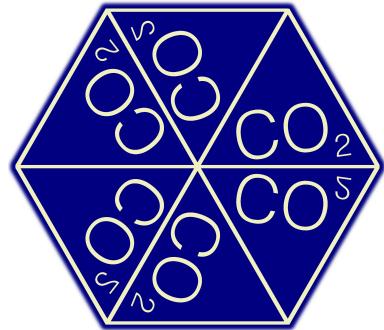


Constraining Sea-air CO₂ Fluxes from Surface-Ocean Carbon Data



Christian Rödenbeck

Max Planck Institute for Biogeochemistry, Jena

D. C. E. Bakker, P. Landschützer,
R. Keeling, and M. Heimann



In collaboration with

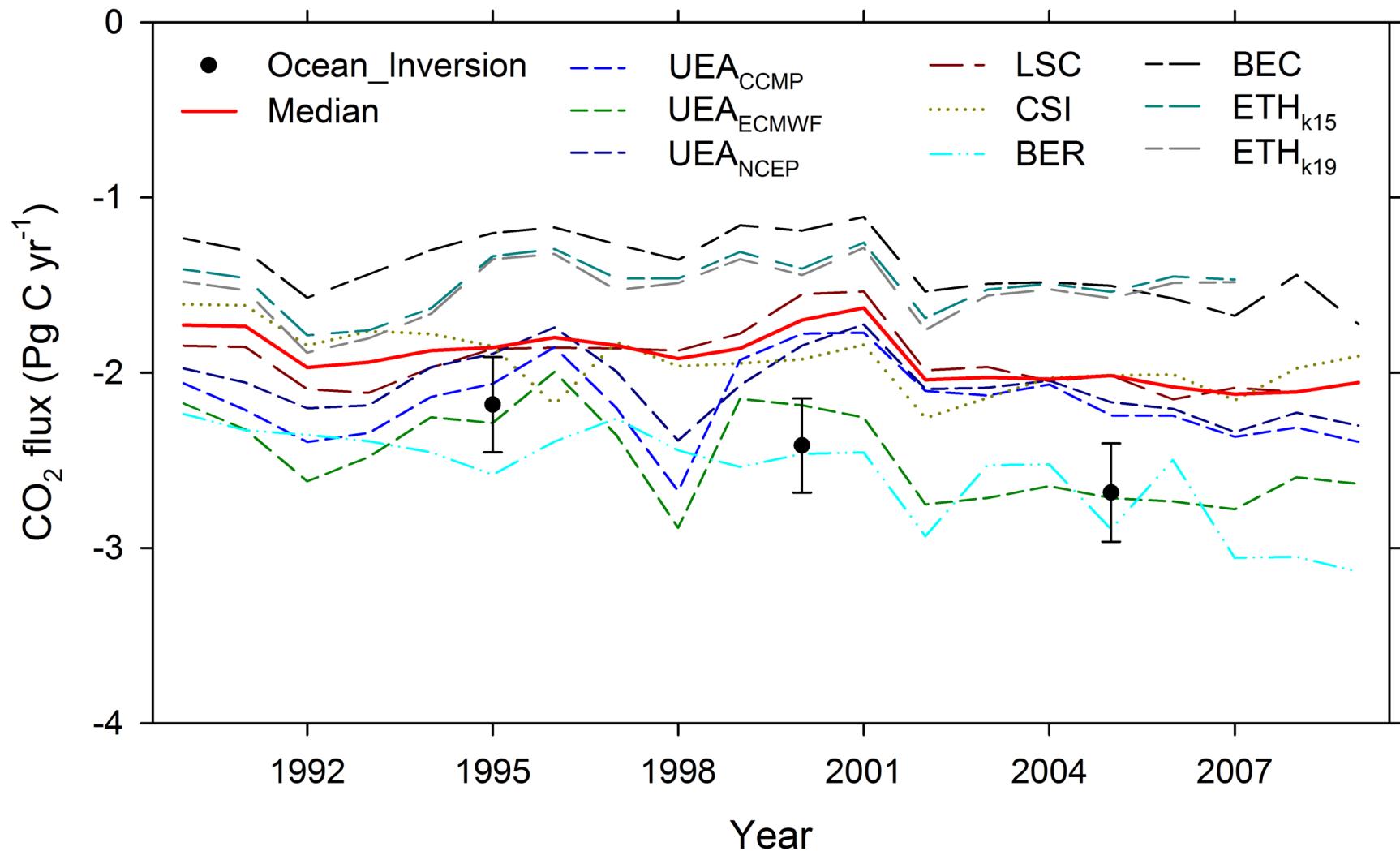
N. Gruber, Y. Iida, A.R. Jacobson, S. Jones,
N. Metzl, S. Nakaoka, A. Olsen, G.-H. Park,
P. Peylin, K.B. Rodgers, T.P. Sasse,
U. Schuster, J.D. Shutler, V. Valsala,
R. Wanninkhof, J. Zeng



Many thanks to:

Data contributors, DKRZ, CarboChange, IMBER / SOLAS

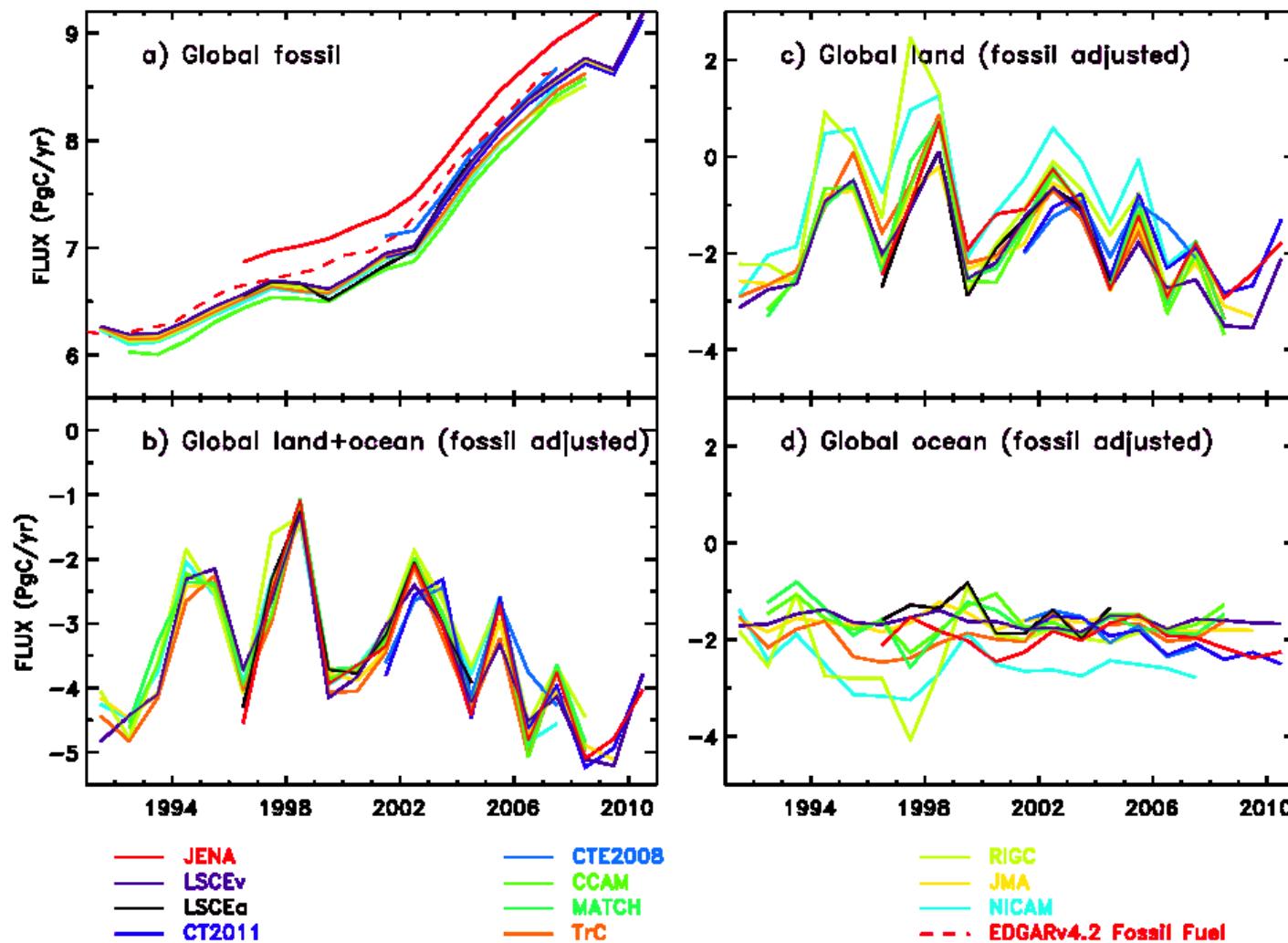
Motivation



Ocean process models

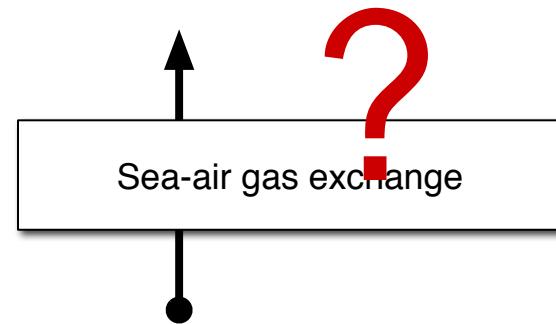
[Wanninkhof et al., RECCAP (2013)]

Motivation

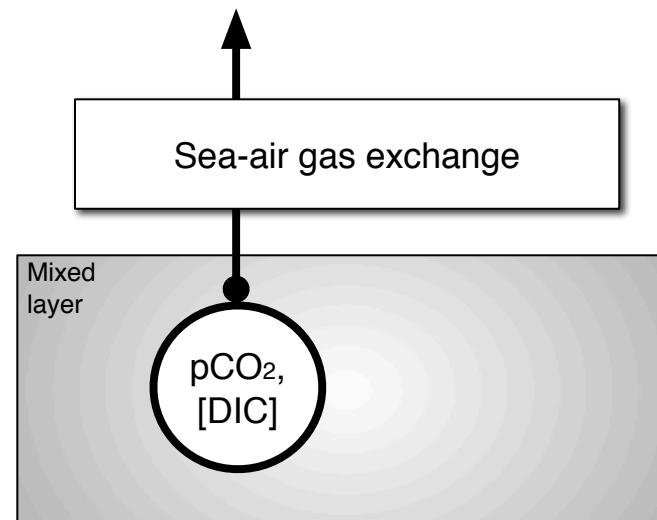


Atmospheric inversions

[Peylin et al., RECCAP (2013)]



Carbon



Carbon

Ocean carbon data collections:

- **SOCAT** v3 $p\text{CO}_2$ [www.socat.info/]
- **LDEO** v2014 $p\text{CO}_2$ [cdiac.ornl.gov/oceans/LDEO_Underway_Database/]
- **GLODAP** v2 [DIC], [Alk] [cdiac.ornl.gov/oceans/glodap/]

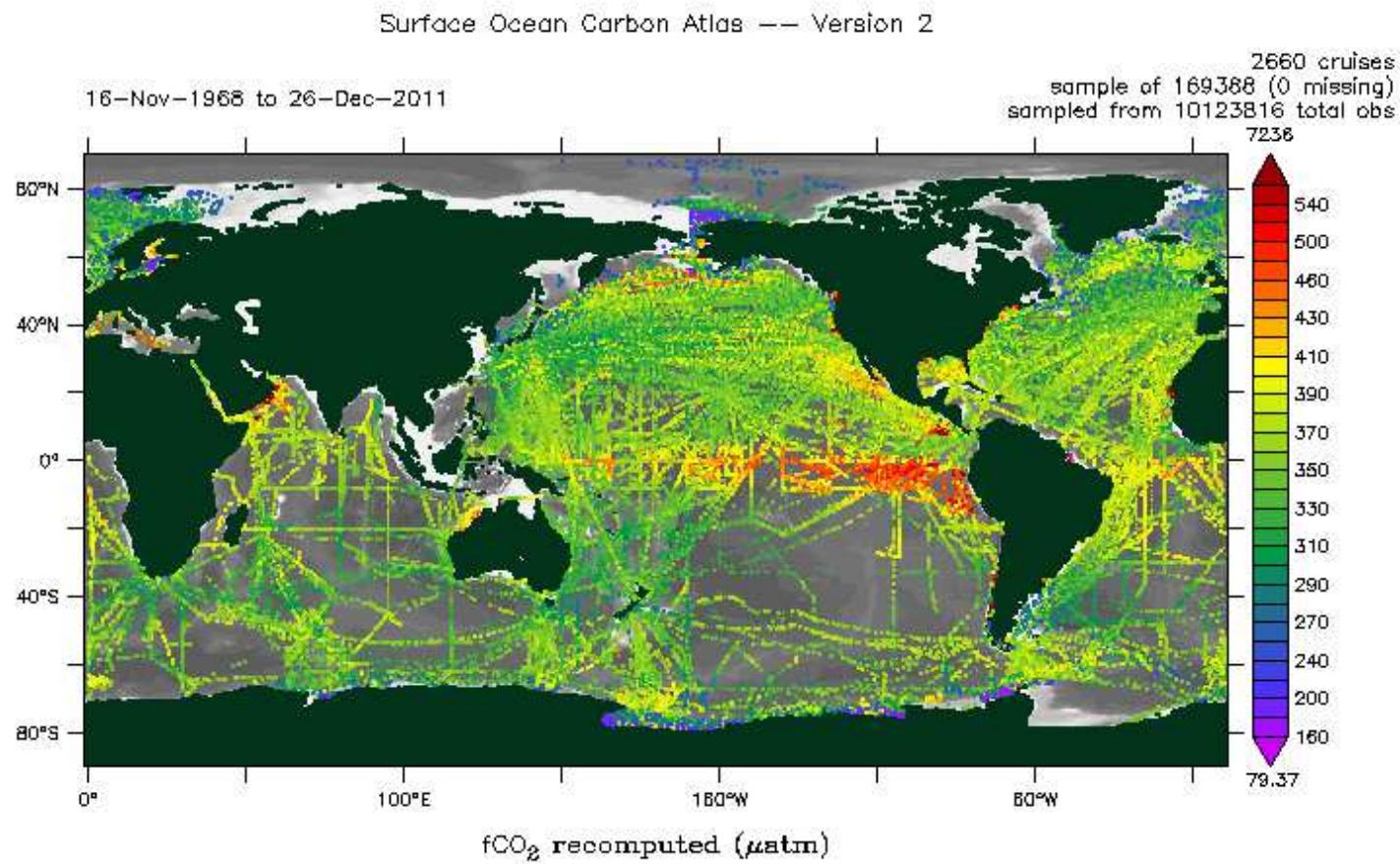
The screenshot shows the "Welcome to SOCAT" page. At the top right is the SOCAT logo with the tagline "SURFACE OCEAN CO₂ ATLAS". Below it is the heading "Welcome to SOCAT" and the subtext "A Collection of Underway Ocean CO₂ Observations Quality Controlled by the Science Community". To the left is the SOLAS logo. In the center is a map of the world's oceans showing a dense network of green lines representing measurement tracks. To the right is the IMBER logo. On the left side, there is a sidebar titled "Version 2 Data Products:" containing links to "Cruise Data Viewer", "Gridded Data Viewer", "Table of Cruises", "Data Download", "Data Use Policy", "Products using SOCAT", "SOCAT Credits", and "SOCAT Version 1.5". On the right side, there is a sidebar titled "SOCAT Documentation:" containing links to "About", "News", "Meetings", "Publications", and "Presentations". At the bottom, there is a "SOCAT Help:" sidebar with links to "Videos" and "Frequently Asked Questions". At the very bottom, there is footer text: "Follow @SOCAT_CO2", "Please contact submit@socat.info to report problems.", and two lines of small print about page hosting and design.

[Follow @SOCAT_CO2](#)

Please contact submit@socat.info to report problems.

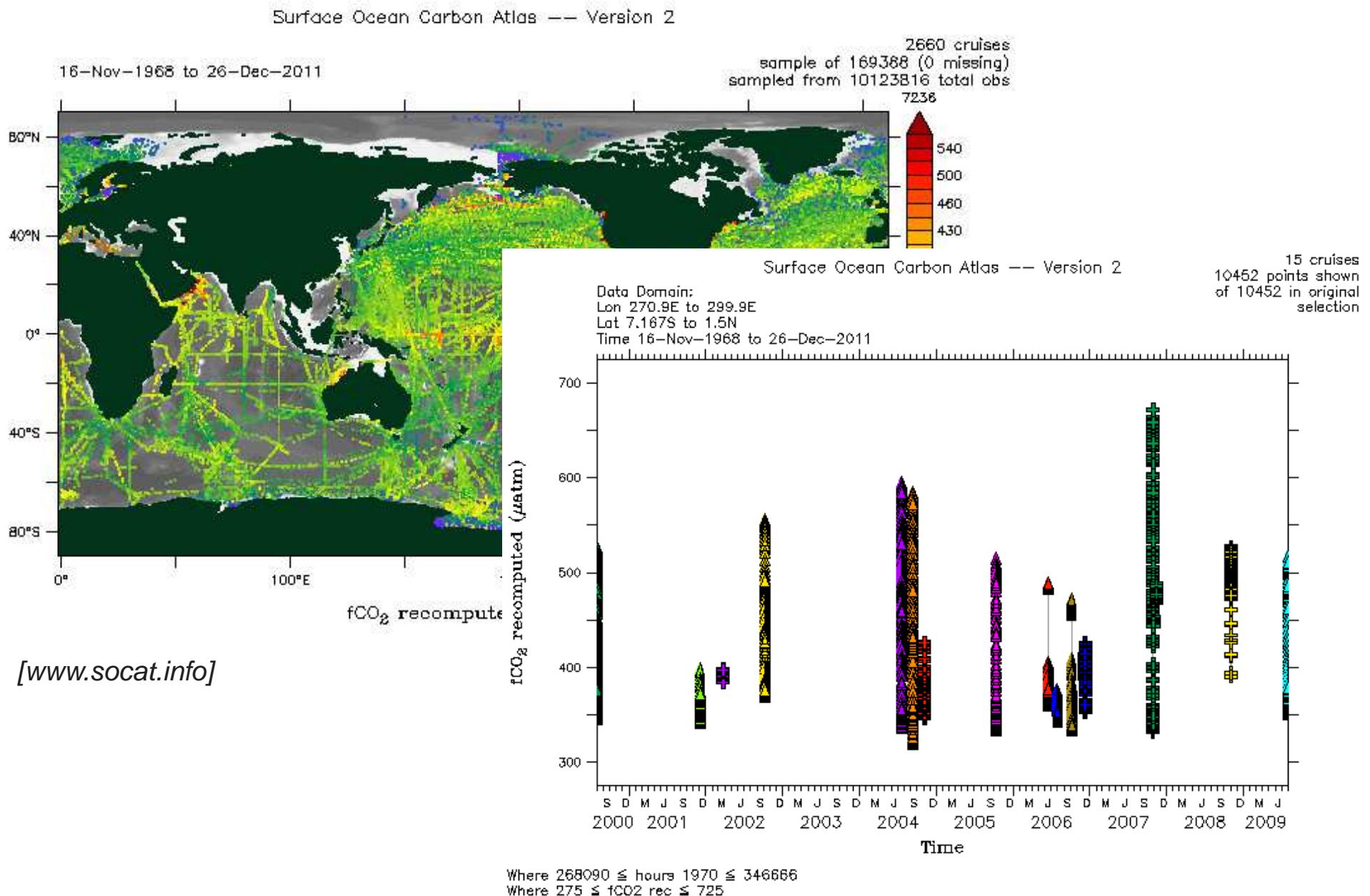
This page is hosted by [Benjamin Pfeil](#), University of Bergen/Bjerknes Centre for Climate Research/SKD, Bergen (Norway)
This page has been designed by Heather Koyuk, University of Washington/JISAO, Seattle (USA)

Data density / distribution

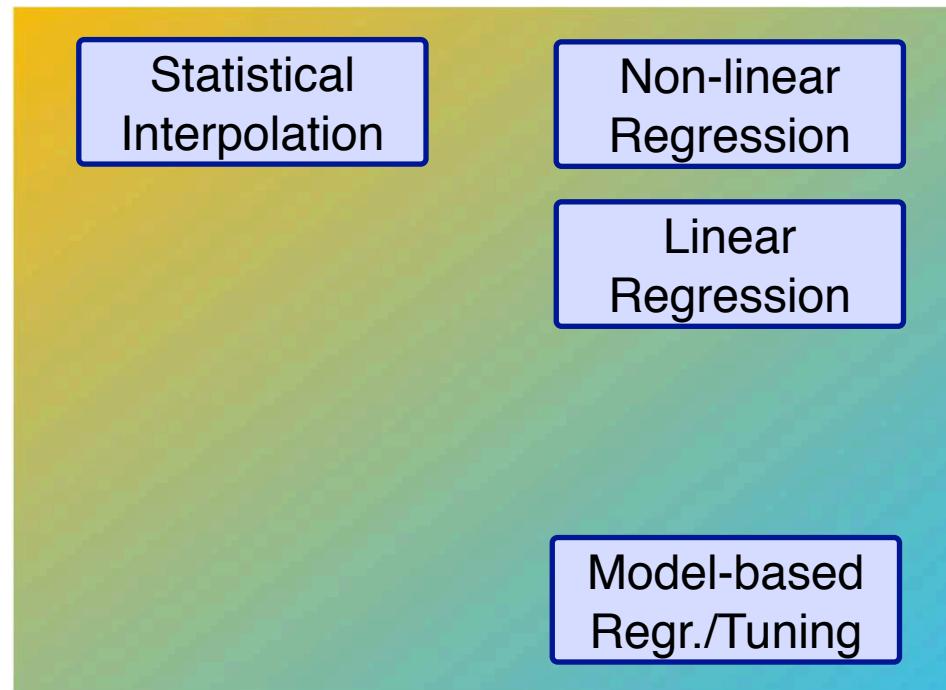


[www.socat.info]

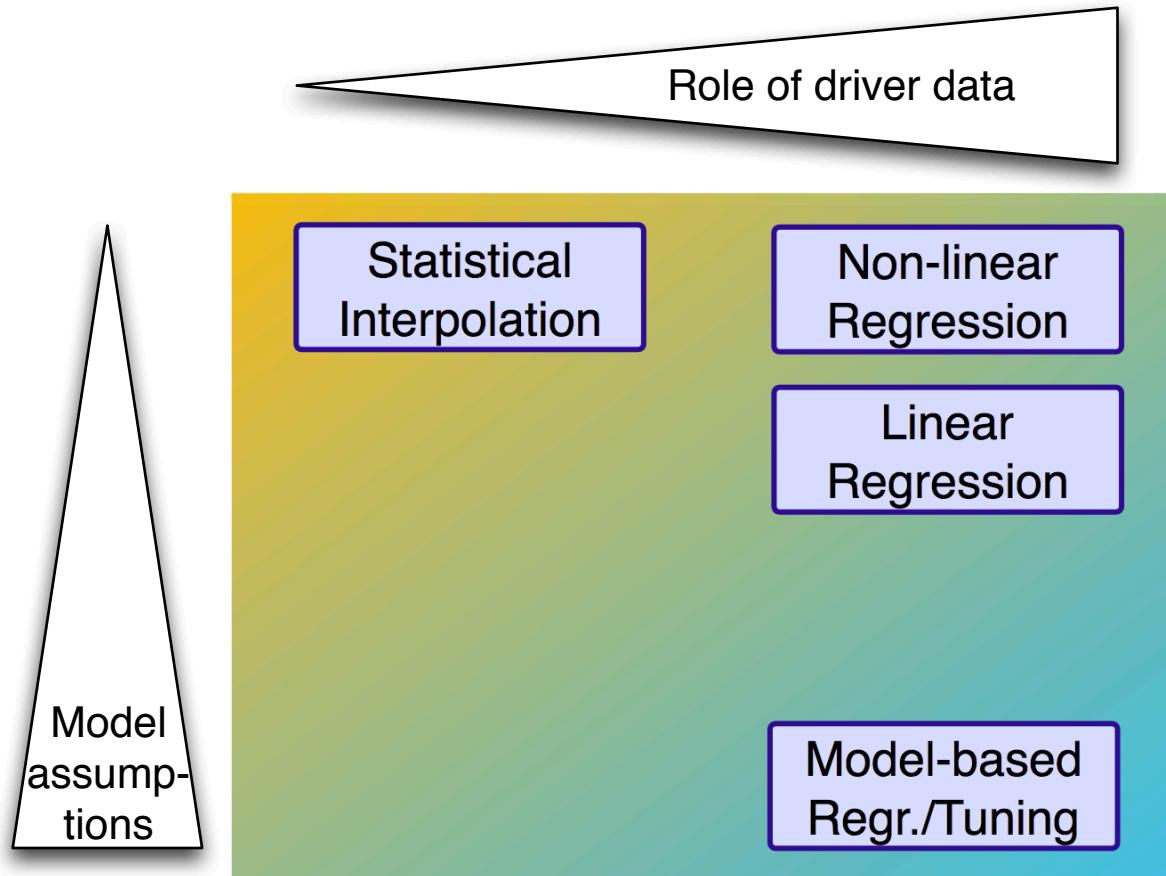
Data density / distribution



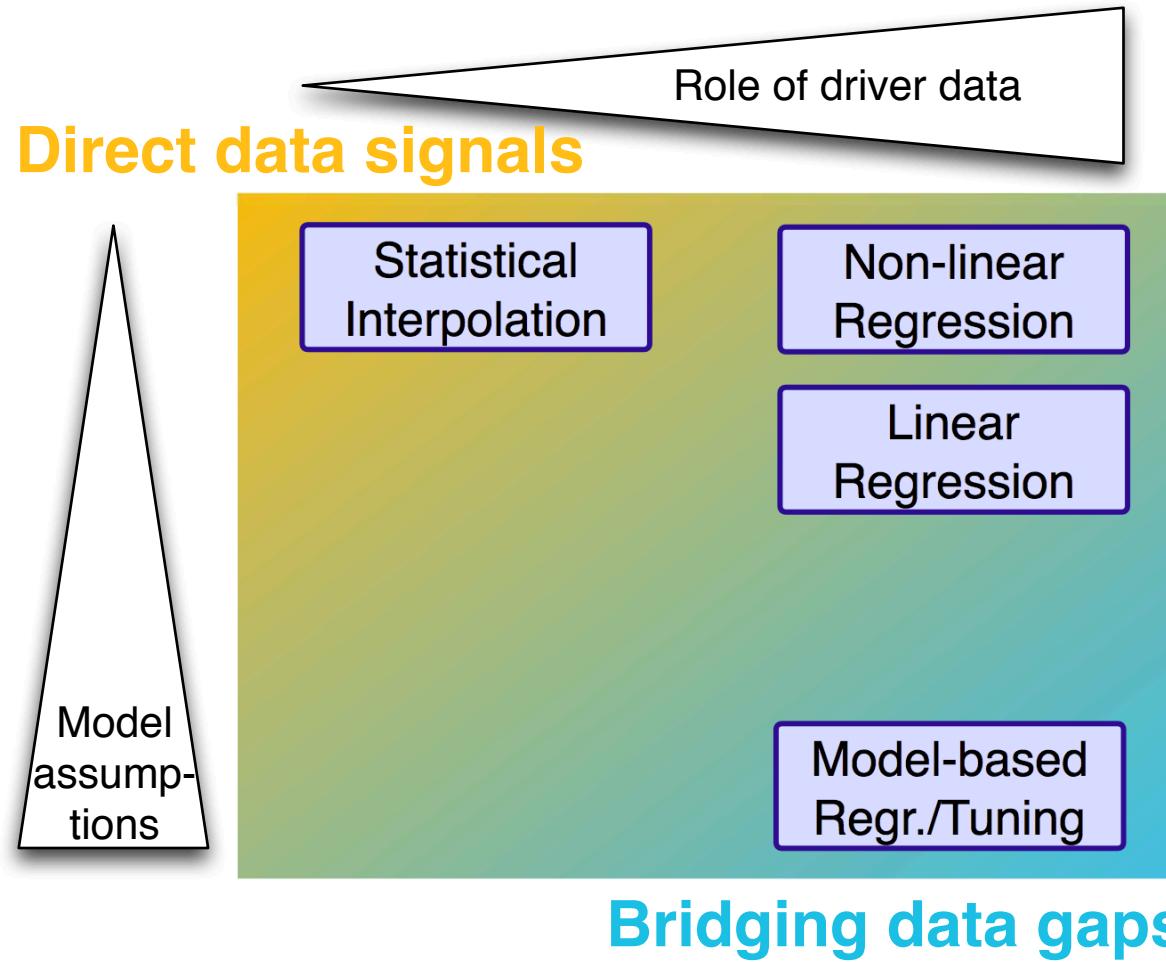
Mapping methods



Mapping methods



Mapping methods



- Interesting complementarity
- Extracting robust features

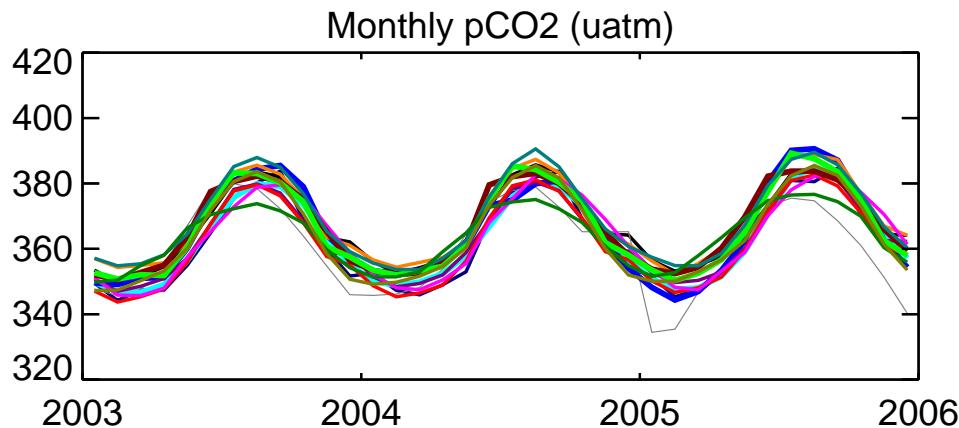
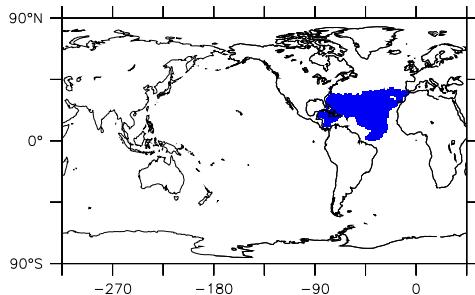
SOCOM: Collating 14 mapping methods



First results [Rödenbeck et al., BG (2015)]

Legend:

- UEA-SI
- OceanFlux-SI
- Jena-MLS
- CU-SCSE
- AOML-EMP
- UEx-MLR
- JMA-MLR
- UNSW-SOMLO
- ETH-SOMFFN
- CARBONES-NN
- NIES-SOM
- NIES-NN
- PU-MCMC
- NIES-OTTM



Seasonality:

Most methods roughly agree
on phasing and amplitude

(also to Takahashi et al., 2009)

→ Seasonality well constrained from data

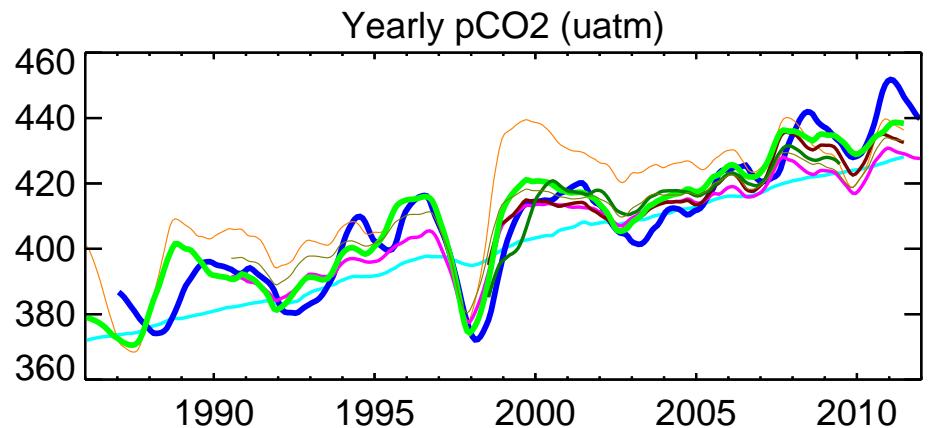
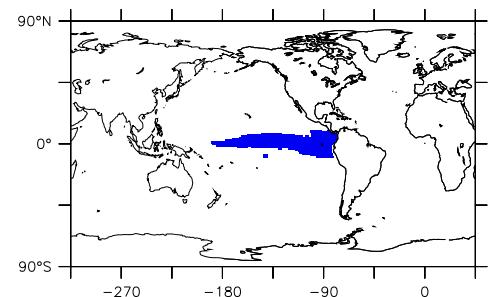
First results [Rödenbeck et al., BG (2015)]

Interannual Variations (IAV):

- secular rise
- Tropical Pacific:
 - * Biome with largest IAV
 - * Link to ENSO

Legend:

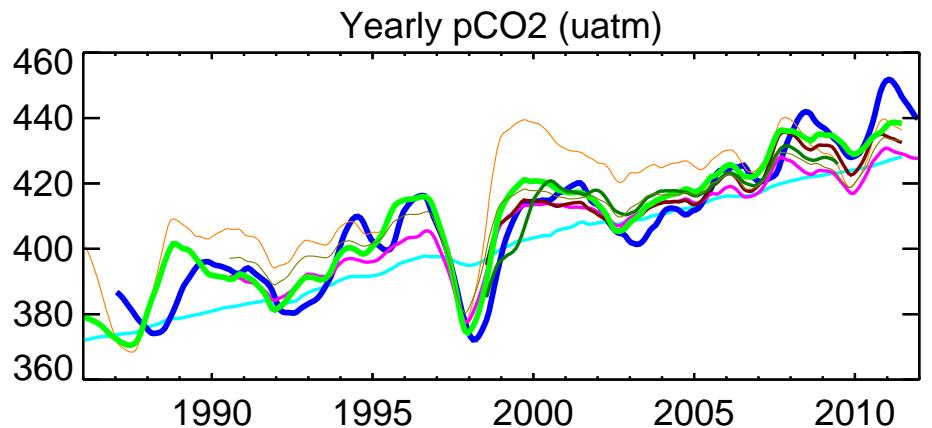
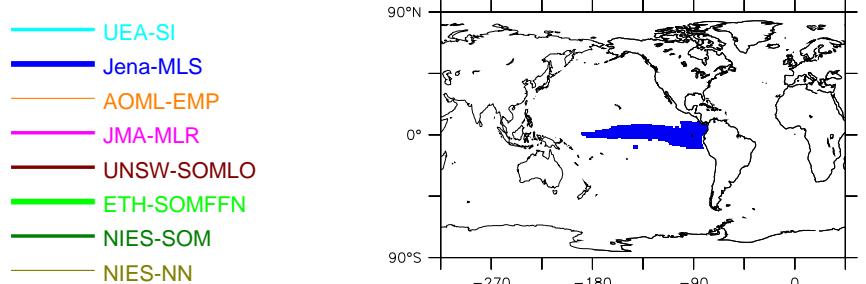
- UEA-SI
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First results [Rödenbeck et al., BG (2015)]

Interannual Variations (IAV):

- secular rise
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 - * Biome with largest IAV
 - * Link to ENSO



*Methods selected / weighted by
relative IAV mismatch to SOCATv2*

better match to data
→ also closer mutual agreement

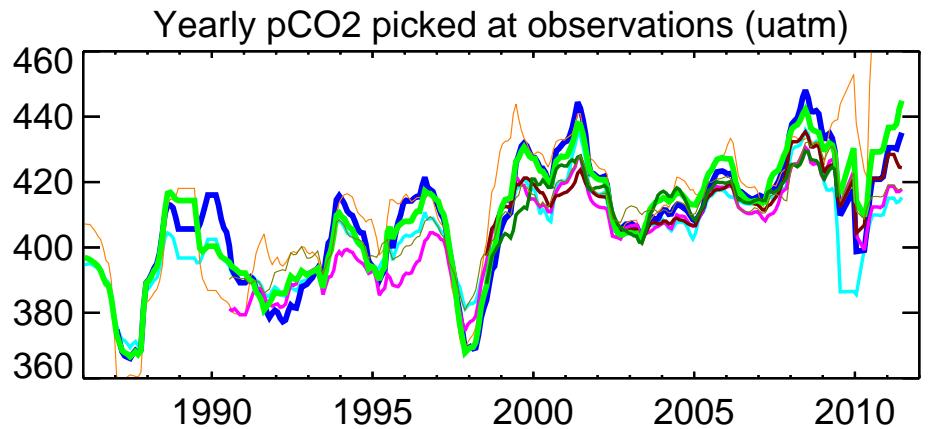
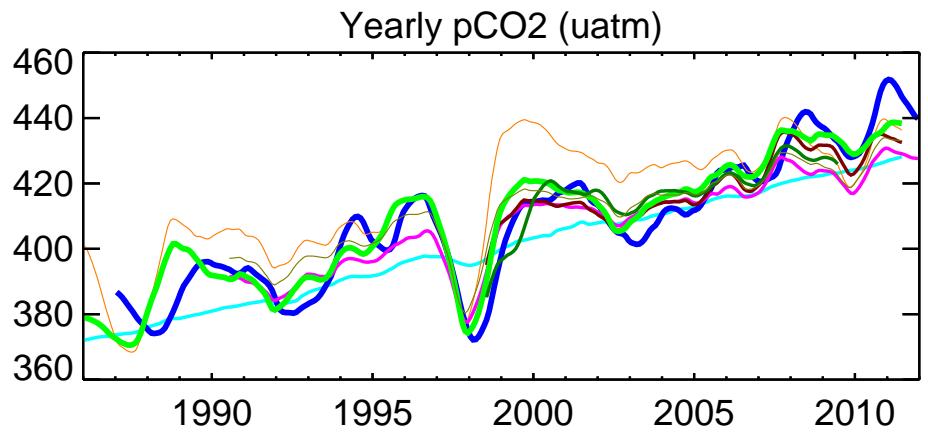
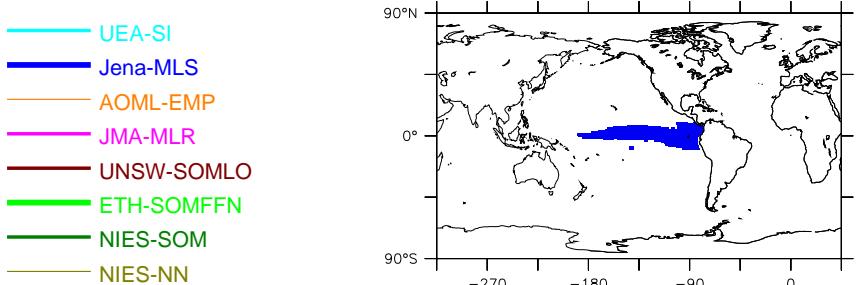
First results [Rödenbeck et al., BG (2015)]

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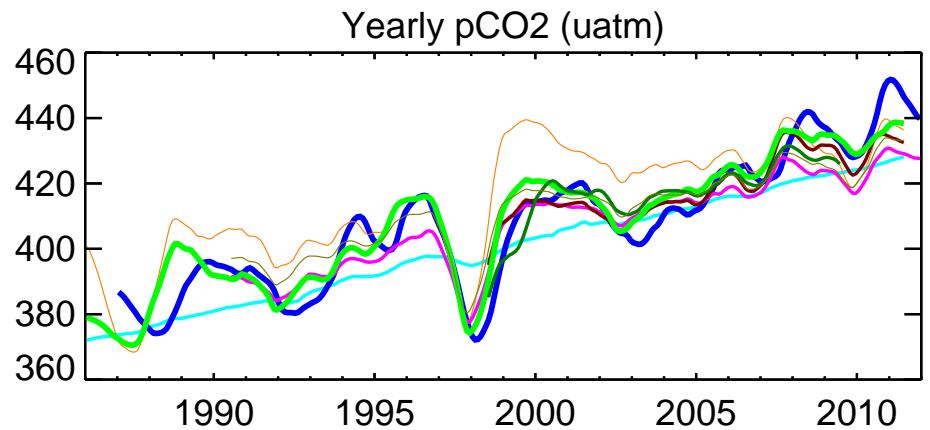
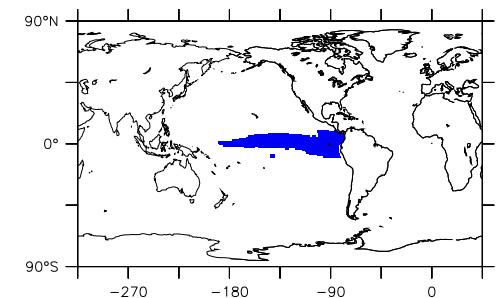
Data-covered pixels only: (SOCAT v2)

- Smaller ensemble spread
- Altered time variations
 - sampling bias (seasonally, spatially)
 - challenge for mapping



First results: Sea-air CO₂ fluxes [Rödenbeck et al., BG (2015)]

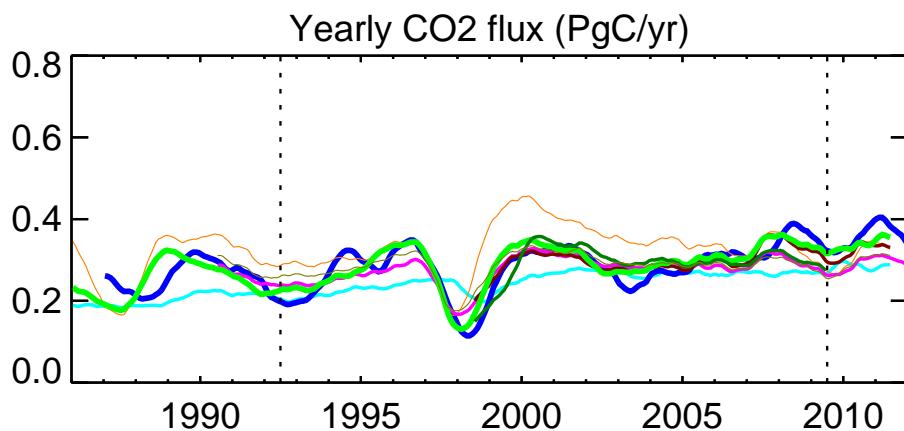
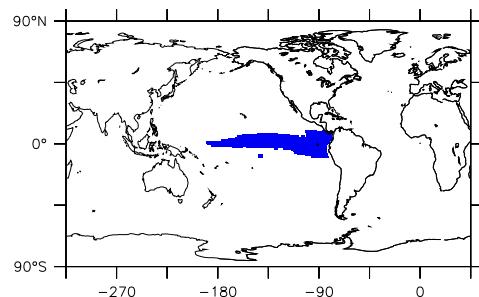
- UEA-SI
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- NIES-SOM
- NIES-NN



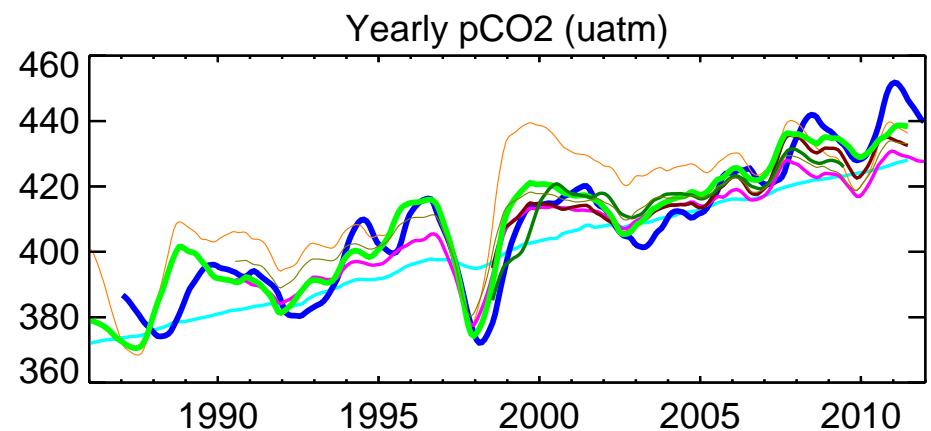
First results: Sea-air CO₂ fluxes

[Rödenbeck et al., BG (2015)]

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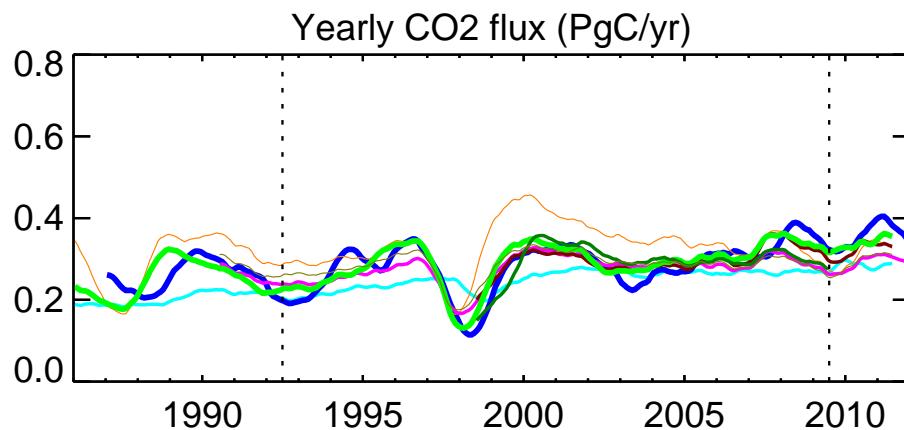
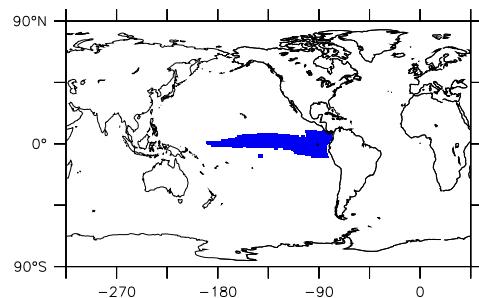
$$f = k(u^2) \cdot \varrho L \cdot (p\text{CO}_2 - p\text{CO}_2^{\text{atm}})$$

→ Flux IAV dominated by pCO₂ IAV

First results: Sea-air CO₂ fluxes

[Rödenbeck et al., BG (2015)]

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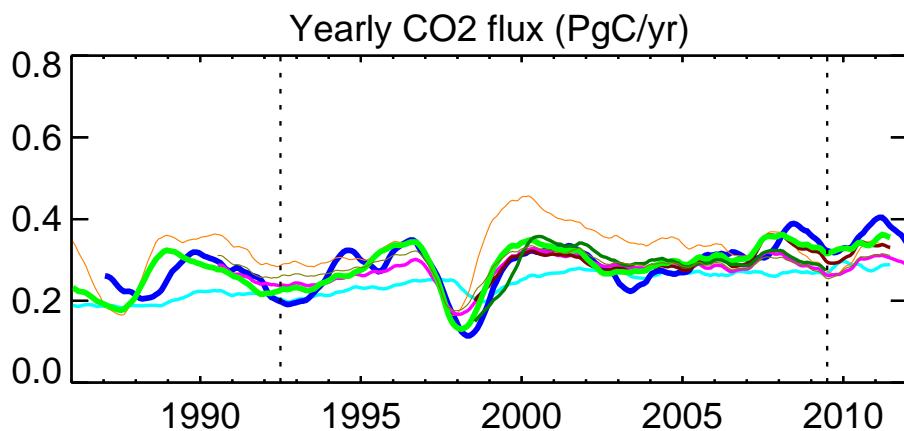
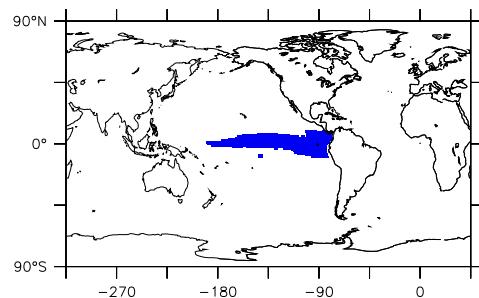
$$f = k(u^2) \cdot \varrho L \cdot (p\text{CO}_2 - p\text{CO}_2^{\text{atm}})$$

→ Flux IAV dominated by $p\text{CO}_2$ IAV

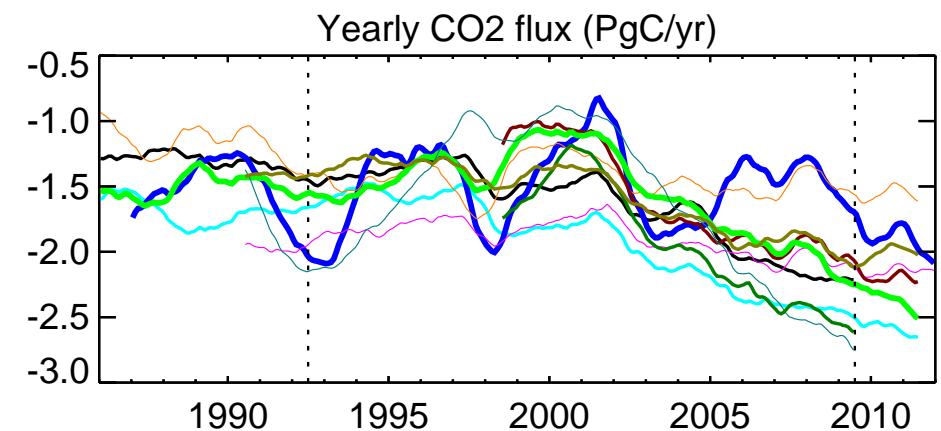
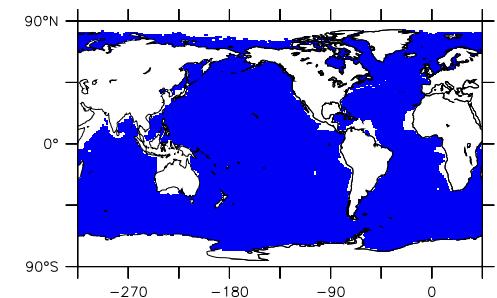
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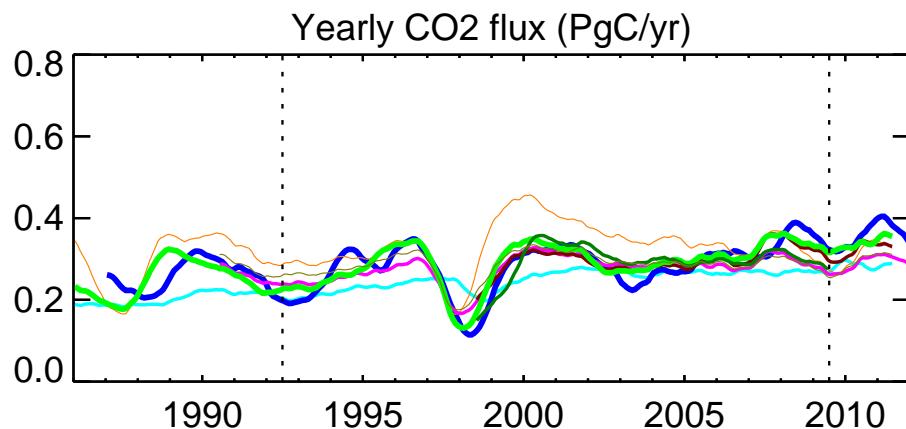
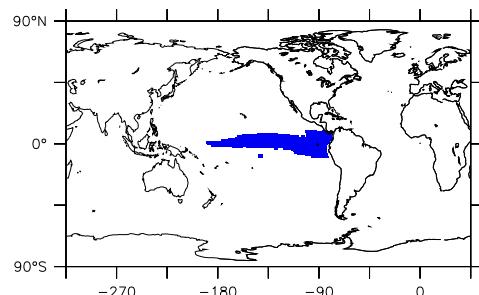
→ Flux IAV dominated by pCO₂ IAV

Little decadal change Increasing sink

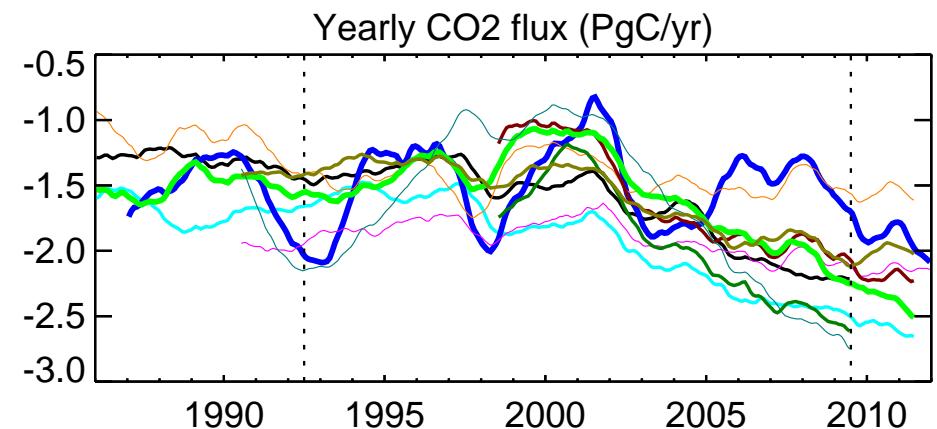
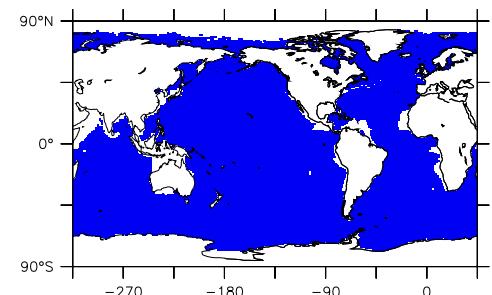
First results: Sea-air CO₂ fluxes

[Rödenbeck et al., BG (2015)]

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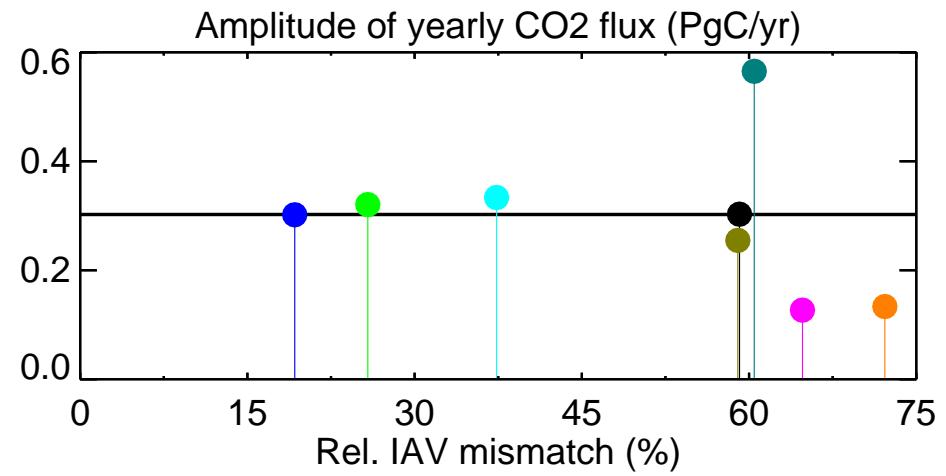
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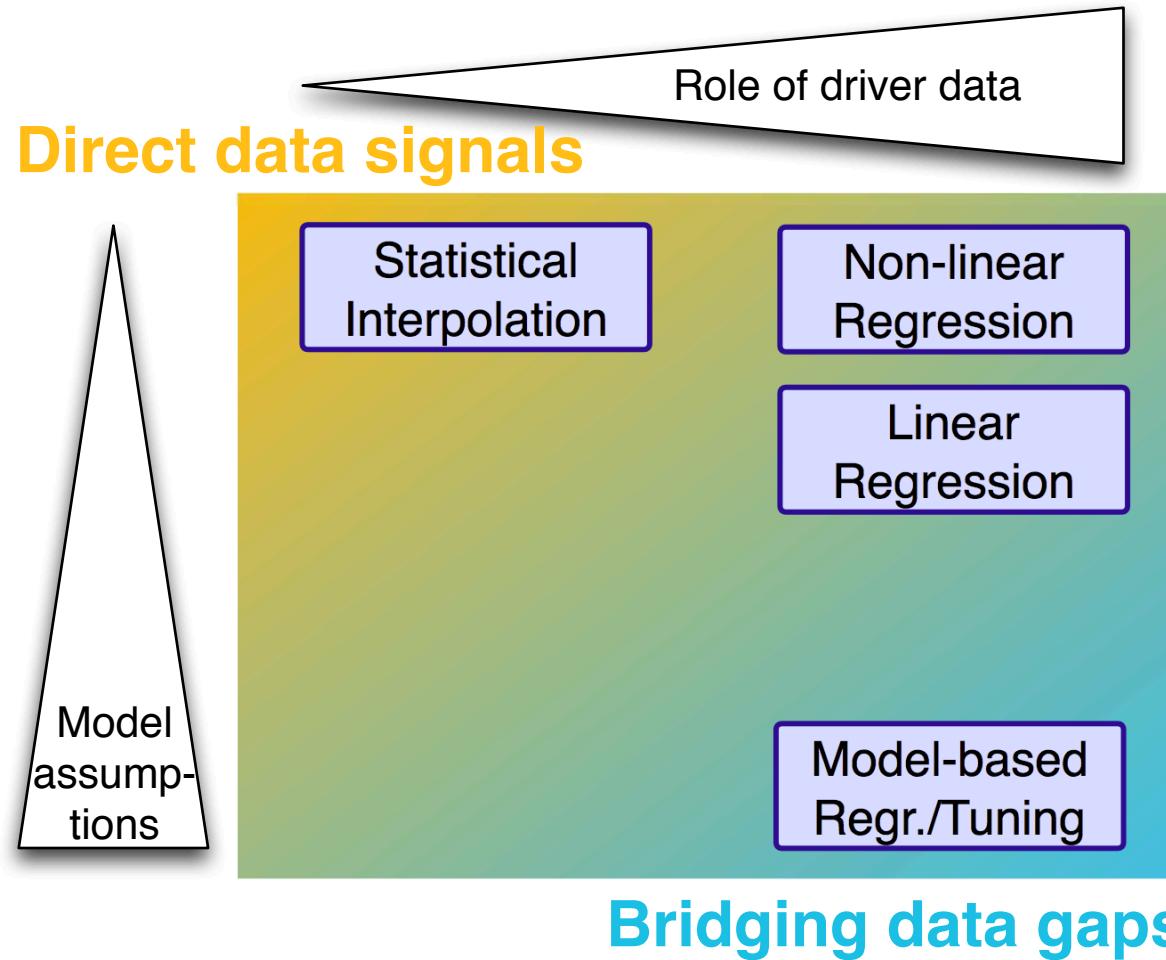
Weighted mean

global IAV amplitude: 0.31 PgC yr^{-1}

→ Underestimated by process models



Mapping methods

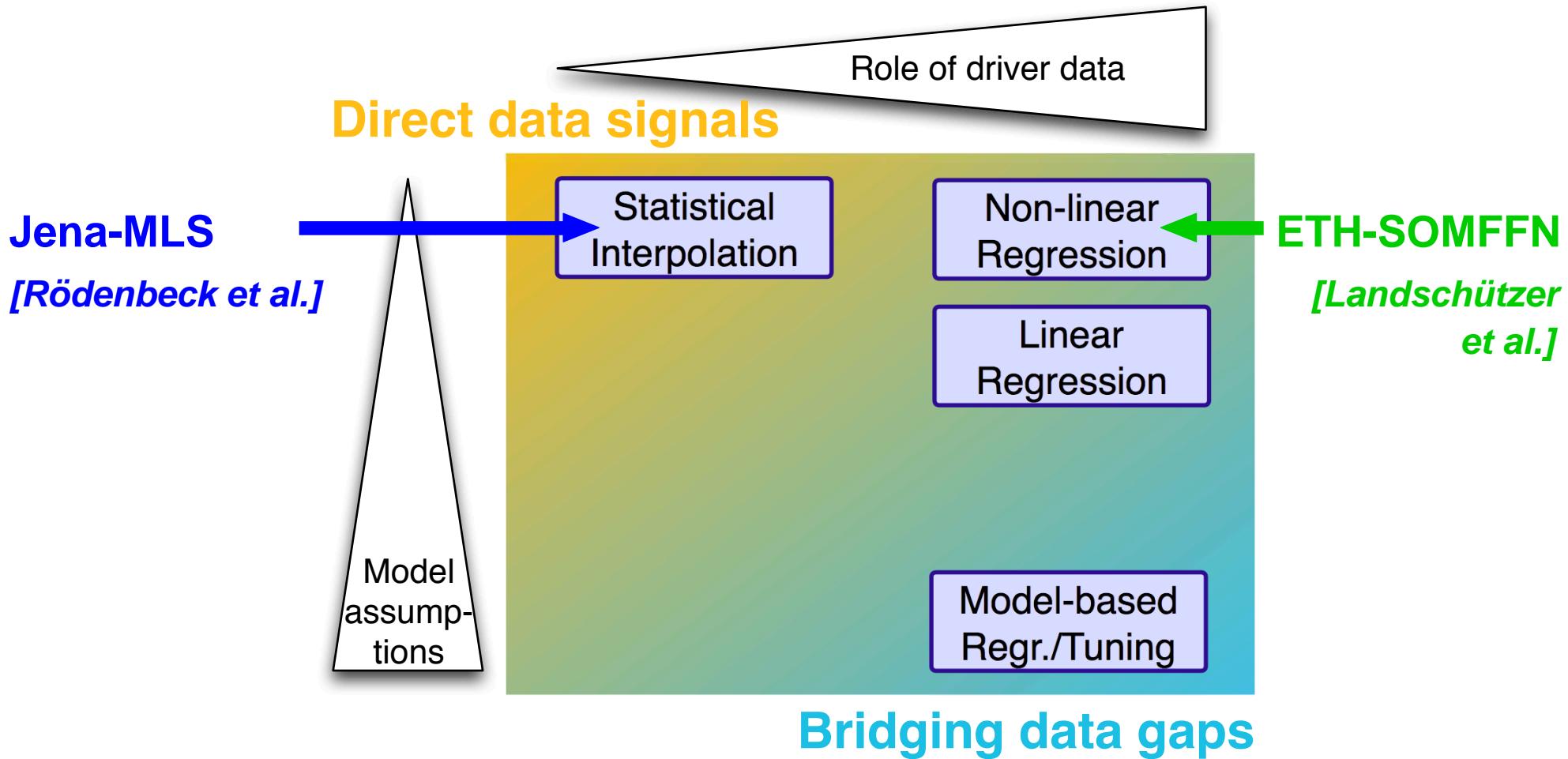


- Interesting complementarity
- Extracting robust features

SOCOM: Collating 14 mapping methods



Mapping methods



→ Interesting complementarity

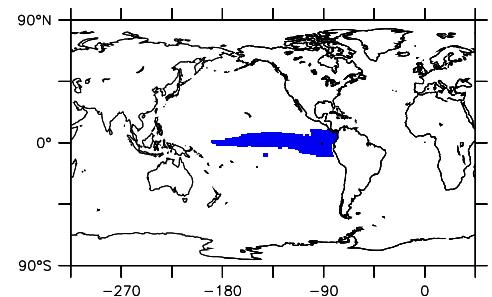
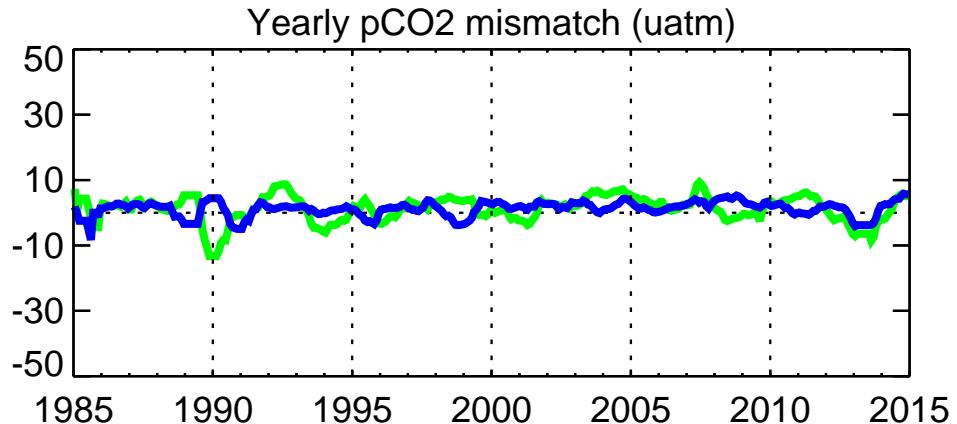
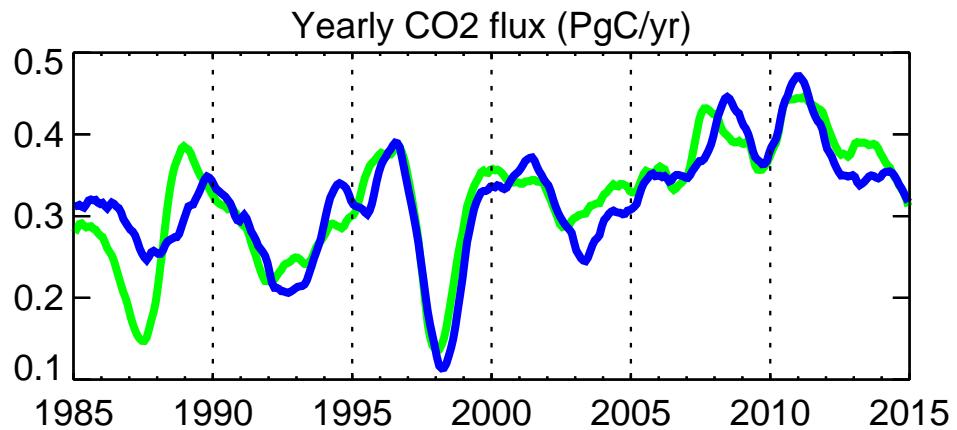
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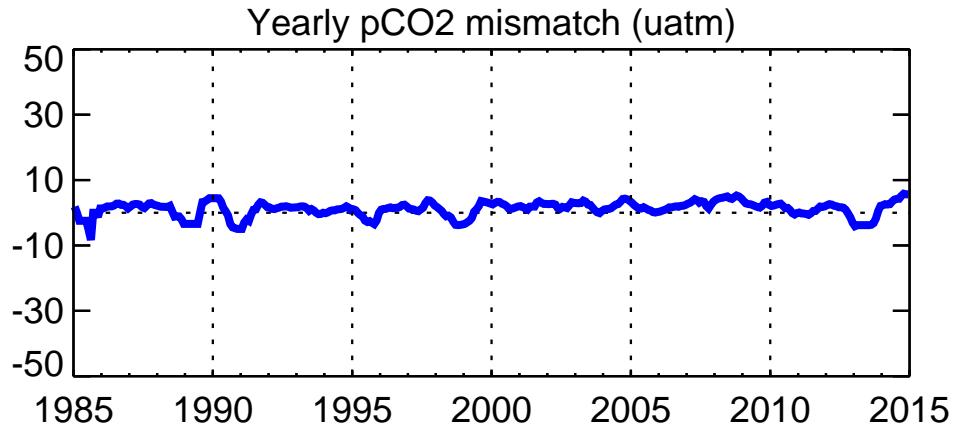
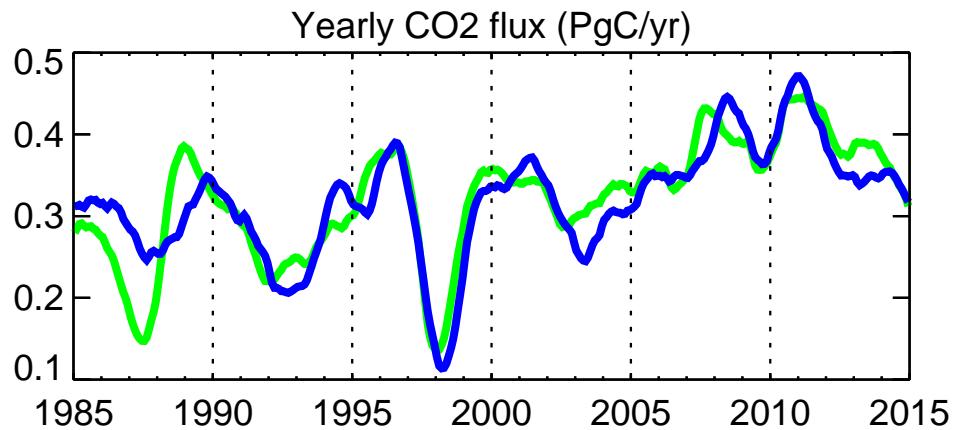
Cross Validation

— (18%) Jena oc_v1.4S
— (28%) ETH-SOMFFN2016

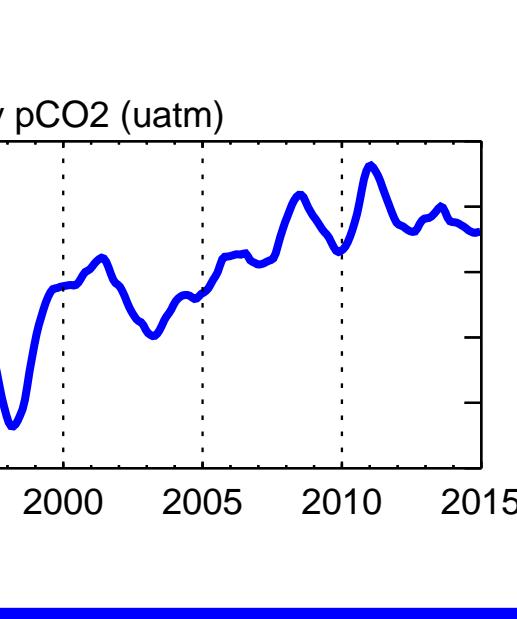
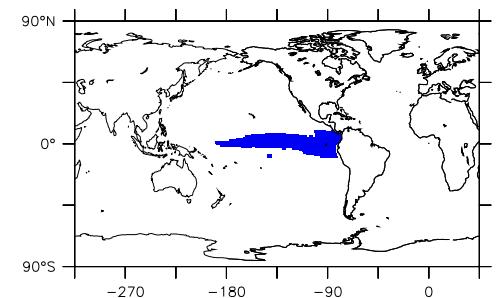
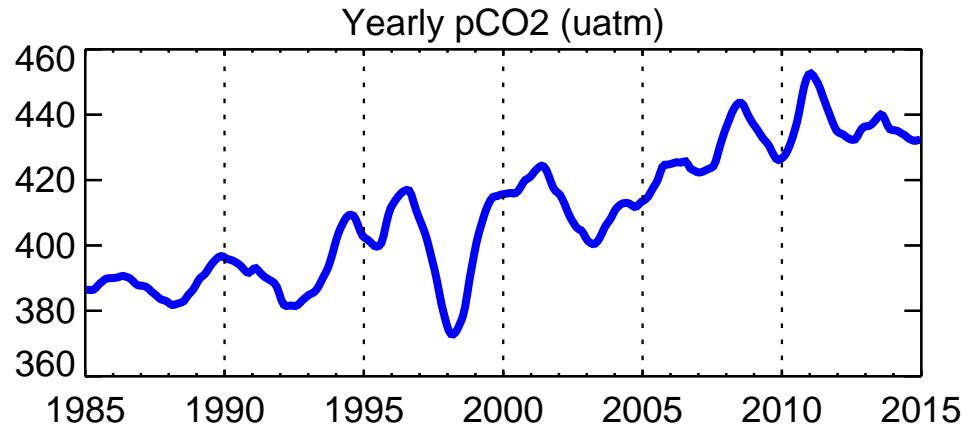


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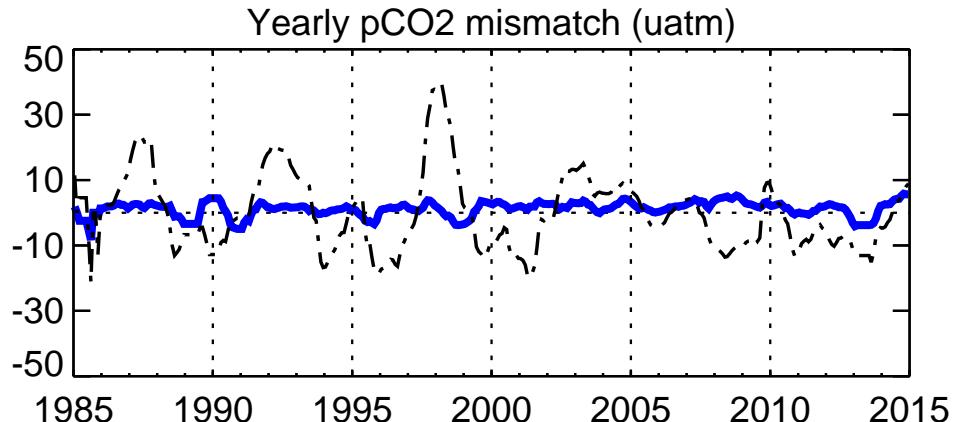
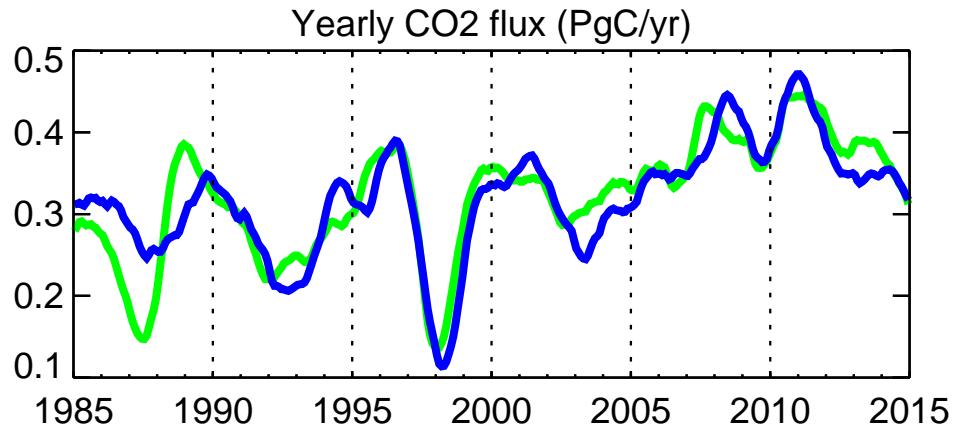


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Cross Validation

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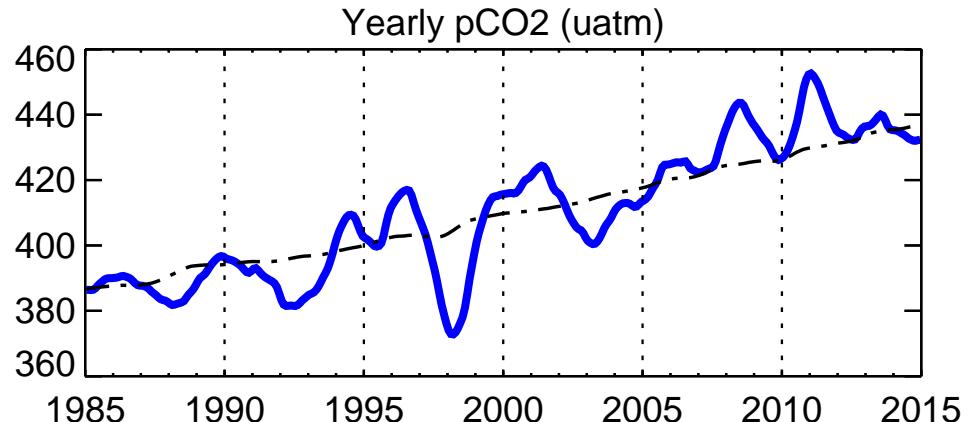
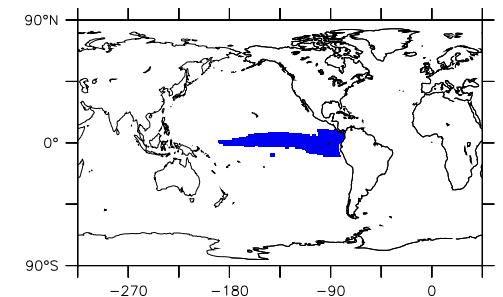


“Benchmark”:

Keep seasonality+trend, but **no IAV**
→ Mismatch ≈ signal size
→ “100% error”

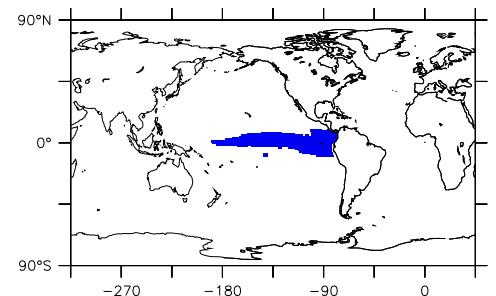
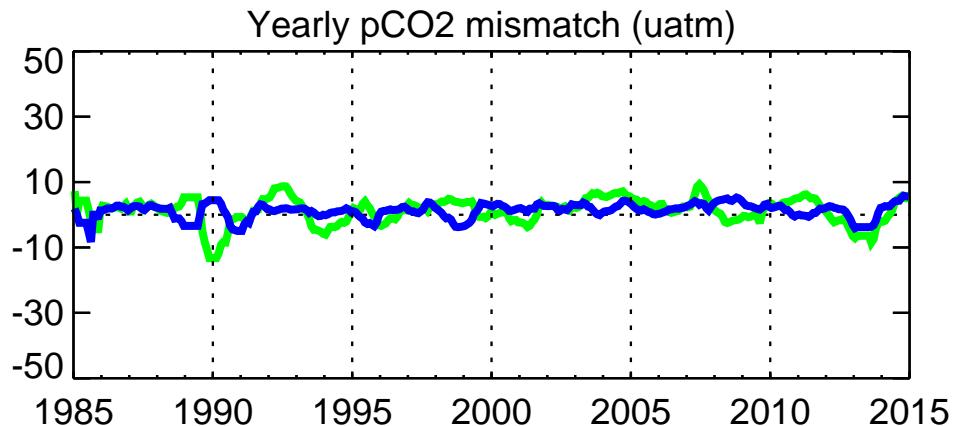
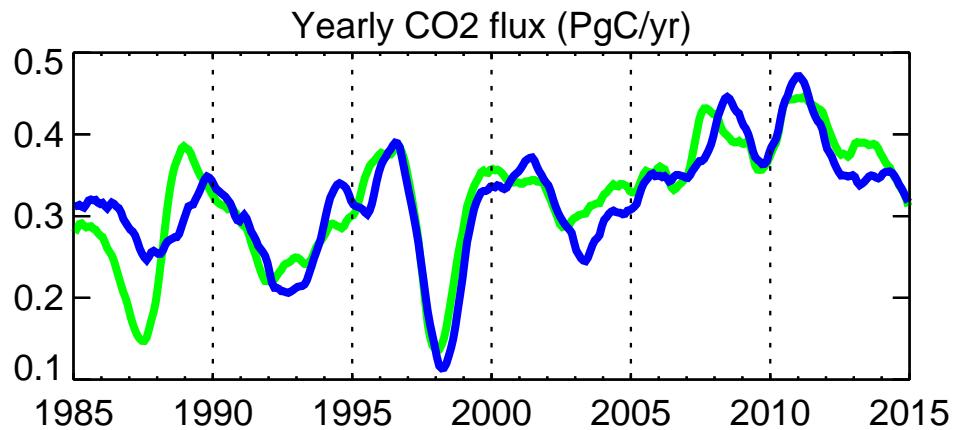
— (18%) Jena oc_v1.4S

-- (100%) Jena oc_v1.4S Benchmark



Cross Validation

— (18%) Jena oc_v1.4S
— (28%) ETH-SOMFFN2016



Interpolation:

Time-dep. DoF's
→ Any IAV possible

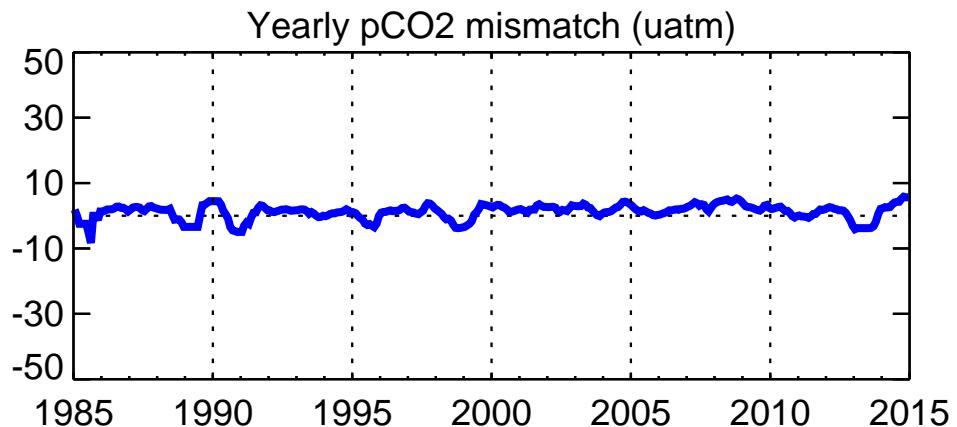
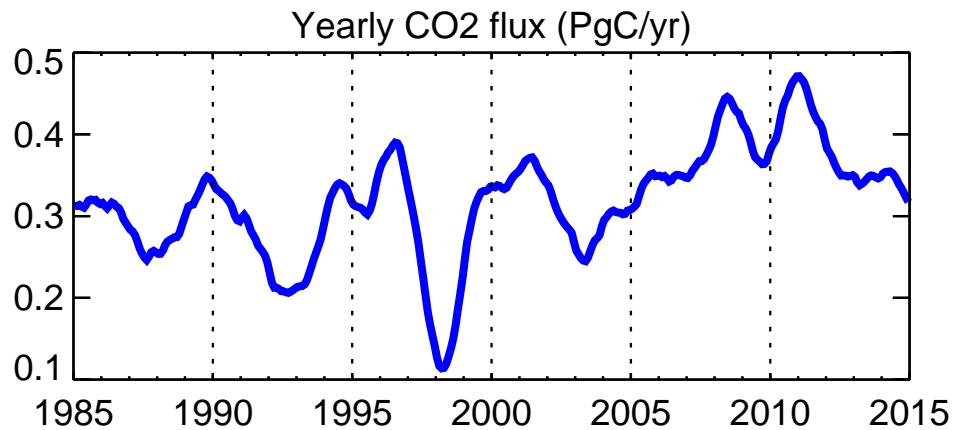
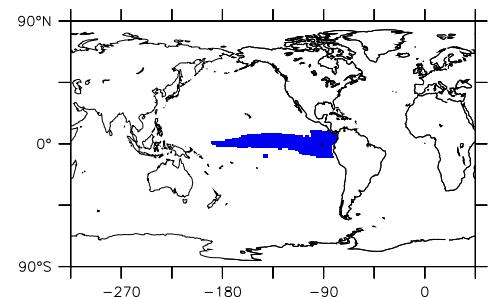
Regression:

Constant DoF's
→ IAV from drivers



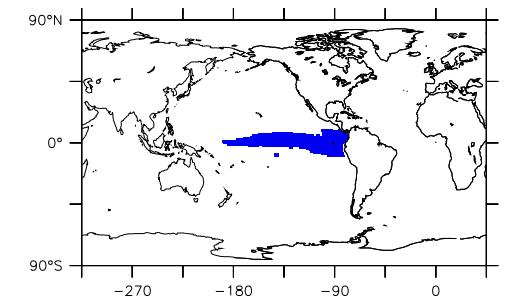
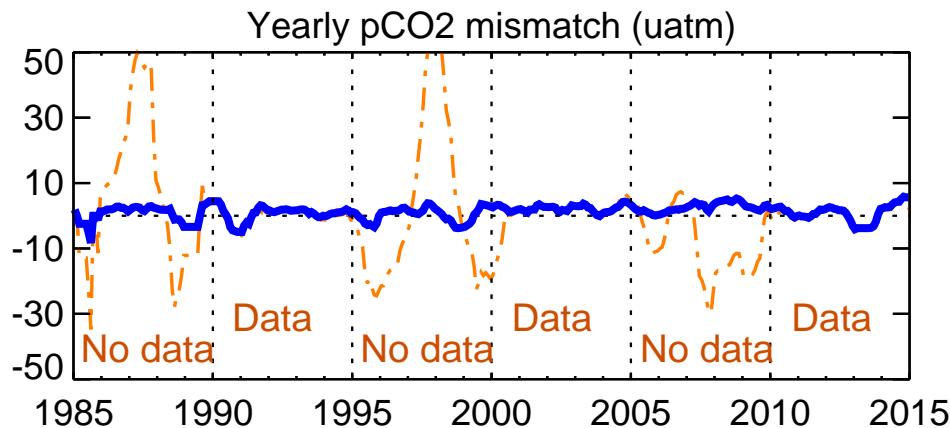
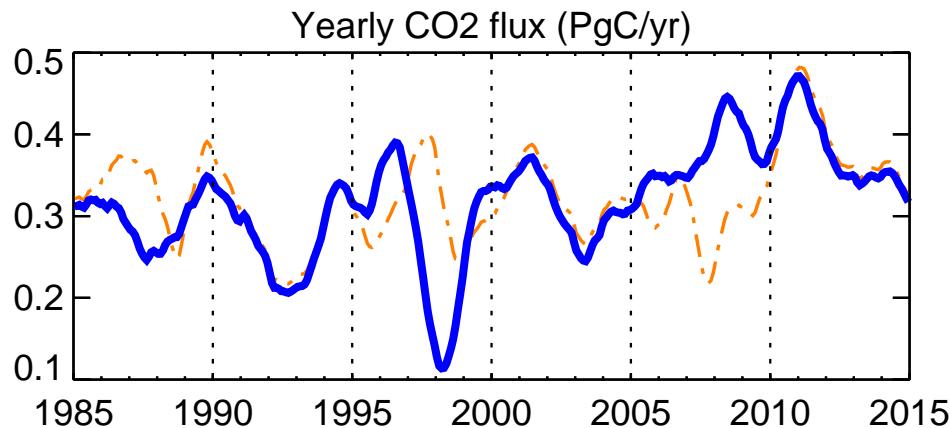
Cross Validation

— (18%) Jena oc_v1.4S



Cross Validation

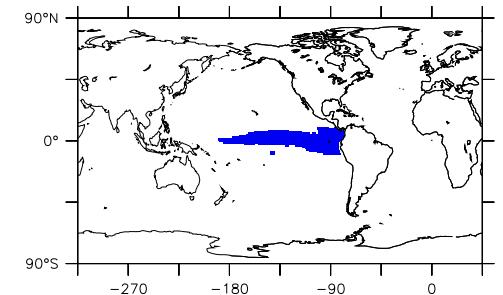
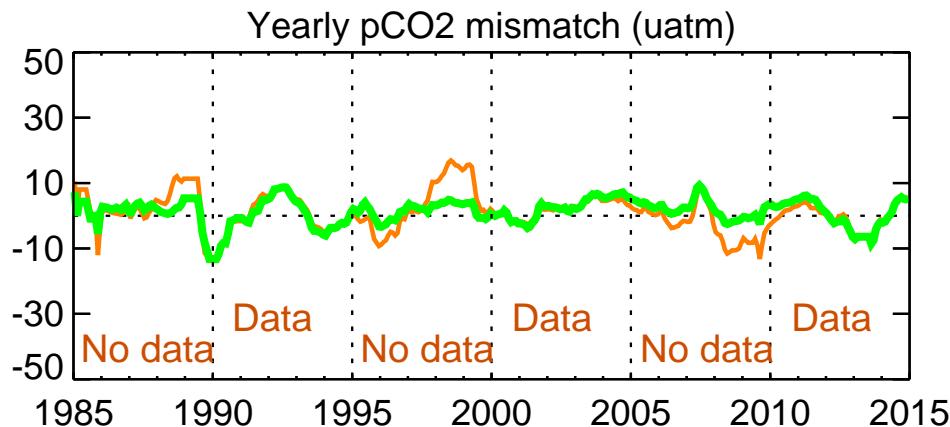
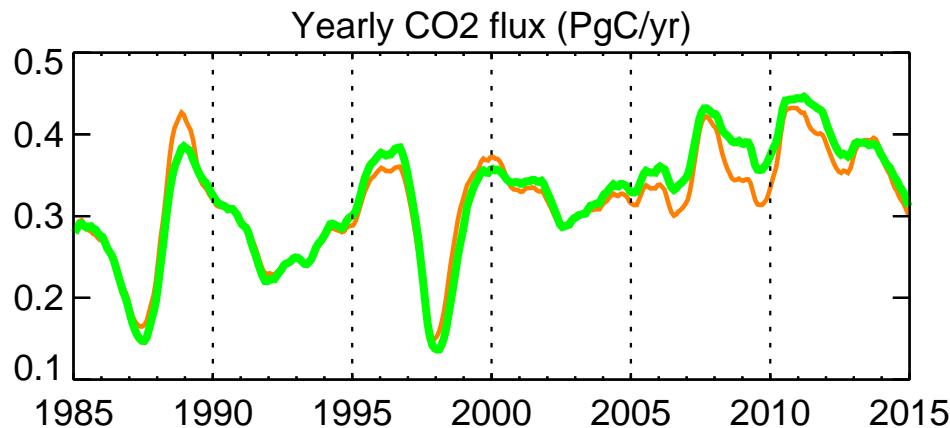
— (18%) Jena oc_v1.4S
- - - (121%) Jena oc_v1.4S (CrossVal5yr0)



→ Data-only interpolation
cannot bridge multi-year gaps

Cross Validation

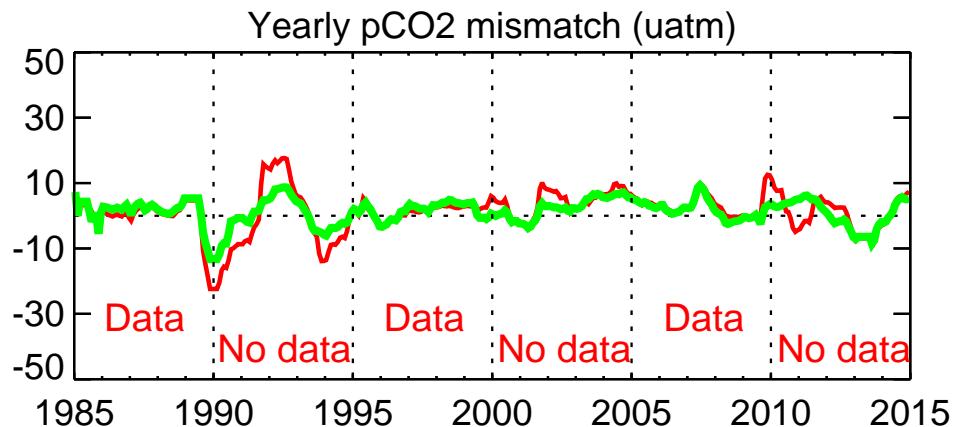
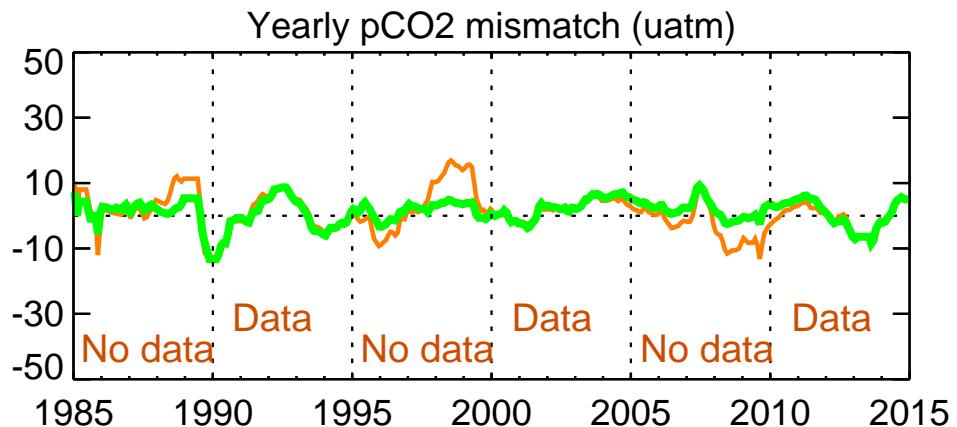
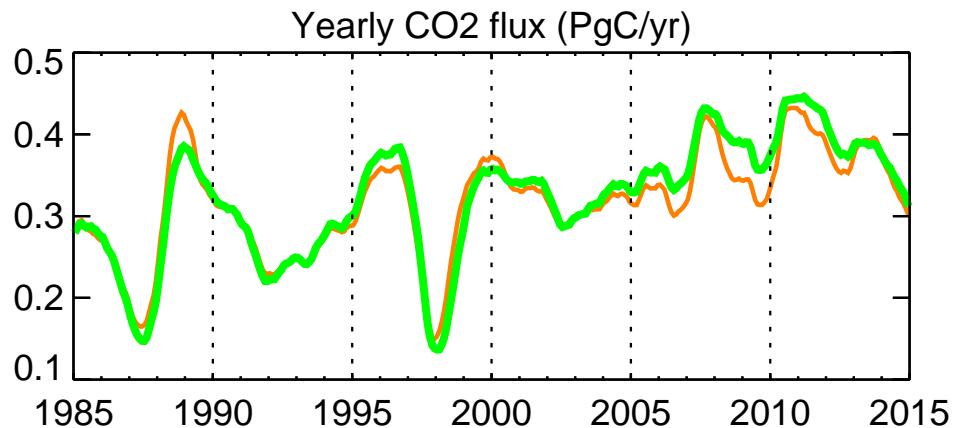
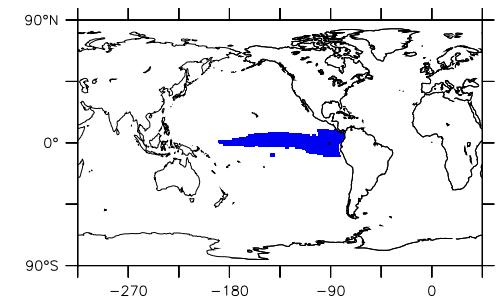
— (28%) ETH-SOMFFN2016
— (48%) ETH-SOMFFN2016 (CrossVal5yr0)



→ Regression against drivers
(SST, SSS, Chl-a, atm. CO₂)
offers some bridging capacity

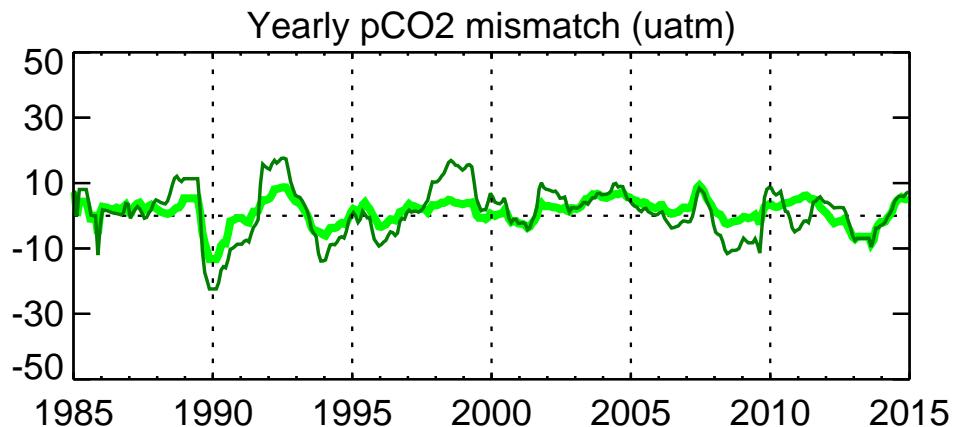
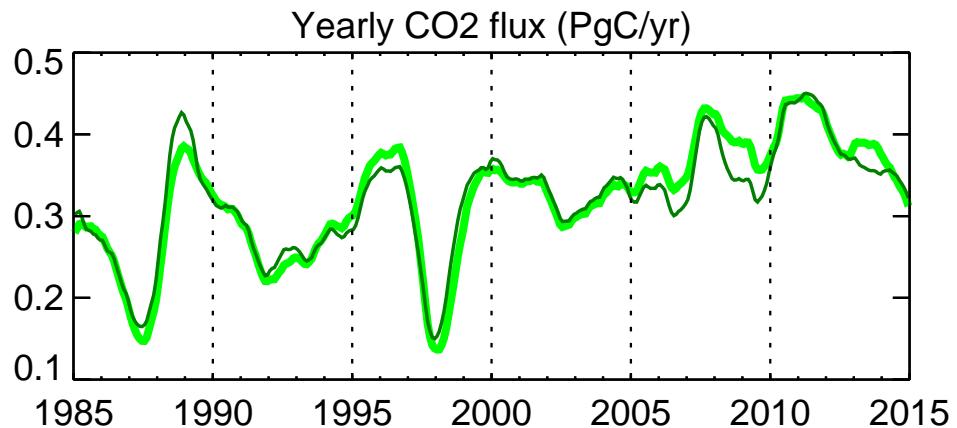
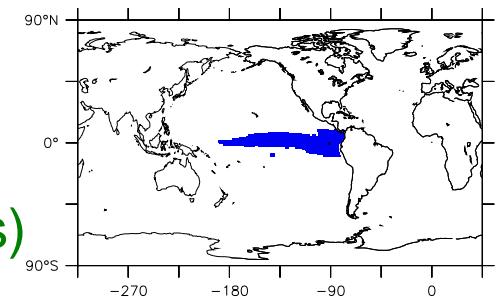
Cross Validation

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Cross Validation

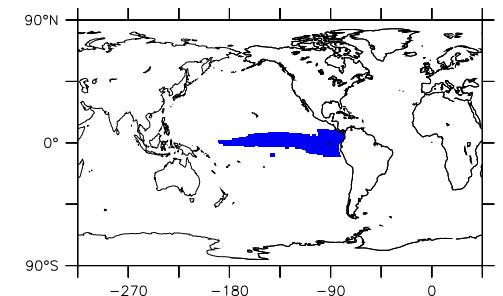
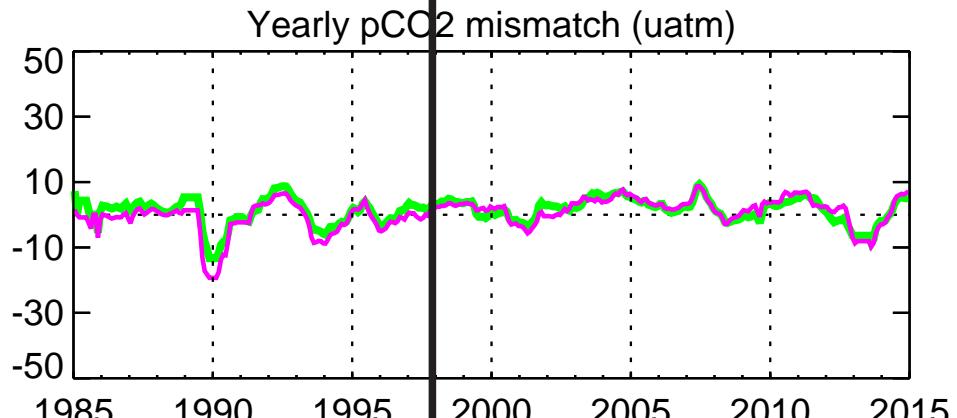
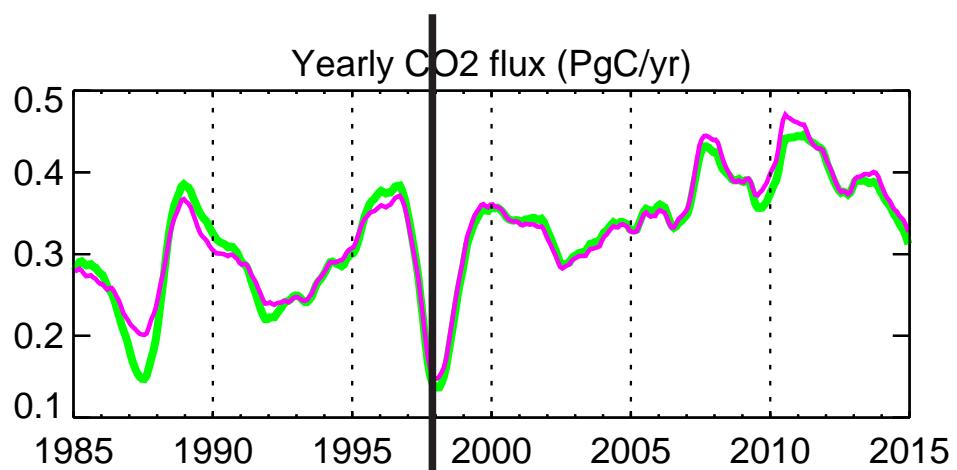
— (28%) ETH-SOMFFN2016
— (62%) ETH-SOMFFN2016 (Unconstrained periods)



→ Regression against drivers
(SST, SSS, Chl-a, atm. CO₂)
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Cross Validation

- (28%) ETH-SOMFFN2016
- (35%) ETH-SOMFFN2016, regr. SST & SSS

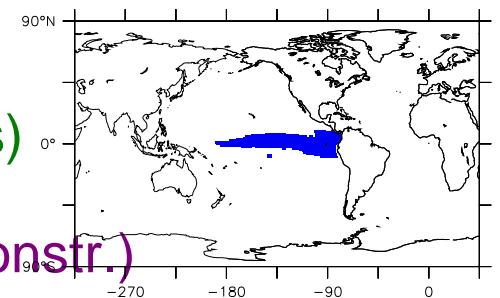
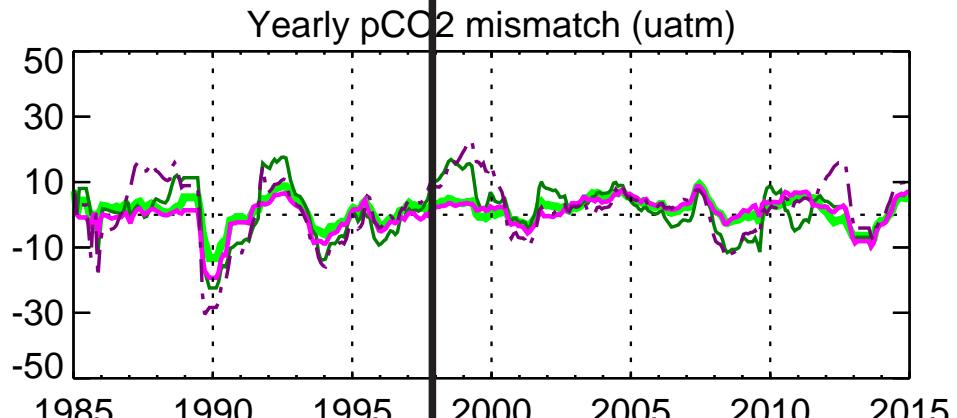
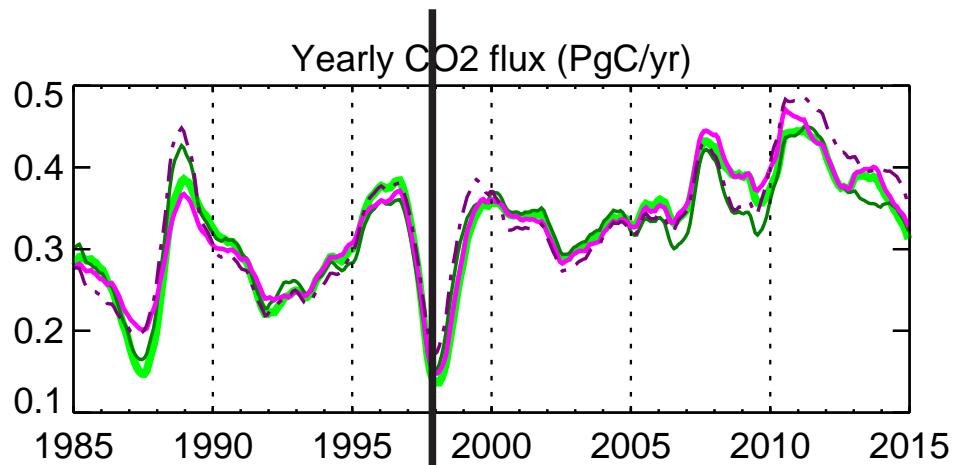


Chl-a data only available since 1998
– do SST and SSS suffice?

→ Less fitting capacity
(but main modes similar)

Cross Validation

- (28%) ETH-SOMFFN2016
- (62%) ETH-SOMFFN2016 (Unconstrained periods)
- (35%) ETH-SOMFFN2016, regr. SST & SSS
- - - (77%) ETH-SOMFFN2016, regr. SST & SSS (Unconstr.)



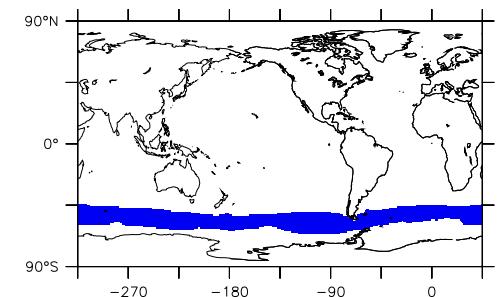
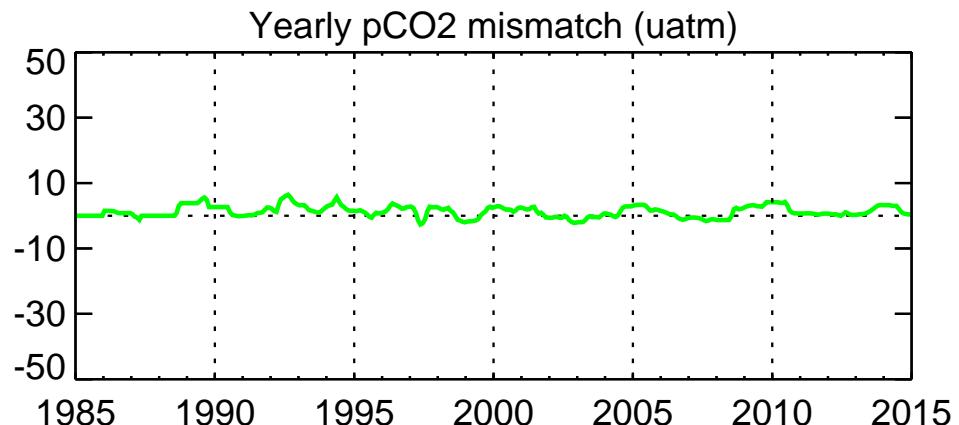
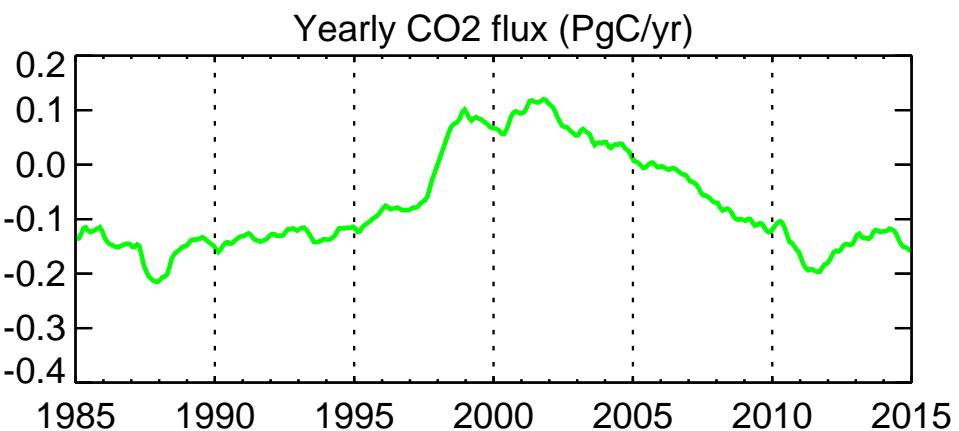
Chl-a data only available since 1998

– do SST and SSS suffice?

→ Less fitting capacity
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→ Less bridging capacity

Cross Validation

— (47%) ETH-SOMFFN2016

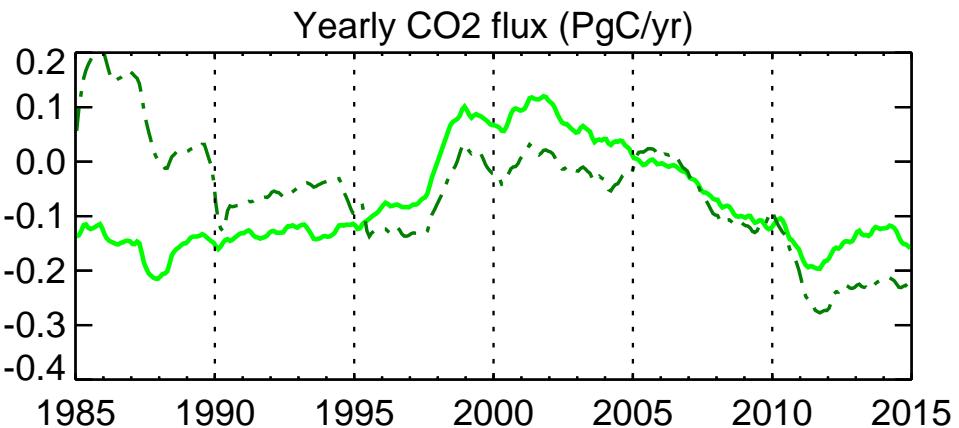
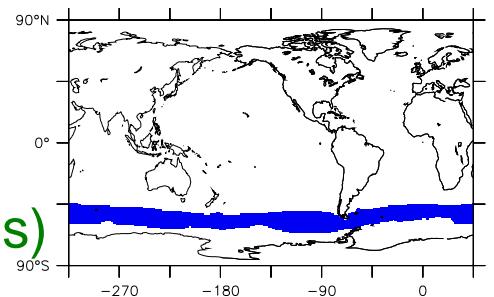


Southern Ocean – sparse data

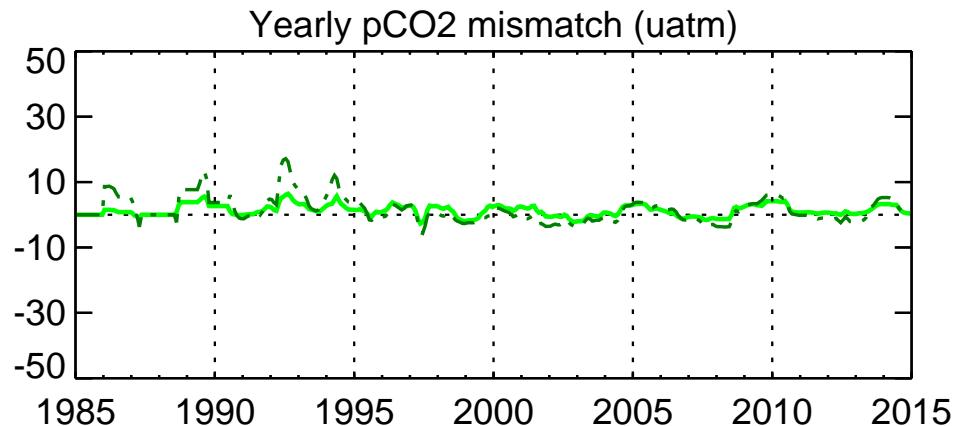


Cross Validation

— (47%) ETH-SOMFFN2016
- - - (106%) ETH-SOMFFN2016 (Unconstrained periods)



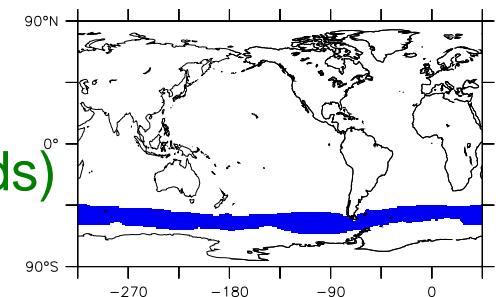
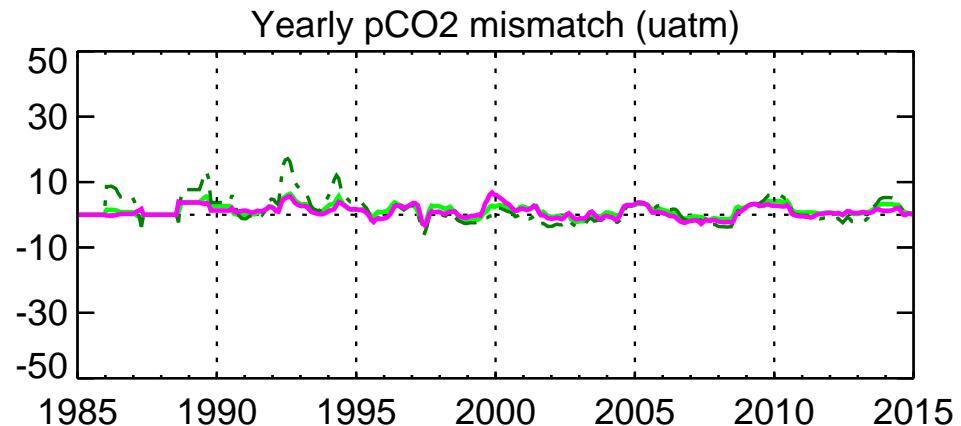
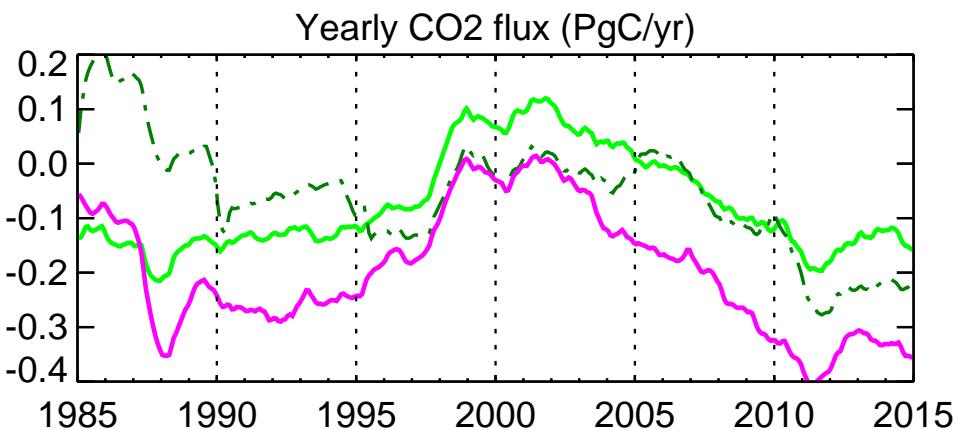
Southern Ocean – sparse data



→ Bridging difficult &
difficult to test

Cross Validation

— (47%) ETH-SOMFFN2016
- - - (106%) ETH-SOMFFN2016 (Unconstrained periods)
— (53%) ETH-SOMFFN2016, regr. SST & SSS

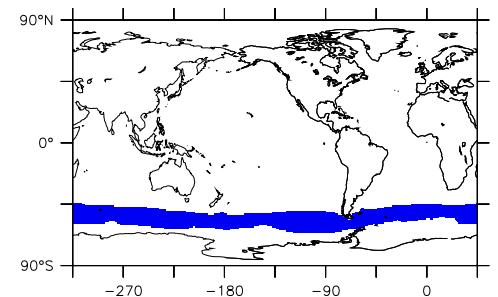
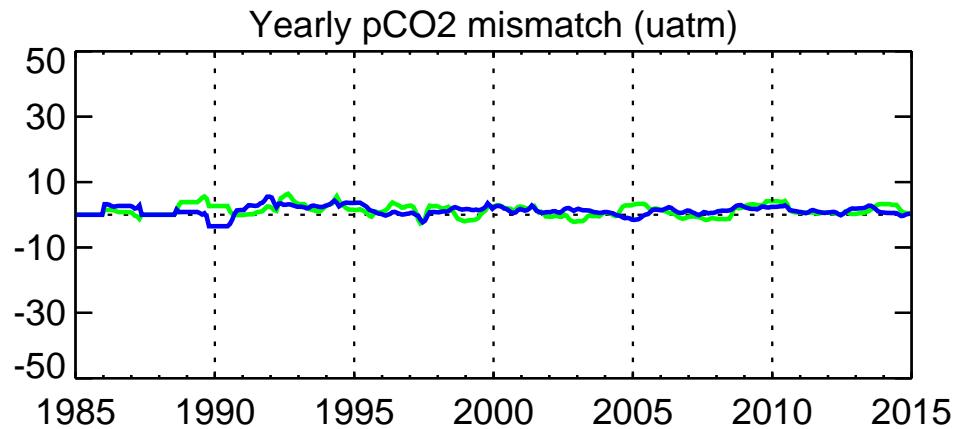
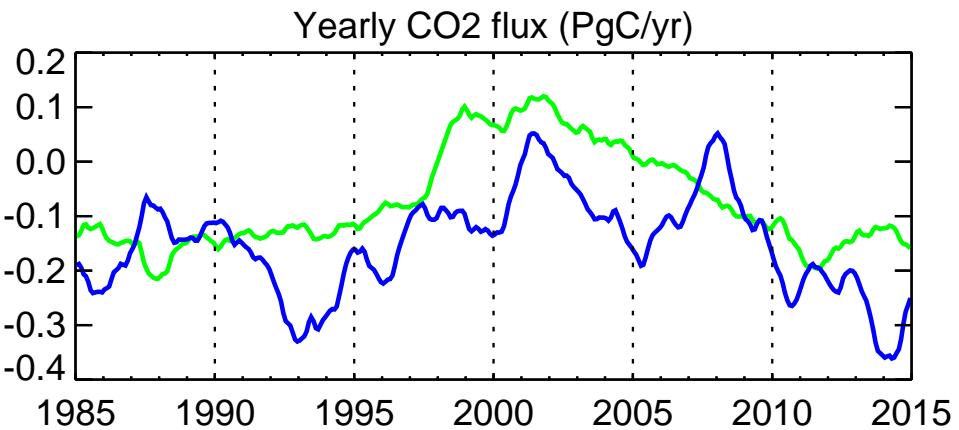


Southern Ocean – sparse data

→ Bridging difficult &
difficult to test
→ again main modes similar w/o Chl-a

Cross Validation

— (37%) Jena oc_v1.4S
— (47%) ETH-SOMFFN2016

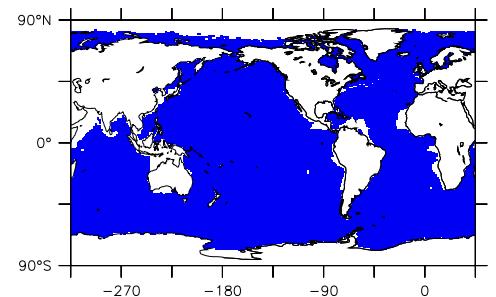
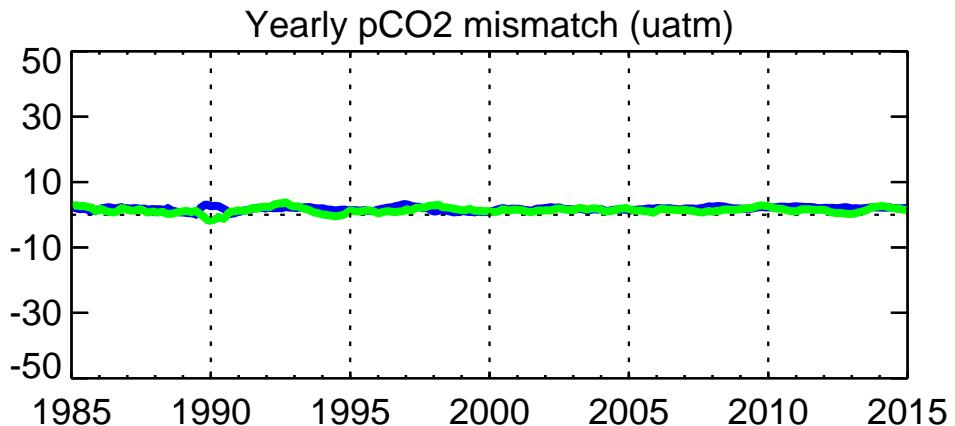
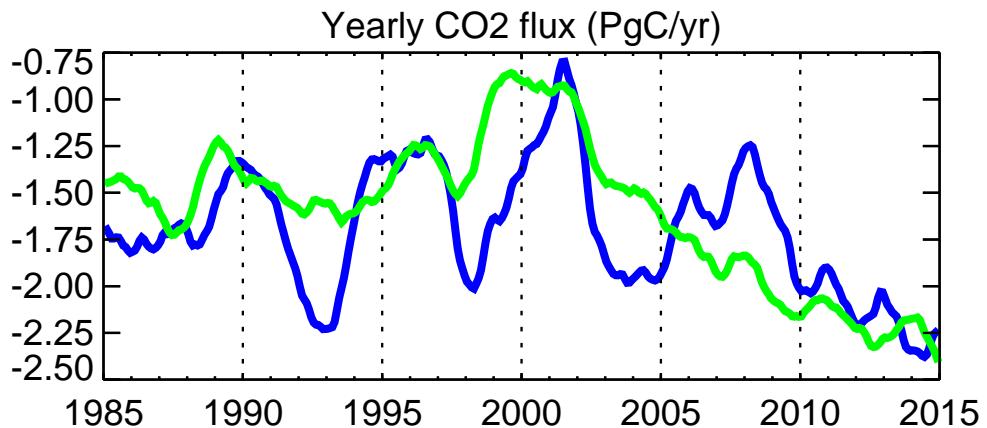


Southern Ocean – sparse data

- Bridging difficult & difficult to test
- again main modes similar w/o Chl-a
- Decadal trends also from data directly

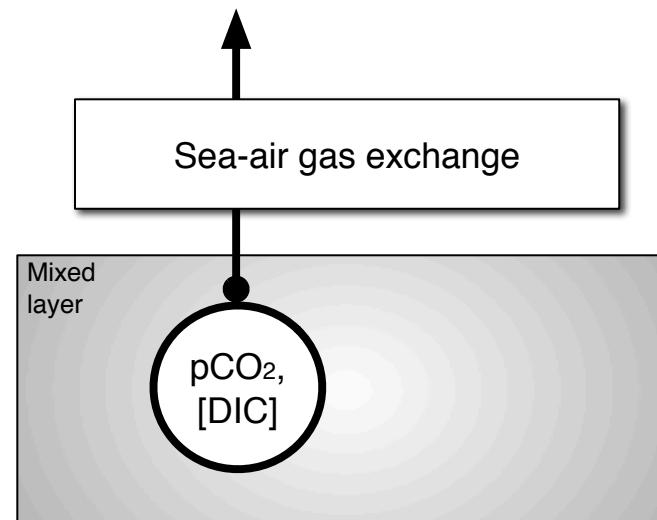
Cross Validation

(25%) ETH-SOMFFN2016
(18%) Jena-MLS14SSS



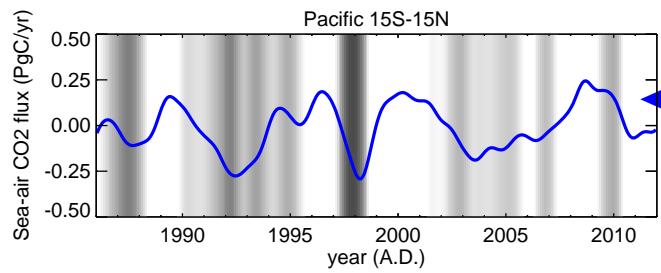
Global Ocean flux
– affected by data-sparse regions

→ Complementary mapping methods
(interpolation, regression)
help to assess robustness

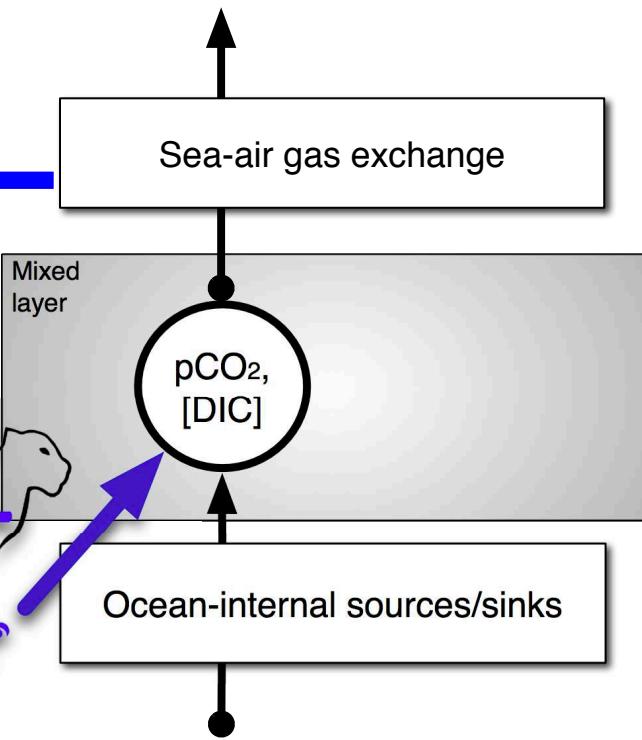


Carbon

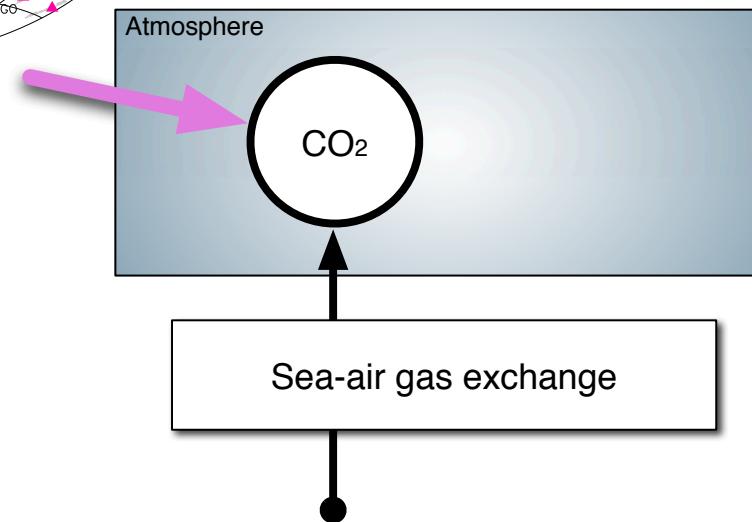
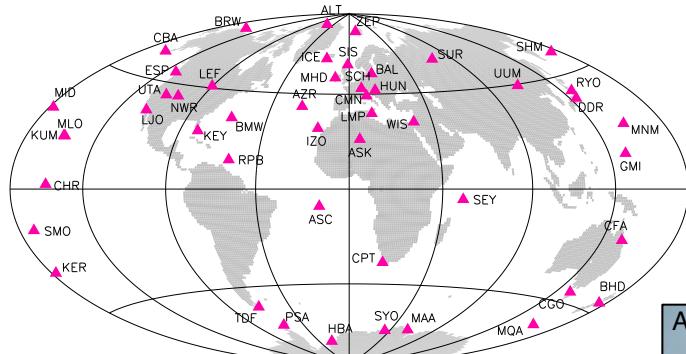
CO_2 flux inferred from $p\text{CO}_2$ interpolation



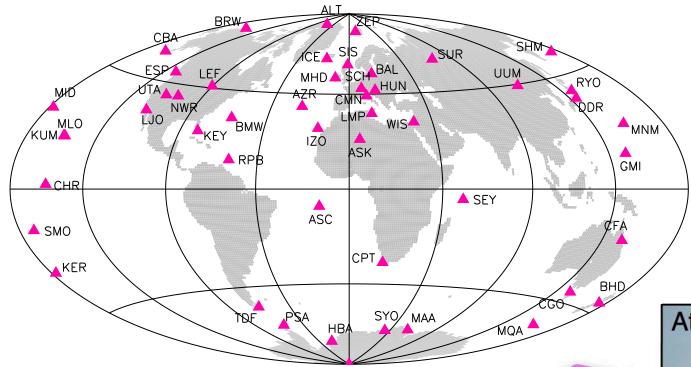
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Carbon



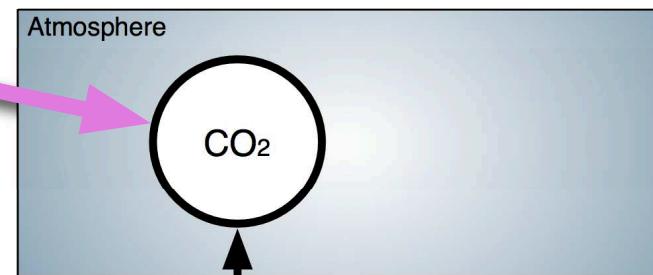
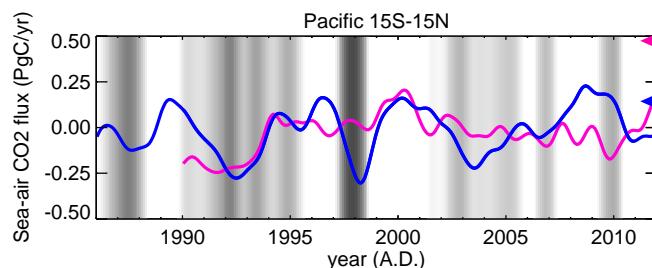
Carbon



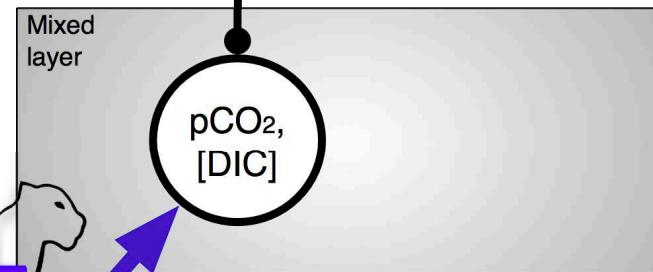
CO₂ flux

inferred from CO₂ inversion

inferred from *p*CO₂ interpolation

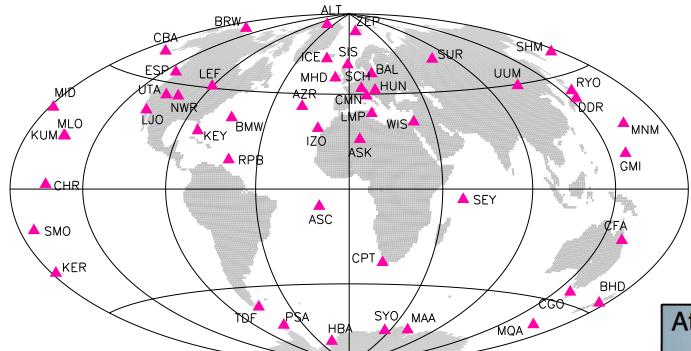


Sea-air gas exchange



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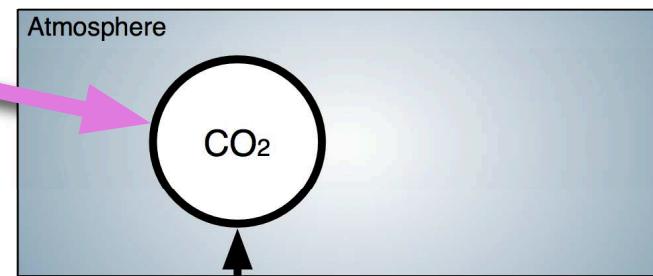
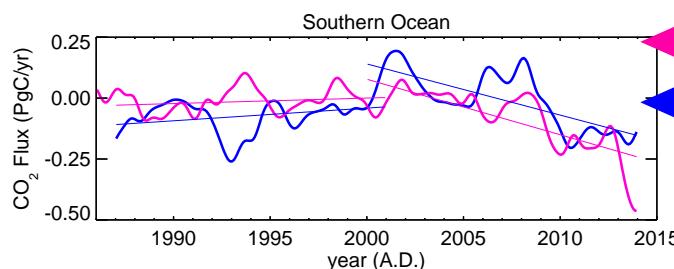
Carbon



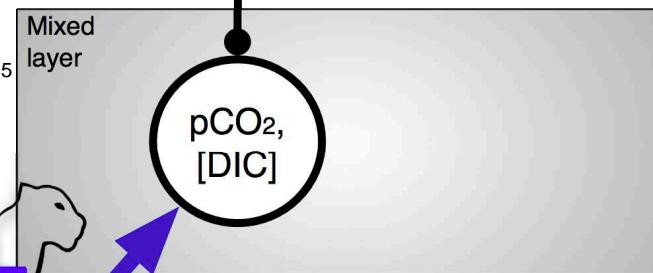
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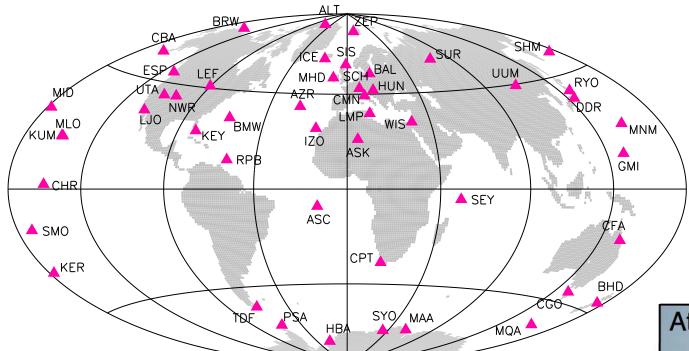


Sea-air gas exchange



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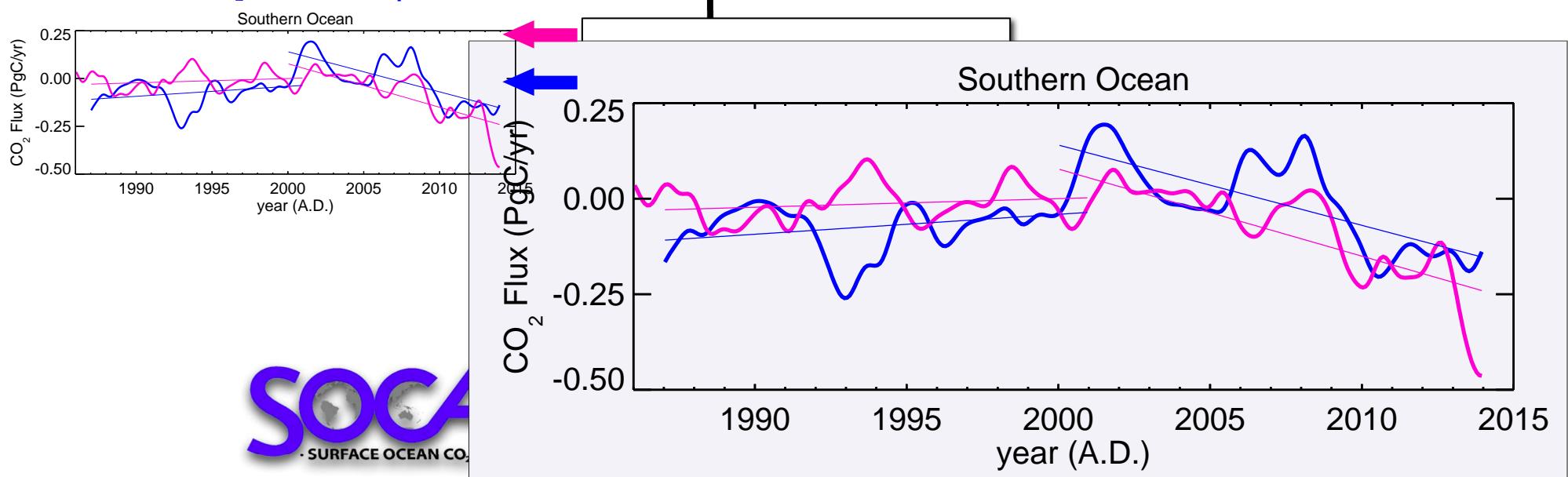
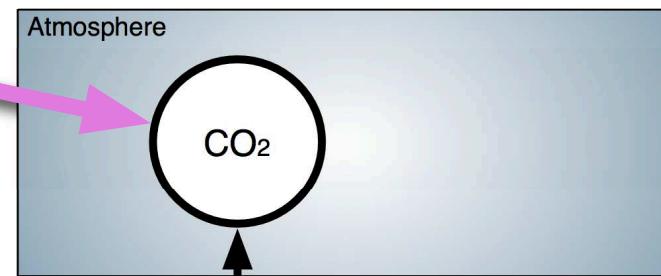
Carbon



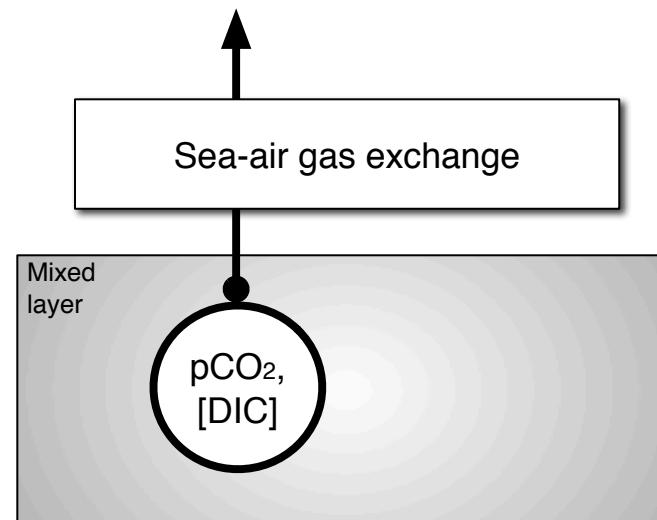
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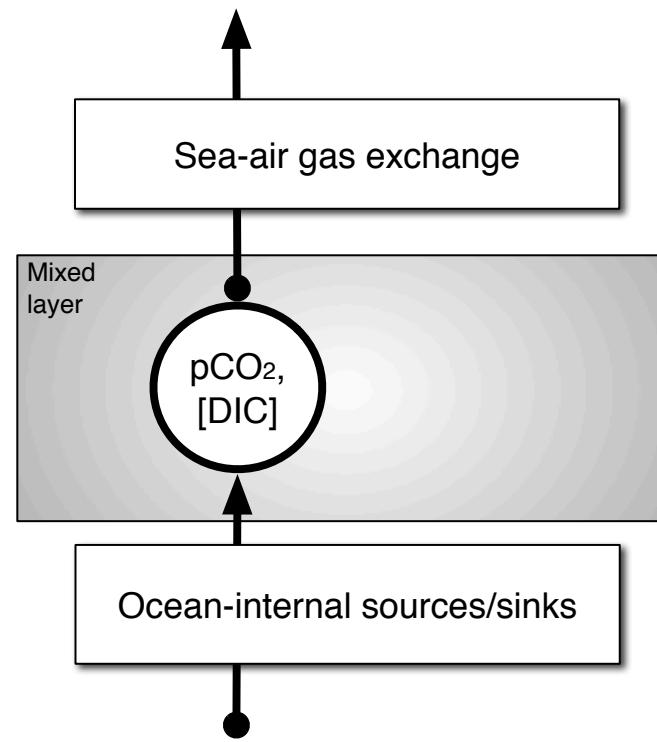
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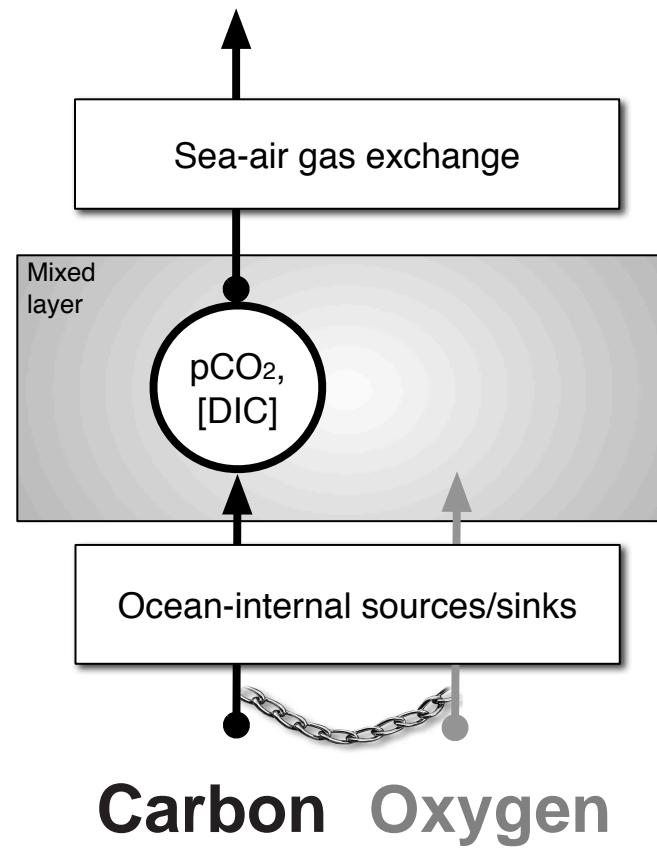
Carbon



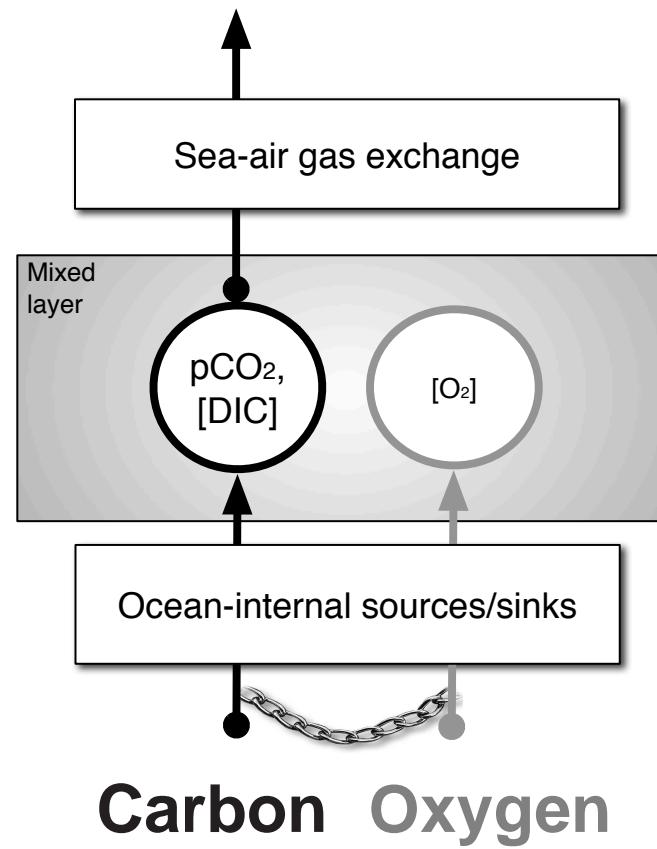
Carbon



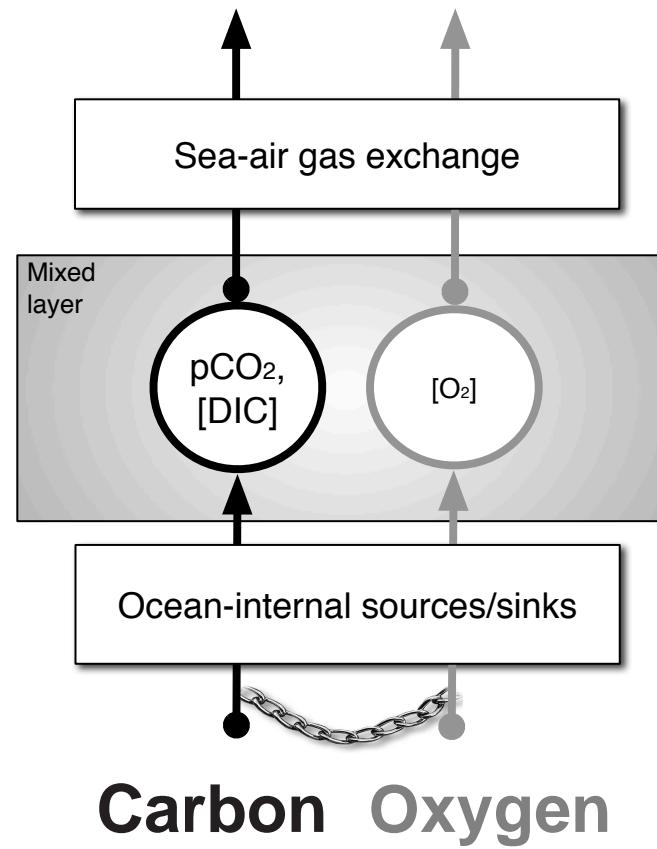
Carbon



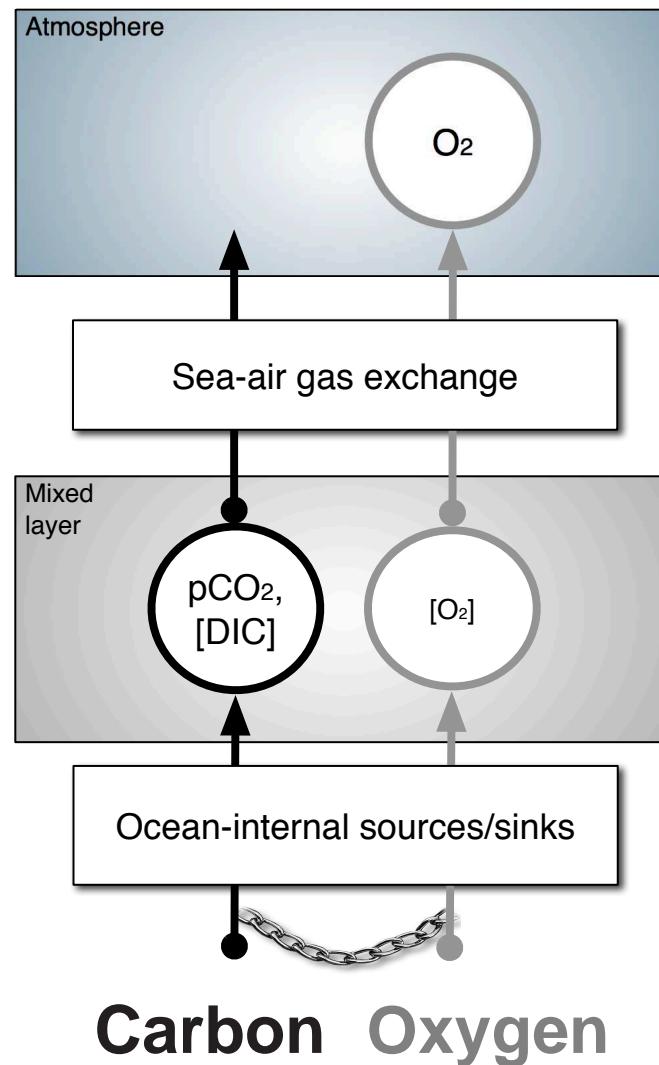
- **Biology:**
Redfield stoichiometry
 $R_{\text{O:C}} \approx -1.4$
- **Transport+Mixing:**
Common pathways



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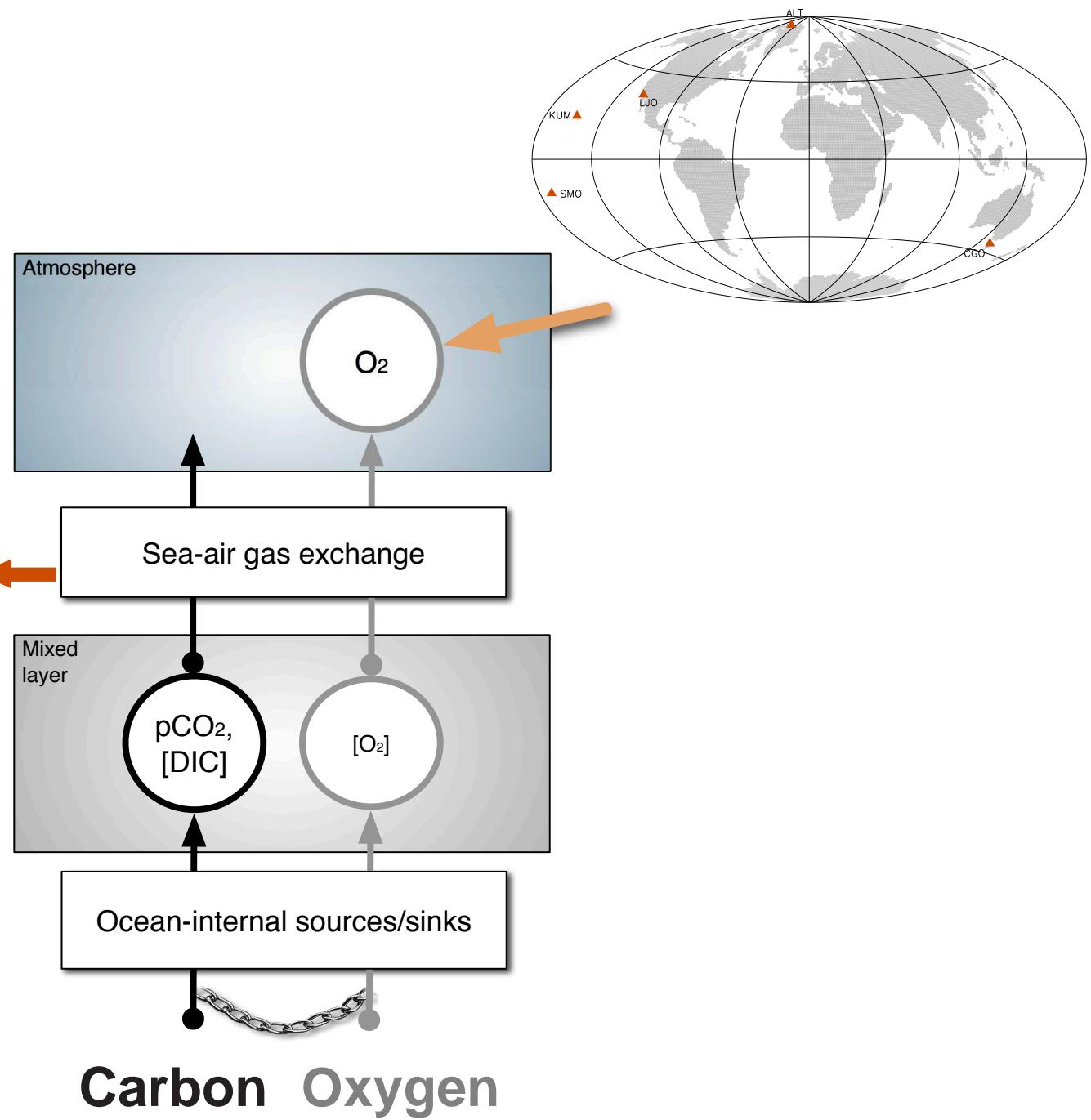
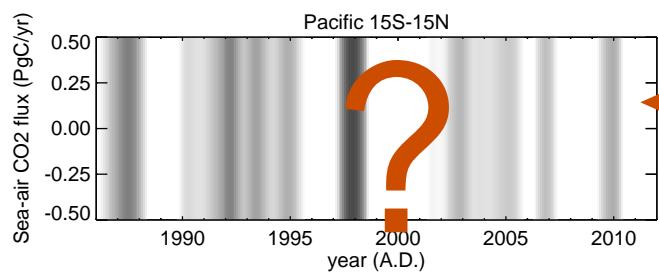


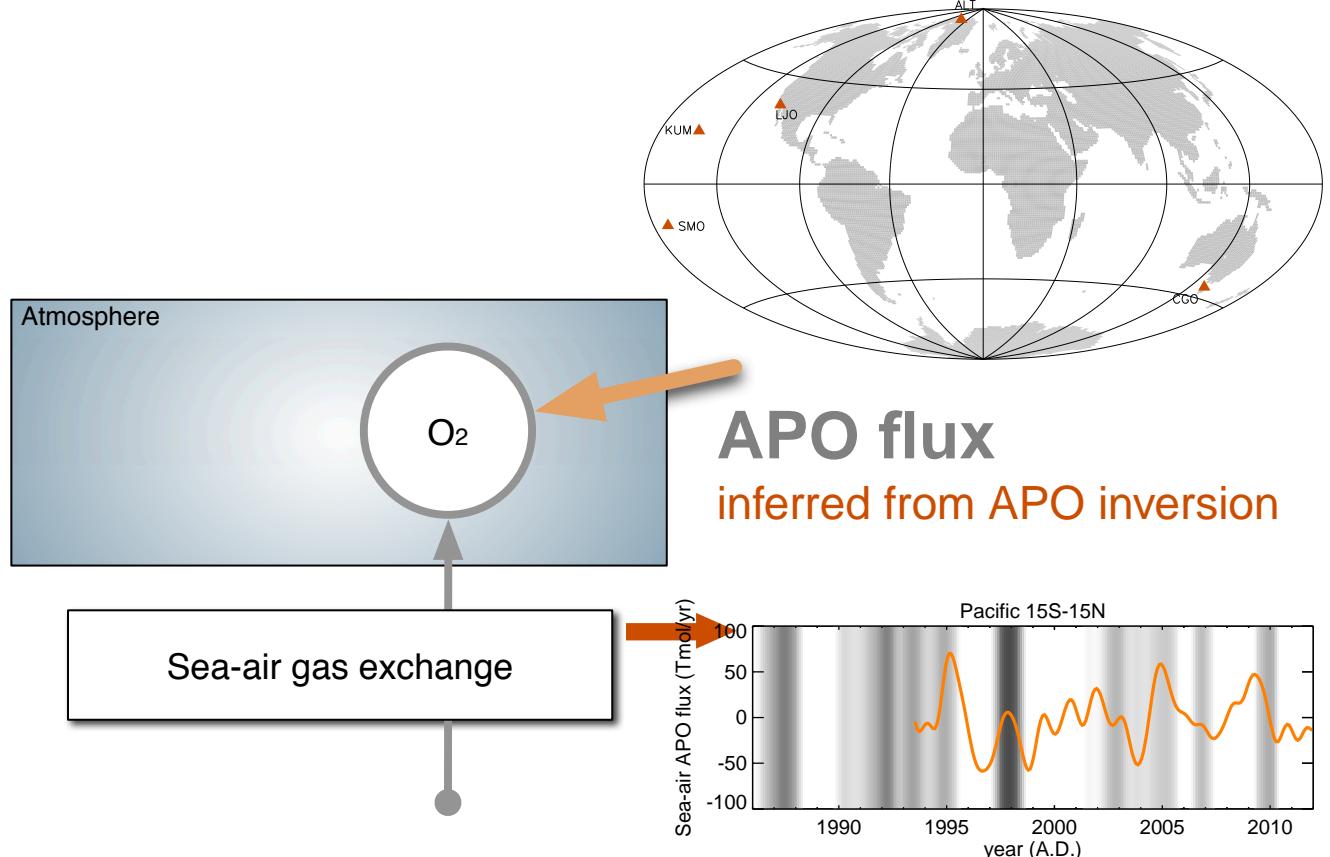
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- **Biology:**
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 - $R_{O:C} \approx -1.4$
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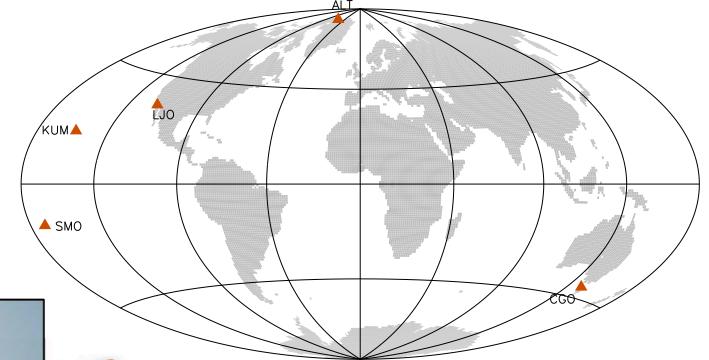
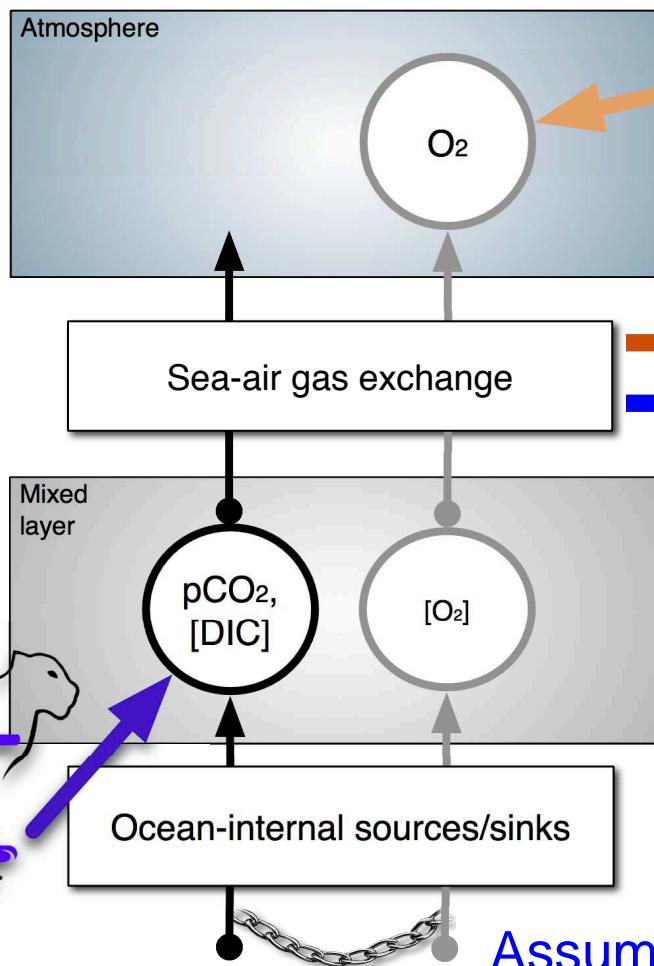
CO_2 flux inferred from O_2/N_2





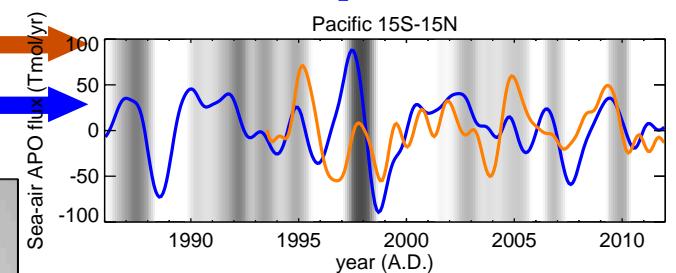
Carbon Oxygen

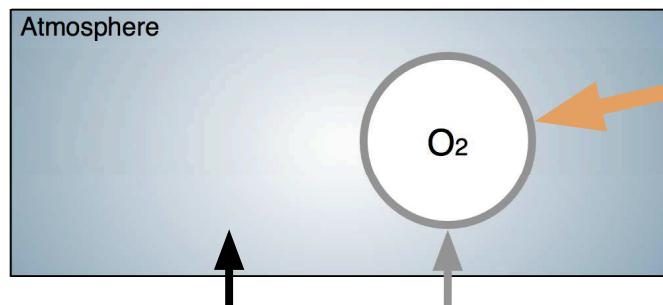
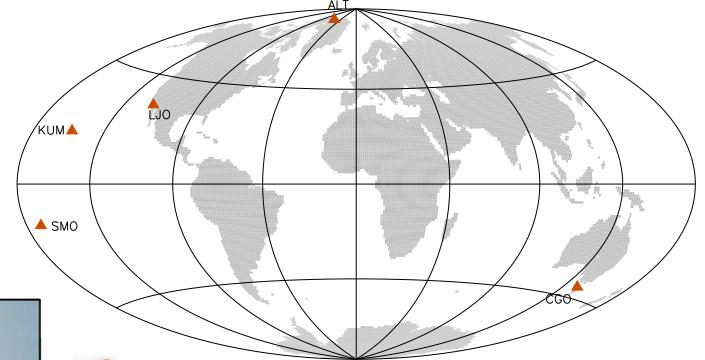
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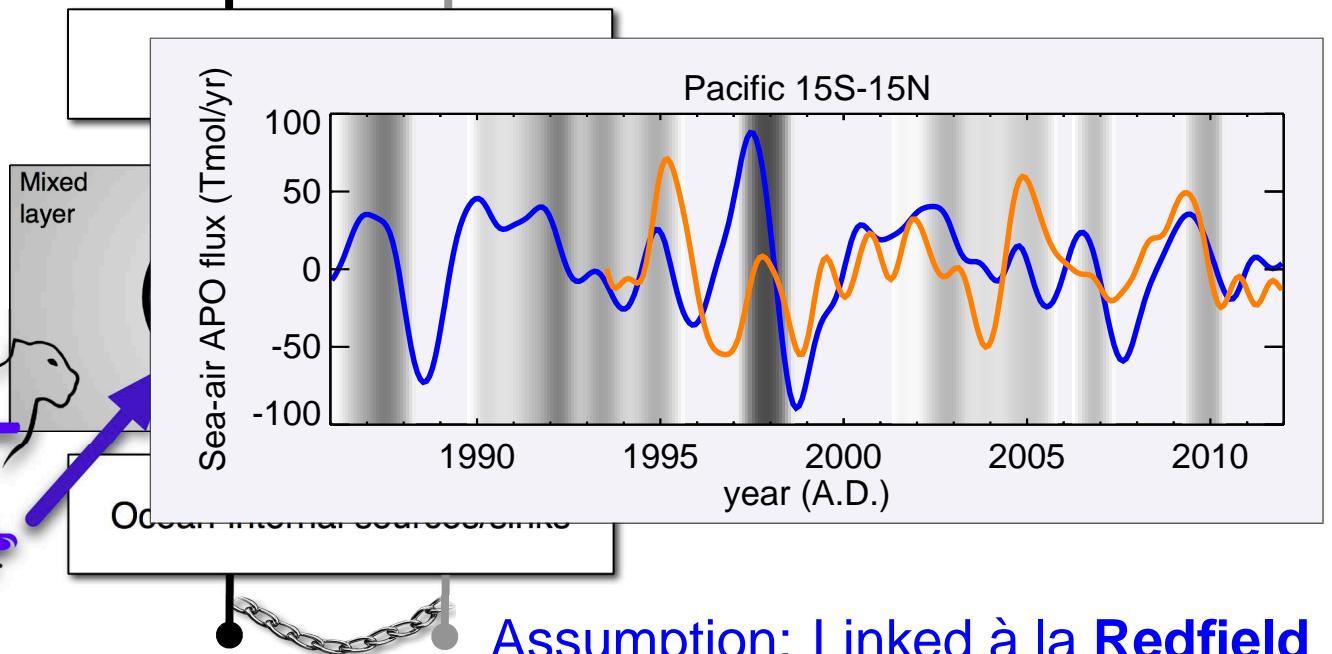
APO flux

inferred from APO inversion
inferred from pCO_2



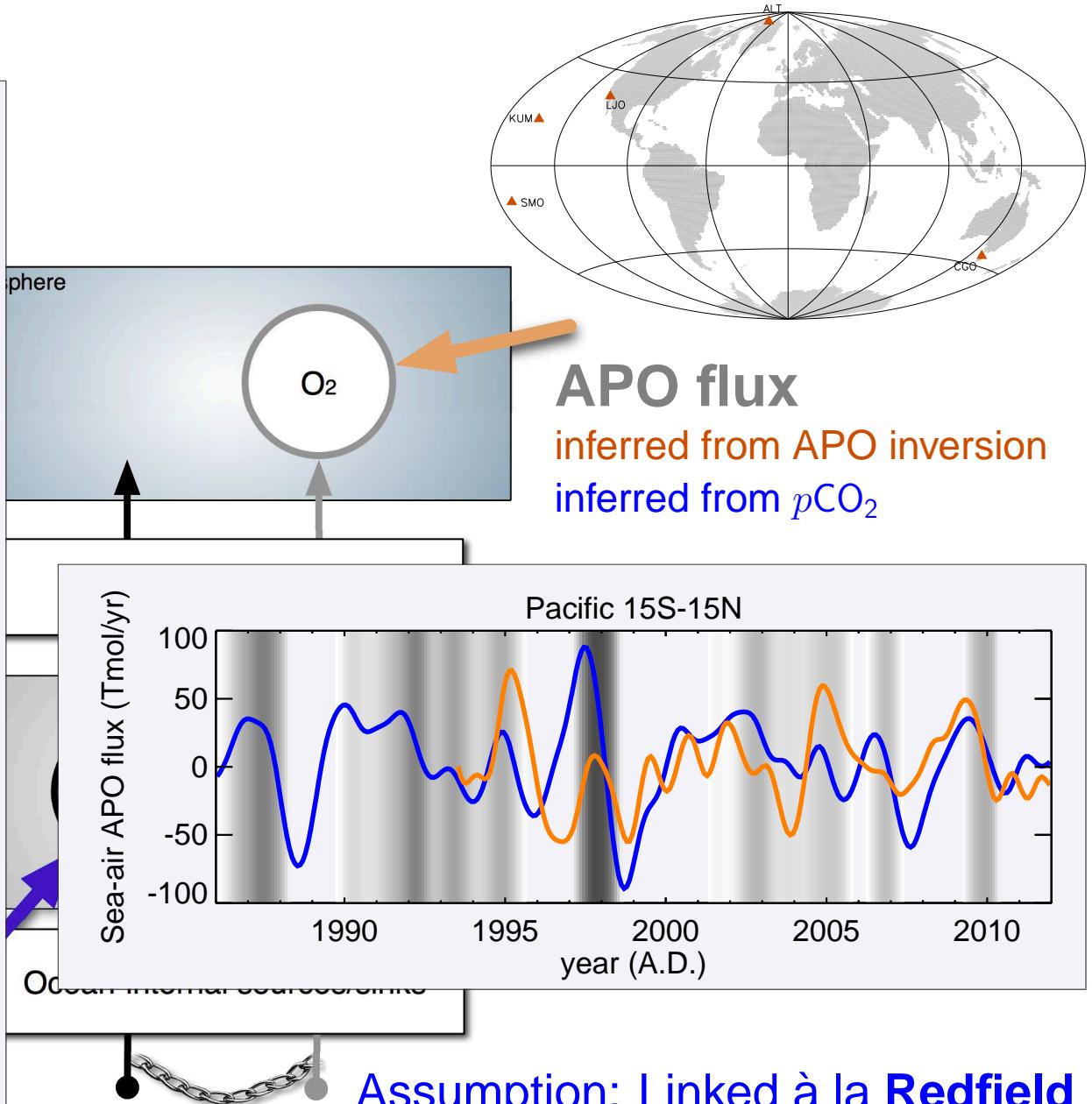
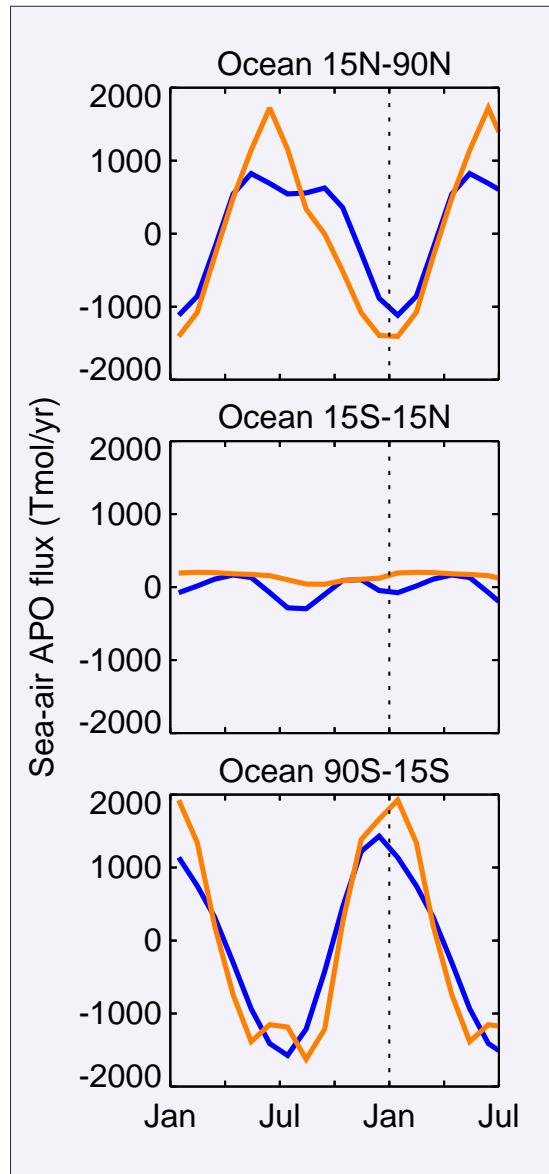


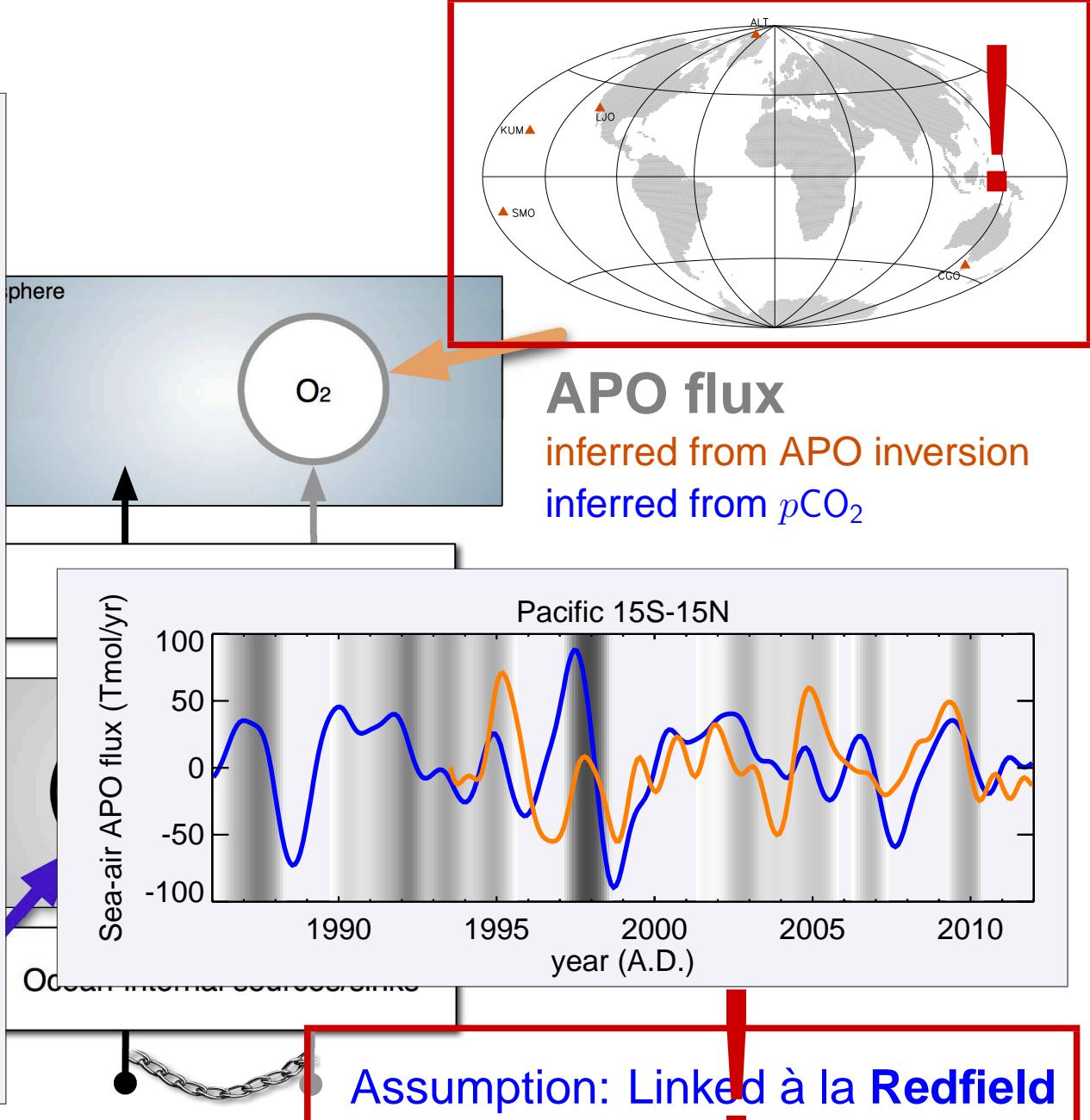
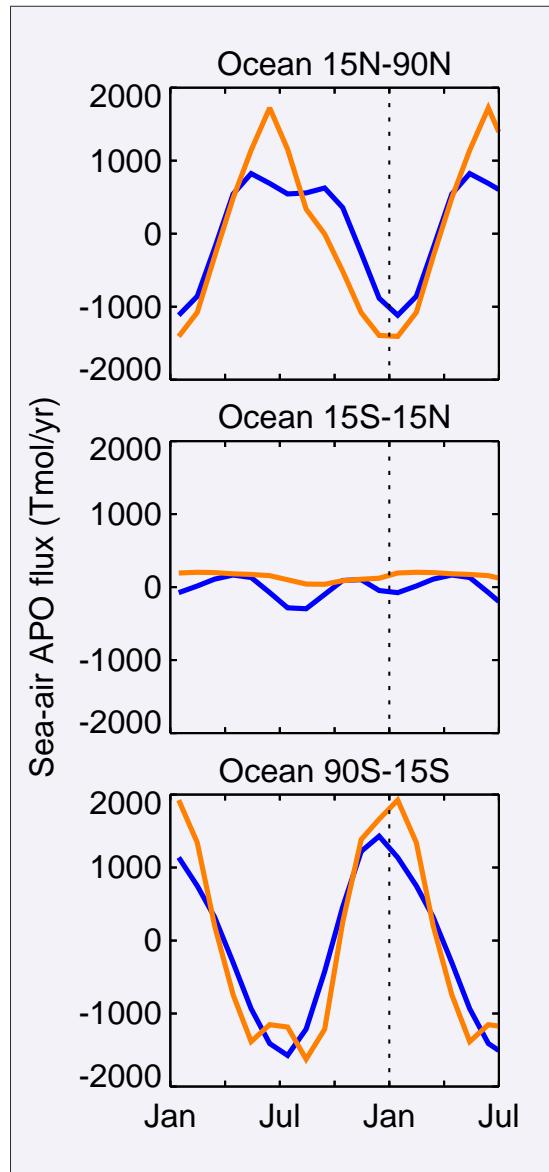
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Carbon Oxygen





Carbon Oxygen

Conclusions

Aim:

Quantify variability of ocean biogeochemistry
from data

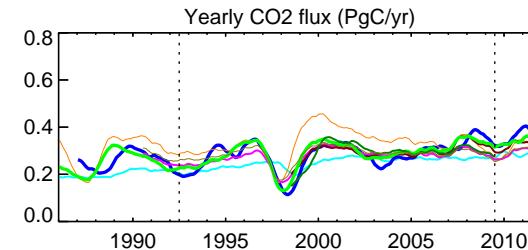
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$p\text{CO}_2$ constraint & mapping methods:

- Well-constrained seasonality
- IAV constrained e.g. in Eq. Pac.



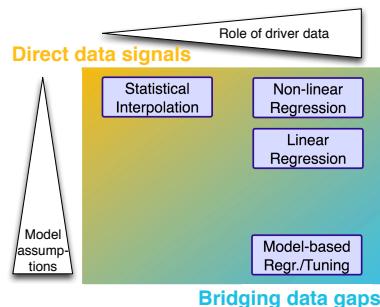
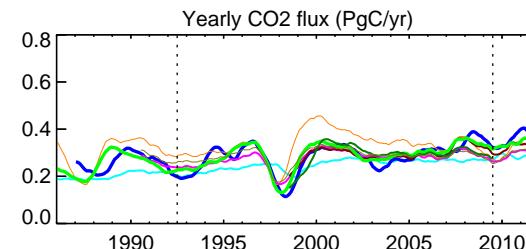
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Interpolation: Can *fit any IAV signals* in the data

Regression: Can *bridge temporal data gaps*

Robustness check through complementary methods

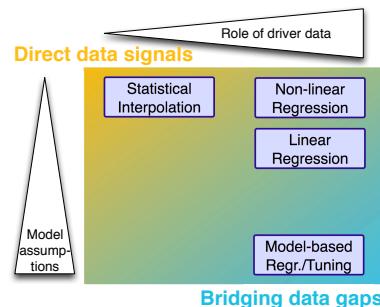
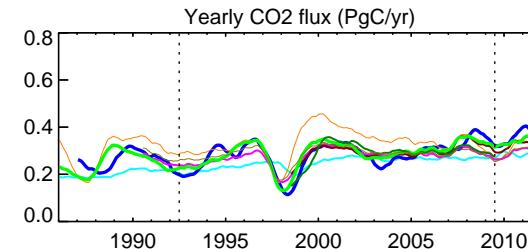
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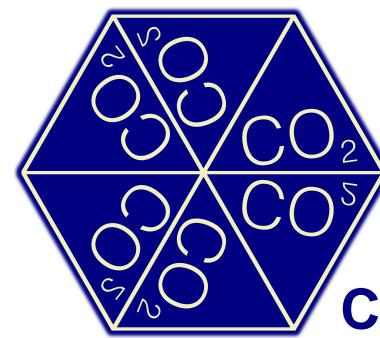


Interpolation: Can *fit any IAV signals* in the data

Regression: Can *bridge temporal data gaps*

Robustness check through complementary methods

Multiple constraints:
surface-ocean $p\text{CO}_2$ •
atmospheric CO_2 •
atmospheric O_2/N_2 •
combined through mixed-layer scheme



Jena
CarboScope