GFDL's ESM2 Series simulations of coupled carbon, climate and ecosystems

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Outline

- Overview of GFDL's planned contributions to CMIP5
- Earth System Model (ESM) motivation and description
- Prototype ESM2.1 ocean carbon response to SRES forcing
- Overview of ESM2M/ESM2G climate and carbon cycling
- Sensitivity of ocean carbon cycle to ESM2M/ESM2G configuration

Overview of GFDL's planned contributions to CMIP5

Starting point: GFDL's CM2.1 contribution to CMIP3

- 2x2.5 degree finite volume atmosphere with 24 hybrid σ/pressure layers
- Atmosphere-land coupling every 30 minutes; atmosphere-ocean coupling every 2 hours
- 1 degree sea ice and Modular Ocean Model v4.0

The Four Streams:

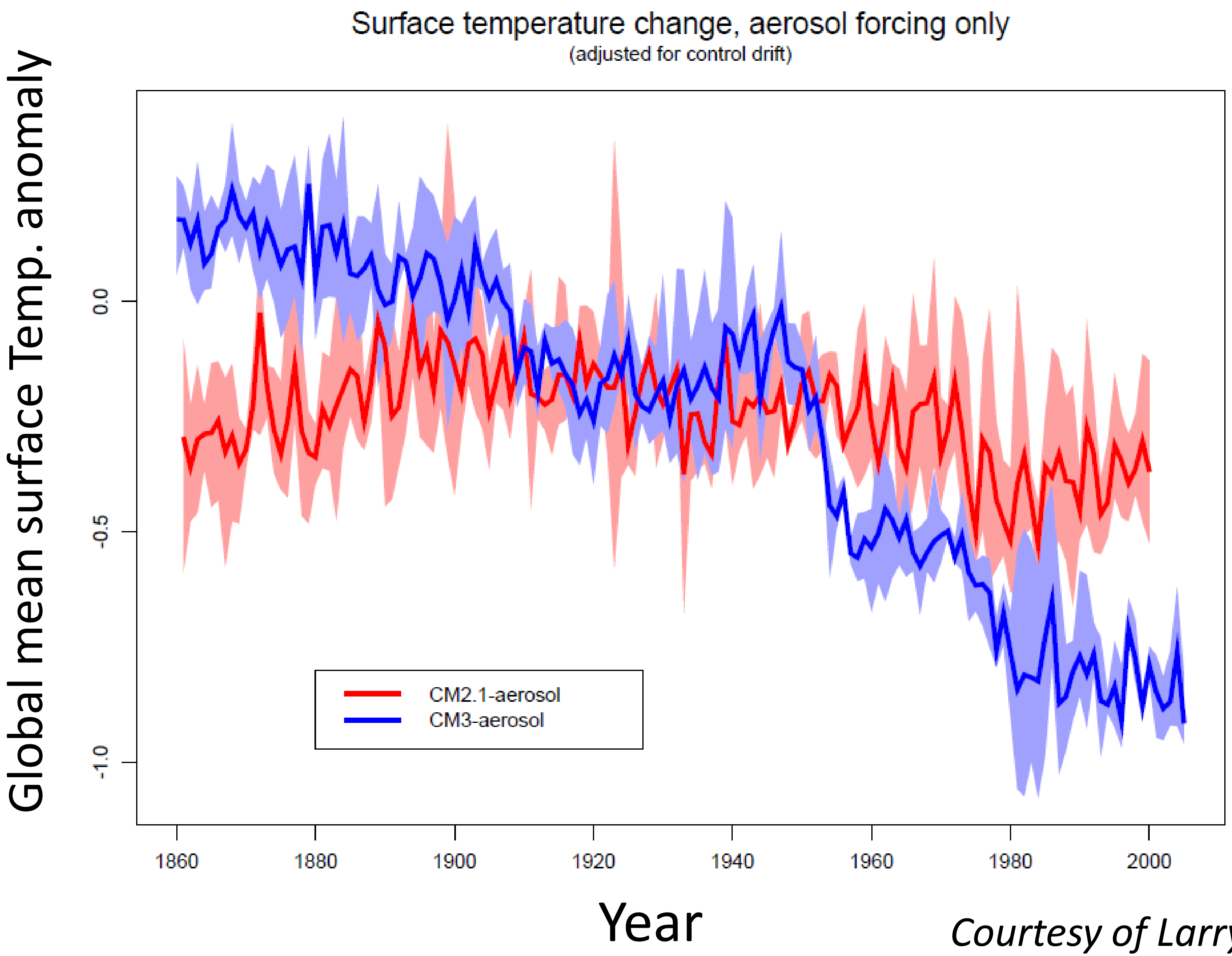
1. **Next Generation Coupled Climate Model (CM3):** new physics for aerosol/cloud interactions and chemistry-climate interactions; new land model; 48 layer cubed sphere

2. **Decadal Prediction Activities**: CM2.1 and coupled assimilation system to improve understanding of decadal climate variability and predictability including the relative roles of internal variability and forced change; moving toward higher resolution models

3. **High resolution atmospheric model downscaling:** HIRAM 50-km grid global atmospheric model, possibly 25-km grid model; More realistic tropical cyclone simulation and topographic forcing for present climate

4. **Earth System Models:** Carbon cycle simulations to assess ecological and biogeochemical impacts and feedbacks on anthropogenic CO_2

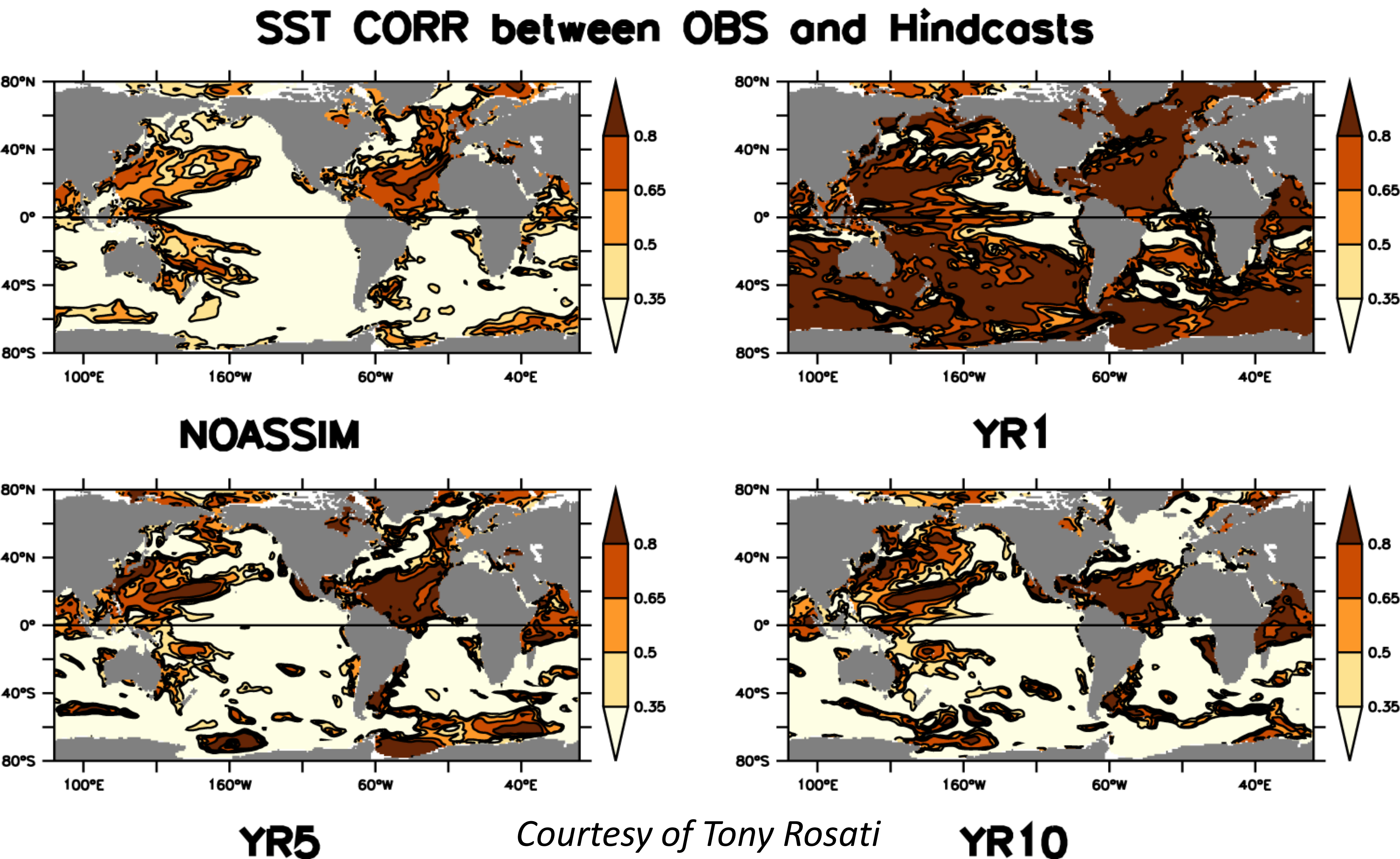
Stream 1: Interactive chemistry and aerosols gives much stronger sensitivity to aerosols



Courtesy of Larry Horowitz

Stream 2: Data assimilation exploring inter-annual predictability

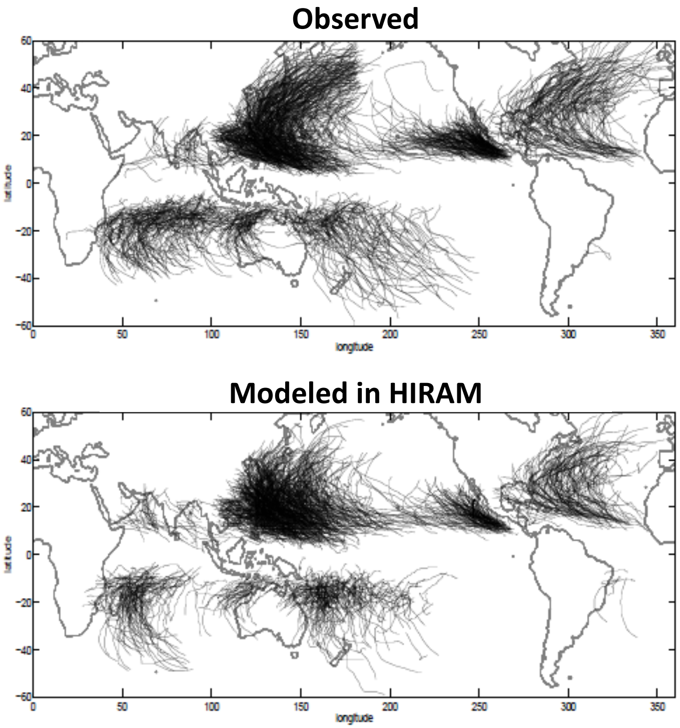
10 member Ensemble Coupled Data Assimilation starting Jan every year (1961-2011) using NCEP Reanalysis2 (T,u,v,ps), ocean obs (xbt,mbt,ctd,sst,ssh,ARGO) and radiative forcing (GHG, solar, volcanoes, aerosols)



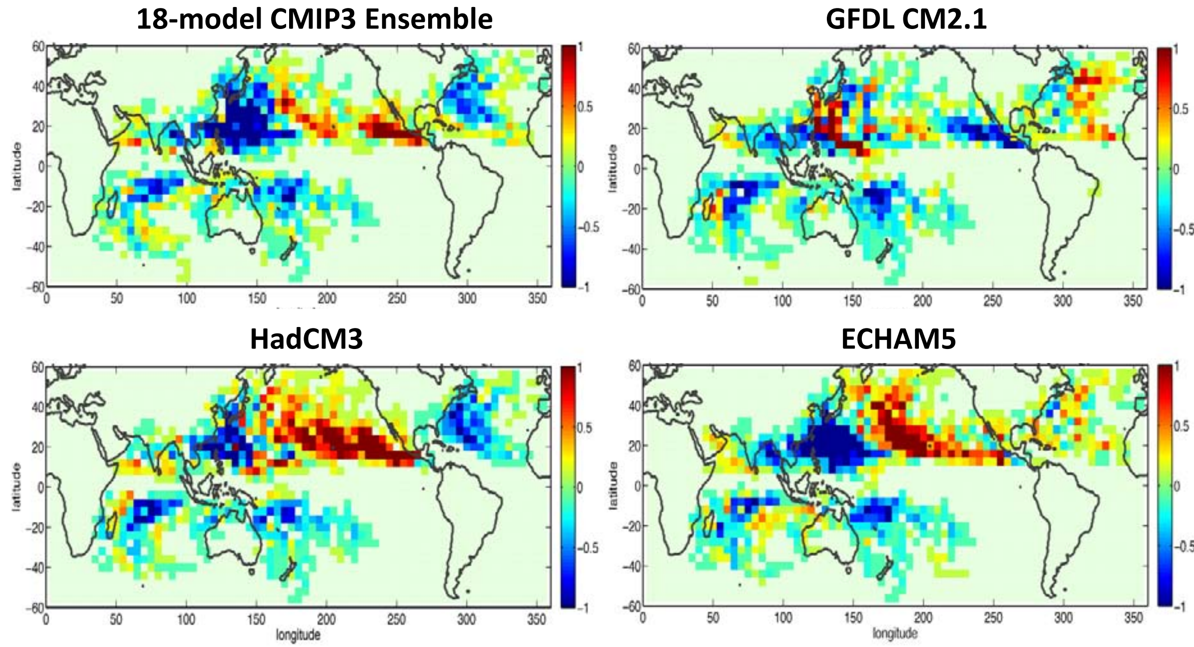
Courtesy of Tony Rosati

Stream 3: Tropical cyclones in 50-km High Resolution Atmospheric Model (HIRAM): Comparison with observations and late 21st century changes

Tropical Storm Tracks (1981-2005)



HIRAM driven by four CMIP3-based SST projections



Red/yellow = increase
Blue/green = decrease

Unit: Number per year

Excellent reproduction of hurricane track statistics when forced by SST

- Regional changes much larger than the global
- Pattern depends on details of SST change

Source: Zhao et al. (2009; J. Climate)

Stream 4: Earth System Modeling

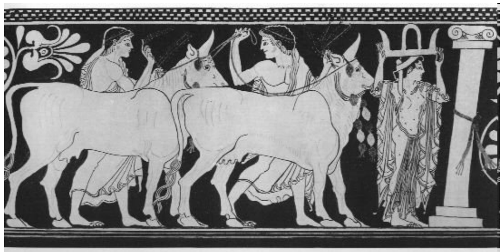
Hercules’ Fifth Labor: The Augean stables

(abridged)

The cleansing of the stables of Augeias from a relief in Rome

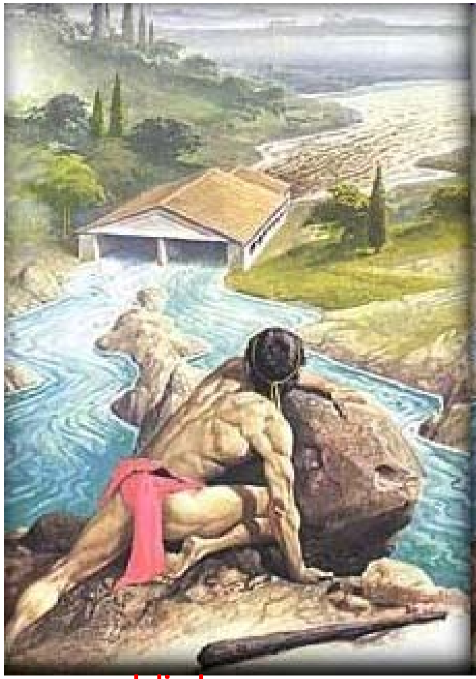
Every night the cowherds, goatherds and shepherds drove thousands of animals to King Augeas’ stables. The largest in Greece, the stables had never before been cleaned. Eurystheus ordered Hercules to clean up the stables in a single day. To complete the task, Hercules directed his great strength not to lift out the dung, a truly arduous task, but rather to tear an opening in the wall of the stables. Then he made another opening in the wall on the opposite side of the yard. Next, he dug wide trenches to two rivers which flowed nearby. The rivers rushed through the stables, flushing them out… and gave birth to the adage:

‘The solution to pollution is dilution!’

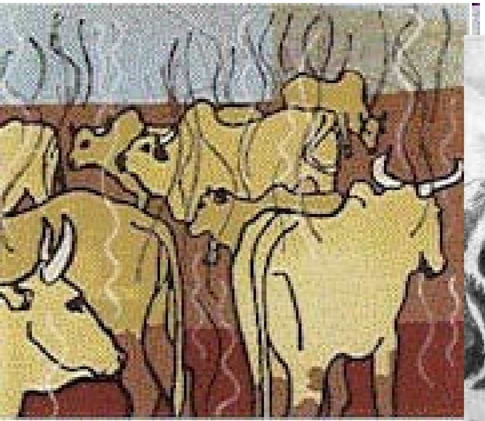


www.leeds.ac.uk

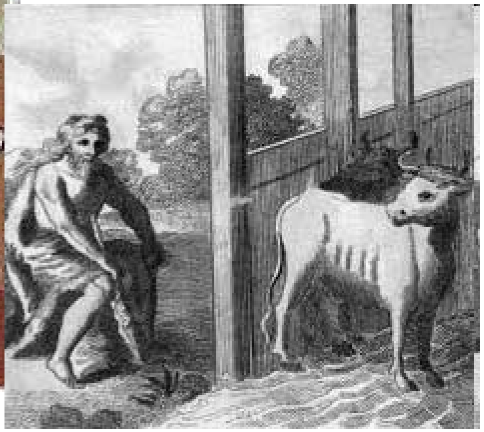
www.mlahanas.de



www.rudylimberger.com



Andy Lovell, "Augean Stables", Collyer-Bristow Gallery



Hercules.smercgames.com

Quantification of the greenhouse effect

Svante Arrhenius

- 1896 - Used observations of water vapor and CO_2 for a theory of ice ages and future climate – that doubling or halving CO_2 will bring a ~5°C rise or fall of surface temperature, respectively.
- 1906 – Revised his estimate down to 2.1°C
- …but thought such a rise would take millenia… i.e. the solution to pollution is dilution

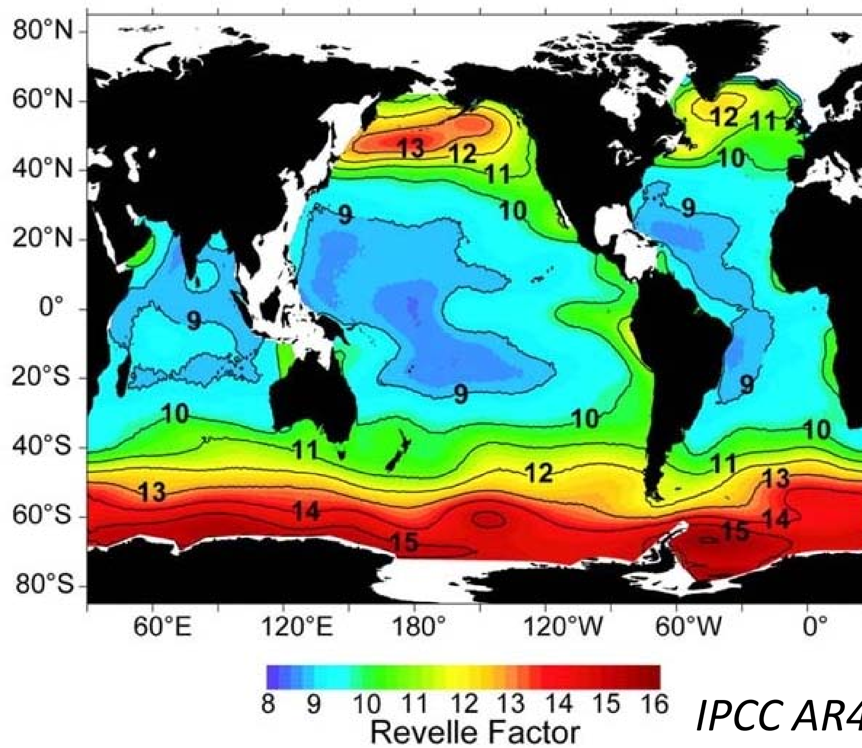
The 'Revelle Factor'

- Most ocean CO_2 is not in gas form, but as HCO_3^-

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \;\;\&\;\; H_2CO_3 + CO_3^{2-} \Leftrightarrow 2HCO_3^-$$

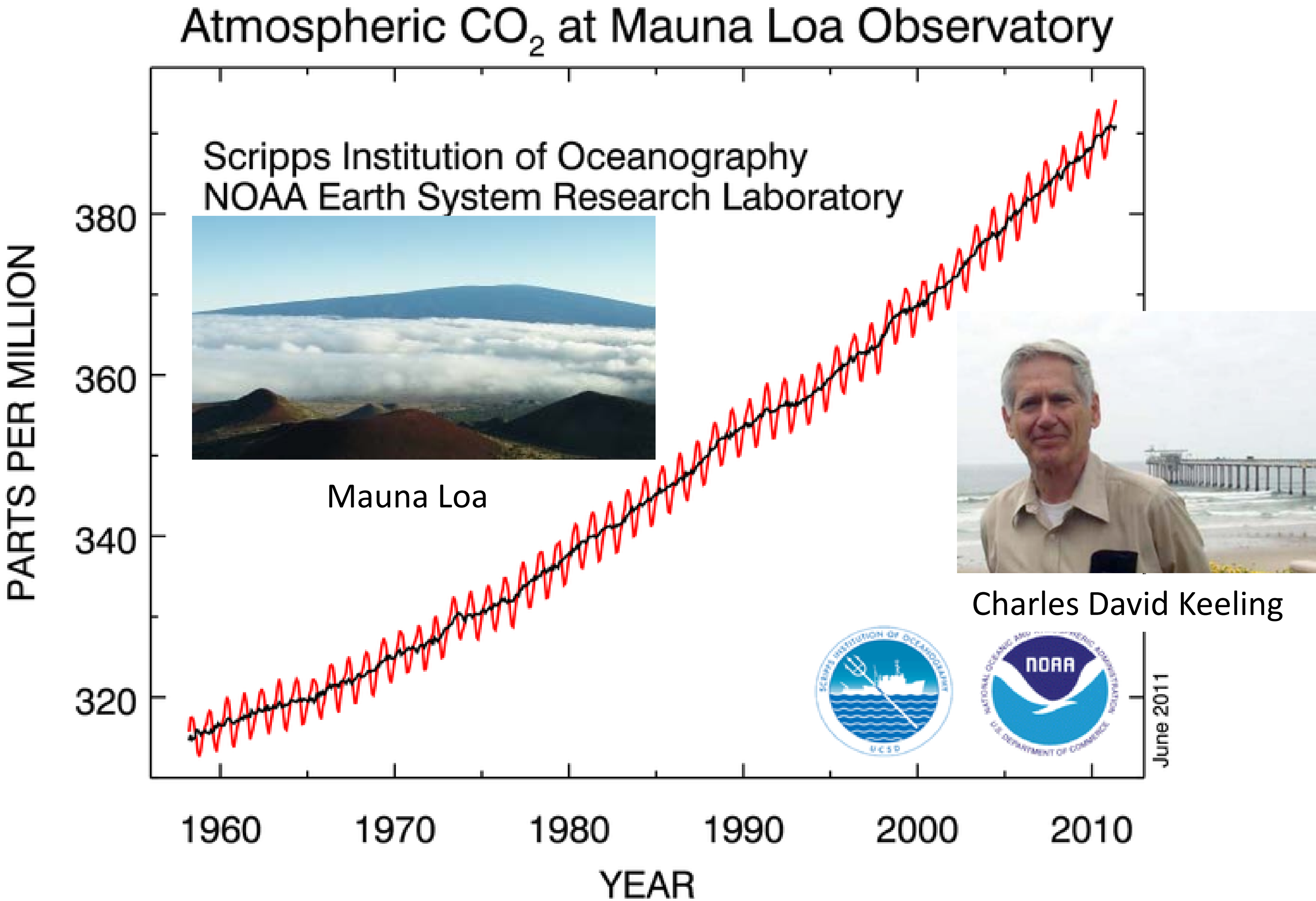
- Because the ocean buffer capacity is low, increasing the atmosphere by 10% increases the surface ocean concentration by only 1% (Revelle and Seuss, 1957)
  - Revelle factor (R) = $(\Delta[CO_2] / [CO_2]) / (\Delta[DIC] / [DIC])$

Roger Revelle



IPCC AR4; Figure 7.3.10

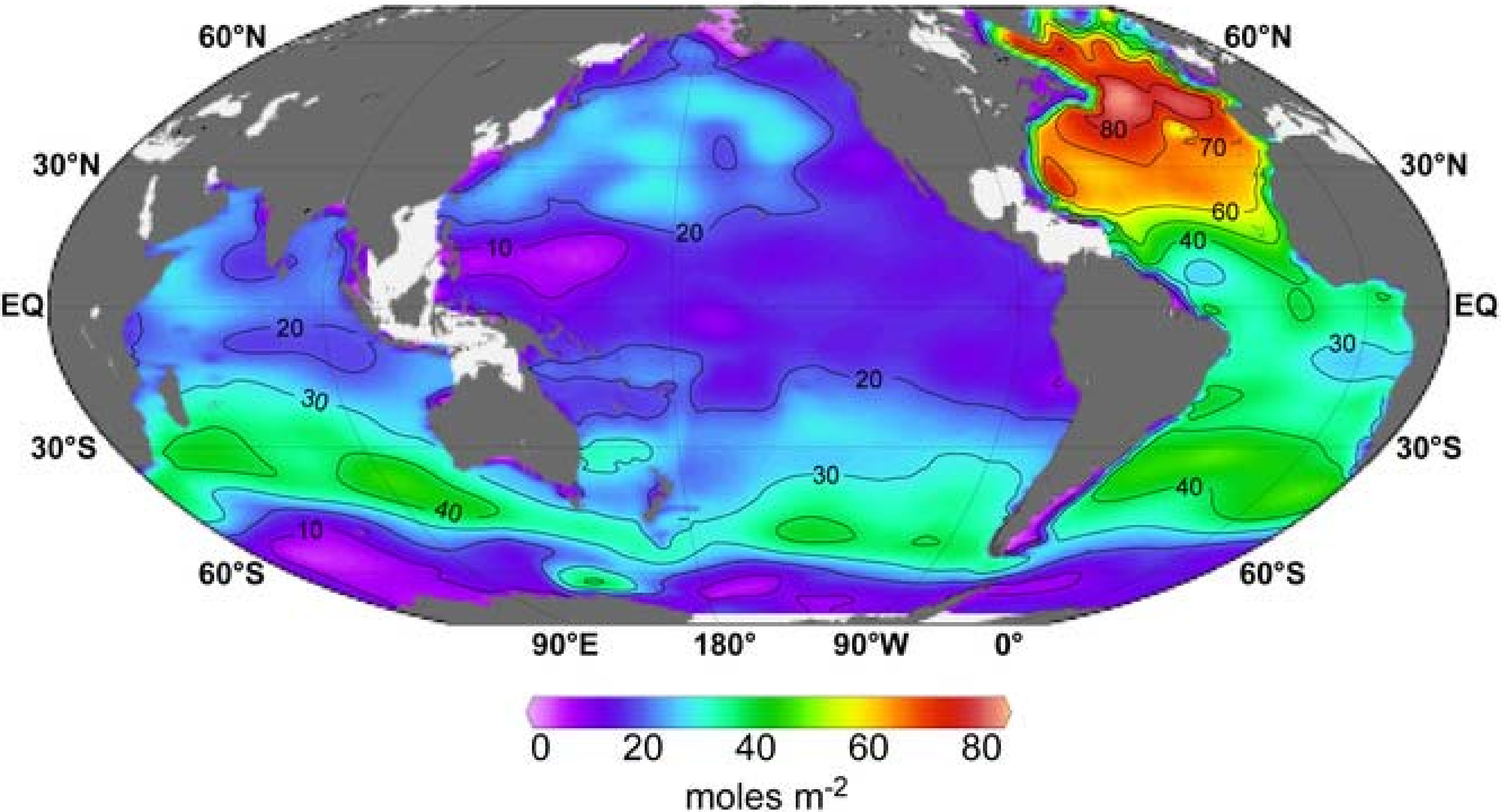
Testing the dilution hypothesis for global CO_2:
The 'Keeling Curve'



Mauna Loa

Charles David Keeling

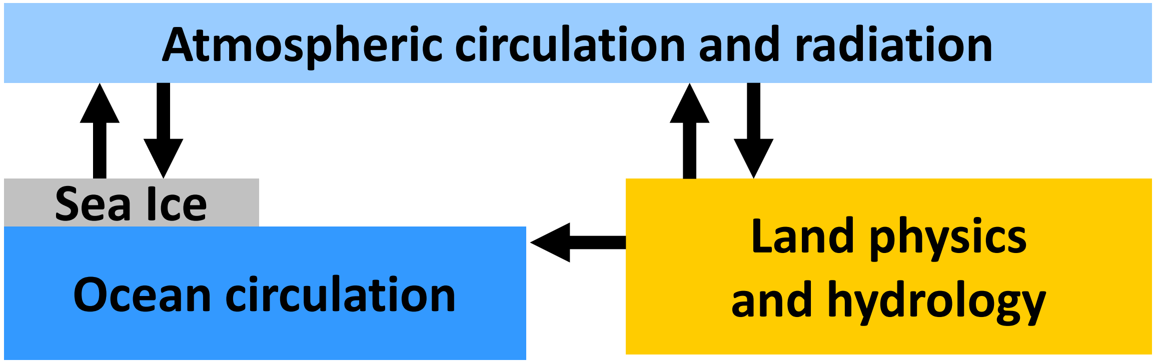
Powerful data constraints are available on ocean CO_2 uptake



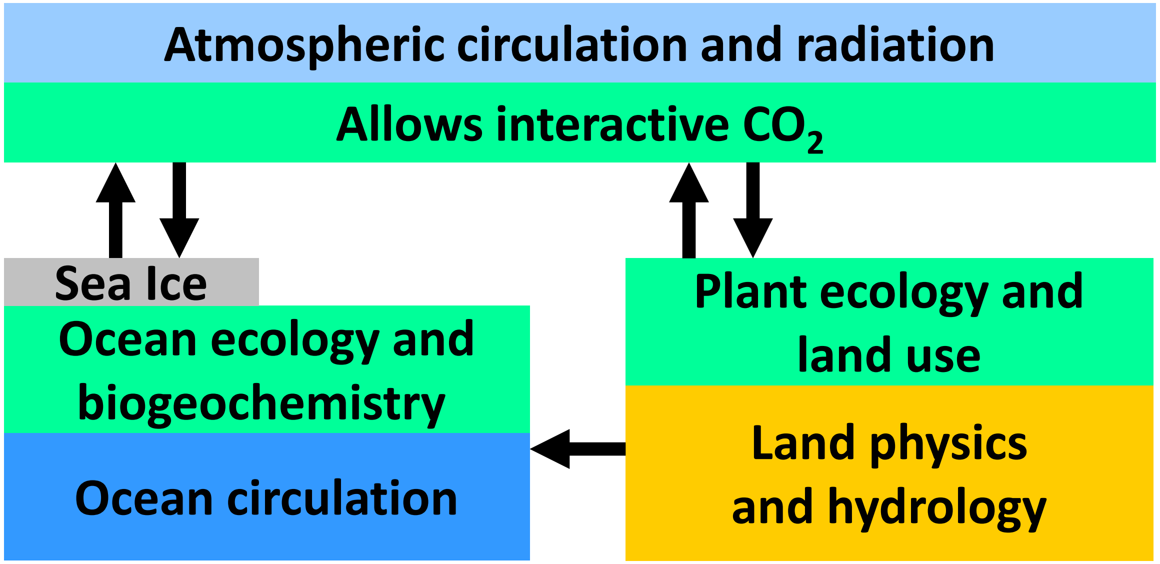
Source: Sabine et al. (2004; Science)

Earth System Model Description

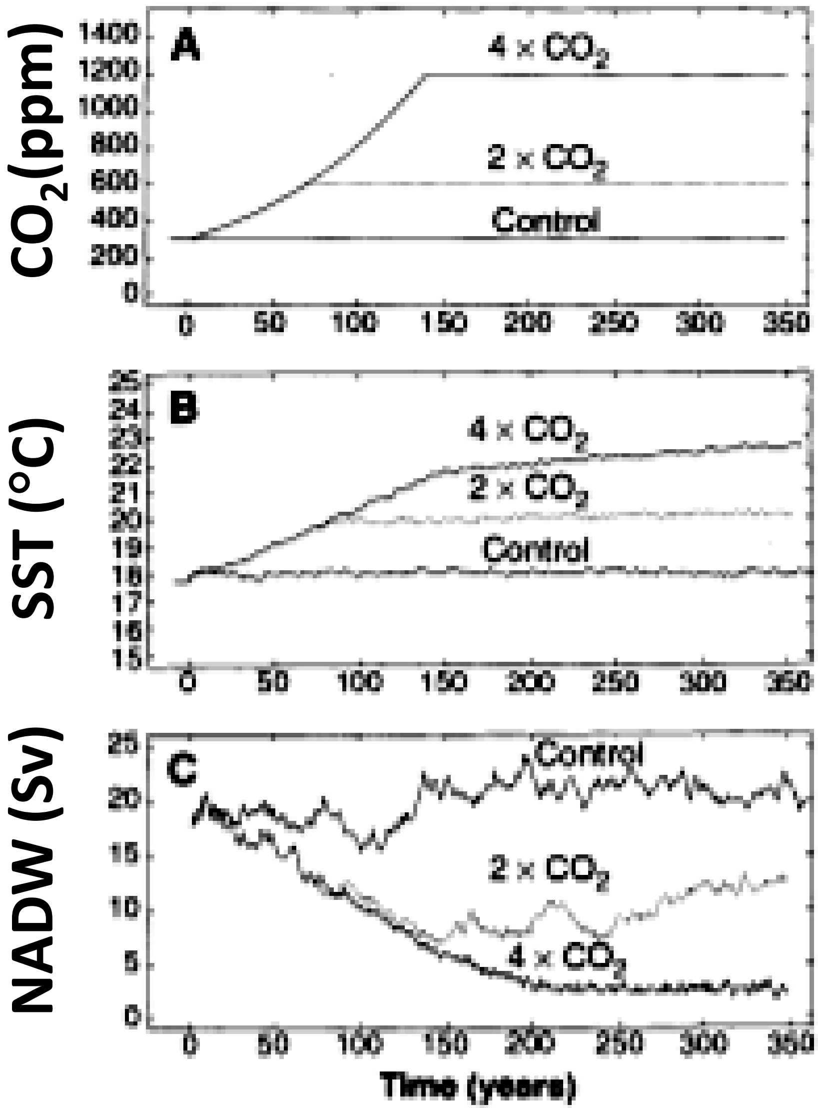
A Climate Model closes the radiative and hydrologic cycles



An Earth System Model closes additional cycles as well



Coupled Carbon-Climate Cycling: Large uncertainty in ocean physical and biogeochemical response

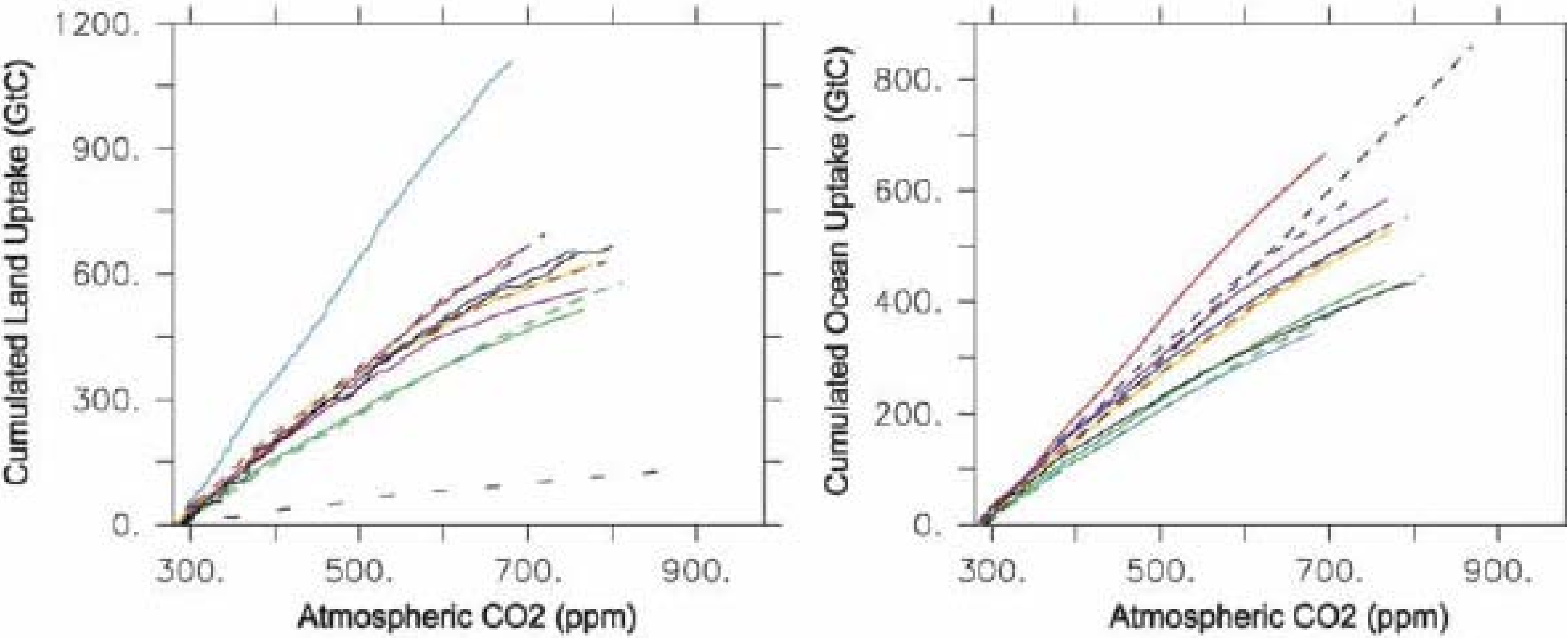


Early work showed critical role for ocean feedbacks:

- Collapse in NADW and other circulation changes reduced uptake by almost 50%.
- Compensation by the biological pump ameliorated 17% of this impact.
- Enhancement of the biological pump could potentially make up the difference.
- …very simple model!

Sarmiento and Le Quere (1996; Science)

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**

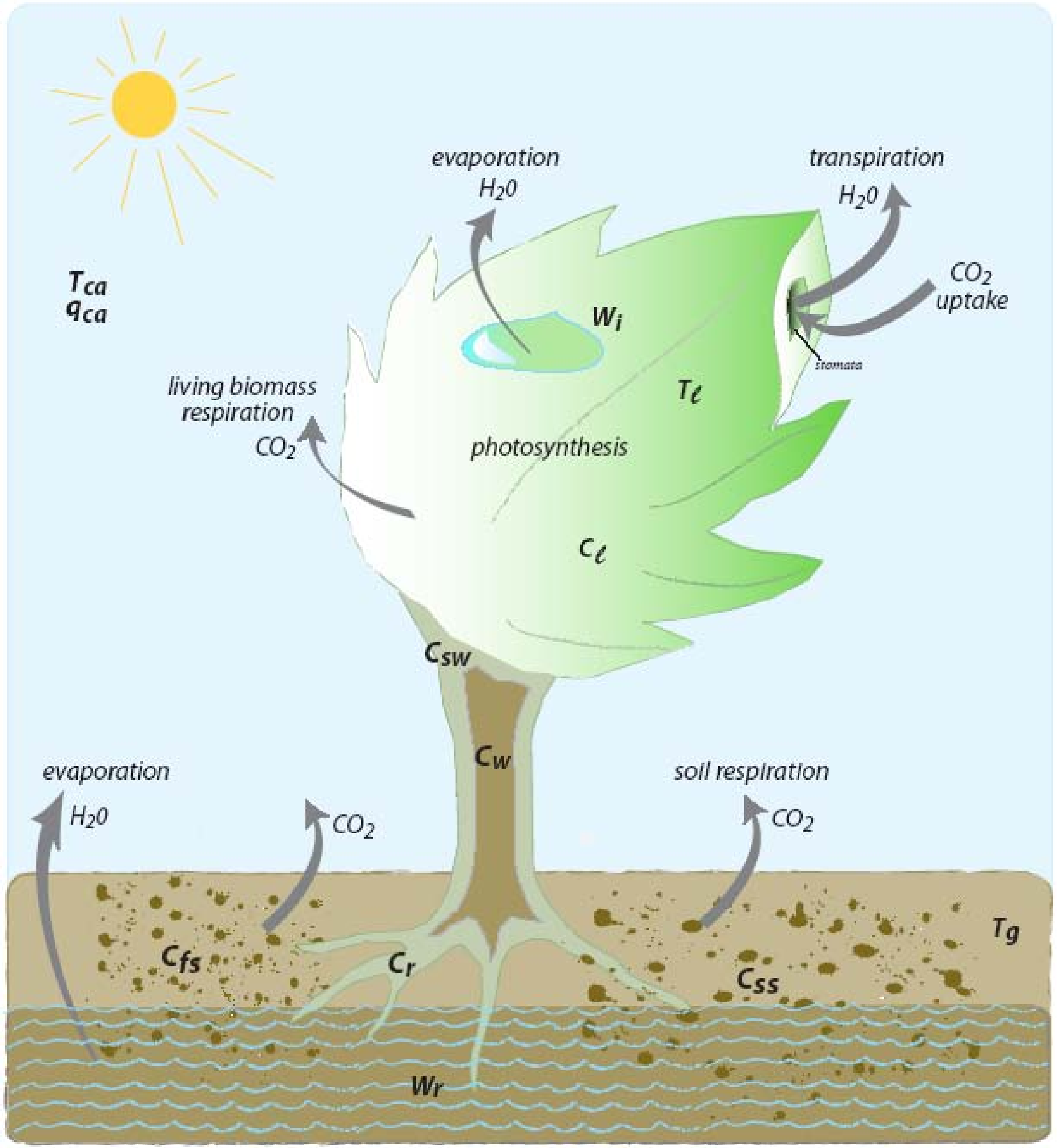
Source: Friedlingstein et al. (2006; J. Climate)

GFDL Earth System Model Status

- **ESM2.1 – Prototype**
  - Based on GFDL's CM2.1
  - Interactive land and ocean carbon
  - Has been run with AR4 scenarios (SRES)
  - Useful for component testing and science projects

- **ESM2M and ESM2G**
  - LM3 vertically resolved soil temperature and hydrology
  - Revised version of TOPAZ
  - 2 different ocean components for heat and carbon sensitivity
    - 50 layer MOM4.1; B-grid. Based on MOM4.0 but adds:
      - z* vertical distribution of height anomalies
      - Improved numerics
      - Tidal mixing, submeso, geothermal heating, and other mechanistic improvements
    - 63 layer GOLD; isopycnal interior; bulk mixed layer; C-grid
  - Run with CMIP5 scenarios (Representative Concentration Pathways)
  - ESM2M simulations complete
  - ESM2G spin-up complete, simulations ongoing

Vegetation Structure in the LM3 Land Model



5 vegetation types: warm grasses, cold grasses, tropical, deciduous, coniferous

5 vegetation C pools: leaves, sapwood, wood, fine roots, virtual leaves

2 soil C pools: fast, *slow*

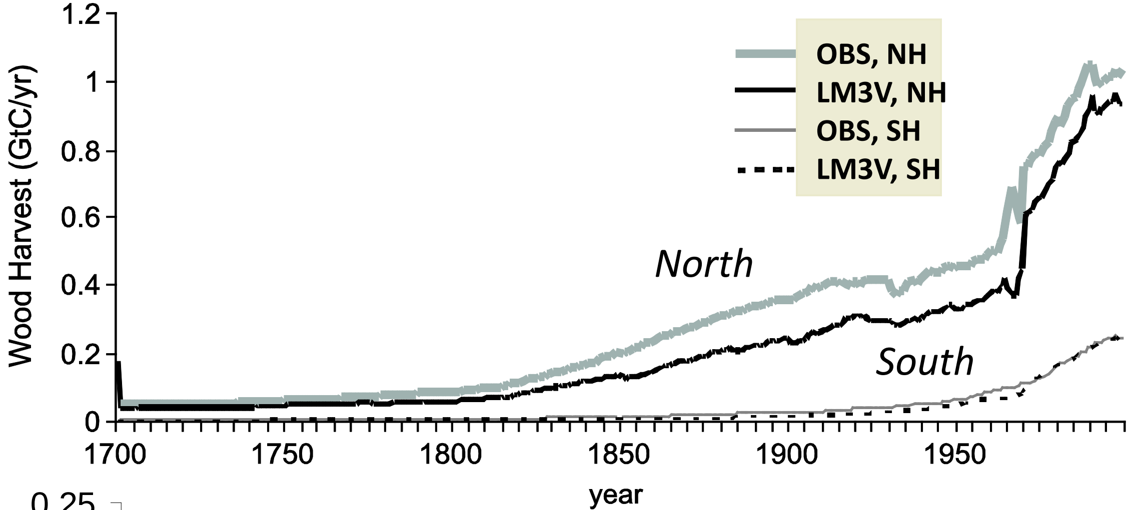
4 land-use types: Primary, Crop, Pasture, Secondary Forest

Up to 15 tiles of different forest ages per grid-cell

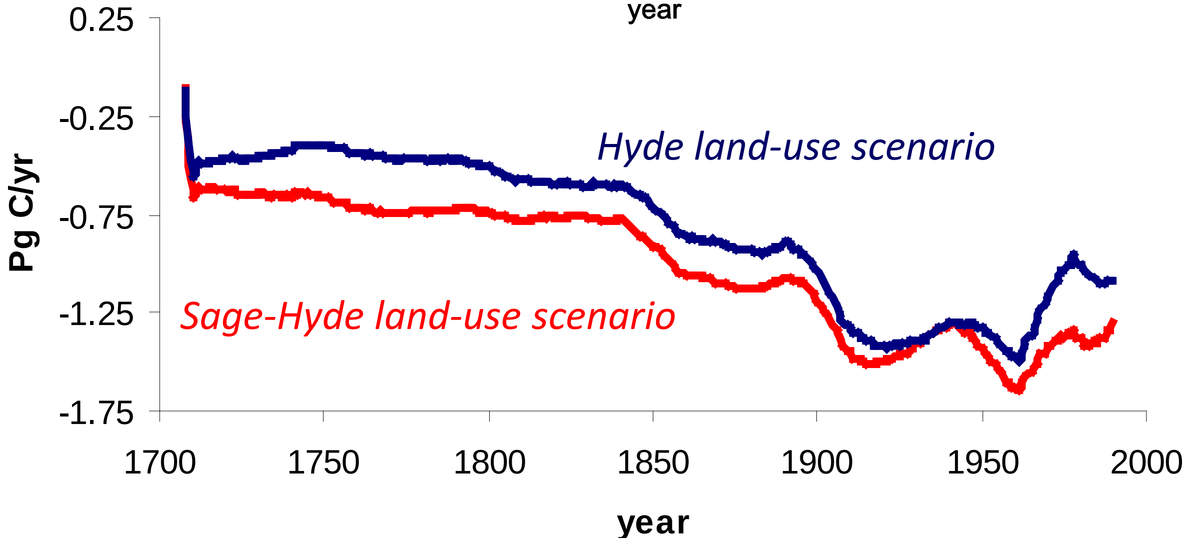
Natural mortality and annual fire

Source: Shevliakova et al., 2009

Land Carbon Cycling: Large land-use perturbation forced with observed climate



Simulated historical wood harvests forced with Hurtt et al. (2006) land use compare well with the FAO-based estimates



The model's estimate of the 90s land use flux, *1.1-1.3 PgC/a*, is about half of previous estimates and implies a smaller "missing sink"

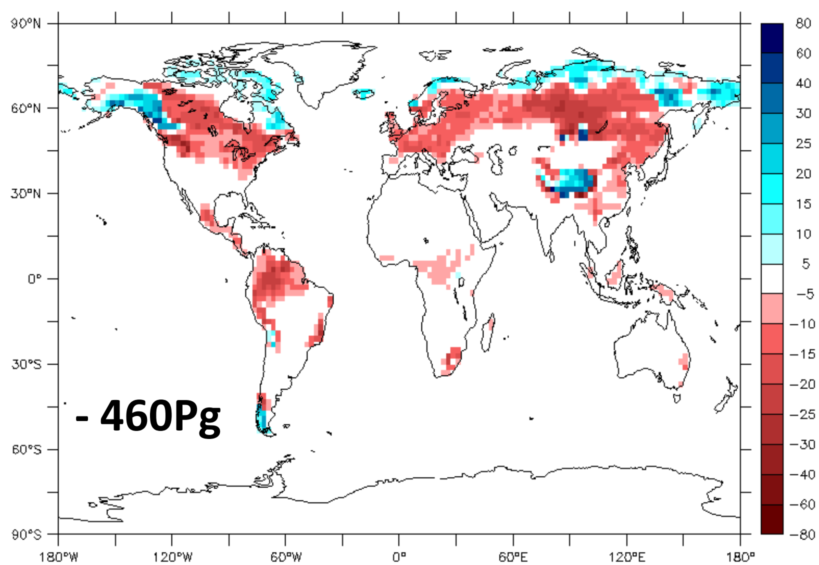
Source: Shevliakova et al. (2009; GBC)

Land Carbon Cycling: Large uncertainty in CO_2 fertilization under climate change

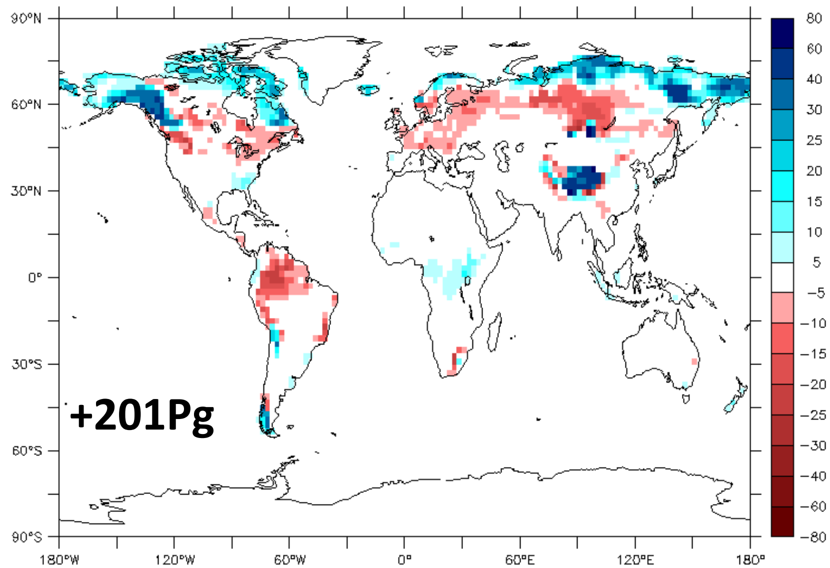
GFDL Slab-Ocean Climate Model (SM2.1-LM3V)

Equilibrium changes in land C from preindustrial levels

No fertilization, photosynthesis at 286 ppm



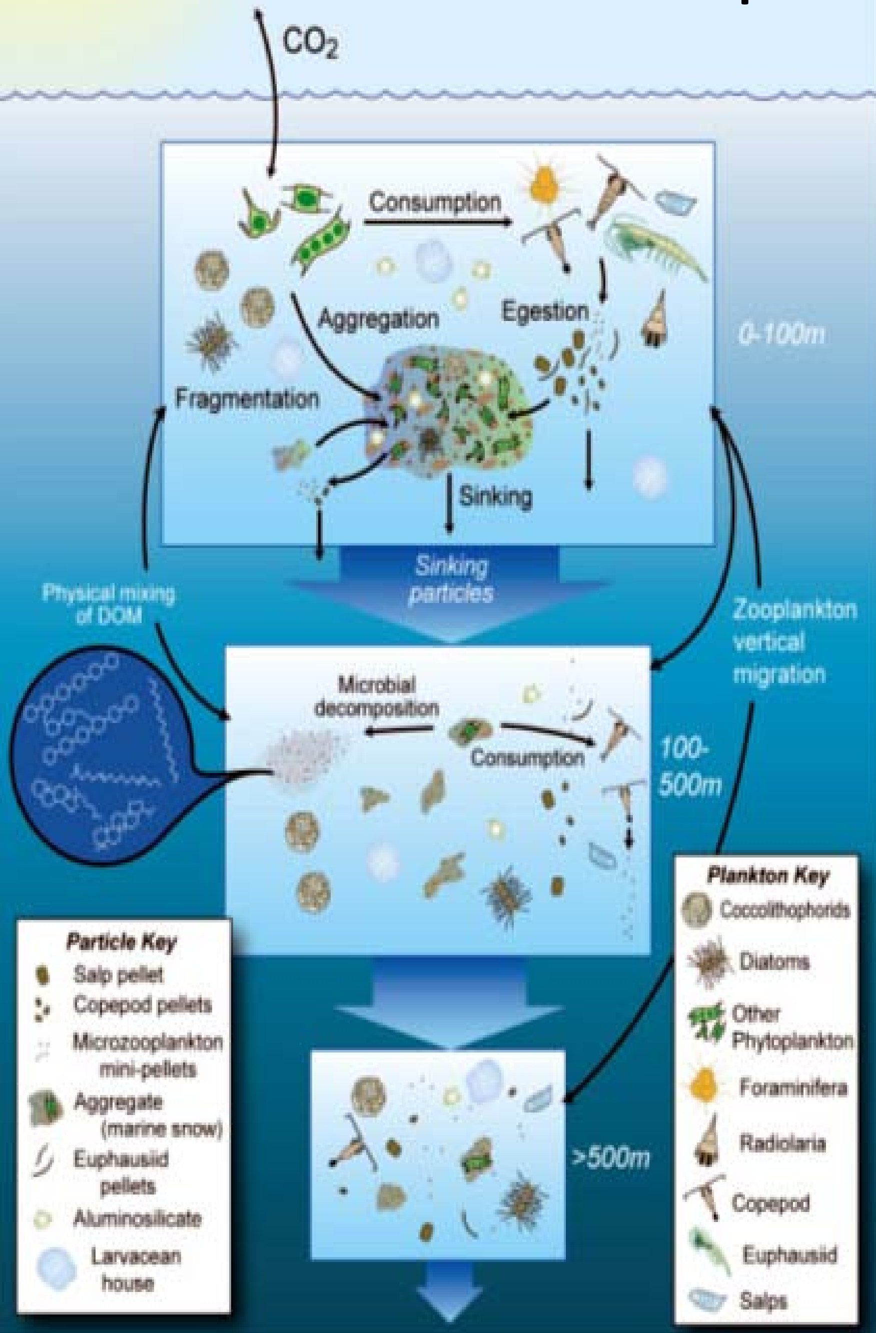
Fertilization, photosynthesis at 572 ppm

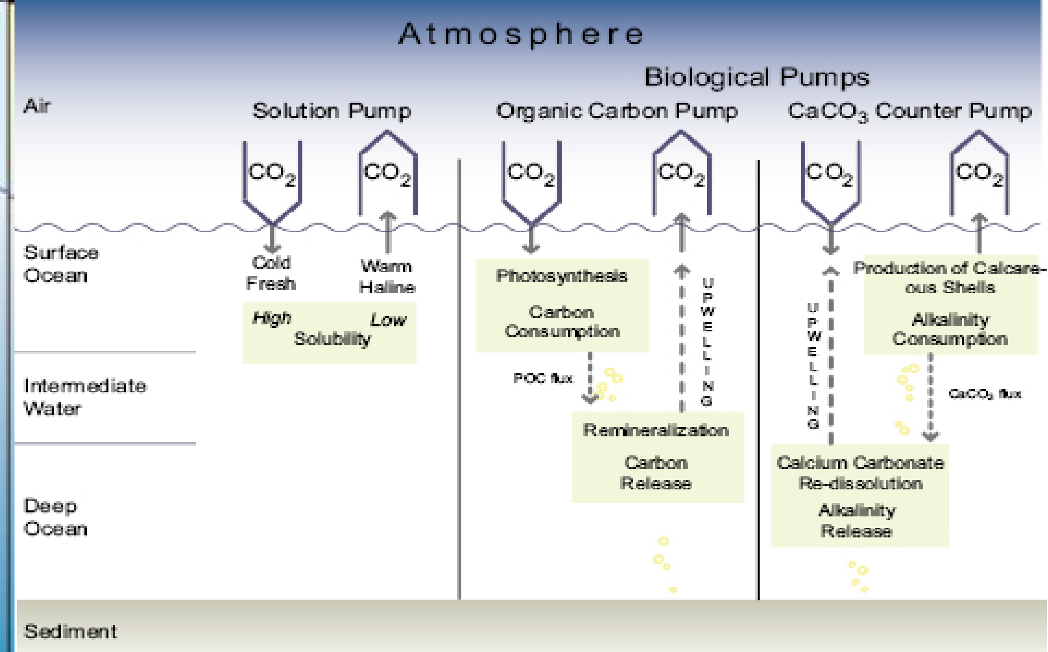


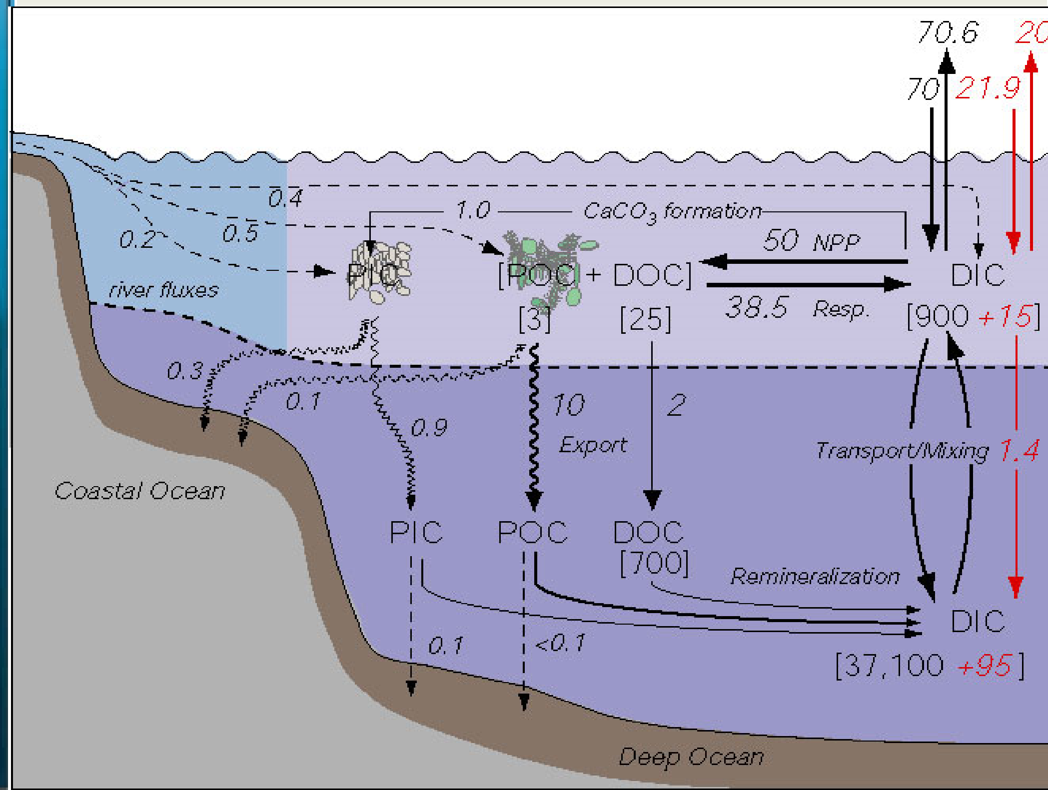
Model CO_2 fertilization assumptions are critical

Source: Shevliakova et al., subm.

Ocean Carbon Pumps



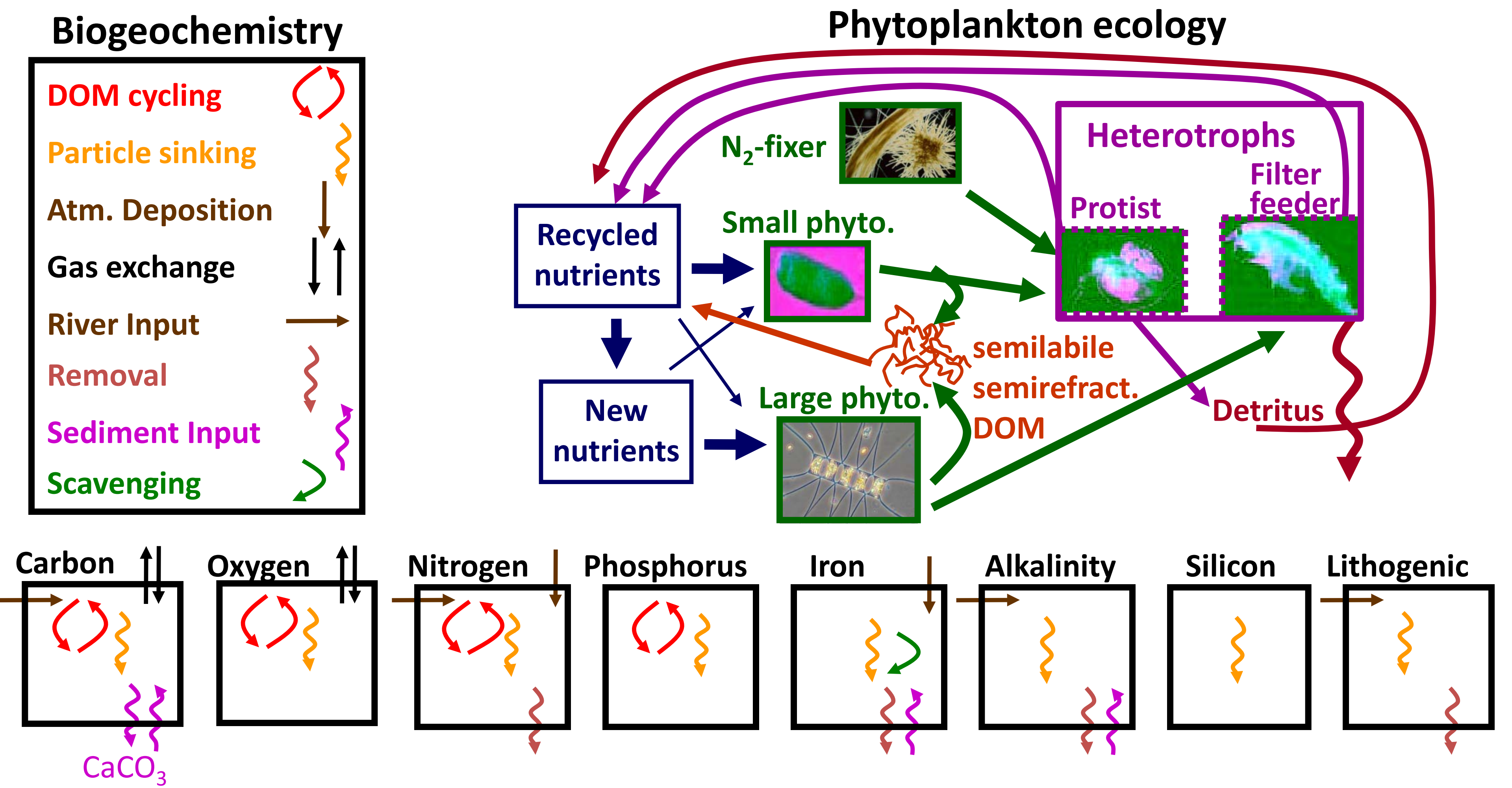




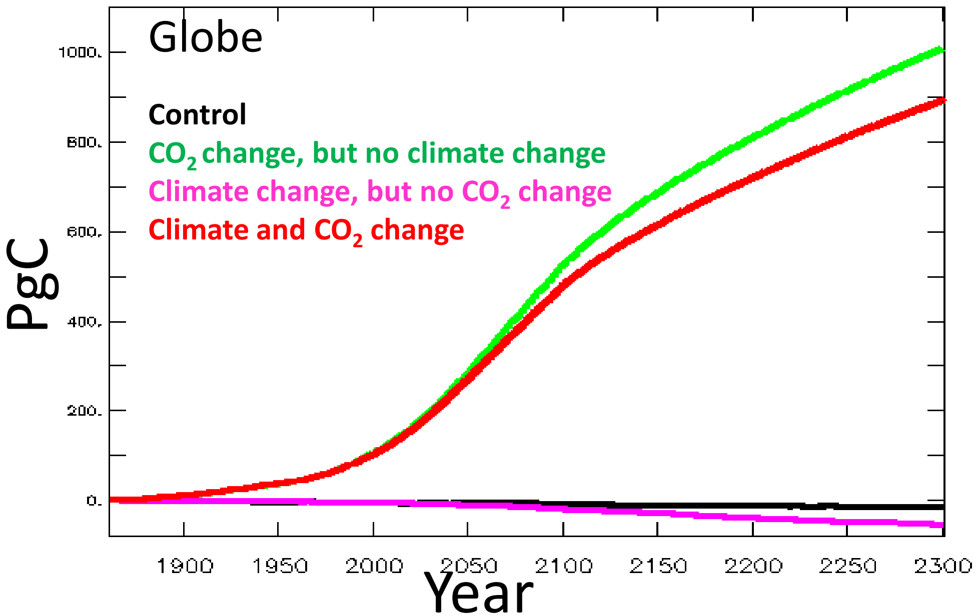
Tracers of Phytoplankton with Allometric Zooplankton (TOPAZ)

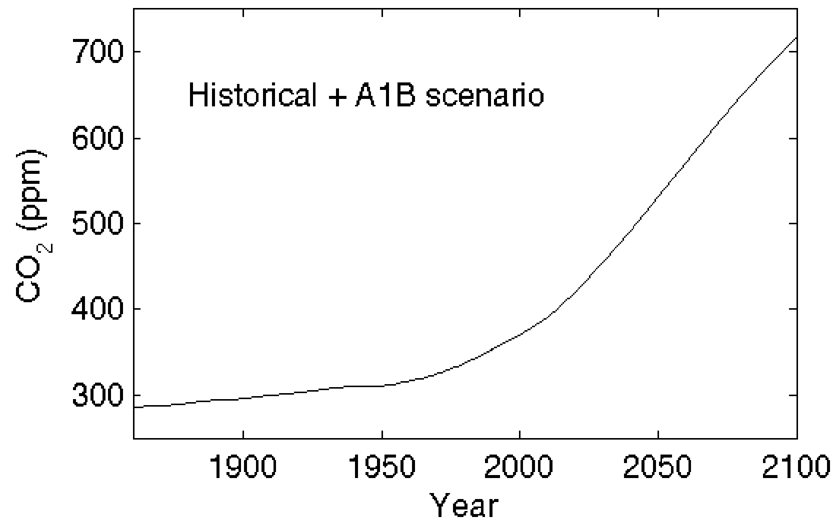
Implicit grazing dynamics
Flexible N:P:Si:Fe:Chl
Aragonite and Calcite

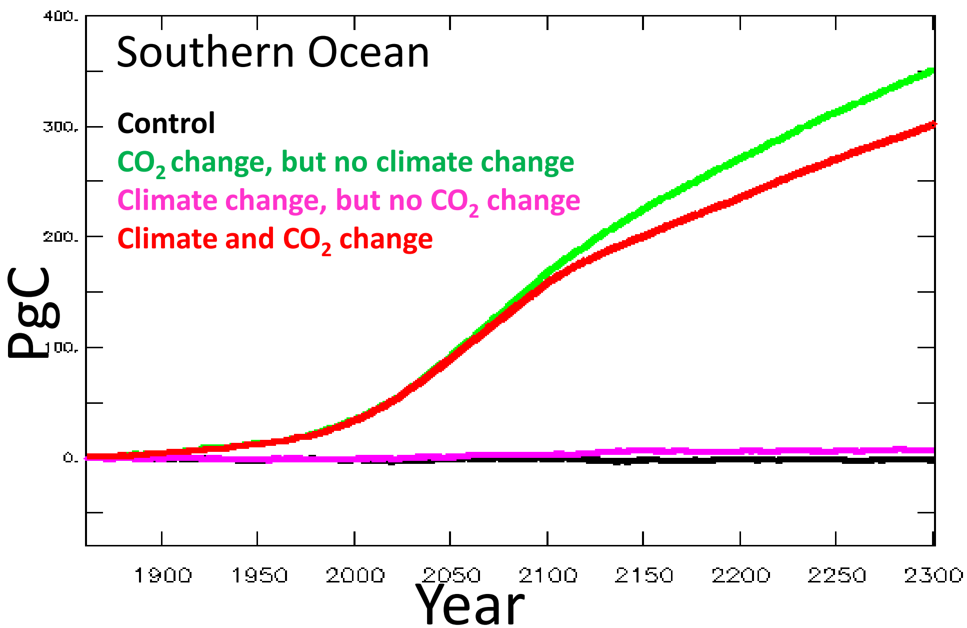
30 Tracers



ESM2.1 Ocean Carbon Uptake under SRES A1B

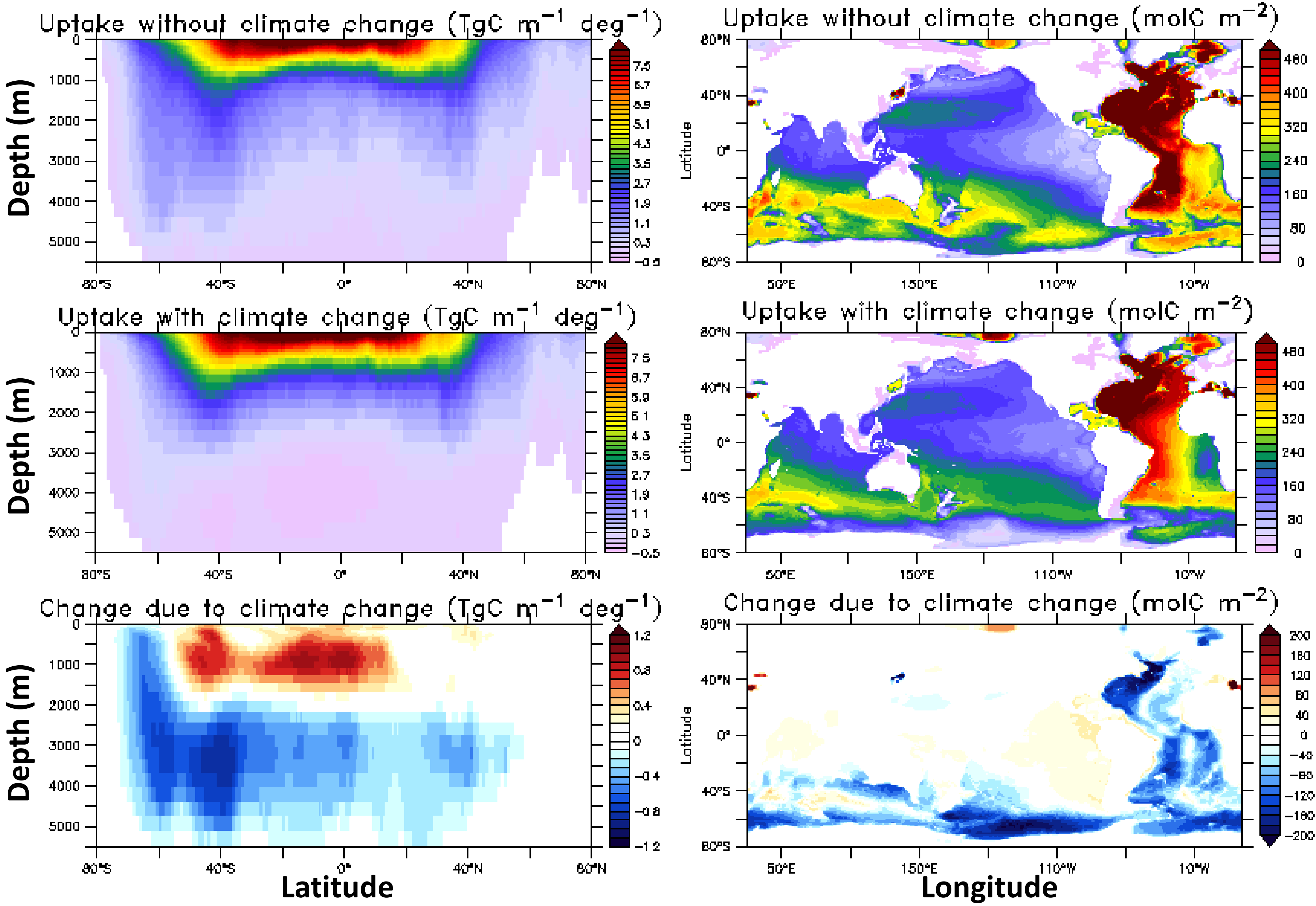




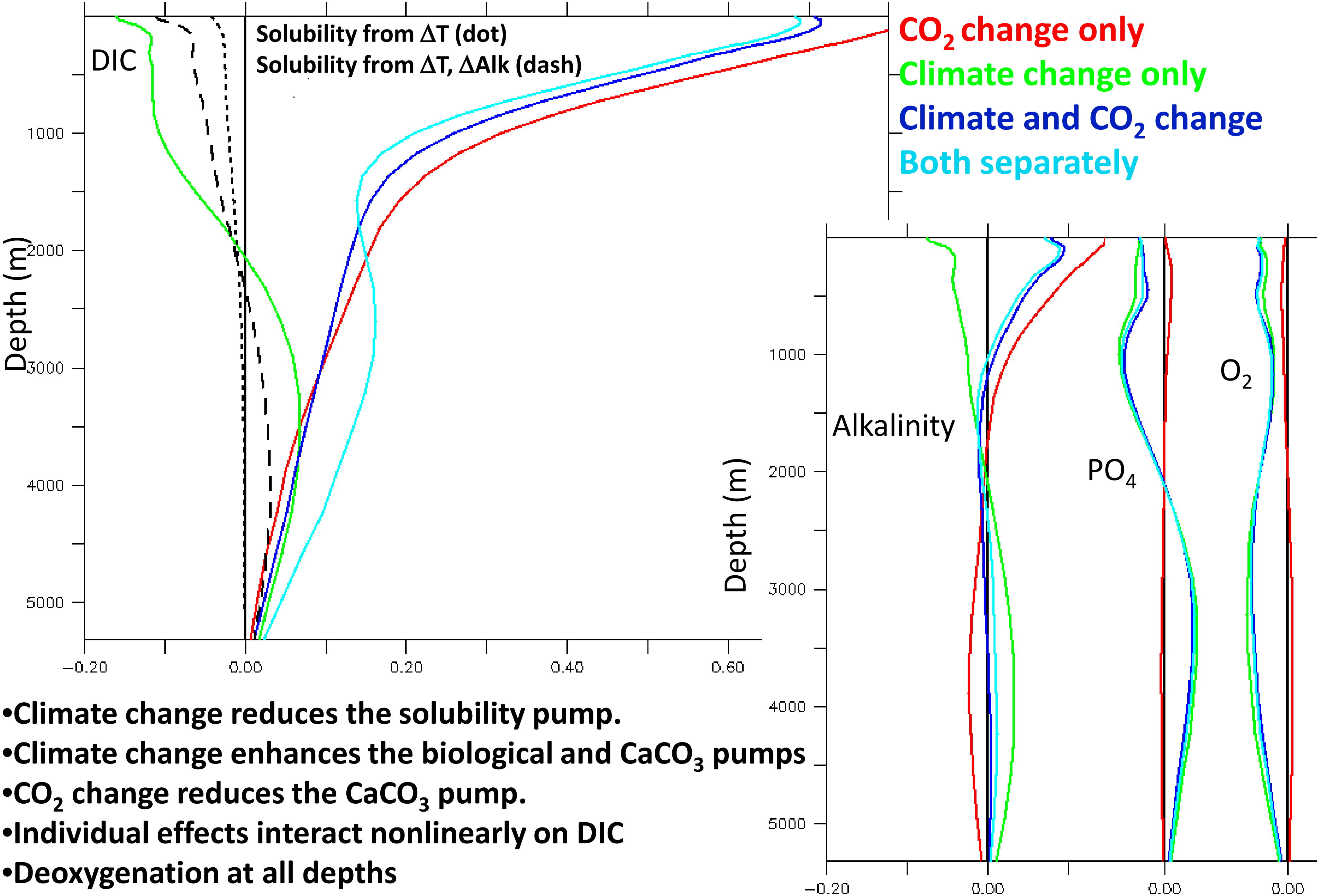


- **Climate change reduces ocean CO_2 uptake by 12% (65 PgC) by 2100.**
- **Strong biogeochemical compensation with only minor degassing of natural CO_2 under climate warming.**
- **In the Southern Ocean, climate change enhances the biological pump as ventilation decreases.**

ESM2.1 Uptake Sensitivity to Climate Change



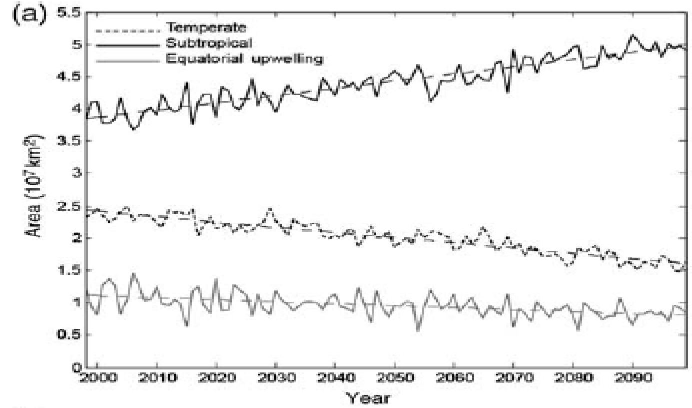
ESM2.1 ΔInventories at 2300 (PgC eq. m^{-1})

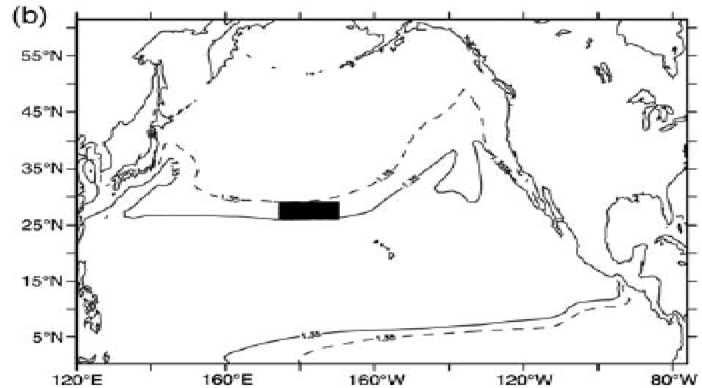


- Climate change reduces the solubility pump.
- Climate change enhances the biological and $CaCO_3$ pumps
- CO_2 change reduces the $CaCO_3$ pump.
- Individual effects interact nonlinearly on DIC
- Deoxygenation at all depths

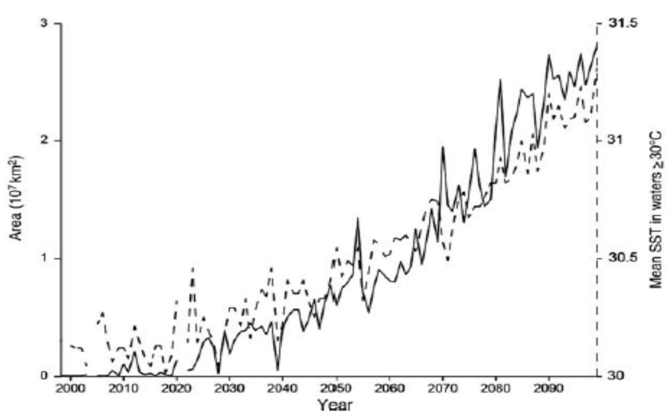
Pacific Ecological Biome responses in ESM2.1

Biome Area

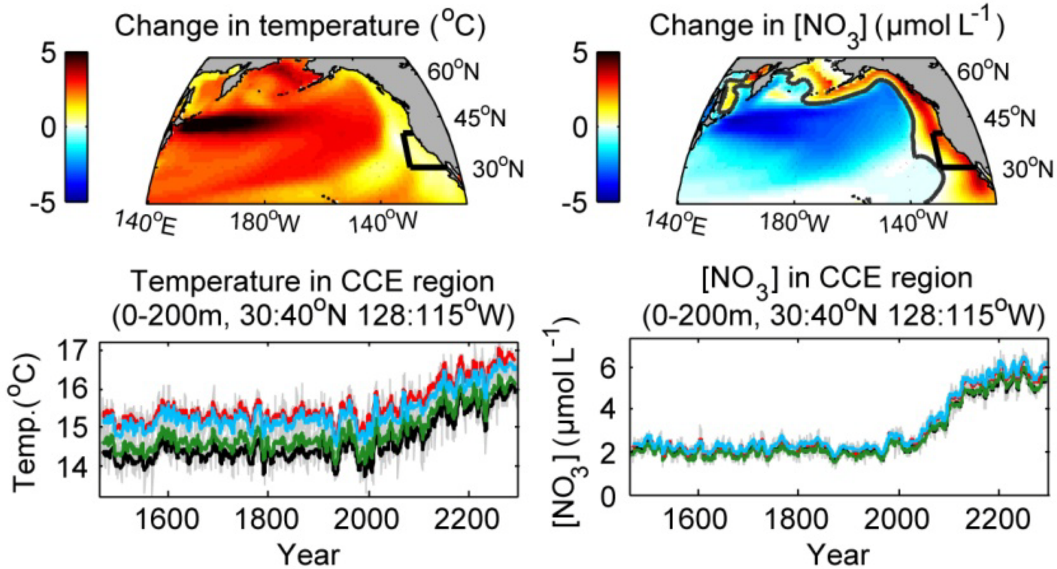


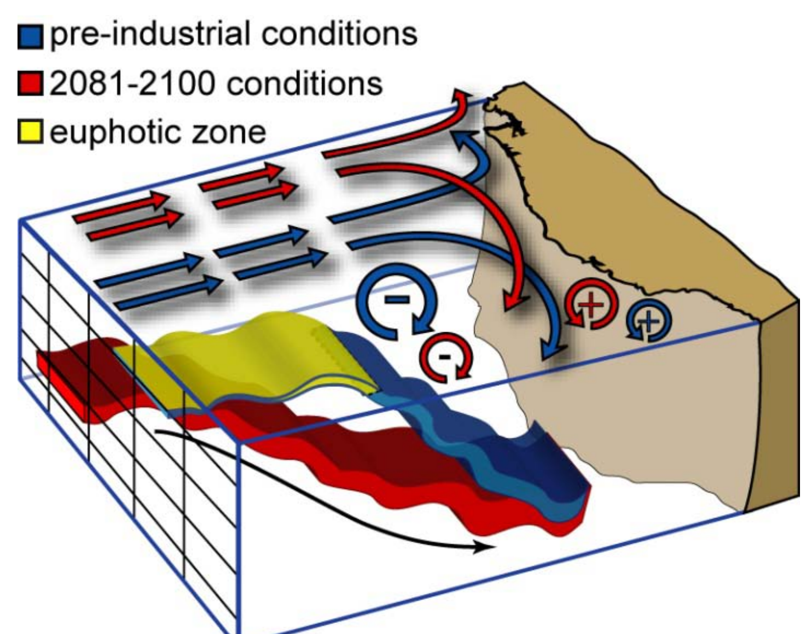


>30°C Biome Area



Source: *Polovina et al. (2011; ICES J. Mar. Sci.)*

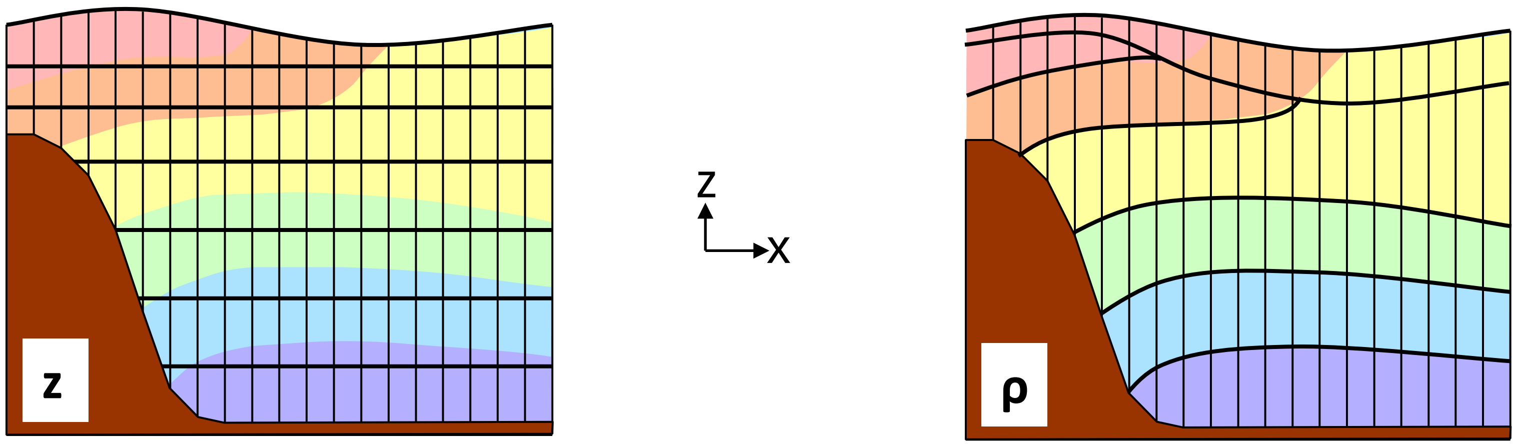




Source: *Rykaczewski and Dunne (2010; GRL)*

The ESM2M and ESM2G experiment: sister models that differ only in ocean physics

Goal: Comparison of implications of ocean vertical coordinate choice



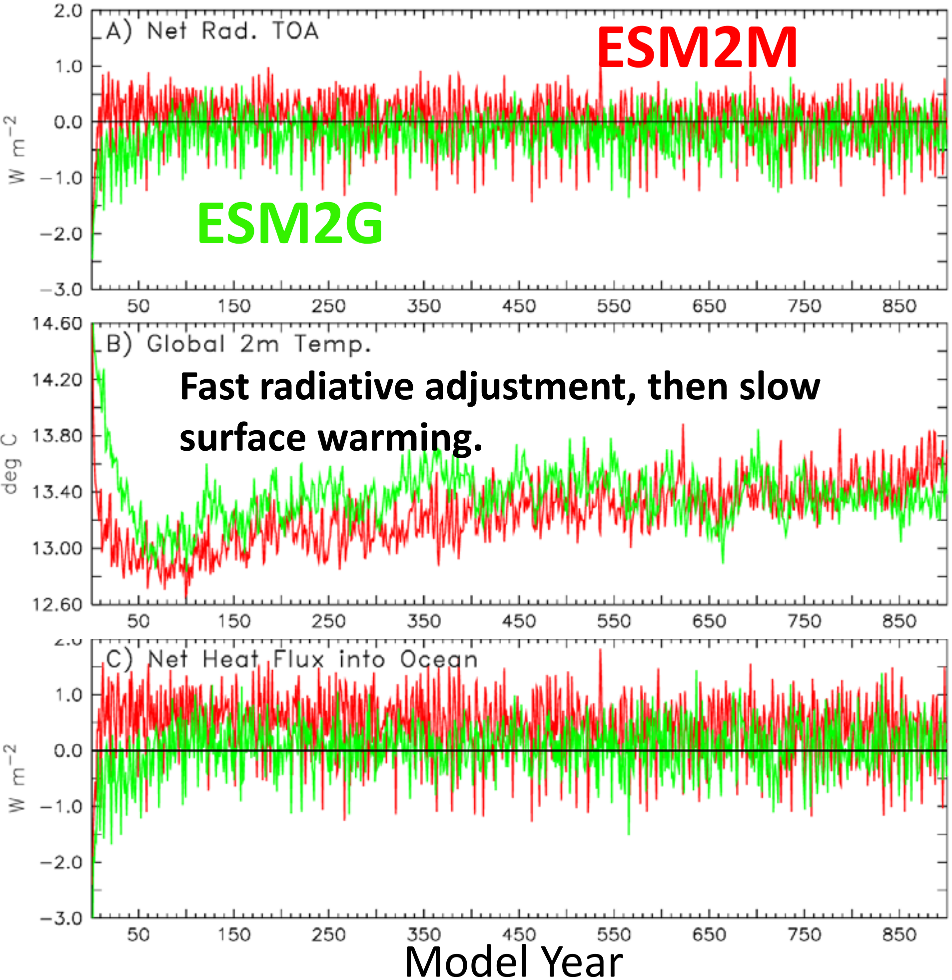
z* (MOM4.1):
- Laterally adjacent pressures interact
- Good representation of near surface
- Eulerian framework relatively straightforward to interpret
- Over 40 years of experience with it

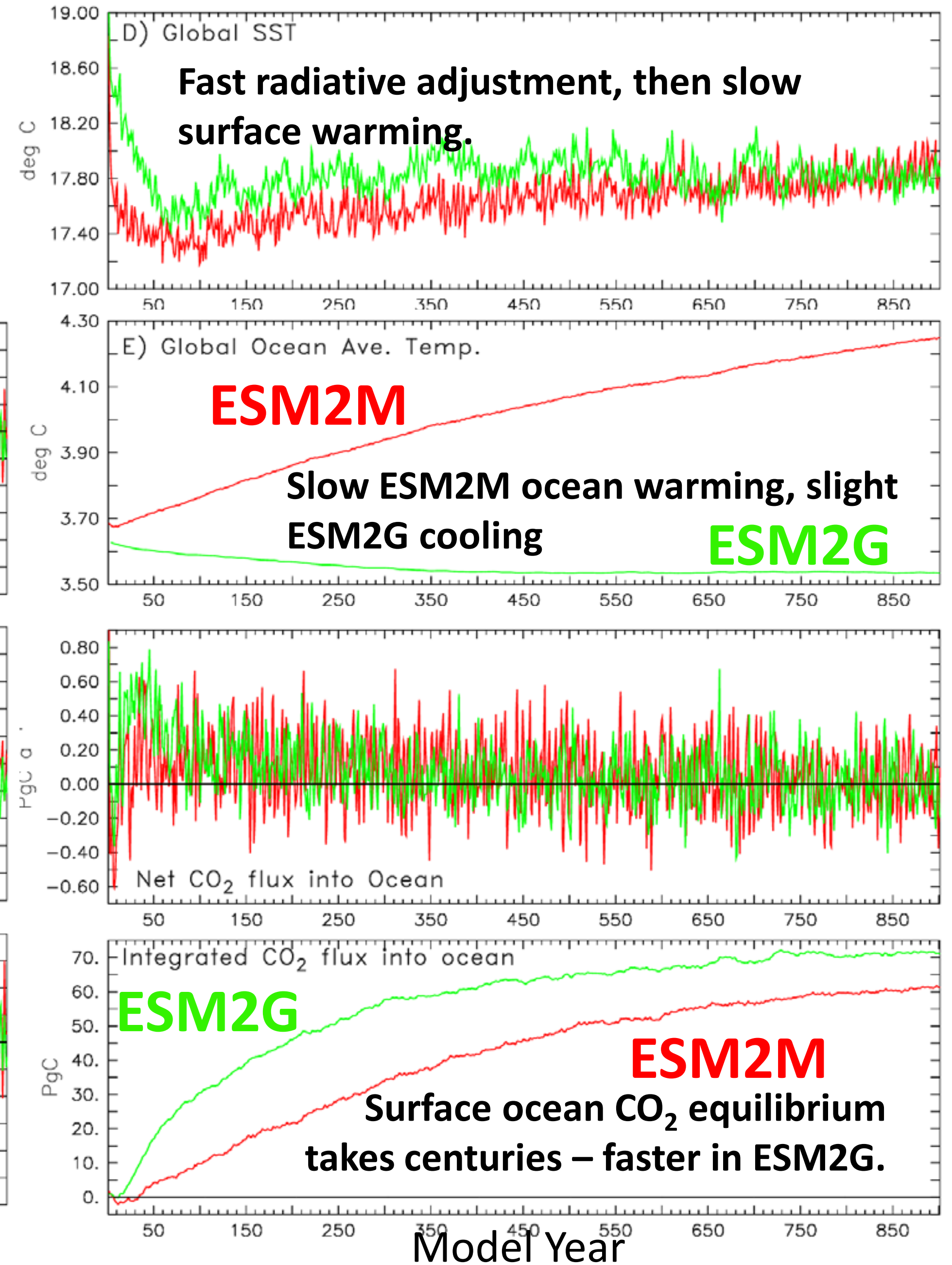
ρ (GOLD):
- Laterally adjacent densities interact.
- Bulk mixed layer allows continuously varying mixed layer properties
- Good representation of overflows
- No numerical diapycnal mixing

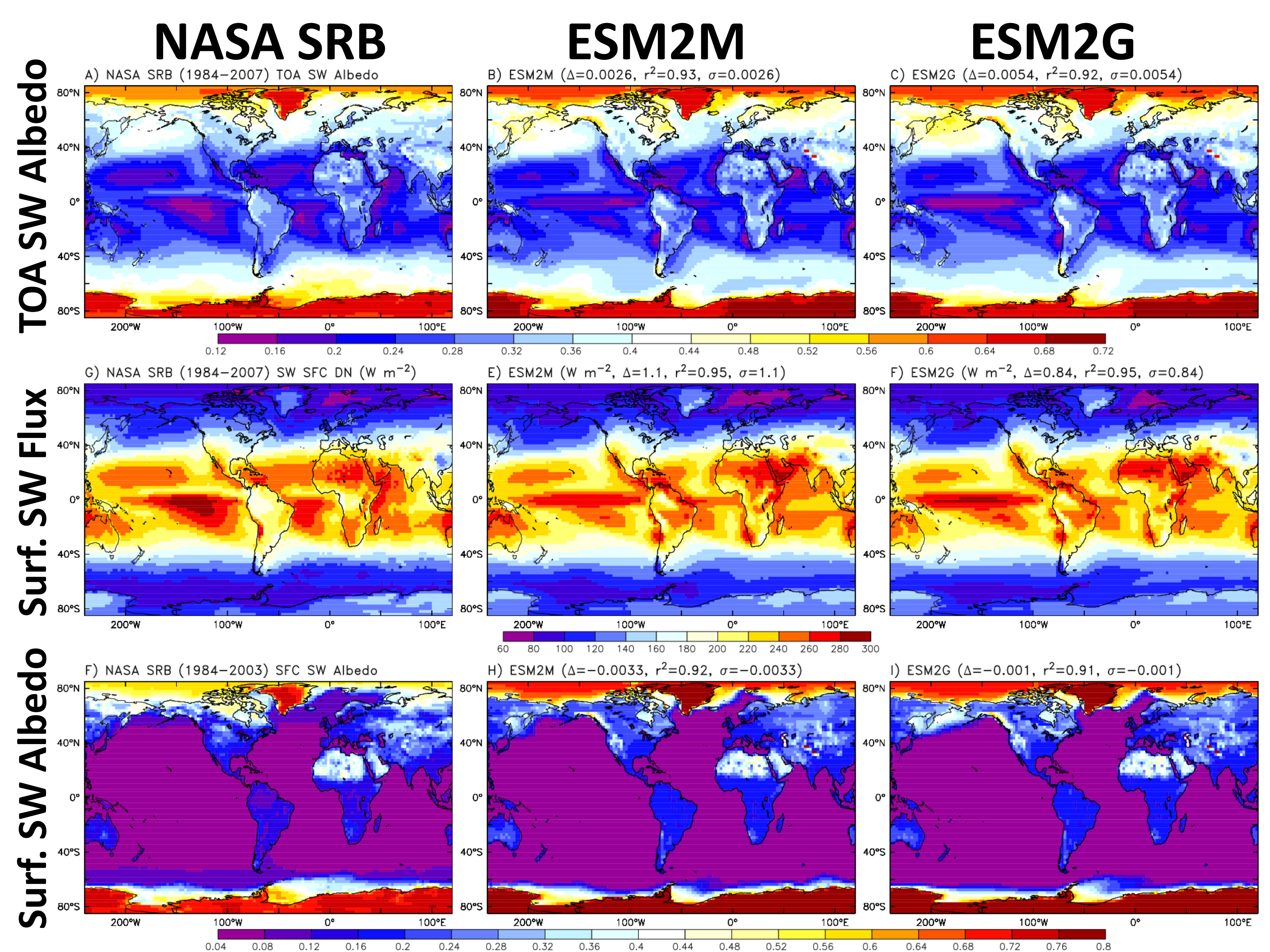
Task one: can they both give credible climates?

Spinup in ESM2M and ESM2G

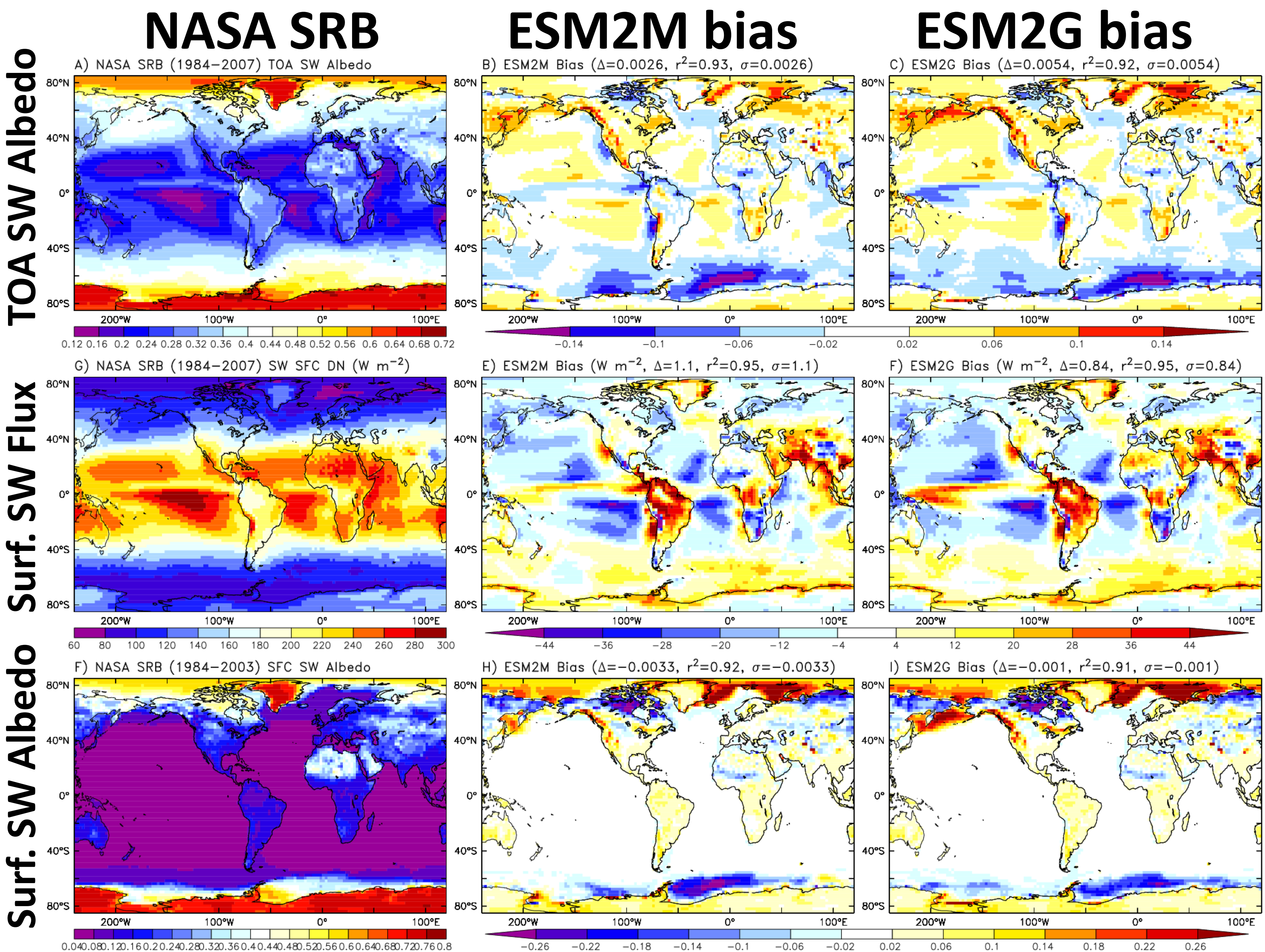
Initialized with present day values
Forced with 1860 radiative conditions





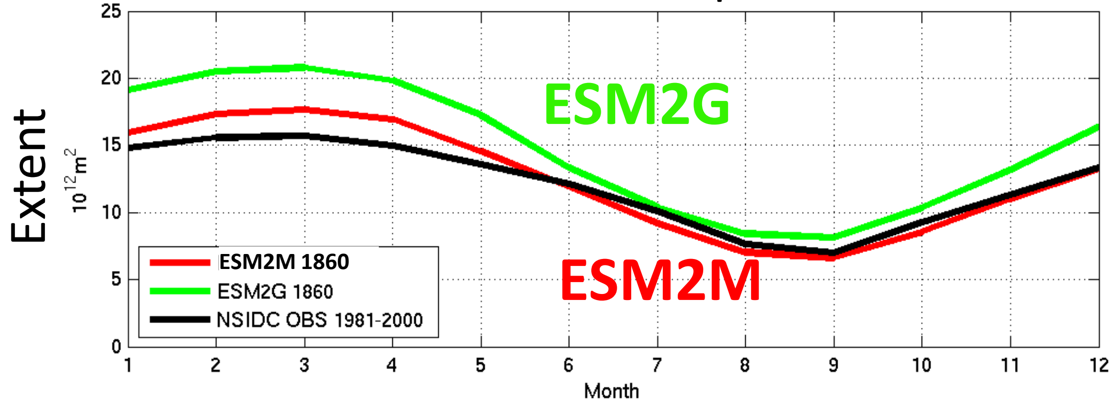


NASA SRB
ESM2M
ESM2G
TOA SW Albedo
Surf. SW Flux
Surf. SW Albedo
A) NASA SRB (1984–2007) TOA SW Albedo
B) ESM2M (Δ=0.0026, r²=0.93, σ=0.0026)
C) ESM2G (Δ=0.0054, r²=0.92, σ=0.0054)
0.12 0.16 0.2 0.24 0.28 0.32 0.36 0.4 0.44 0.48 0.52 0.56 0.6 0.64 0.68 0.72
G) NASA SRB (1984–2007) SW SFC DN (W m⁻²)
E) ESM2M (W m⁻², Δ=1.1, r²=0.95, σ=1.1)
F) ESM2G (W m⁻², Δ=0.84, r²=0.95, σ=0.84)
60 80 100 120 140 160 180 200 220 240 260 280 300
F) NASA SRB (1984–2003) SFC SW Albedo
H) ESM2M (Δ=−0.0033, r²=0.92, σ=−0.0033)
I) ESM2G (Δ=−0.001, r²=0.91, σ=−0.001)
0.04 0.08 0.12 0.16 0.2 0.24 0.28 0.32 0.36 0.4 0.44 0.48 0.52 0.56 0.6 0.64 0.68 0.72 0.76 0.8
80°N 40°N 0° 40°S 80°S
200°W 100°W 0° 100°E

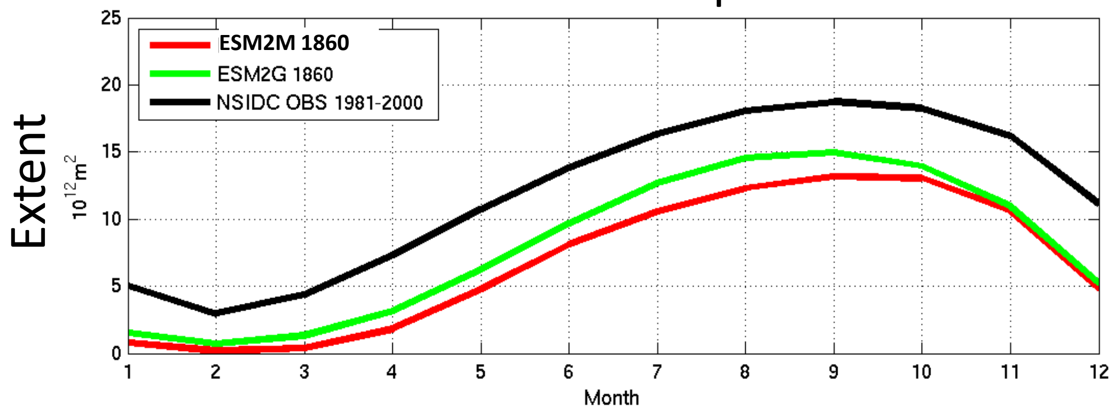

NASA SRB
ESM2M bias
ESM2G bias
TOA SW Albedo
Surf. SW Flux
Surf. SW Albedo
A) NASA SRB (1984–2007) TOA SW Albedo
B) ESM2M Bias (Δ=0.0026, r²=0.93, σ=0.0026)
C) ESM2G Bias (Δ=0.0054, r²=0.92, σ=0.0054)
G) NASA SRB (1984–2007) SW SFC DN (W m⁻²)
E) ESM2M Bias (W m⁻², Δ=1.1, r²=0.95, σ=1.1)
F) ESM2G Bias (W m⁻², Δ=0.84, r²=0.95, σ=0.84)
F) NASA SRB (1984–2003) SFC SW Albedo
H) ESM2M Bias (Δ=−0.0033, r²=0.92, σ=−0.0033)
I) ESM2G Bias (Δ=−0.001, r²=0.91, σ=−0.001)
80°N
40°N
0°
40°S
80°S
200°W
100°W
0°
100°E
0.12 0.16 0.2 0.24 0.28 0.32 0.36 0.4 0.44 0.48 0.52 0.56 0.6 0.64 0.68 0.72
−0.14 −0.1 −0.06 −0.02 0.02 0.06 0.1 0.14
60 80 100 120 140 160 180 200 220 240 260 280 300
−44 −36 −28 −20 −12 −4 4 12 20 28 36 44
0.04 0.08 0.12 0.16 0.2 0.24 0.28 0.32 0.36 0.4 0.44 0.48 0.52 0.56 0.6 0.64 0.68 0.72 0.76 0.8
−0.26 −0.22 −0.18 −0.14 −0.1 −0.06 −0.02 0.02 0.06 0.1 0.14 0.18 0.22 0.26

Sea Ice Extent

Northern Hemisphere



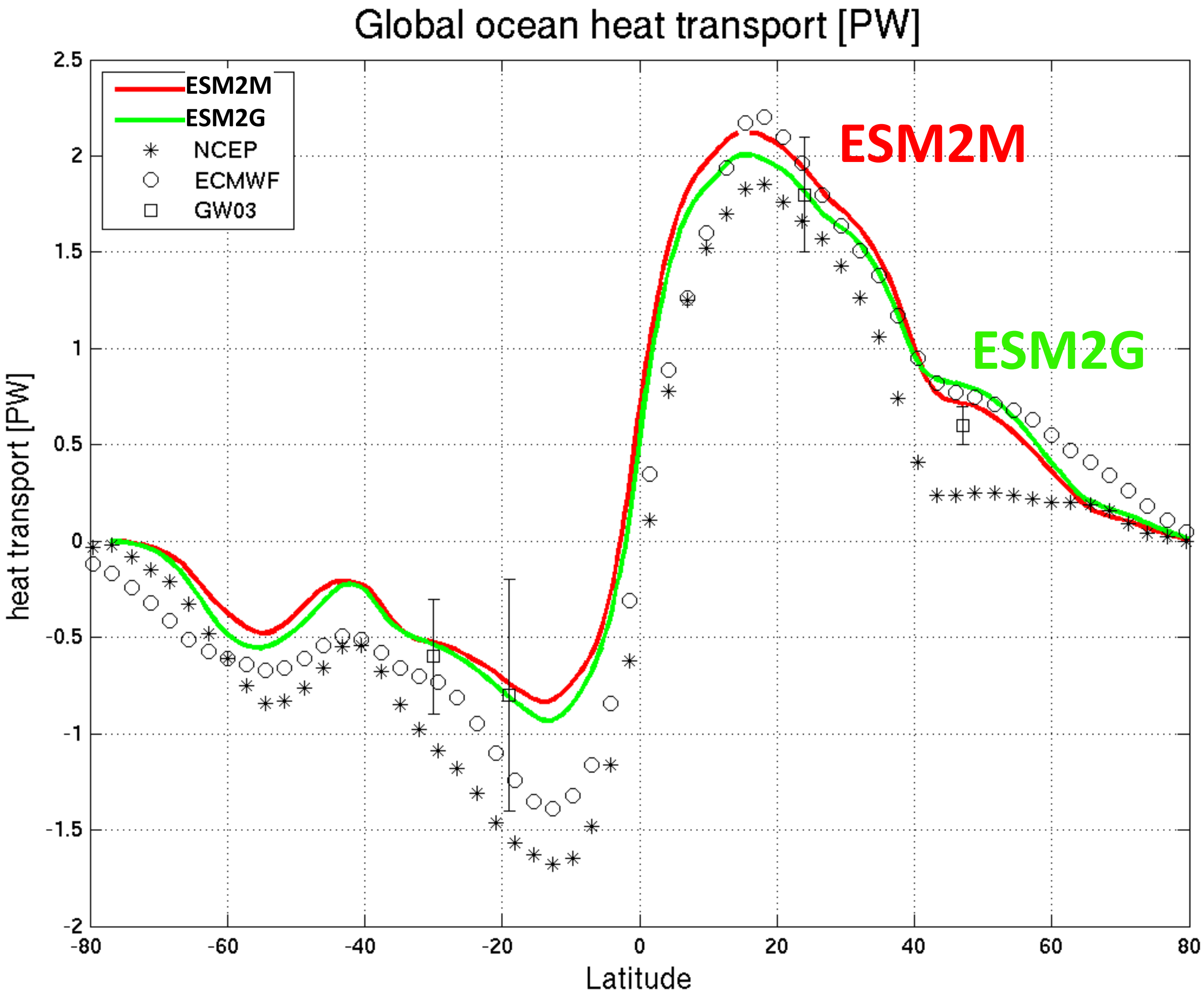
Southern Hemisphere



ESM2G has too much in the North.

Both models have too little in the South, though ESM2G has more.

Poleward Ocean Heat Transport



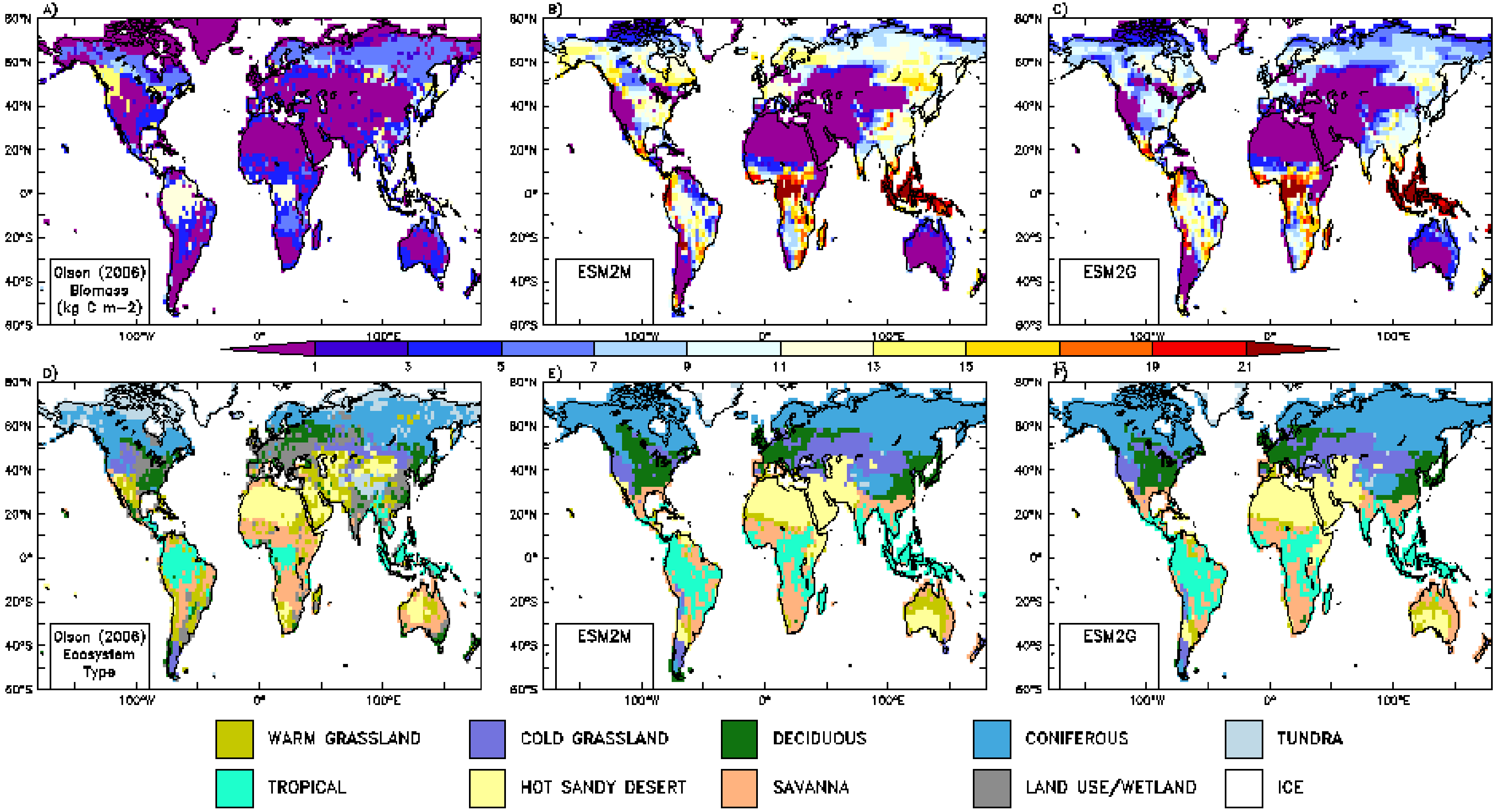
ESM2M and ESM2G are very similar

LM3 allows competition between vegetation types

Olson (2006) ESM2M ESM2G

Potential Biomass

Veg Type



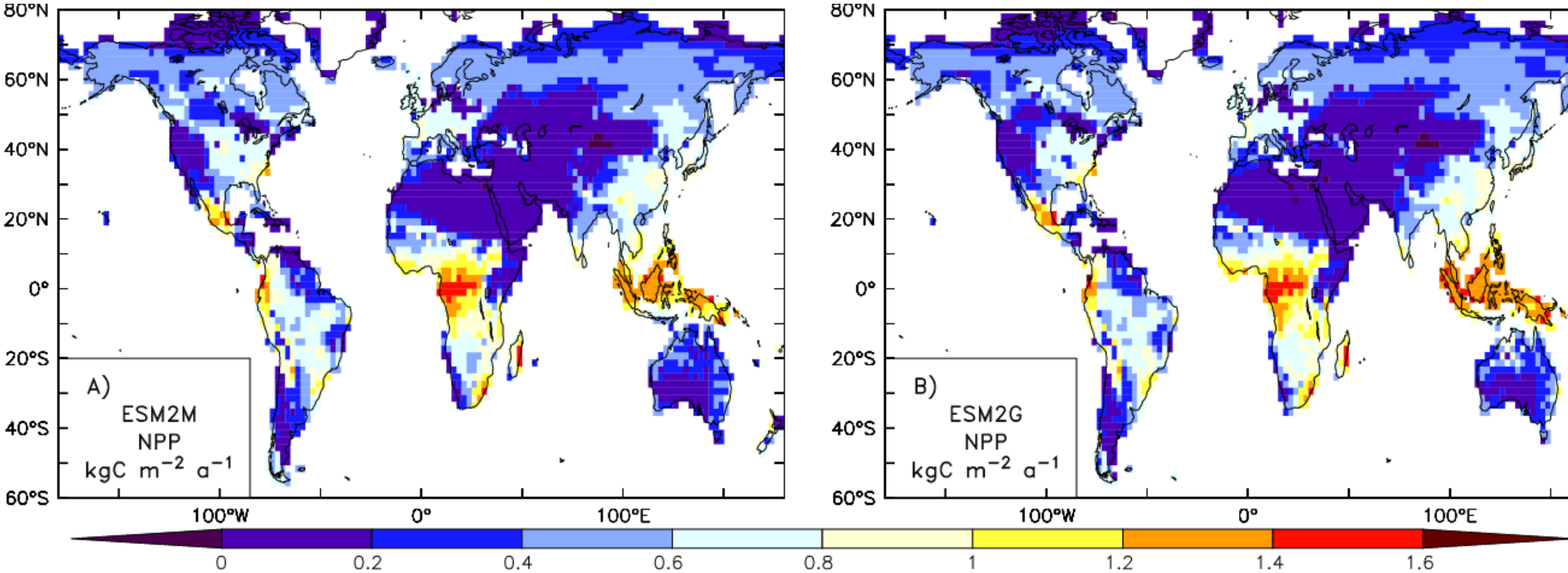
Biomass in the right place, but perhaps too much of it

Captures broad-scale boundaries: desert-savanna-tropical; coniferous-deciduous

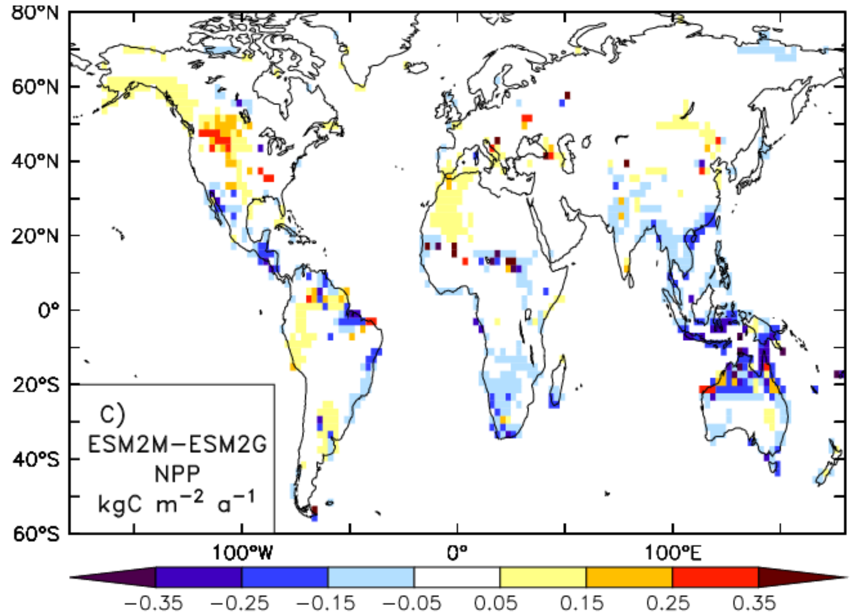
Very Similar Land Net Primary Production

ESM2M

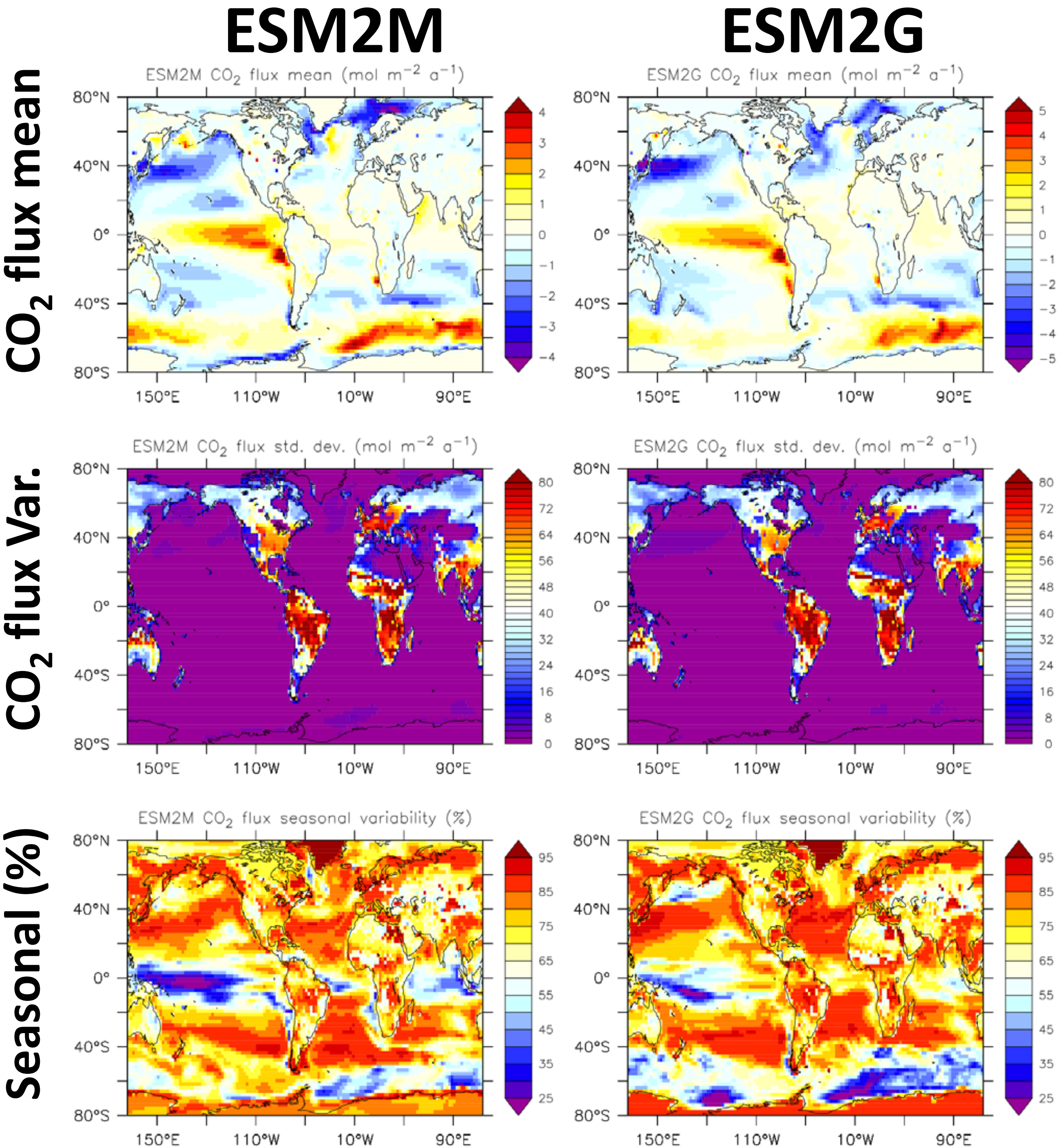
ESM2G



ESM2M-ESM2G



Very similar overall
ESM2M has less NPP in Oceania
ESM2M more in W. Canada

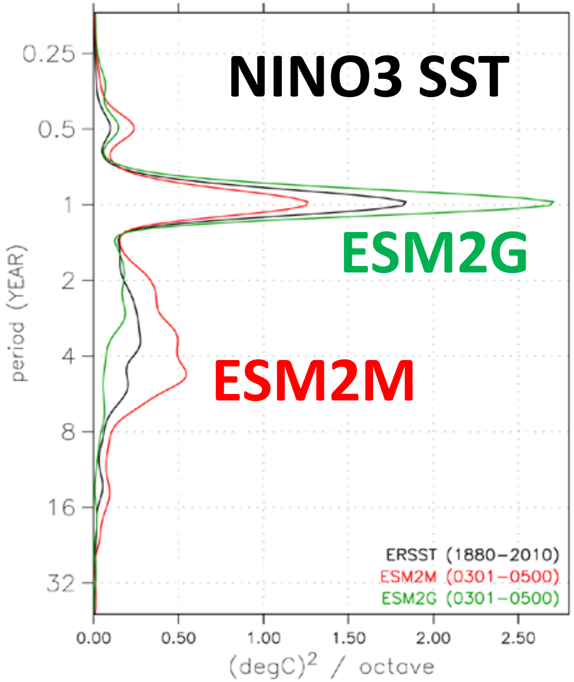


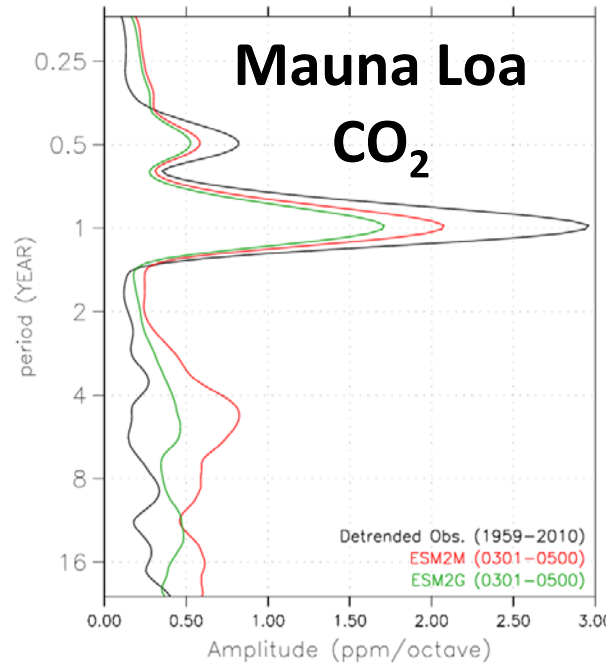
Mean fluxes show the ocean carbon pumps

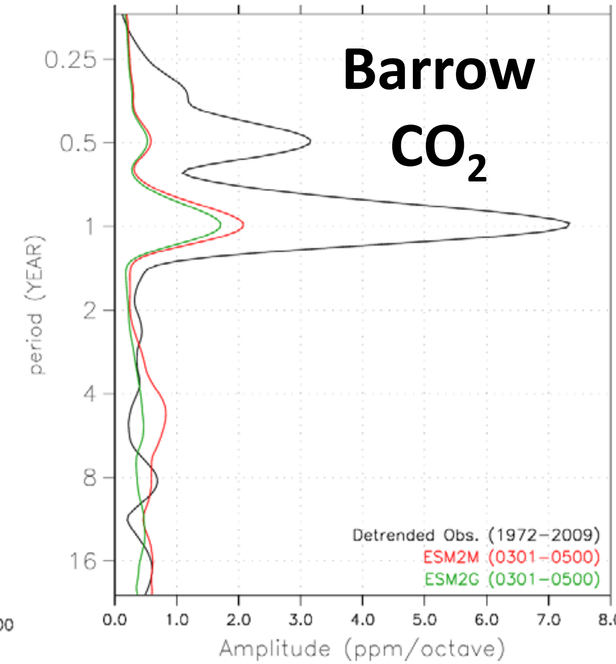
Flux variability shows the terrestrial cycle

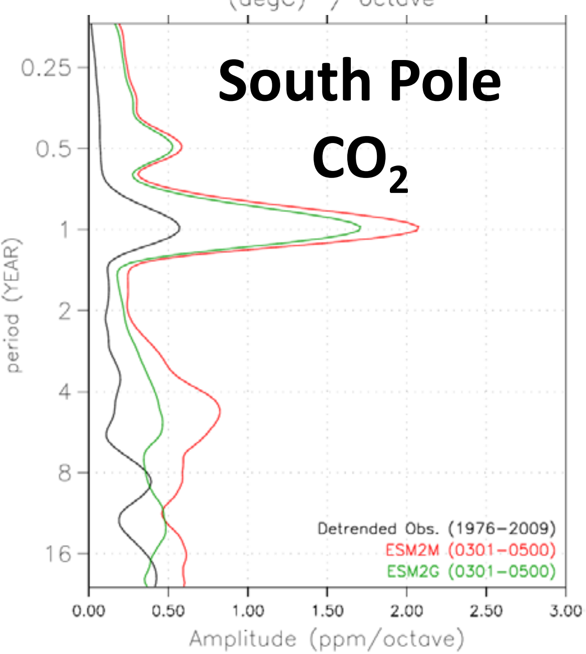
Most of the variability is in the seasonal cycle, except for ENSO (esp. ESM2M) and SO (esp. ESM2G)

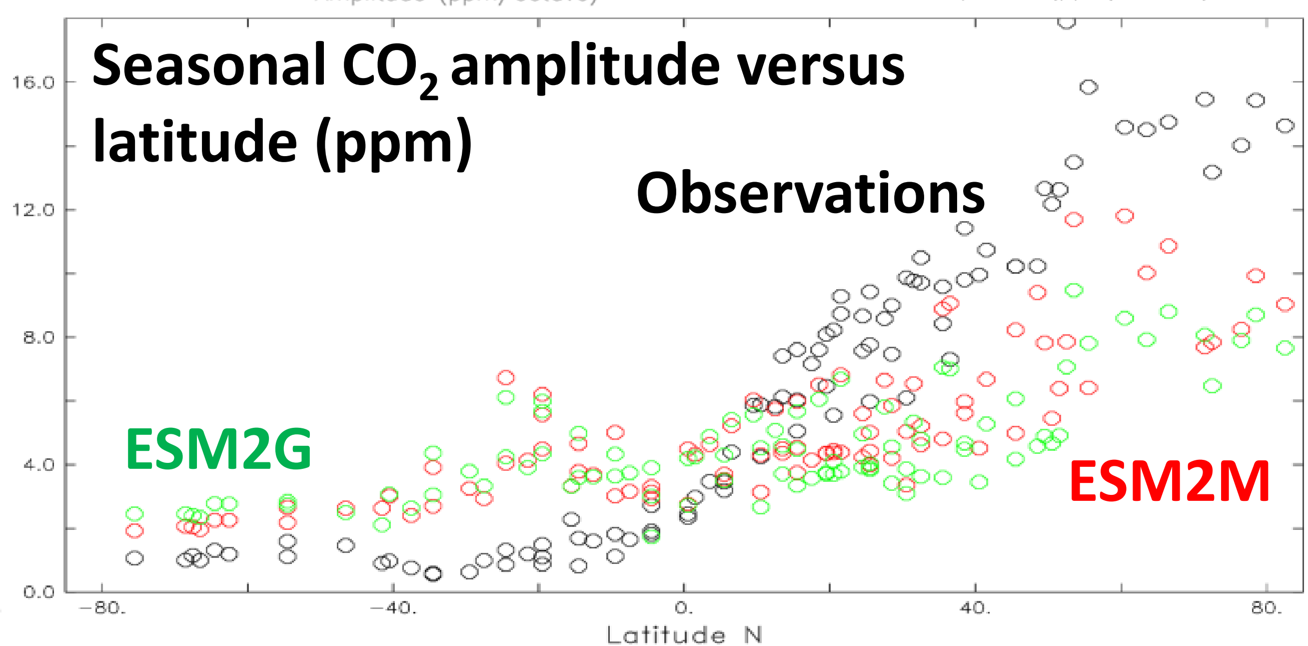
Is the climate and CO_2 variability realistic?







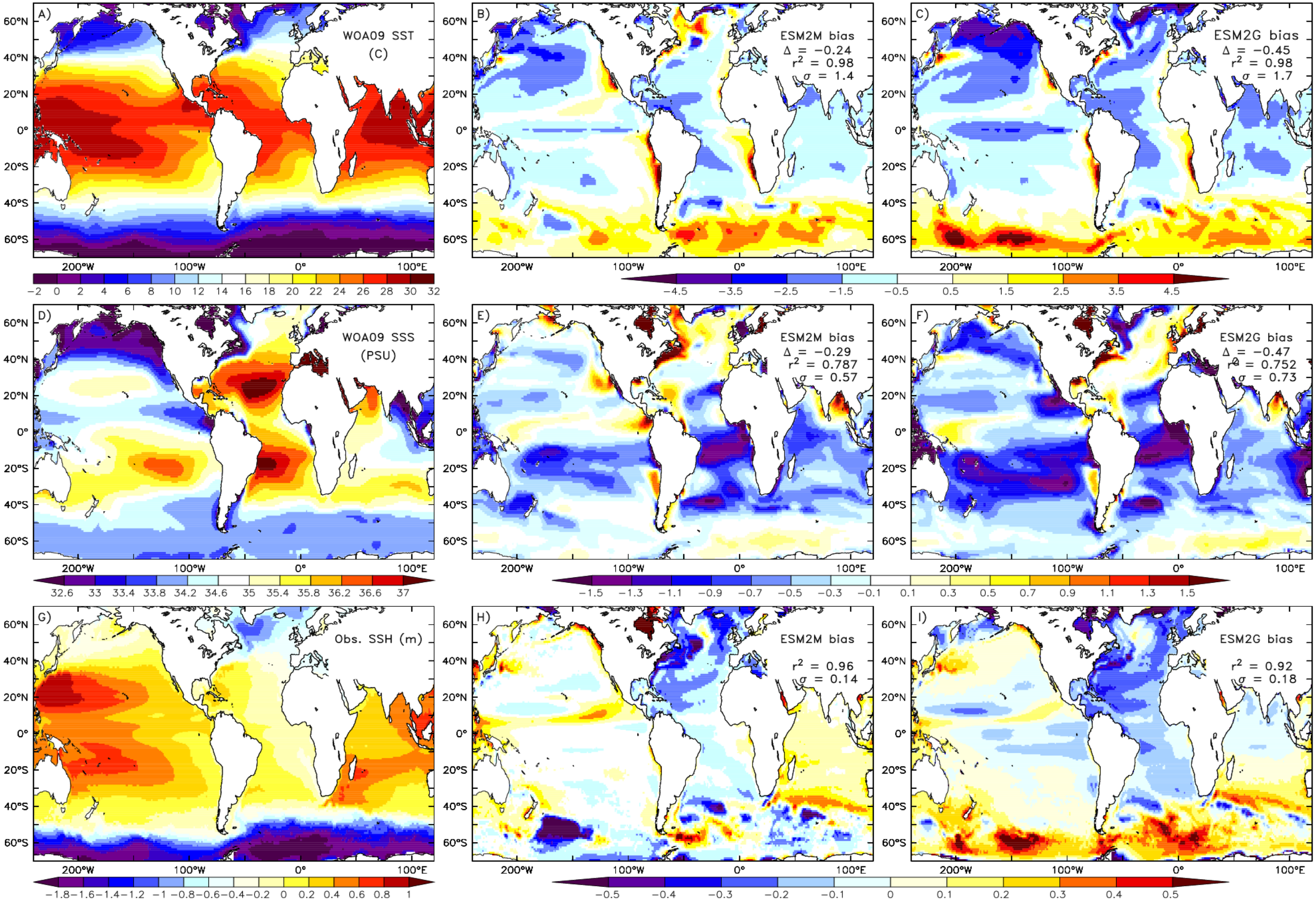




Similar Surface Ocean Physical Bias Patterns

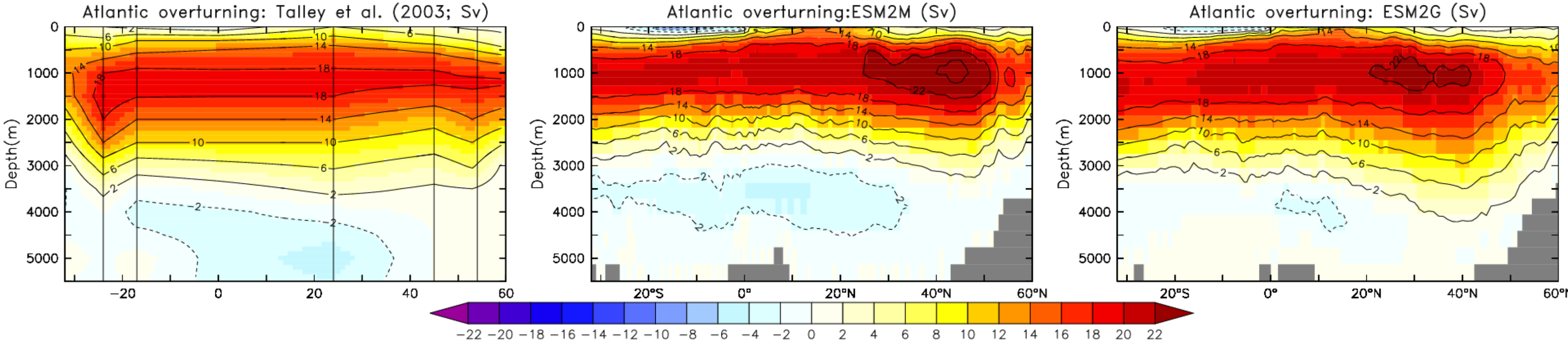
Observations | ESM2M bias | ESM2G bias

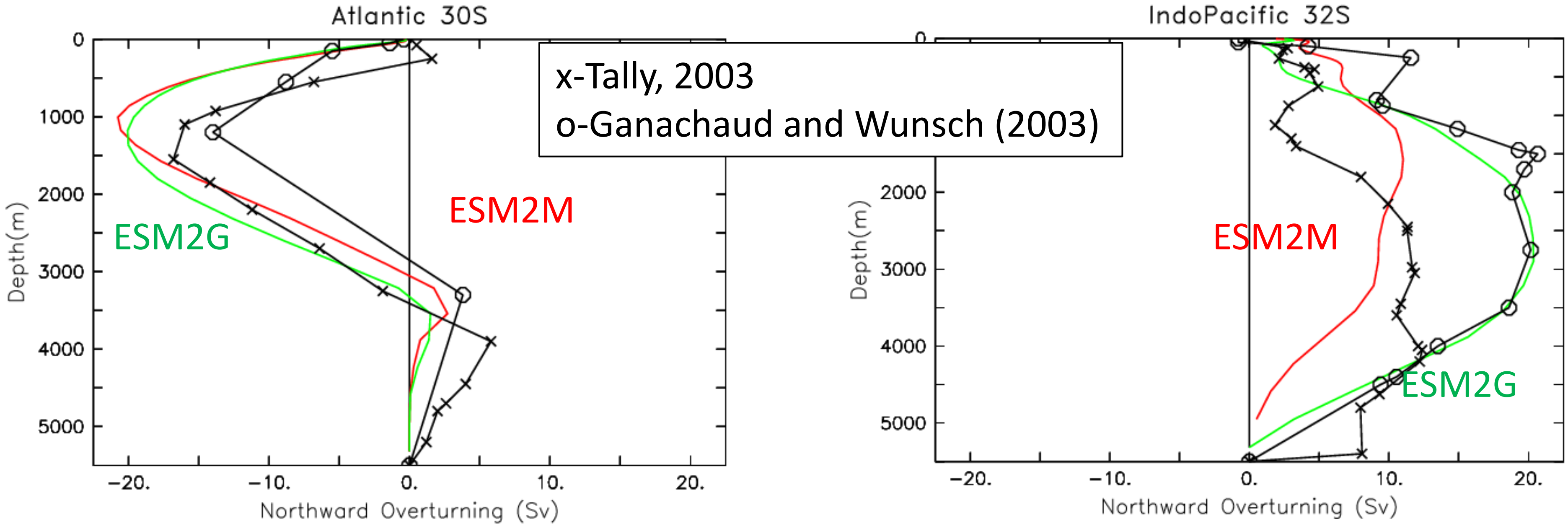
SS Temperature / SS Salinity / SS height



Similar NADW Overturning Streamfunctions

'Observations' ESM2M ESM2G



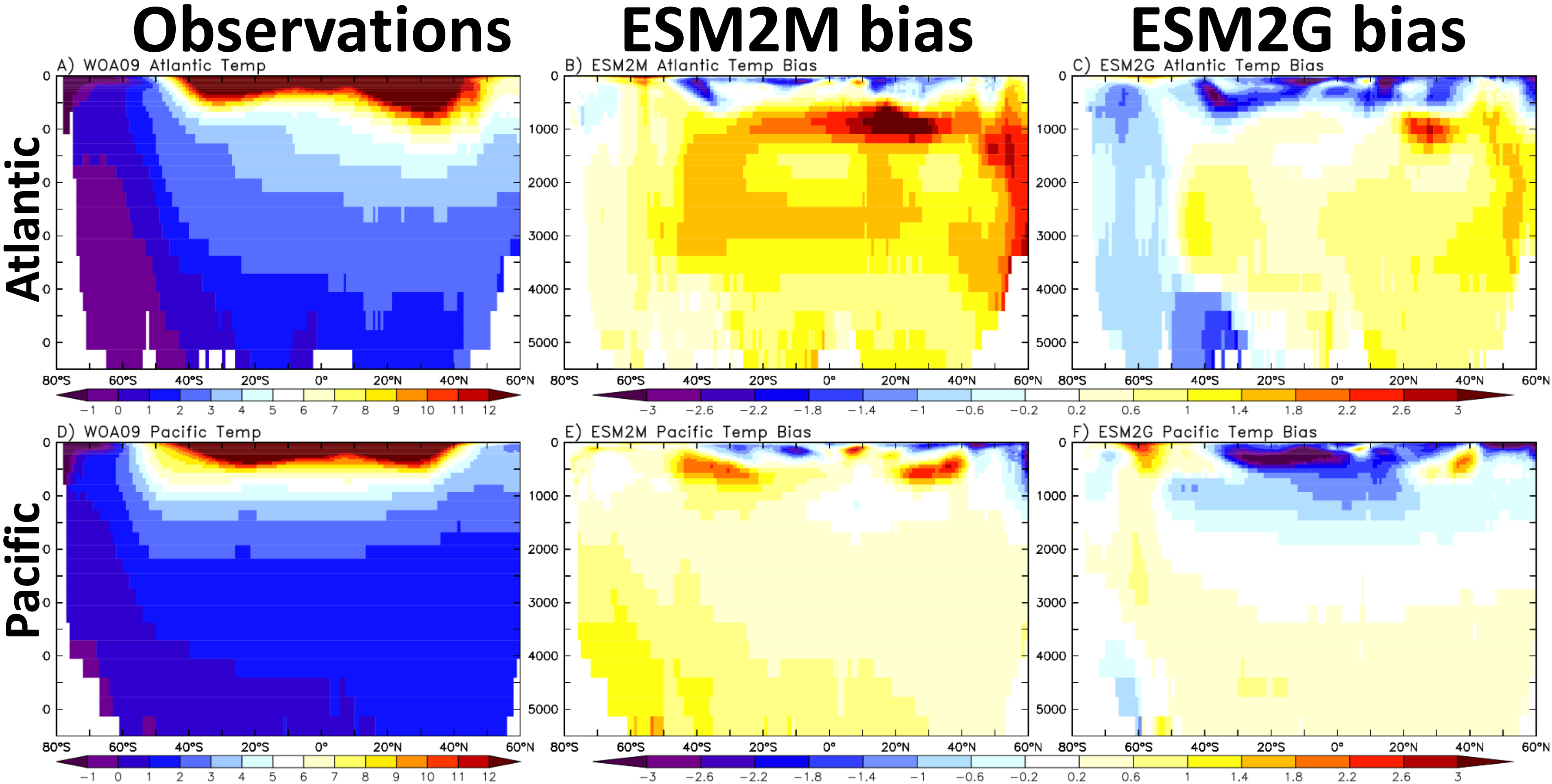


Both have robust North Atlantic Deep Water (NADW) formation

ESM2G has deeper NADW penetration

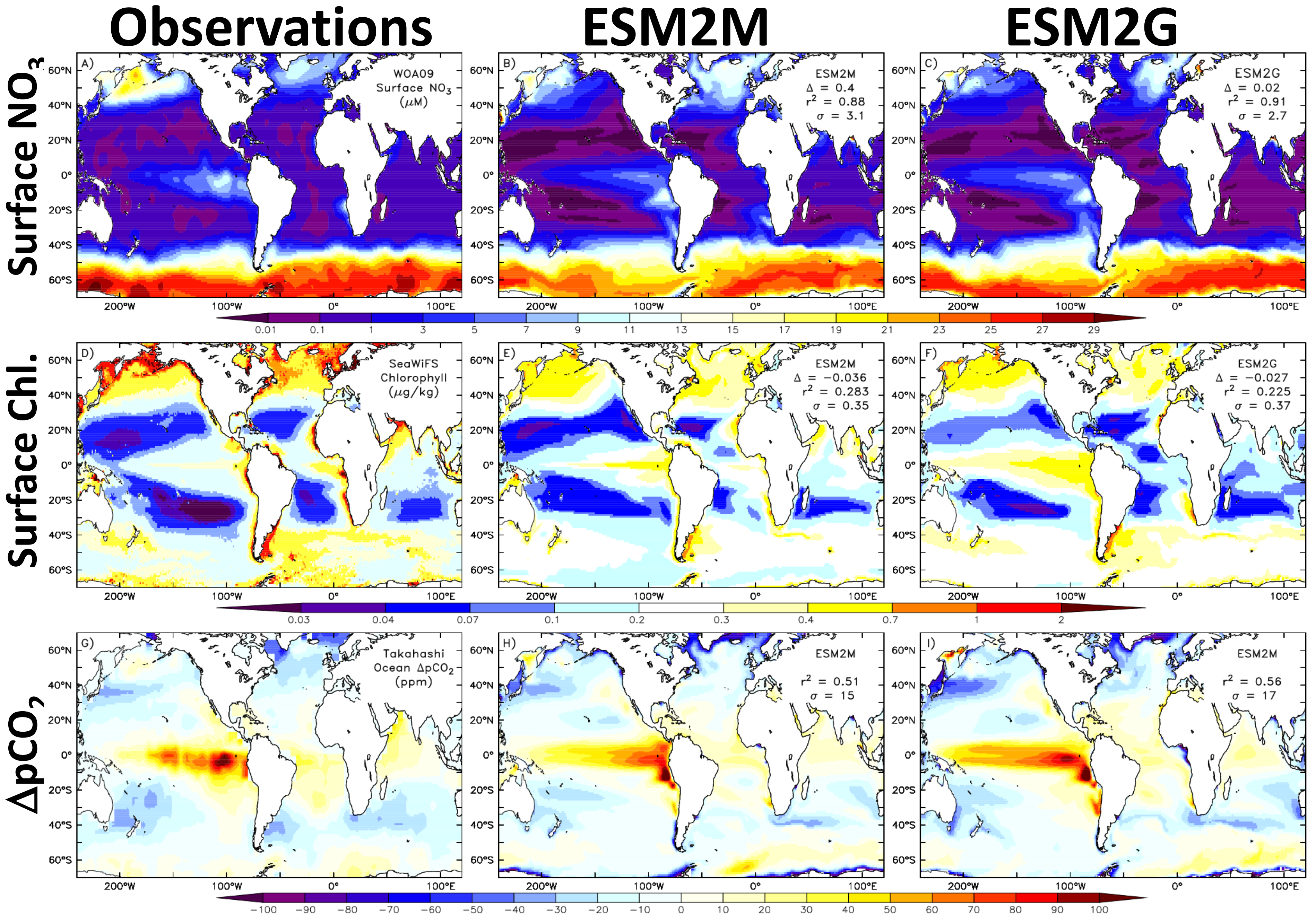
ESM2G has more AABW in IndoPacific

Basin Temperature Comparison

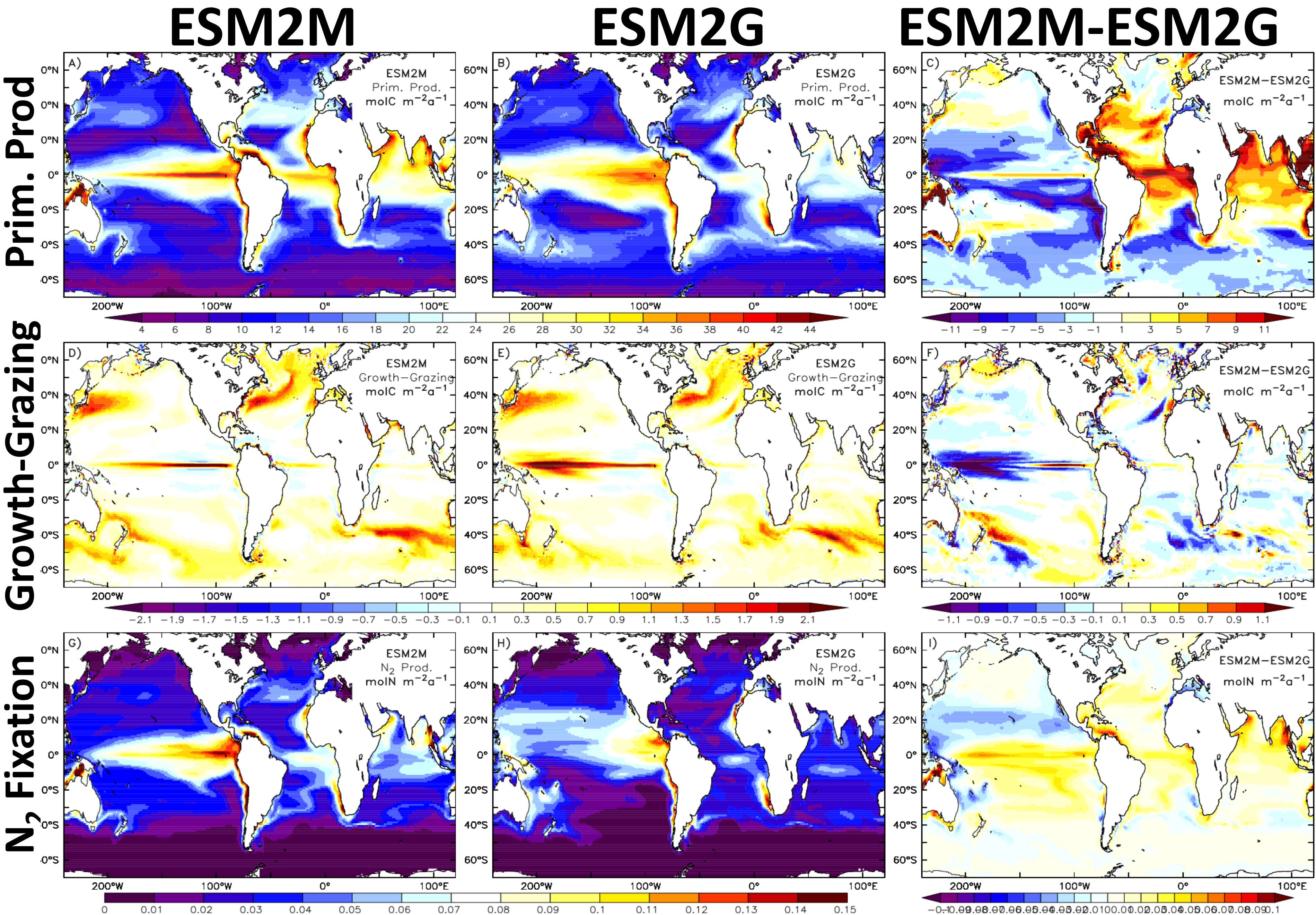


Relative to ESM2M, ESM2G has much reduced warm biases in NADW, Antarctic Bottom Water, and Intermediate waters, but adds additional cold bias in the thermocline and Atlantic sector of Southern Ocean.

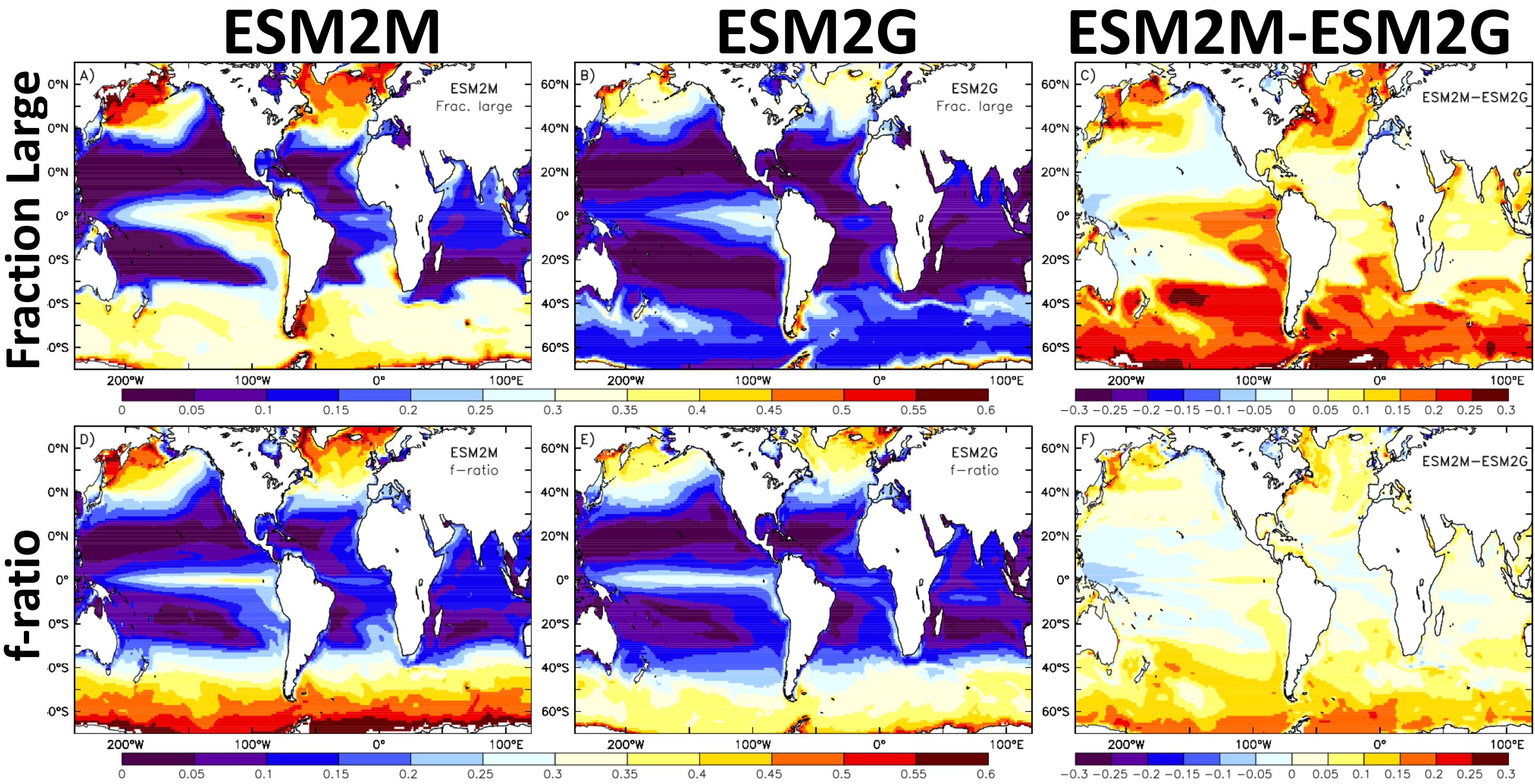
Similar Surface Ocean Biogeochemical Signatures



Moderate Differences in Productivity Patterns



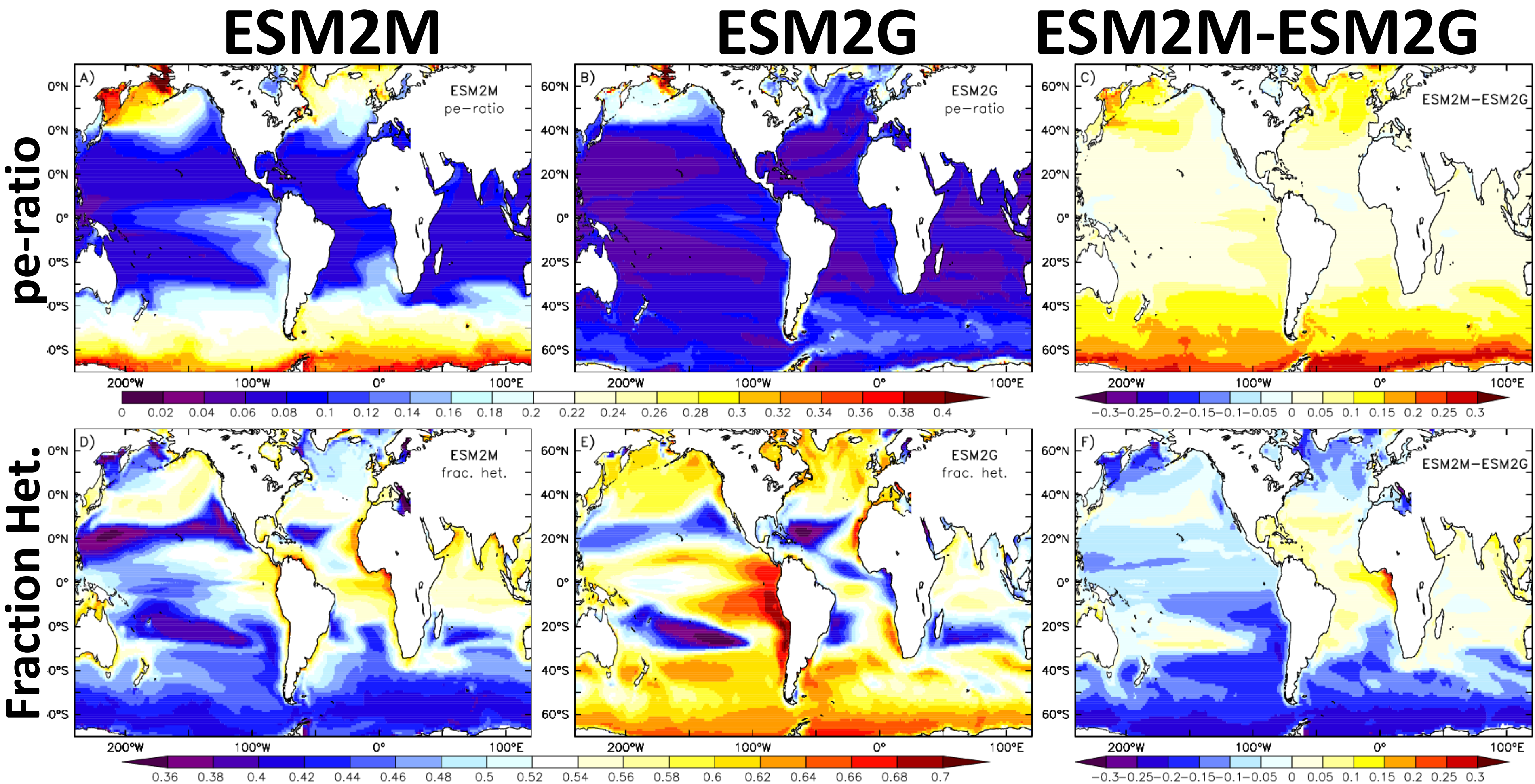
Large differences in phytoplankton ecology



Fraction Large = biomass large / (biomass: large + small + diazotrophs)

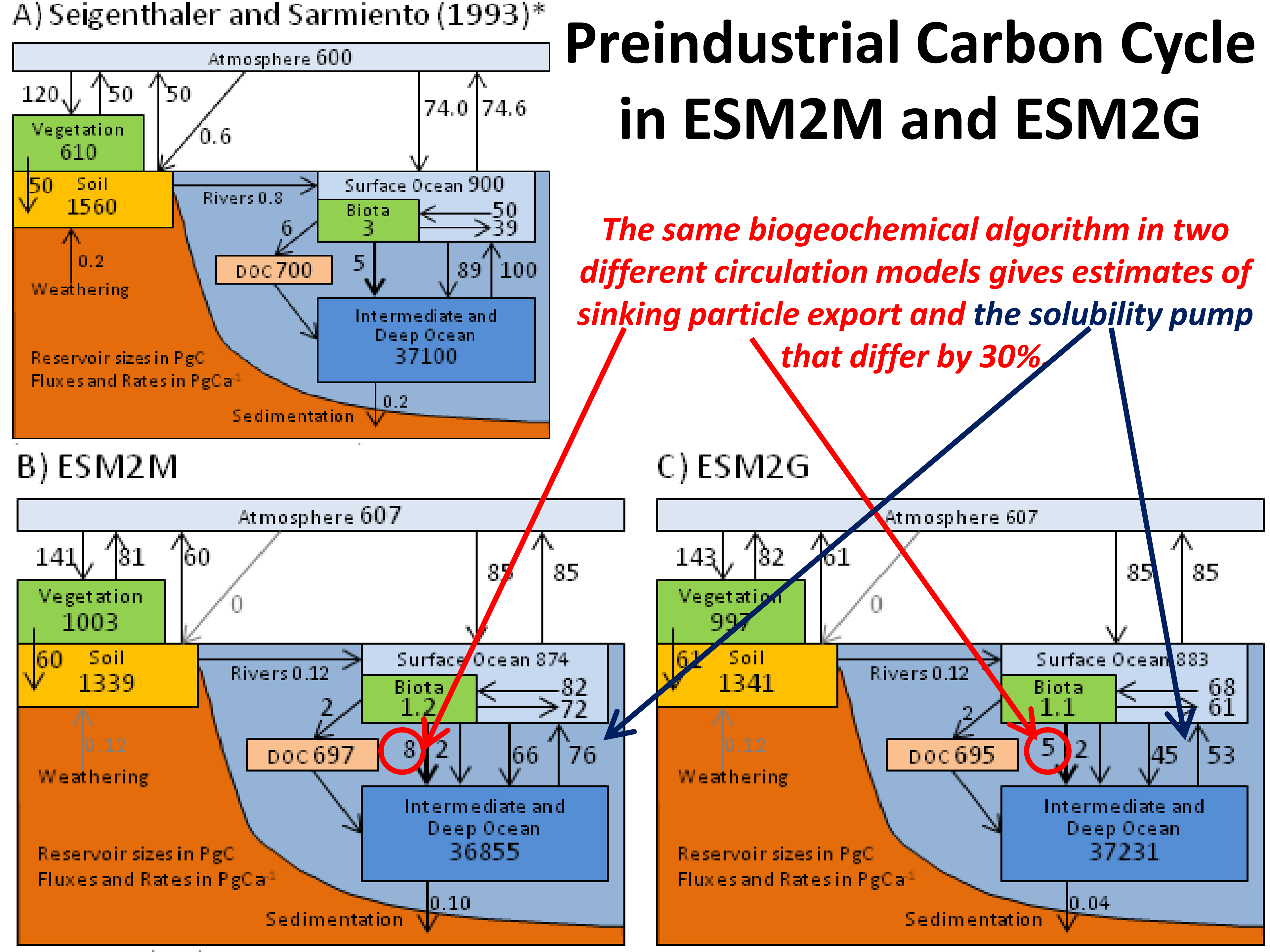
f-ratio = $Prod_{NO3}$ / ($Prod_{N2}$ + $Prod_{NH4}$ + $Prod_{NO3}$)

Large differences in ecosystem recycling



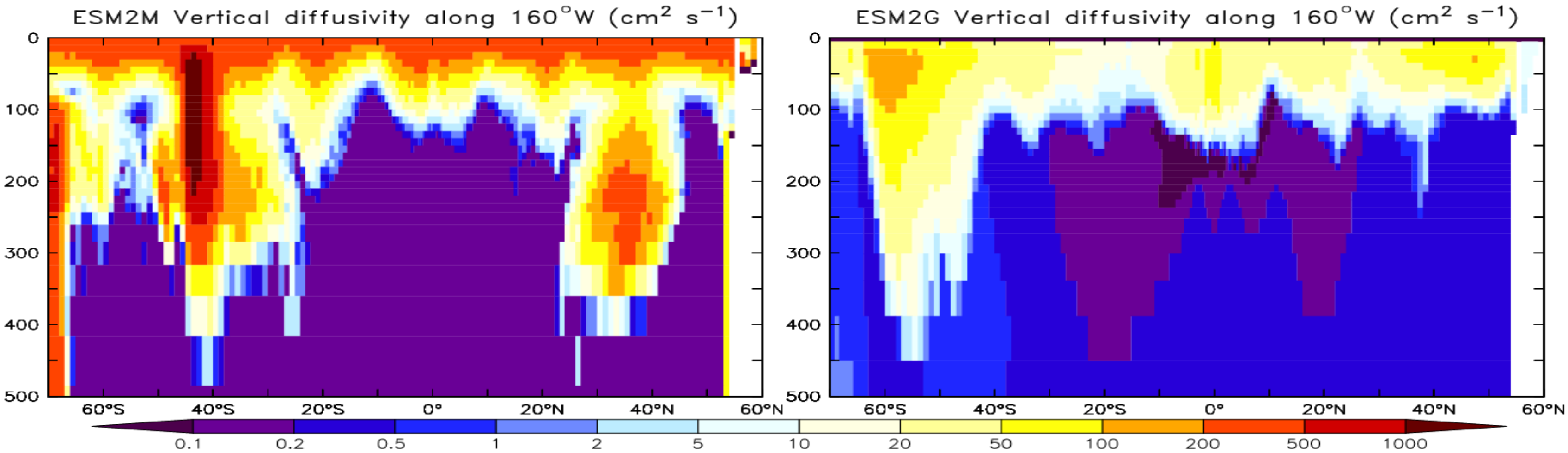
pe-ratio = Sinking flux at 100 m / ($Prod_{N2}$ + $Prod_{NH4}$ + $Prod_{NO3}$)

Fraction Het. = (Heterotrophic Biomass) / (Heterotrophic Biomass + Phytoplankton Biomass)


Preindustrial Carbon Cycle
in ESM2M and ESM2G
The same biogeochemical algorithm in two different circulation models gives estimates of sinking particle export and the solubility pump that differ by 30%.
A) Seigenthaler and Sarmiento (1993)*
Atmosphere 600
120
50
50
0.6
74.0
74.6
Vegetation
610
50
Soil
1560
Rivers 0.8
Surface Ocean 900
Biota
3
50
39
6
DOC 700
5
89
100
0.2
Weathering
Intermediate and
Deep Ocean
37100
Reservoir sizes in PgC
Fluxes and Rates in PgCa-1
0.2
Sedimentation
B) 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
Reservoir sizes in PgC
Fluxes and Rates in PgCa-1
0.10
Sedimentation
C) 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
Reservoir sizes in PgC
Fluxes and Rates in PgCa-1
0.04
Sedimentation

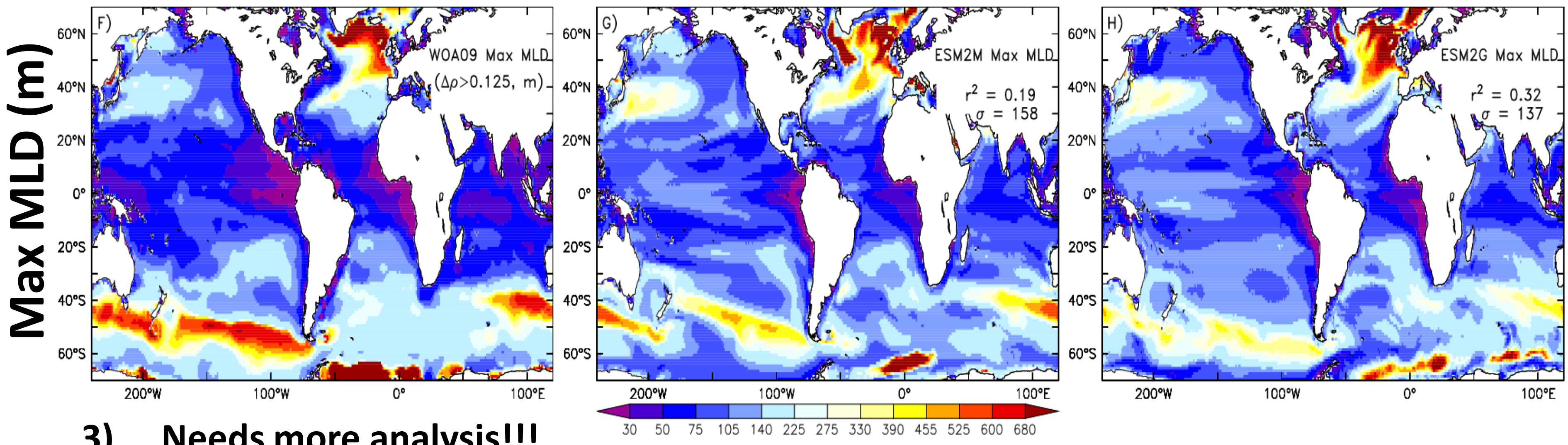
Why are their carbon pumps so different?

1) **Lower shallow mixing in ESM2G limits nutrient supply and promotes recycling**



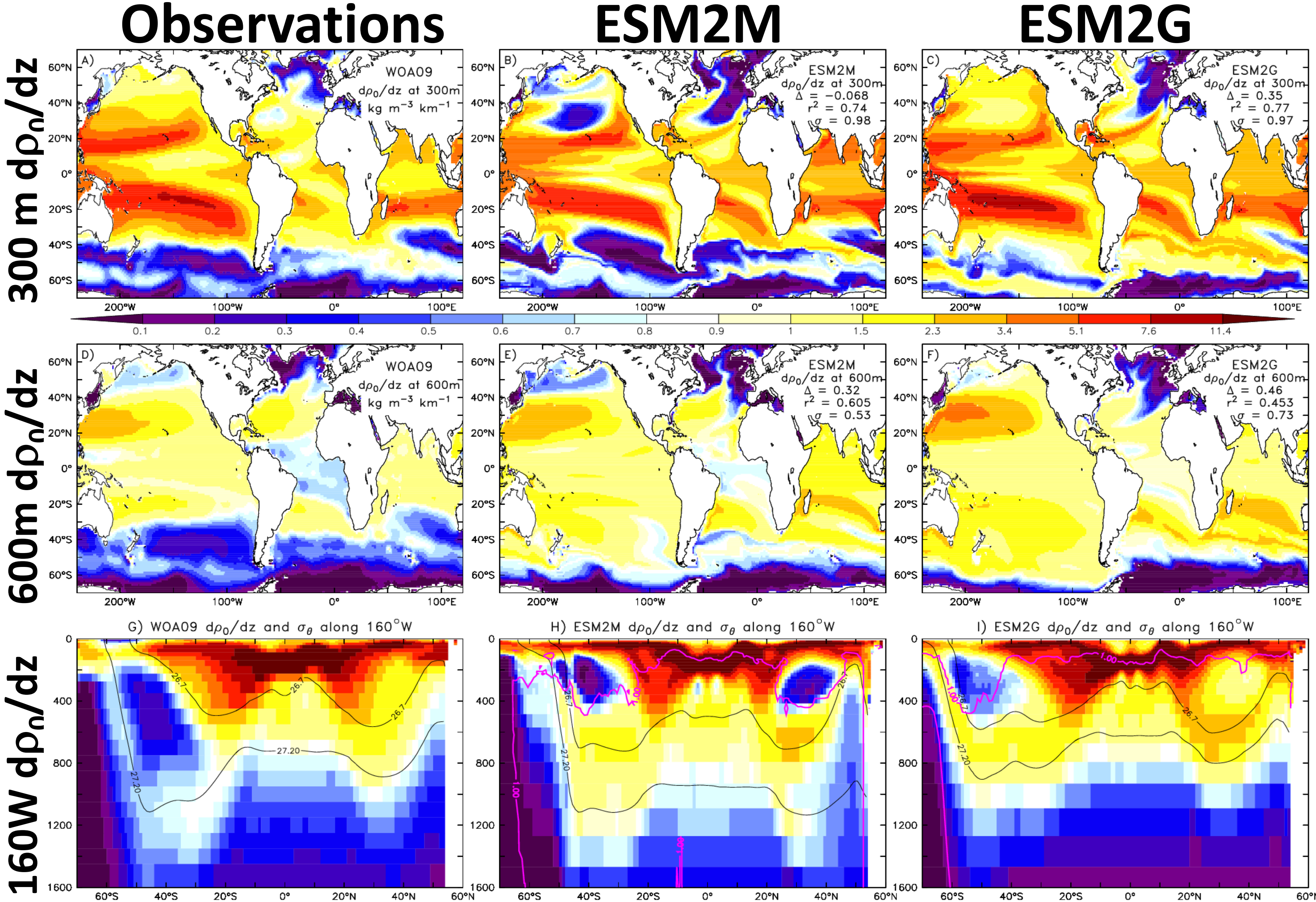
2) **Shallow Southern Ocean subduction limits ventilation in both, but more in ESM2G**

Observations ESM2M ESM2G

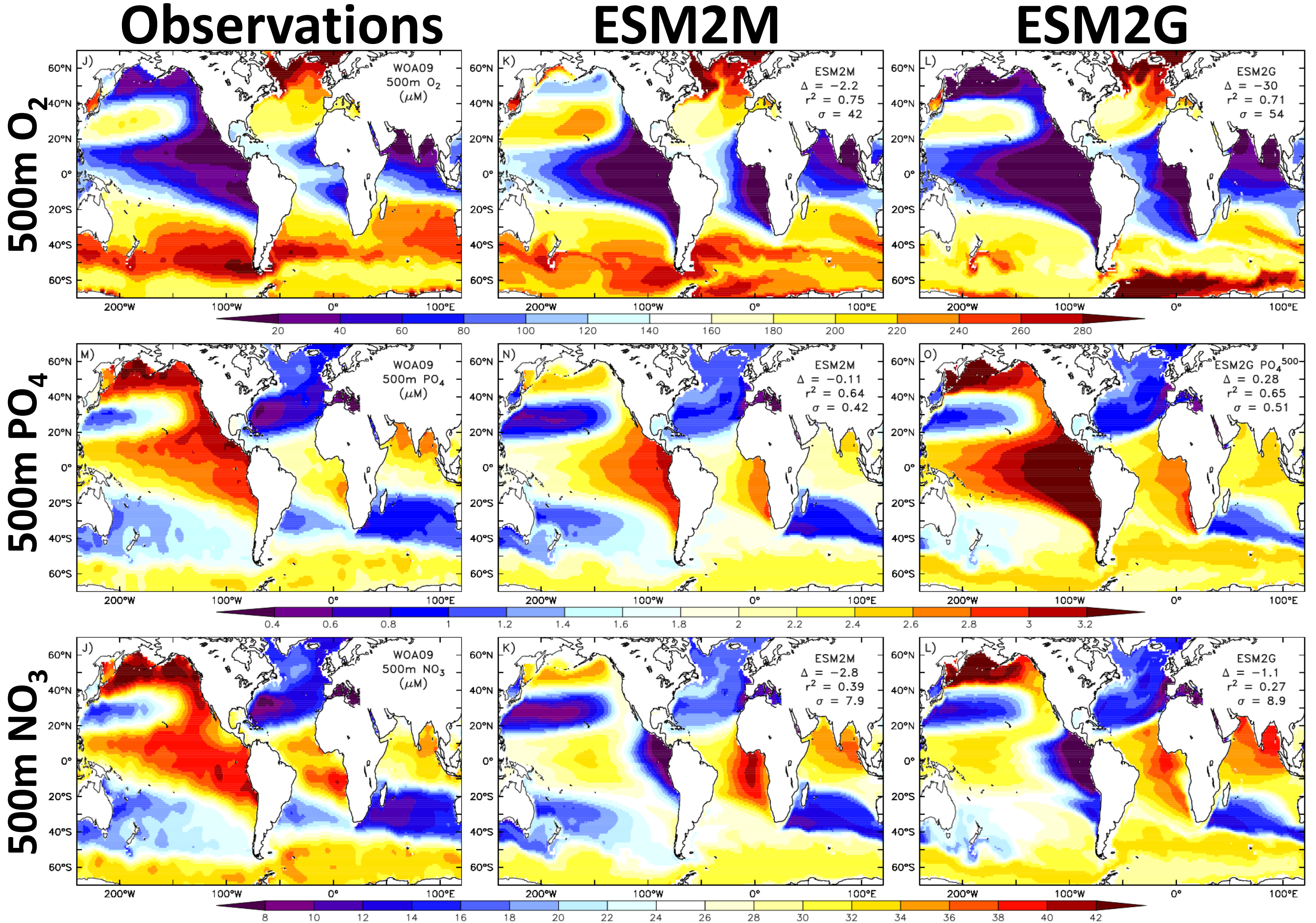


3) **Needs more analysis!!!**

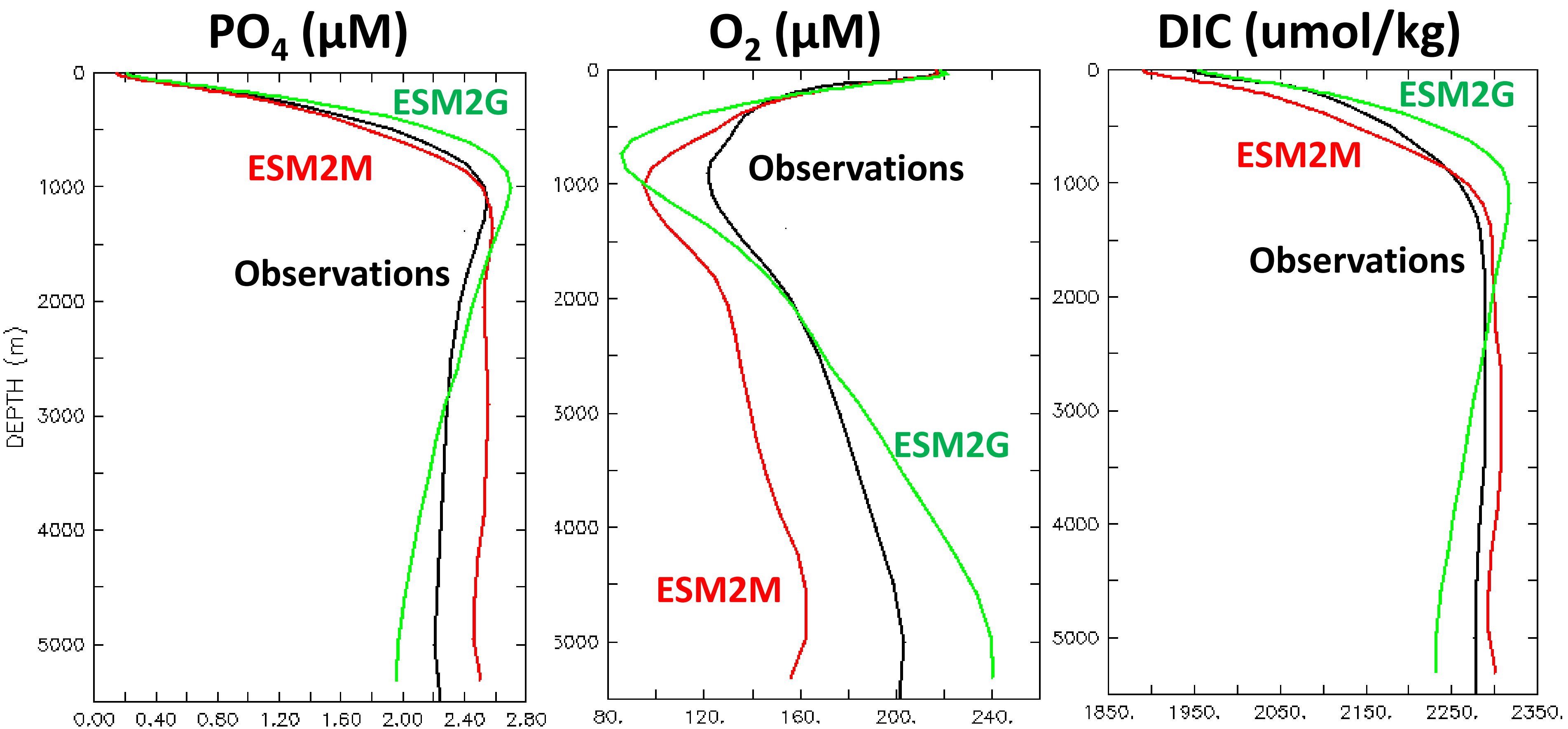
Mode water formation a critical factor for BGC



Biogeochemical similarities and differences at 500m



Pacific 40°S-40°N Averages: Classic Goldilocks



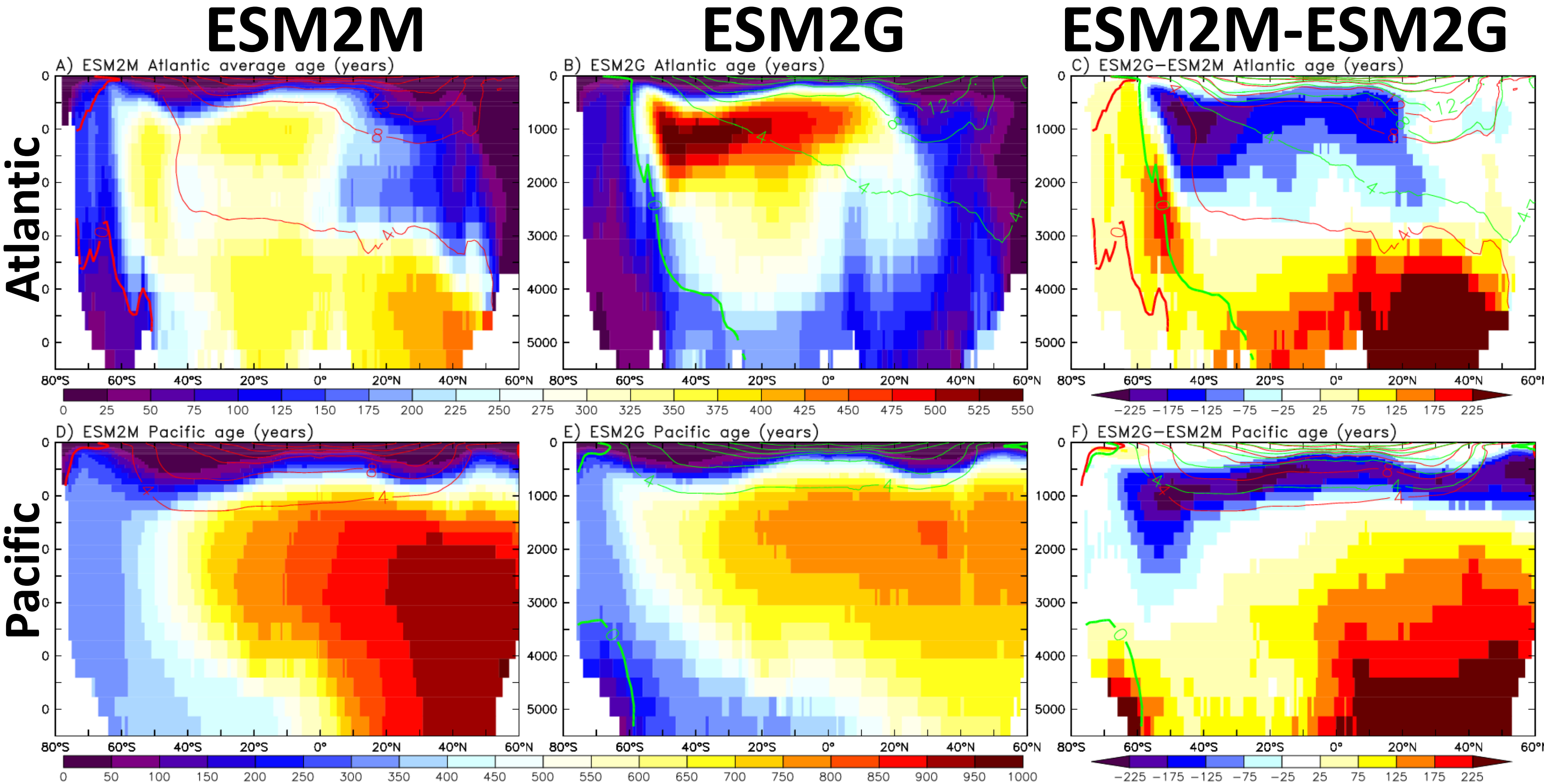
ESM2G's nutricline and oxycline too shallow, while ESM2M's is too deep.

ESM2G too much O_2 at the bottom, ESM2M too little.

ESM2M too much PO_4 and DIC at the bottom, ESM2M too little.

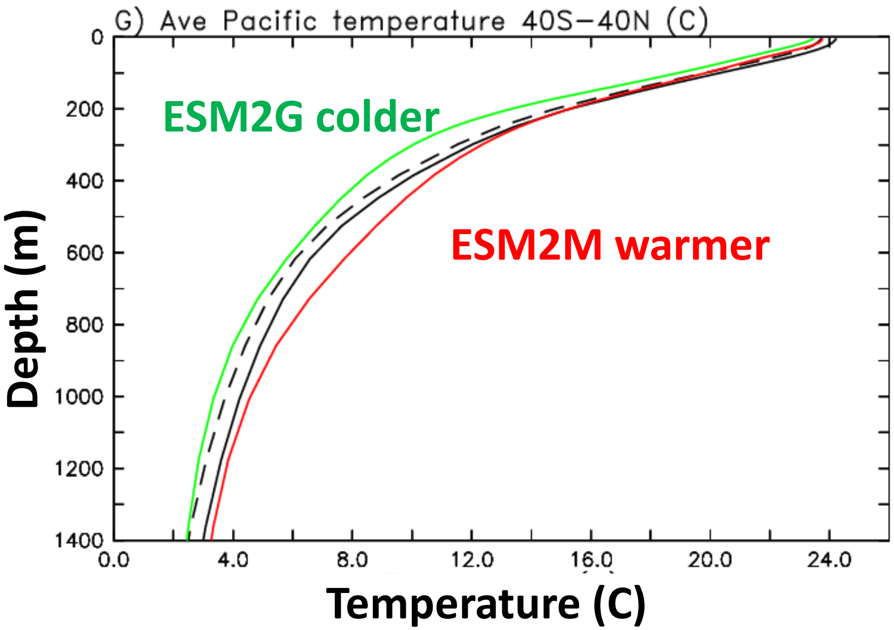
Both models over-express the O_2 minimum.

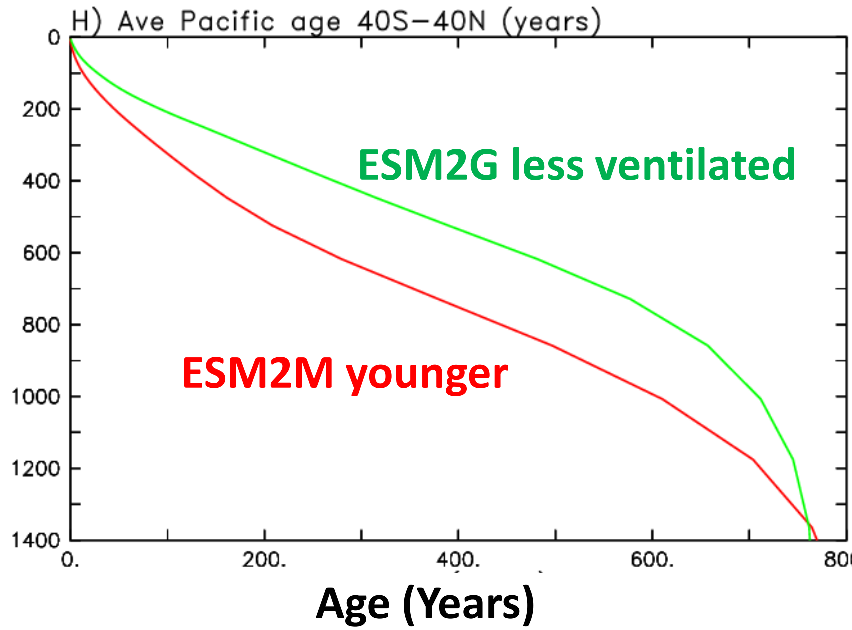
Basin age relative to surface ventilation

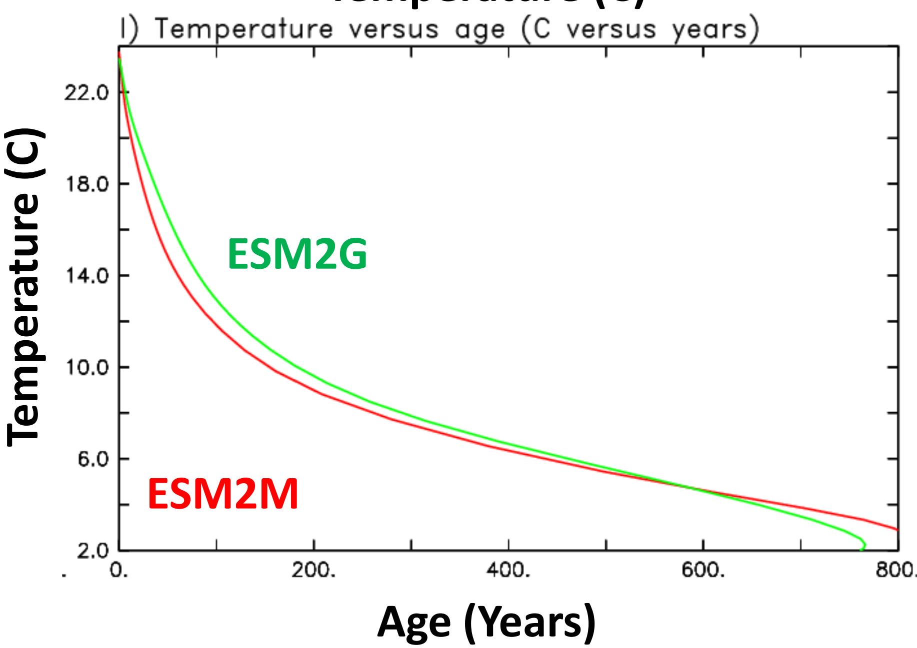


ESM2M much younger than ESM2G between 500-1000 m, particularly at 40S.
ESM2M much older than ESM2G in abyssal N. Atlantic and North Pacific

Though thermocline ventilation in ESM2M and ESM2G may look very different, the underlying advective pathways are very similar.







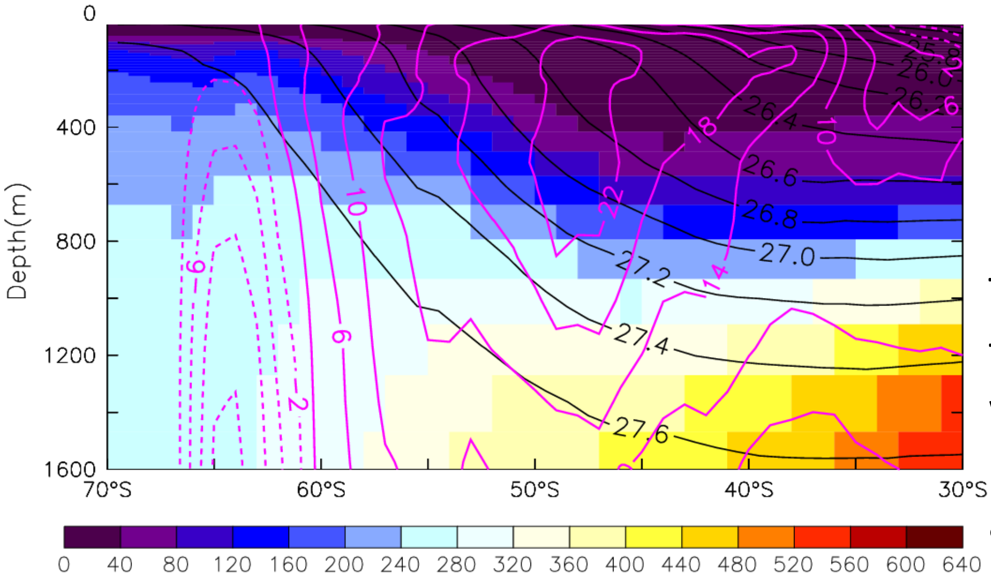
Global Warm Water Sphere (>8C)

Source	V (10^{15} m^3)	Age (Yr)	Ventilation (Sv)
WOA09	135-145	???	???
ESM2M	177	103	54
ESM2G	132	102	41

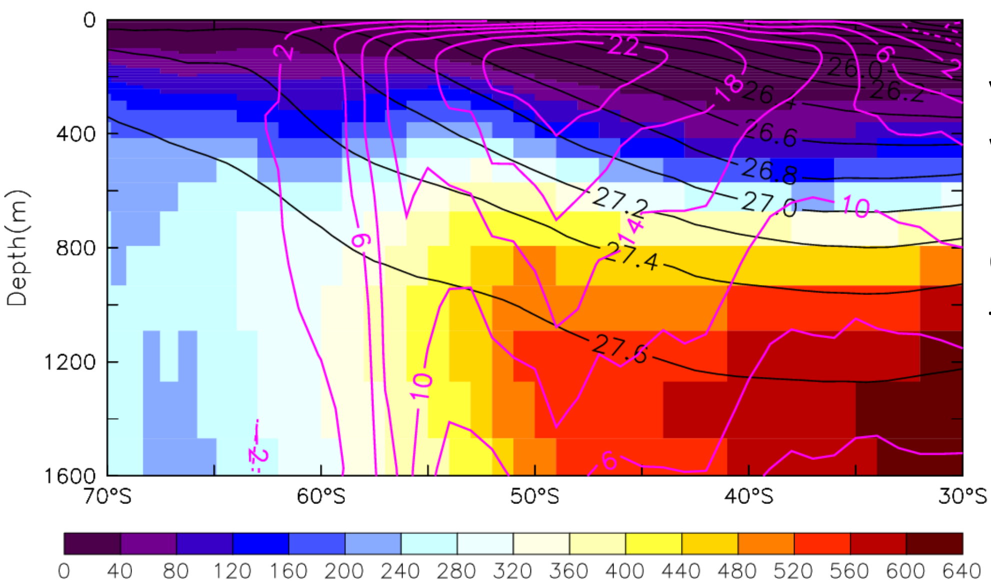
Smaller warm water sphere in ESM2G, but similar age within it for 31% more ventilation in ESM2M than ESM2G.

Example: Southern Ocean Subduction/Ventilation

ESM2M



ESM2G



Maximum overturning stream function (pink) penetrates about 400 m more deeply in ESM2M than ESM2G.

This allows density contours (black) in ESM2M to be much more steep (and more consistent with observations)

and youngest waters (deep purple) to penetrate much more deeply in ESM2M.

ESM2M stimulates convection throughout the year, priming the low stratification region for wintertime mixing.

Causality goes to a variety of differences in the numerics between the two models.

Implications for GFDL's contributions to Coupled Carbon-Climate efforts in CMIP5

Successes

- Coupled carbon through dynamic vegetation without degrading CM2.1 climate
- Swapped ocean component to GOLD isopycnal model without altering other components
  - Improved North Pacific and several other water masses
  - Allows powerful opportunities for exploration and attribution of sensitivities.
- Models valuable for approaching a variety of science questions.

Ongoing challenges

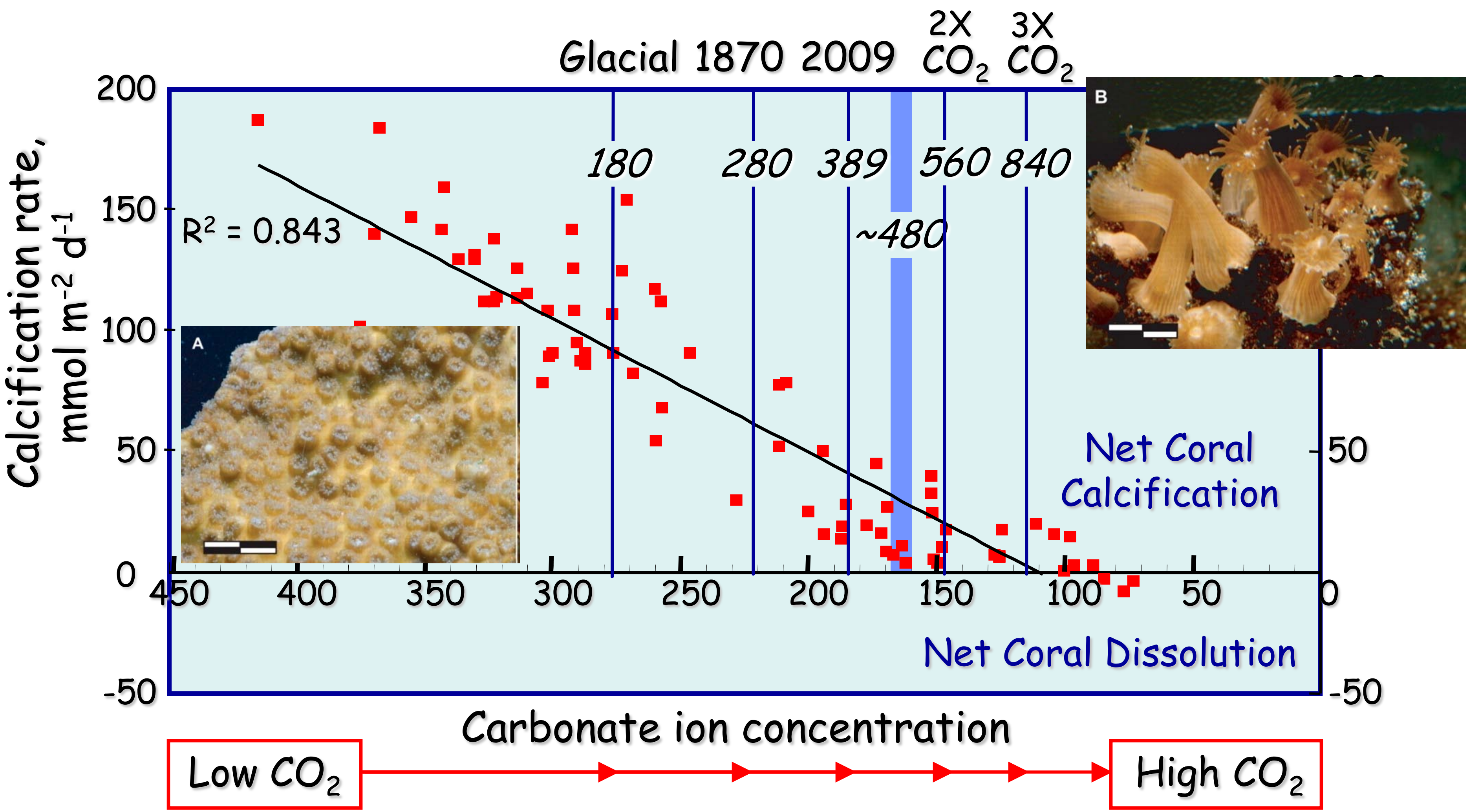
- CM2.1 atmospheric biases remain:
  - Eq. cold bias, dry Amazon, double ITCZ, warm Southern Ocean, cold North Polar region, poor boundary currents
- ESM2G would benefit from further development (both physics and BGC)
- CFC and other tracer simulations should prove helpful in attribution.
- Overall, we expect current biases to underestimate Southern Ocean heat and carbon uptake in both models, with ESM2M overestimating northern uptake.
- Lot's more work to do determine coupled carbon climate feedbacks!
  - Logistics of spinup and development are paramount
  - Looking toward building collaborations
- Also looking to couple additional cycles such as Iron, Nitrogen, CH_4 and others

Extra Slides

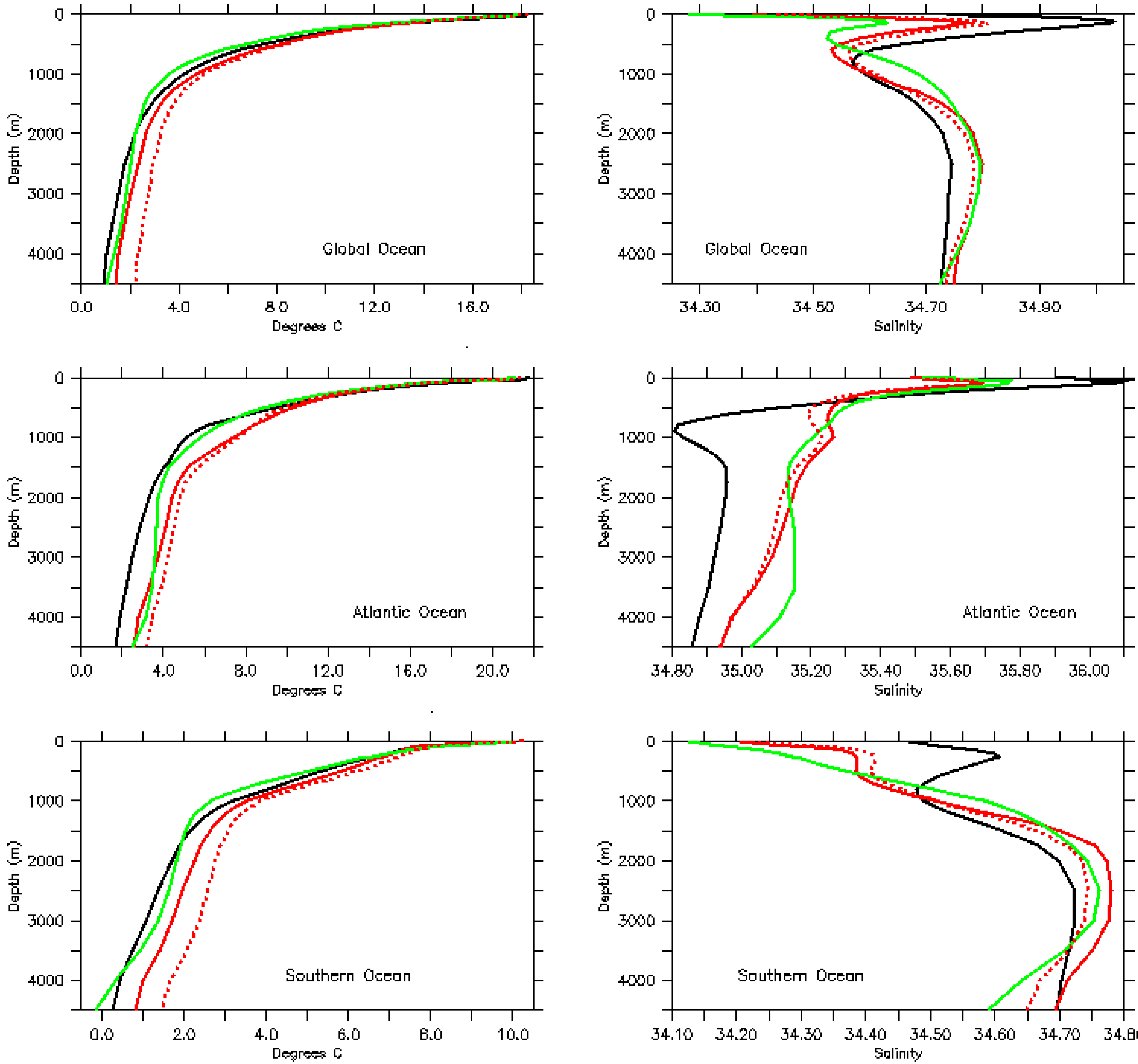
So… which model is better?

- Overall, the two models are extremely competitive.
- ESM2G superior at:
  - Overflows and bottom water formation
  - North Pacific ventilation
  - Channel flows due to it’s C-grid
- ESM2M superior at:
  - Coupling with B-grid ice model
  - Suboxia, and probably thermocline age (CFC’s will tell for sure)
  - Mixed layer dynamics, maybe
  - ENSO, maybe
  - Resolution of exotic densities
- ESM2M is more consistent with expectations based on previous z-coordinate models (i.e. TOPAZ and other algorithms were developed within it).
- ESM2G has more flexibility when it comes to adding new mixing parameterizations of mixing.

CO_2 beyond climate: Ocean Acidification



Langdon & Atkinson, (2005)



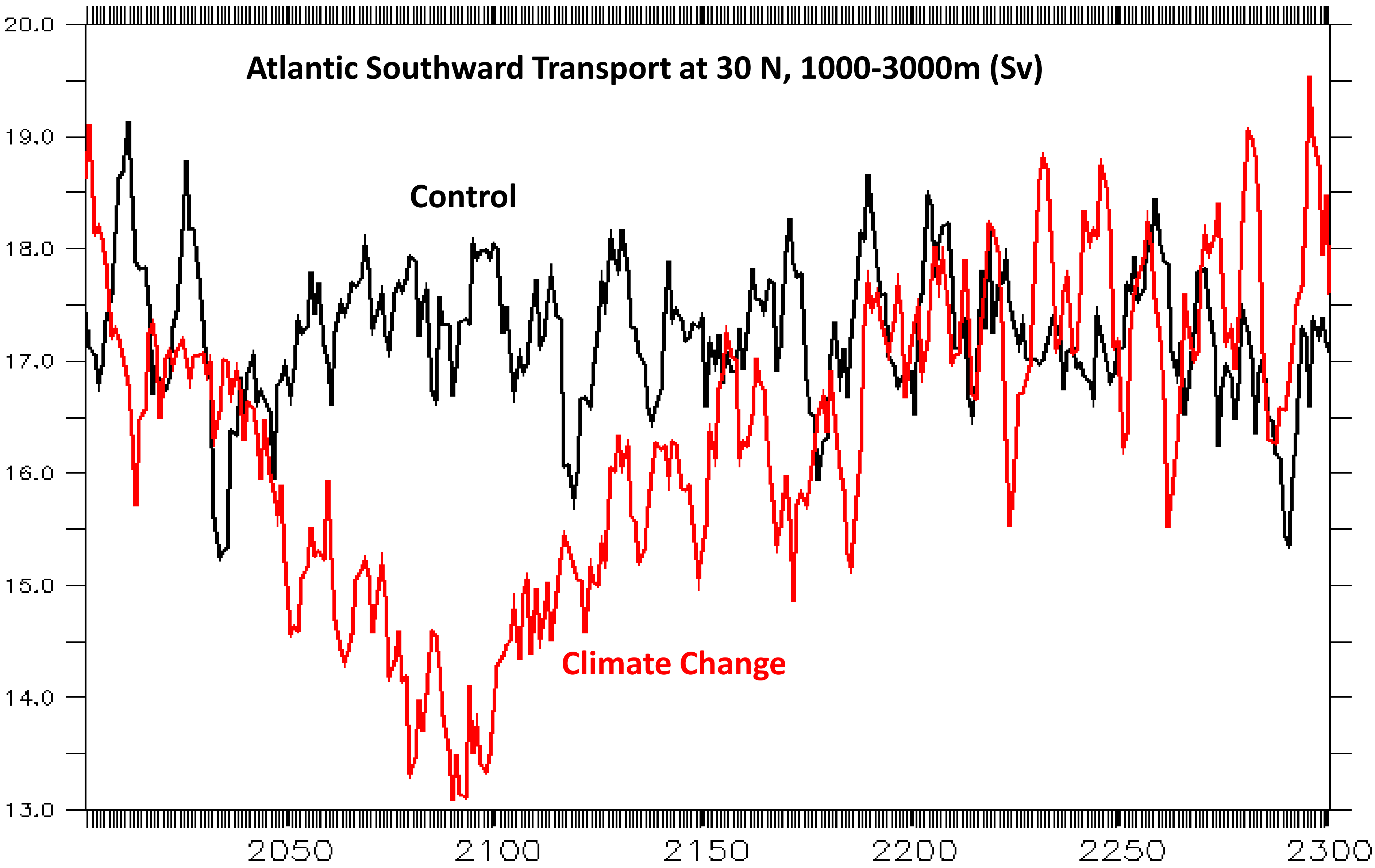
Global Ocean
Depth (m)
Degrees C
Global Ocean
Salinity
Atlantic Ocean
Depth (m)
Degrees C
Atlantic Ocean
Salinity
Southern Ocean
Depth (m)
Degrees C
Southern Ocean
Salinity

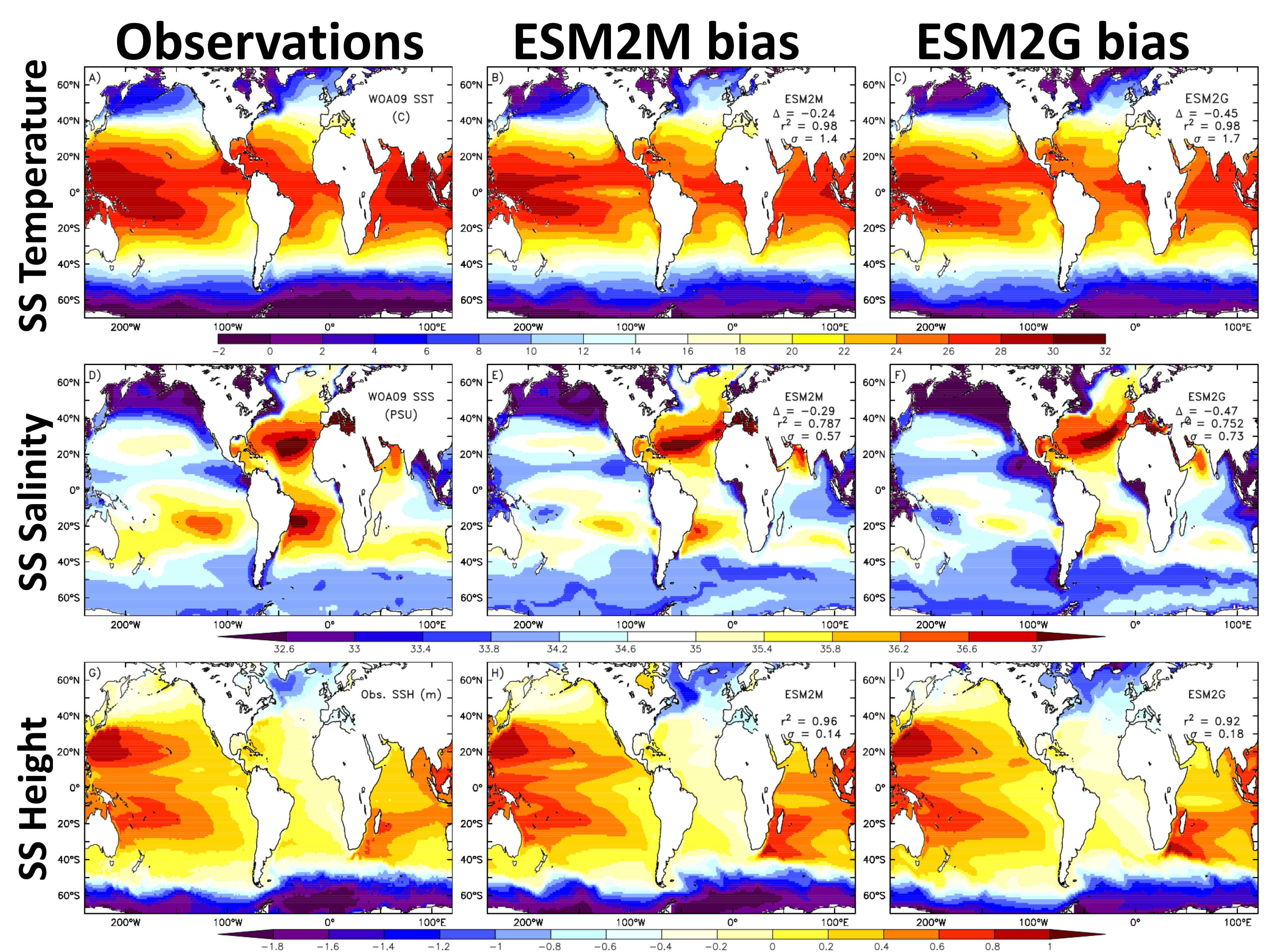
Prototype ESM2.1 Ocean Carbon Response

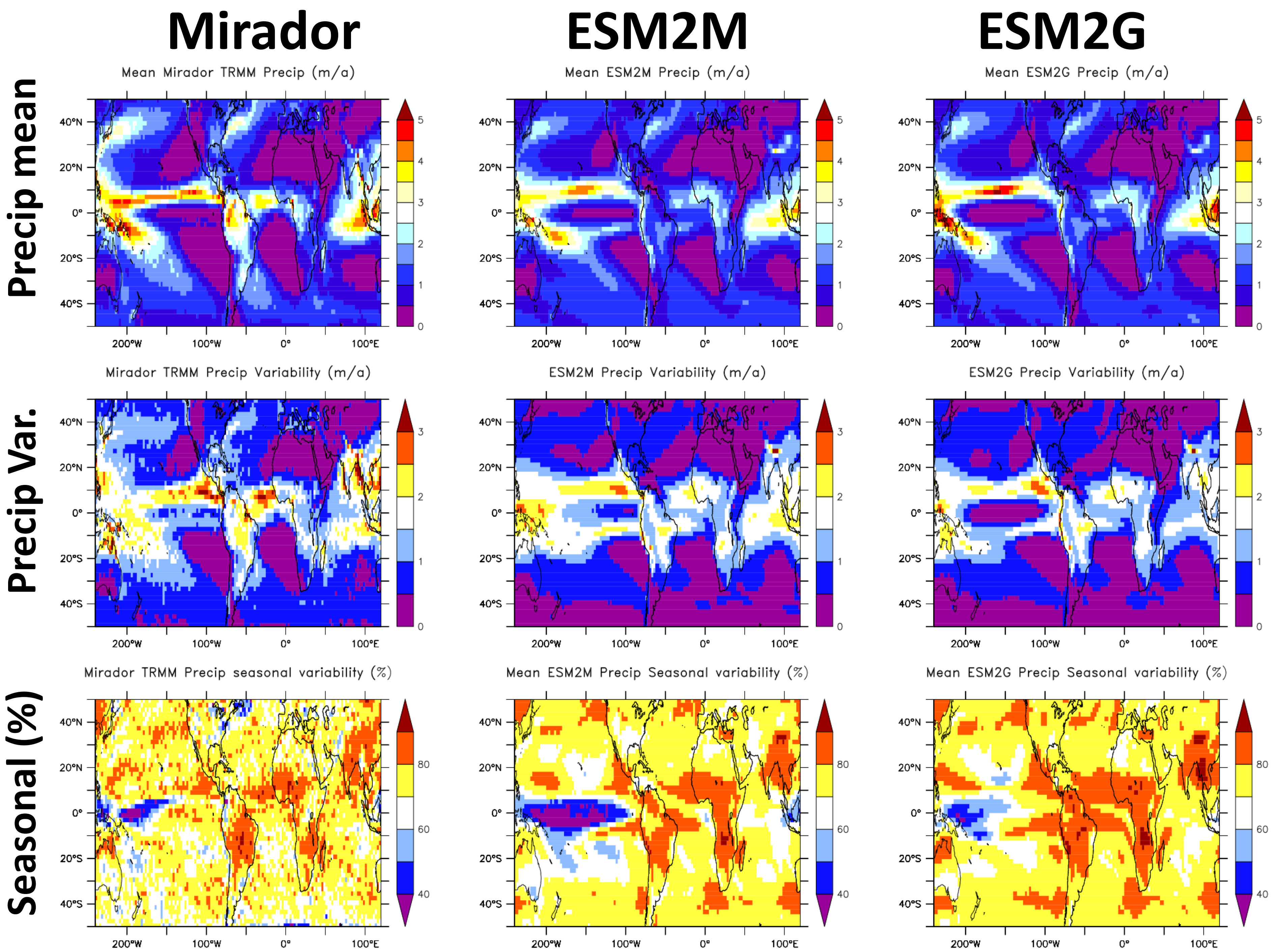
Four carbon-climate feedback simulations:

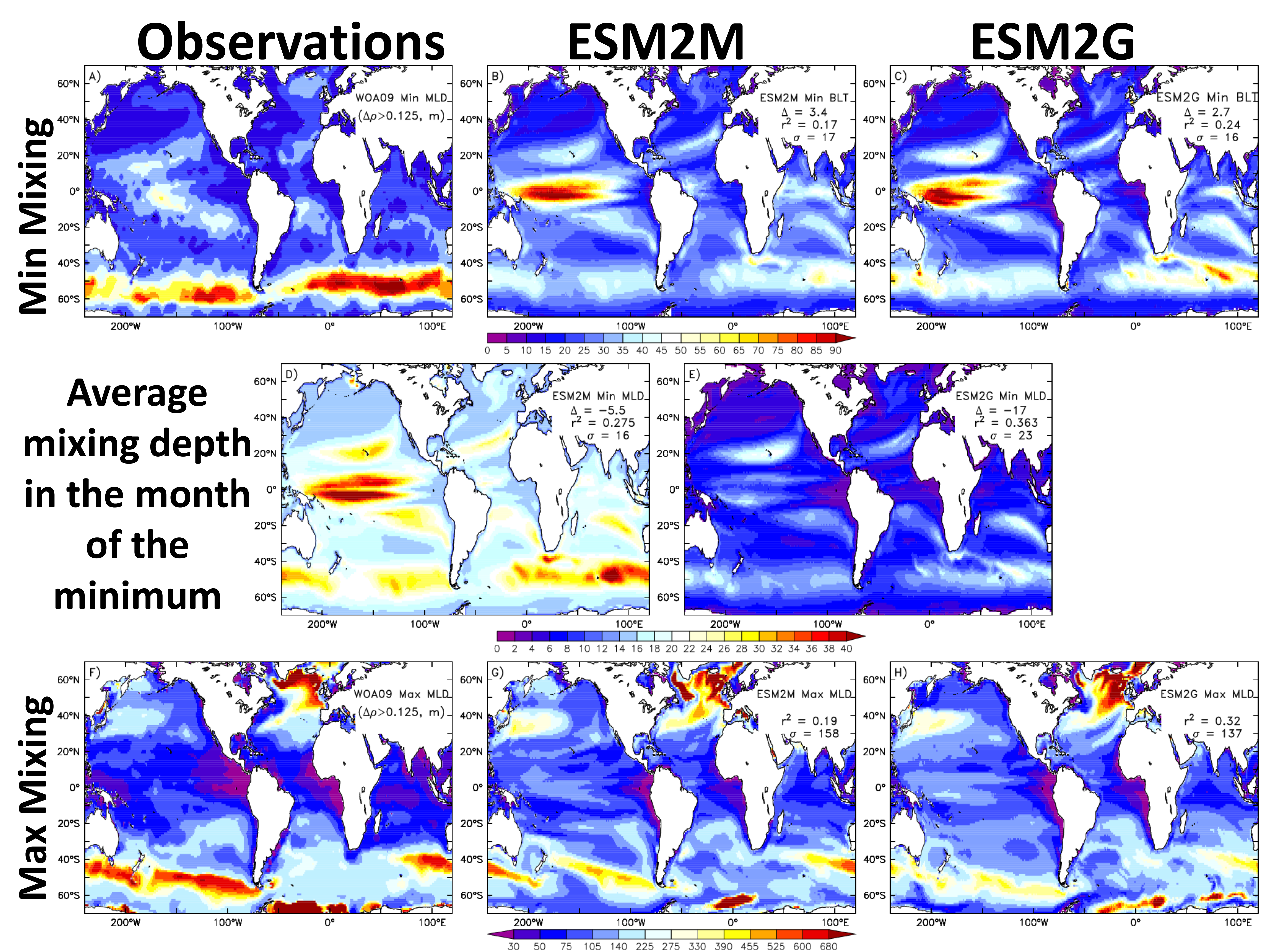
a) **Control**: radiative forcings are held at 1860 values and CO_2 is restored to 286ppm on a 1-year timescale.
b) **Climate only**: radiative forcings vary in time (historical/SRES A1B), but CO_2 is restored to 286 ppm as in the Control simulation.
c) **CO_2 only**: radiative forcings are held constant at 1860 values, while CO_2 restored to historical/SRES A1B values.
d) **Climate and CO_2**: radiative forcings are time-varying, and CO_2 is restored to historical/SRES A1B values.

ESM2.1 North Atlantic Deep Water Formation




Observations
ESM2M bias
ESM2G bias
SS Temperature
SS Salinity
SS Height
A)
WOA09 SST
(C)
B)
ESM2M
Δ = −0.24
r² = 0.98
σ = 1.4
C)
ESM2G
Δ = −0.45
r² = 0.98
σ = 1.7
−2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
D)
WOA09 SSS
(PSU)
E)
ESM2M
Δ = −0.29
r² = 0.787
σ = 0.57
F)
ESM2G
Δ = −0.47
r² = 0.752
σ = 0.73
32.6 33 33.4 33.8 34.2 34.6 35 35.4 35.8 36.2 36.6 37
G)
Obs. SSH (m)
H)
ESM2M
r² = 0.96
σ = 0.14
I)
ESM2G
r² = 0.92
σ = 0.18
−1.8 −1.6 −1.4 −1.2 −1 −0.8 −0.6 −0.4 −0.2 0 0.2 0.4 0.6 0.8 1
60°N 40°N 20°N 0° 20°S 40°S 60°S
200°W 100°W 0° 100°E

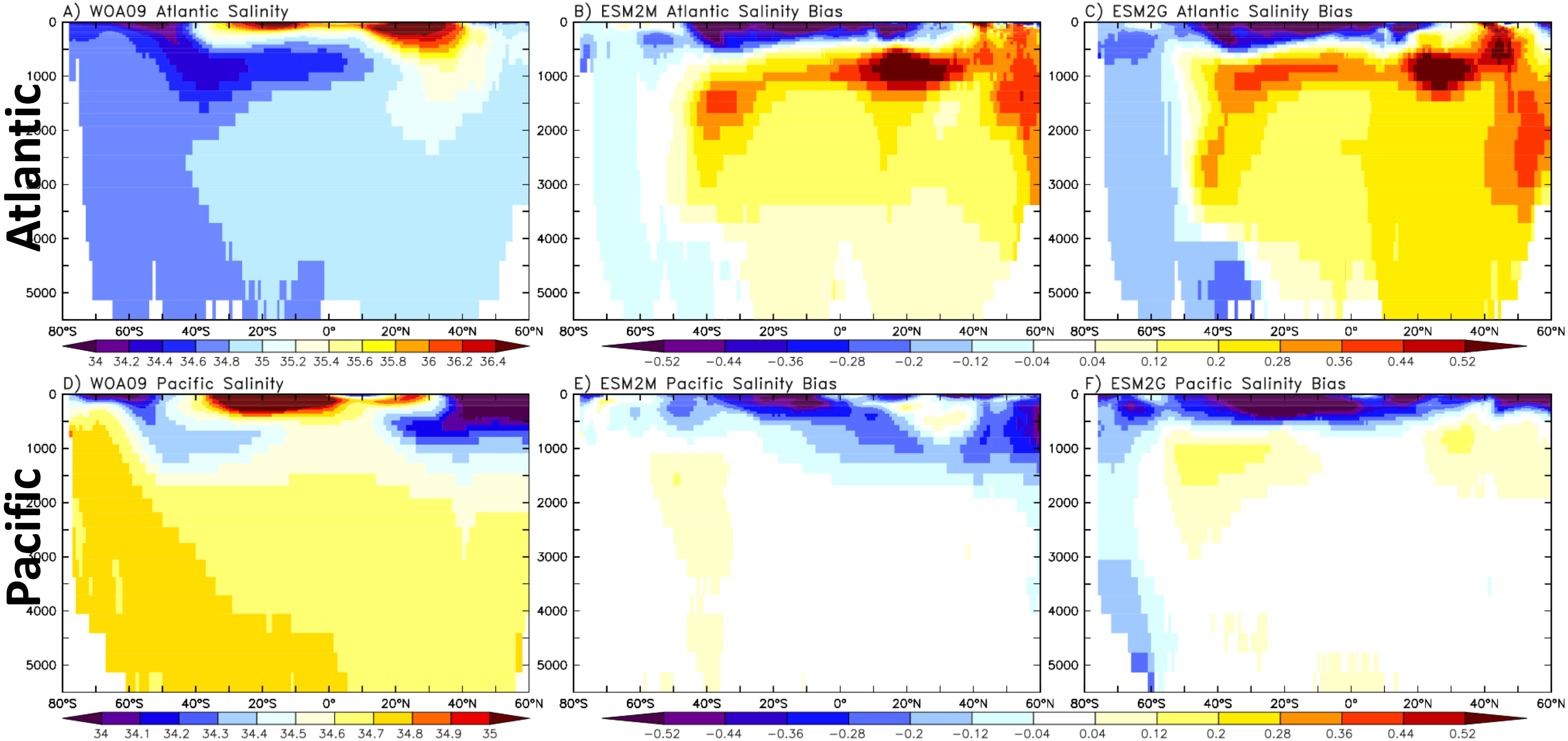

Mirador
ESM2M
ESM2G
Precip mean
Precip Var.
Seasonal (%)
Mean Mirador TRMM Precip (m/a)
Mean ESM2M Precip (m/a)
Mean ESM2G Precip (m/a)
Mirador TRMM Precip Variability (m/a)
ESM2M Precip Variability (m/a)
ESM2G Precip Variability (m/a)
Mirador TRMM Precip seasonal variability (%)
Mean ESM2M Precip Seasonal variability (%)
Mean ESM2G Precip Seasonal variability (%)
40°N
20°N
0°
20°S
40°S
200°W
100°W
0°
100°E
0
1
2
3
4
5
40
60
80



Observations
ESM2M
ESM2G
Min Mixing
A) WOA09 Min MLD (Δρ>0.125, m)
B) ESM2M Min BLT Δ = 3.4 r² = 0.17 σ = 17
C) ESM2G Min BLT Δ = 2.7 r² = 0.24 σ = 16
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90
Average mixing depth in the month of the minimum
D) ESM2M Min MLD Δ = −5.5 r² = 0.275 σ = 16
E) ESM2G Min MLD Δ = −17 r² = 0.363 σ = 23
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
Max Mixing
F) WOA09 Max MLD (Δρ>0.125, m)
G) ESM2M Max MLD r² = 0.19 σ = 158
H) ESM2G Max MLD r² = 0.32 σ = 137
30 50 75 105 140 225 275 330 390 455 525 600 680
60°N 40°N 20°N 0° 20°S 40°S 60°S
200°W 100°W 0° 100°E

Basin Salinity Comparisons

Observations | **ESM2M** | **ESM2G**

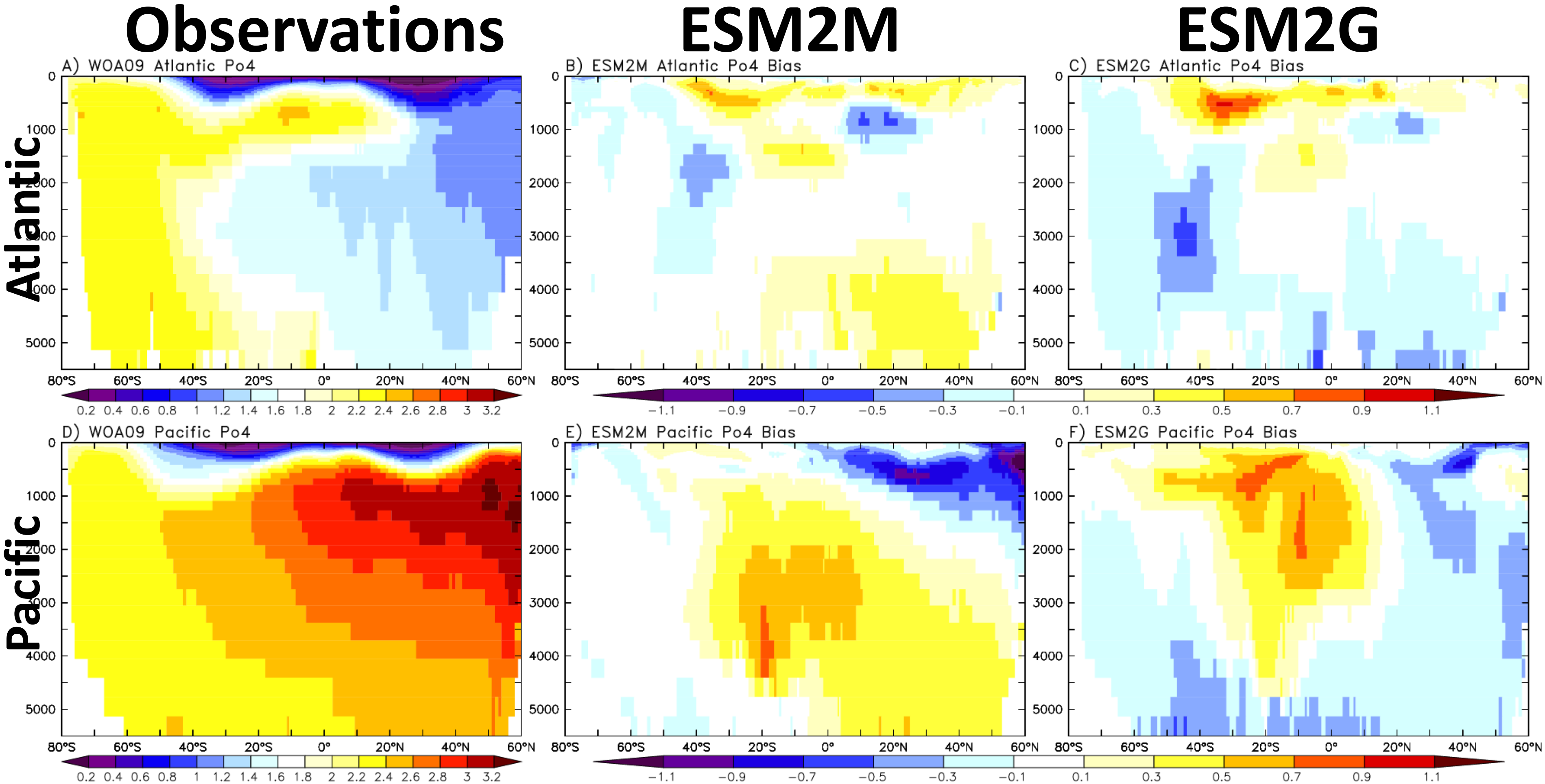


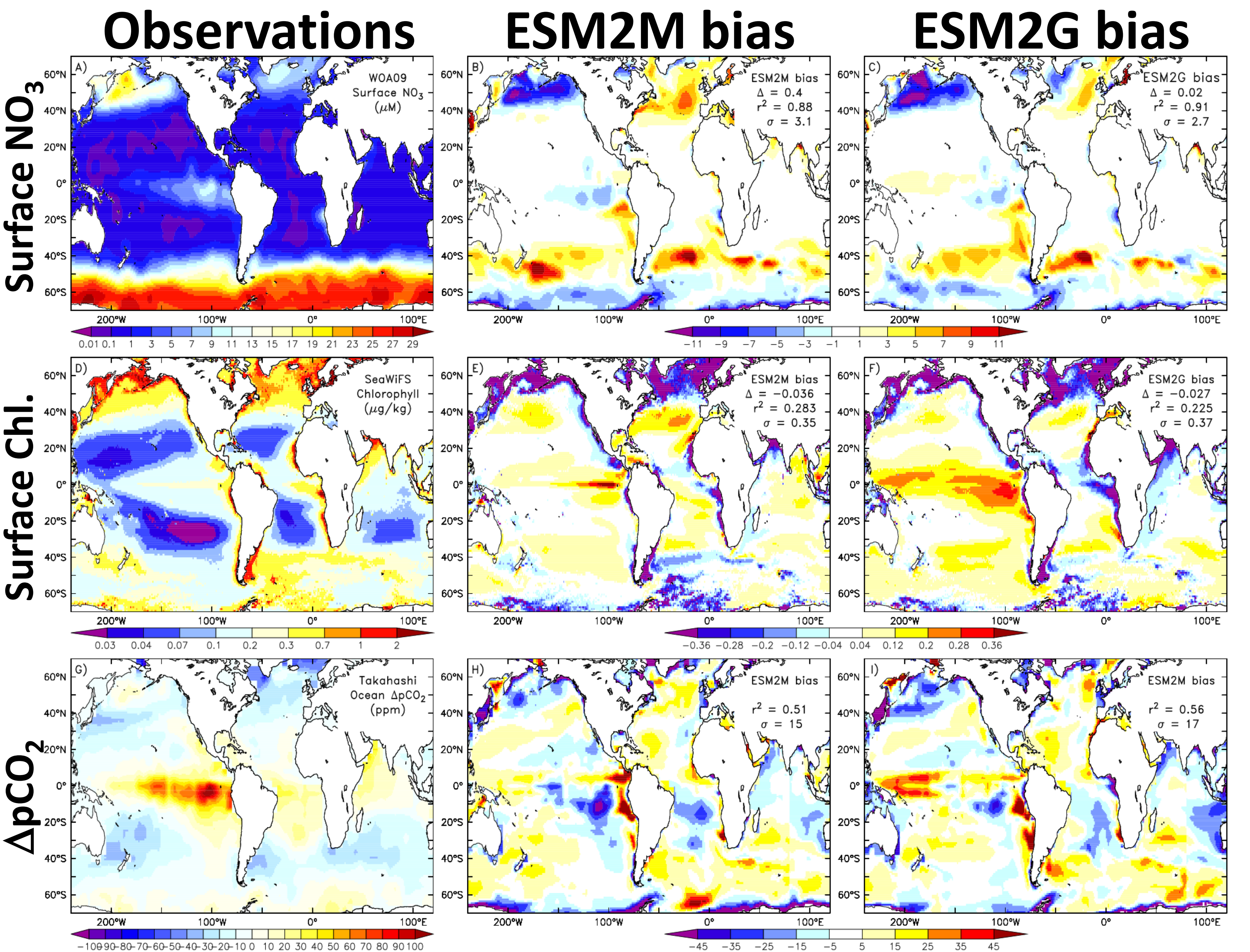
ESM2M warm bias can be attributed to combination of relatively warm NADW and mode waters and a lack of cold AABW

ESM2G gives much smaller warm bias in NADW and mode waters

ESM2G adds additional cold bias in the thermocline

Basin PO_4 Comparisons

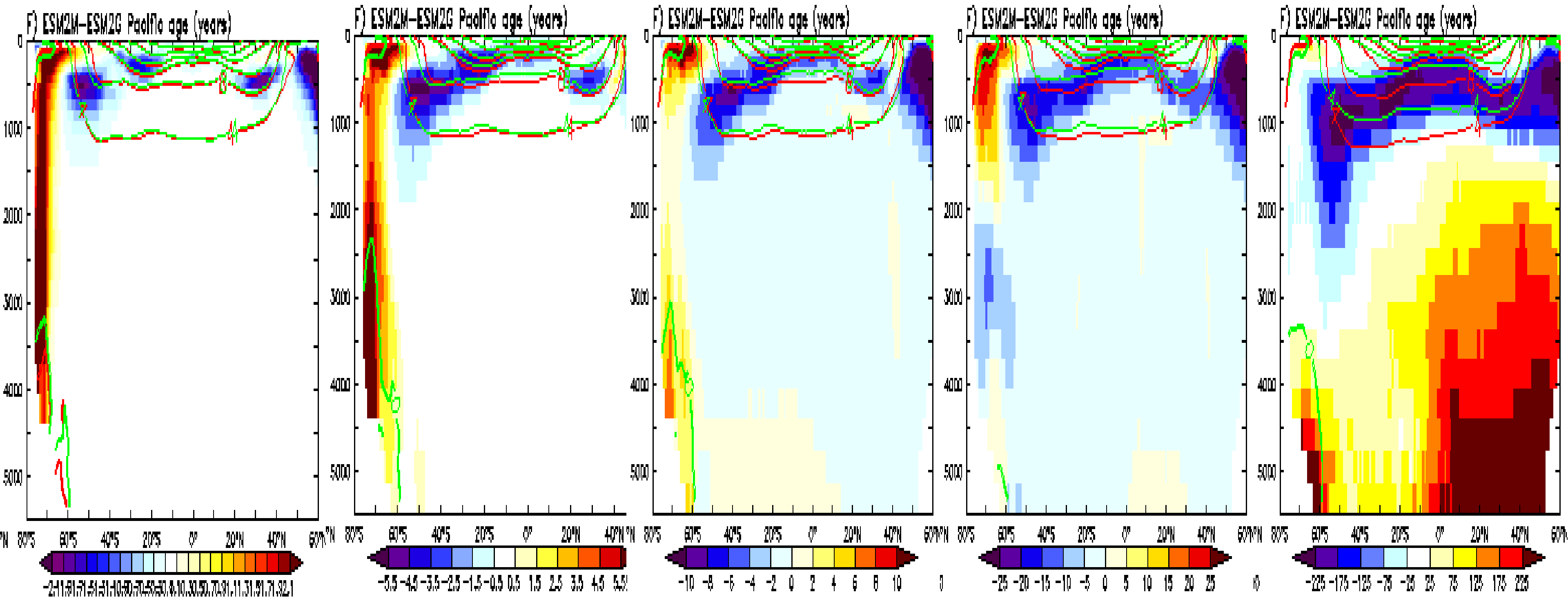




Observations
ESM2M bias
ESM2G bias
Surface NO3
Surface Chl.
ΔpCO2
A)
WOA09
Surface NO3
(μM)
B)
ESM2M bias
Δ = 0.4
r2 = 0.88
σ = 3.1
C)
ESM2G bias
Δ = 0.02
r2 = 0.91
σ = 2.7
0.01 0.1 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29
−11 −9 −7 −5 −3 −1 1 3 5 7 9 11
D)
SeaWiFS
Chlorophyll
(μg/kg)
E)
ESM2M bias
Δ = −0.036
r2 = 0.283
σ = 0.35
F)
ESM2G bias
Δ = −0.027
r2 = 0.225
σ = 0.37
0.03 0.04 0.07 0.1 0.2 0.3 0.7 1 2
−0.36 −0.28 −0.2 −0.12 −0.04 0.04 0.12 0.2 0.28 0.36
G)
Takahashi
Ocean ΔpCO2
(ppm)
H)
ESM2M bias
r2 = 0.51
σ = 15
I)
ESM2M bias
r2 = 0.56
σ = 17
−100 −90 −80 −70 −60 −50 −40 −30 −20 −10 0 10 20 30 40 50 60 70 80 90 100
−45 −35 −25 −15 −5 5 15 25 35 45
60°N
40°N
20°N
0°
20°S
40°S
60°S
200°W
100°W
0°
100°E

Pacific Age Difference patterns at various years

10 30 50 110 1050



Summary

GFDL is planning contributions to CMIP5 in 4 areas:

- Next generation climate model with interactive chemistry and aerosols
- Decadal prediction activities
- High resolution atmospheric downscaling
- Coupled carbon-climate Earth System Modeling

GFDL's prototype ESM2.1 has yielded intriguing scientific results

ESM2M and ESM2G have qualitatively similar climate, but very different shallow mixing, water masses, and biogeochemistry.

Moving forward post CMIP5, foci for improvement include:

- Ocean eddy rectification and other mechanisms not represented well at 1° resolution
- General concerns about model biases (dry Amazon; double ITCZ; Boundary Currents)
- Direct CO_2 effect on plant growth, particularly N_2 fixation
- Biodiversity, ecosystem diversity, biogeochemical thresholds, and other complexity