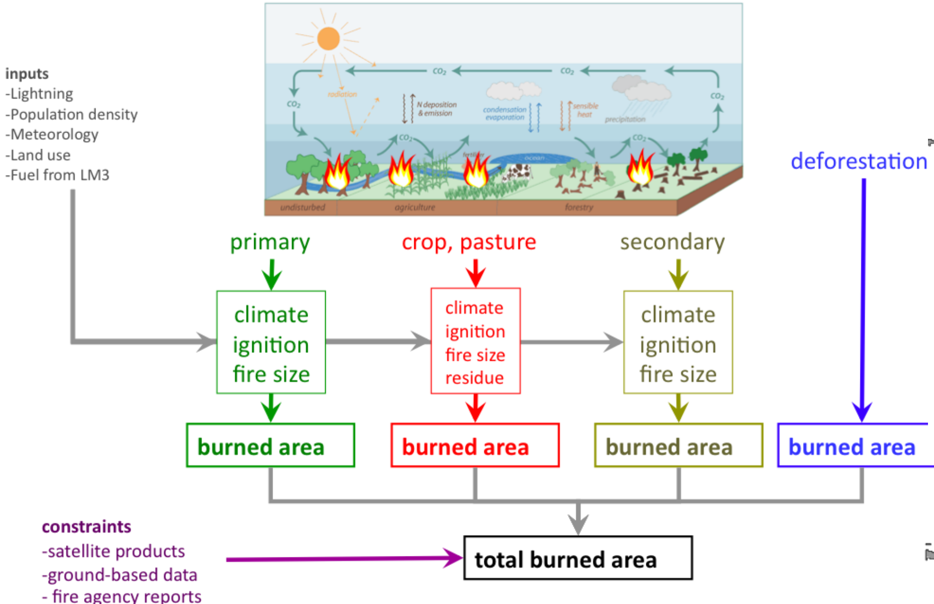




Gerber et al. 2010, 2013; Lee 2014

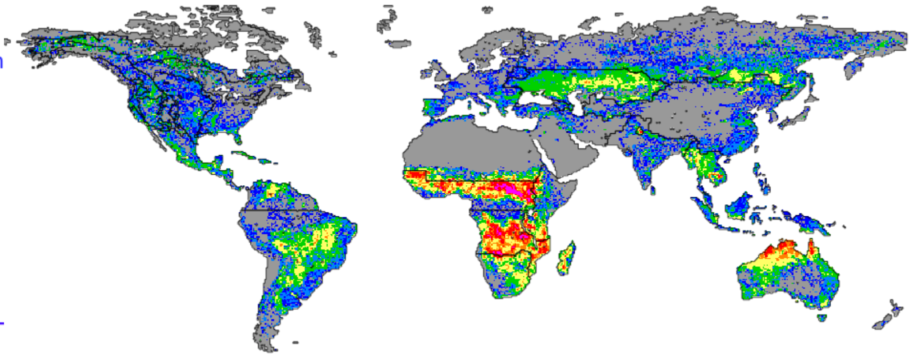
- Fixed C:N vegetation pools
- Prognostic biological N fixation
- 4 competing sinks of mineral N
  - plant uptake, immobilization, sorption to particles, denitrification
- Organic removal of N
  - leaching, ecosystem losses through fire
- Riverine N Biogeochemistry
  -

Fire - Land Use Interactions

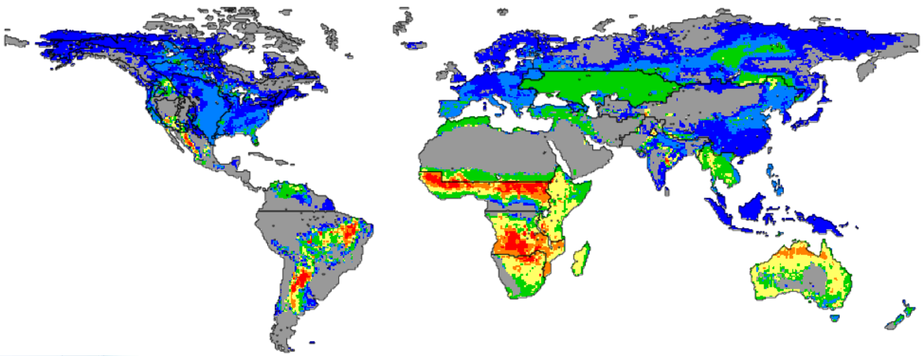


FIRE model parameters are statistically estimated

Observed area burned, 2003-2008



Estimated area burned, 2003-2008

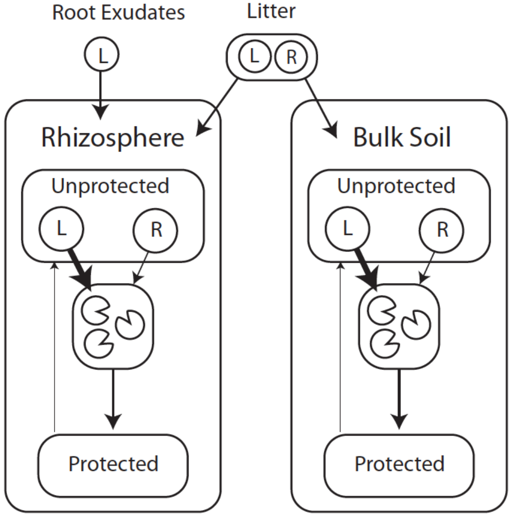


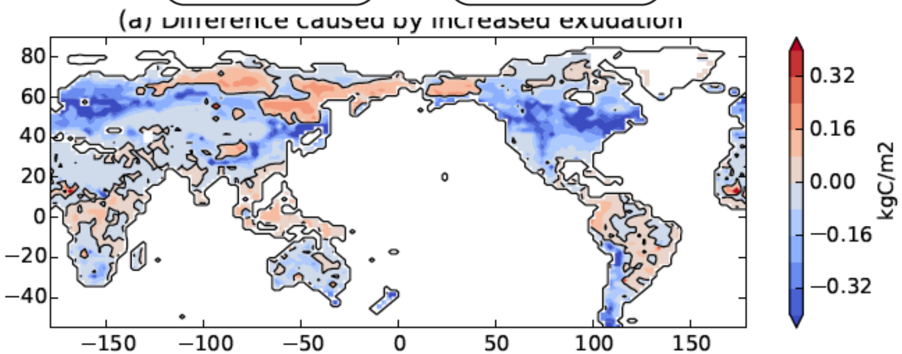
Rabin et al. in prep

Land-use specific fire models =>
LU-specific datasets to estimate these parameters , *Magi et al 2011*

New daily fire model to enable prognostic biomass burning aerosols in CM4/ESM4

Soil Microbial Dynamics: BGC LM3-CORPSE





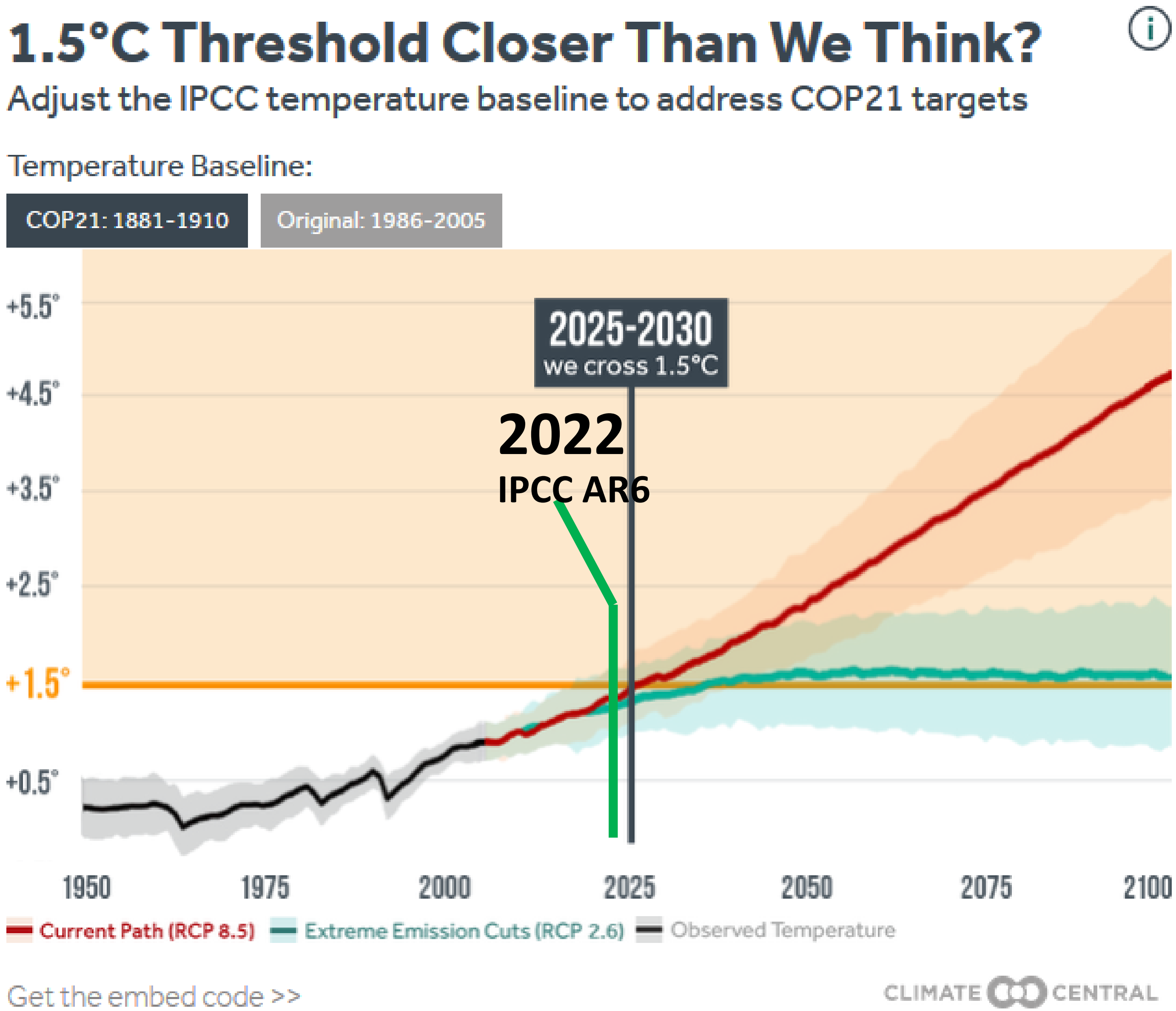
Sulman et al., 2015

Carbon, Organisms, Respiration, and Protection in the Soil Environment (LM3-CORPSE) model

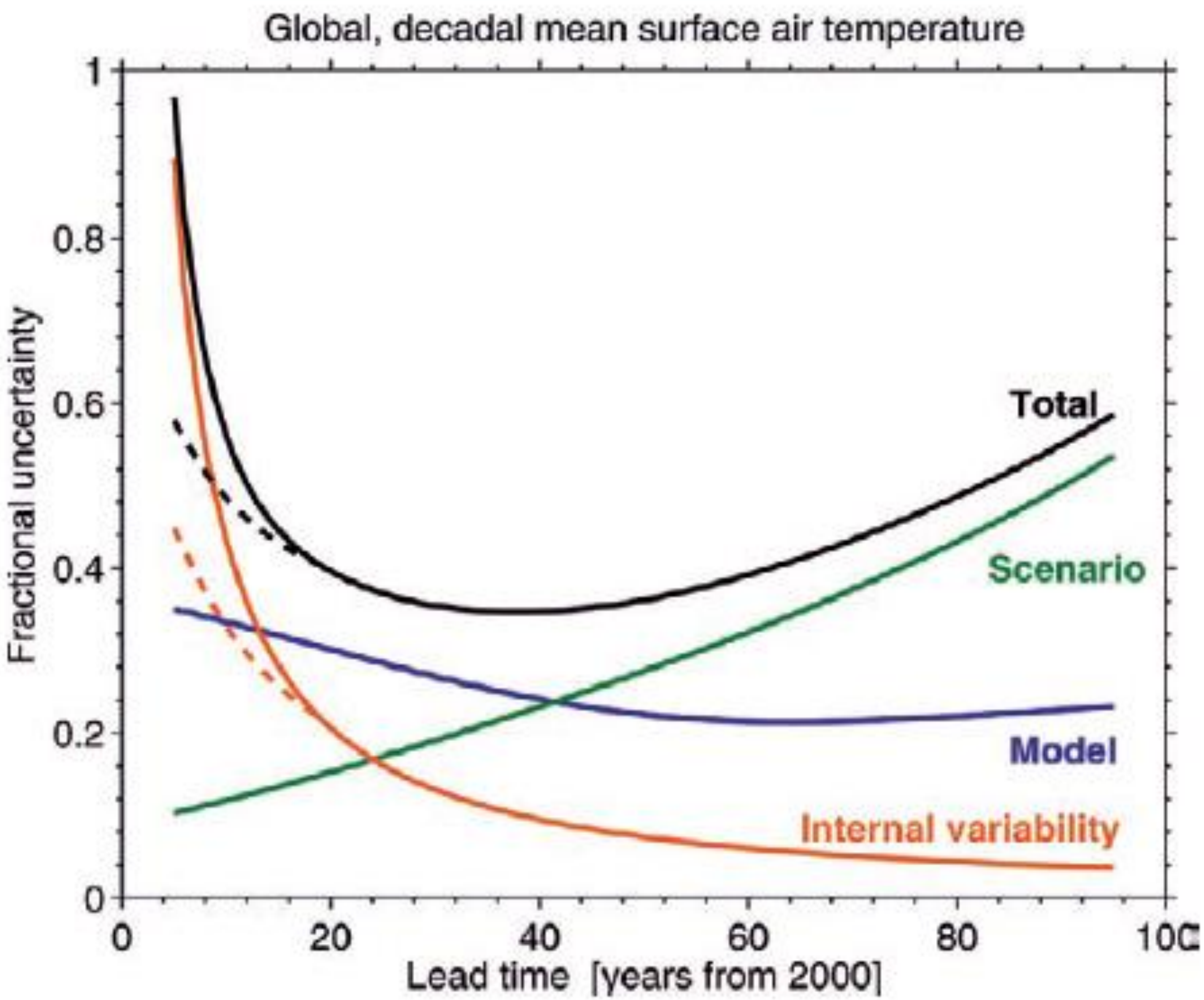
- Vertical structure
- Explicit above and below ground litter
- DOC leaching
- Dynamic microbial activity
- Protected carbon pools
- Root exudates
- Implemented in water-tiled version (LM3-TiHy)
- *Currently adding N*
- *P is next*

Key uncertainty: the sensitivity of soil Carbon to changing climate

Carbon Cycle Research After IPCC AR6



Partitioning Climate Change Uncertainty into its Structural, Scenario and Internal Components



Hawkins and Sutton, 2009, BAMS

Carbon Cycle Research After IPCC AR6

If the COP21 momentum continues to drive policy, the climate modeling community will shift projections from change under future warming to ongoing equilibrium to current climate.

With the 1.5C threshold met and 2C threshold approaching, the focus on scenarios should narrow towards net emissions near zero – "Climate Change" research will become "Climate sustainability" research"

Carbon Cycle research should transition from rudimentary structural description focused on scenario uncertainty towards Structural and Internal variability Uncertainty

Under 'sustainable' (net zero) emissions, climate services provided by land and ocean carbon cycles re-equilibrating to changed climate will largely determine allowable energy trajectories.

These challenges requiring more comprehensive Earth System Modeling include:

- **Blue Carbon – Identification of climate services of carbon storage in marine environments**
- **Comprehensive Biofuels and other land use**
- **Tipping Points like AMOC, biodiversity change, permafrost CO_2 and CH_4**
- **Detection and attribution of carbon change**
- **Climate carbon feedbacks and trajectories like the Southern Ocean, Soils, biogeochemistry**

Future GFDL Carbon Cycle Research

- **Application:** Multi-member ensembles for detection and attribution, centennial-millennial scales, idealized sensitivity, diverse impacts
- **Comprehensiveness:** Comprehensive and robust ecosystem, biogeochemistry and human interaction models and self consistent representation of aerosol, Fe, CH_4 and N cycles
- **Resolution:** Regional atmosphere-land interactions, the ocean mesoscale and boundaries, and the human and marine applications
- **Prediction:** Integration with seasonal-decadal climate effort, exploring opportunities for biogeochemistry predictability