Variability and trends in the North Atlantic carbon sink

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Are trends in the global carbon cycle already detectable?

Reduction in fraction of anthropogenic carbon stored in the ocean
(Canadell et al. 2007)

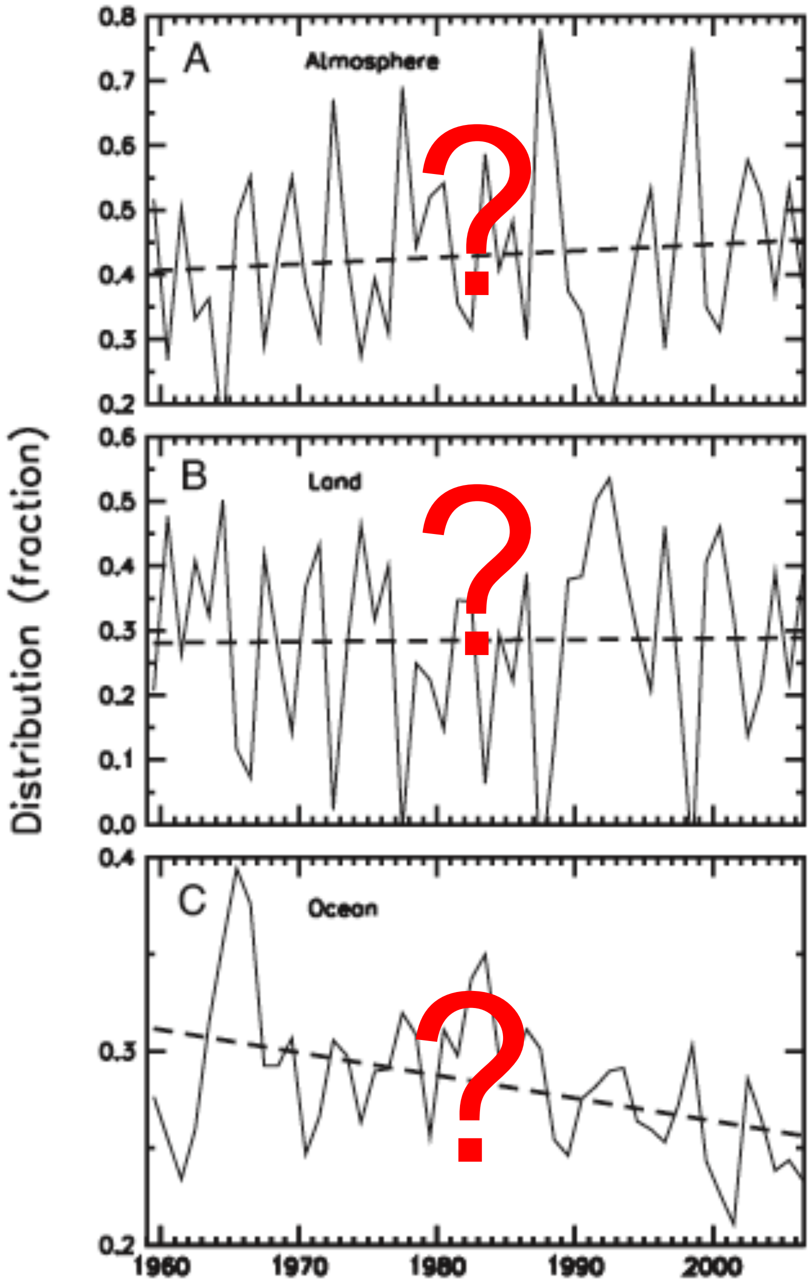


Fig. 2. Fraction of the total emissions (F_{Foss} + F_{LUC}) that remains in the atmosphere (*A*), the land biosphere (*B*), and the ocean (*C*).

Modeled-based assessment of global CO_2 sink impacts due to climate feedbacks: 1981-2007 = -0.20 PgC/decade

Mechanism	Sink impact	Regional notes
Warming	-20%	50% in North Atlantic alone
Wind change	-63%	>80% in Tropical Pacific >30% in S. Ocean Compensation elsewhere
Heat, Freshwater flux	+15%	In Northern Hemisphere
Nonlinear	-32%	>65% in Tropics

LeQuéré et al. 2010

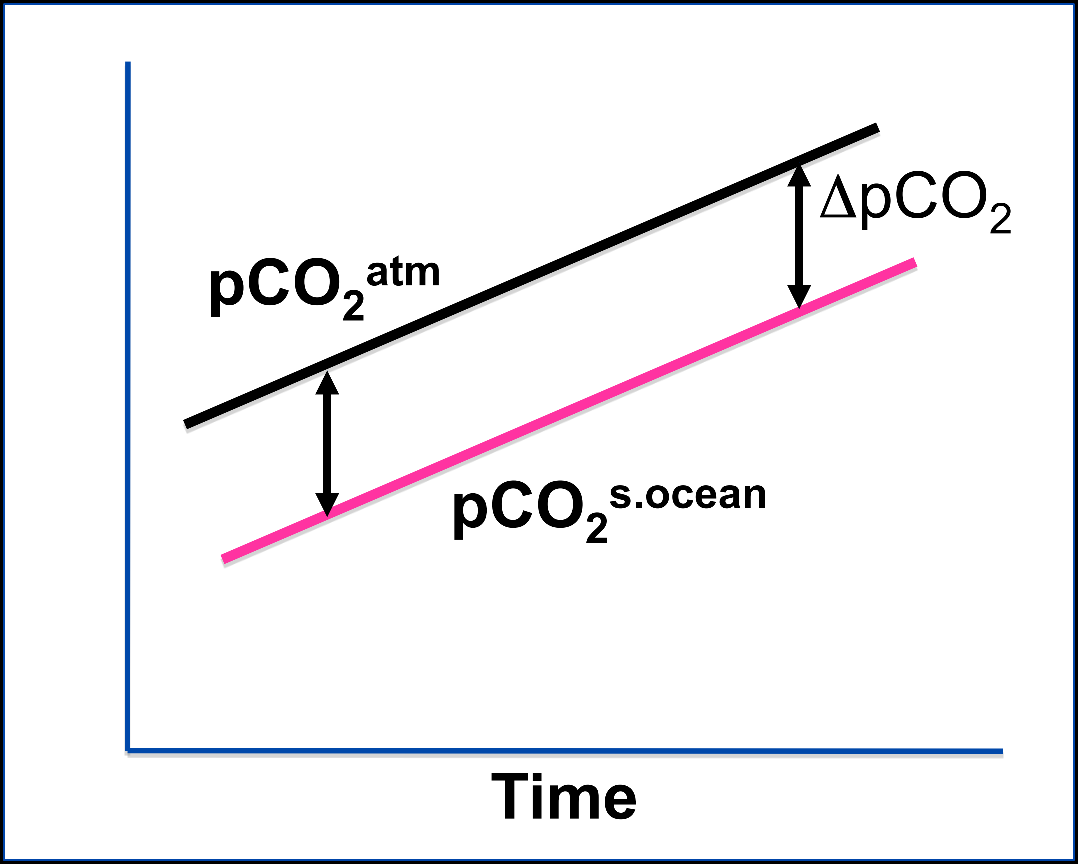
Earlier modeling found that warming to be dominant negative feedback (-84%) on CO_2 sink in first 100yrs after 4xCO2 pulse (Sarmiento and LeQuéré, 1996)

Outline

- Background: Ocean carbon sink trends from pCO_2 data and models
- North Atlantic trends from in situ pCO_2 data
  - Gyre-scale biomes
  - Distinguishing variability from trends

Trends from surface ocean pCO_2:

If pCO_2^{atm} only change, i.e. circulation, biology constant



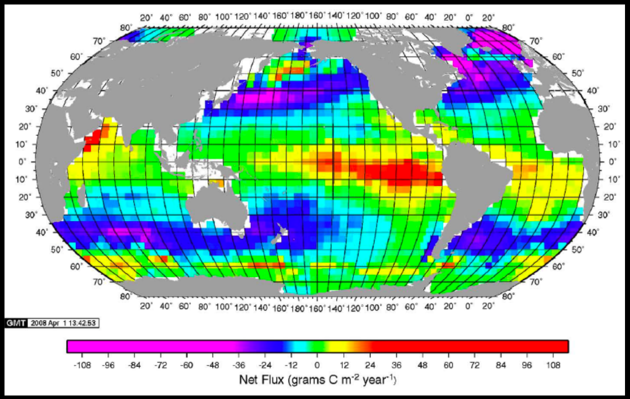
"Equilibration"

$dpCO_2^{s.ocean}/dt = dpCO_2^{atm}/dt$

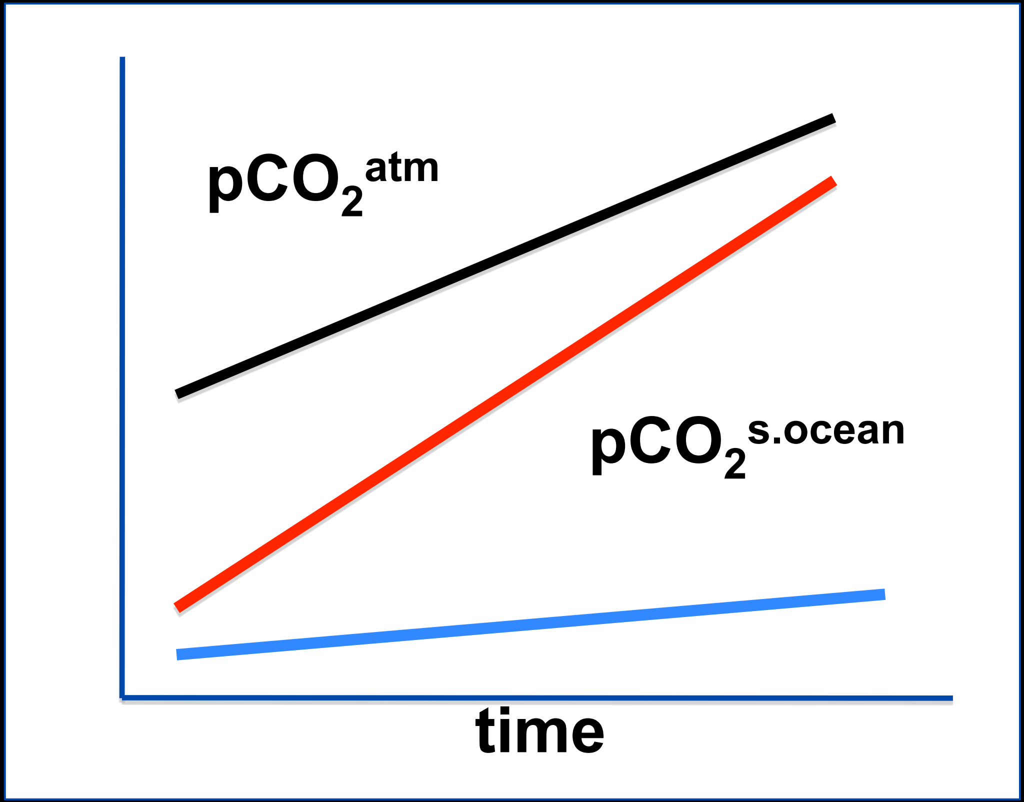
$d\Delta pCO_2/dt = 0$

$d(CO_2Flux)/dt = 0$

STEADY SINKS AND SOURCES



As corollary, $dpCO_2^{s.ocean}/dt \neq dpCO_2^{atm}/dt$ has been interpreted as a change in flux *due to change in biology or circulation*



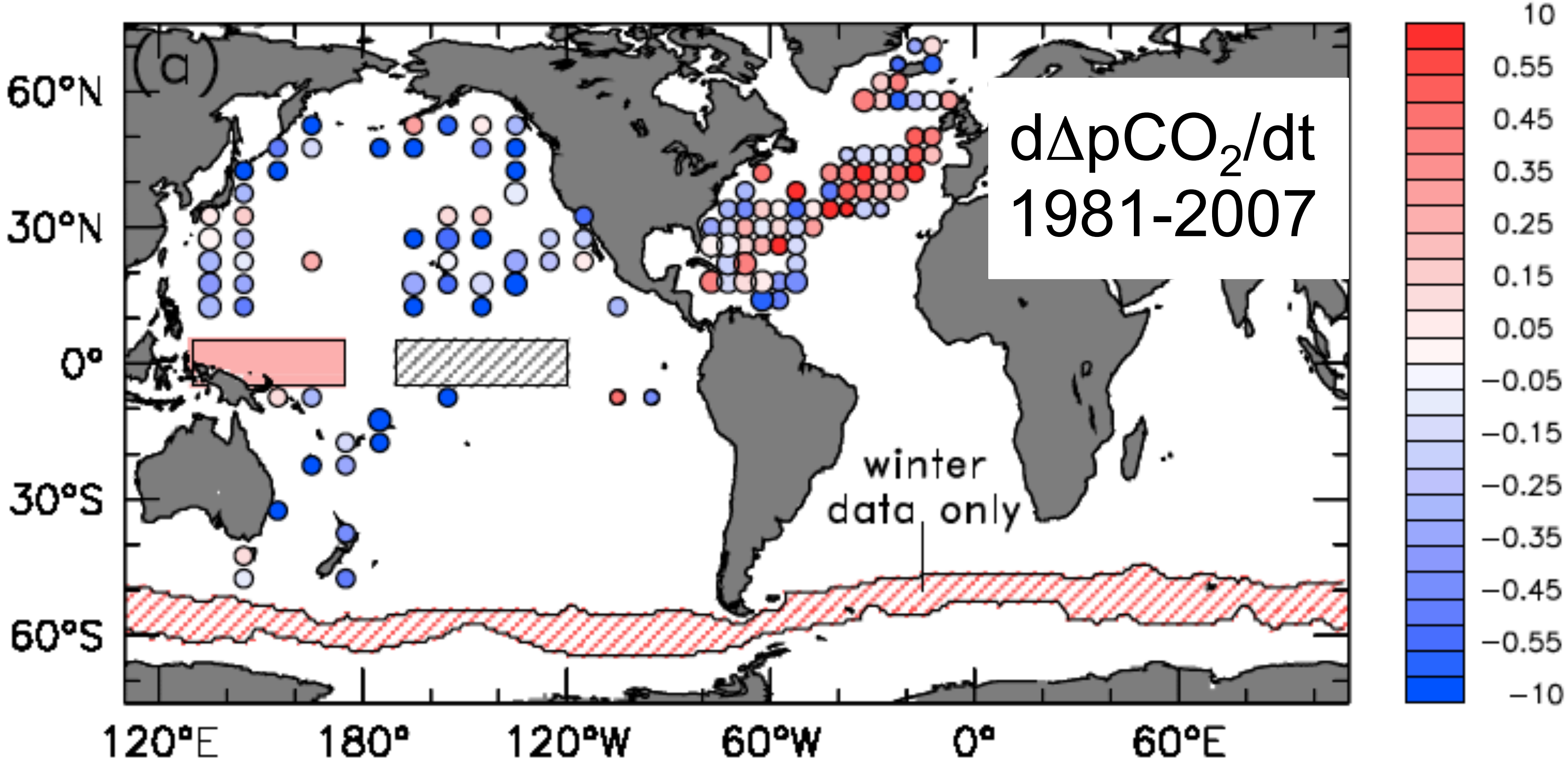
$dpCO_2^{s.ocean}/dt$ > $dpCO_2^{atm}/dt$

DECLINING SINK

$dpCO_2^{s.ocean}/dt$ < $dpCO_2^{atm}/dt$

INCREASING SINK

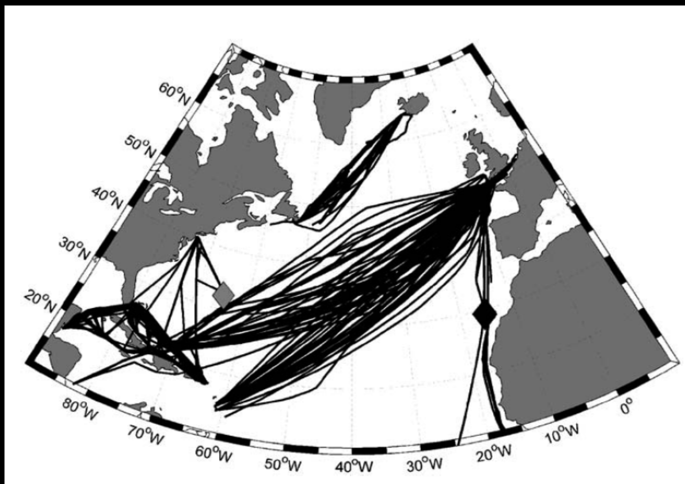
Mostly from Takahashi pCO_2 database, model in S. Ocean



$d\Delta pCO_2/dt$
1981-2007

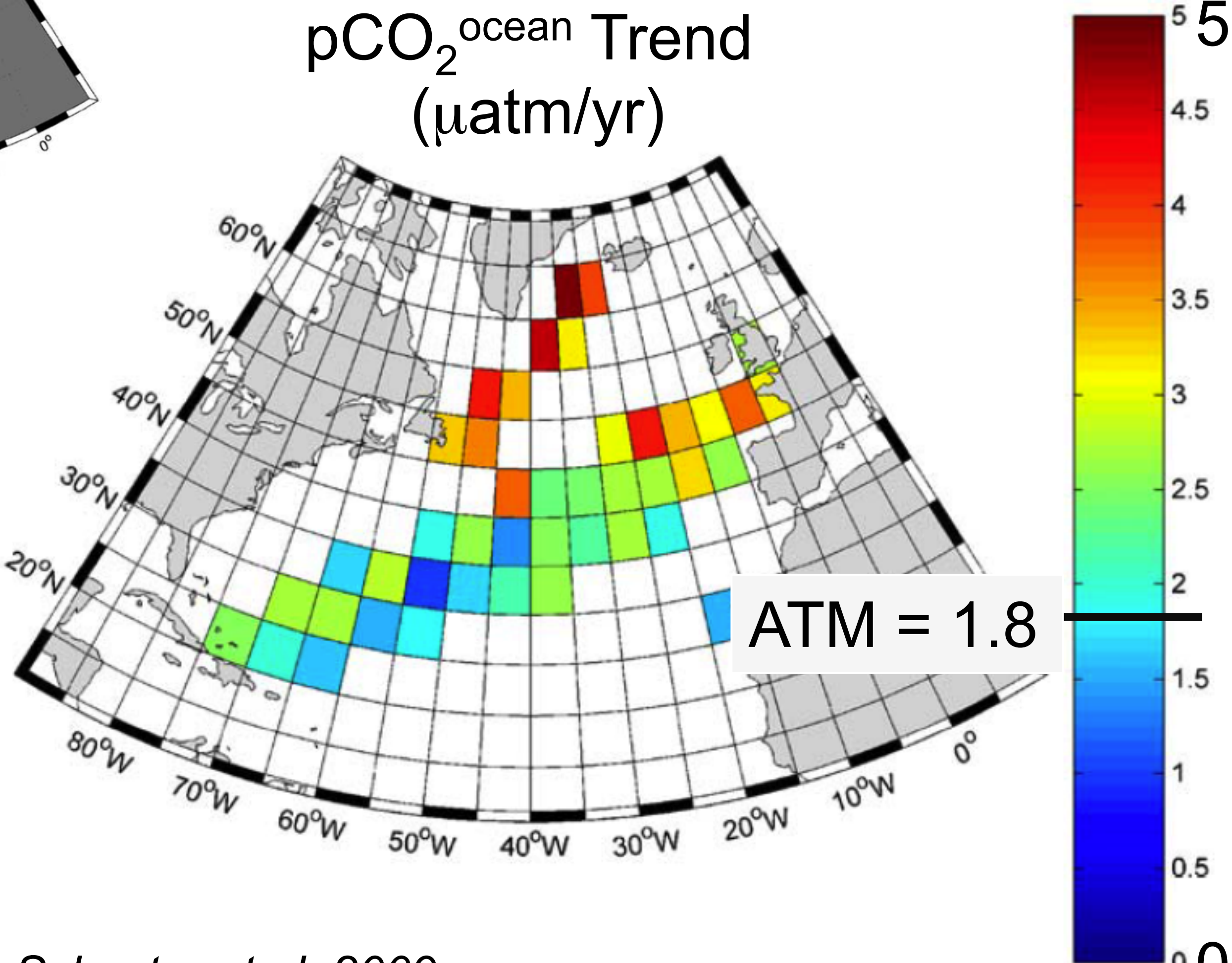
LeQuéré et al. 2010

North Atlantic: VOS datasets, linear trend 1990-2006

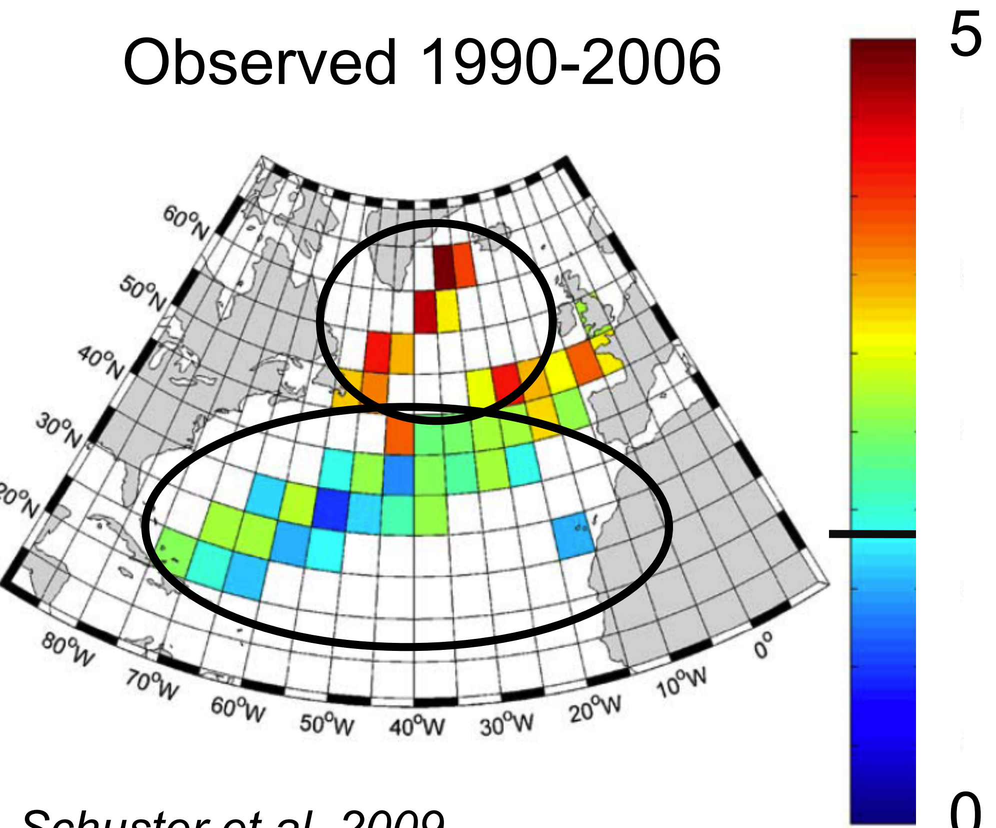


Data of
Corbiere et al. 2007
Shuster & Watson 2007
Bates 2007
Olsen et al. 2004
Santana-Casiano et al. 2007

pCO_2^{ocean} Trend
(μatm/yr)



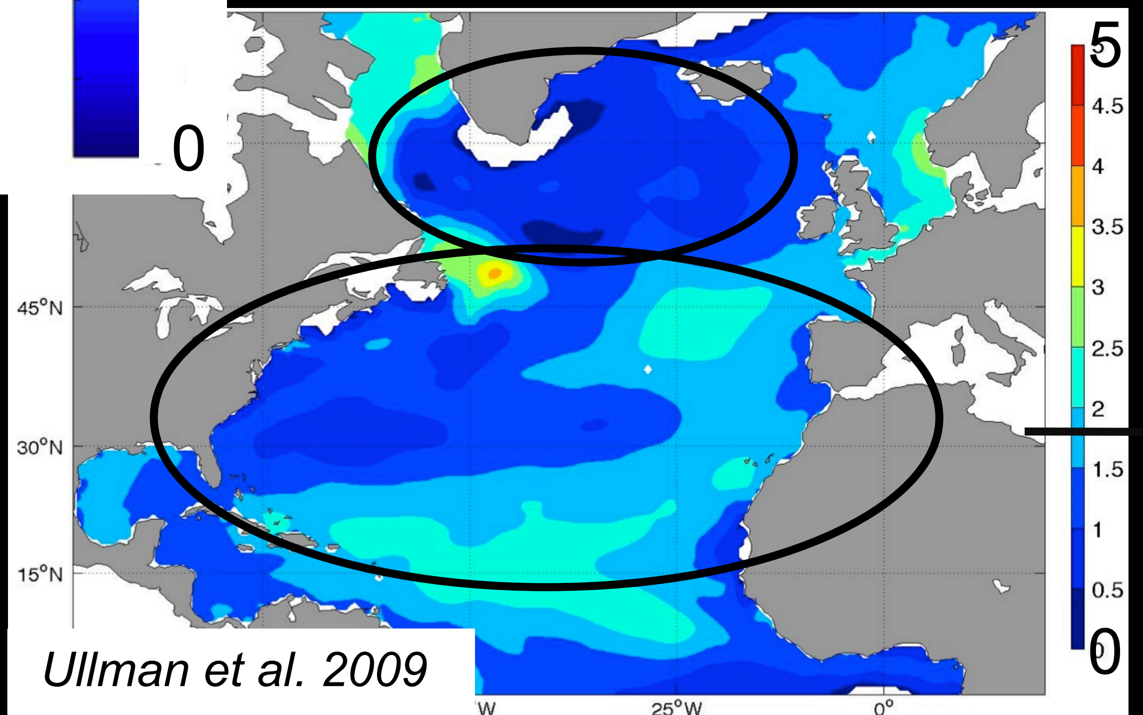
Schuster et al. 2009



Schuster et al. 2009

Modeled subpolar has increasing sink

Modeled, 1992-2006



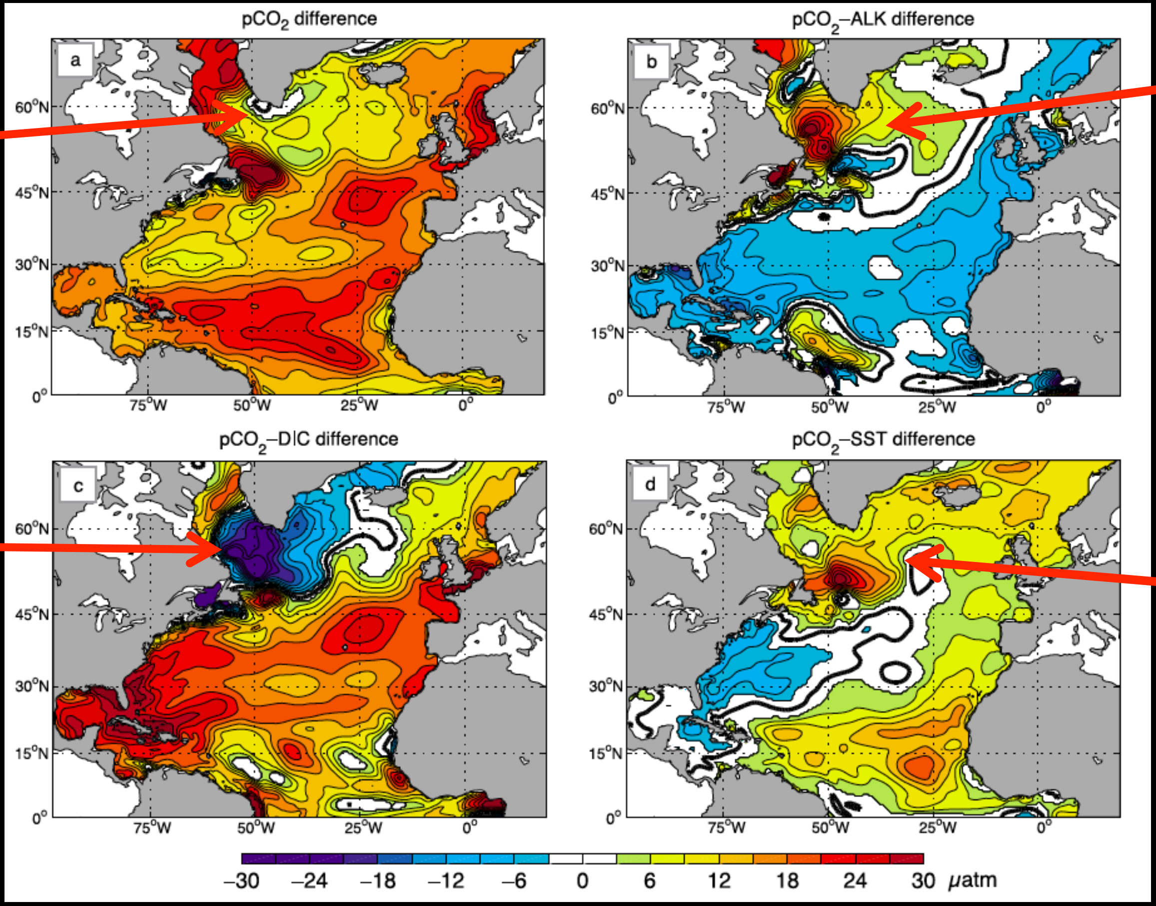
Ullman et al. 2009

Generally consistent <45N, but inconsistent >45N

Modeled mechanism for increased sink
Change in pCO_2 components 1992 to 2006
$pCO_2 \approx pCO_2\text{-ALK} + pCO_2\text{-DIC} + pCO_2\text{-SST}$

damped pCO_2 trend

ALK down with less productivity; pCO_2 up



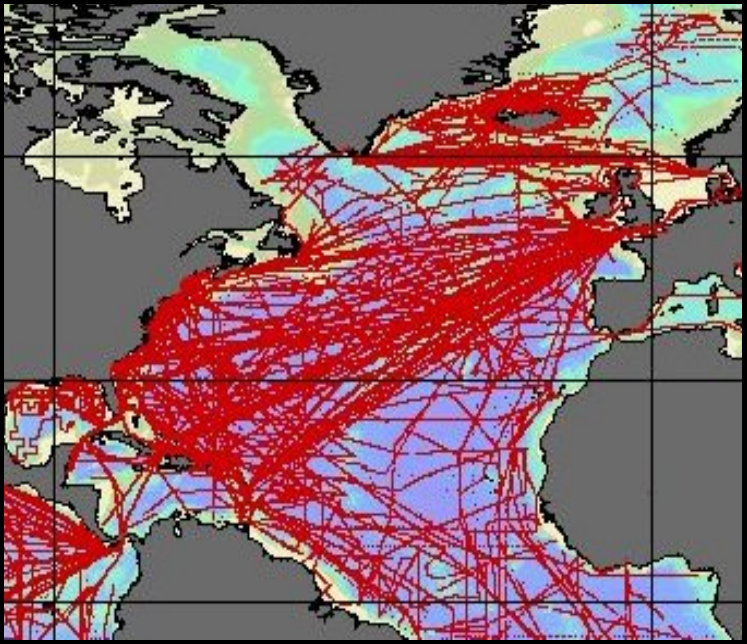
DIC down; due to shallower mix; pCO_2 down

Warming; pCO_2 up

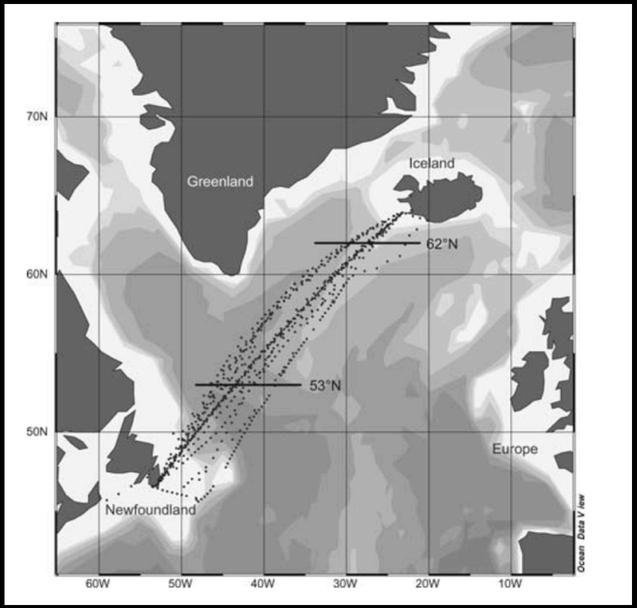
Ullman et al. 2009

North Atlantic pCO_2 trends from in-situ observations

Takahashi et al. 2010



Metzl et al. 2009



McKinley et al. 2011

Objectives
with *in situ* pCO_2 data, discern:

- Timescales: variability vs. trends
- Mechanisms: Warming vs. carbon uptake
- Spatial scale: Gyre-size “biomes”

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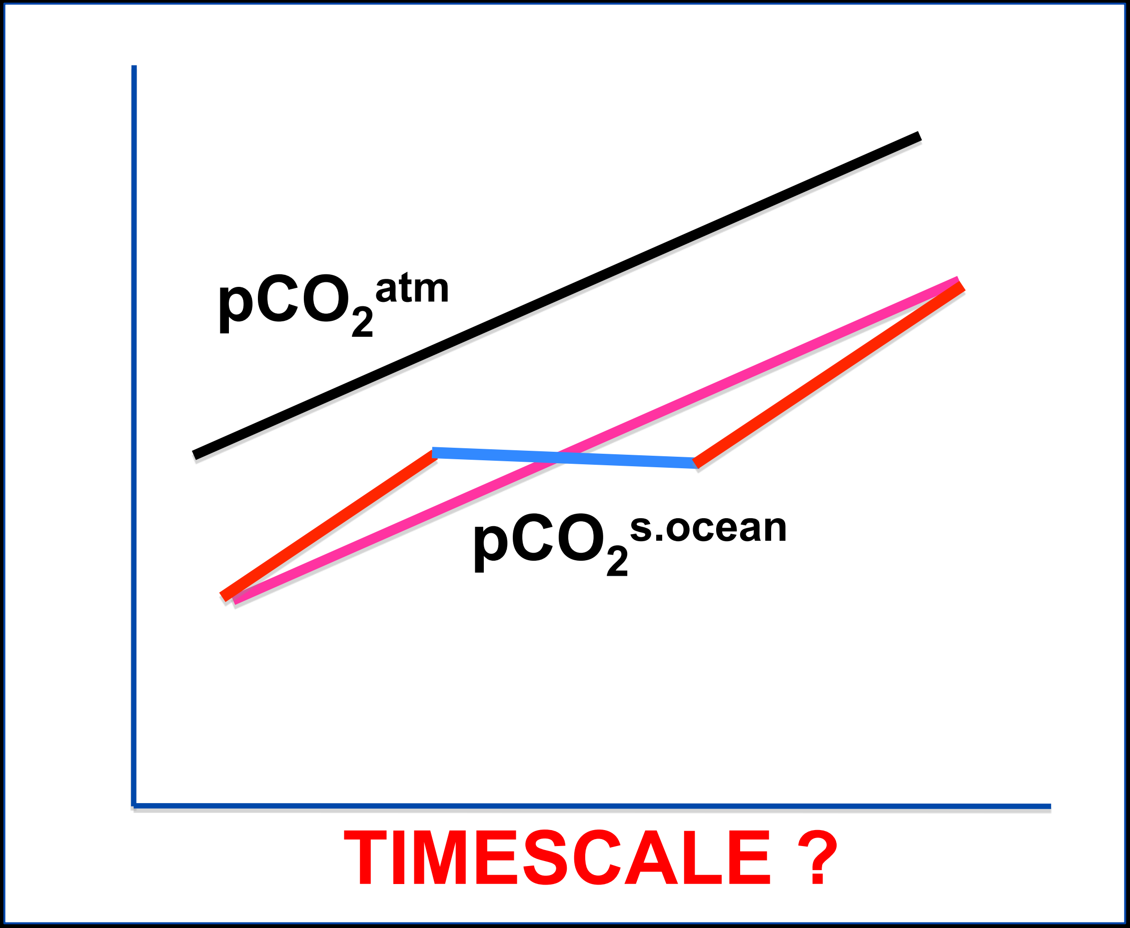
On what timescale does the ocean follow the atmosphere?



Objectives

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- Spatial scale: Gyre-size “biomes”

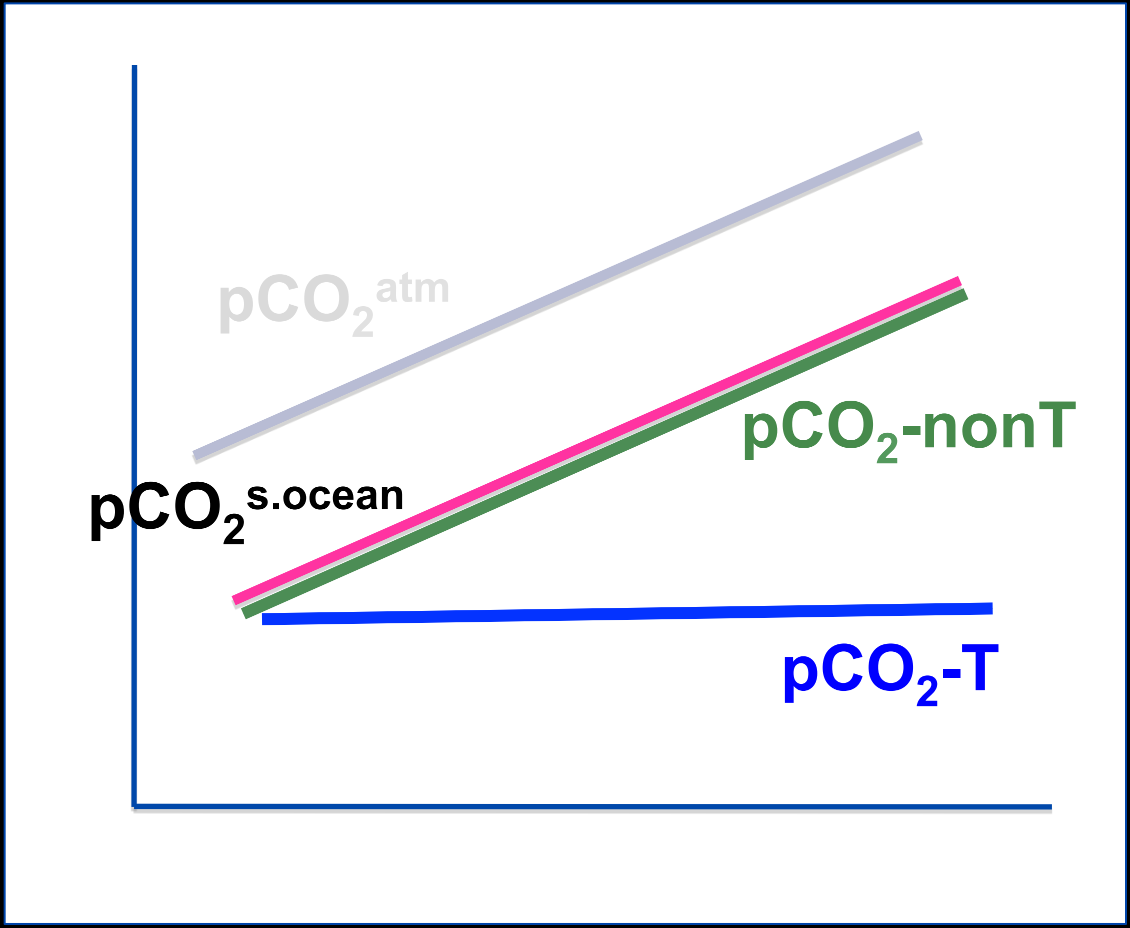
Decompose pCO_2 into temperature driven component (pCO_2-T) and biological/chemical component (pCO_2-nonT)

$$pCO_2 - T = \overline{pCO_2} * \exp(0.0423 * (SST - \overline{SST}))$$

$$pCO_2 - nonT = pCO_2 * \exp(0.0423 * (\overline{SST} - SST))$$

Takahashi et al. 2002

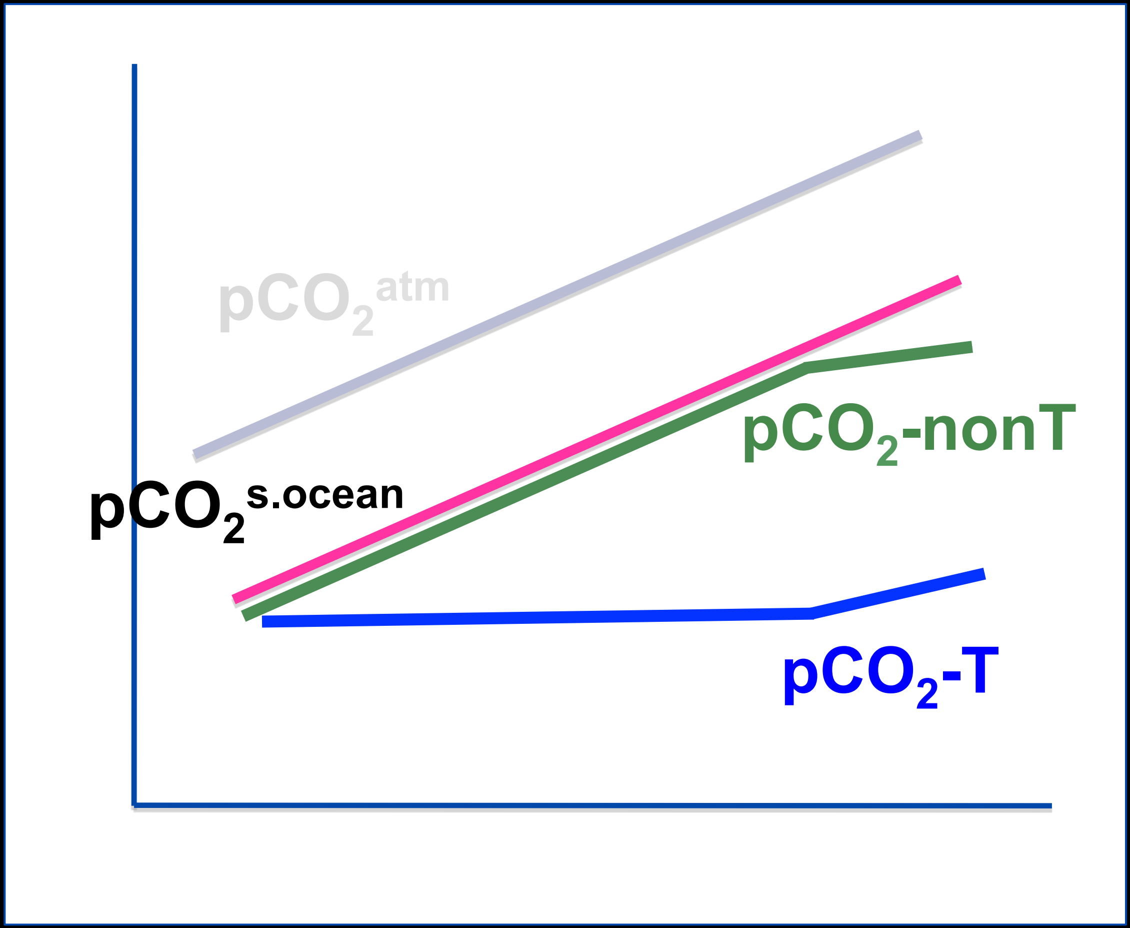
Trend mechanisms



Biogeochemical change only

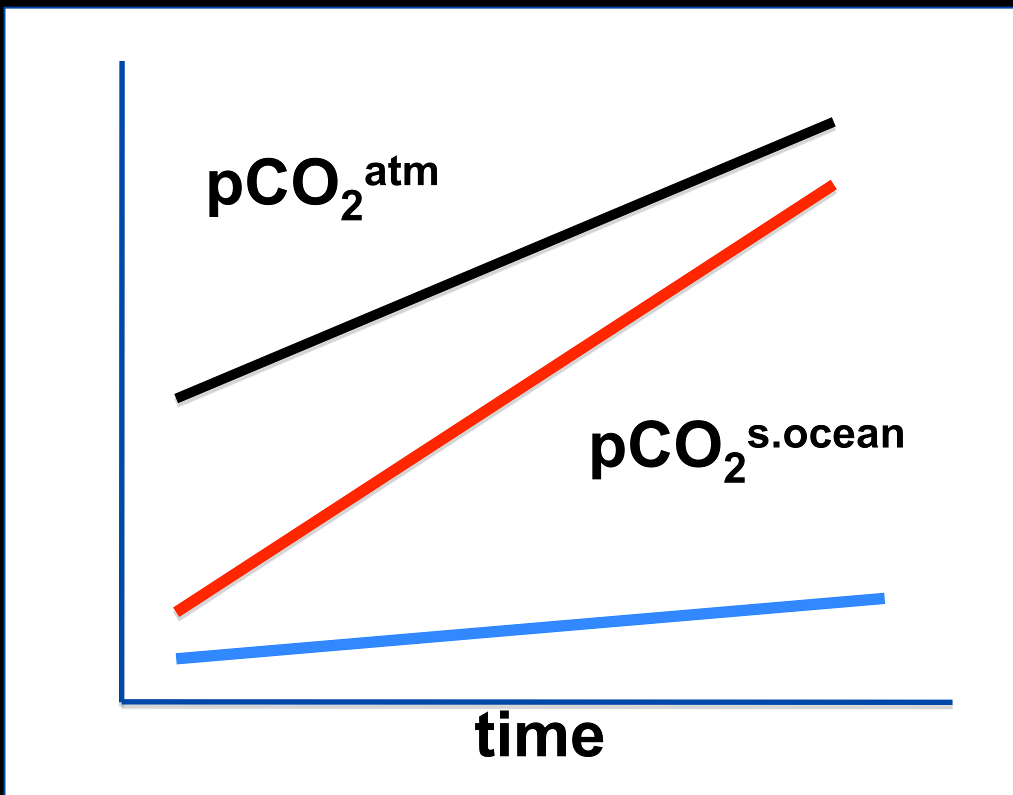
Consistent with carbon uptake

Trend mechanisms



If warming contributes, less carbon uptake required for equilibration with atmosphere

Mechanistic approach allows more nuanced understanding



$dpCO_2^{s.ocean}/dt >$
$dpCO_2^{atm}/dt$

OVER-EQUILIBRATION

$dpCO_2^{s.ocean}/dt <$
$dpCO_2^{atm}/dt$

UNDER-EQUILIBRATION

Objectives

with *in situ* pCO_2 data, discern:

- Timescales: variability vs. trends
- Mechanisms: Warming vs. carbon uptake
- Spatial scale: Gyre-size “biomes”

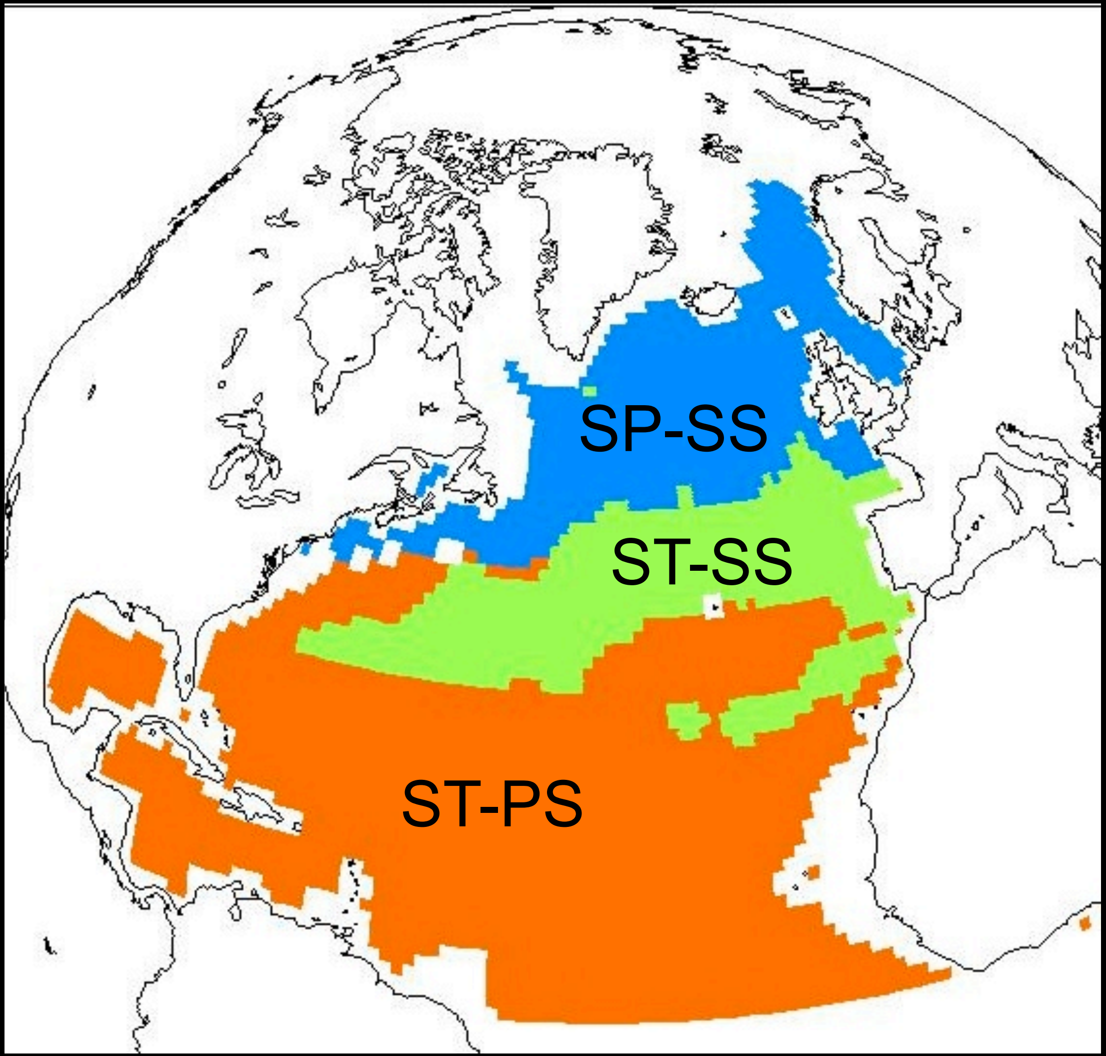
Biomes

- Gyre-scale biogeographic regions (Sarmiento et al (2004)
- Selection criteria: observed climatological SST, max MLD, and chlorophyll-a

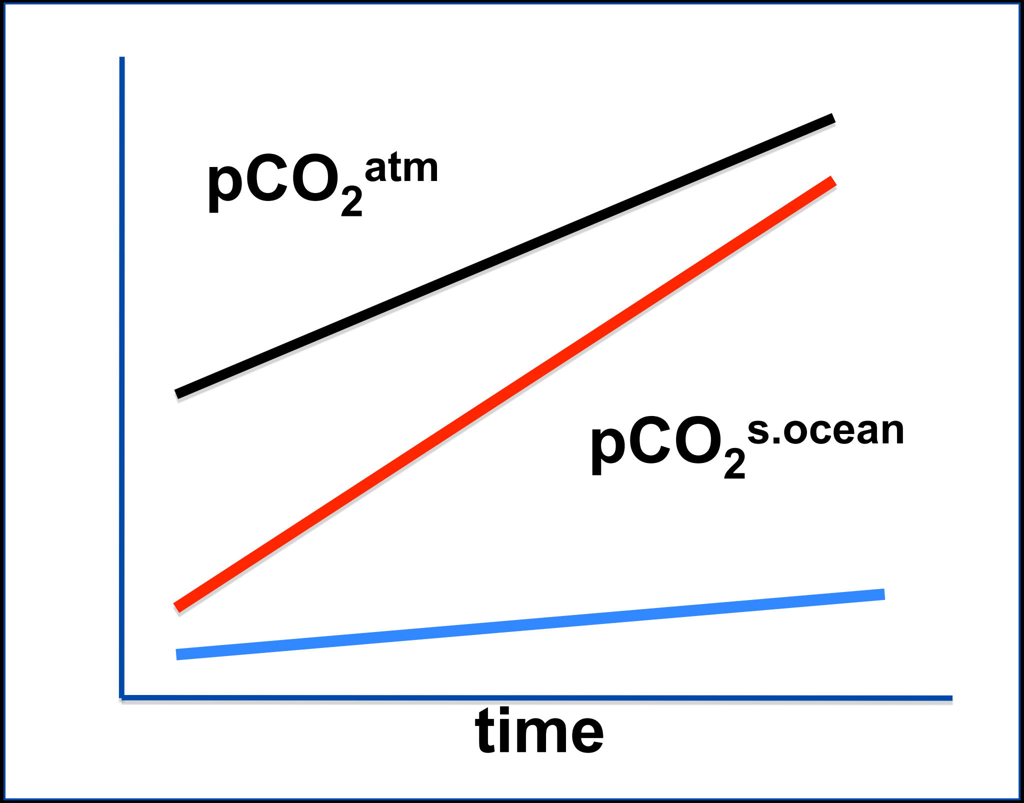
Seasonally Stratified Subpolar (SP-SS)

Seasonally Stratified Subtropical (ST-SS)

Permanently Stratified Subtropical (ST-PS)



Results



$dpCO_2^{s.ocean}/dt >$
$dpCO_2^{atm}/dt$

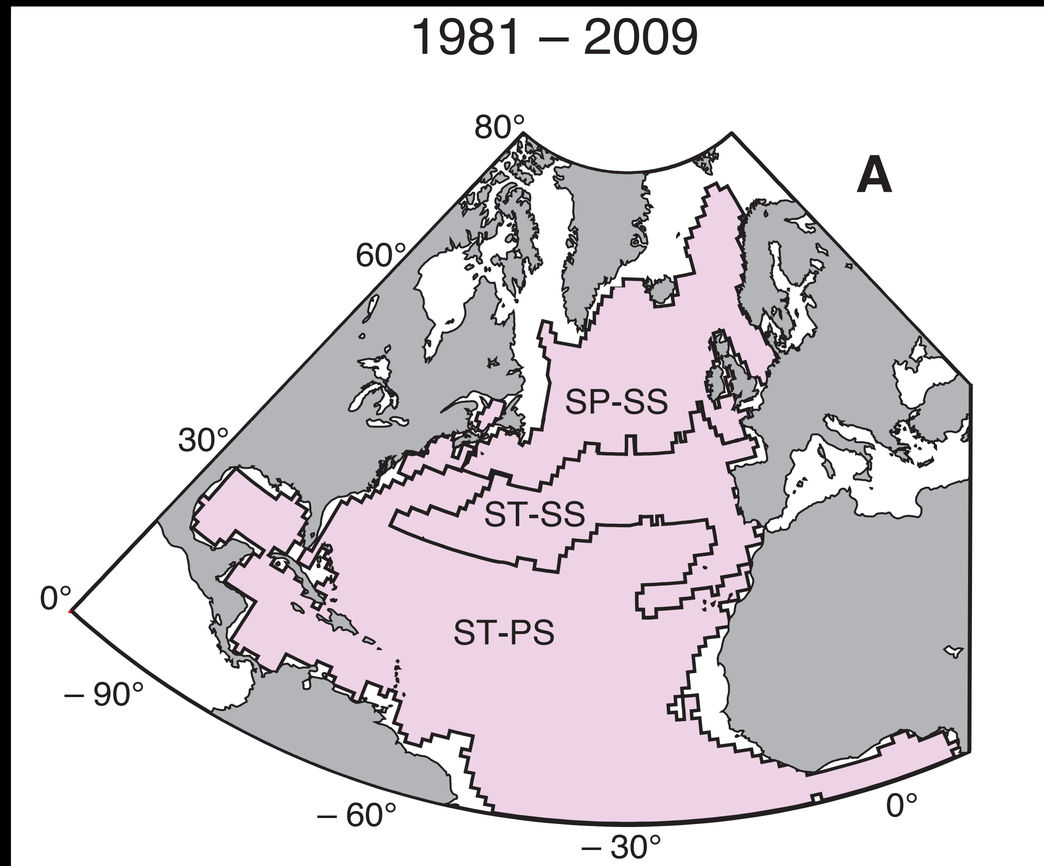
OVER-EQUILIBRATION

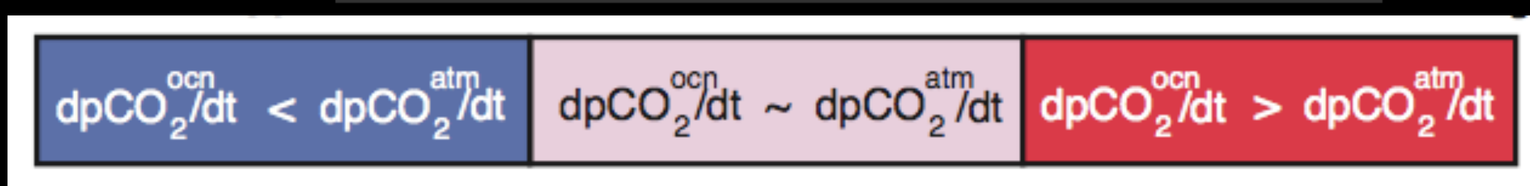
$dpCO_2^{s.ocean}/dt <$
$dpCO_2^{atm}/dt$

UNDER-EQUILIBRATION

Trend in pCO_2^{ocean} compared to pCO_2^{atm}

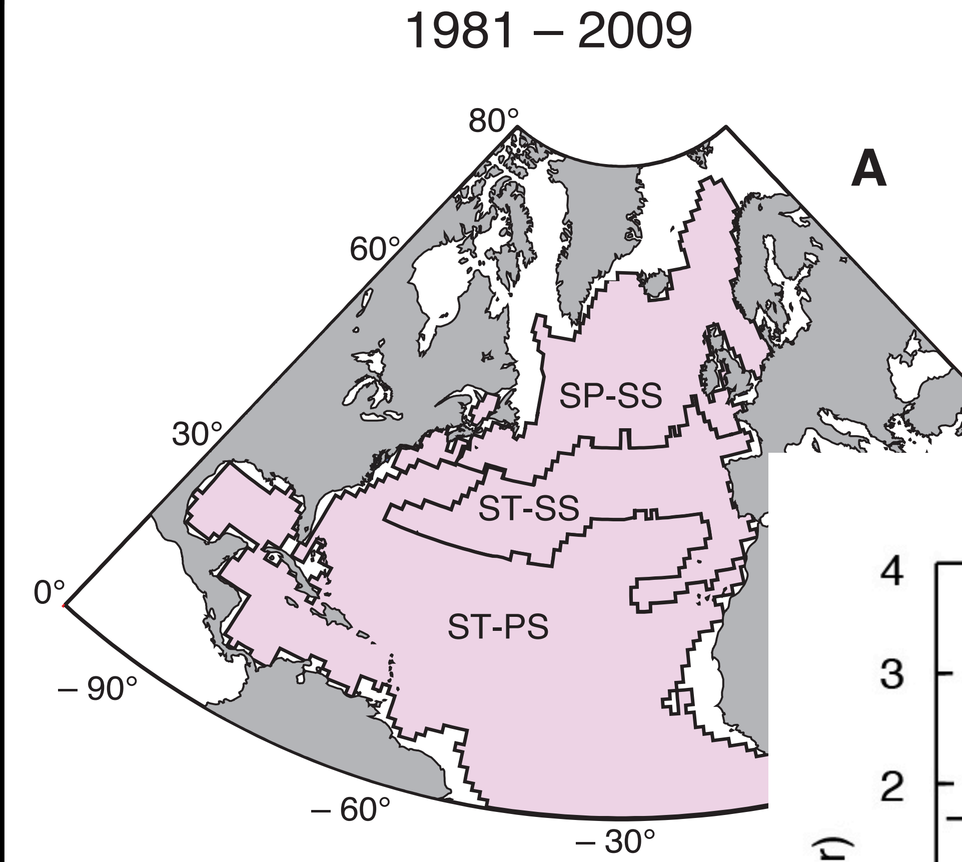
Multi-decadal:
1981-2009

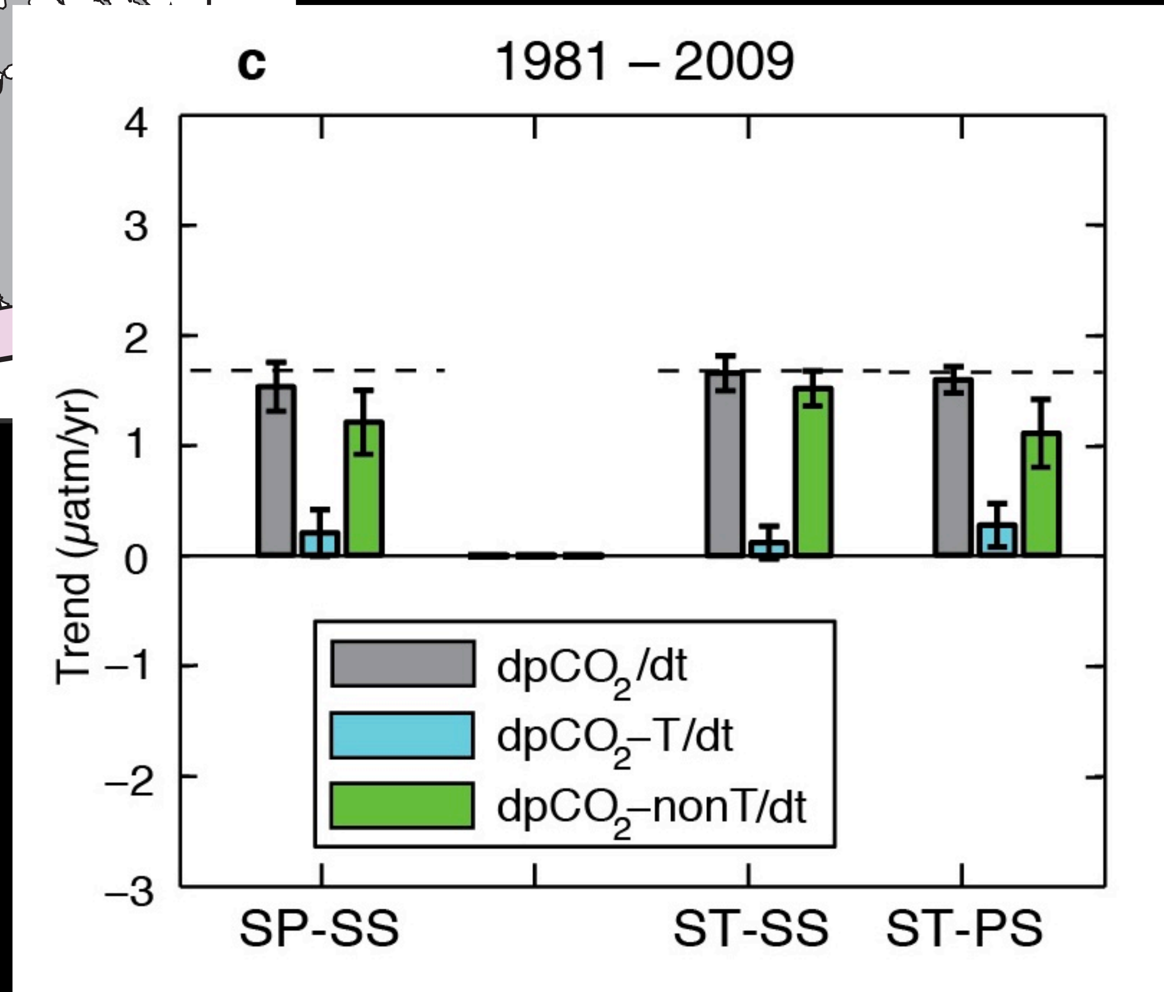




under-equilibration equilibration over-equilibration

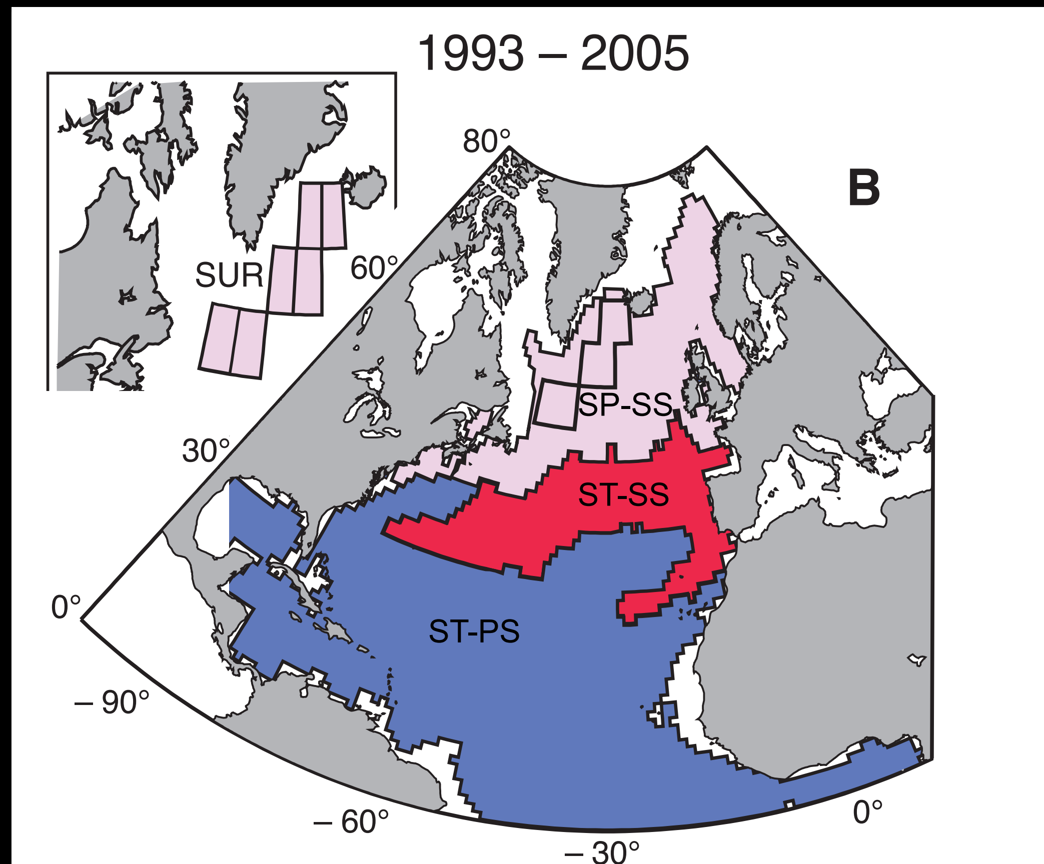
Chemical change dominates on multidecadal timescale





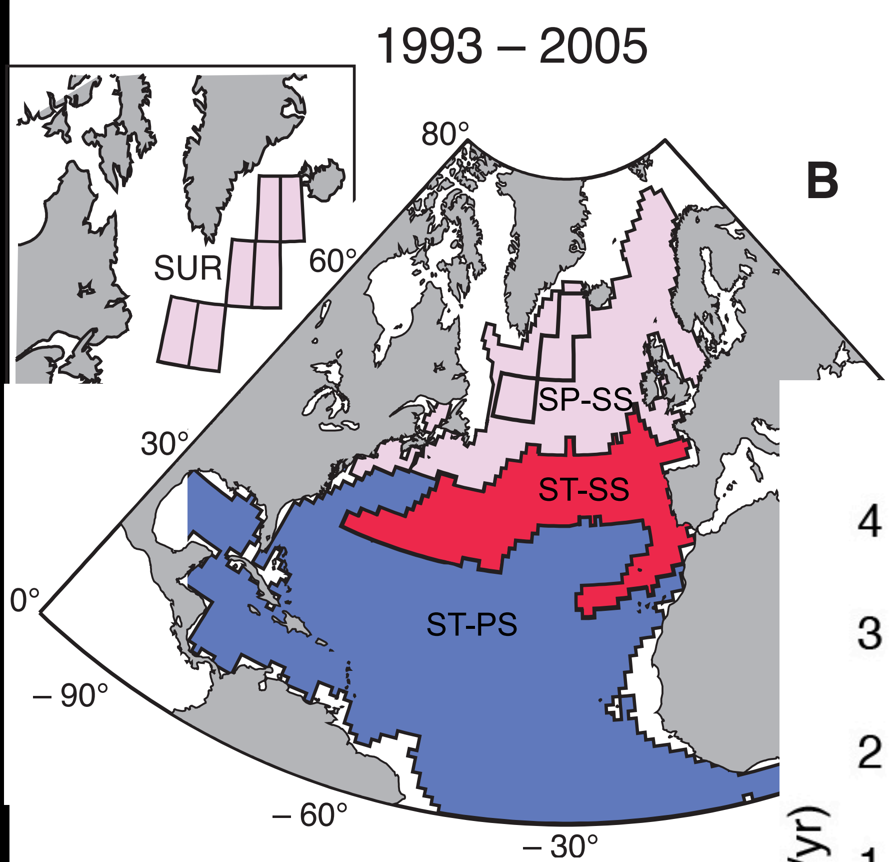
Trend in pCO_2^{ocean} compared to pCO_2^{atm}

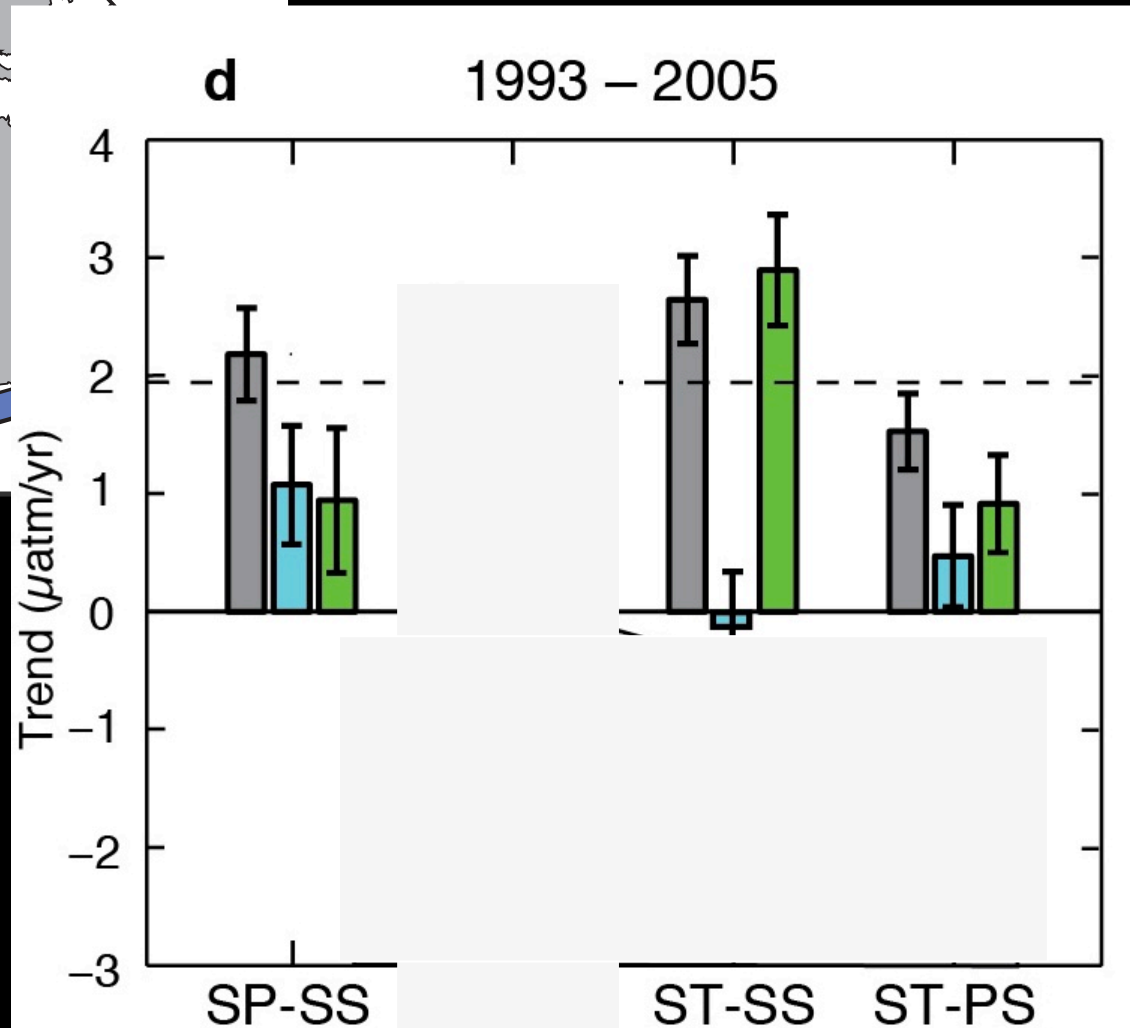
Decadal:
1993-2005



$dpCO_2^{ocn}/dt < dpCO_2^{atm}/dt$	$dpCO_2^{ocn}/dt \sim dpCO_2^{atm}/dt$	$dpCO_2^{ocn}/dt > dpCO_2^{atm}/dt$
under-equilibration	equilibration	over-equilibration

Influence of climate variability appears on decadal timescales





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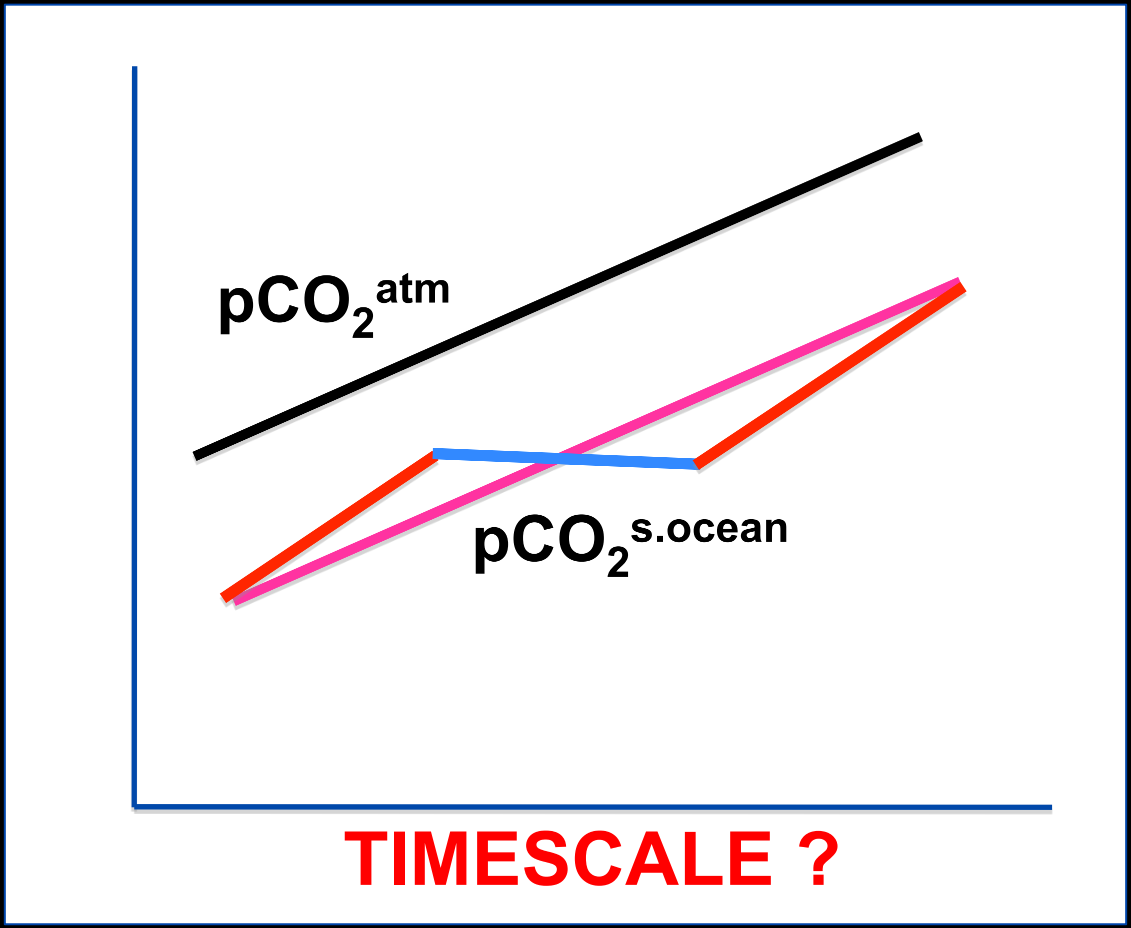
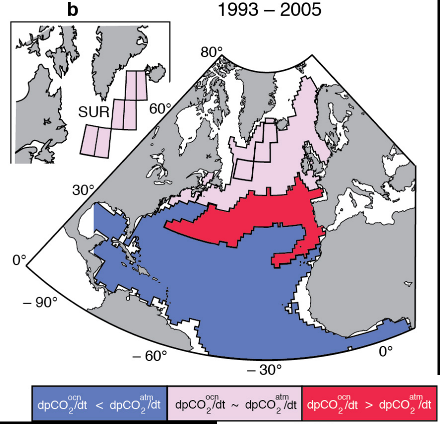
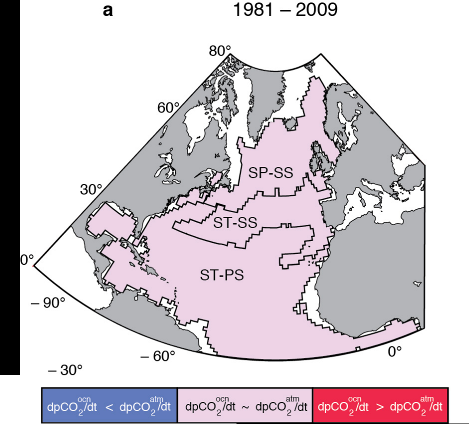
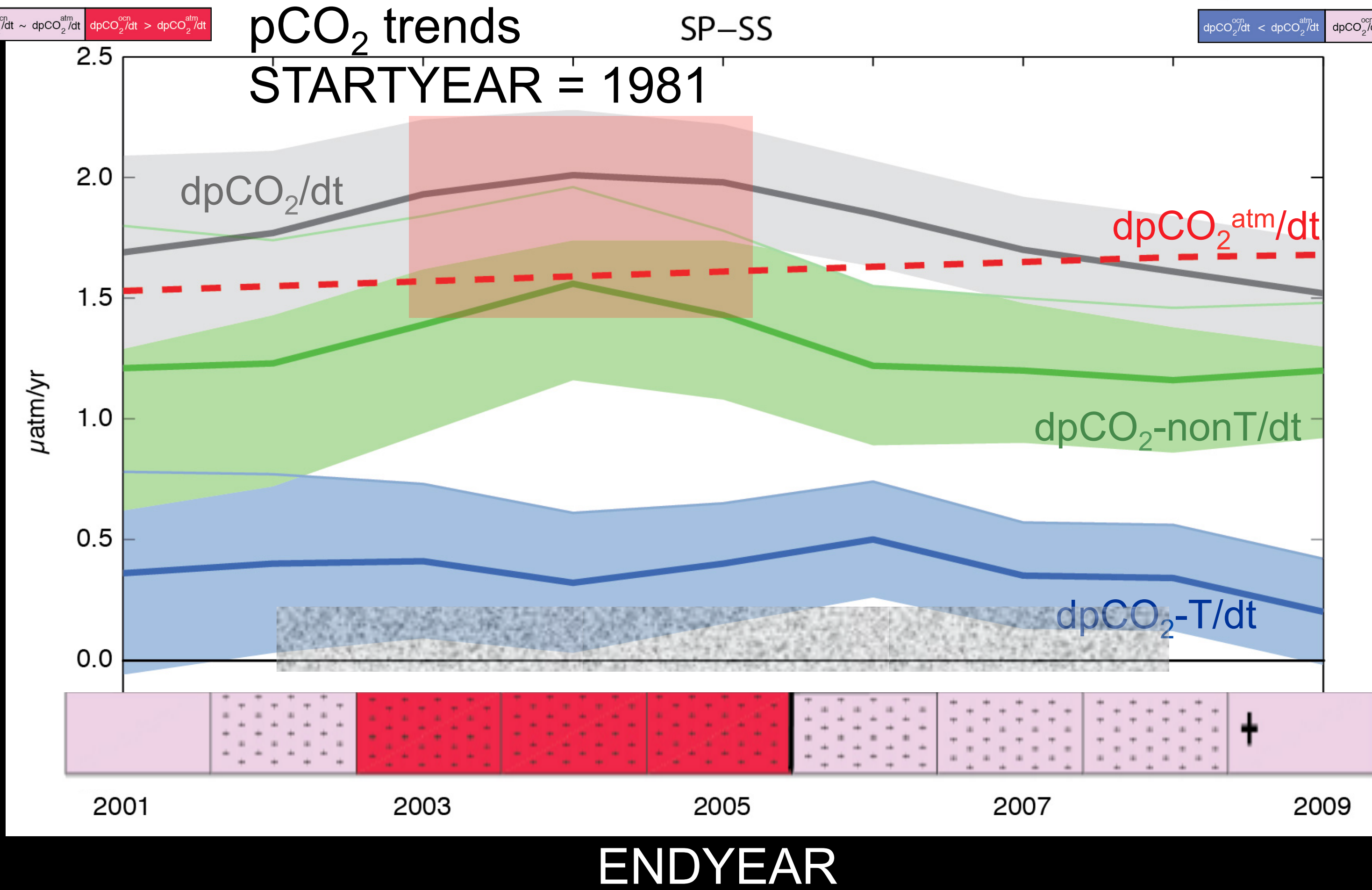




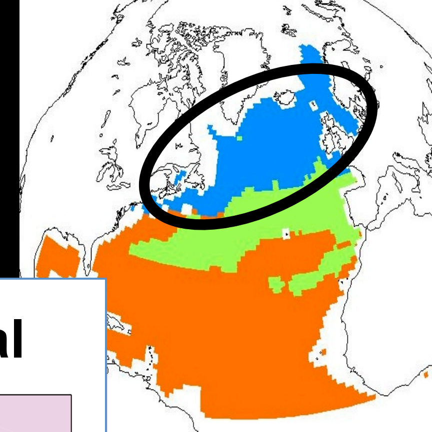
Evaluate transition from decadal to multidecadal

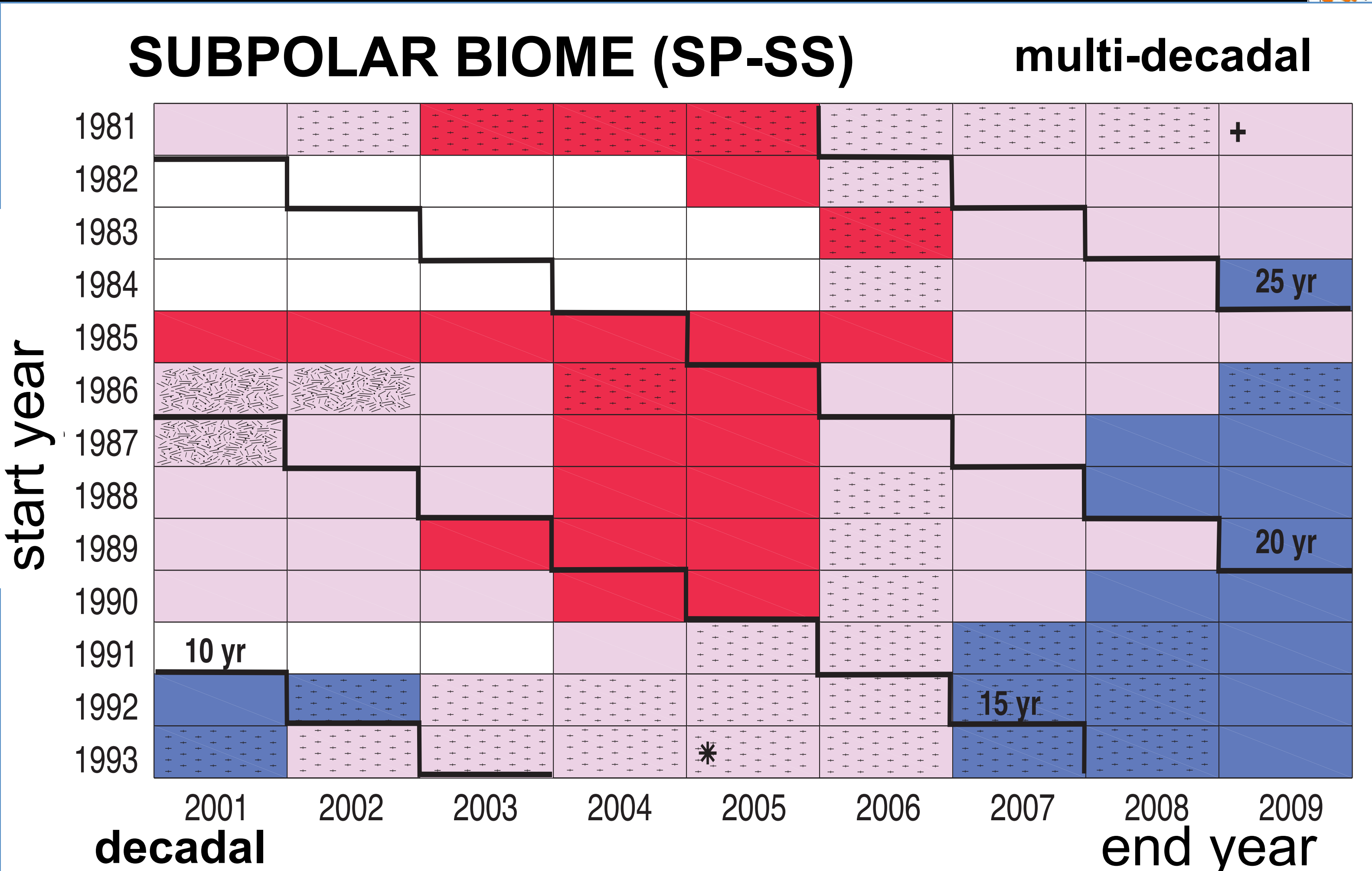


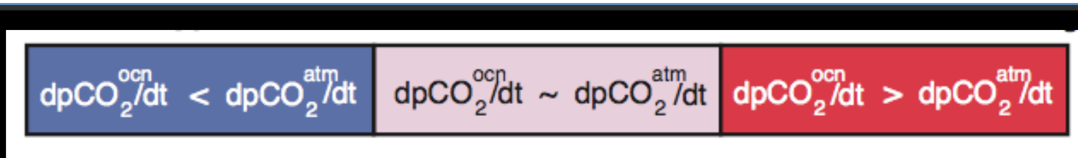


Considering varying timescales

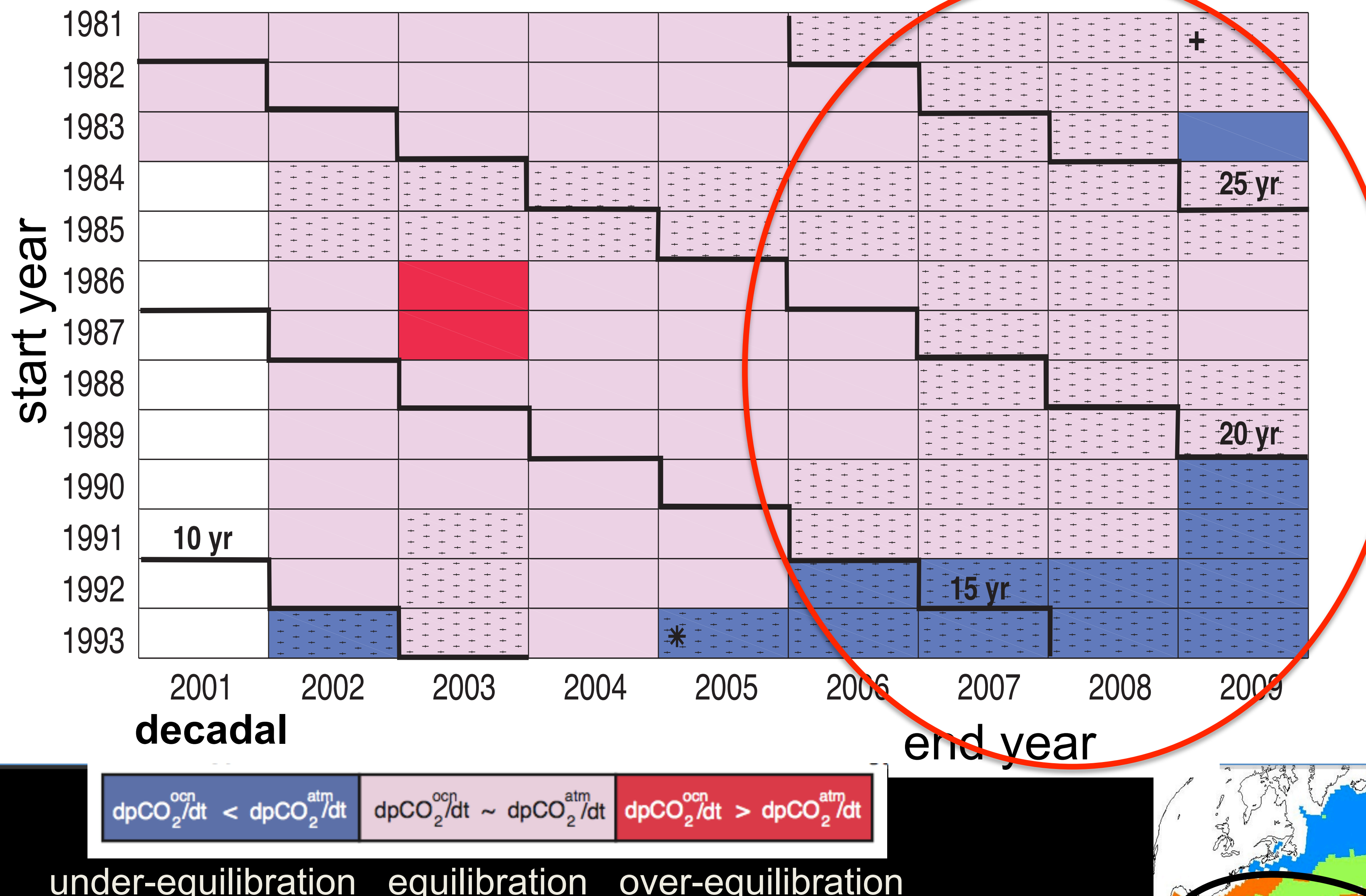
Dotted = warming influence significant

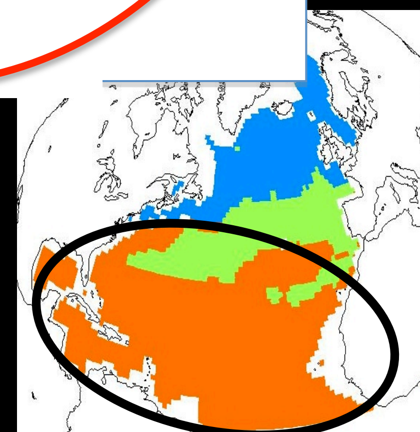






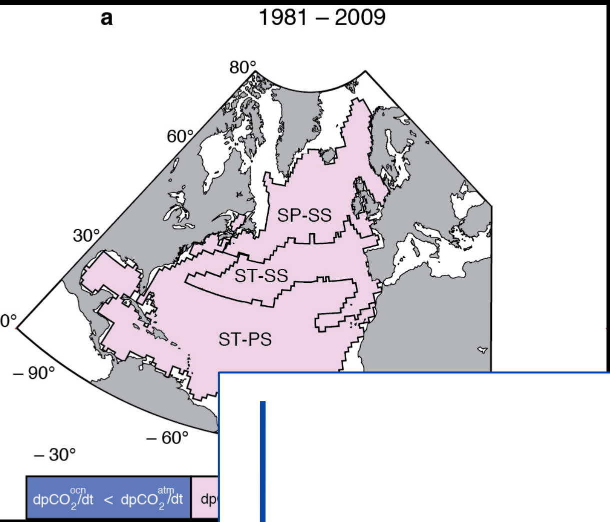
SUBTROPICAL PERMANENTLY STRATIFIED (ST-PS)

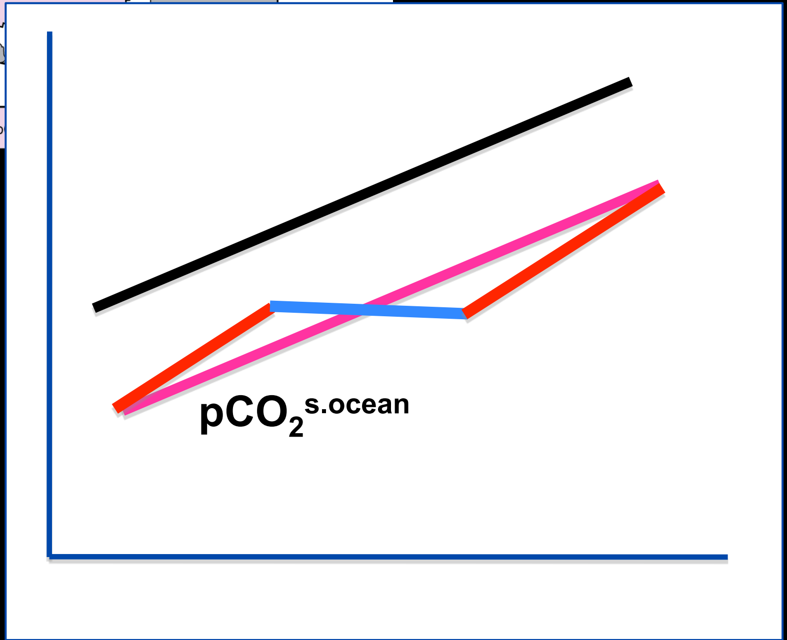


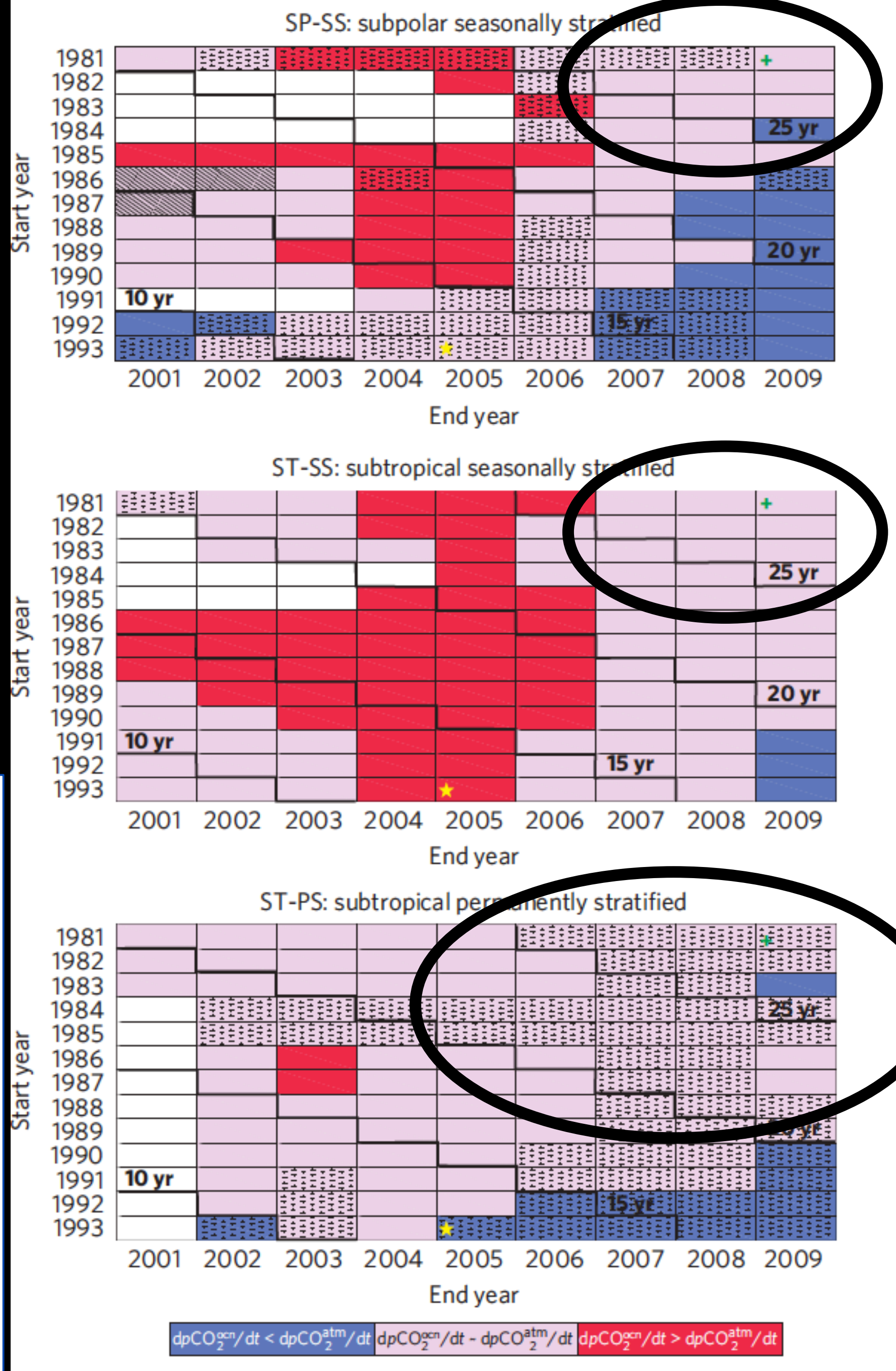


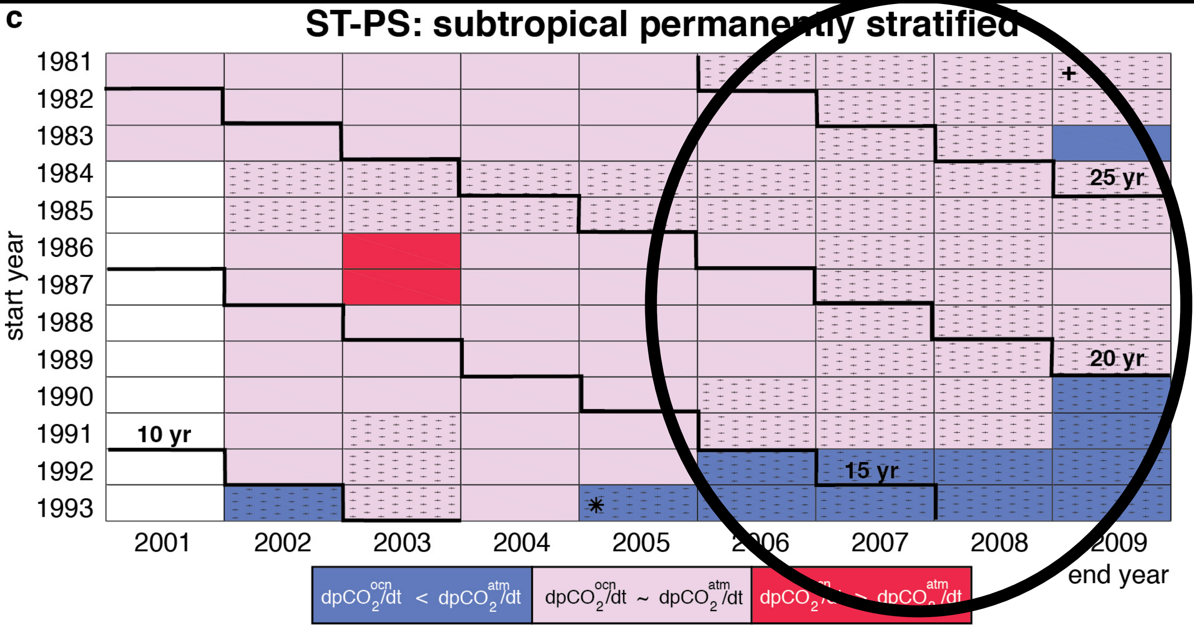
Dotted = warming influence significant

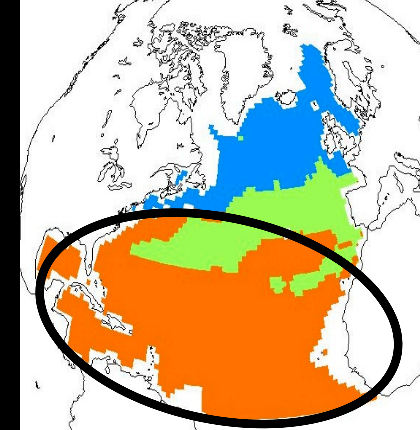
More than two decades for carbon accumulation to dominate $pCO_2^{s.ocean}$ trend



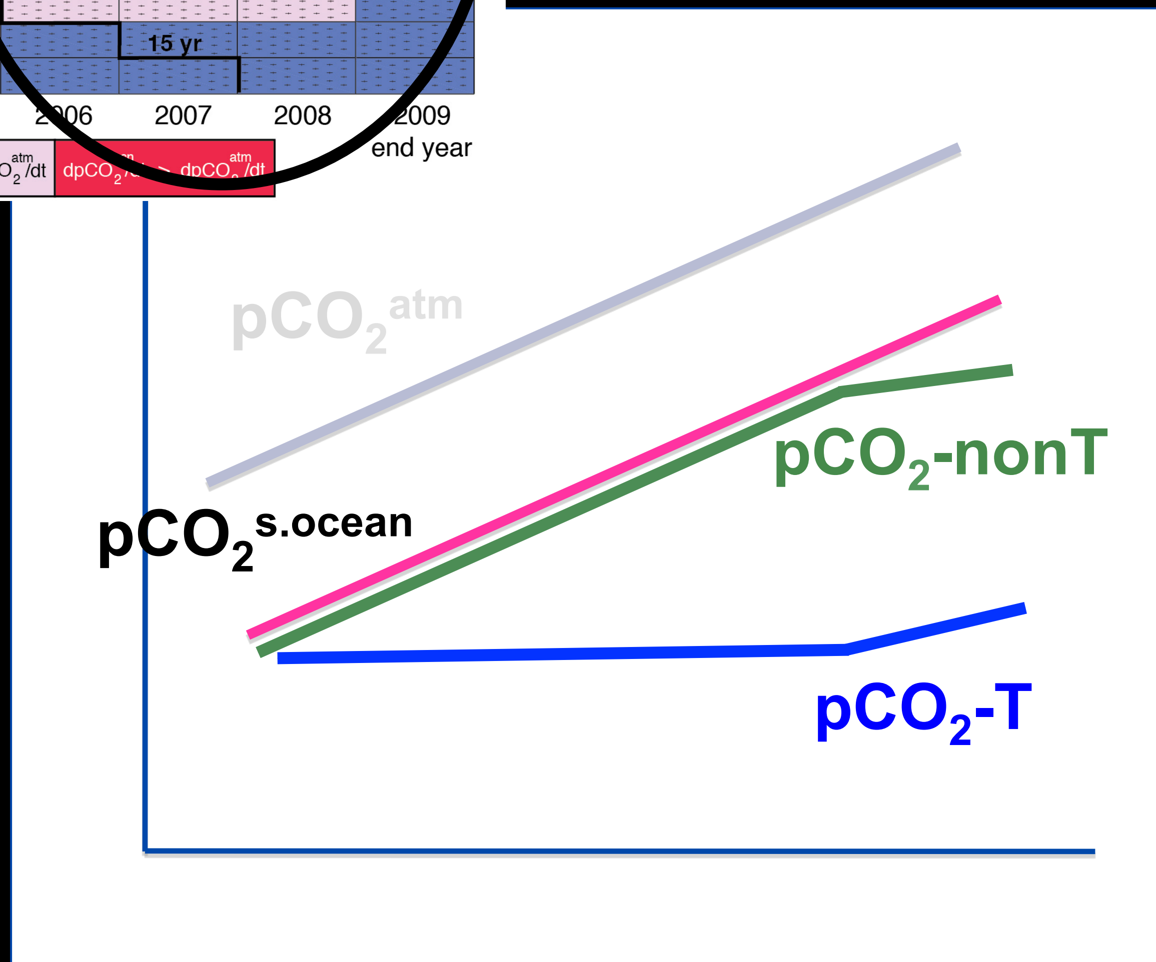








Warming beginning to reduce subtropical N. Atlantic carbon sink



Modeling assessment of global CO_2 sink impacts due to climate change: 1981-2007 = -0.20 PgC/decade

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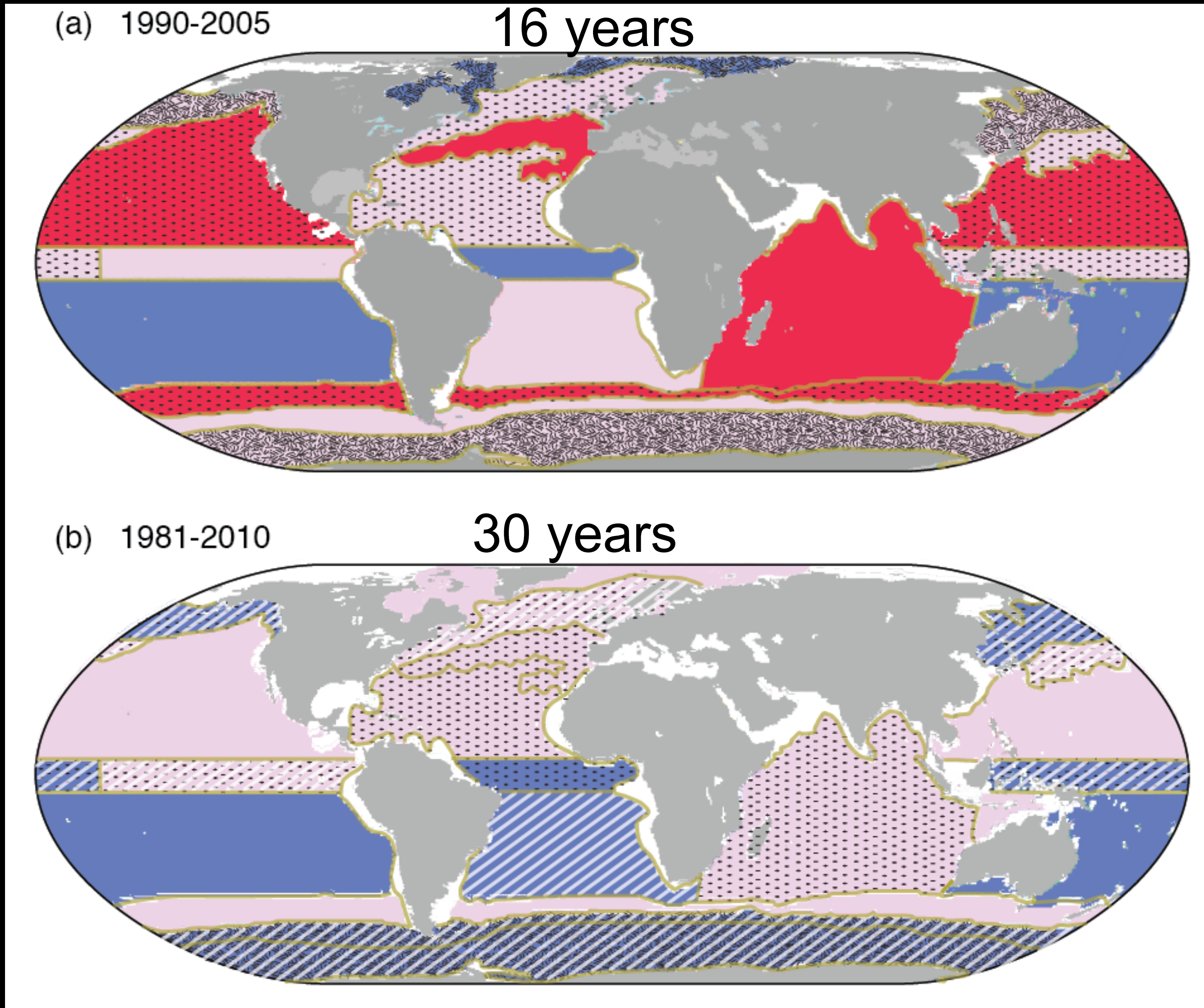
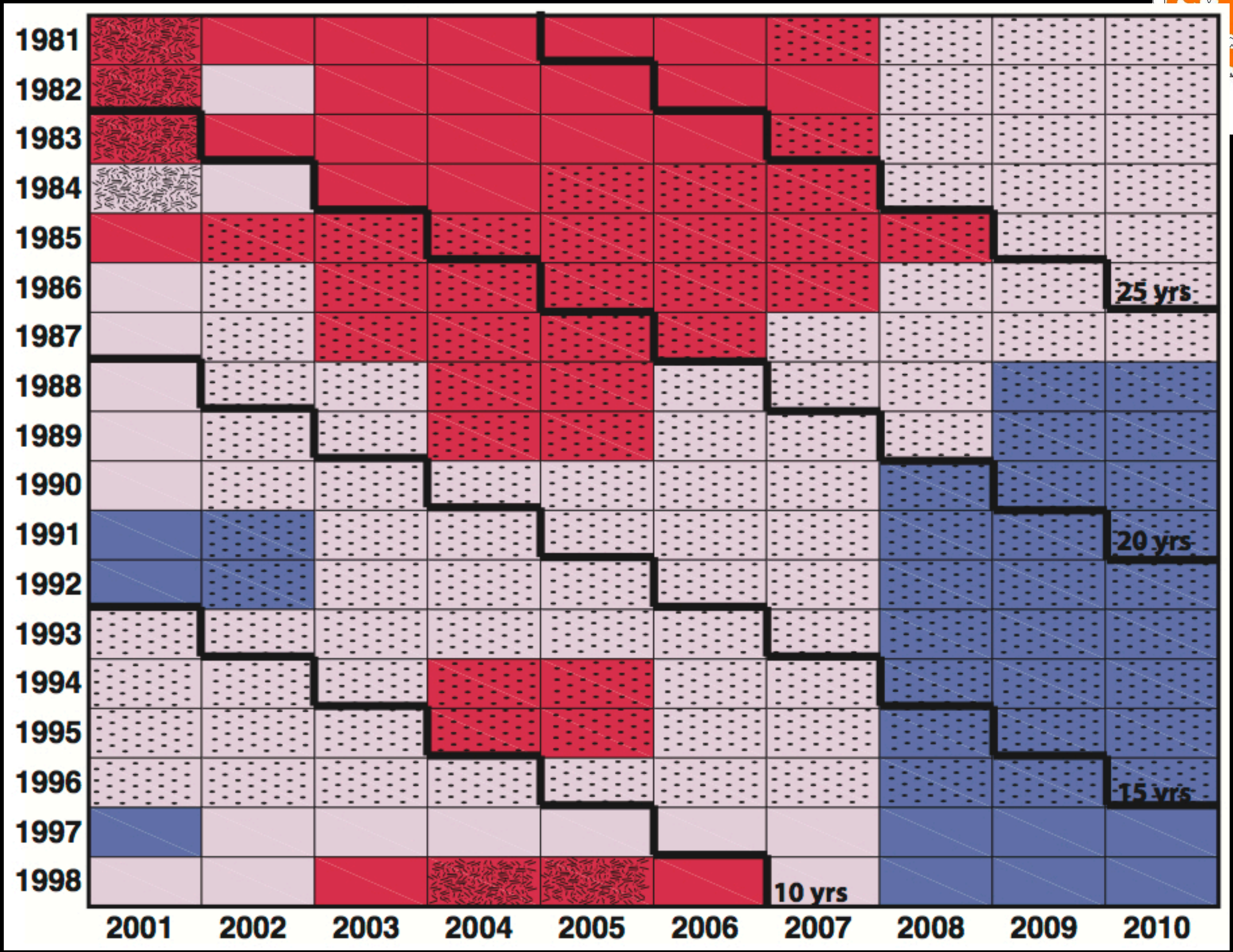
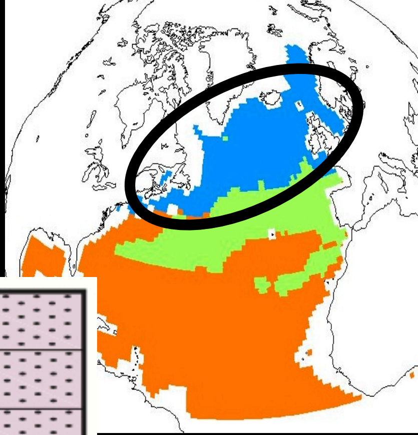
Global Analysis

Fay and McKinley, submitted

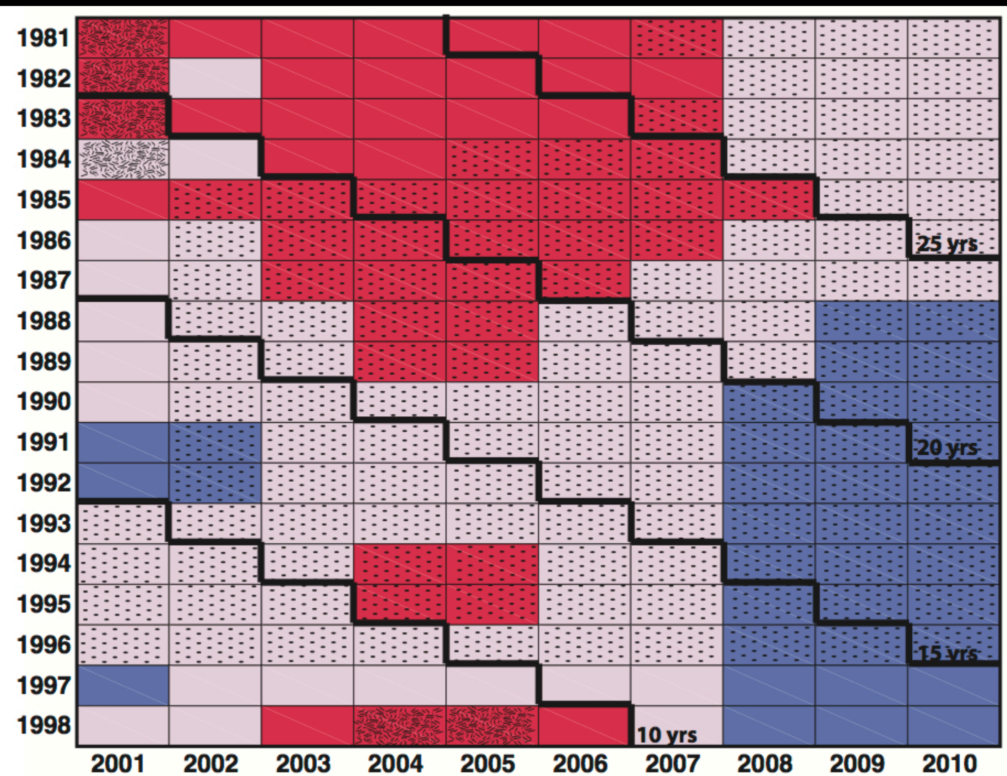


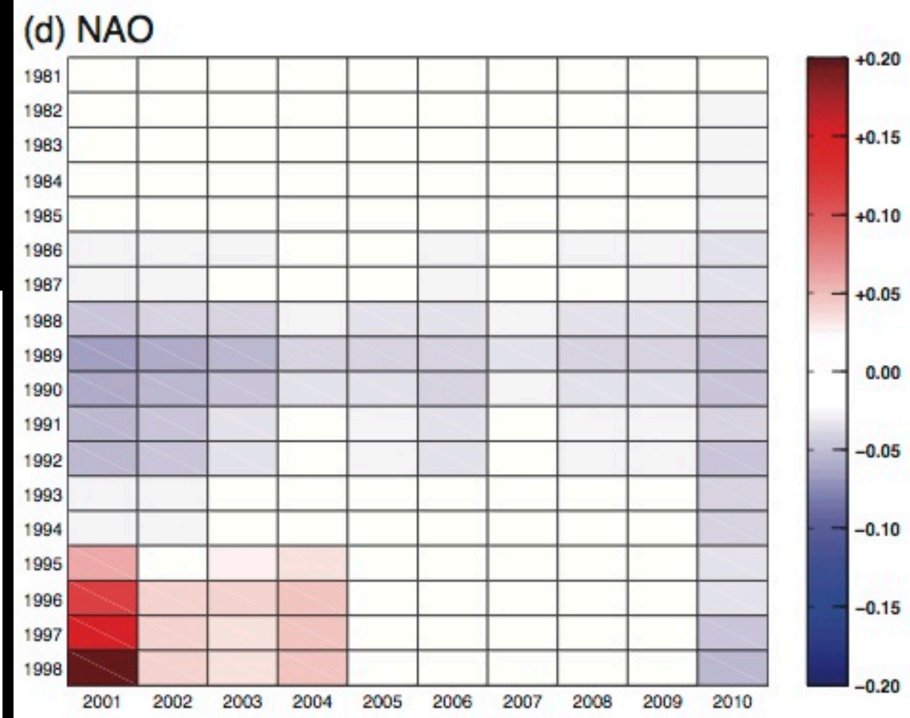
North Atlantic Subpolar, updated has more warming; Grid extended to 1981-98 to 2001-10

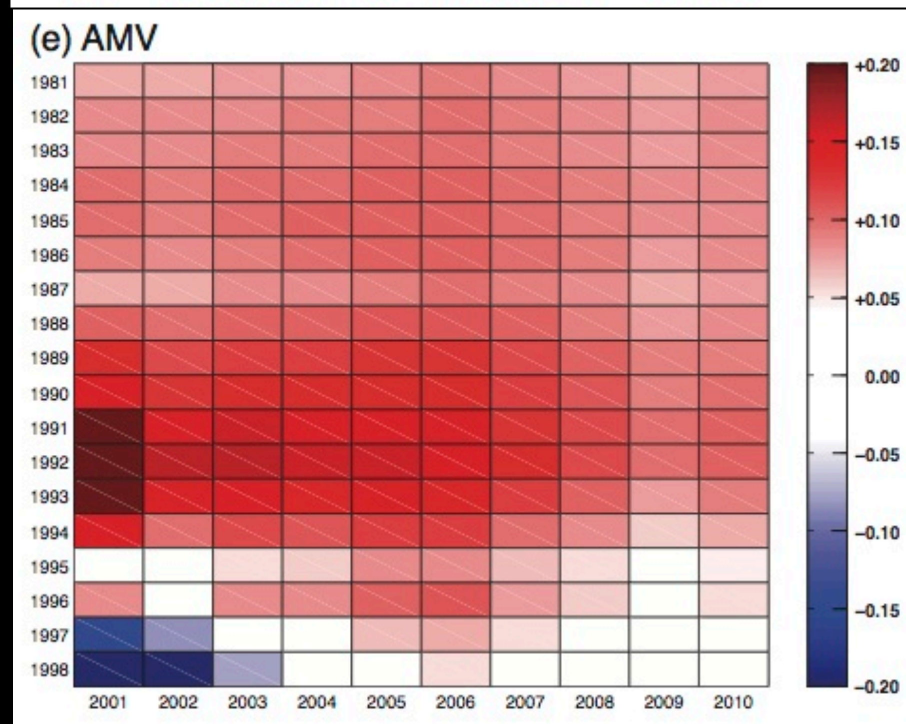




North Atlantic Subpolar; with NAO and AMV grids





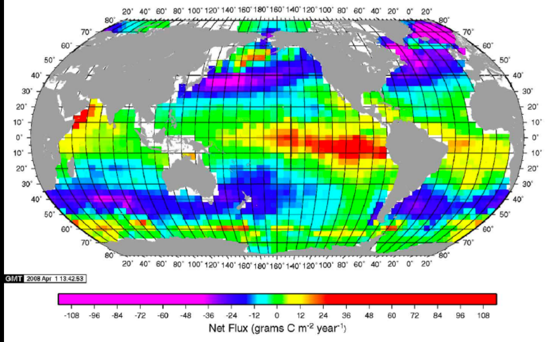


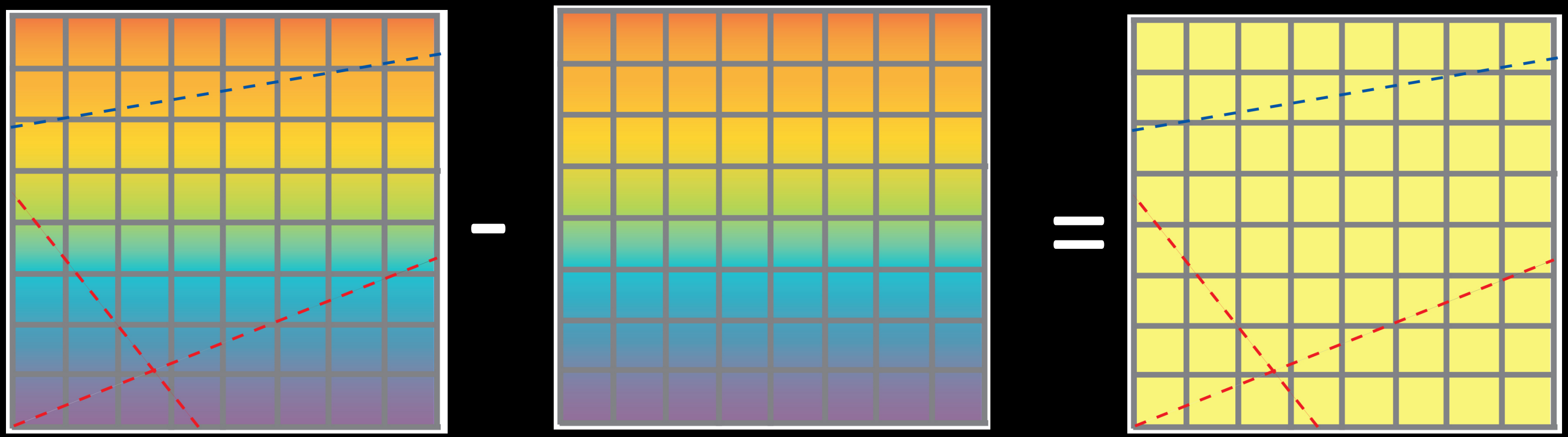
Conclusions

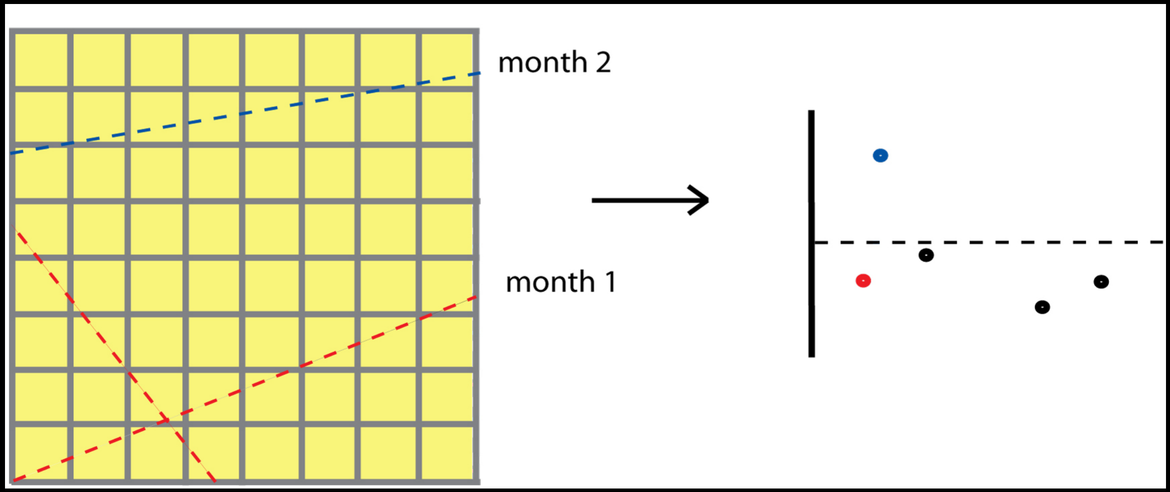
- Decadal variability is dominant signal in pCO_2 trends for at least 2 decades
- Equilibration or under-equilibration appears for longest available timescales (30 years)
- Warming reduces CO_2 sink, esp. in N. Atlantic
  - AMV contributes
  - Consistent with predicted climate change impacts

Methodology detail

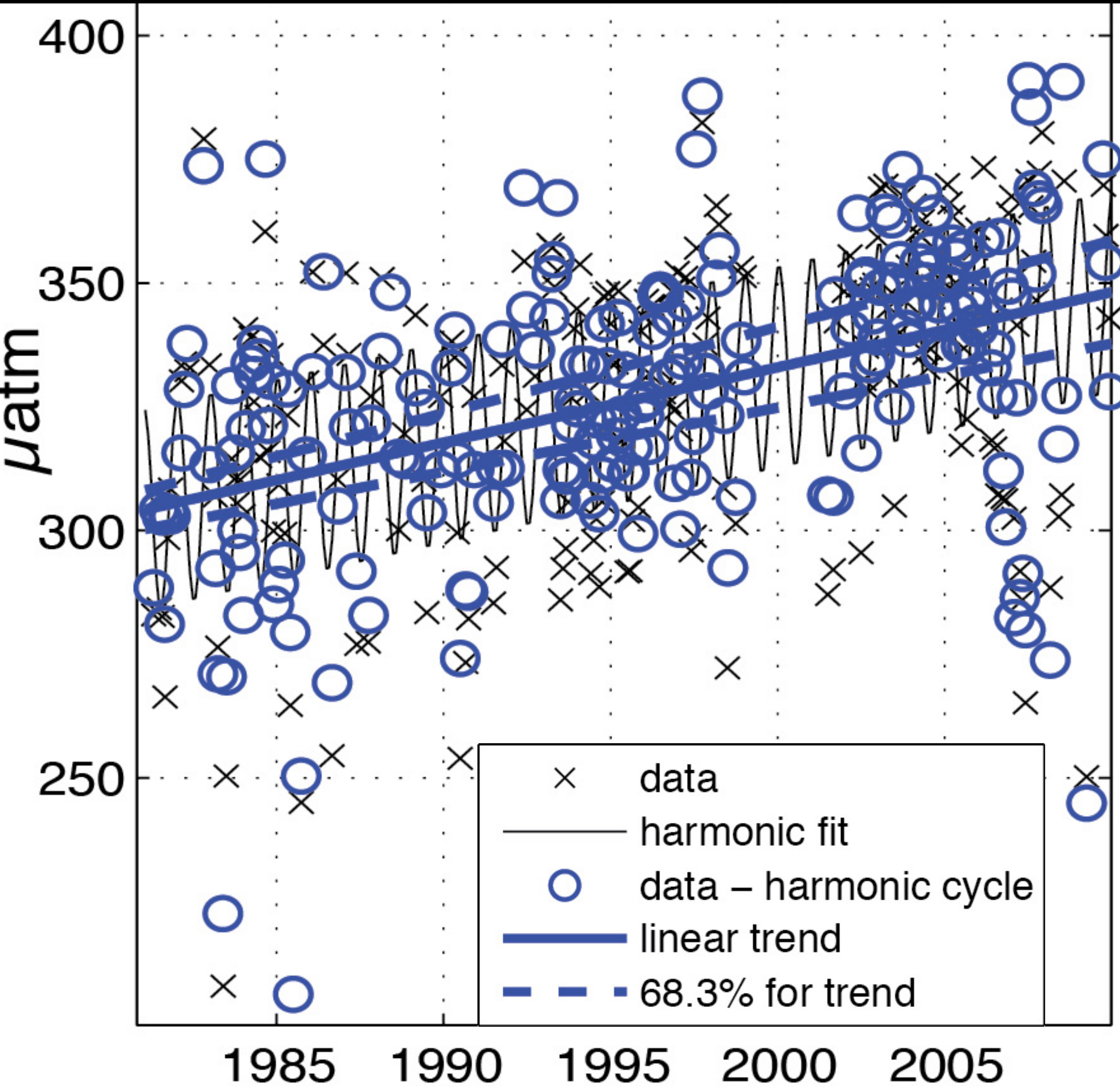
1. Subtract background mean to address spatial aliasing
2. Average to biome timeseries

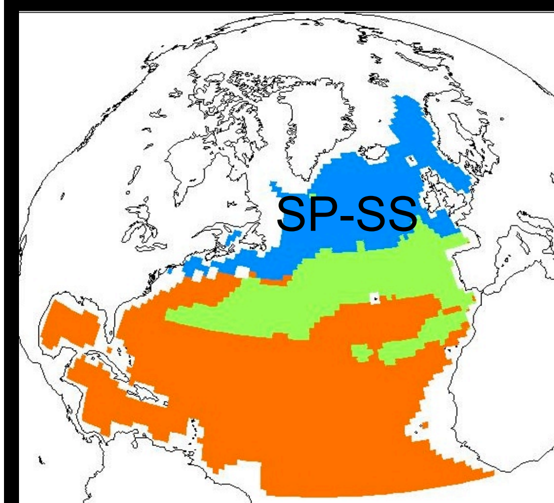




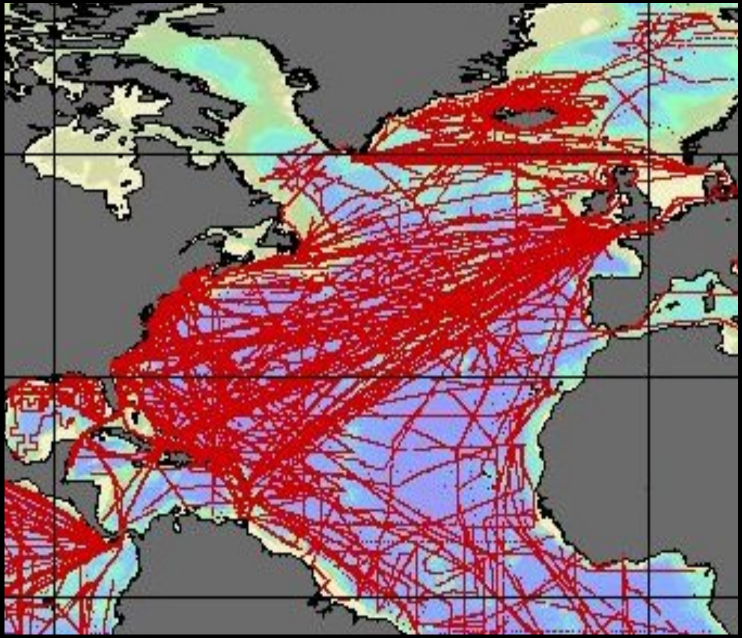


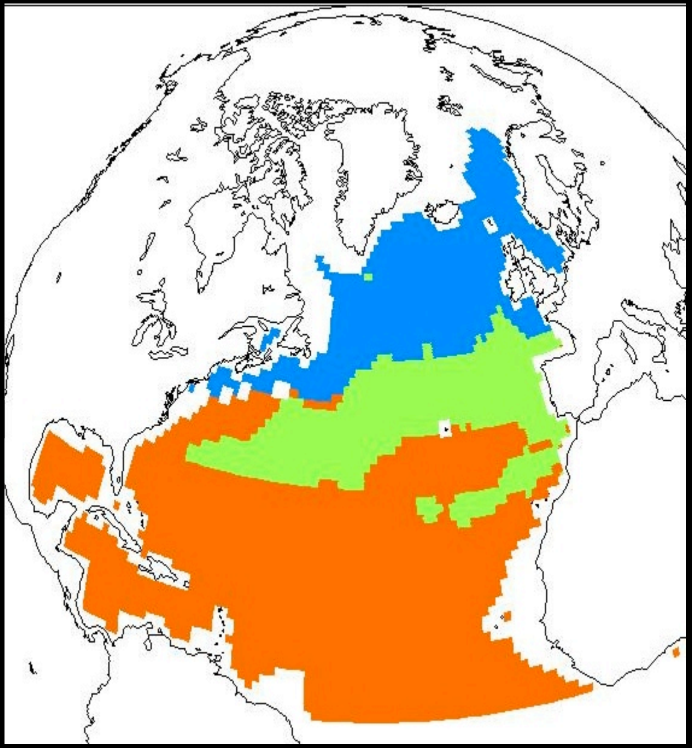
Resulting pCO_2 timeseries, subpolar N. Atlantic

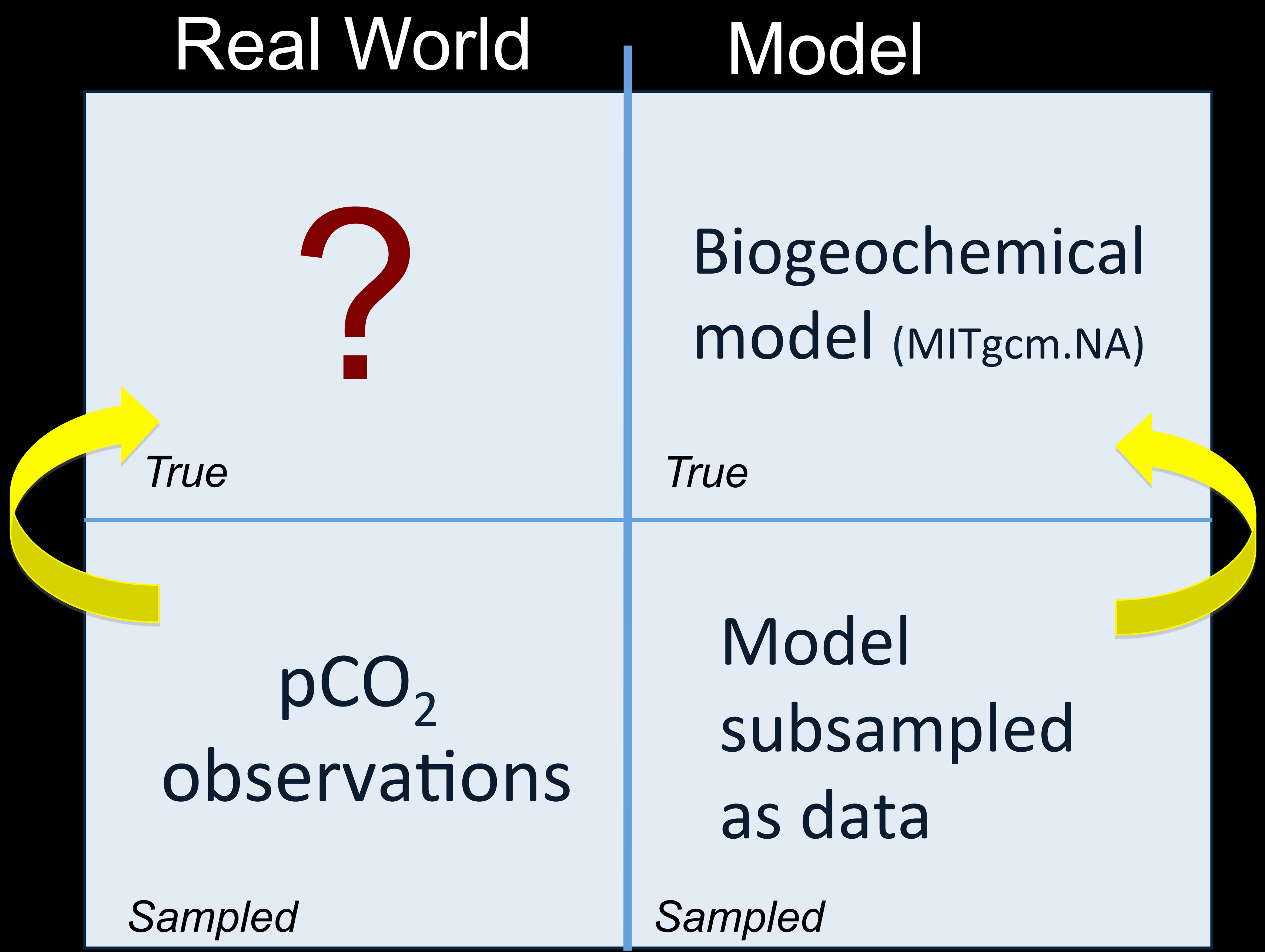




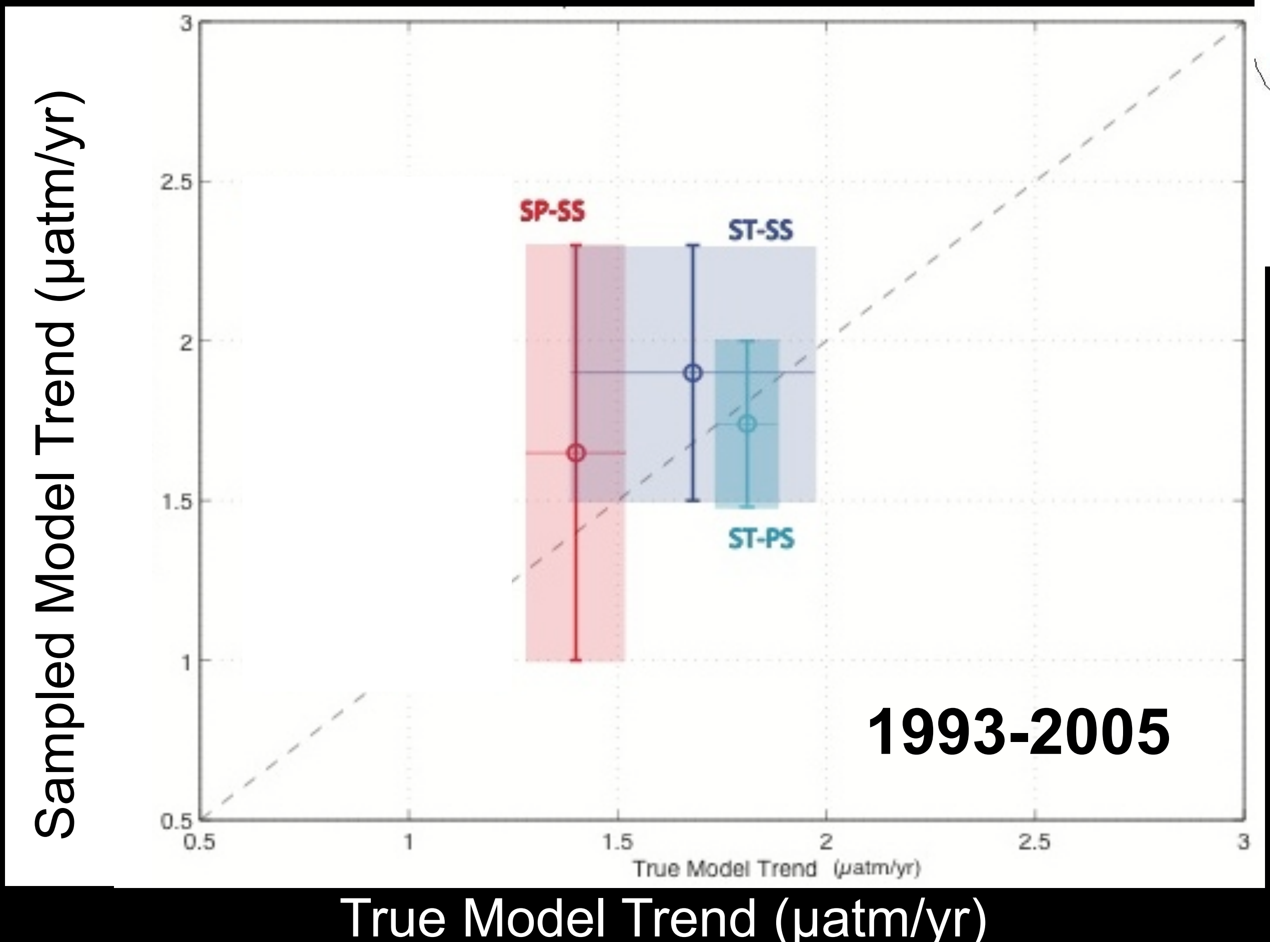
How representative are these trends of the biome?

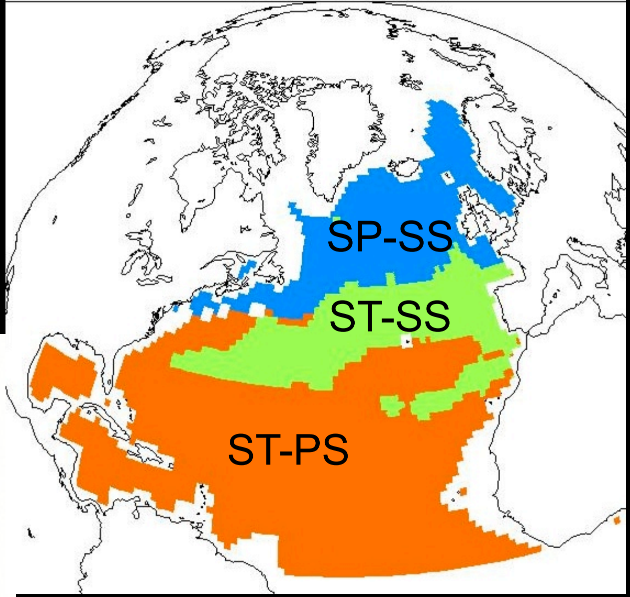





Real World
Model
?
Biogeochemical model (MITgcm.NA)
True
True
pCO_2 observations
Model subsampled as data
Sampled
Sampled

Model Confirmation





Sampled, analyzed model captures trends from all model output at 1σ level

Indicates that sampling and analysis technique are representative