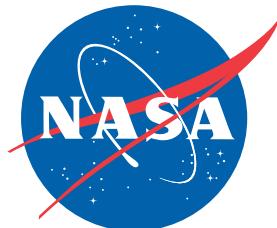


USING DATA TO ELUCIDATE FEEDBACK MECHANISMS IN THE OCEAN CARBON CYCLE

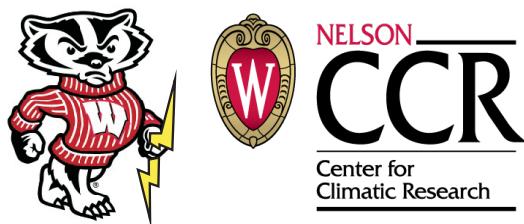


Galen A. McKinley and Amanda Fay

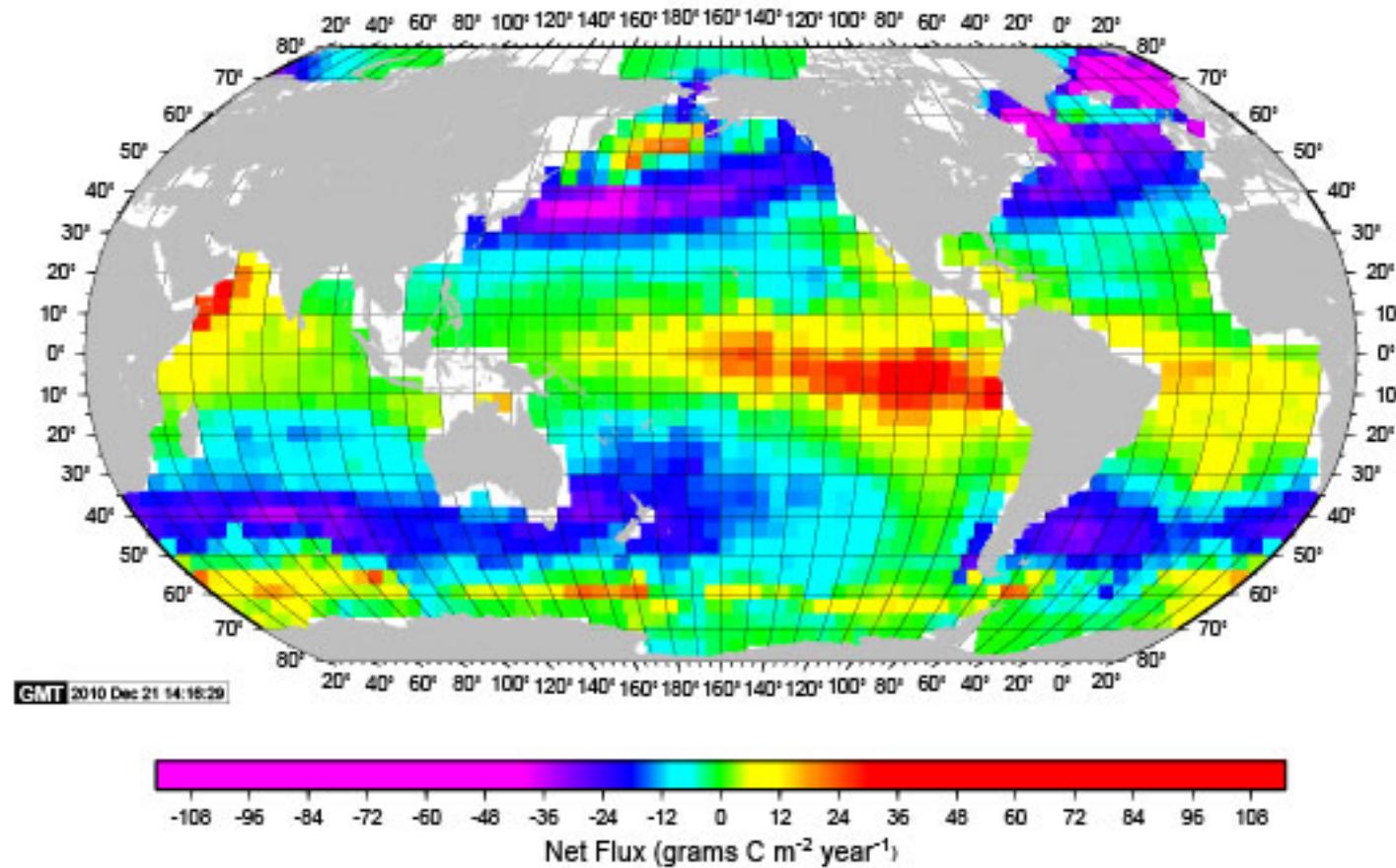
*Atmospheric and Oceanic Sciences
Center for Climatic Research - Nelson Institute
University of Wisconsin - Madison*

9 August 2013

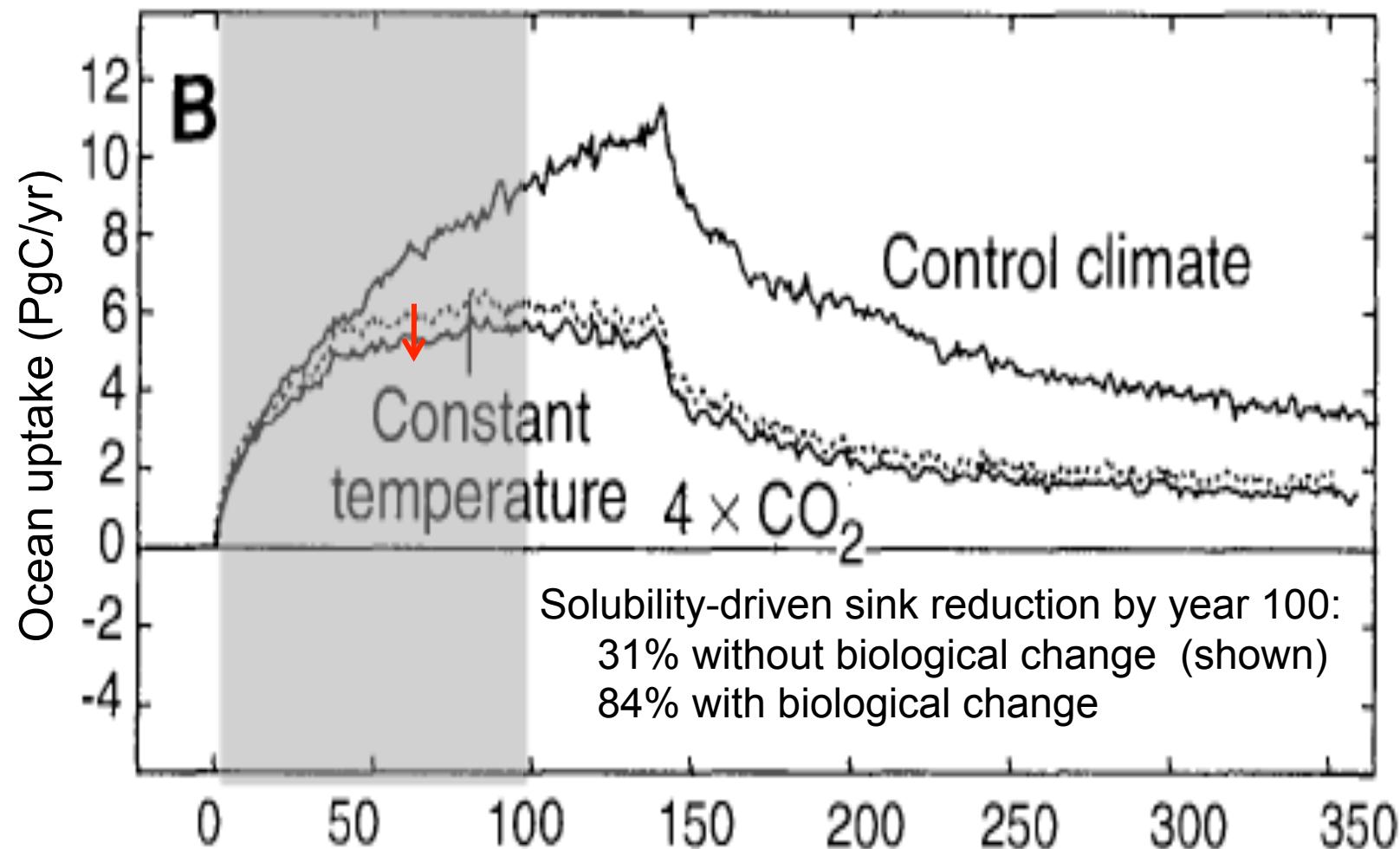
*Key Uncertainties in the Global Carbon Cycle:
Perspectives across terrestrial and ocean ecosystems*



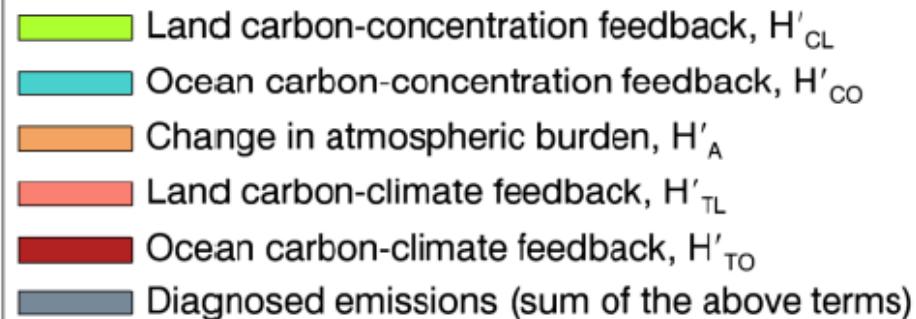
How is the observed ocean carbon sink changing in response to increasing $p\text{CO}_2^{\text{atm}}$ and warming?



Early models: Positive carbon feedback, damped by negative warming feedback for 100 yrs after 4xCO₂

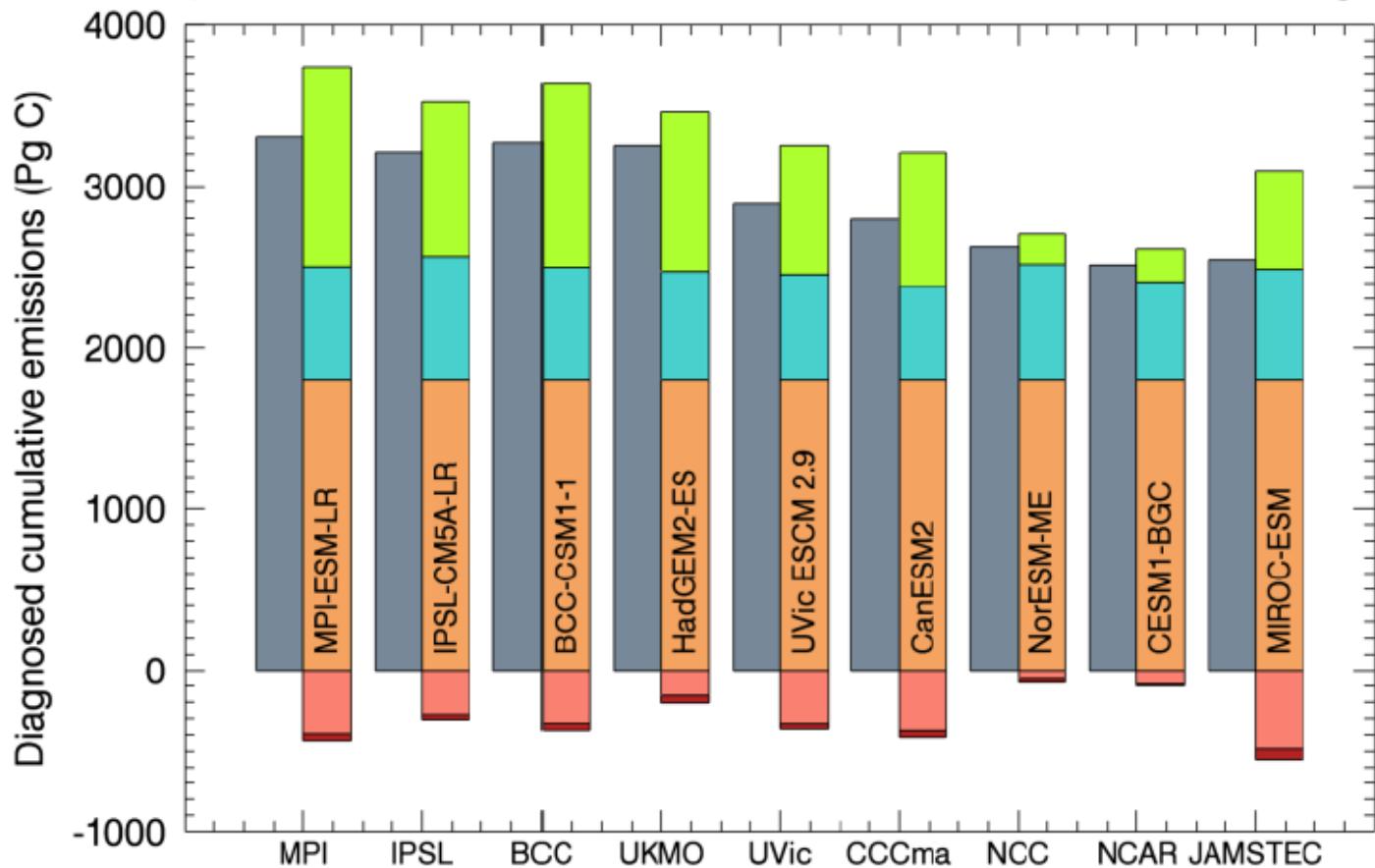


CMIP5, 140 year 1% runs



$$H'_A + H'_{CO} + H'_{CL} + H'_{TO} + H'_{TL} = \tilde{E}_e$$

a) Contribution of land and ocean feedback terms to the carbon budget



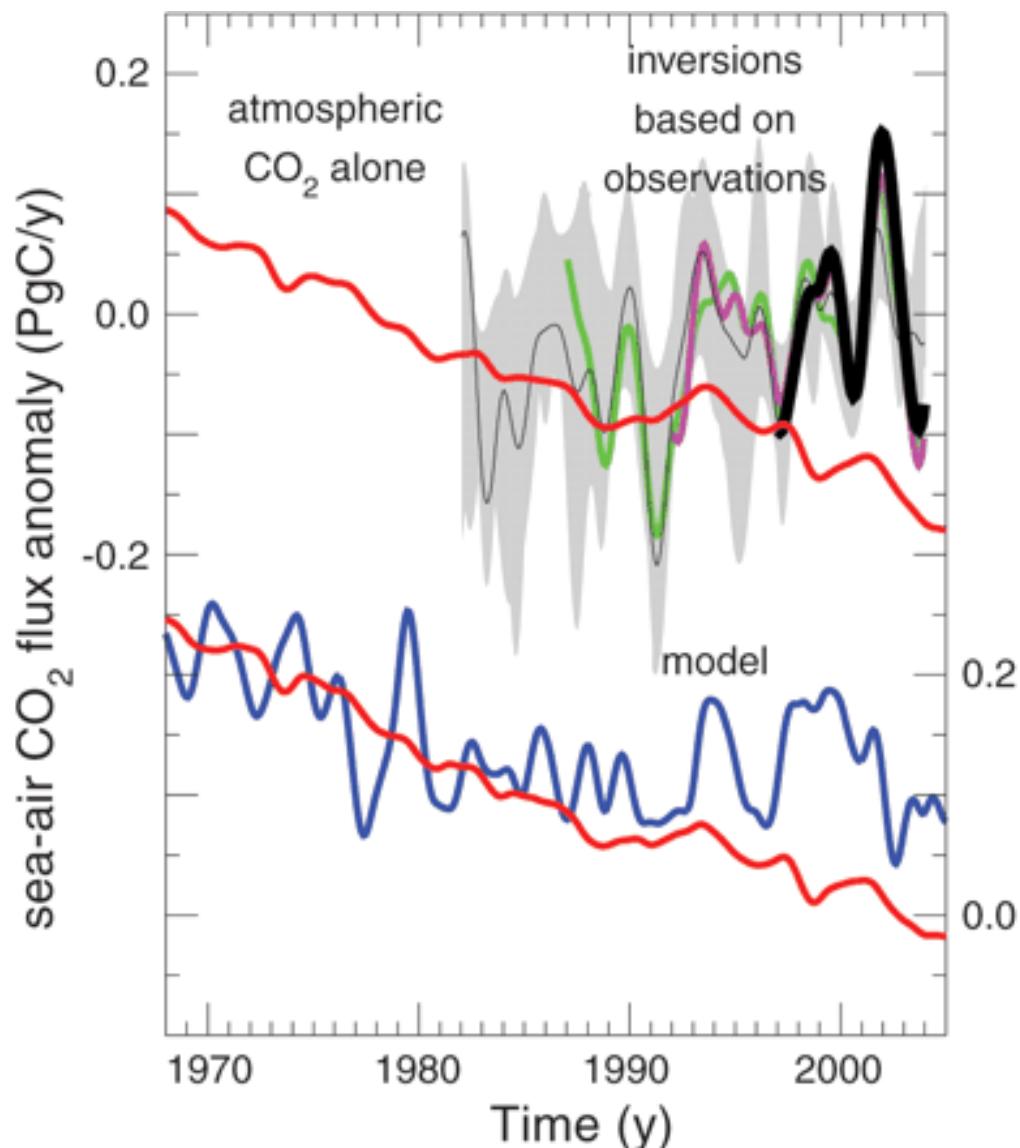
Hindcast model assessment of ocean sink change due to climate variability and change 1981-2007 = 0.20 PgC/decade reduction

| 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.

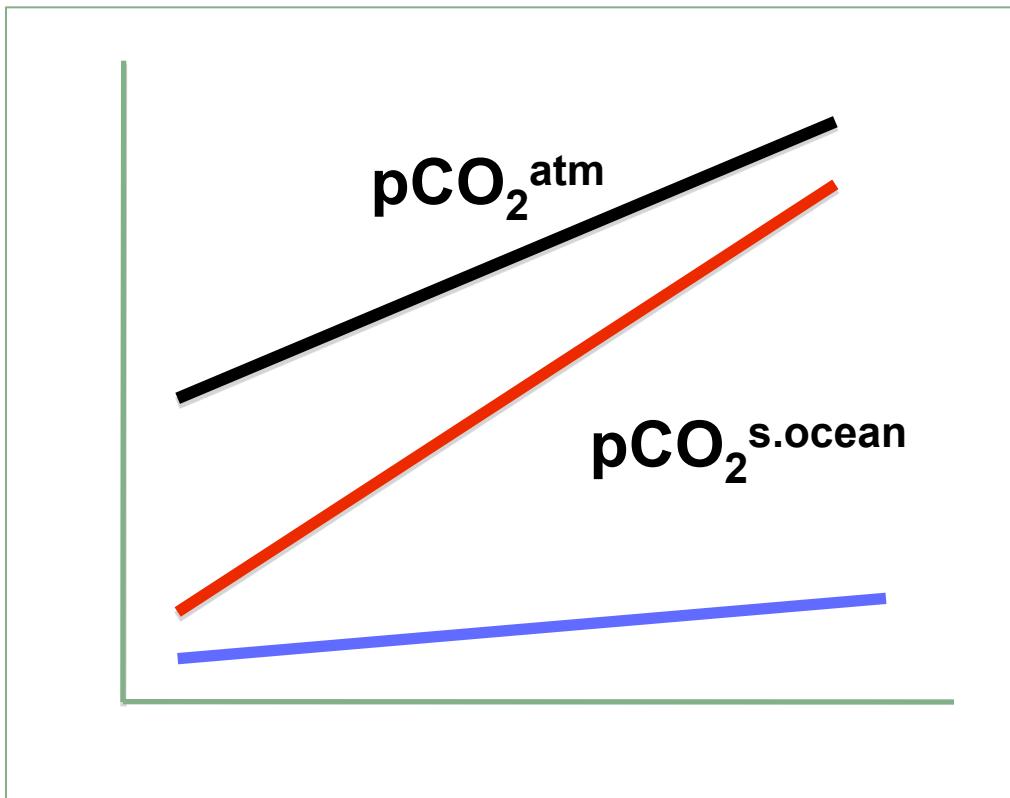
Ito et al 2010, Nature

Gent and Danabasoglu 2011, J. Climate

LeQuere et al. 2007, Science

Surface ocean pCO₂ for assessment of feedback mechanisms

$p\text{CO}_2^{\text{atm}}$ trend vs. $p\text{CO}_2^{\text{s.ocean}}$ trend



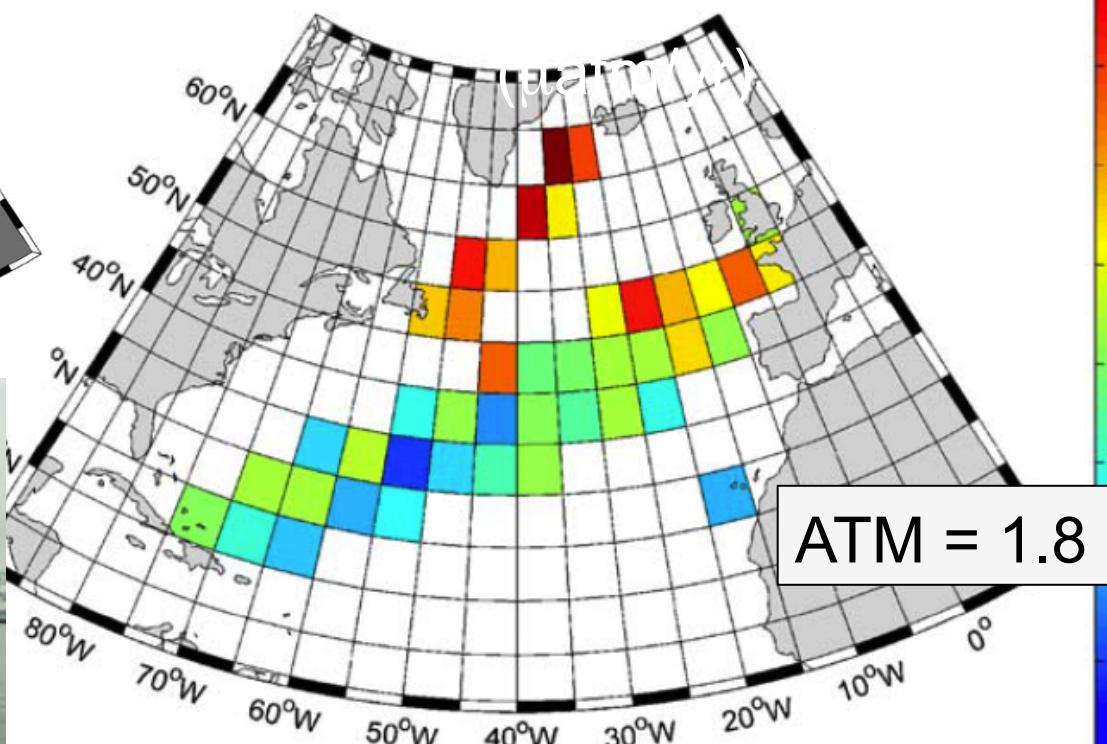
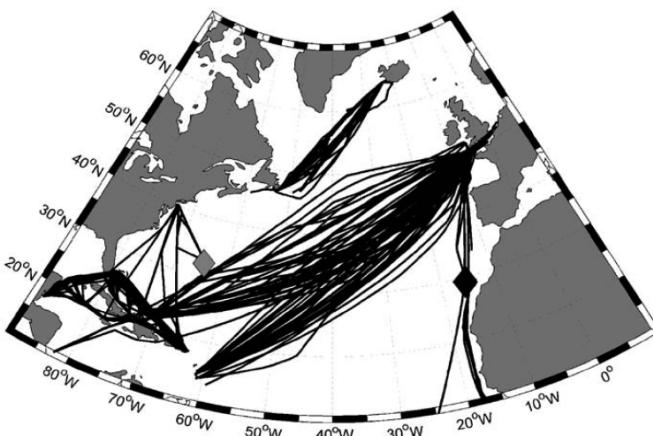
$$\frac{dp\text{CO}_2^{\text{s.ocean}}}{dt} > \frac{dp\text{CO}_2^{\text{atm}}}{dt}$$

steeper $p\text{CO}_2^{\text{s.ocean}}$ trend
DECREASING $\Delta p\text{CO}_2$

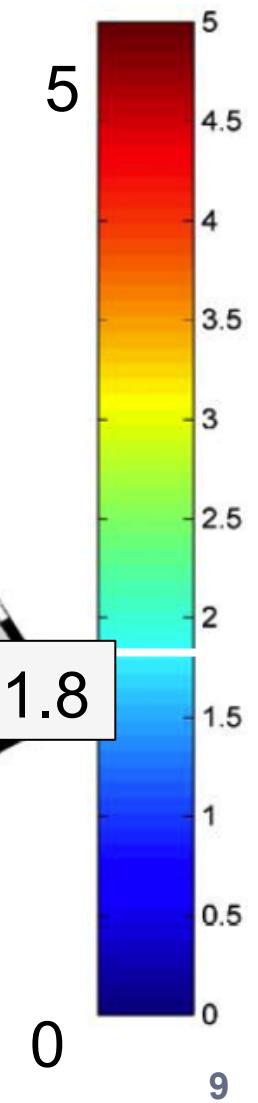
$$\frac{dp\text{CO}_2^{\text{s.ocean}}}{dt} < \frac{dp\text{CO}_2^{\text{atm}}}{dt}$$

shallower $p\text{CO}_2^{\text{s.ocean}}$ trend
INCREASING $\Delta p\text{CO}_2$

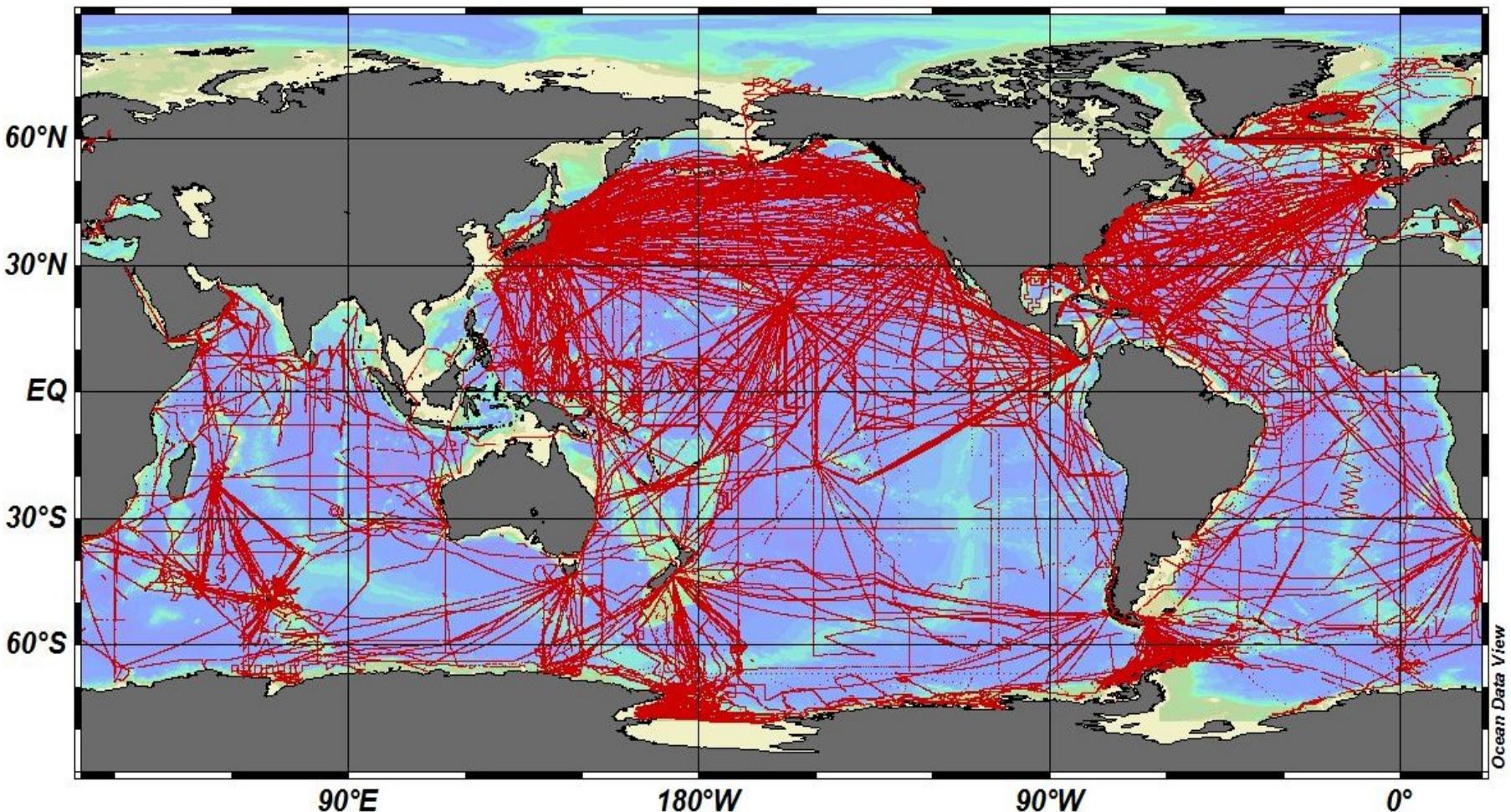
North Atlantic: VOS datasets, linear trend in $p\text{CO}_2^{\text{s.ocean}}$ ($\mu\text{atm}/\text{yr}$) 1990-2006



Schuster et al. 2009, DSR

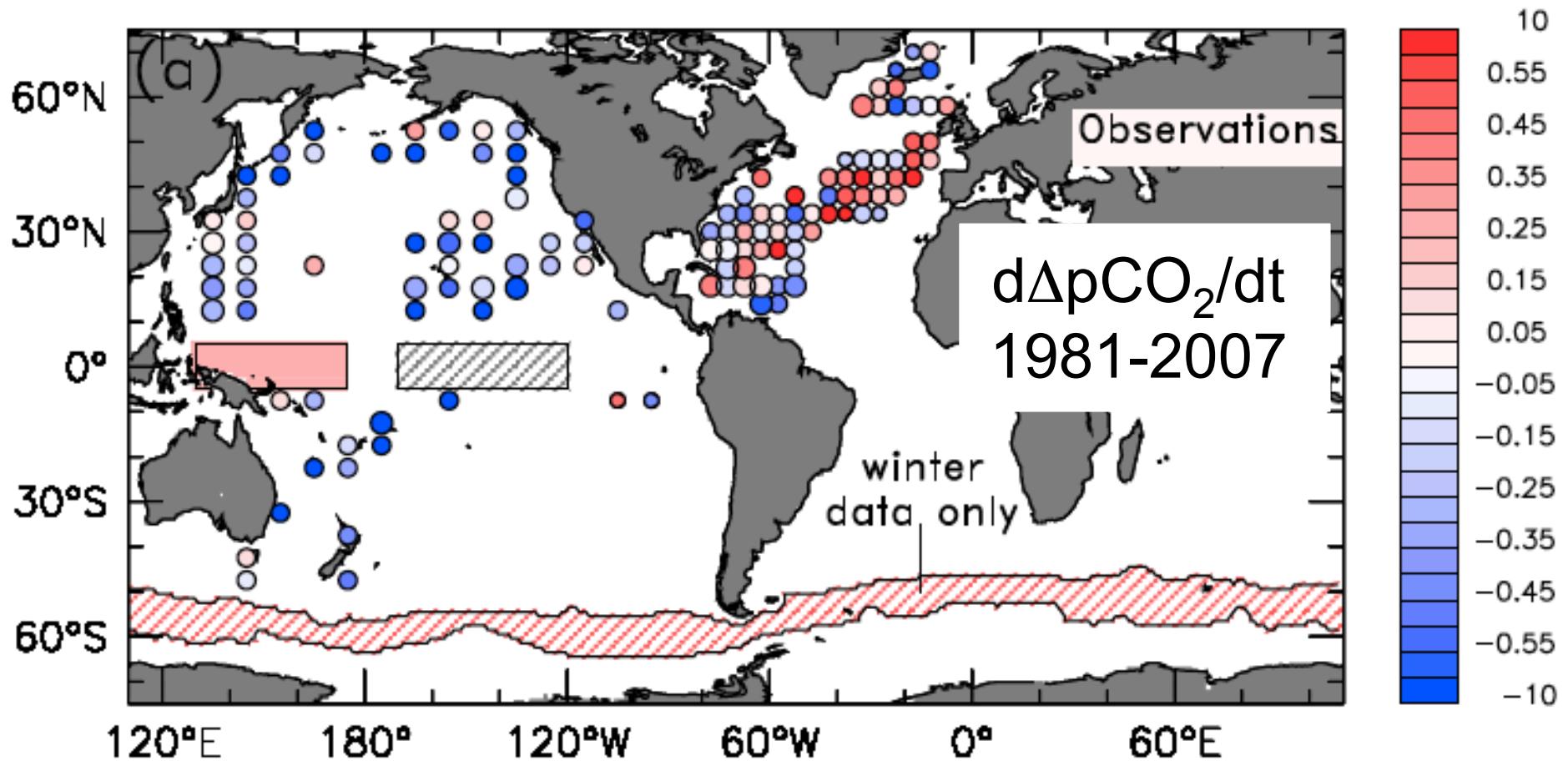


pCO₂ database: >4.5 Million data points



Takahashi et al. 2010, CDIAC

Regional Trends from Takahashi database



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

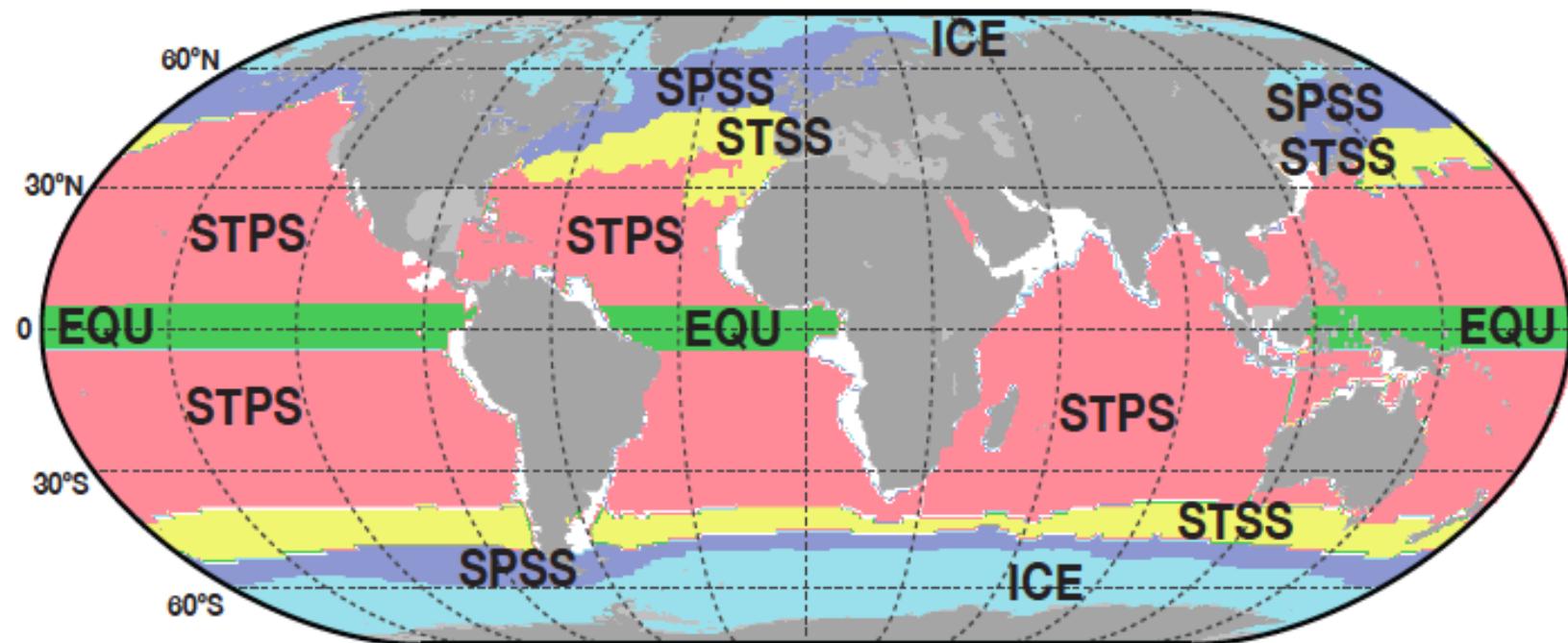
Research questions

- 1) What do the available $pCO_2^{\text{S.Ocean}}$ 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 $pCO_2^{\text{S.Ocean}}$ exhibit a response dominated by the anthropogenically- forced response?

McKinley et al. 2011, Nature Geosci.

Fay and McKinley 2013, Global Biogeochem. Cycles

GLOBAL BIOMES



ICE: Ice **SPSS:** Subpolar seasonally stratified

STSS: Subtropical seasonally stratified

STPS: Subtropical permanently stratified

EQU: Equatorial

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

Trend Mechanisms

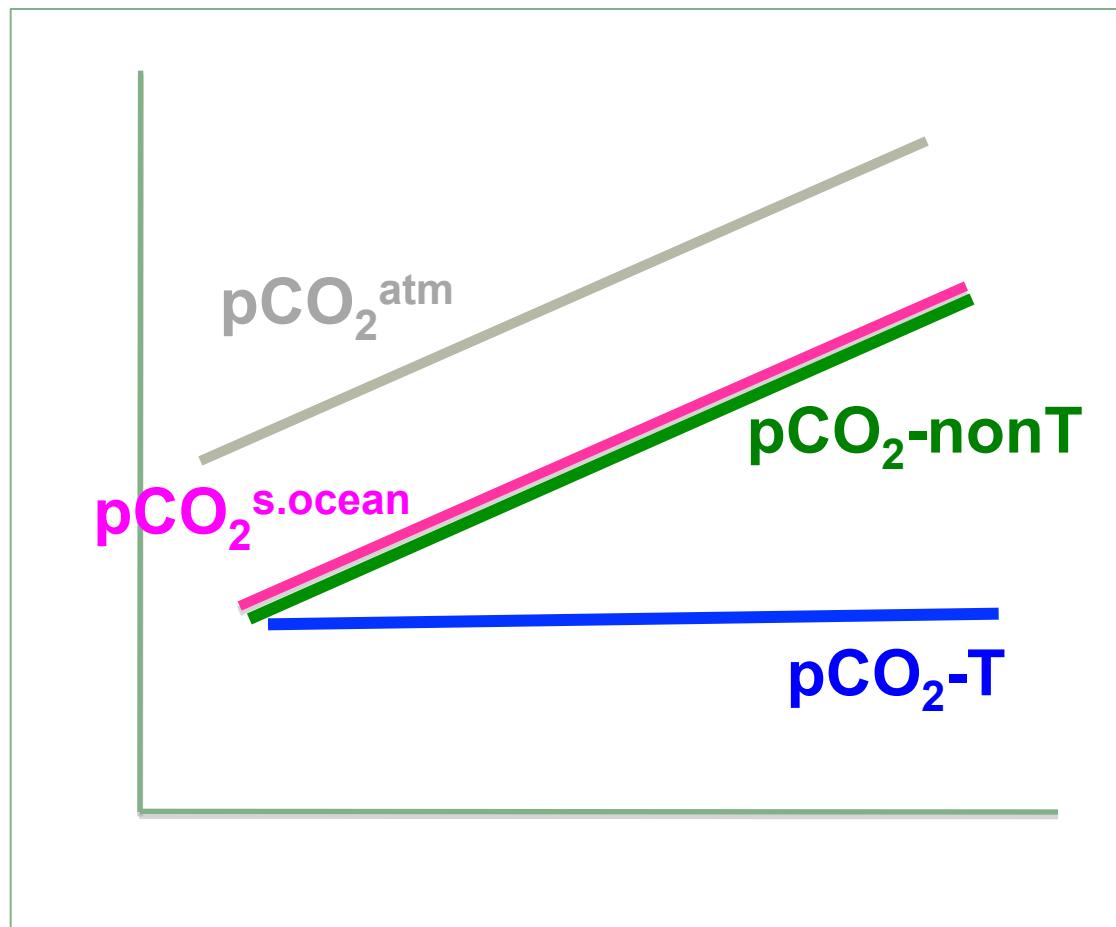
Decompose pCO_2 into temperature driven component ($pCO_2\text{-}T$) and biological/chemical component ($pCO_2\text{-}nonT$)

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

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

Takahashi et al. 2002, DSR II

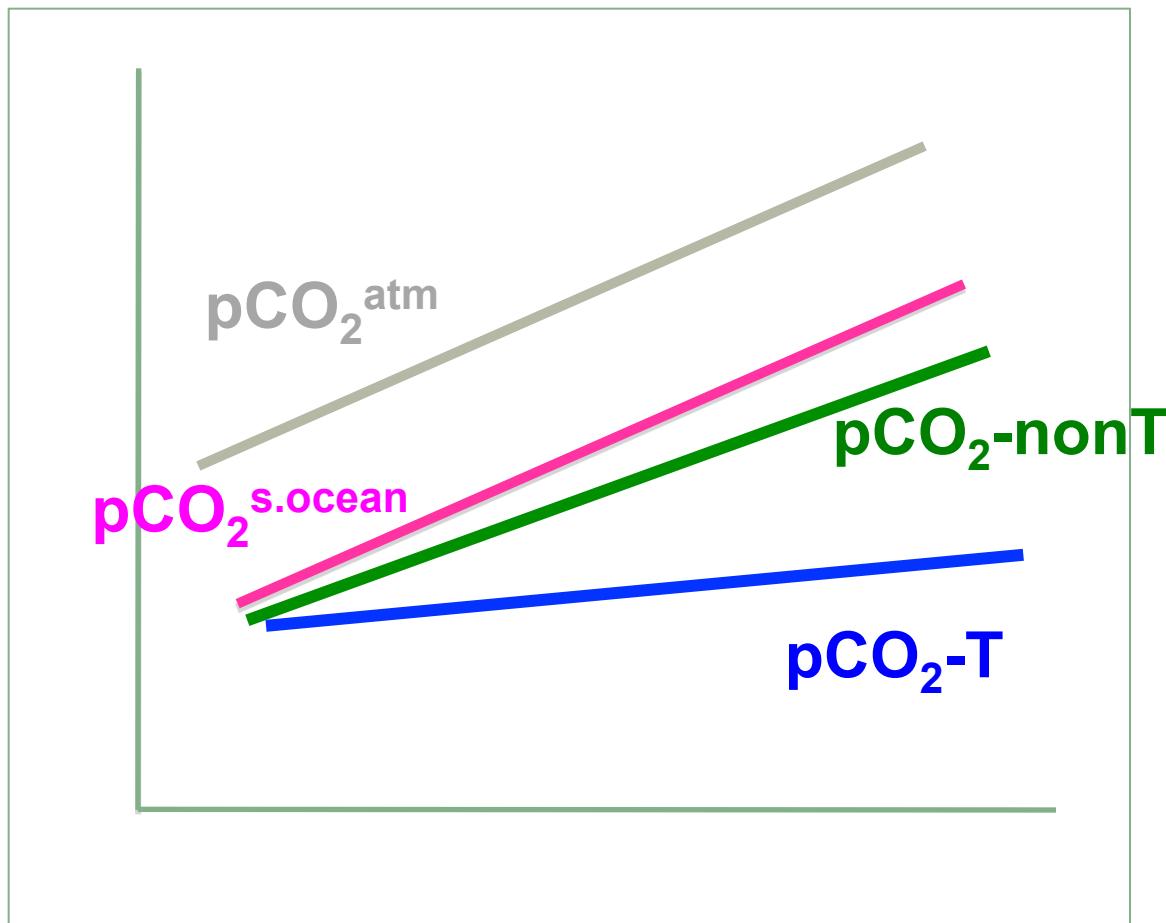
Trend mechanisms



**Biogeochemical
change only**

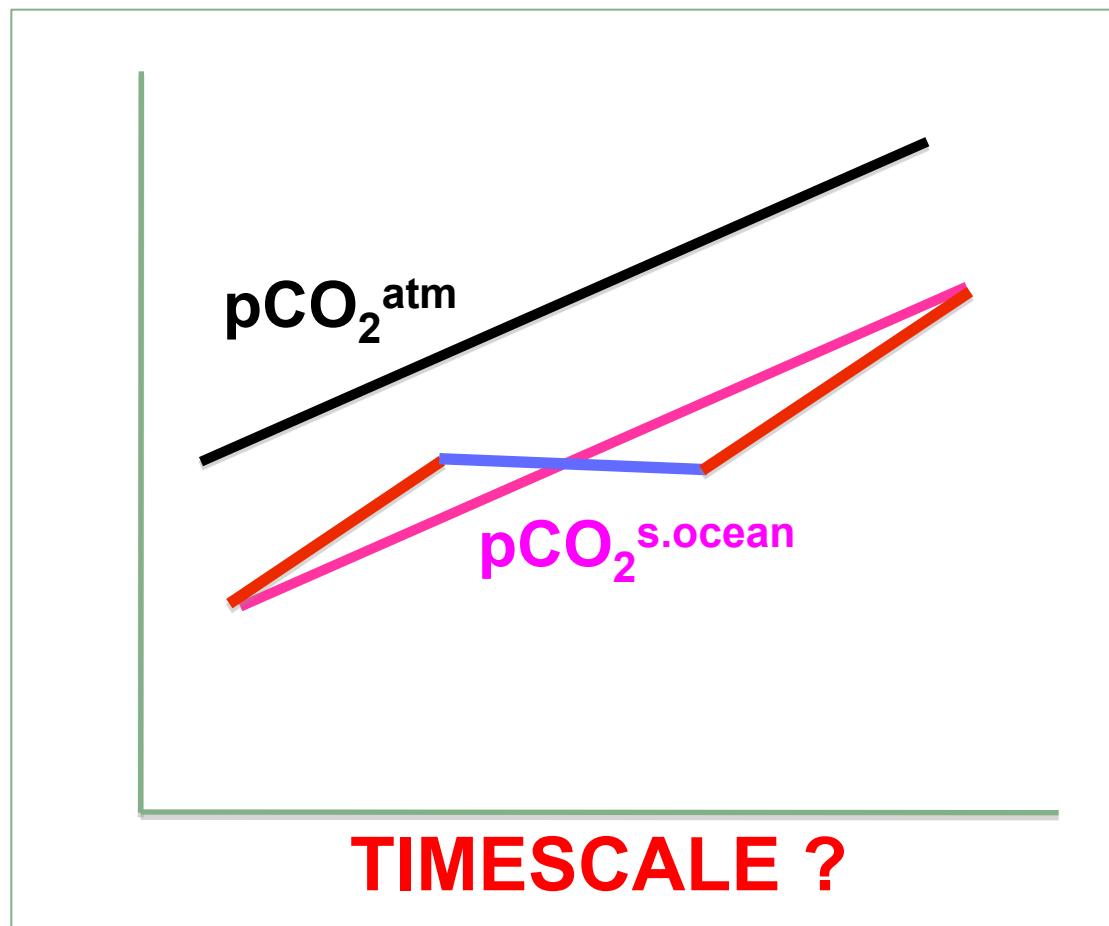
**Consistent with
carbon uptake**

Trend mechanisms



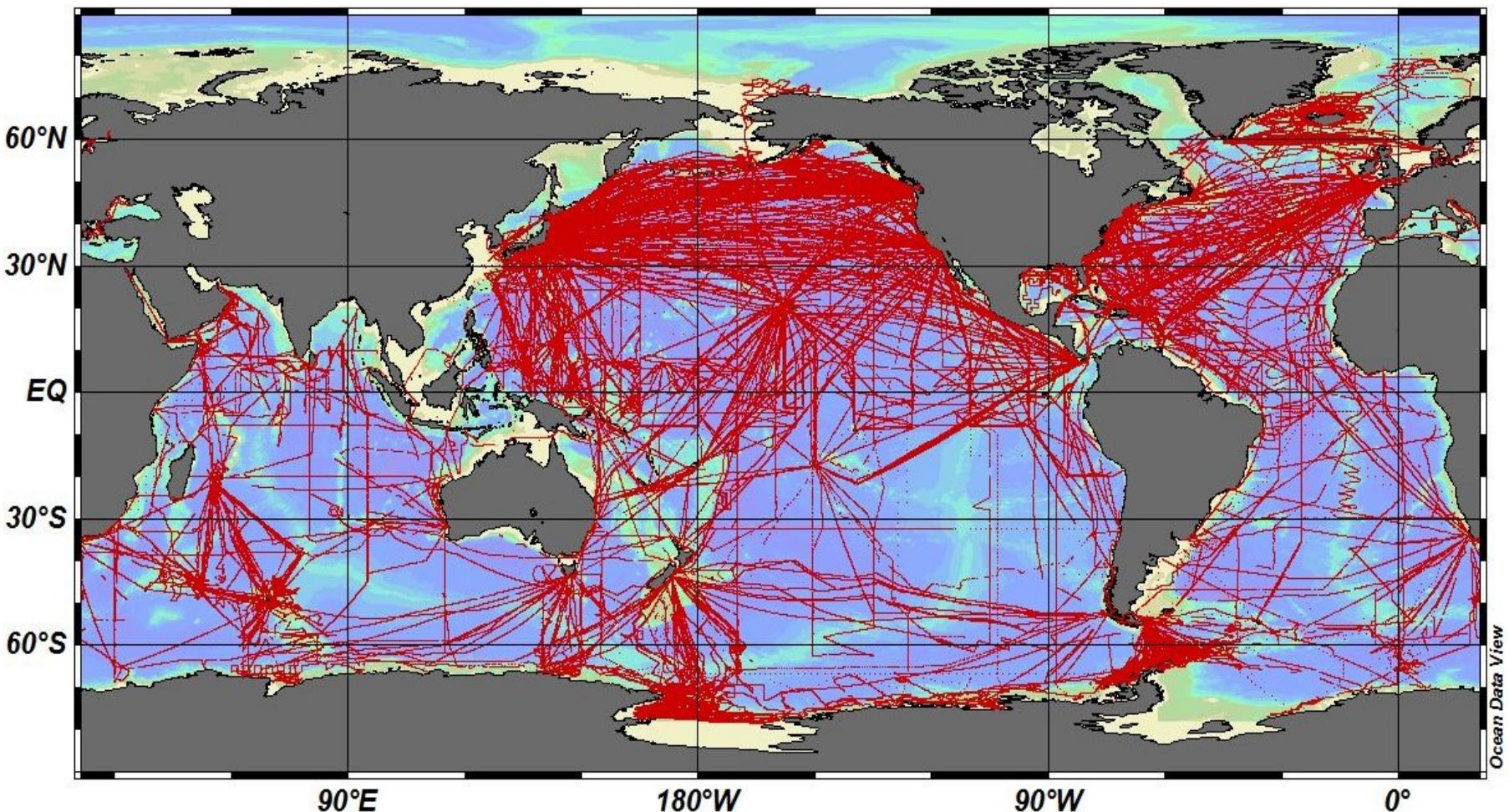
If warming contributes to ocean pCO₂ increase, carbon uptake is diminished

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



Methodology

pCO₂ database: >4.5 Million data points



Takahashi et al. 2010, CDIAC

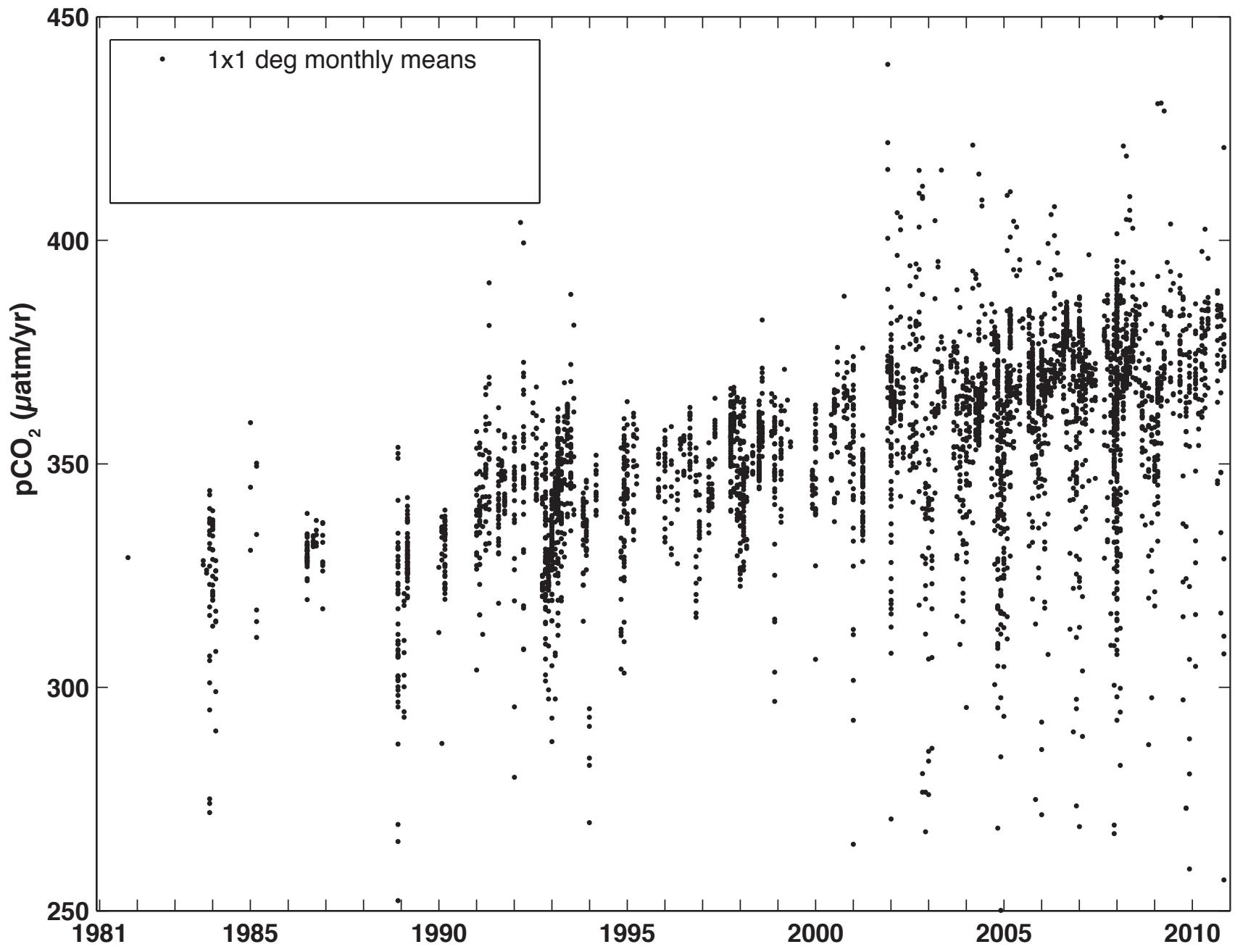
Methodology

1. Calculate monthly means for $1^\circ \times 1^\circ$ 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

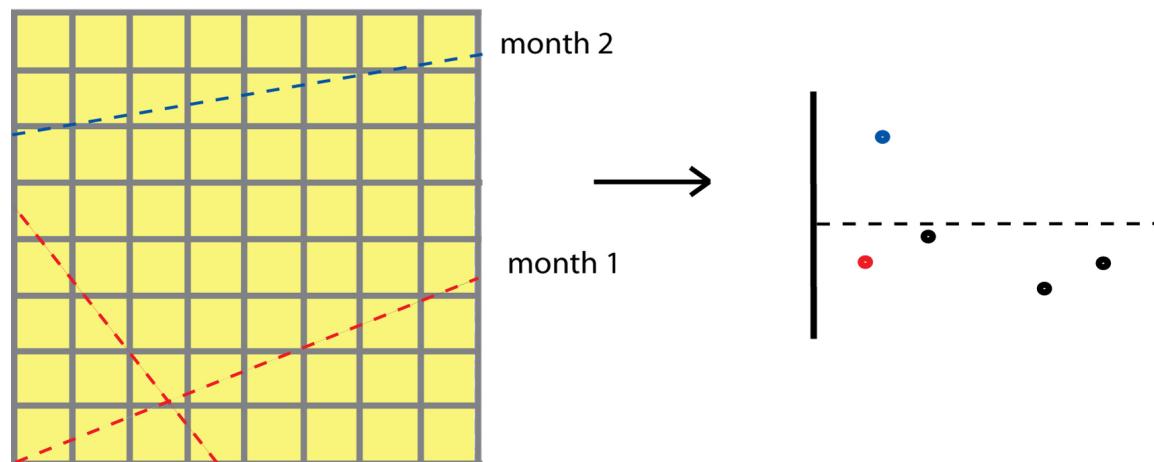
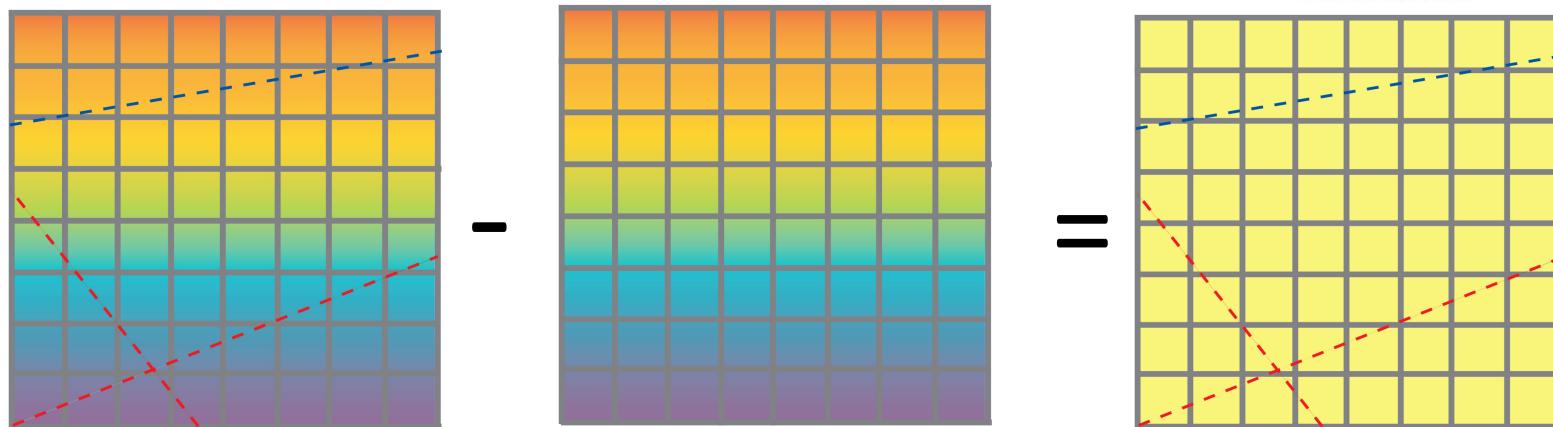
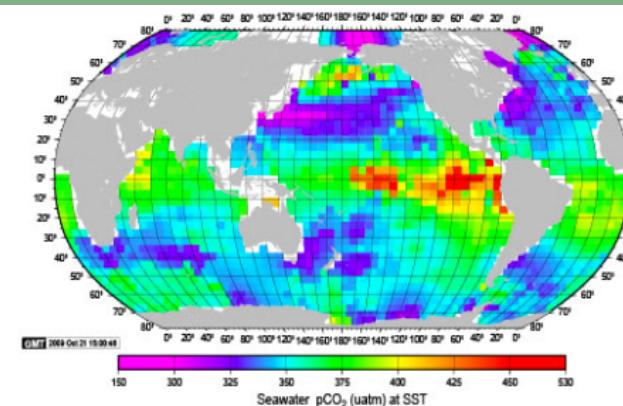


Methodology

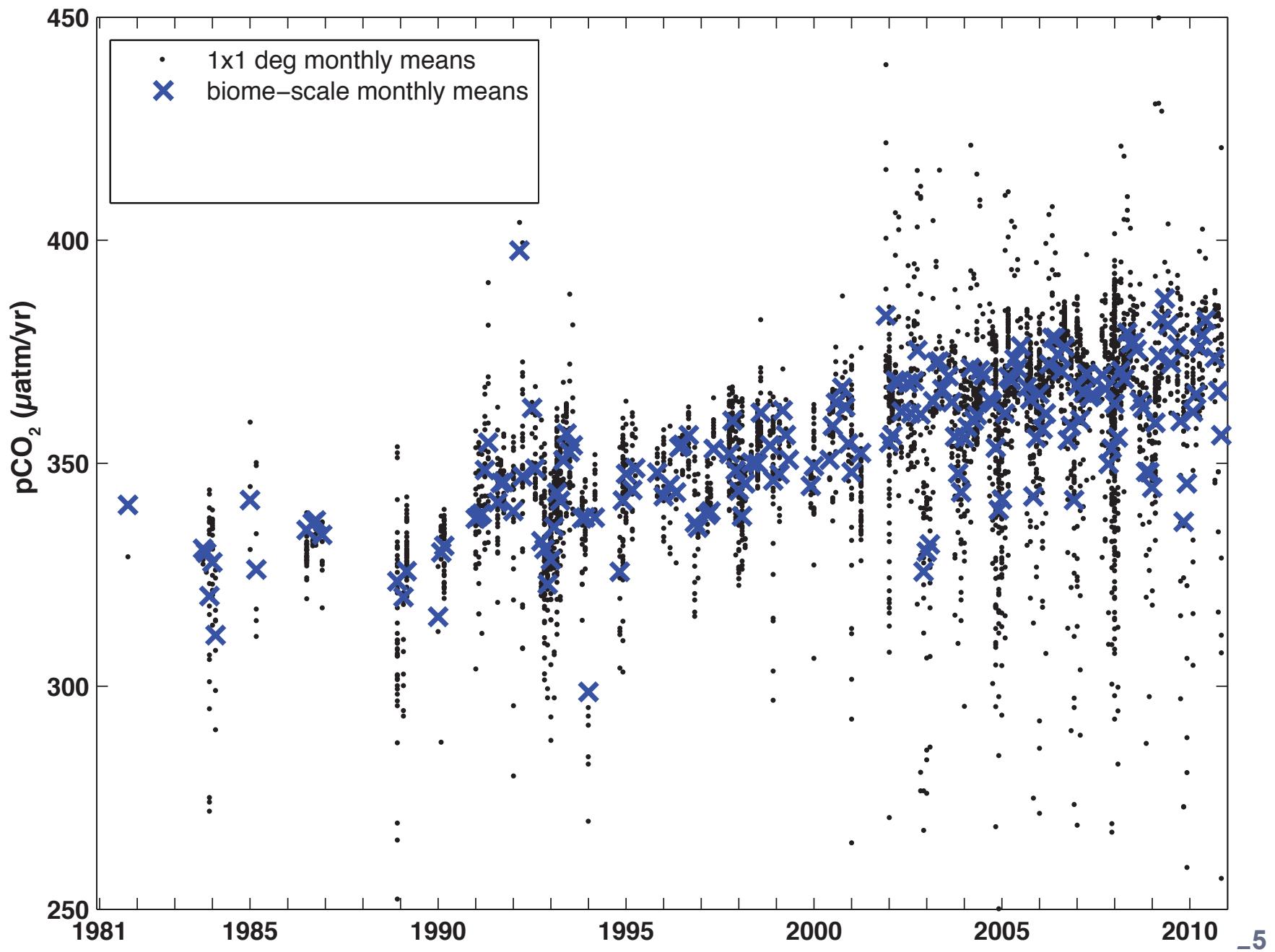
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McKinley et al., 2011
Fay & McKinley, 2013

Subtract background mean to address spatial aliasing



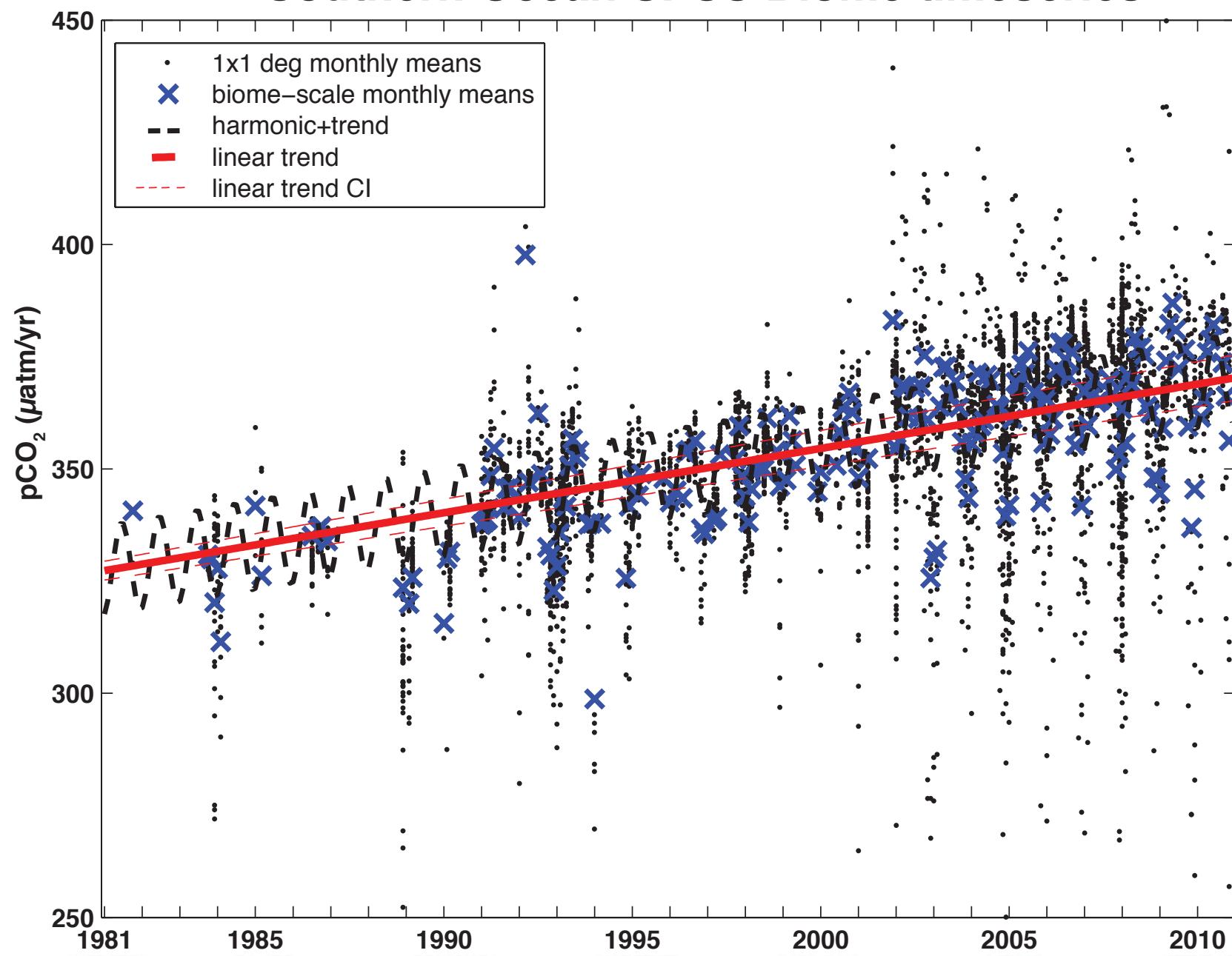
Southern Ocean SPSS Biome timeseries



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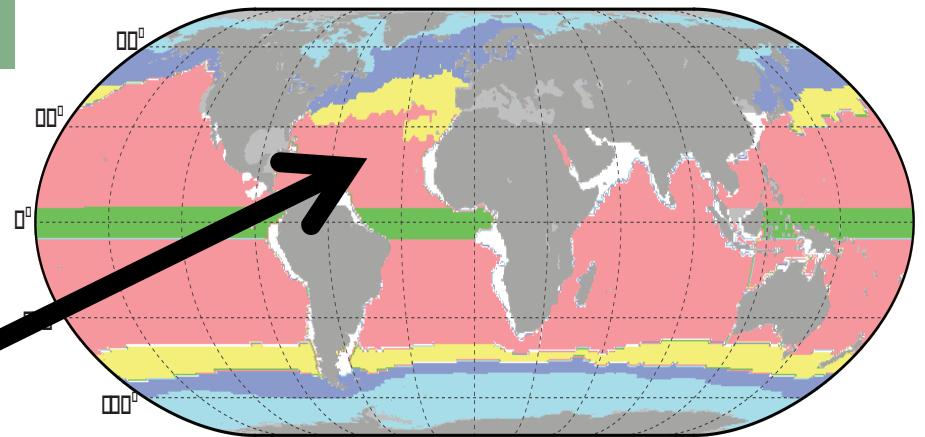
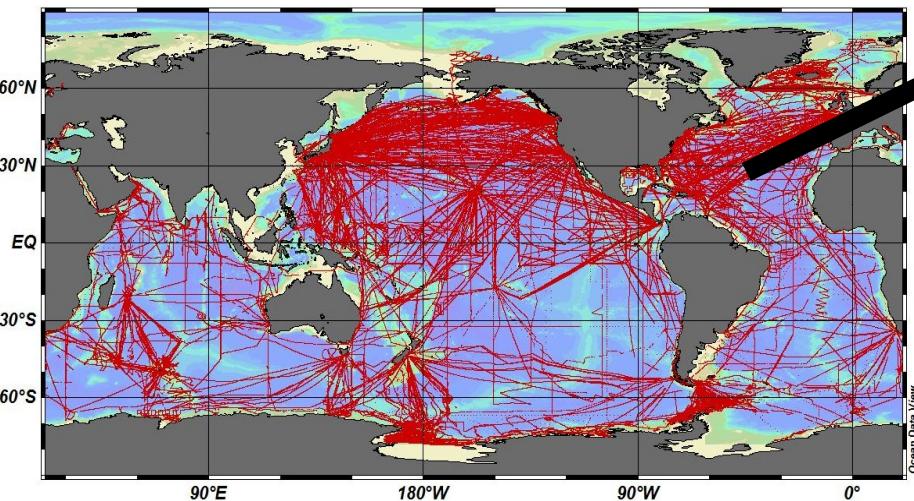
Southern Ocean SPSS Biome timeseries



Methodology

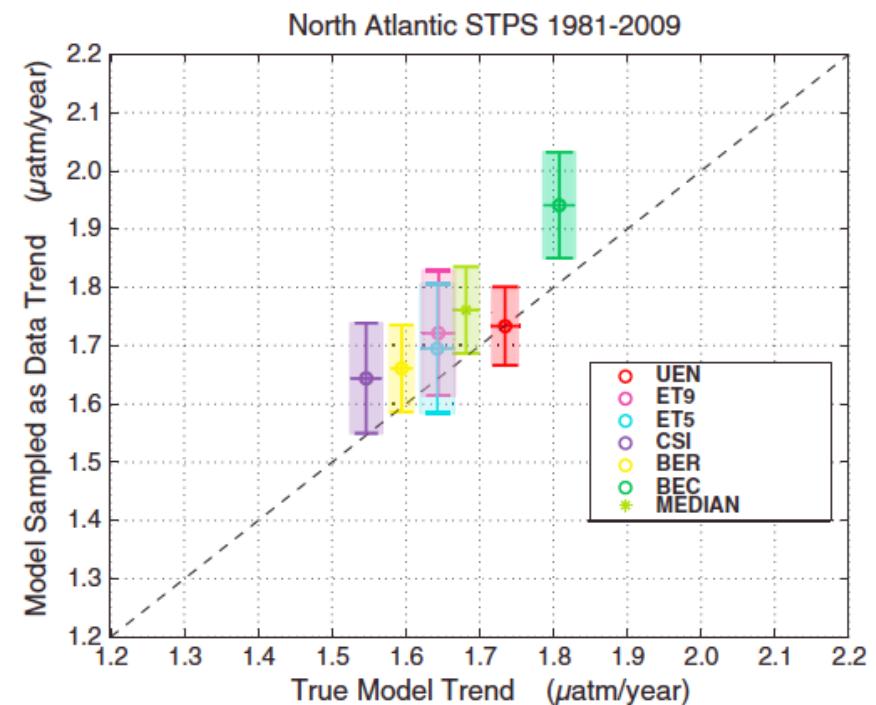
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+ trend $y = a + b*t + c*\cos(2\pi t + d)$
4. Use models to confirm methodology

Representativity error?



RECCAP models are used to confirm sufficient sampling

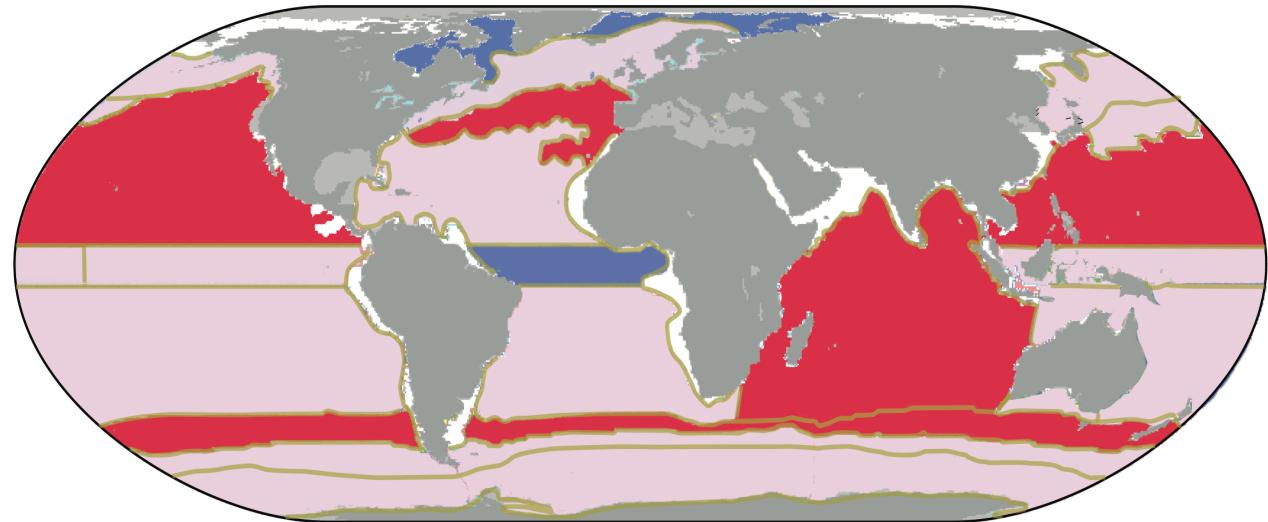
- Sample model as data
- Calculate sampled model trend and true model trend
- If sampled and true trends are within 1σ uncertainty, it is “confirmed”



Results

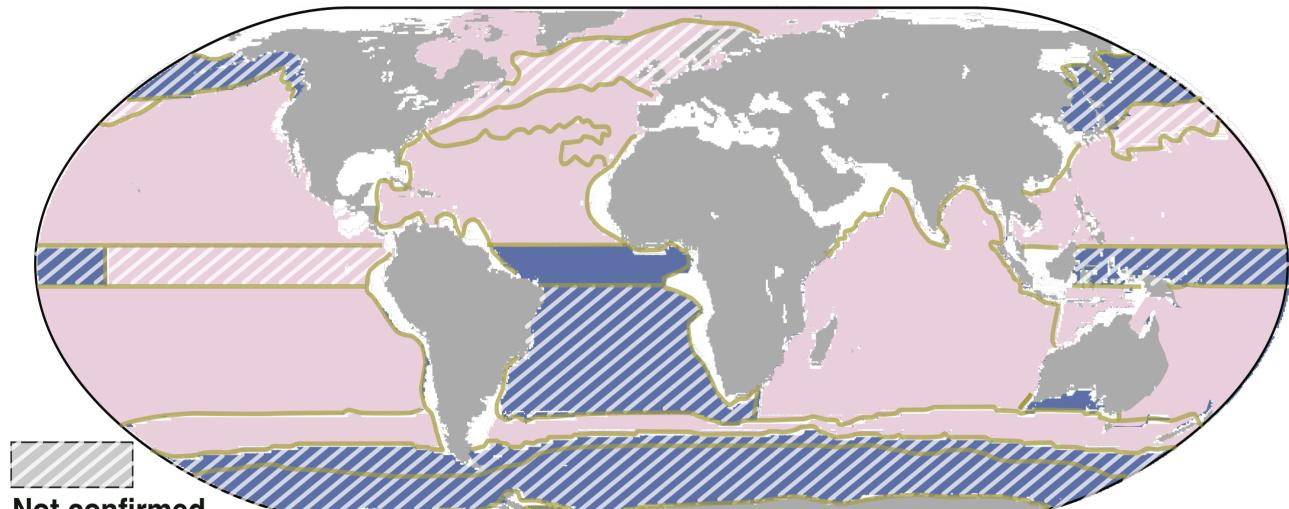
1990-2005

$\text{dpCO}_2^{\text{s.ocean}/\text{dt}} > \text{dpCO}_2^{\text{atm}/\text{dt}}$
steeper $\text{pCO}_2^{\text{s.ocean}}$
**DECREASING
 ΔpCO_2**



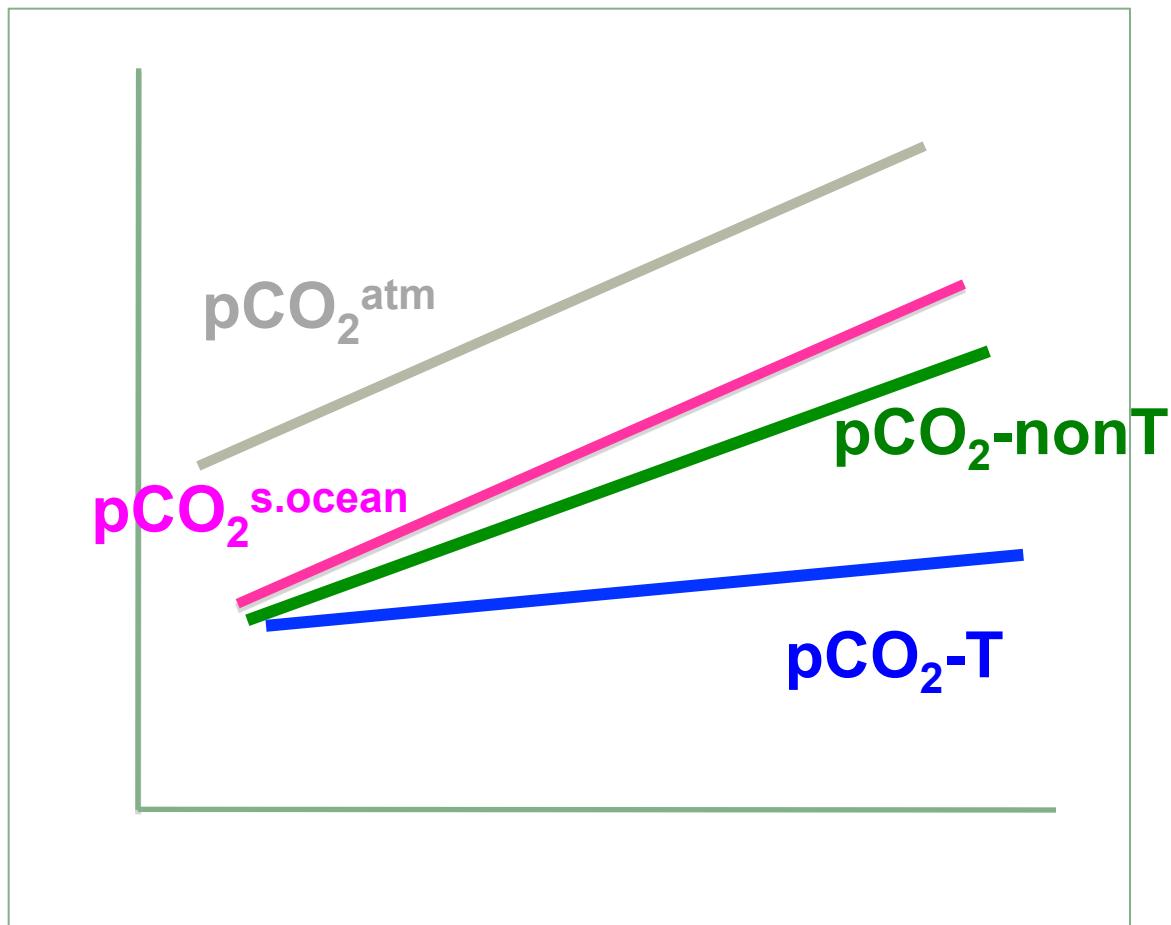
1981-2010

$\text{dpCO}_2^{\text{s.ocean}/\text{dt}} < \text{dpCO}_2^{\text{atm}/\text{dt}}$
shallower $\text{pCO}_2^{\text{s.ocean}}$
**INCREASING
 ΔpCO_2**

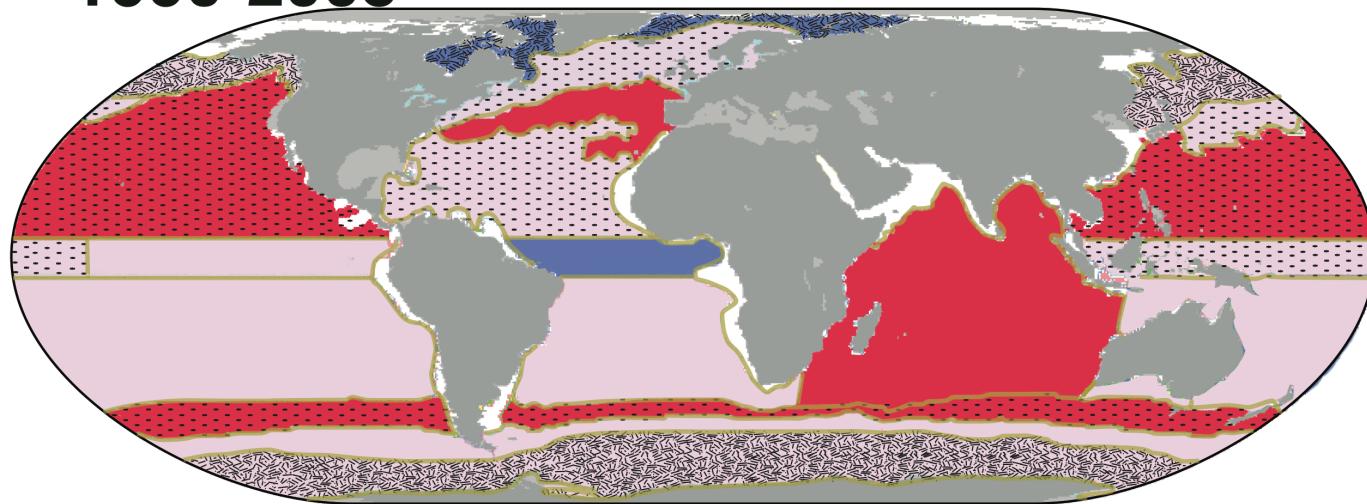


$\text{dpCO}_2^{\text{oce}/\text{dt}} < \text{dpCO}_2^{\text{atm}/\text{dt}}$ $\text{dpCO}_2^{\text{oce}/\text{dt}} \sim \text{dpCO}_2^{\text{atm}/\text{dt}}$ $\text{dpCO}_2^{\text{oce}/\text{dt}} > \text{dpCO}_2^{\text{atm}/\text{dt}}$

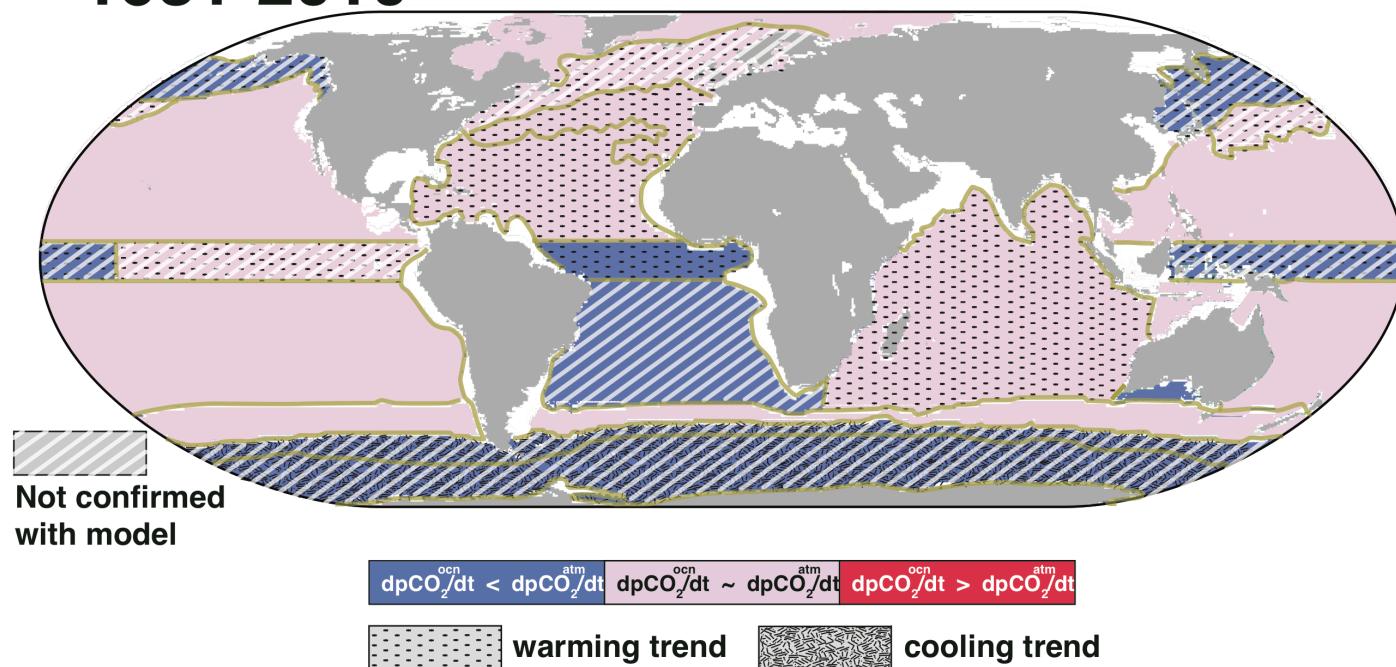
Does warming contribute to pCO₂ trend?



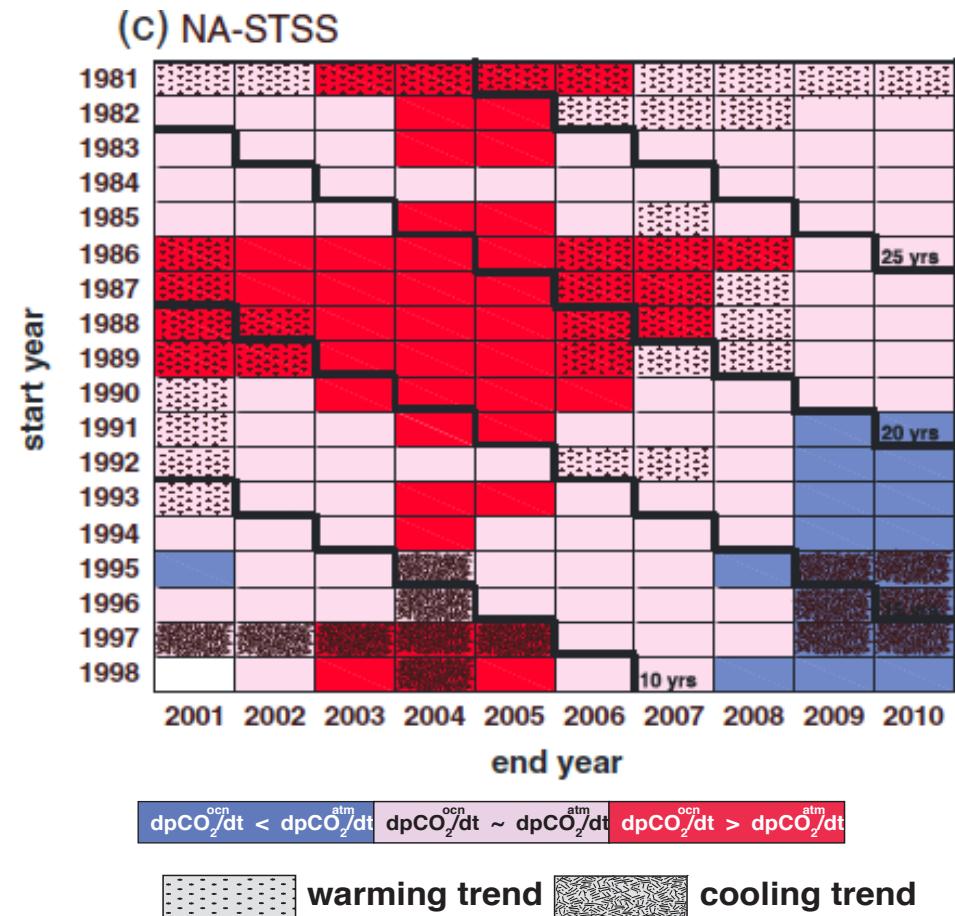
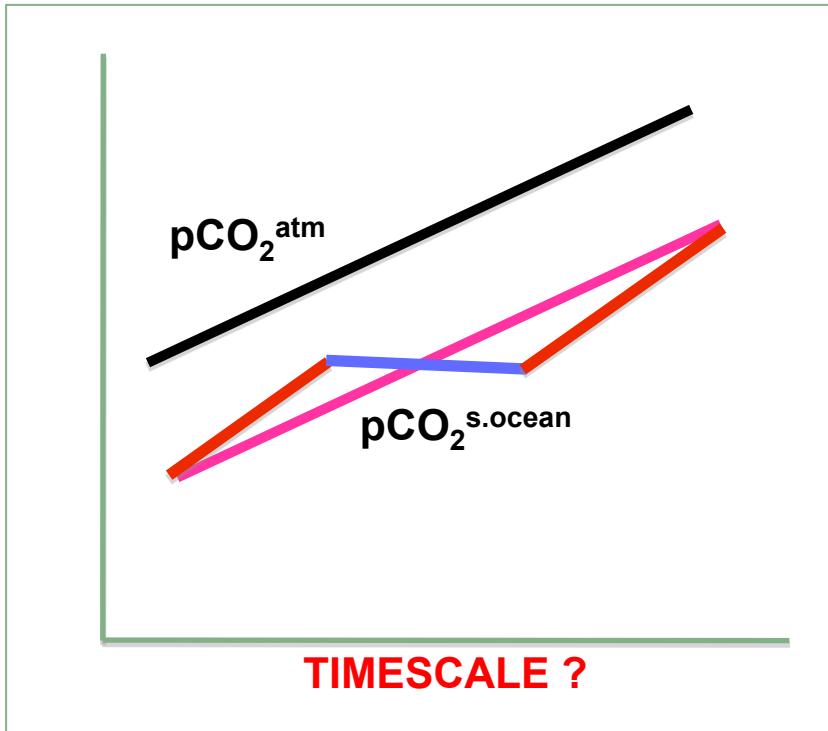
1990-2005



1981-2010

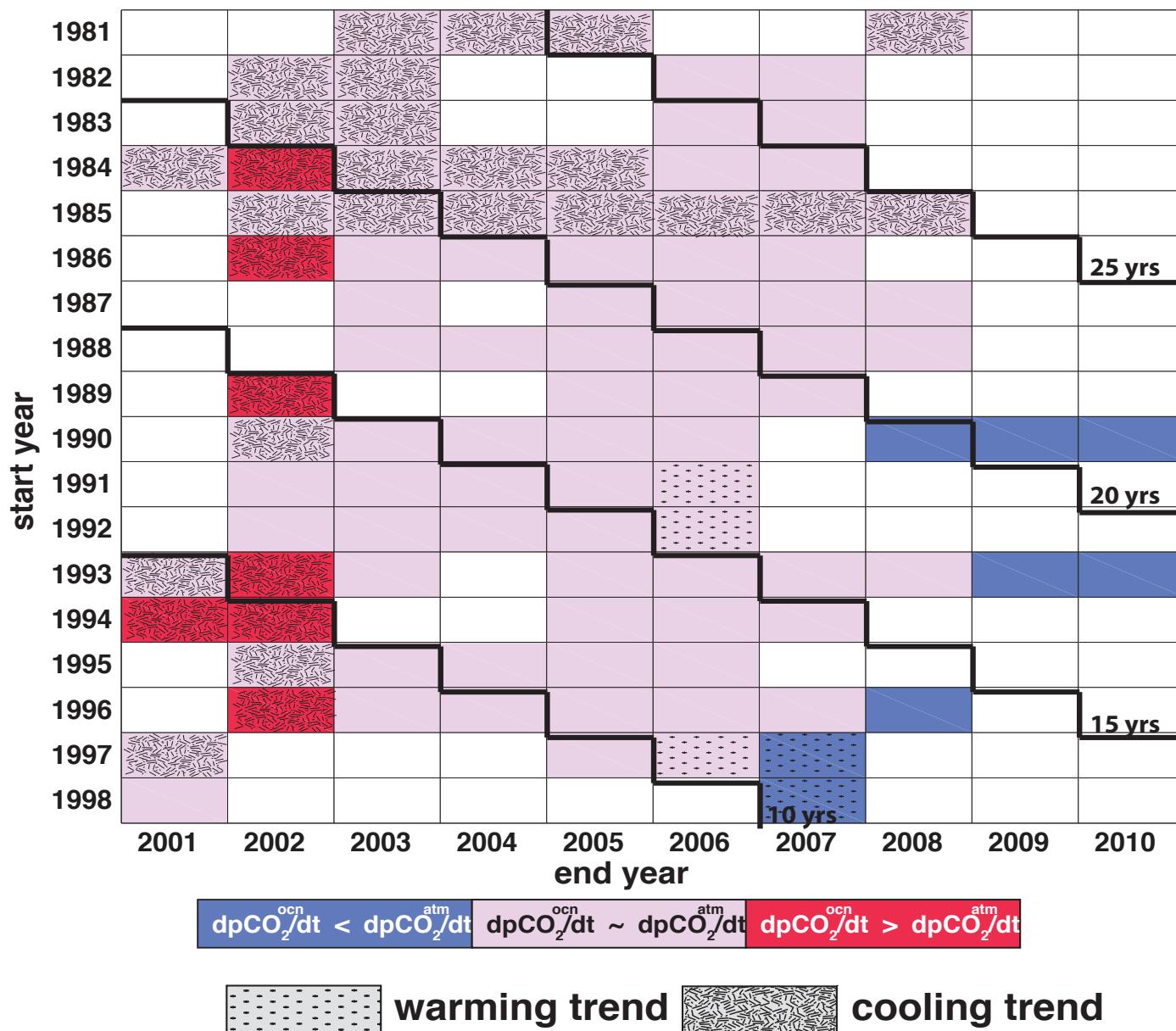
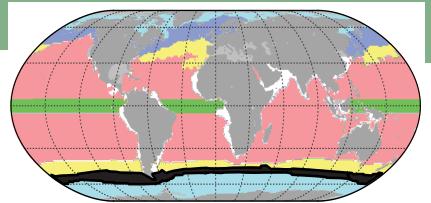


Timescale for long-term response?

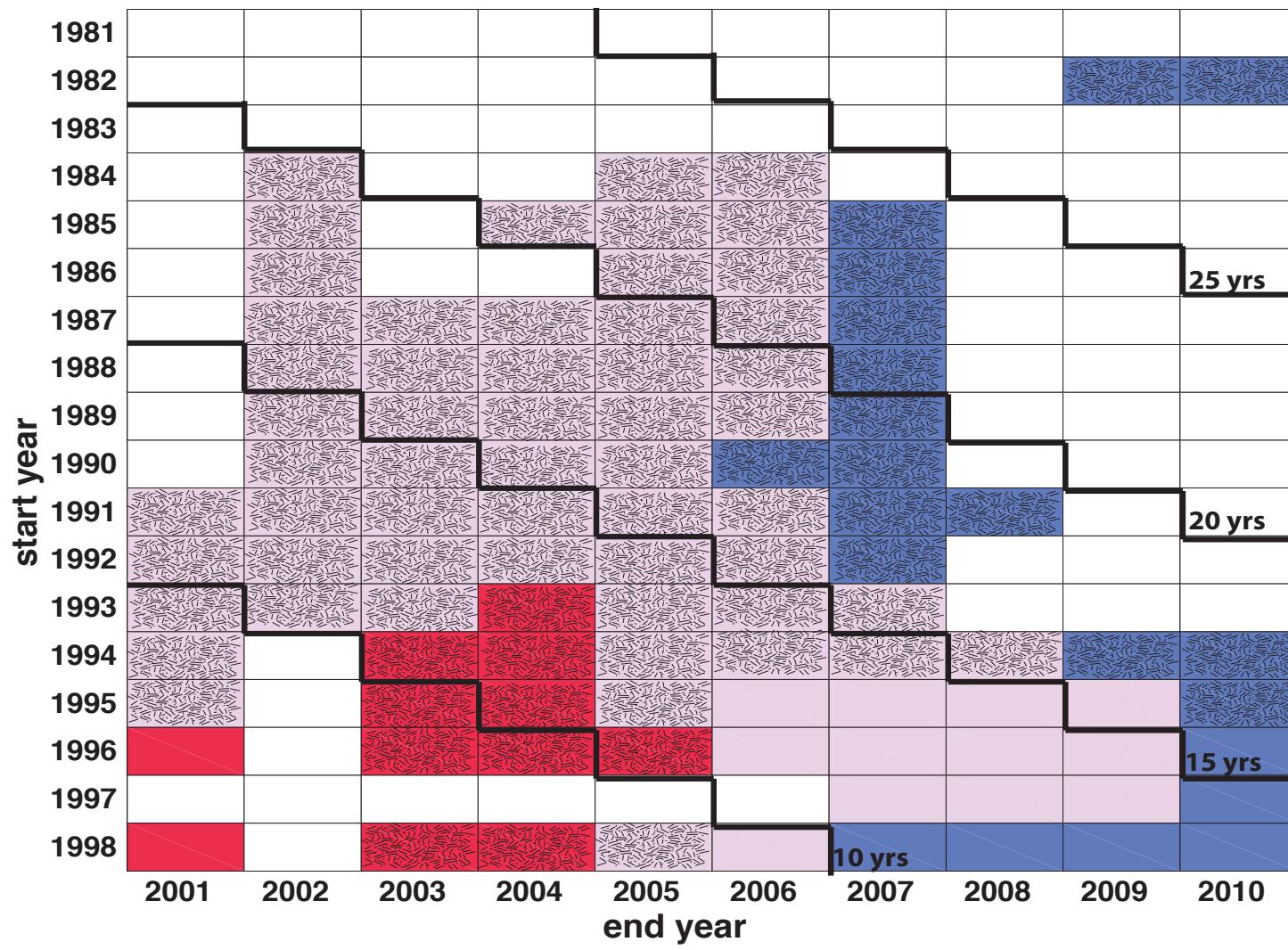
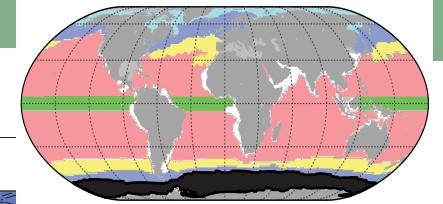


Southern Ocean

SO-SPSS



SO-ICE

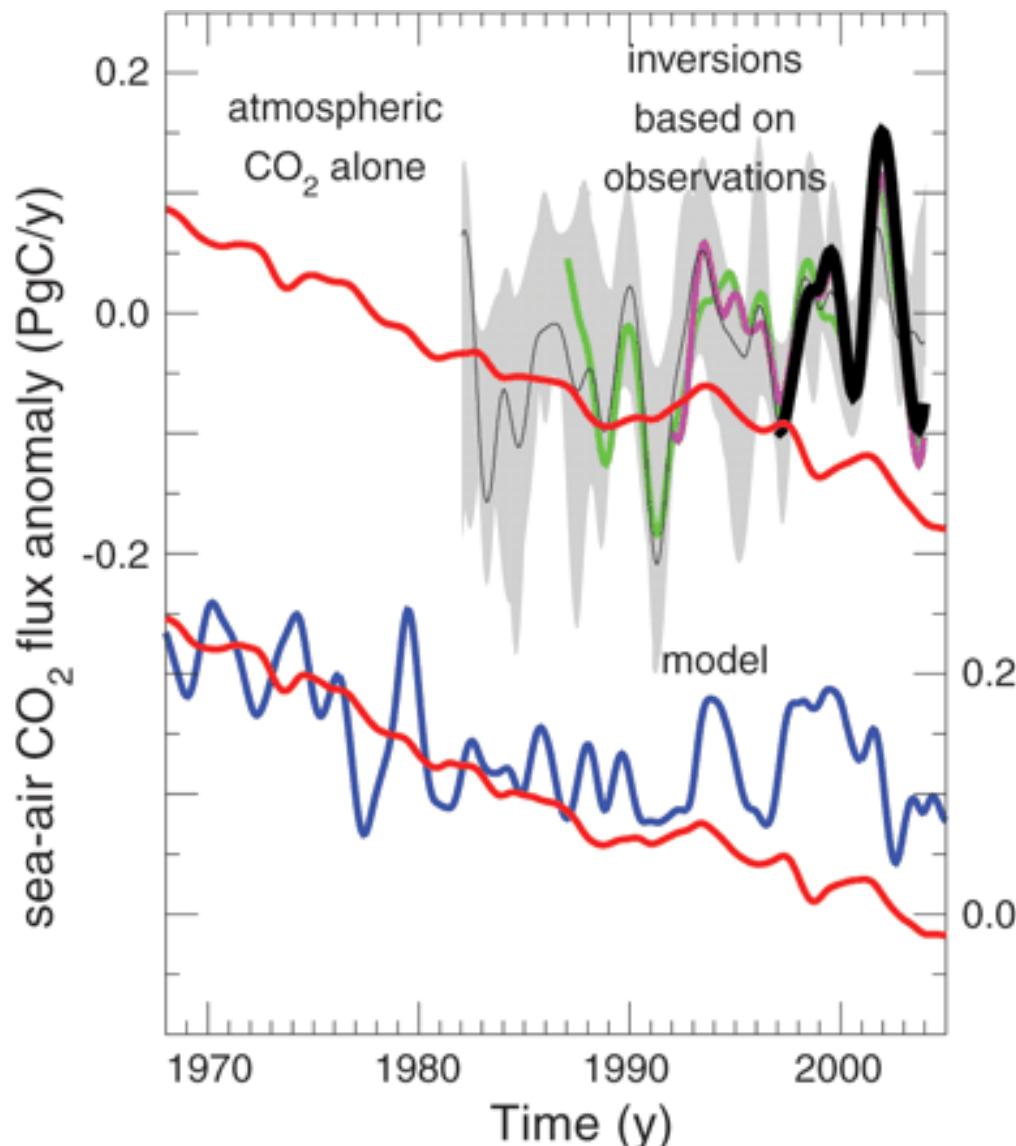


warming trend



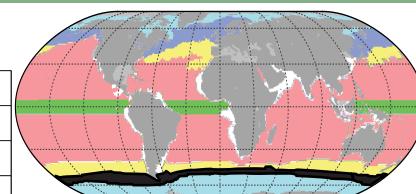
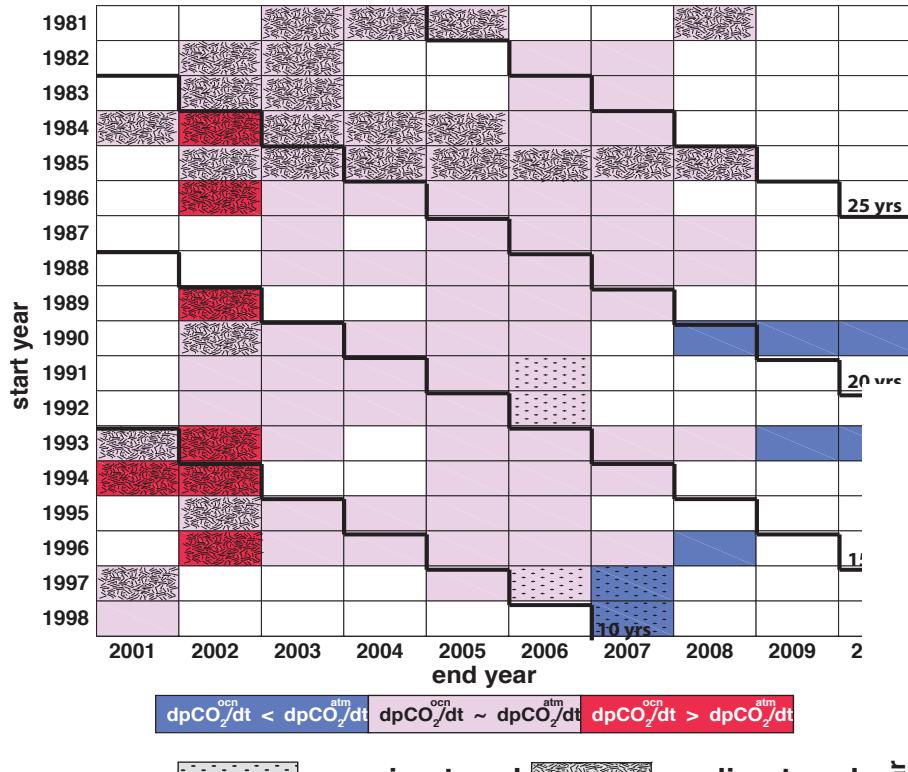
cooling trend

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

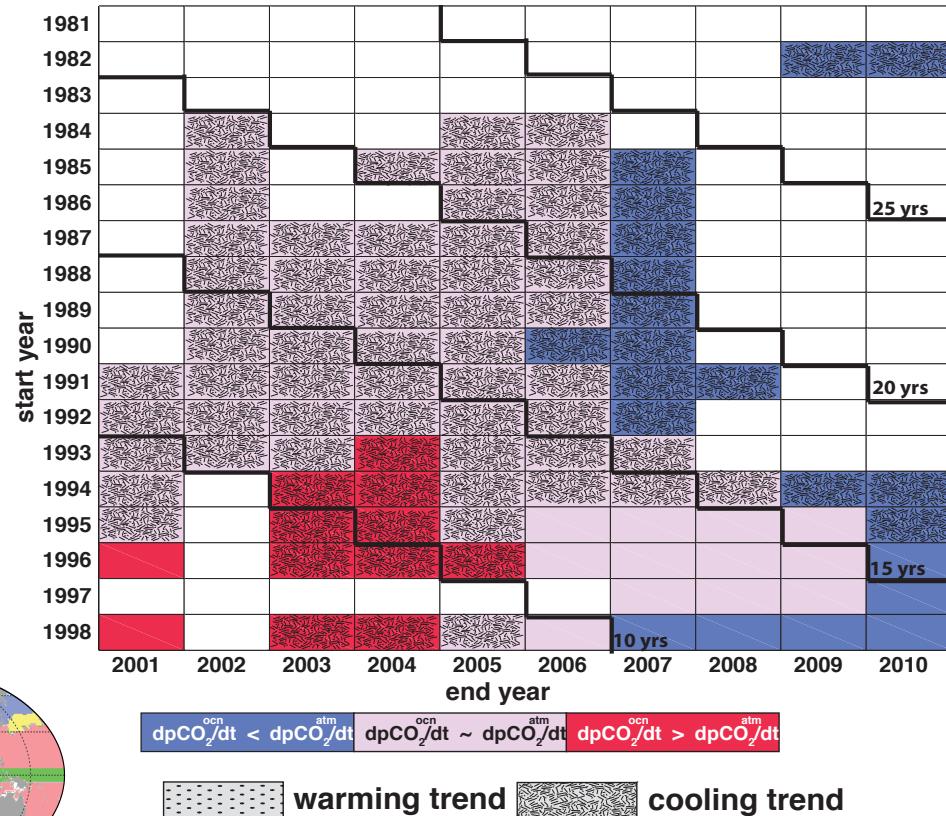


LeQuere et al. 2007, Science

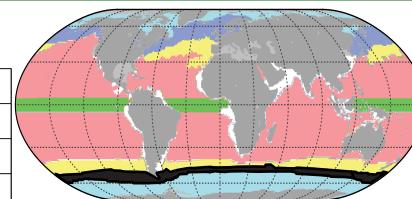
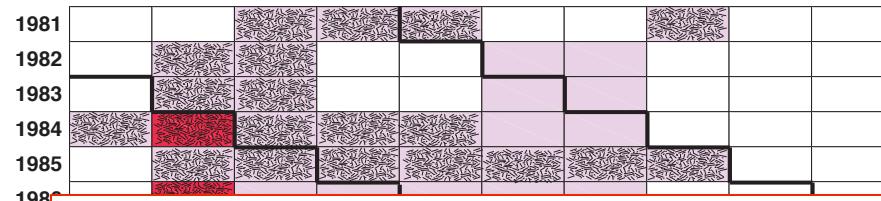
SO-SPSS



SO-ICE



SO-SPSS

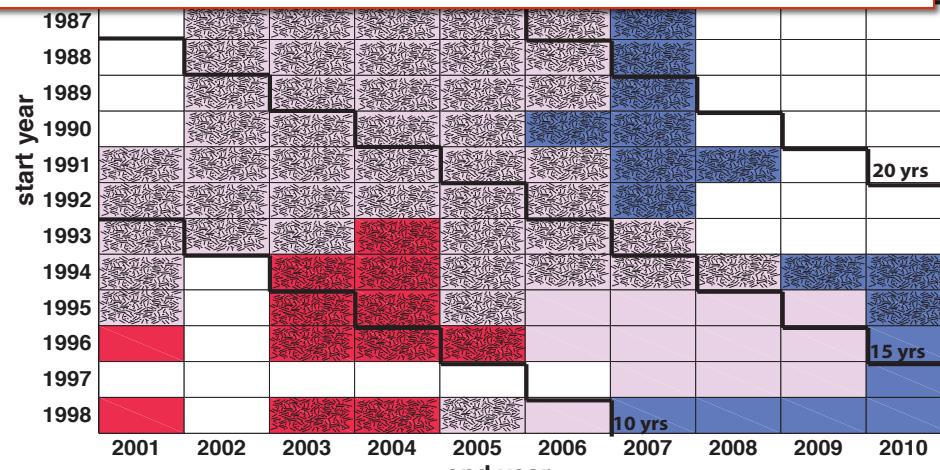


On timescales <20 years, fluctuations in $p\text{CO}_2^{\text{ocean}}$ vs $p\text{CO}_2^{\text{atm}}$ trends at high latitudes

Parallel or shallower trends for longer timescales in Southern Ocean - consistent or increasing $\Delta p\text{CO}_2$

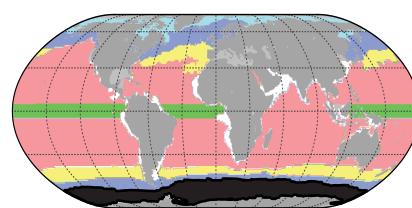
end year
 $\frac{\partial p\text{CO}_2}{\partial t}^{\text{ocean}} < \frac{\partial p\text{CO}_2}{\partial t}^{\text{atm}}$ $\frac{\partial p\text{CO}_2}{\partial t}^{\text{ocean}} \sim \frac{\partial p\text{CO}_2}{\partial t}^{\text{atm}}$ $\frac{\partial p\text{CO}_2}{\partial t}^{\text{ocean}} > \frac{\partial p\text{CO}_2}{\partial t}^{\text{atm}}$

warming trend cooling trend

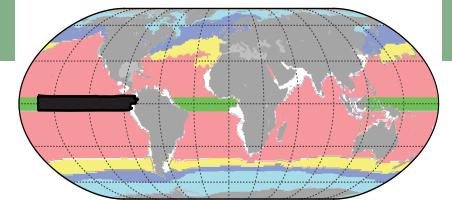


end year
 $\frac{\partial p\text{CO}_2}{\partial t}^{\text{ocean}} < \frac{\partial p\text{CO}_2}{\partial t}^{\text{atm}}$ $\frac{\partial p\text{CO}_2}{\partial t}^{\text{ocean}} \sim \frac{\partial p\text{CO}_2}{\partial t}^{\text{atm}}$ $\frac{\partial p\text{CO}_2}{\partial t}^{\text{ocean}} > \frac{\partial p\text{CO}_2}{\partial t}^{\text{atm}}$

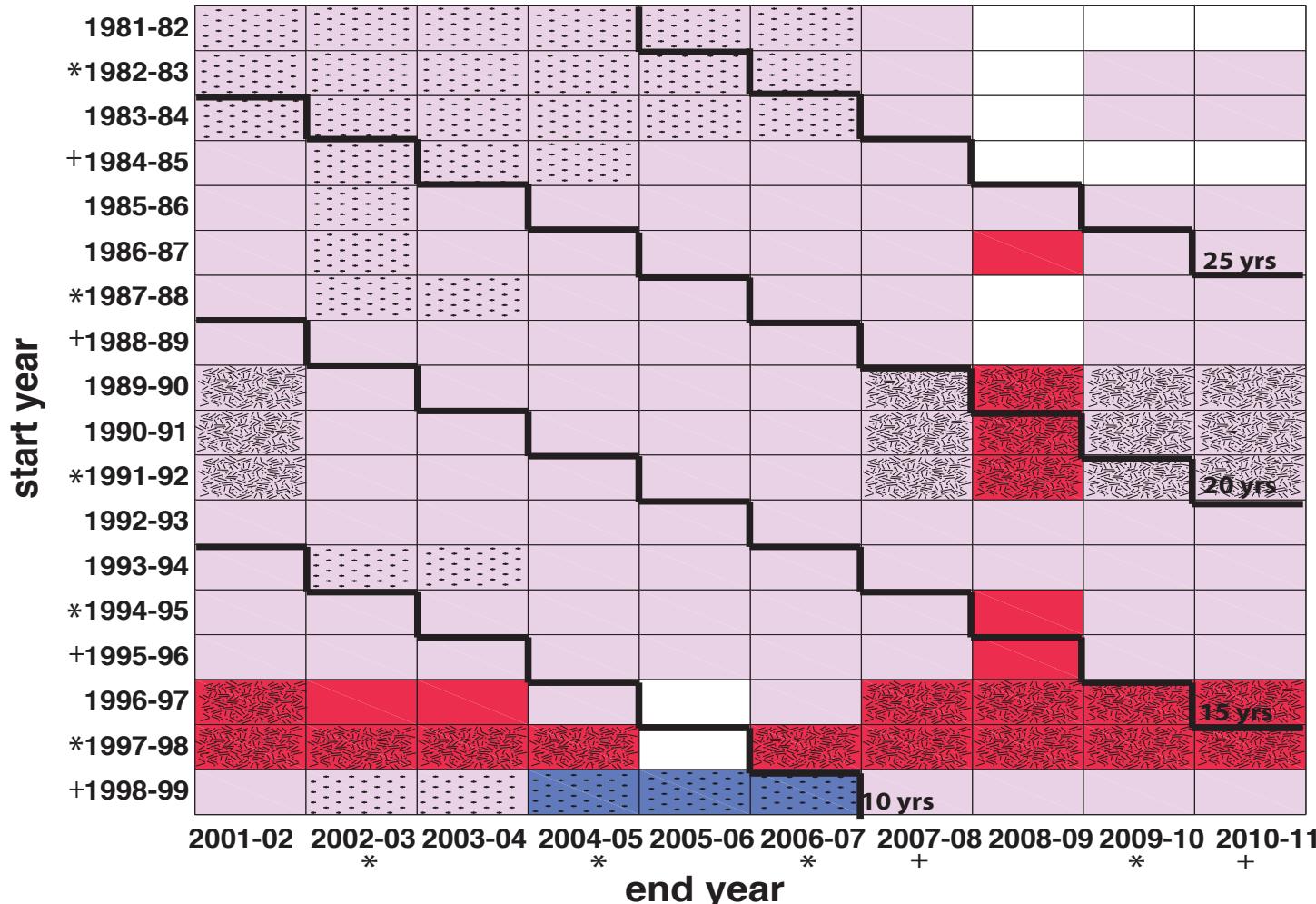
warming trend cooling trend



Equatorial Pacific



East Equatorial Pacific



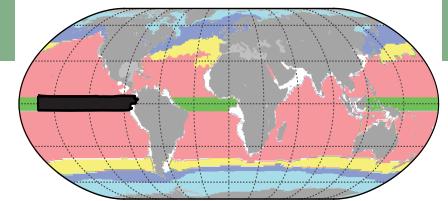
$\text{dpCO}_2^{\text{ocn}}/\text{dt} < \text{dpCO}_2^{\text{atm}}/\text{dt}$ $\text{dpCO}_2^{\text{ocn}}/\text{dt} \sim \text{dpCO}_2^{\text{atm}}/\text{dt}$ $\text{dpCO}_2^{\text{ocn}}/\text{dt} > \text{dpCO}_2^{\text{atm}}/\text{dt}$



warming trend



cooling trend



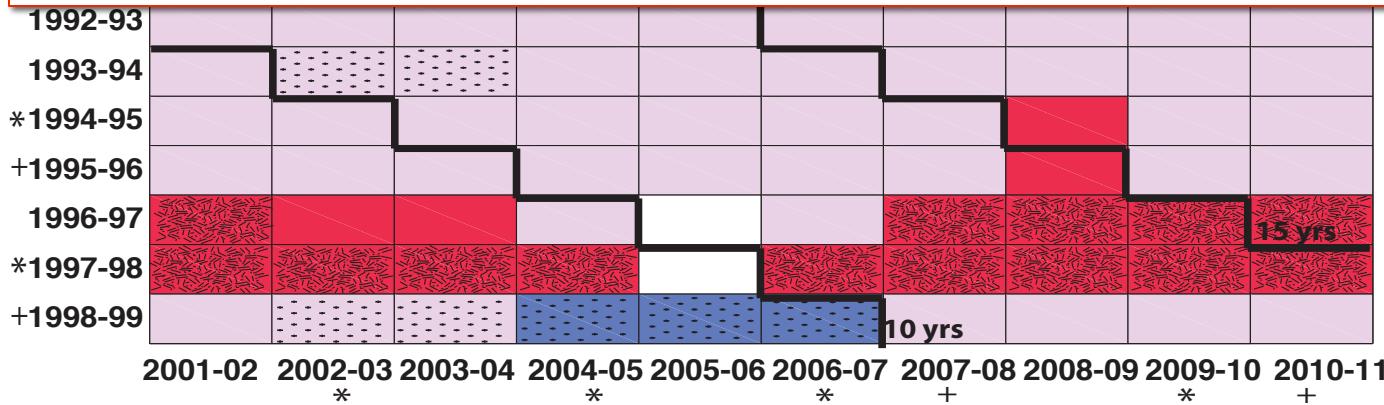
East Equatorial Pacific



Signals of strong El Niño (1997-98) and La Niña events (1998-99) are evident on timescales <15 yrs

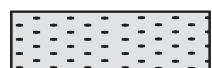
On timescales >15 yrs, nearly all $pCO_2^{s.ocean}$ trends are parallel to the atmosphere

start year



end year

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

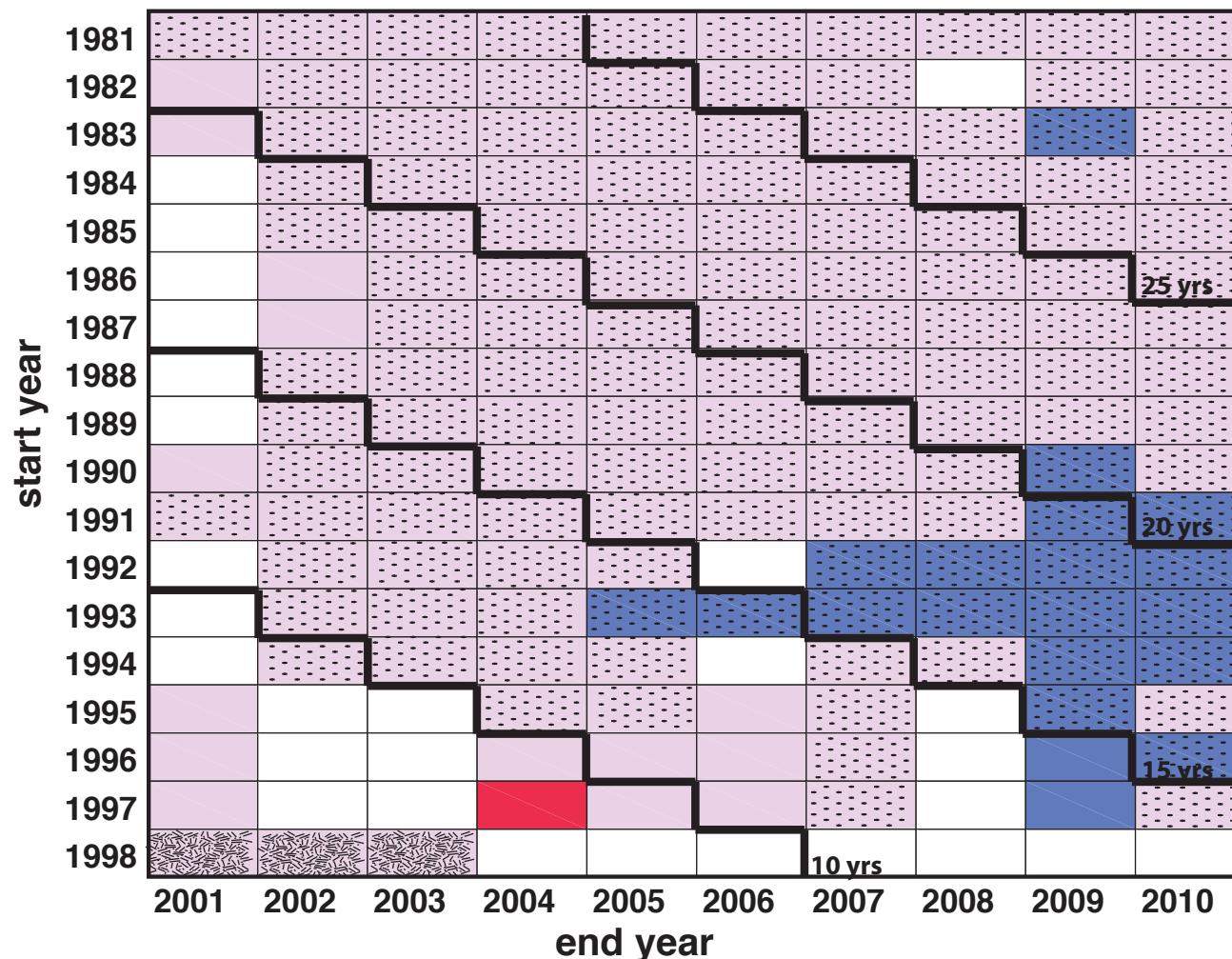
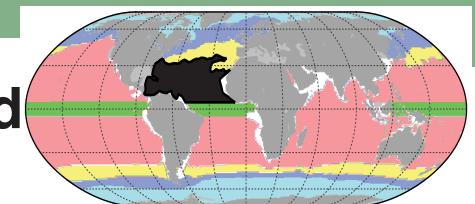


warming trend



cooling trend

North Atlantic Subtropical Permanently Stratified



| | | |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| $\text{dpCO}_2^{\text{ocn}}/\text{dt} < \text{dpCO}_2^{\text{atm}}/\text{dt}$ | $\text{dpCO}_2^{\text{ocn}}/\text{dt} \sim \text{dpCO}_2^{\text{atm}}/\text{dt}$ | $\text{dpCO}_2^{\text{ocn}}/\text{dt} > \text{dpCO}_2^{\text{atm}}/\text{dt}$ |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------|-------------------------------------------------------------------------------|



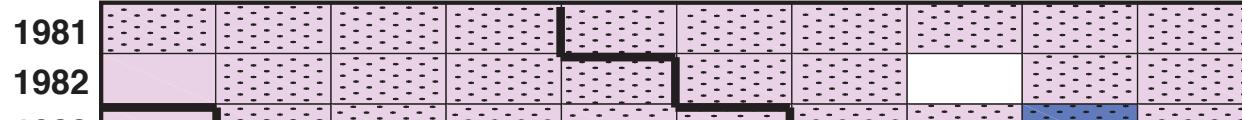
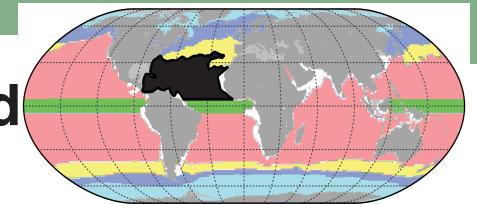
warming trend



cooling trend

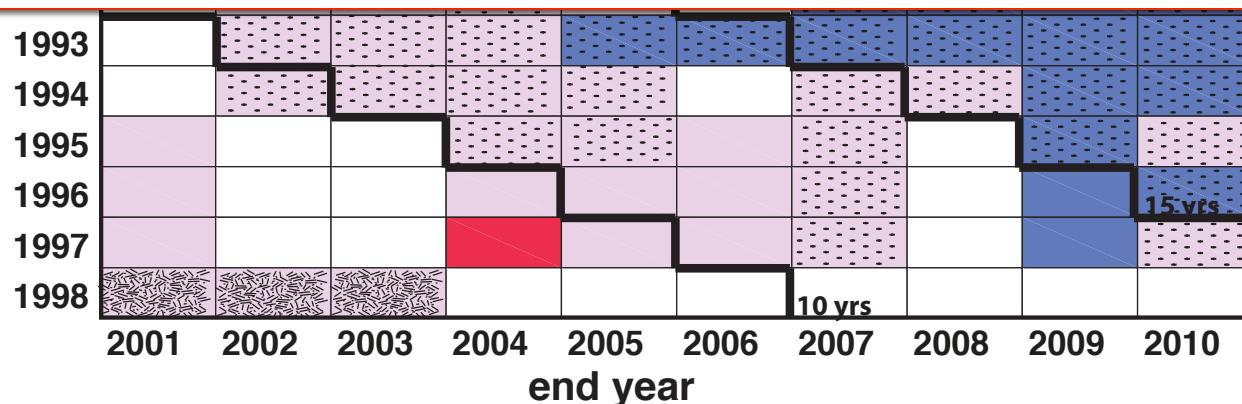
Subtropical North Atlantic

North Atlantic Subtropical Permanently Stratified

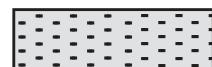


On timescales >20 yrs, $p\text{CO}_2^{\text{ocean}}$ trends parallel $p\text{CO}_2^{\text{atm}}$ trends in subtropical regions

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



| | | |
|-----------------------------------------------------------------|--------------------------------------------------------------------|-----------------------------------------------------------------|
| $d\text{pCO}_2^{\text{ocn}}/dt < d\text{pCO}_2^{\text{atm}}/dt$ | $d\text{pCO}_2^{\text{ocn}}/dt \sim d\text{pCO}_2^{\text{atm}}/dt$ | $d\text{pCO}_2^{\text{ocn}}/dt > d\text{pCO}_2^{\text{atm}}/dt$ |
|-----------------------------------------------------------------|--------------------------------------------------------------------|-----------------------------------------------------------------|

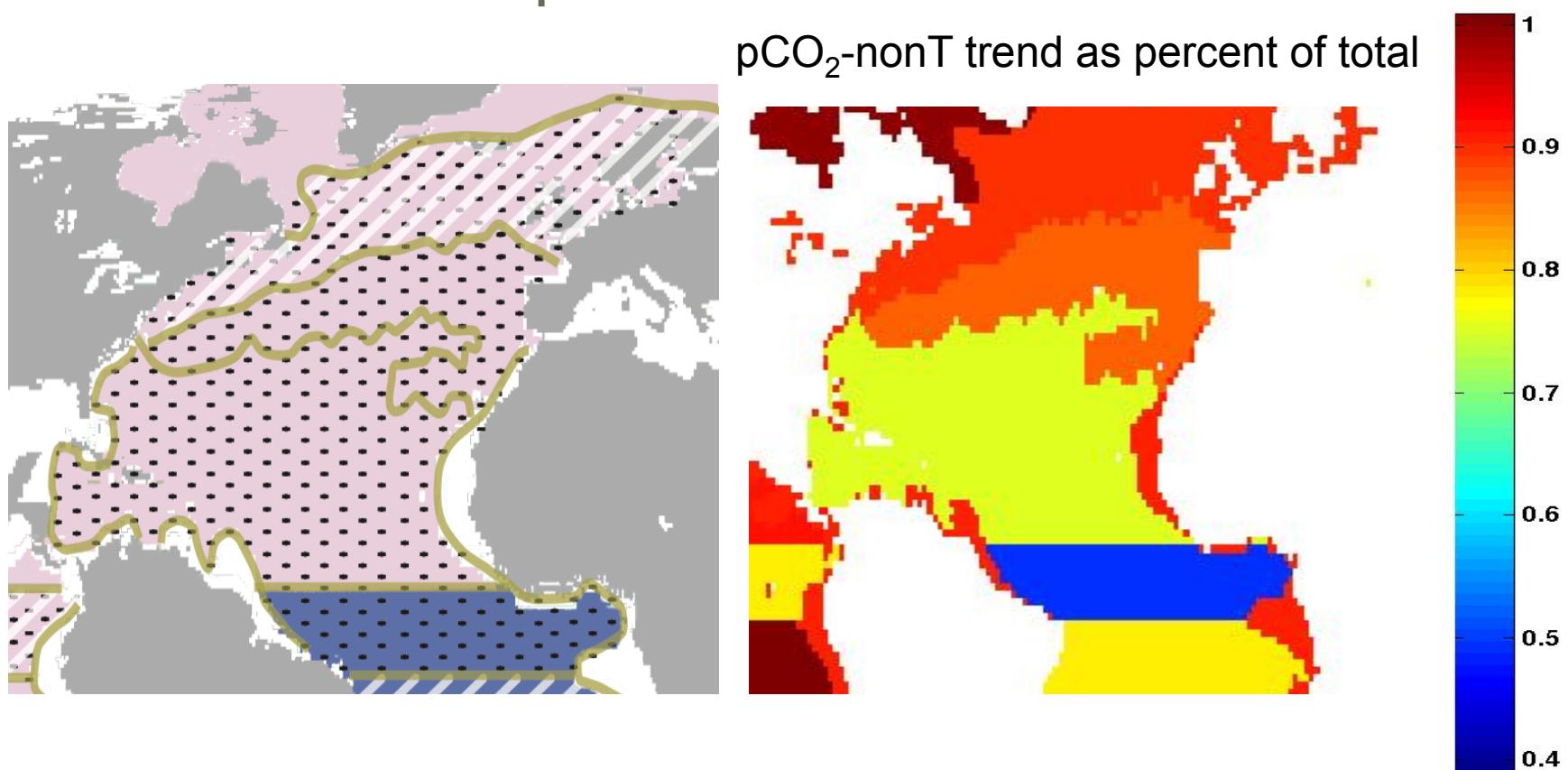


warming trend

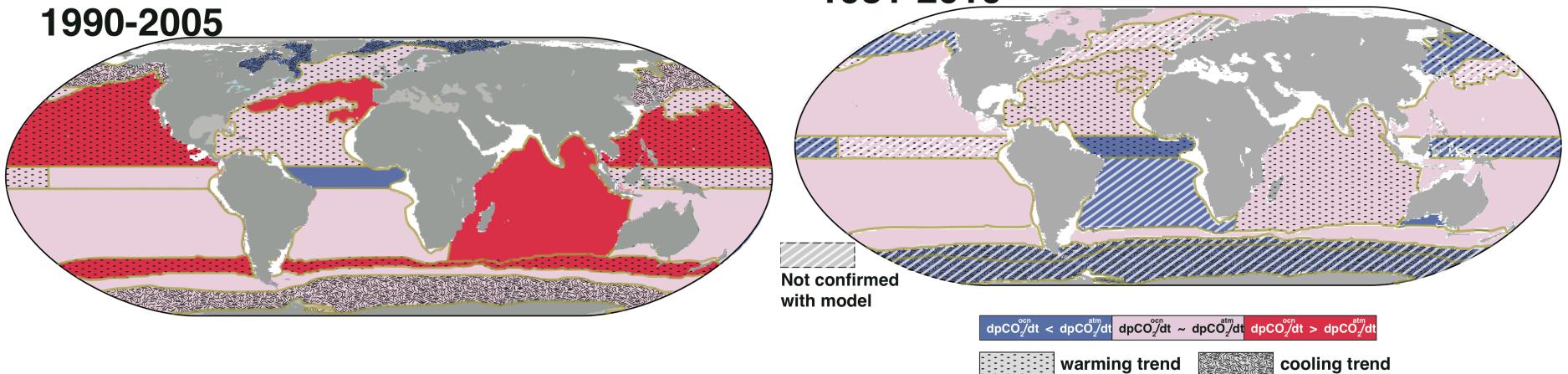


cooling trend

For 30 years, what is the relative impact of chemical trend ($p\text{CO}_2$ -nonT)?
Remainder is temperature.



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

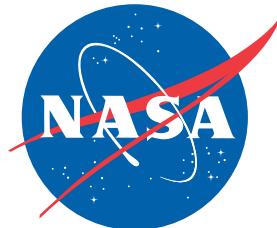
QUESTIONS?

gamckinley@wisc.edu

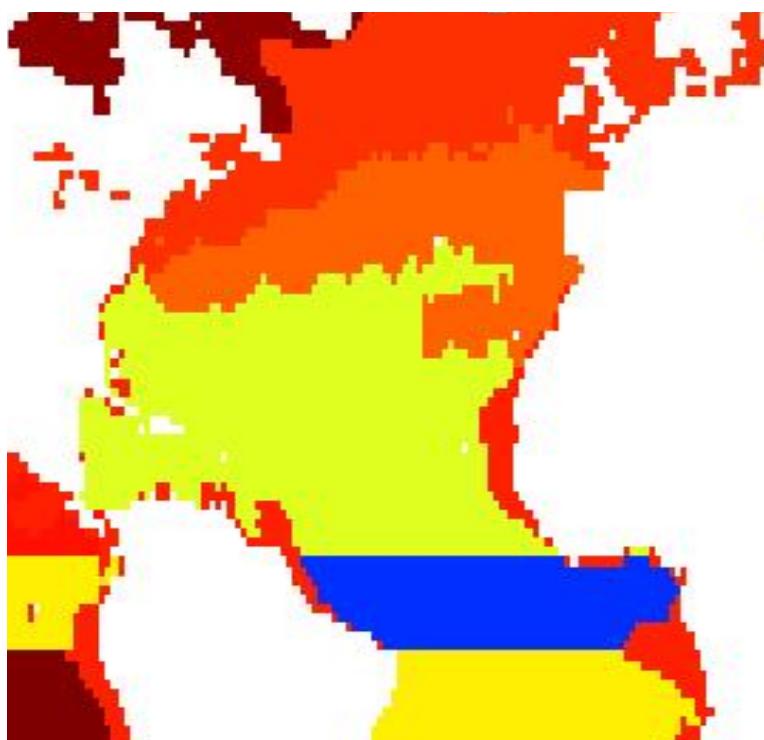
oceancarbon-aos.wisc.edu



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Climatic Research

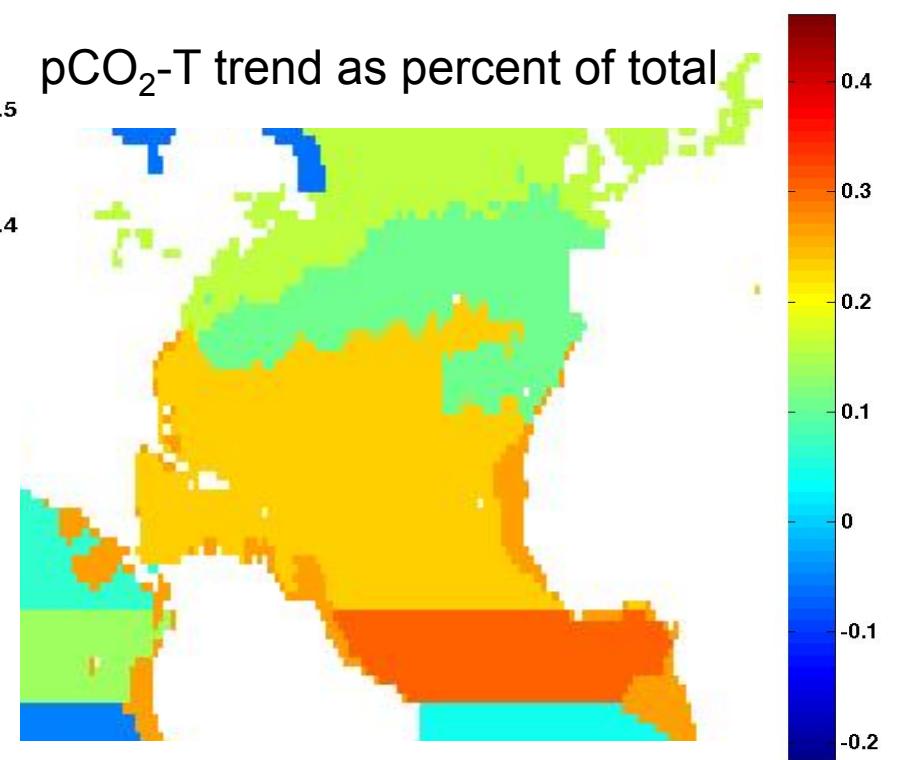


pCO₂-nonT trend as percent of total

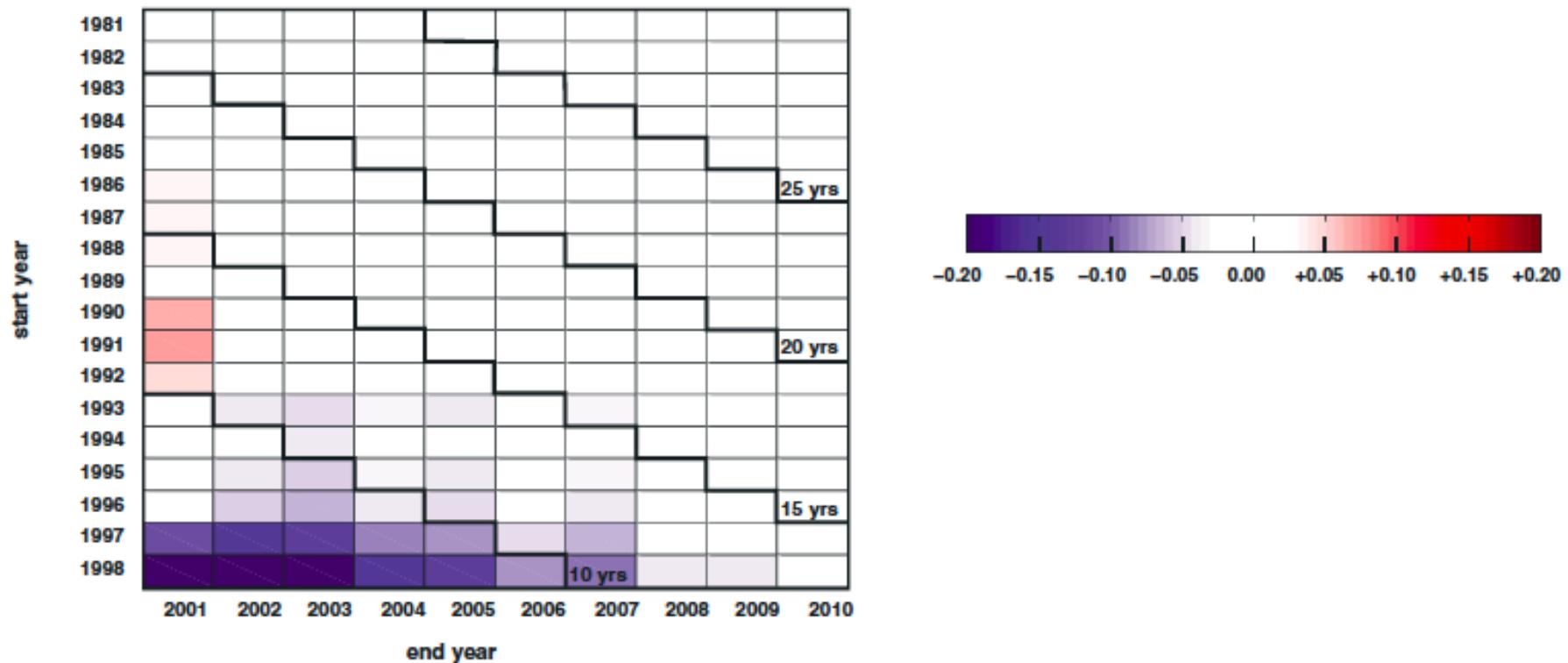


1981-2010

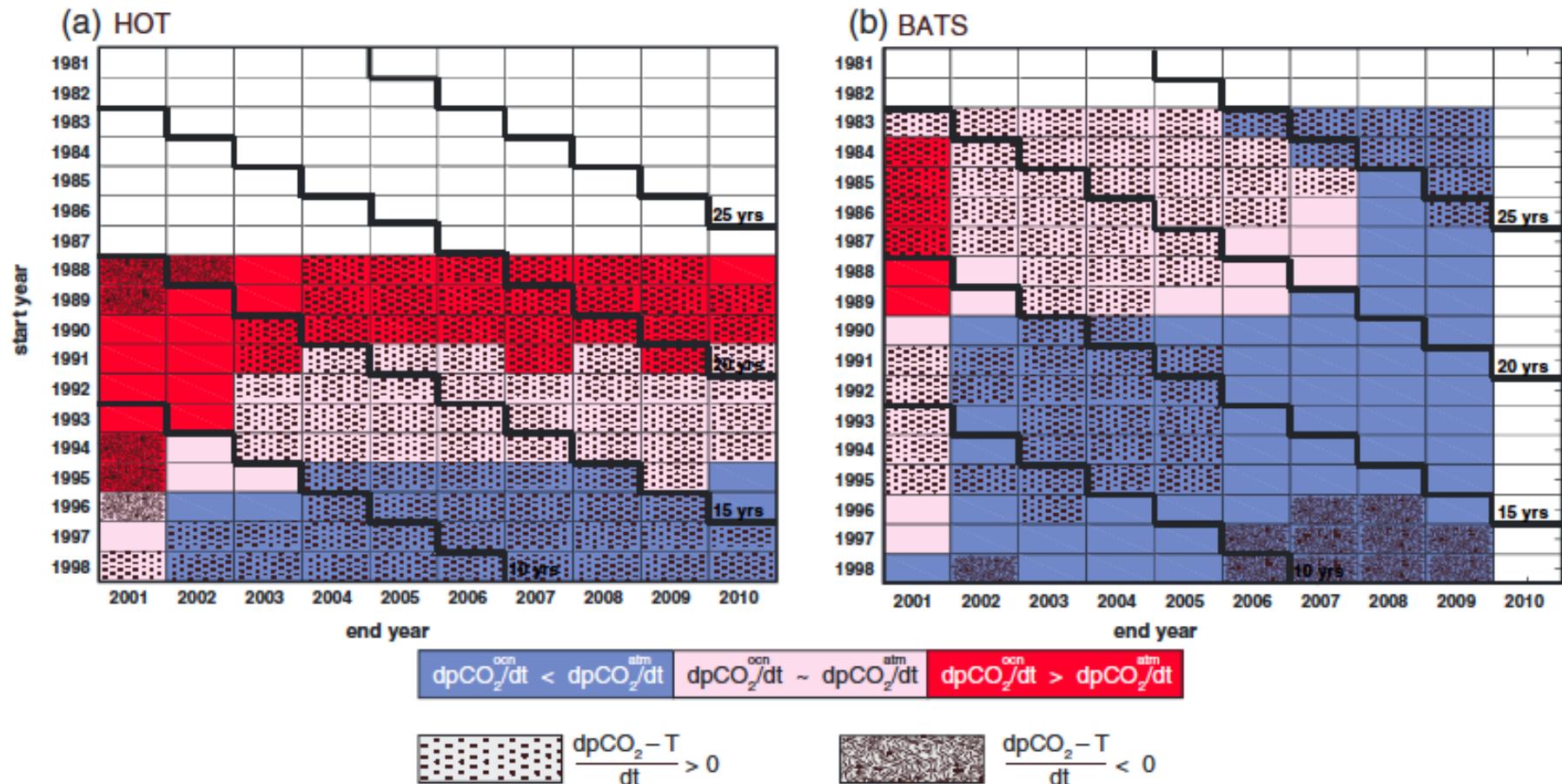
pCO₂-T trend as percent of total



SAM Index grid

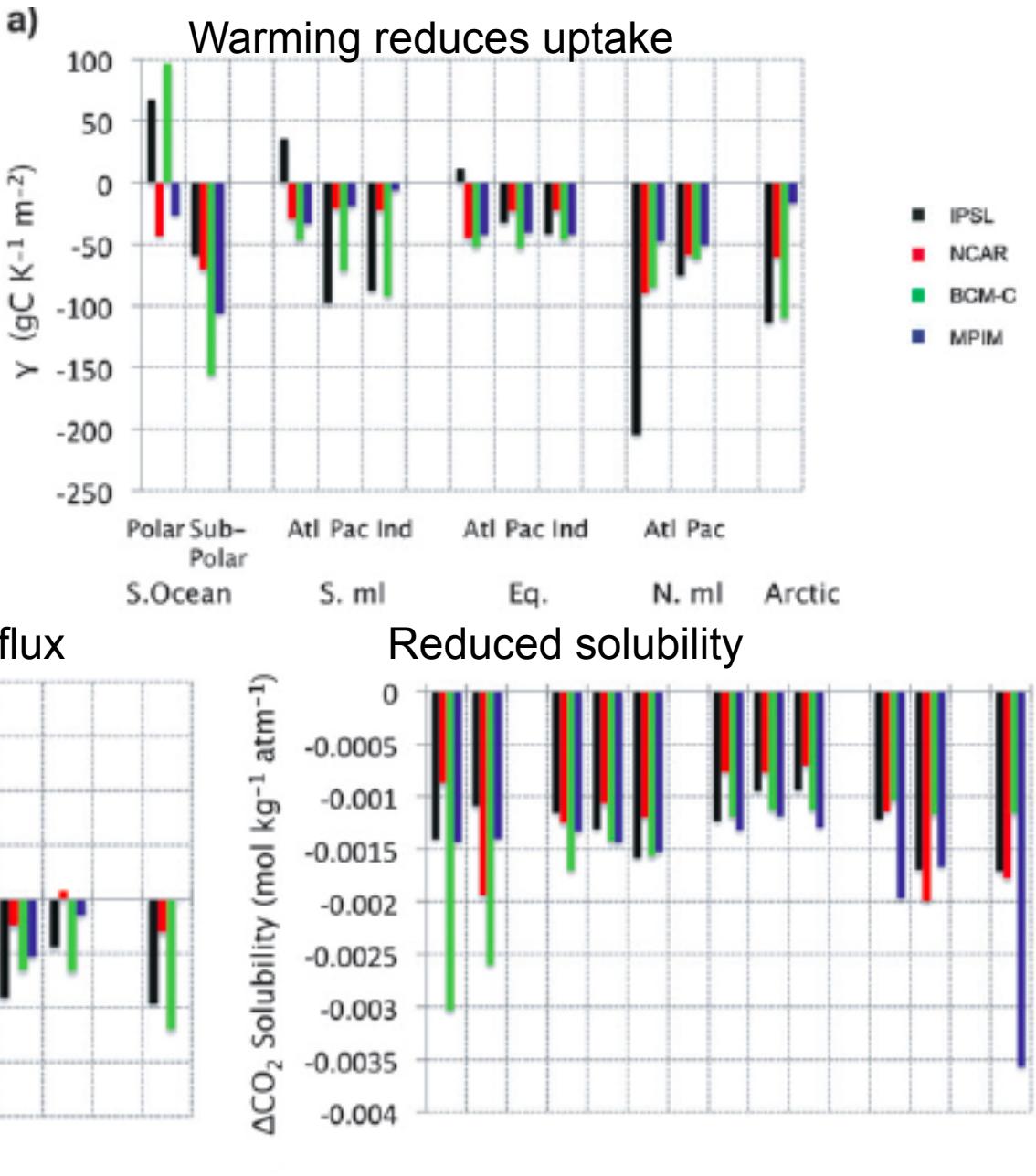


HOT and BATS grids



C⁴MIP

Response of carbon sink to warming 2010 to 2100



Roy et al. 2011, J. Climate