USING DATA TO ELUCIDATE FEEDBACK MECHANISMS IN THE OCEAN CARBON CYCLE

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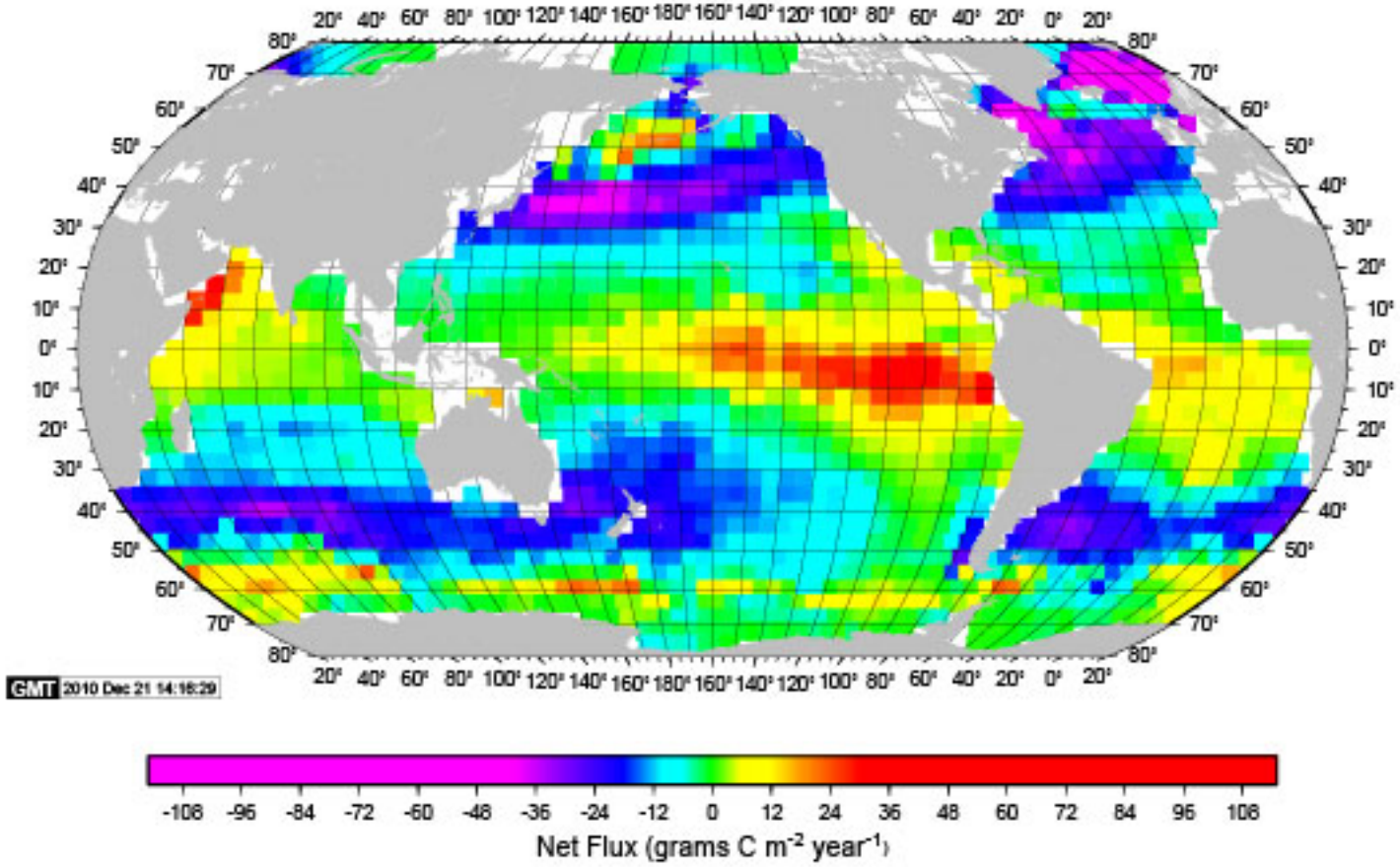
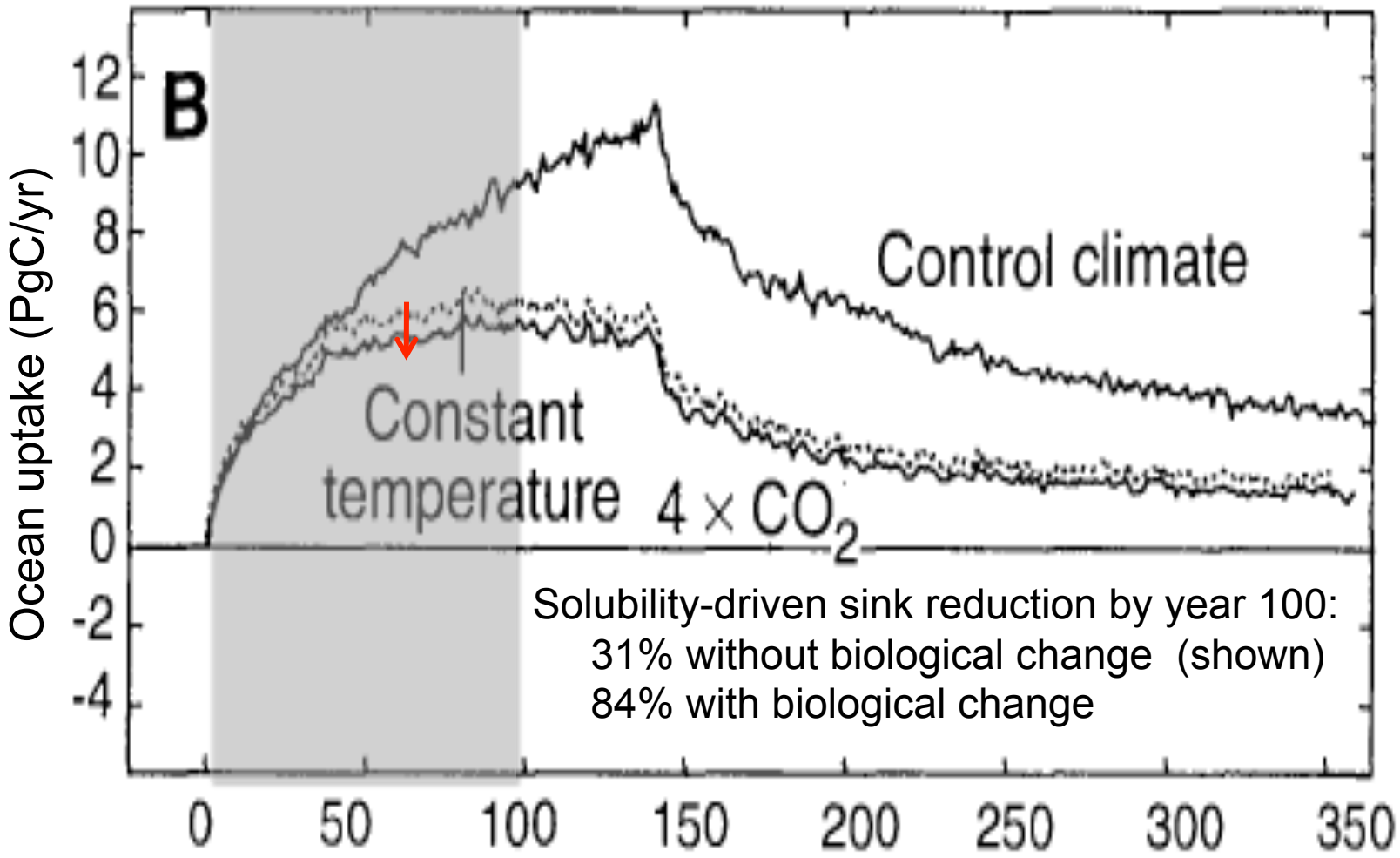
Key Uncertainties in the Global Carbon Cycle: Perspectives across terrestrial and ocean ecosystems

How is the observed ocean carbon sink changing in response to increasing pCO_2^{atm} and warming?

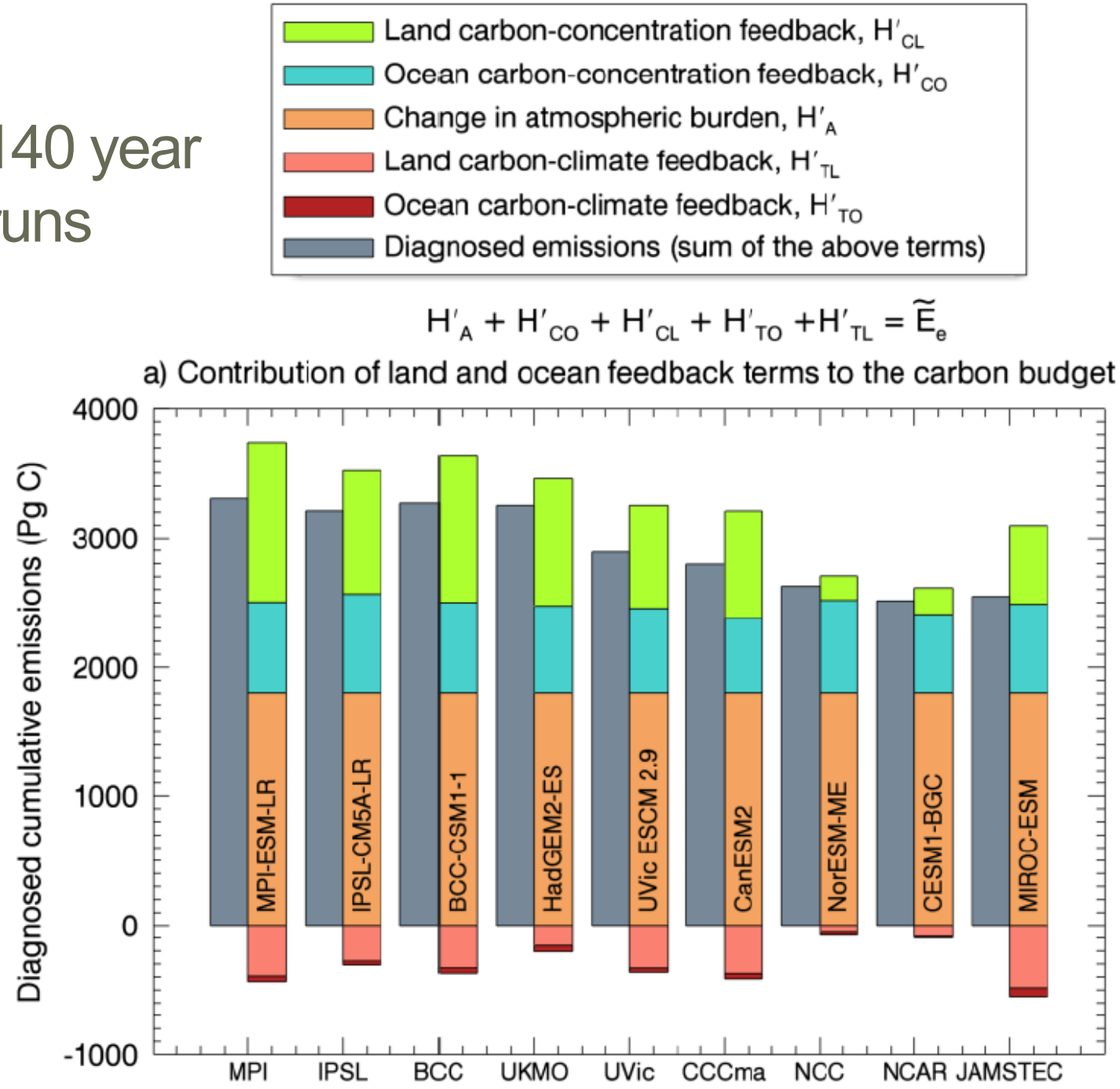


Early models: Positive carbon feedback, damped by negative warming feedback for 100 yrs after 4xCO_2



Sarmiento and LeQuere 1996

CMIP5, 140 year 1% runs



Arora et al. 2013
J. Climate

Hindcast model assessment of ocean sink change due to climate variability and change

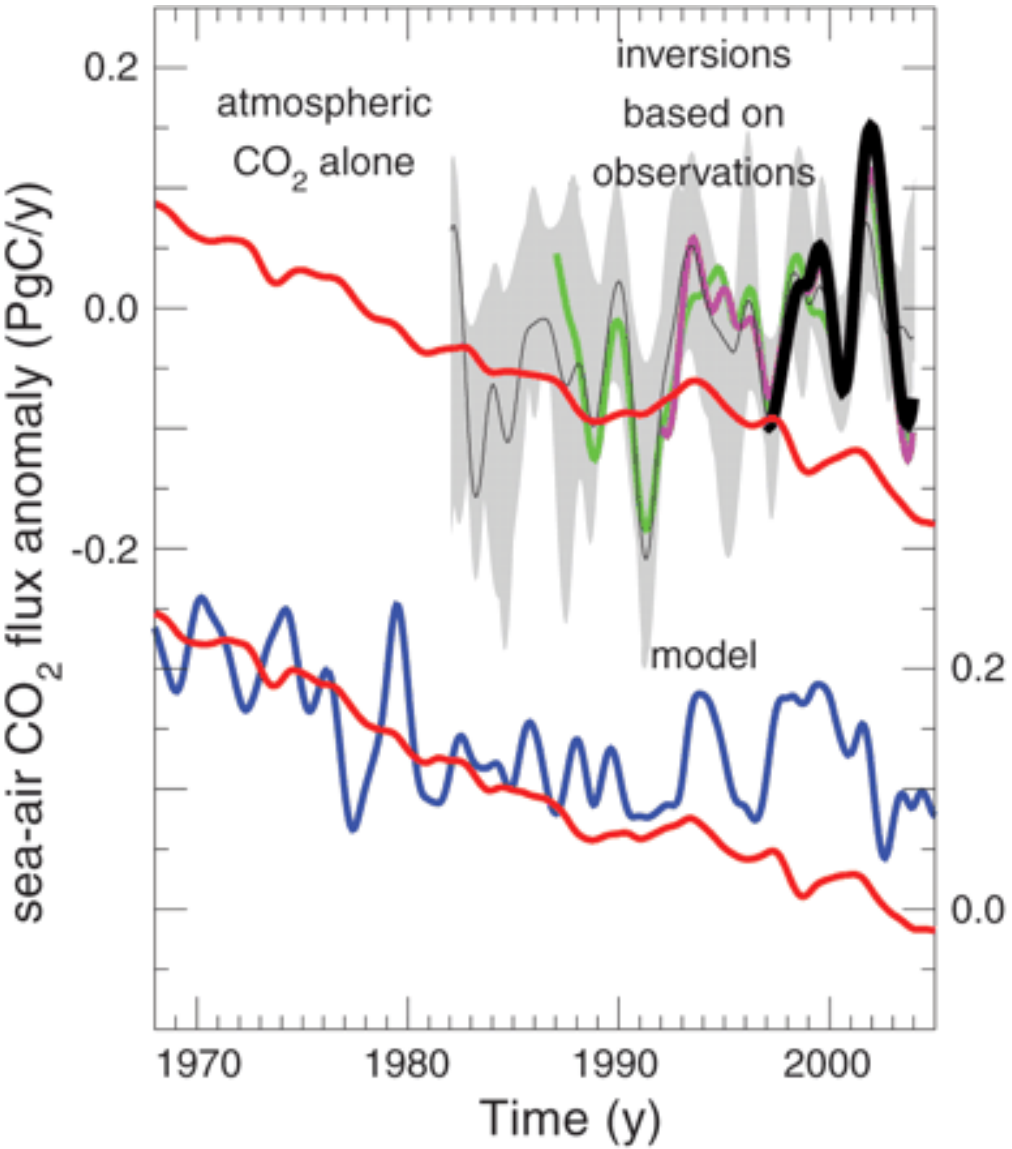
1981-2007 = 0.20 PgC/decade reduction

Mechanism	Sink impact	Regional notes
Warming	-20%	50% in North Atlantic alone
Winds	-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, Global Biogeochem. Cyc.

No biological response to climate

Southern Ocean: Model and atmospheric inversion indicate reduced carbon sink in recent decades.
Proposed mechanism: Increased ventilation of natural DIC.



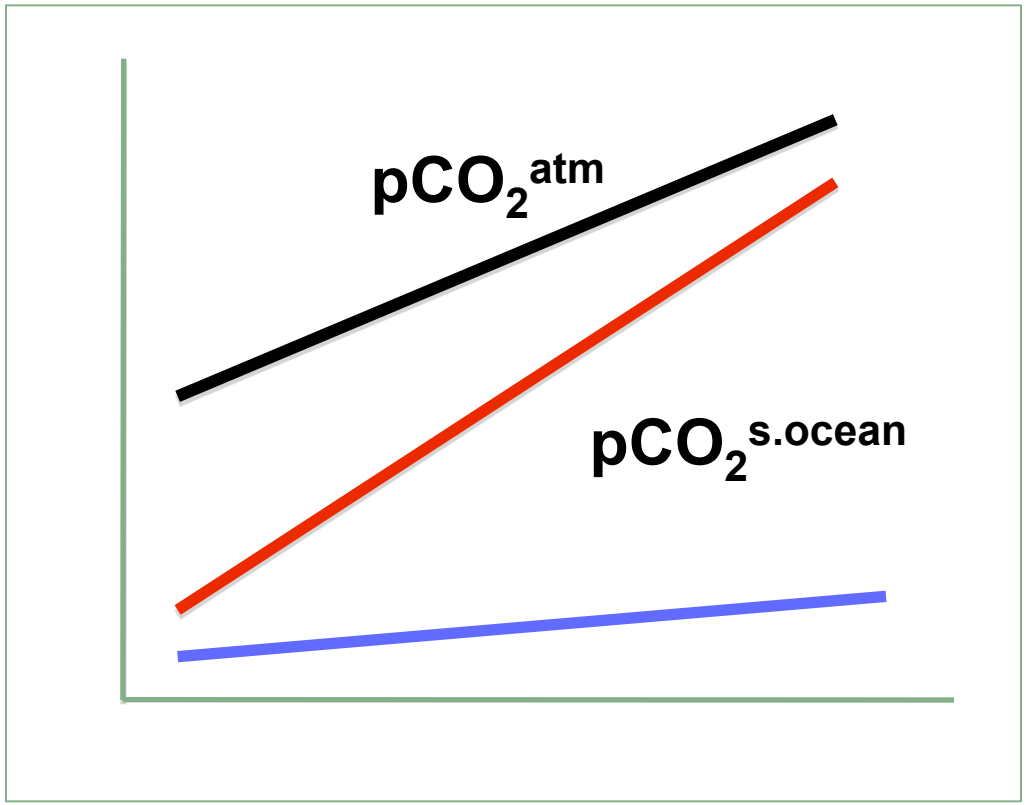
Are modeled mechanisms accurate?

Boning et al. 2008, Nat. Geo.
Ito et al 2010, Nature
Gent and Danabasoglu 2011, J. Climate

LeQuere et al. 2007, Science

Surface ocean pCO_2 for assessment of feedback mechanisms

pCO_2^{atm} trend vs. $pCO_2^{s.ocean}$ trend



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

steeper $pCO_2^{s.ocean}$ trend

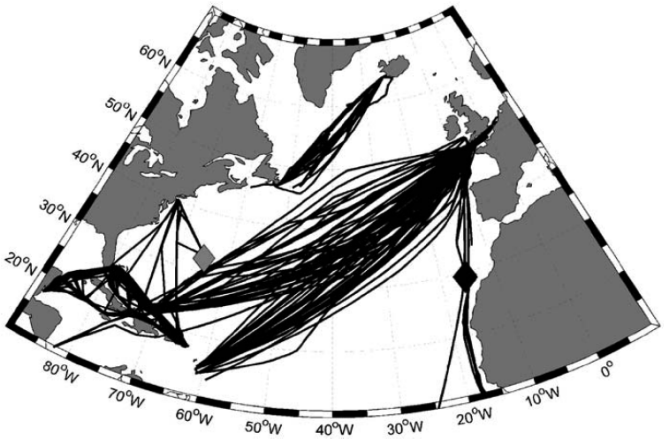
DECREASING ΔpCO_2

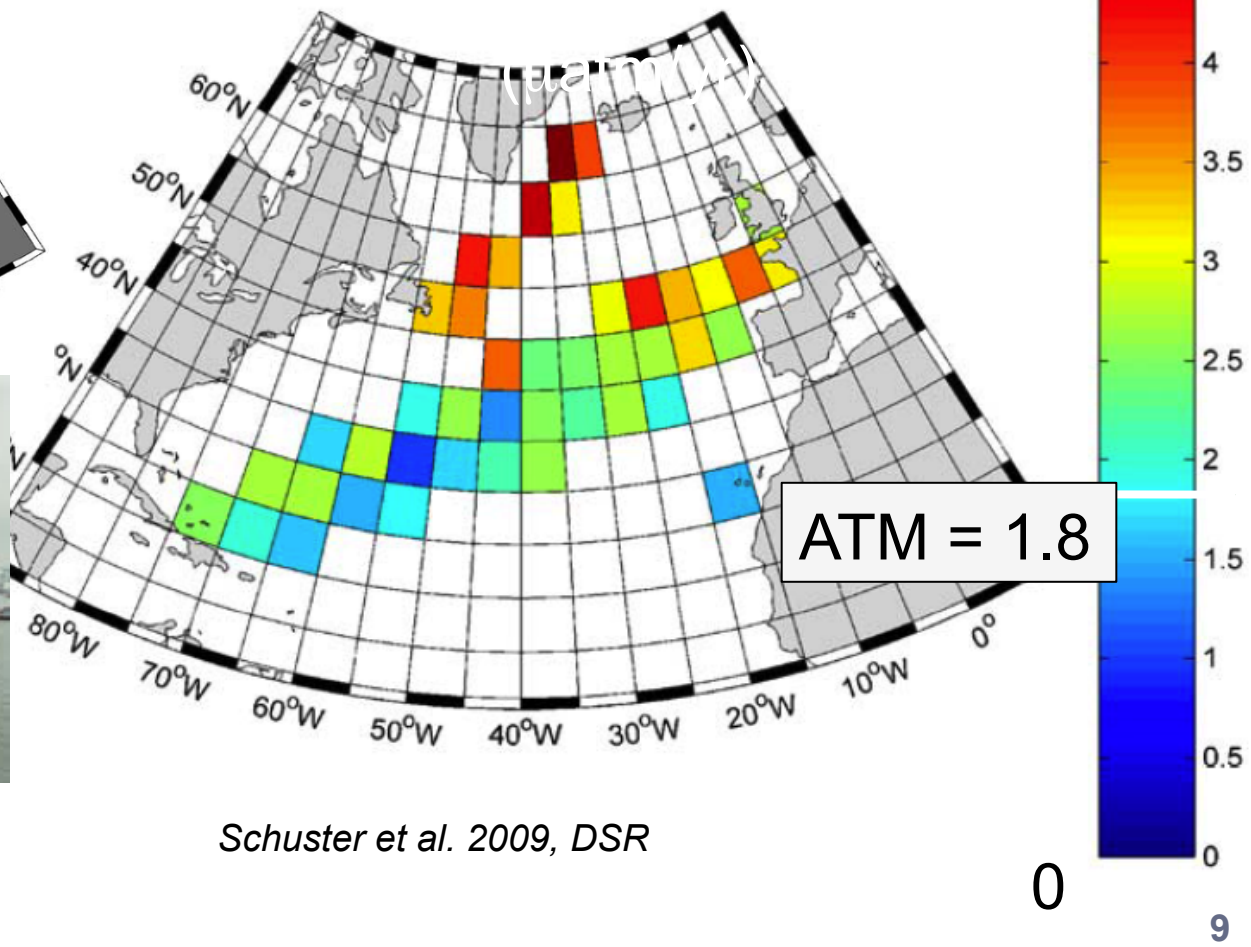
$dpCO_2^{s.ocean}/dt < dpCO_2^{atm}/dt$

shallower $pCO_2^{s.ocean}$ trend

INCREASING ΔpCO_2

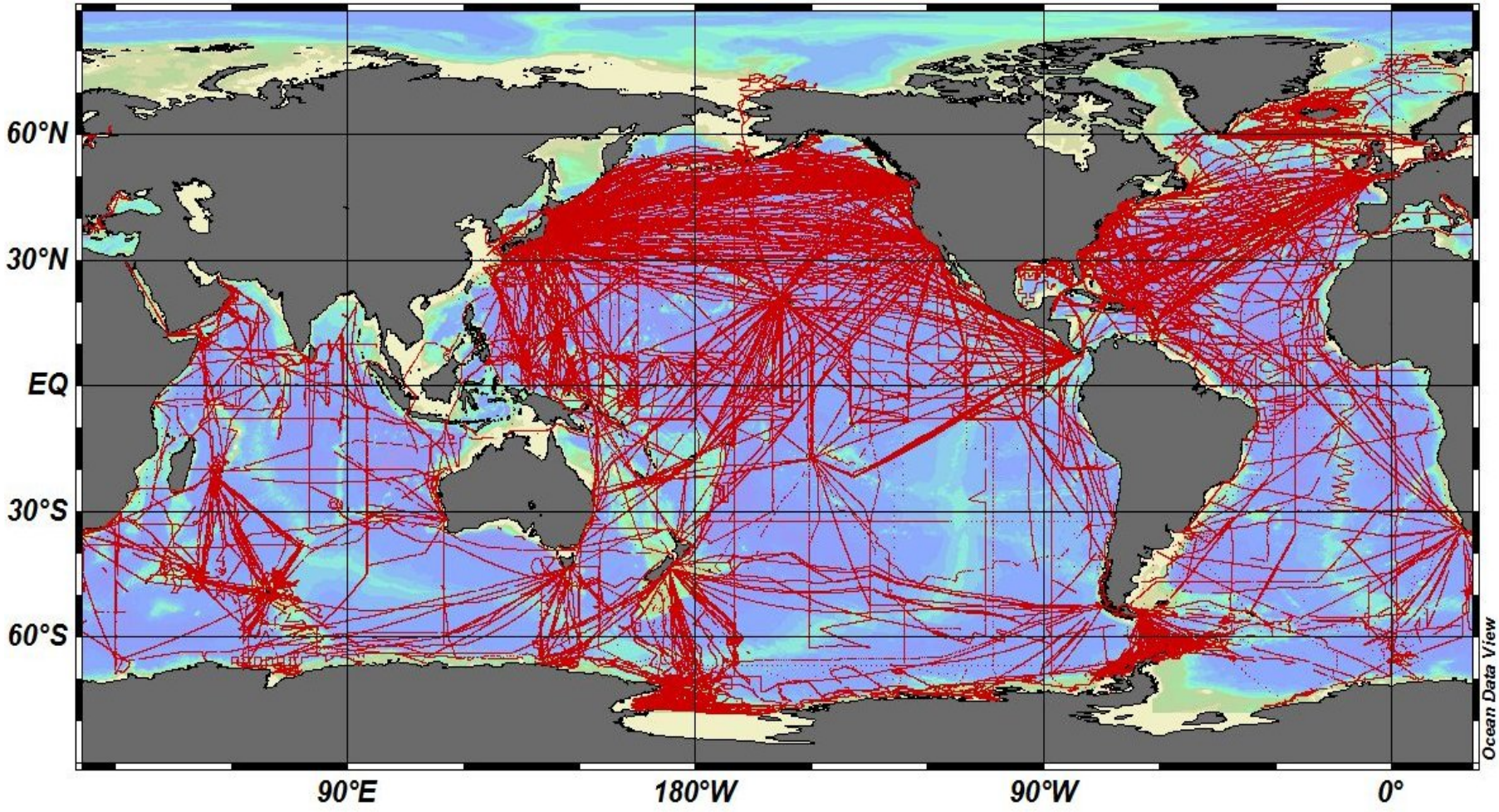
North Atlantic: VOS datasets, linear trend in $pCO_2^{s.ocean}$ (μatm/yr) 1990-2006





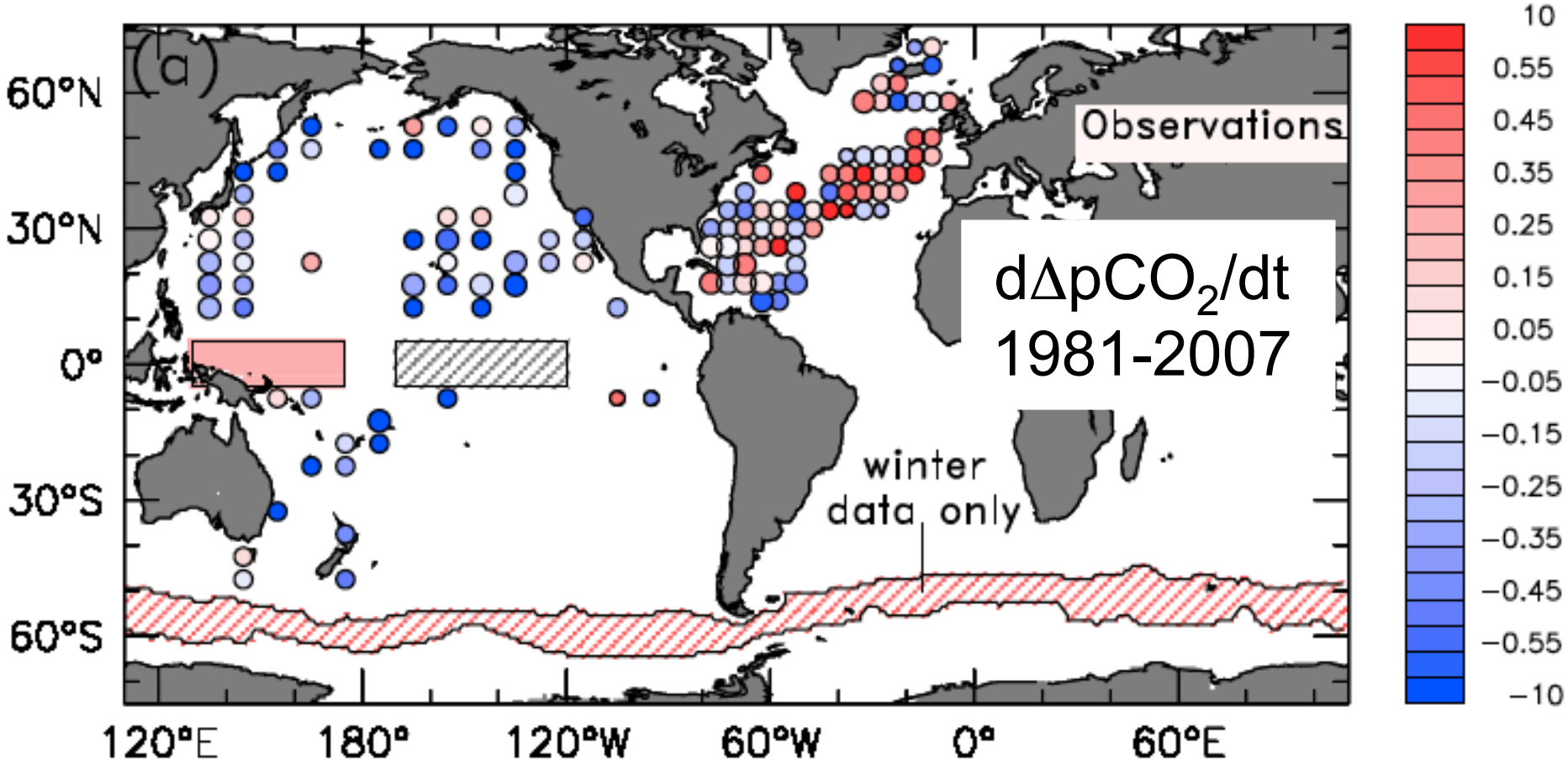
Schuster et al. 2009, DSR

pCO_2 database: >4.5 Million data points



Takahashi et al. 2010, CDIAC

Regional Trends from Takahashi database



Le Quéré et al. 2010, Global Biogeochem. Cyc.

Research questions

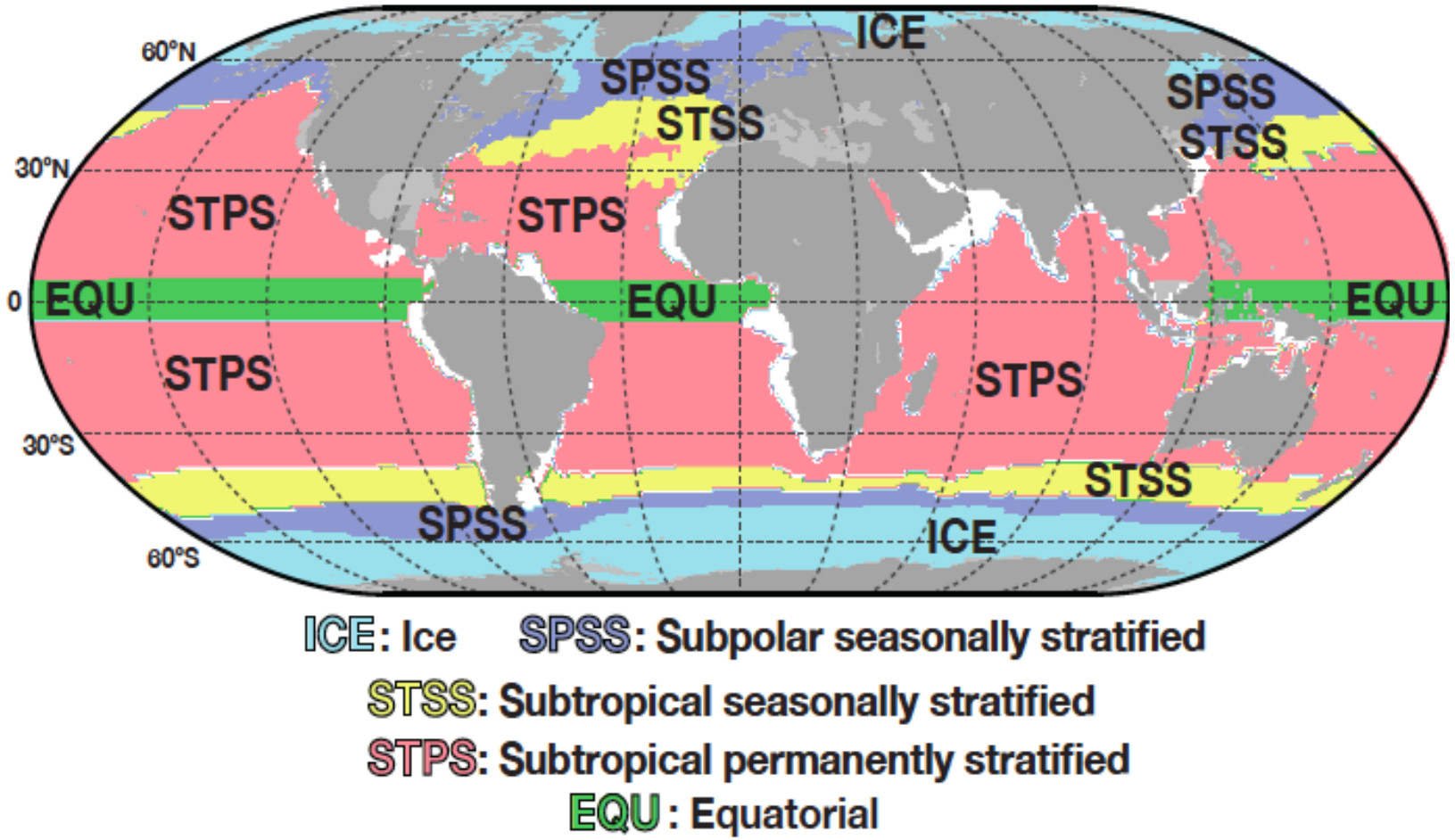
1) What do the available $pCO_2^{S.Ocean}$ data tell us ocean carbon sink change at the gyre scale?

2) What mechanisms drive these trends?

3) Over what timescales does the surface ocean $pCO_2^{S.Ocean}$ exhibit a response dominated by the anthropogenically- forced response?

McKinley et al. 2011, Nature Geosci.
Fay and McKinley 2013, Global Biogeochem. Cycles

GLOBAL BIOMES



Created from criteria based on: SST climatology, Chlorophyll-a climatology, and max MLD

Trend Mechanisms

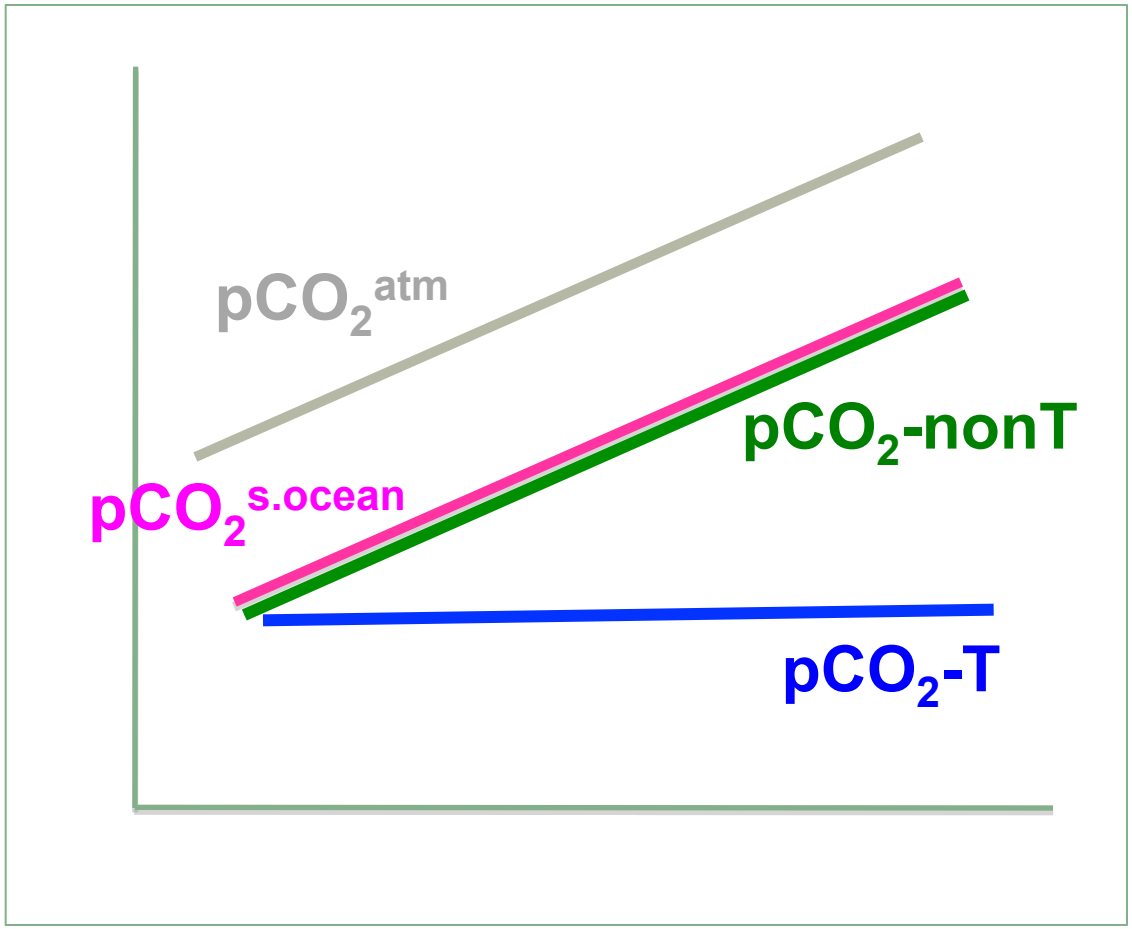
Decompose pCO_2 into temperature driven component (pCO_2-T) and biological/chemical component (pCO_2-nonT)

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

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

Takahashi et al. 2002, DSR II

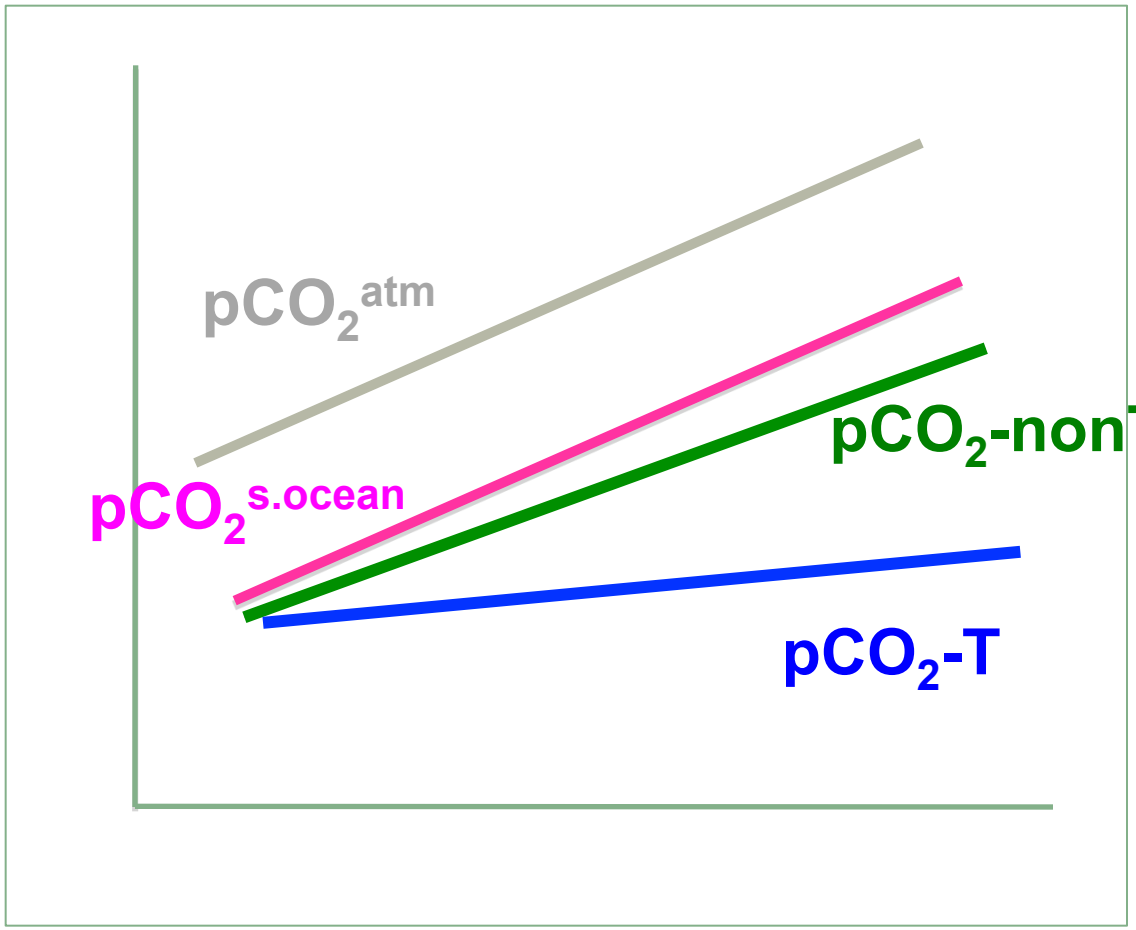
Trend mechanisms



Biogeochemical change only

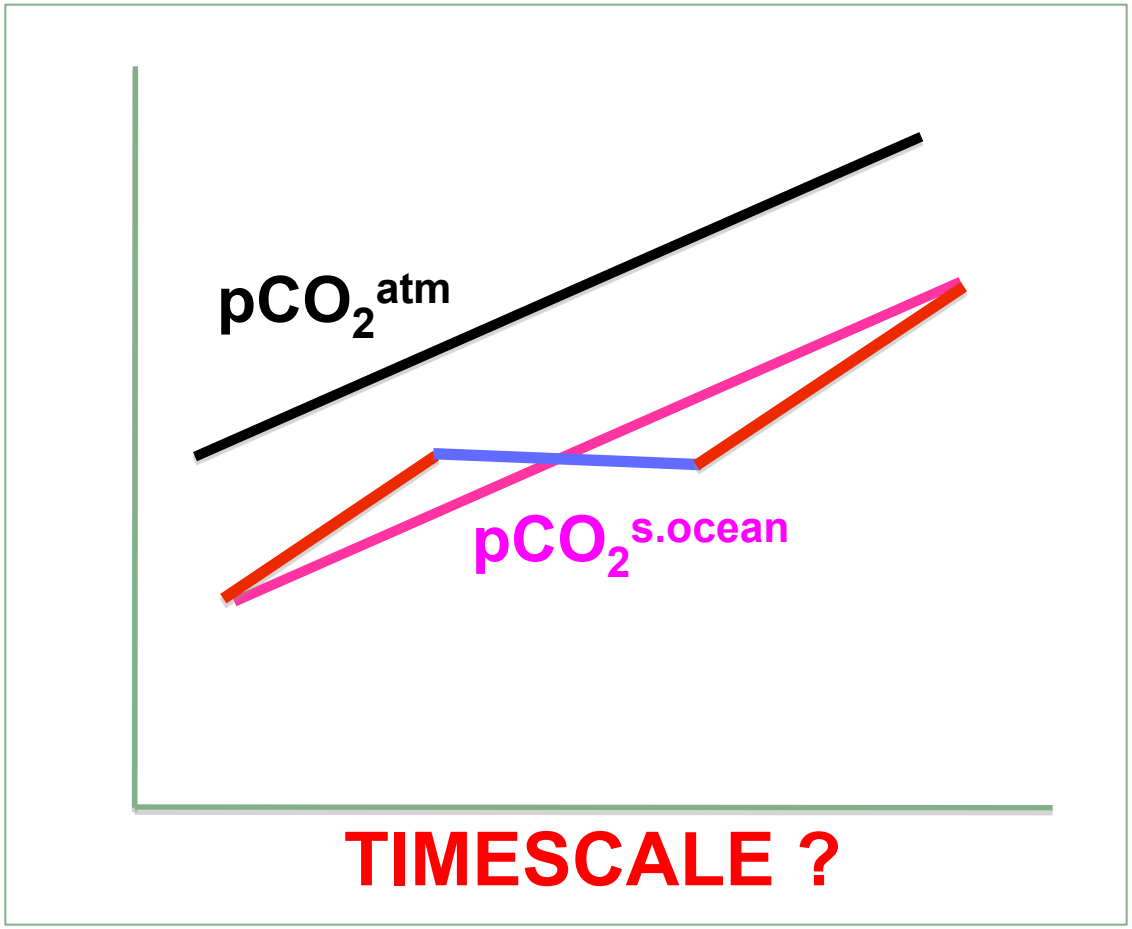
Consistent with carbon uptake

Trend mechanisms



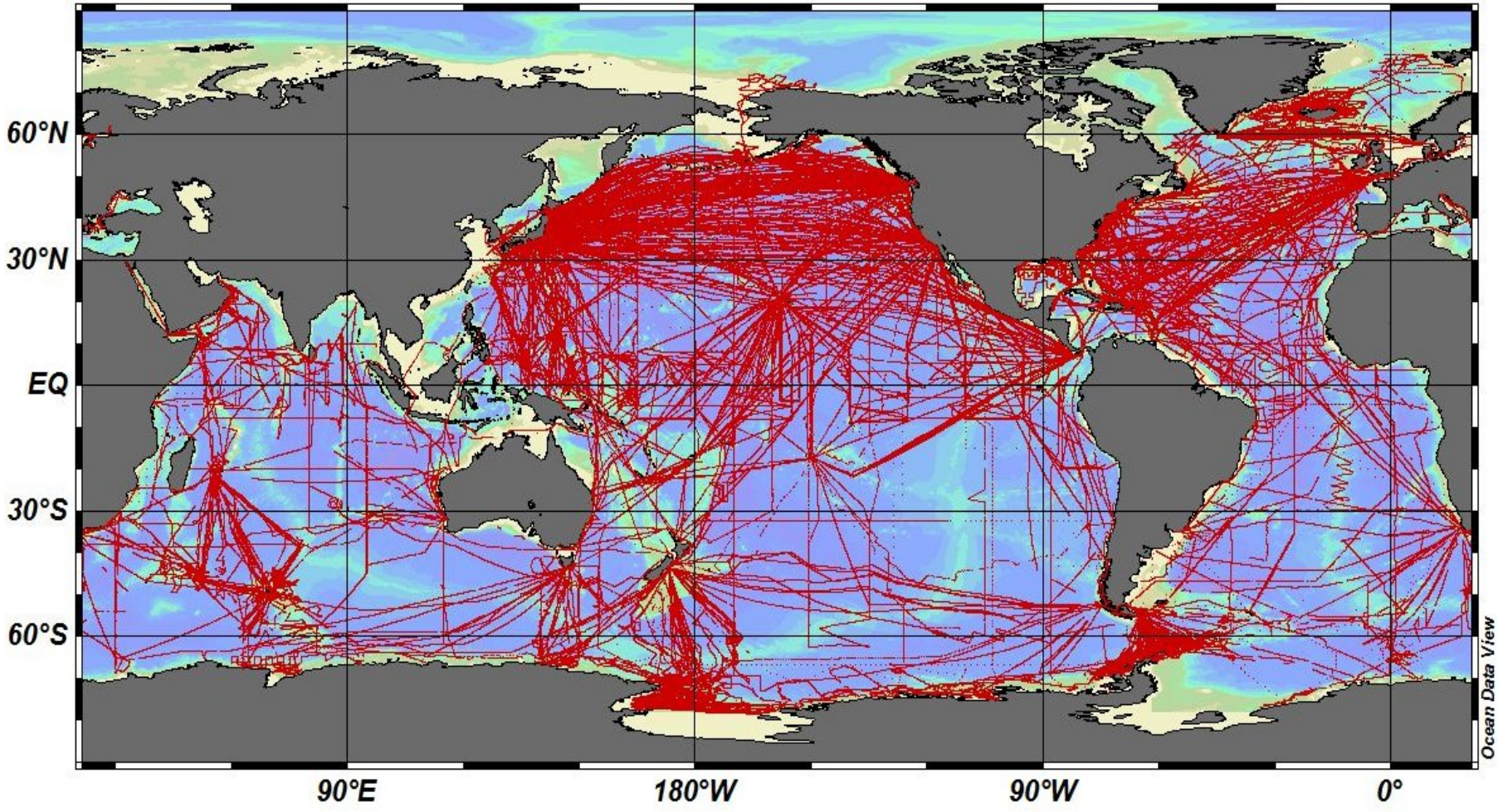
If warming contributes to ocean pCO_2 increase, carbon uptake is diminished

Are the trends representative of variability or a long-term response to increasing atmosphere pCO_2?



Methodology

pCO_2 database: >4.5 Million data points



Takahashi et al. 2010, CDIAC

Methodology

1. Calculate monthly means for 1°x1° boxes
2. Aggregate to large regions (global biomes)
3. Calculate trends on biome scale, with single harmonic + trend $y = a + b*t + c*\cos(2\pi t + d)$
4. Use models to confirm methodology

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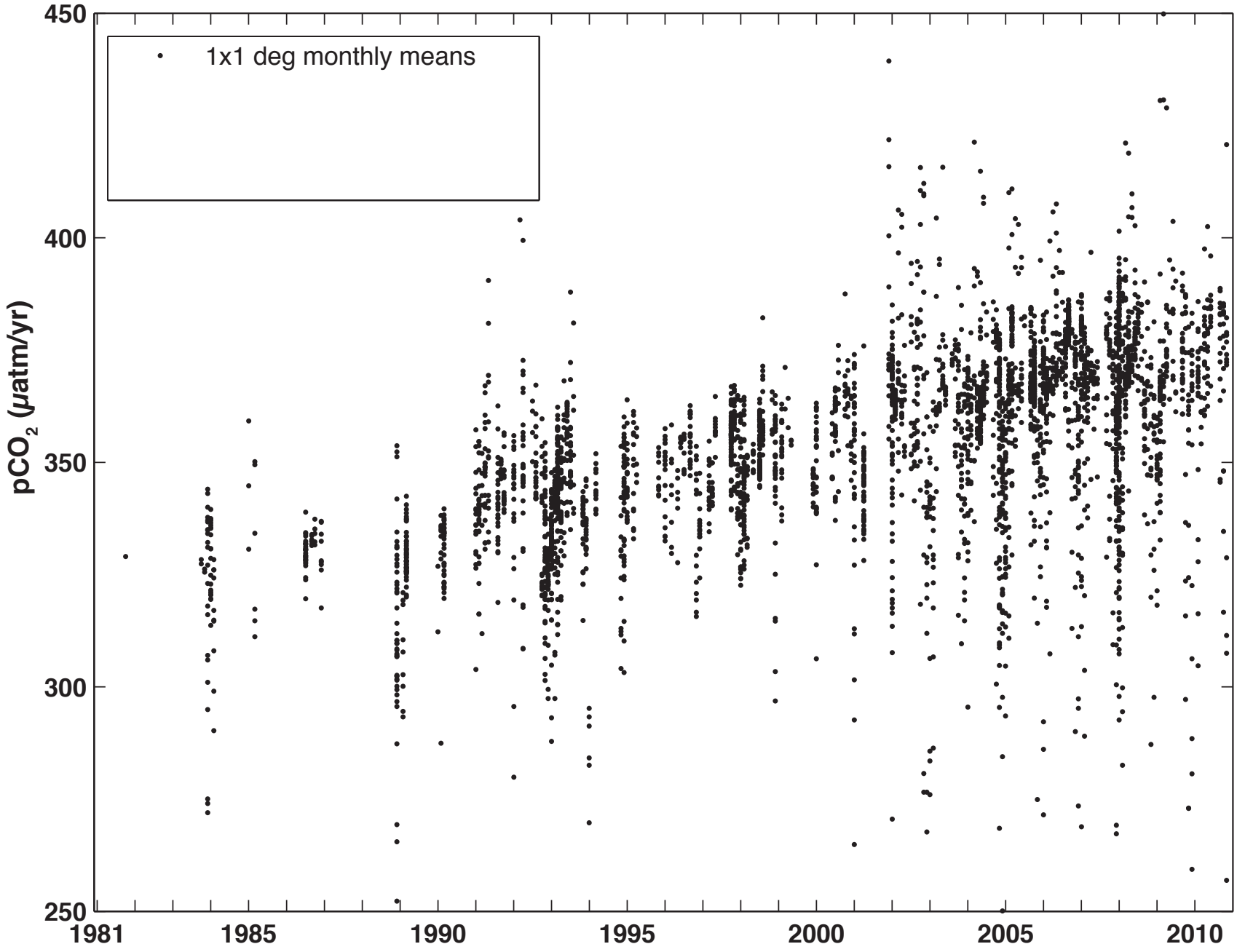
Southern Ocean SPSS Biome timeseries



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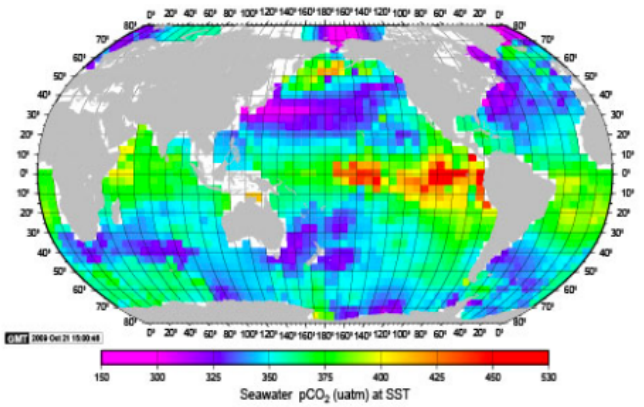
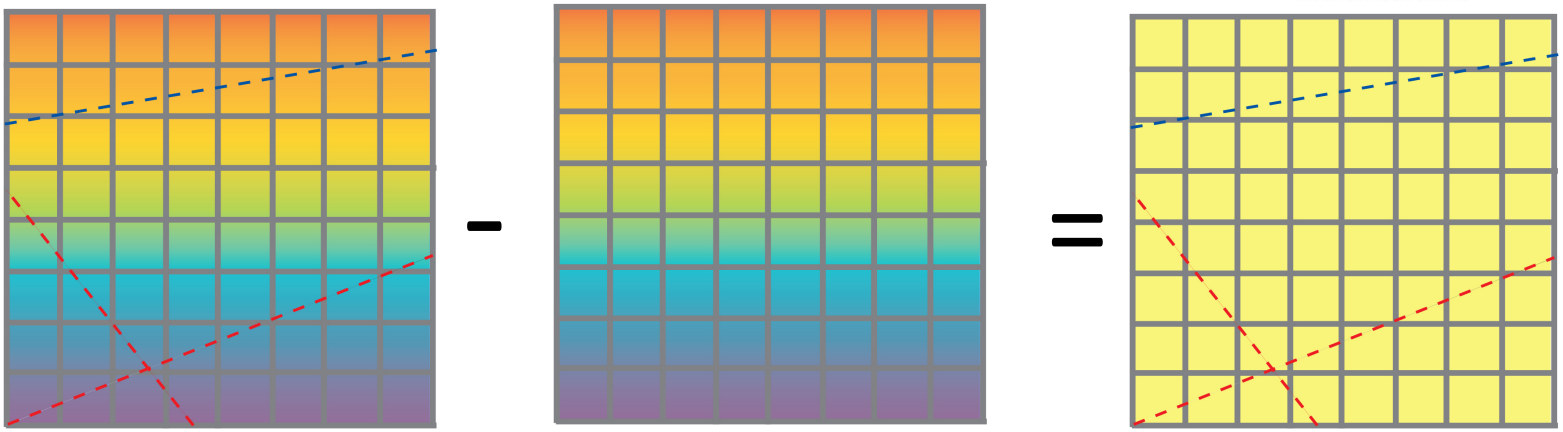
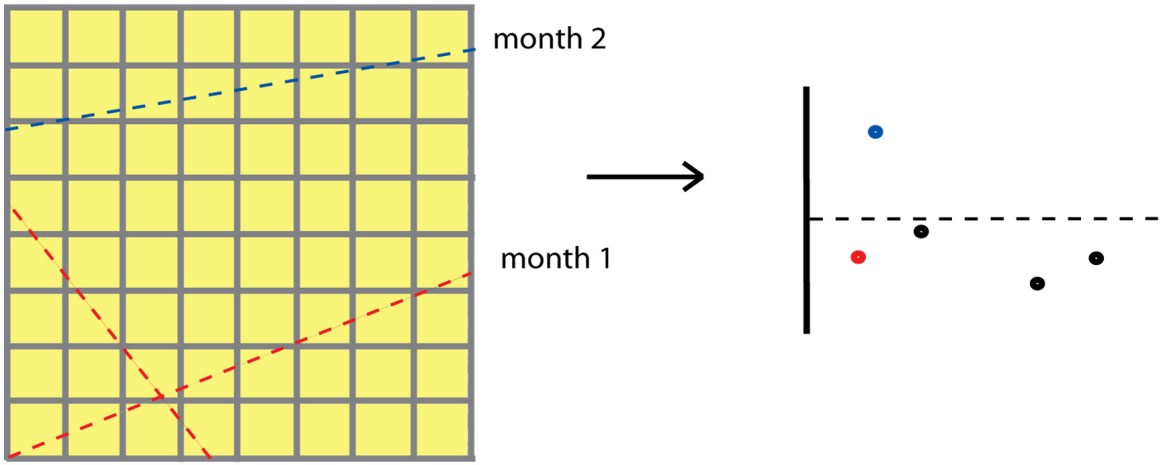
McKinley et al., 2011
Fay & McKinley, 2013

Subtract background mean to address spatial aliasing







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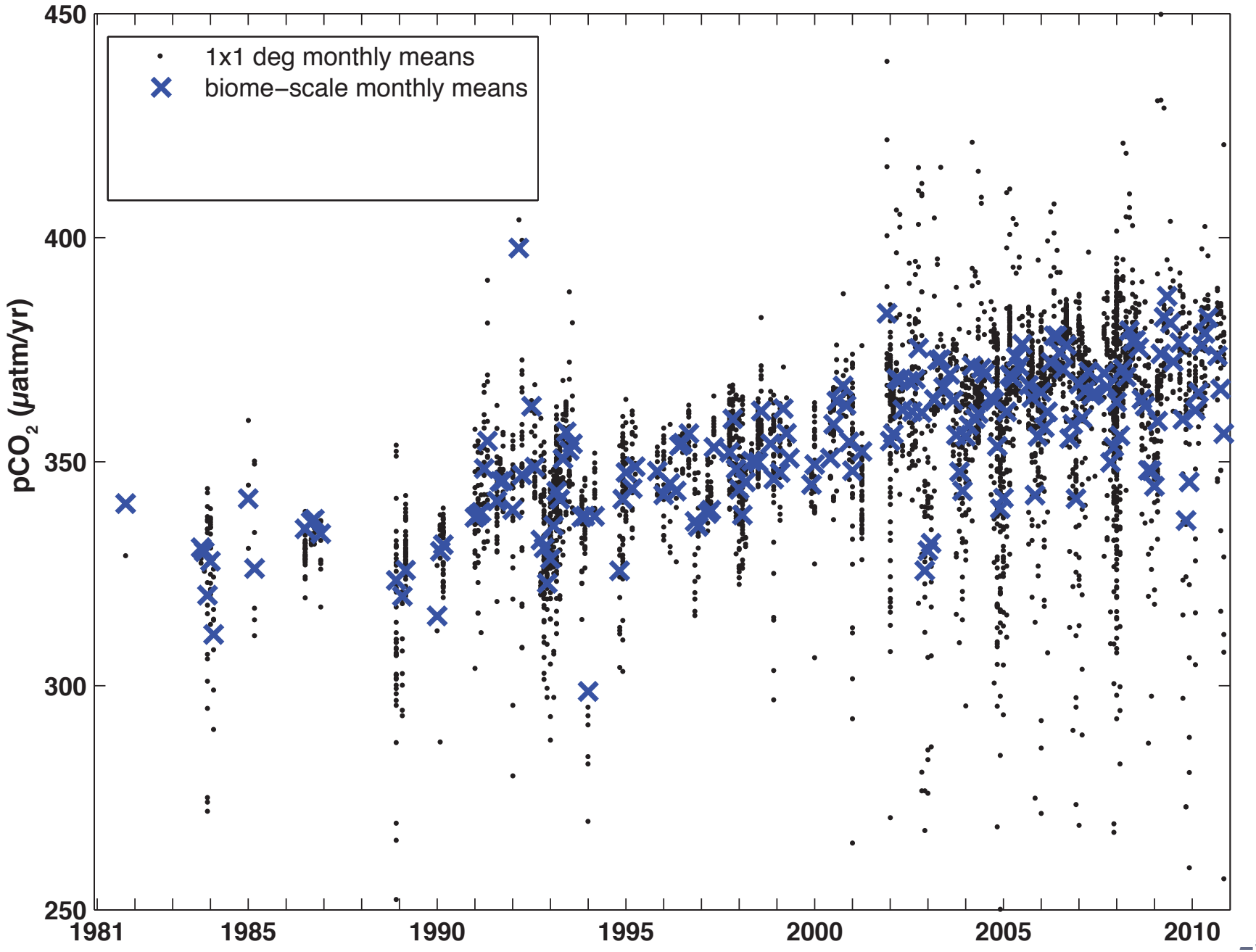

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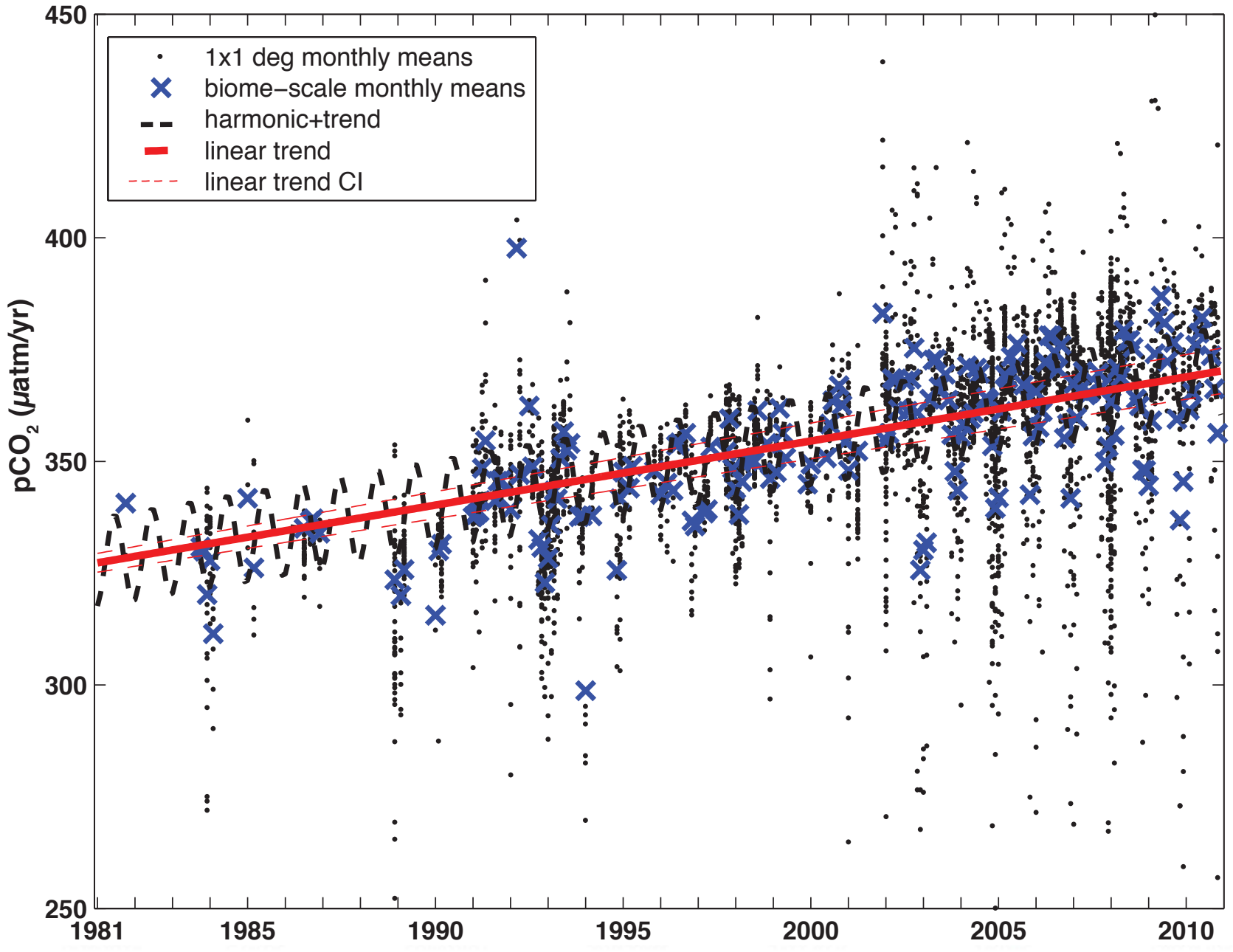

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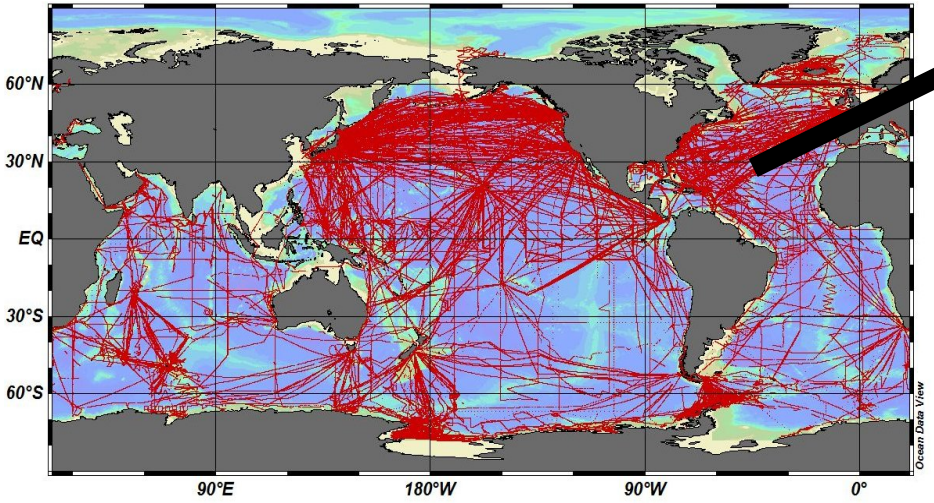
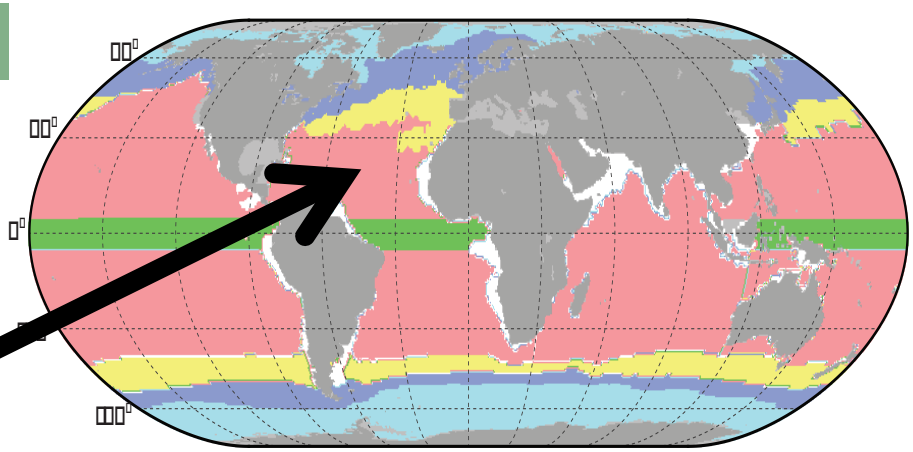
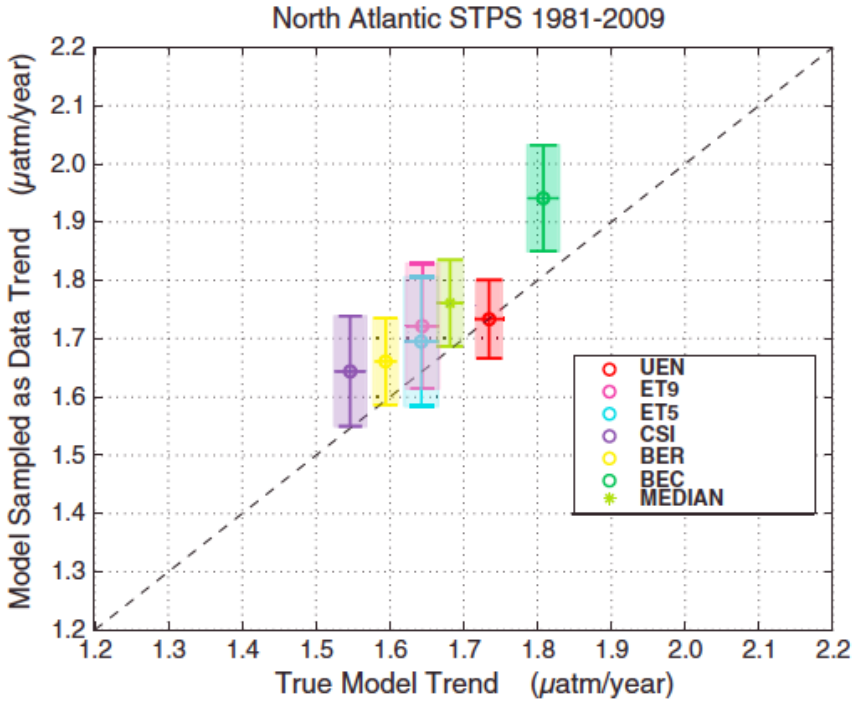
Representativity error?





RECCAP models are used to confirm sufficient sampling

- Sample model as data
- Calculate sampled model trend and true model trend
- If sampled and true trends are within 1σ uncertainty, it is "confirmed"



Results

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

steeper $pCO_2^{s.ocean}$

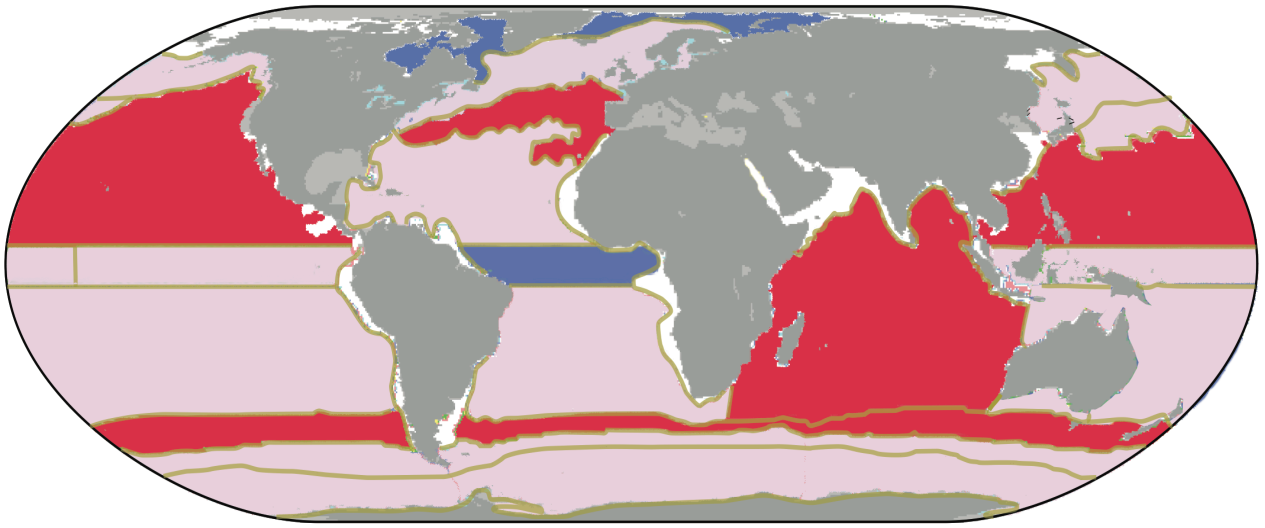
DECREASING ΔpCO_2

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

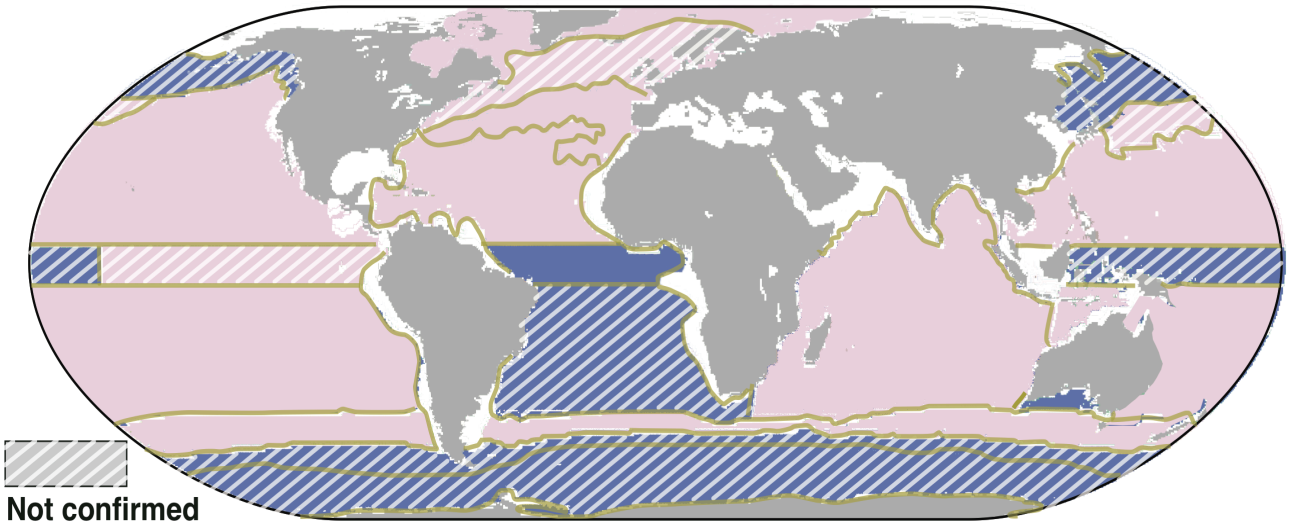
shallower $pCO_2^{s.ocean}$

INCREASING ΔpCO_2

1990-2005



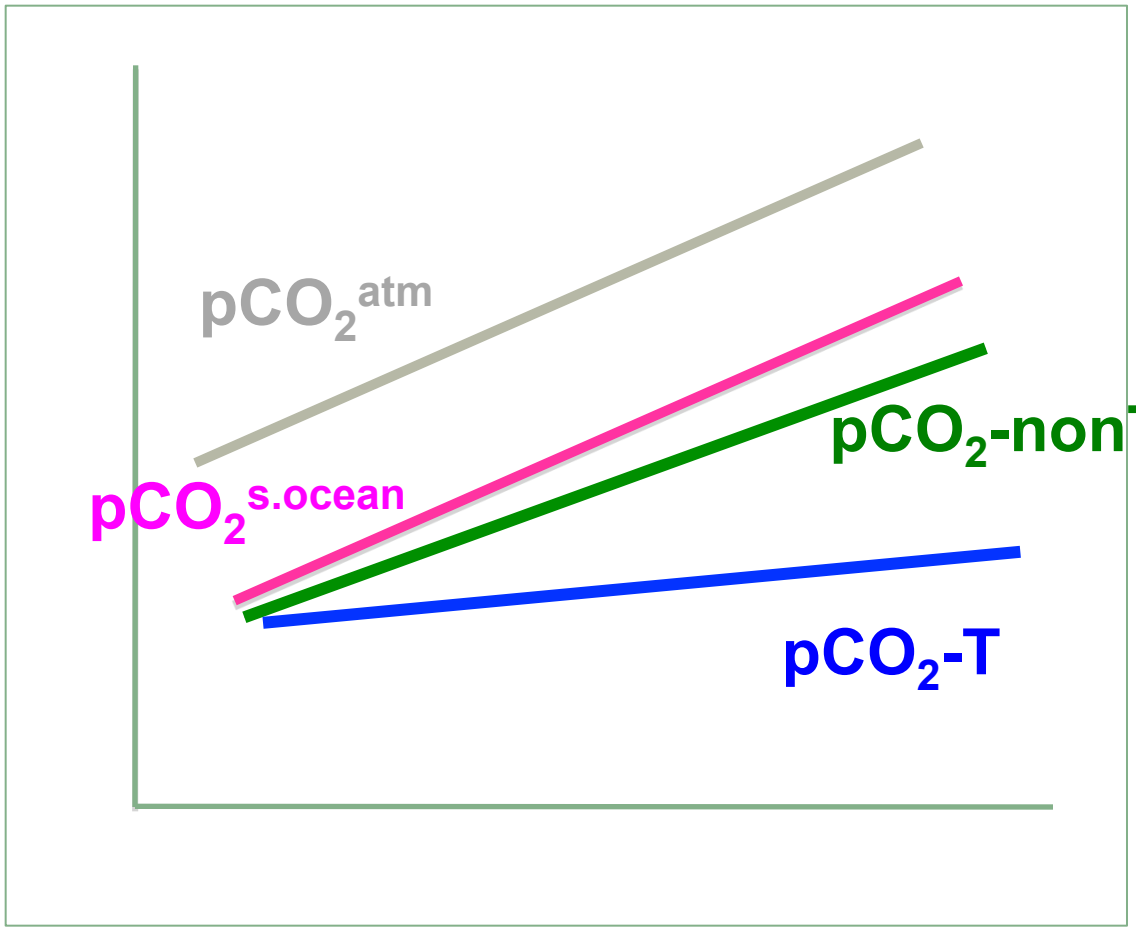
1981-2010

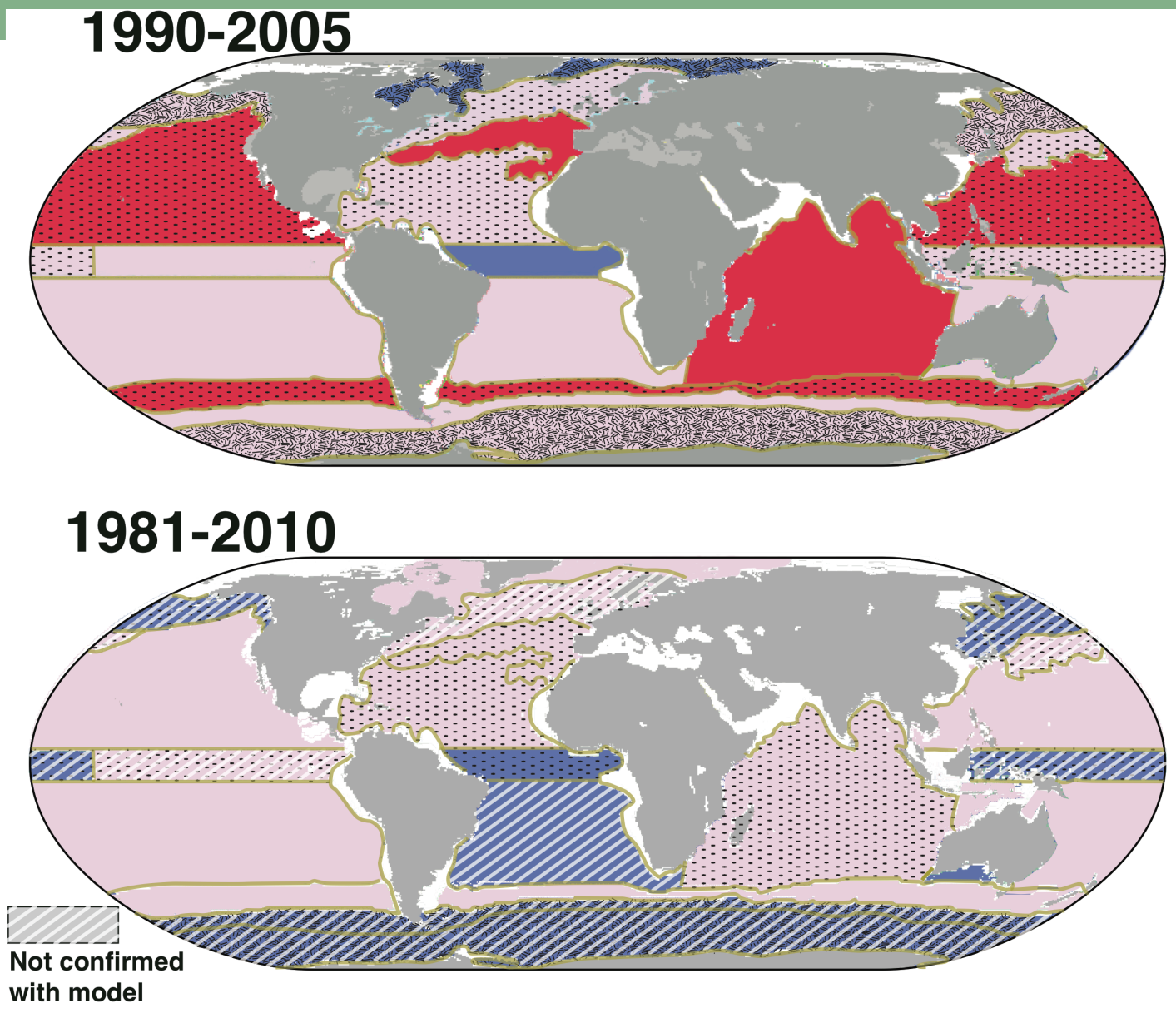


Not confirmed with model

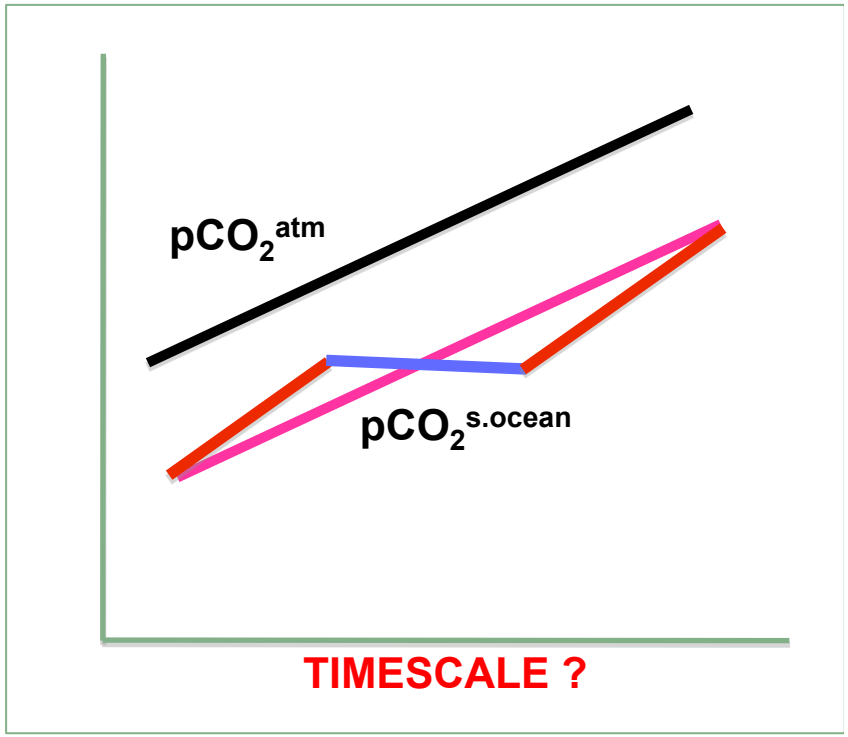
$dpCO_2^{ocn}/dt < dpCO_2^{atm}/dt$ | $dpCO_2^{ocn}/dt \sim dpCO_2^{atm}/dt$ | $dpCO_2^{ocn}/dt > dpCO_2^{atm}/dt$

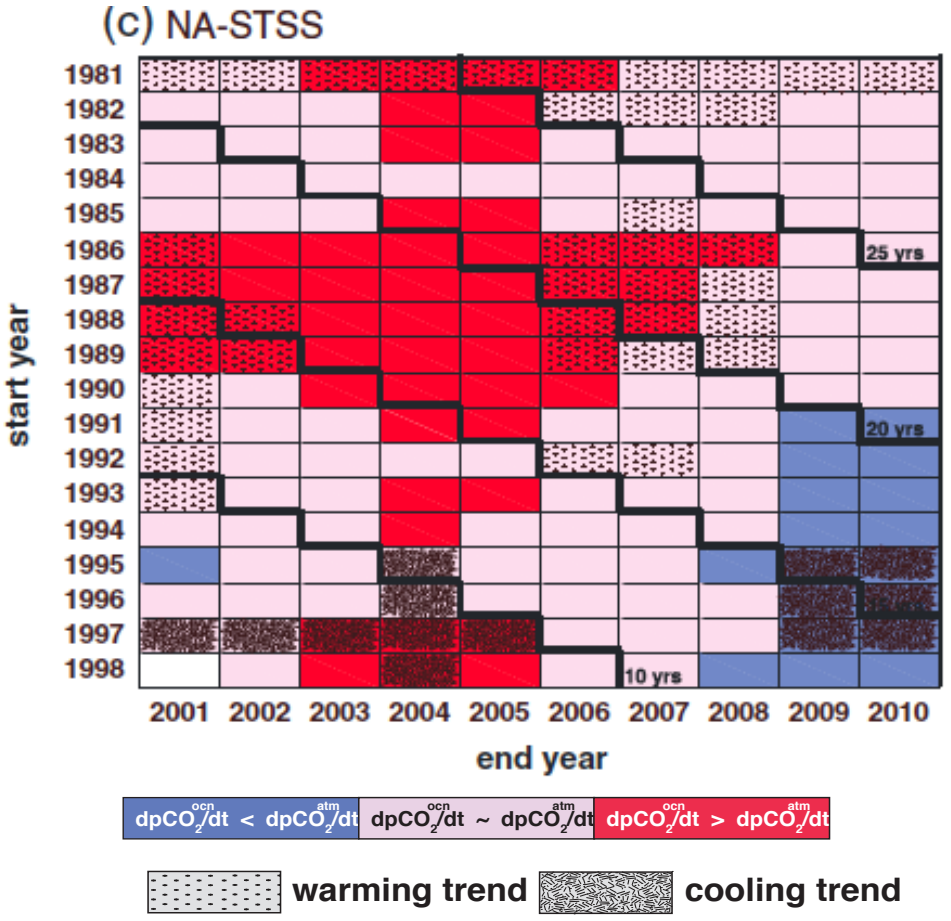
Does warming contribute to pCO_2 trend?




1990-2005
1981-2010
Not confirmed with model
dpCO2ocn/dt < dpCO2atm/dt
dpCO2ocn/dt ~ dpCO2atm/dt
dpCO2ocn/dt > dpCO2atm/dt
warming trend
cooling trend

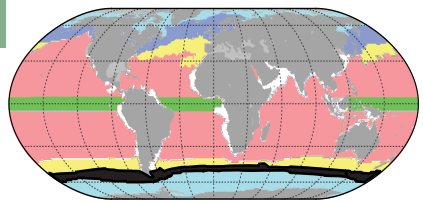
Timescale for long-term response?

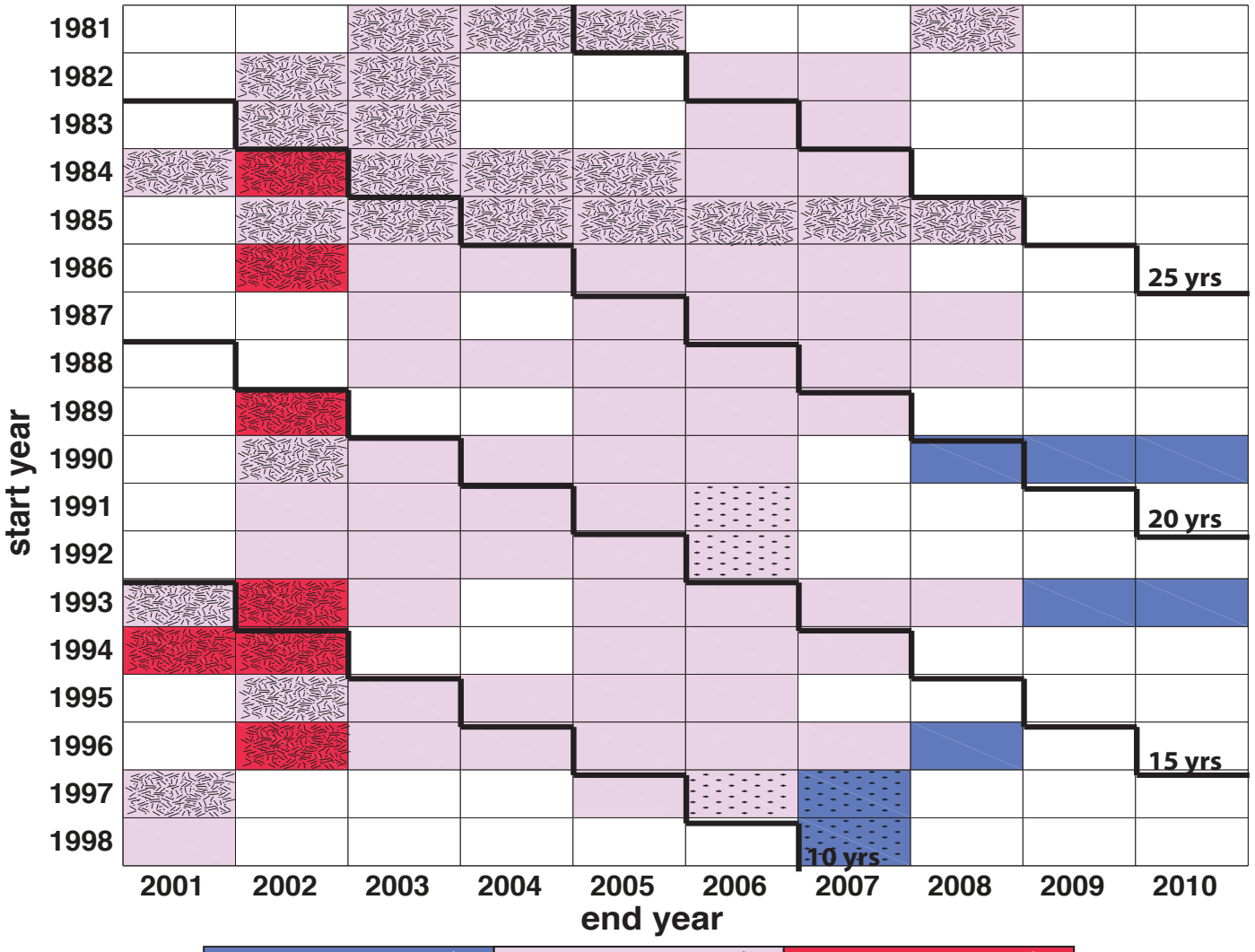




Southern Ocean

SO-SPSS

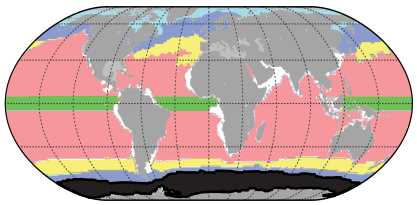


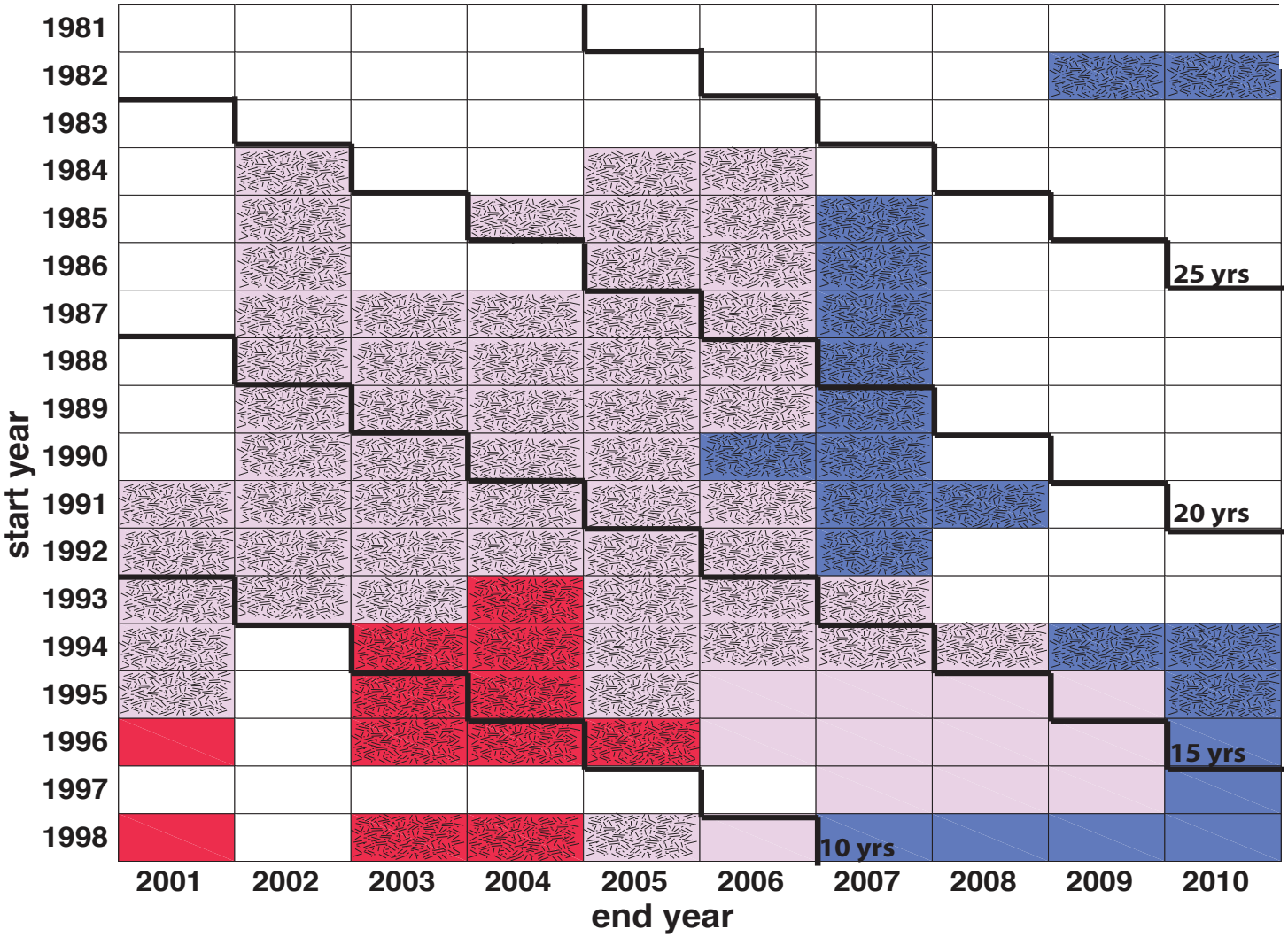


$dpCO_2^{ocn}/dt < dpCO_2^{atm}/dt$ | $dpCO_2^{ocn}/dt \sim dpCO_2^{atm}/dt$ | $dpCO_2^{ocn}/dt > dpCO_2^{atm}/dt$

warming trend | cooling trend

SO-ICE





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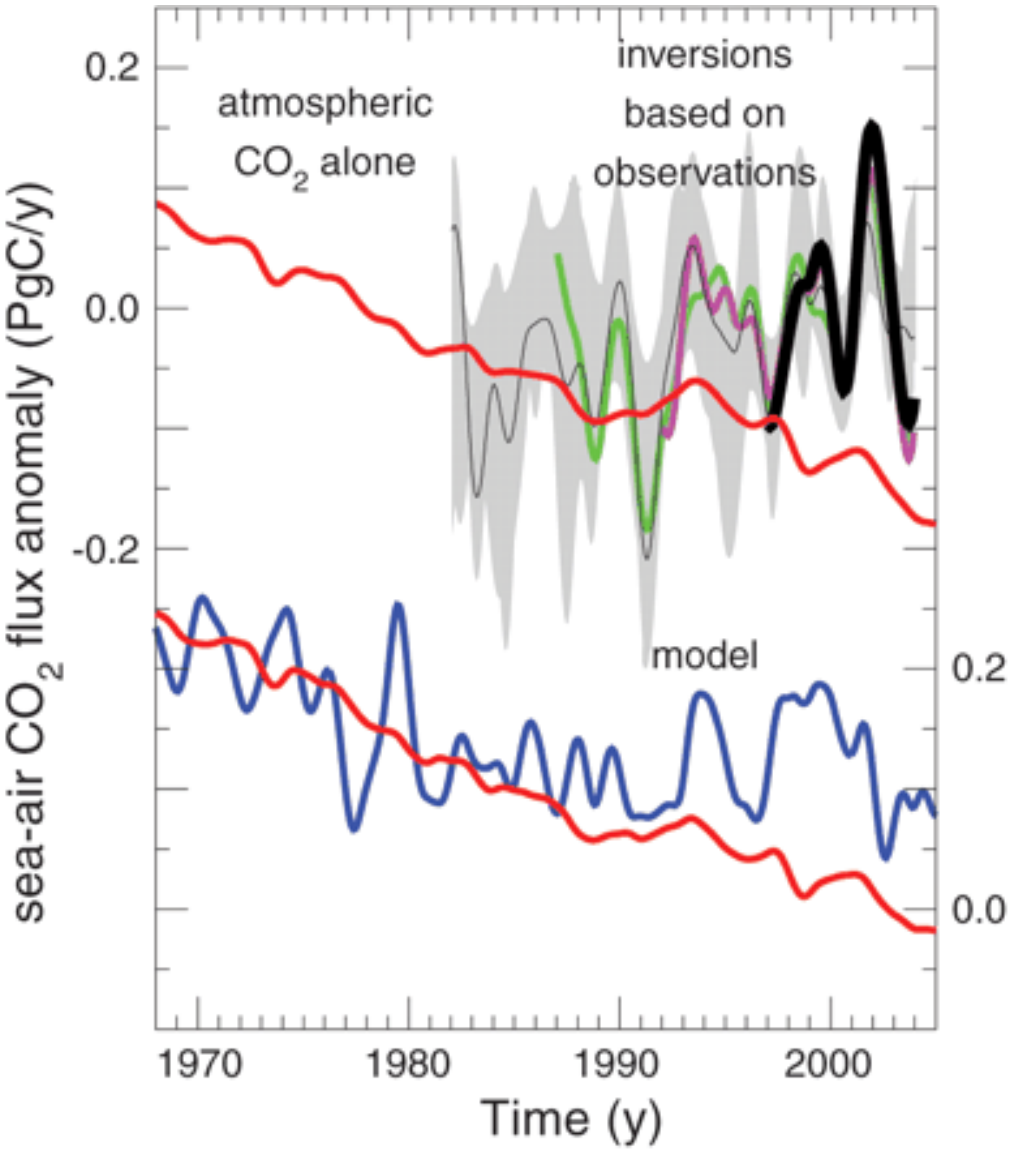
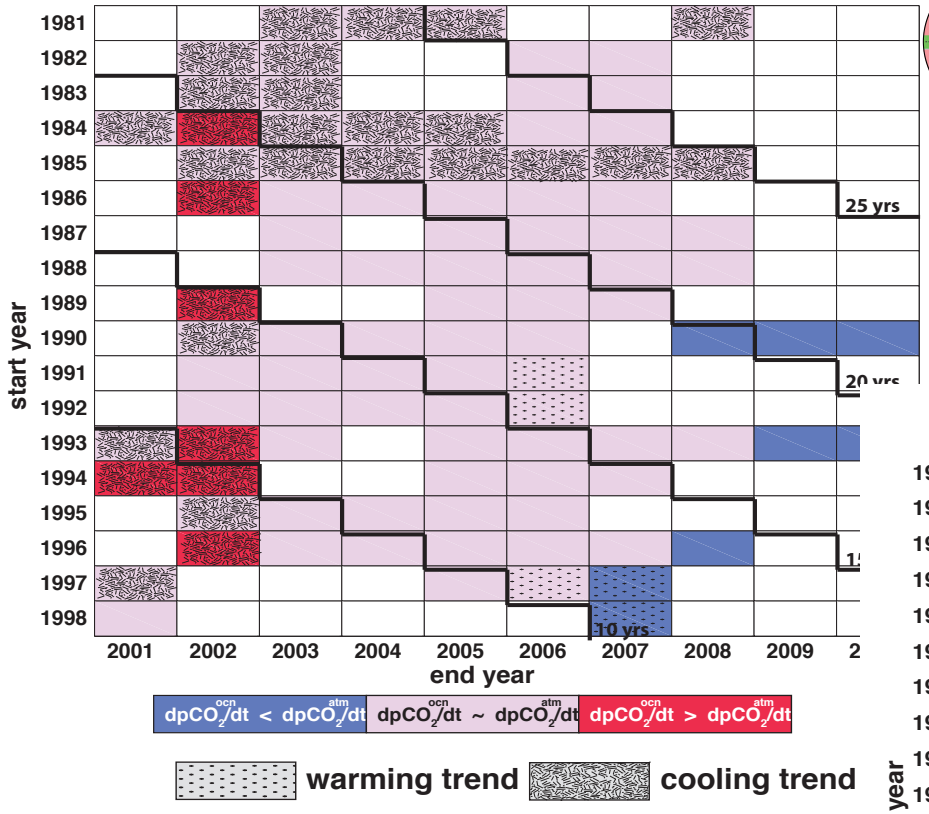
warming trend | cooling trend

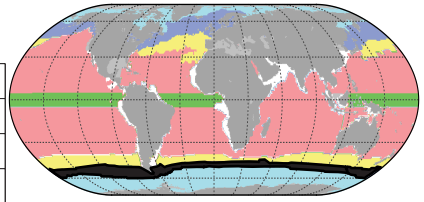
Southern Ocean: Model and atmospheric inversion indicate reduced carbon sink in recent decades.



LeQuere et al. 2007, Science

SO-SPSS





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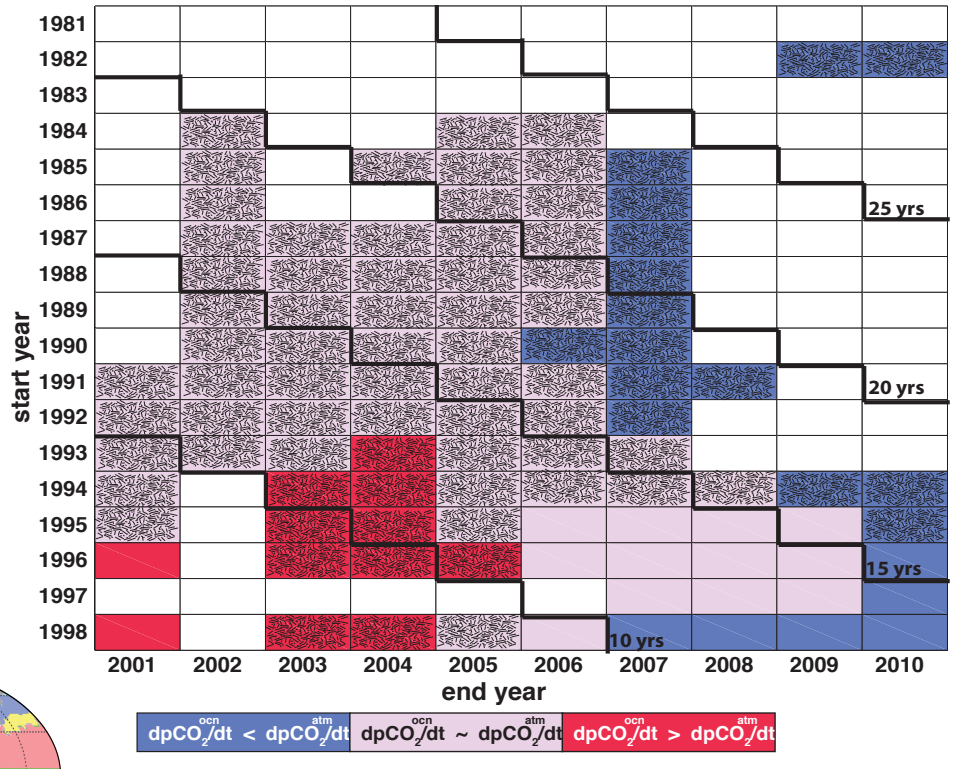
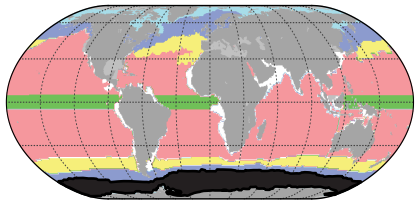
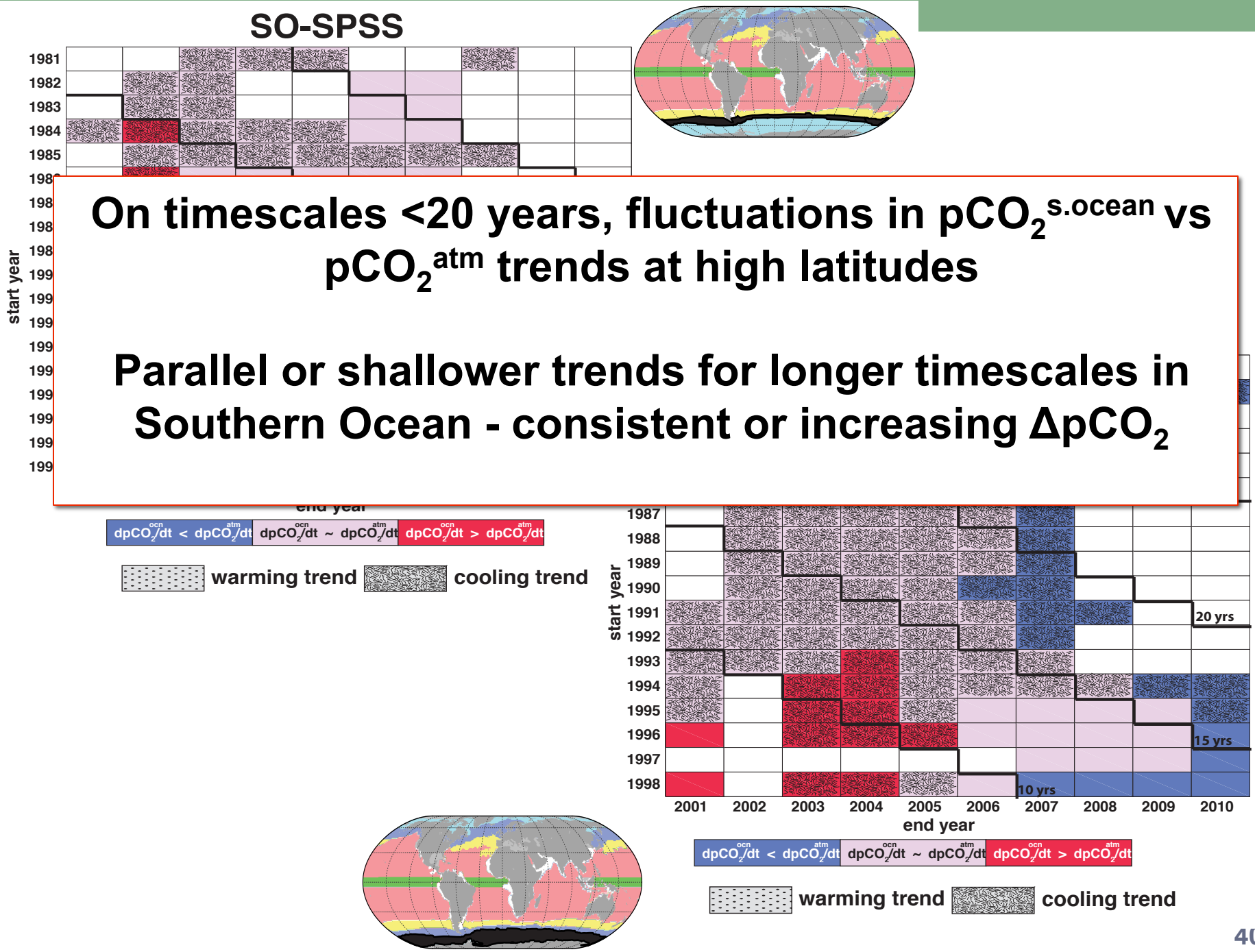




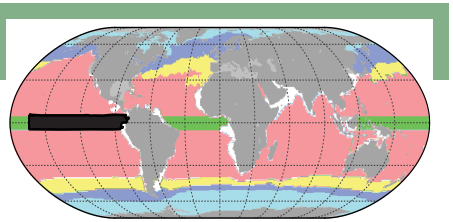


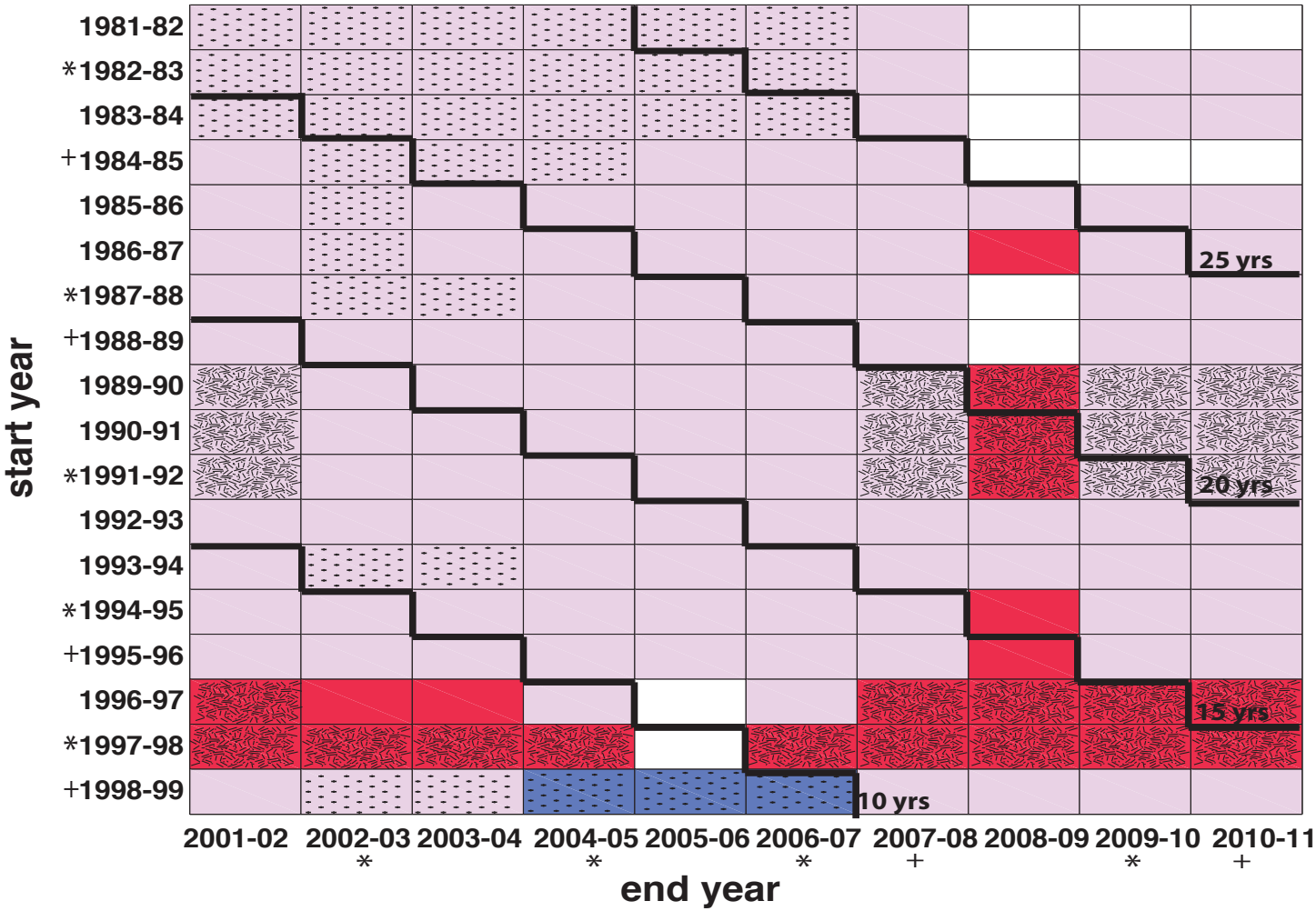
On timescales <20 years, fluctuations in $pCO_2^{s.ocean}$ vs pCO_2^{atm} trends at high latitudes

Parallel or shallower trends for longer timescales in Southern Ocean - consistent or increasing ΔpCO_2

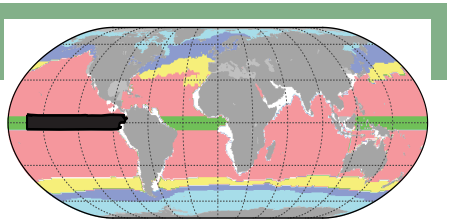
Equatorial Pacific

East Equatorial Pacific



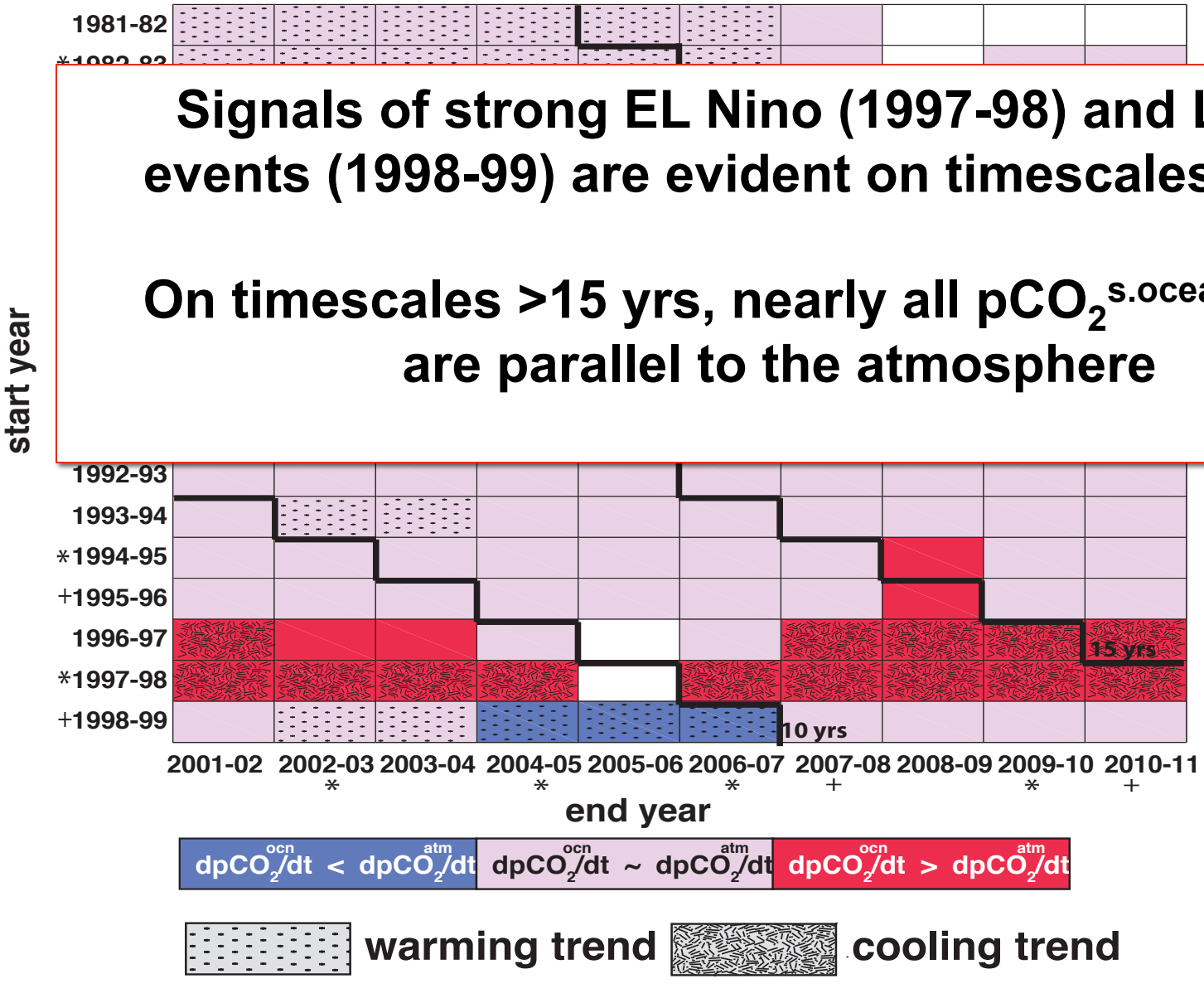


East Equatorial Pacific

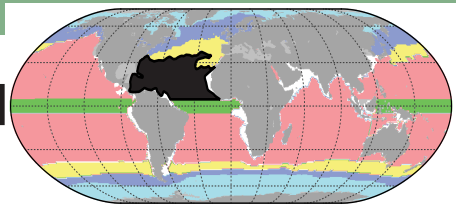


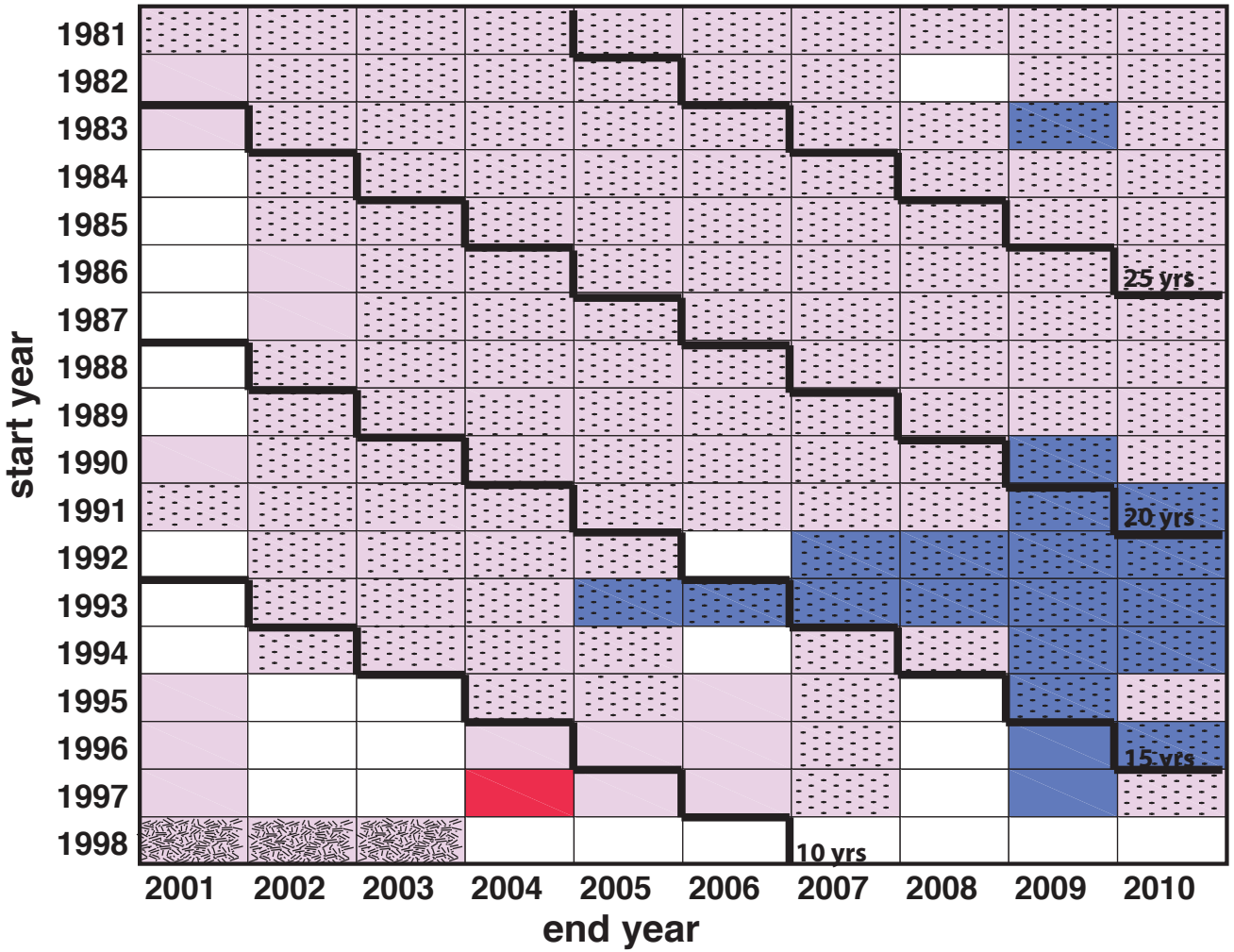
Signals of strong EL Nino (1997-98) and La Nina events (1998-99) are evident on timescales <15 yrs

On timescales >15 yrs, nearly all $pCO_2^{s.ocean}$ trends are parallel to the atmosphere



North Atlantic Subtropical Permanently Stratified



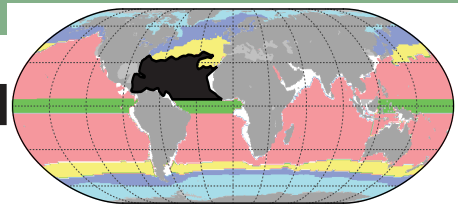


warming trend

cooling trend

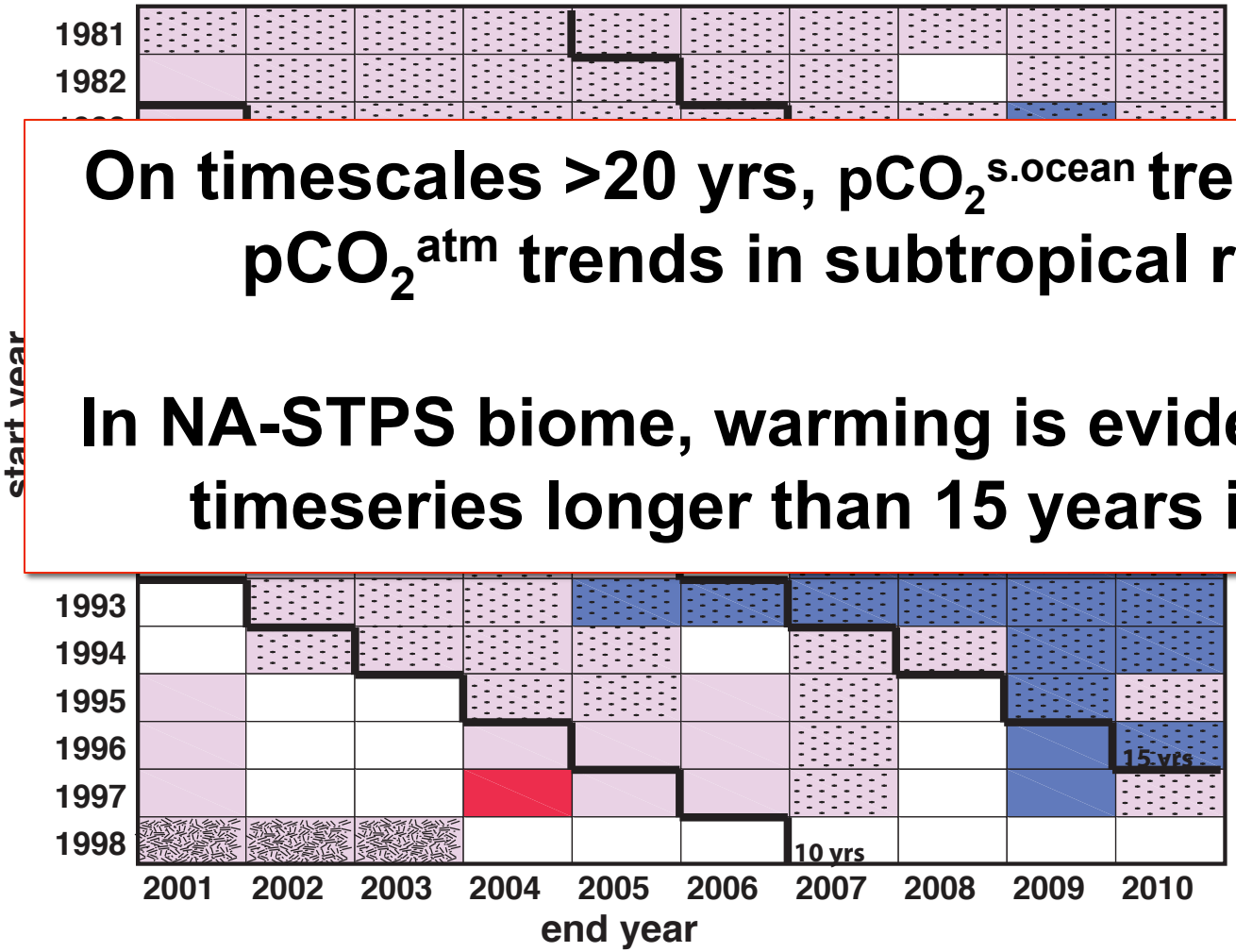
Subtropical North Atlantic

North Atlantic Subtropical Permanently Stratified

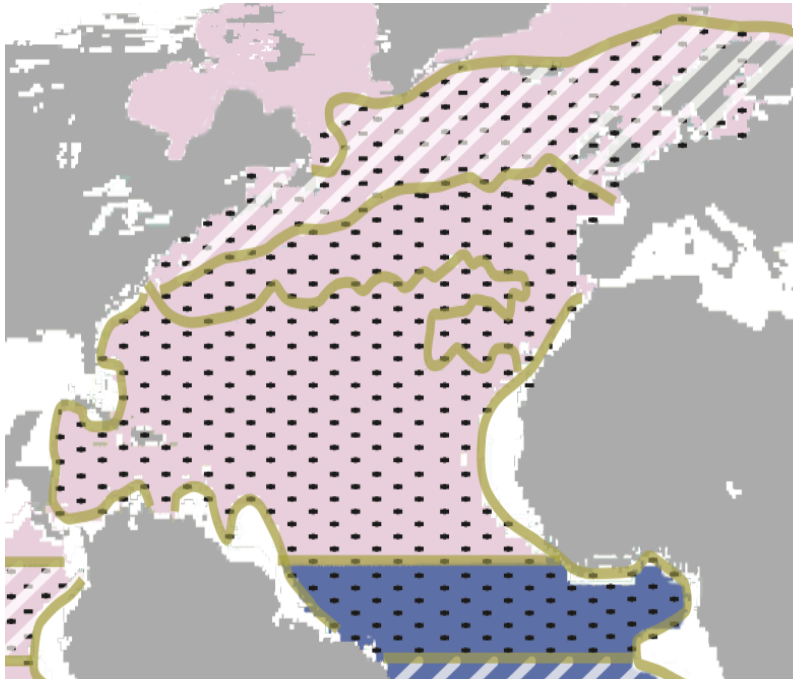


On timescales >20 yrs, $pCO_2^{s.ocean}$ trends parallel pCO_2^{atm} trends in subtropical regions

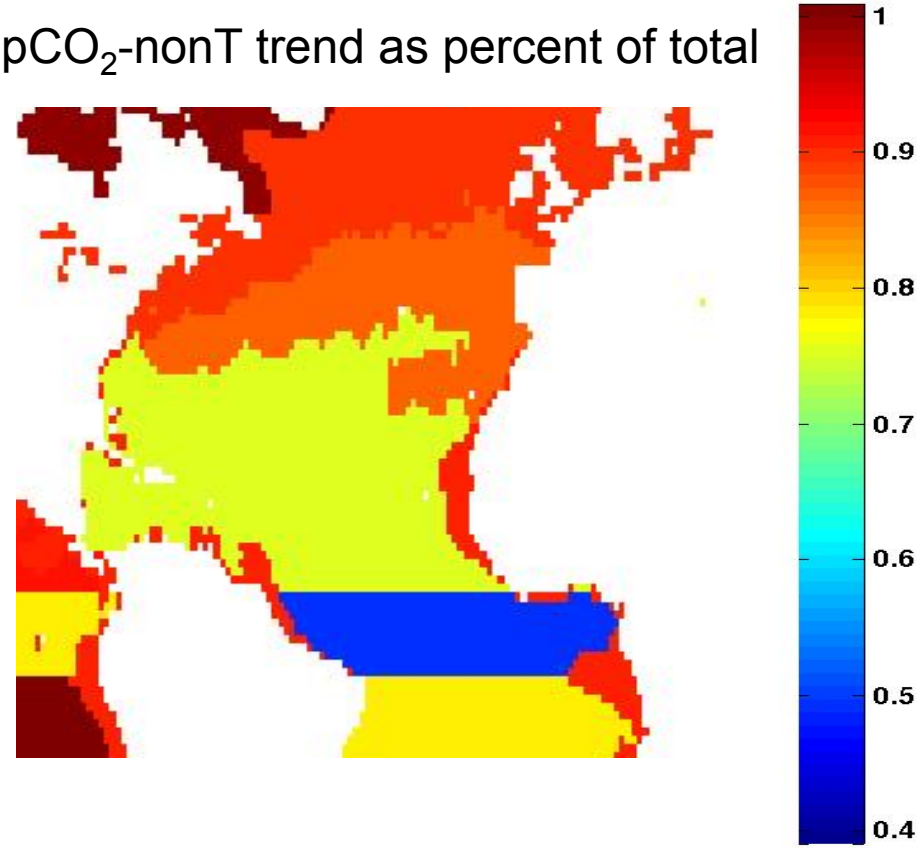
In NA-STPS biome, warming is evident for most timeseries longer than 15 years in length



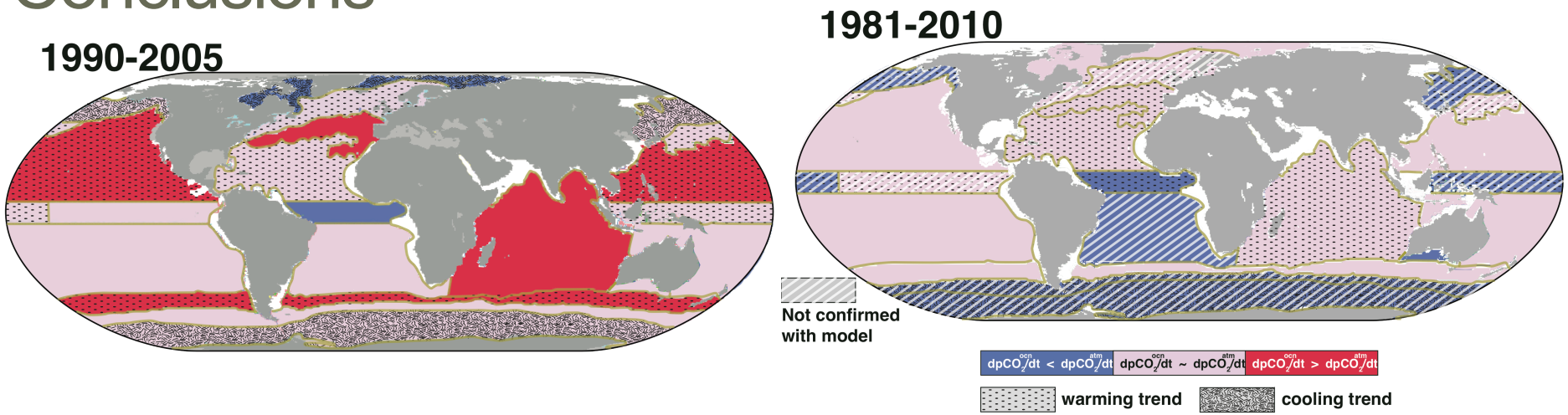
For 30 years, what is the relative impact of chemical trend (pCO_2-nonT)?
Remainder is temperature.



pCO_2-nonT trend as percent of total



Conclusions



- Variability dominates for periods <20 years
- For 30 yrs, $pCO_2^{s.ocean}$ trends are the same or slightly shallower than atmospheric
  - Globally consistent with a positive carbon feedback
  - Regions of shallower trends are consistent with ocean ventilation
- Warming in subtropical North and equatorial Atlantic persists on long timescales - a negative feedback
- Data limitations are significant in many regions

QUESTIONS?

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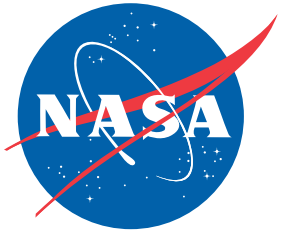
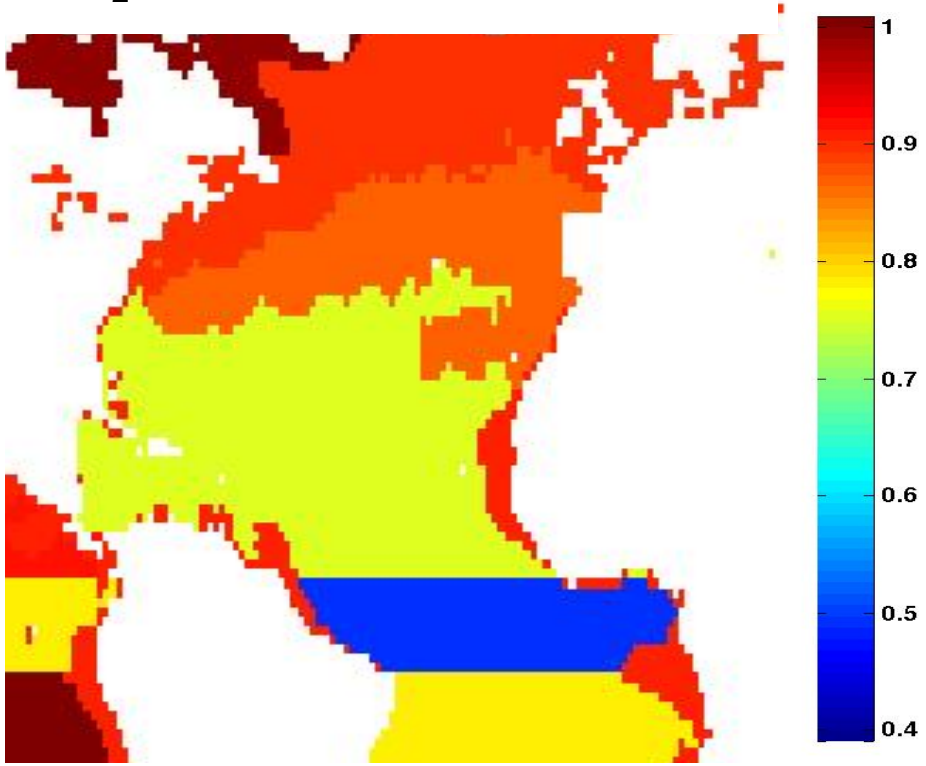
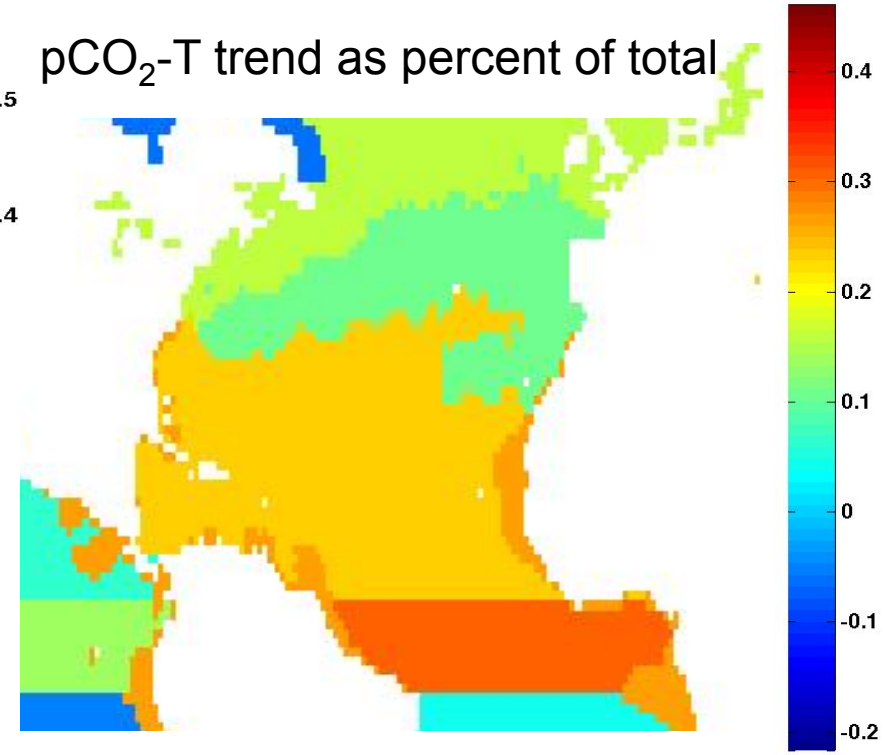


pCO_2-nonT trend as percent of total

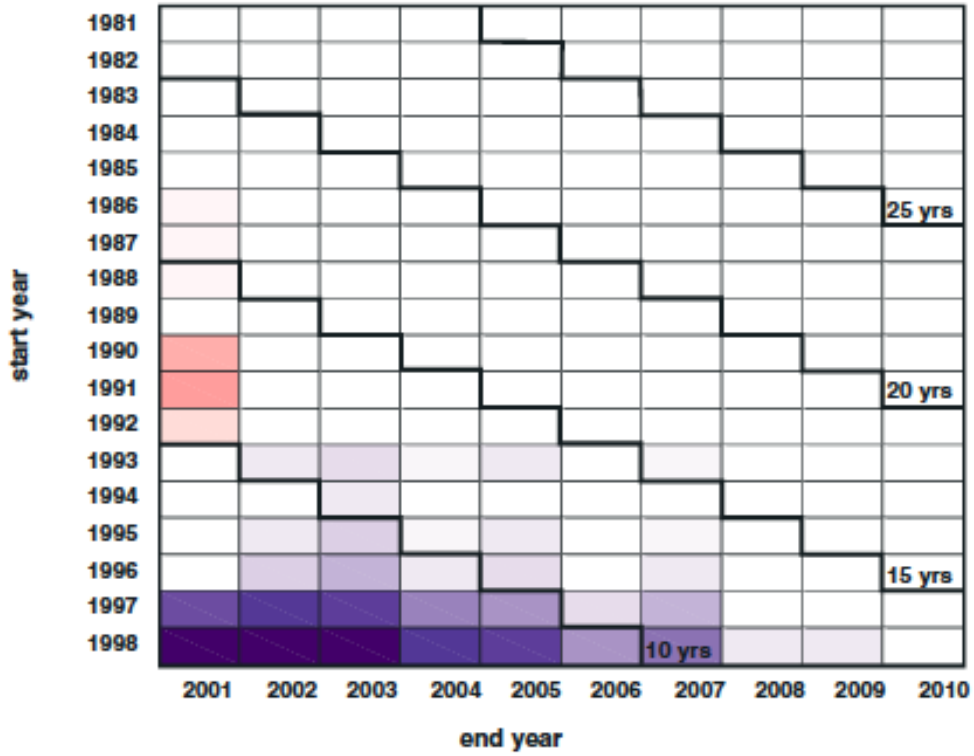


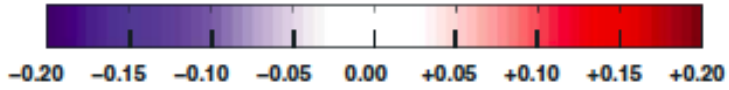
1981-2010

pCO_2-T trend as percent of total

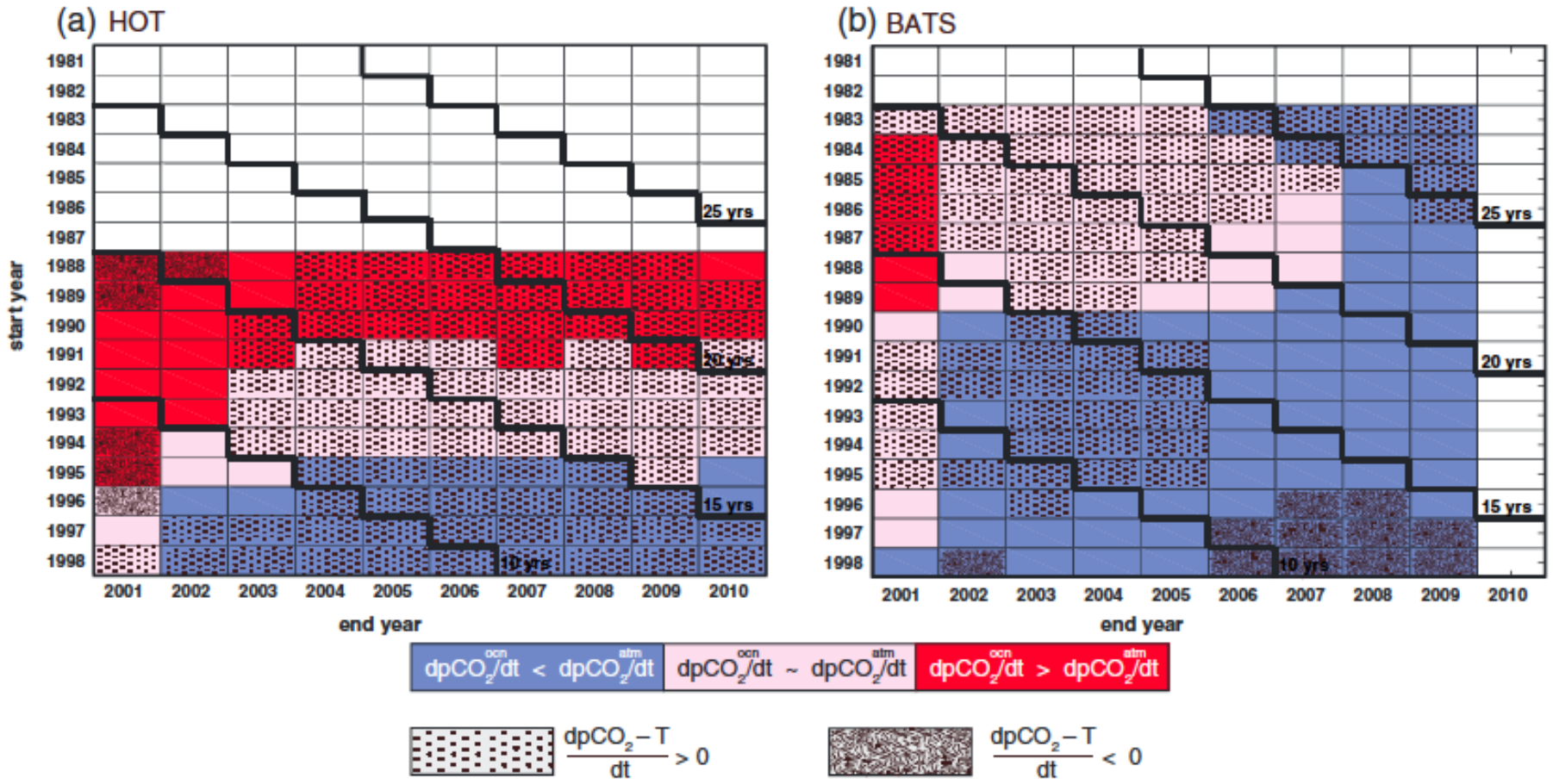


SAM Index grid

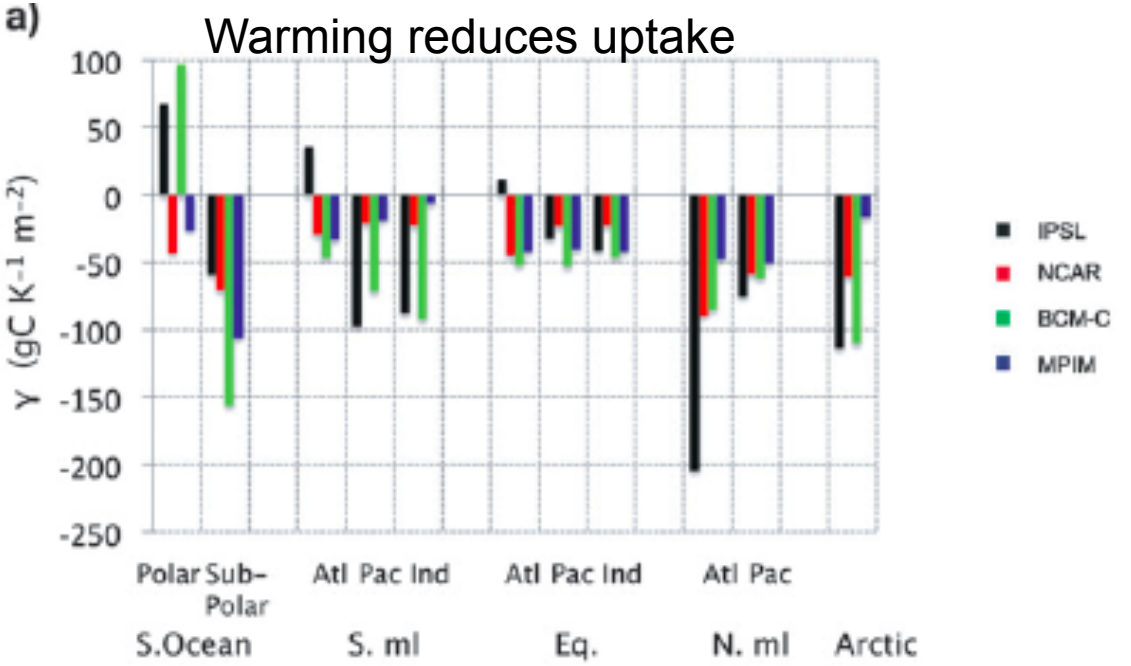




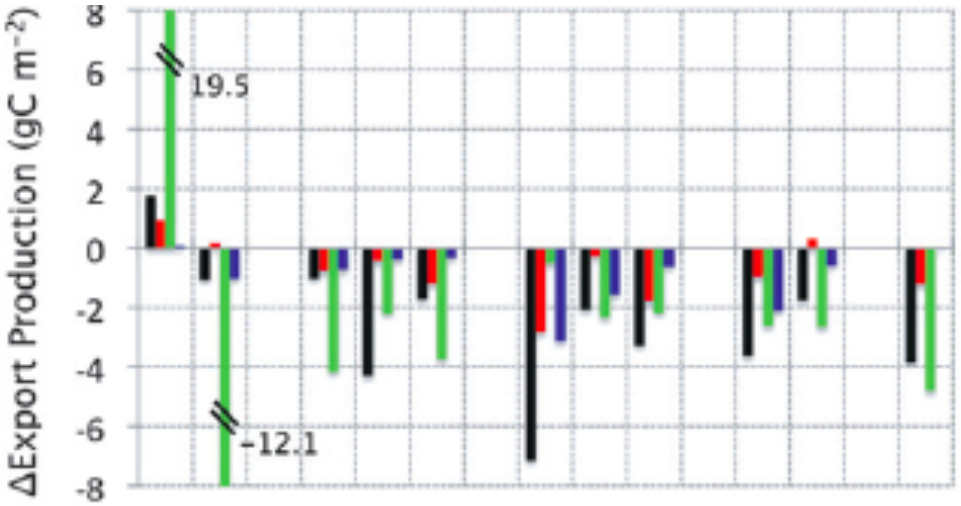
HOT and BATS grids



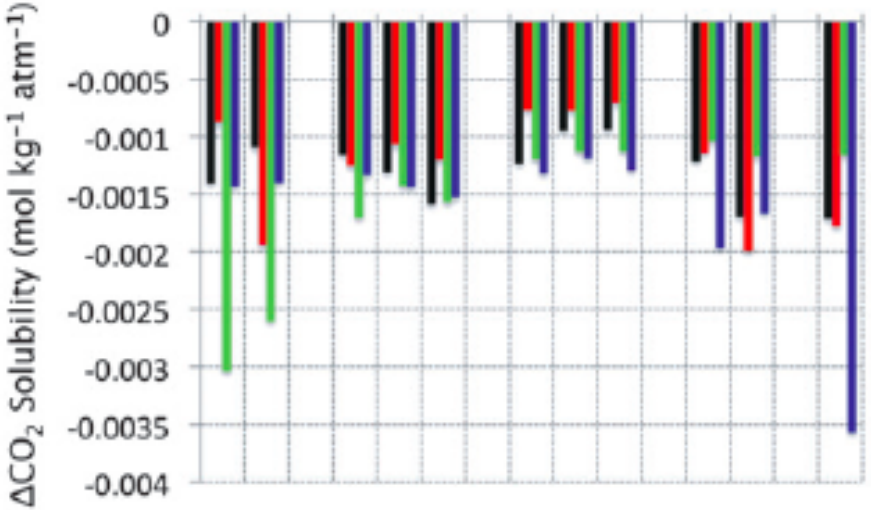
C⁴MIP Response of carbon sink to warming 2010 to 2100



Small reduction in export flux



Reduced solubility



Roy et al. 2011, J. Climate