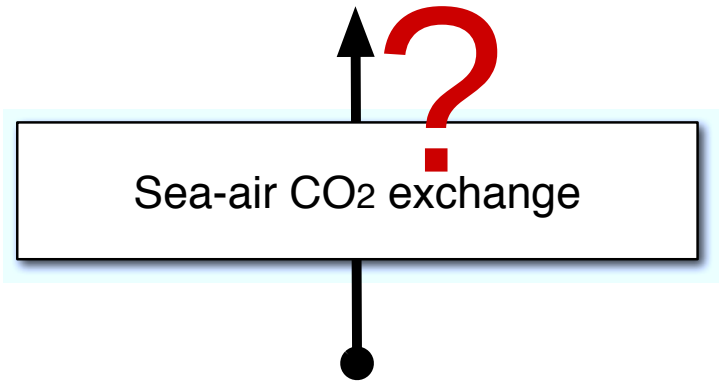
Global sea-air CO_2 flux variability estimated from SOCAT pCO_2 observations

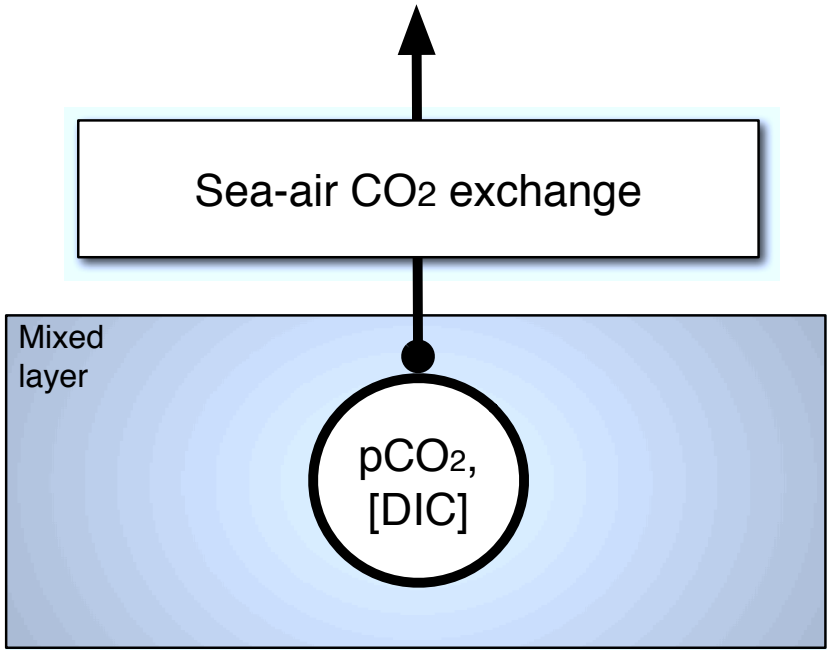
Christian Rödenbeck,
D. C. E. Bakker, N. Metzl, A. Olsen, C. Sabine,
N. Cassar, F. Reum,
R. Keeling, M. Heimann

Many thanks to:
Data contributors, DKRZ, CarboChange, IMBER / SOLAS

Aim: Data-based quantification



Mixed-Layer Scheme



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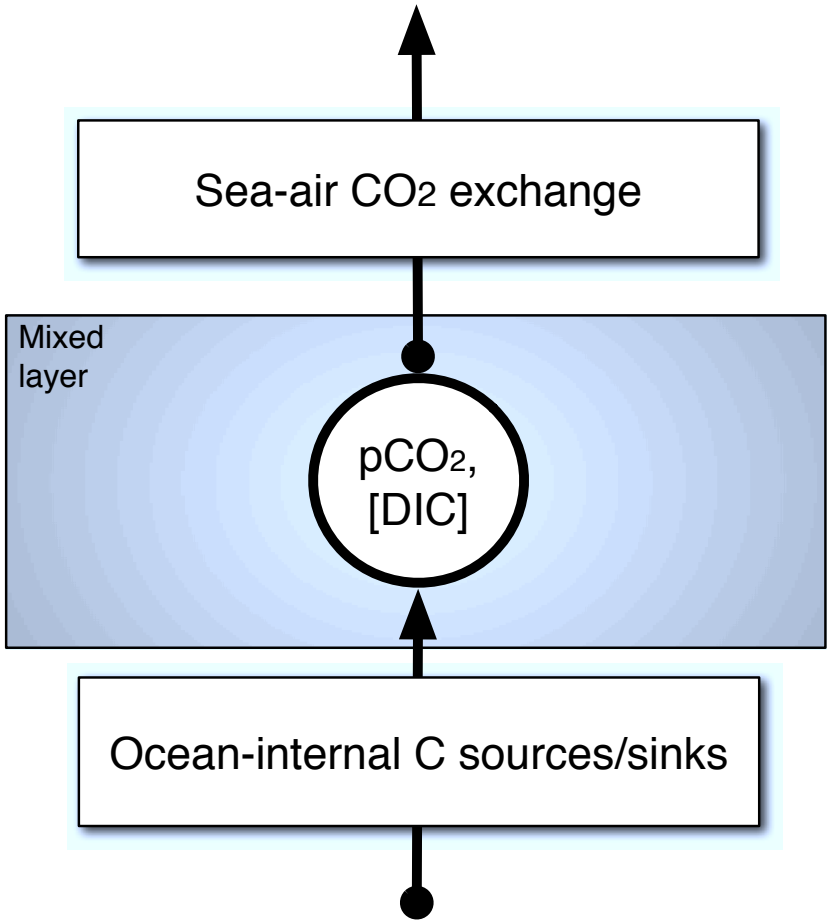

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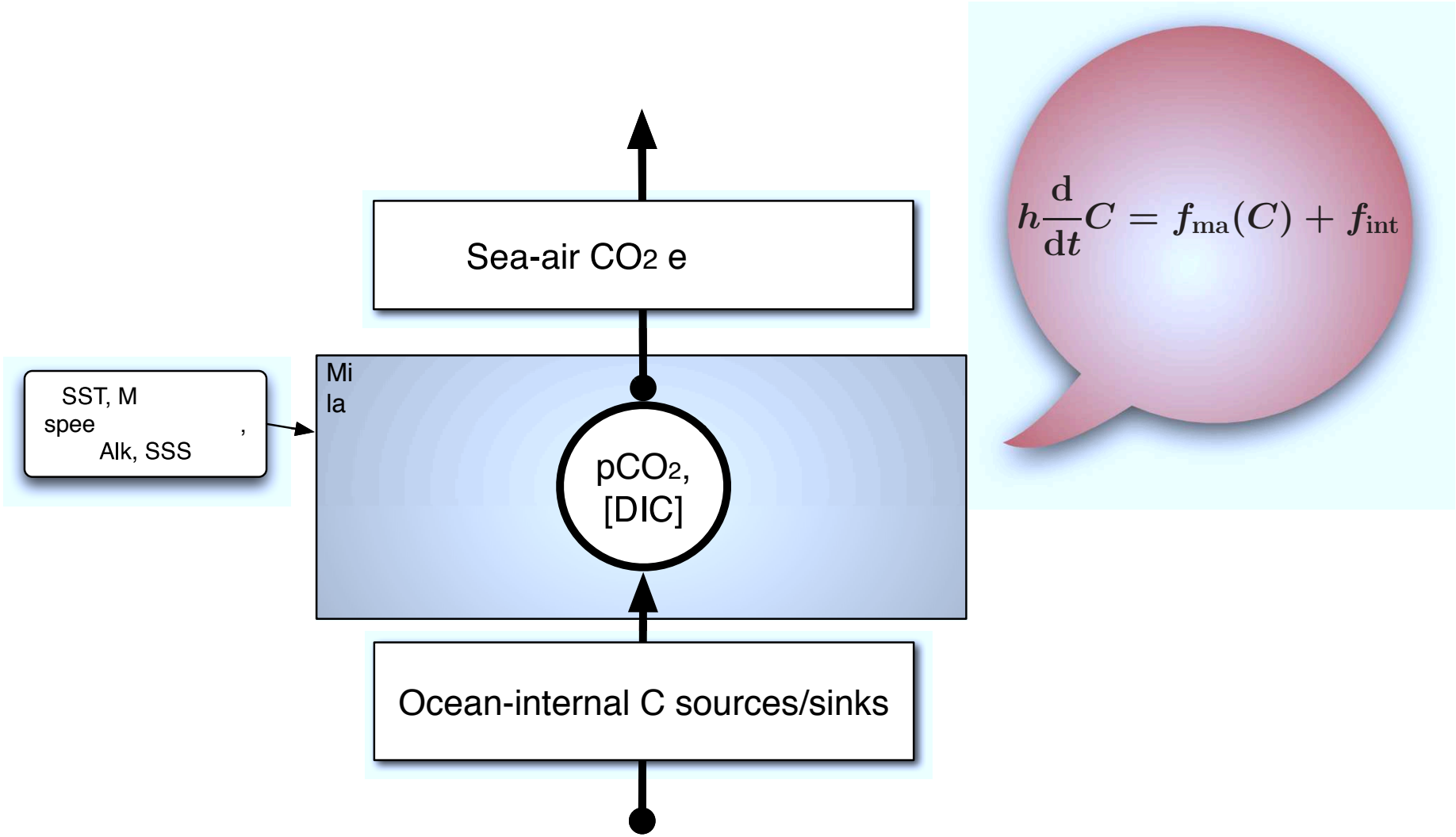

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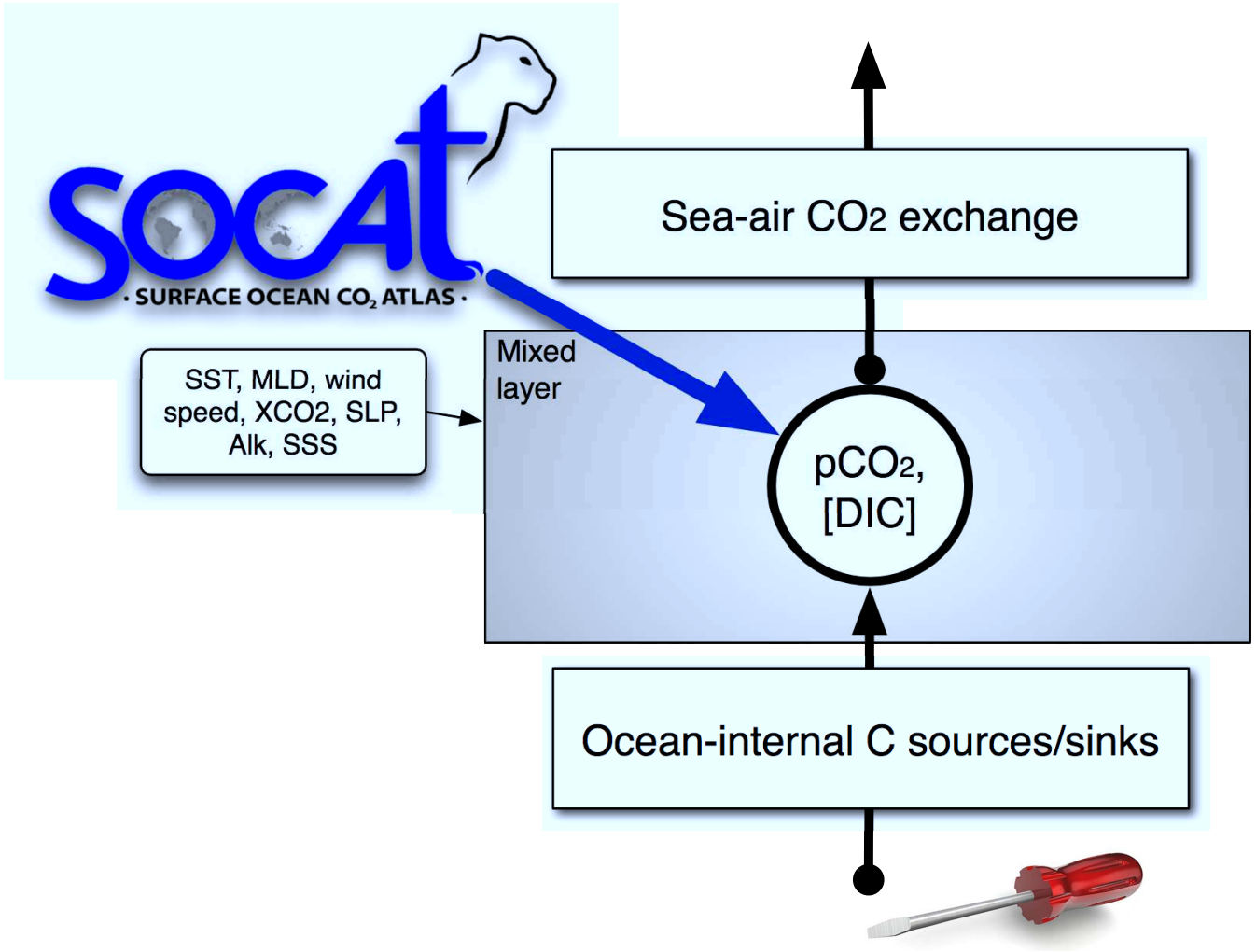
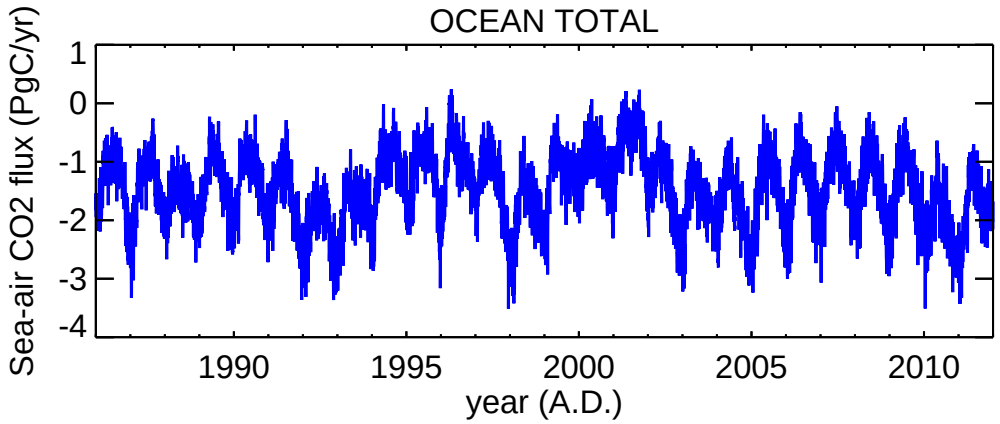
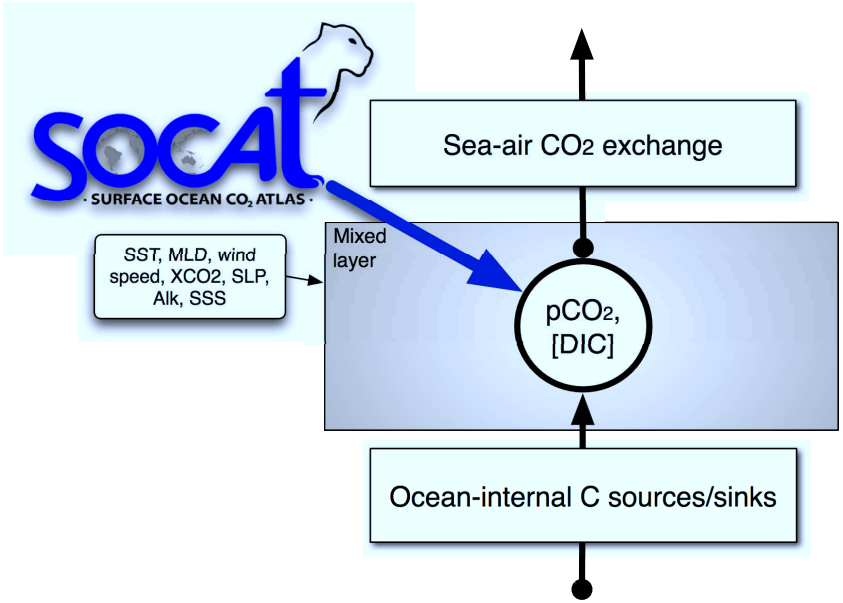
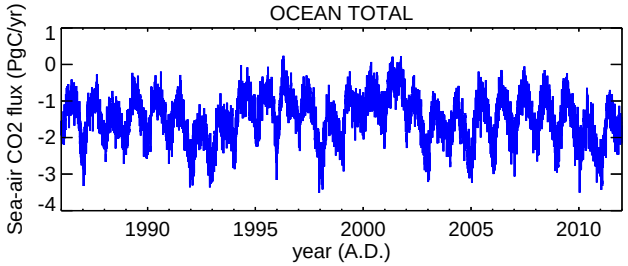



OCEAN TOTAL
Sea-air CO2 flux (PgC/yr)
1
0
-1
-2
-3
-4
1990
1995
2000
2005
2010
year (A.D.)


SOCAT
SURFACE OCEAN CO2 ATLAS
Sea-air CO2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
pCO2, [DIC]
Ocean-internal C sources/sinks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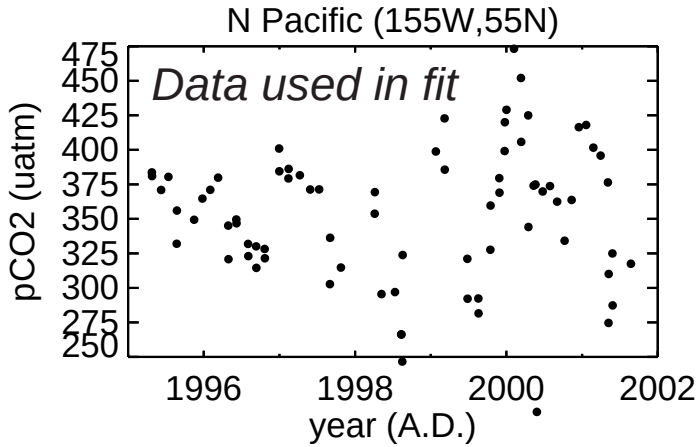
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Data used in fit
pCO2 (uatm)
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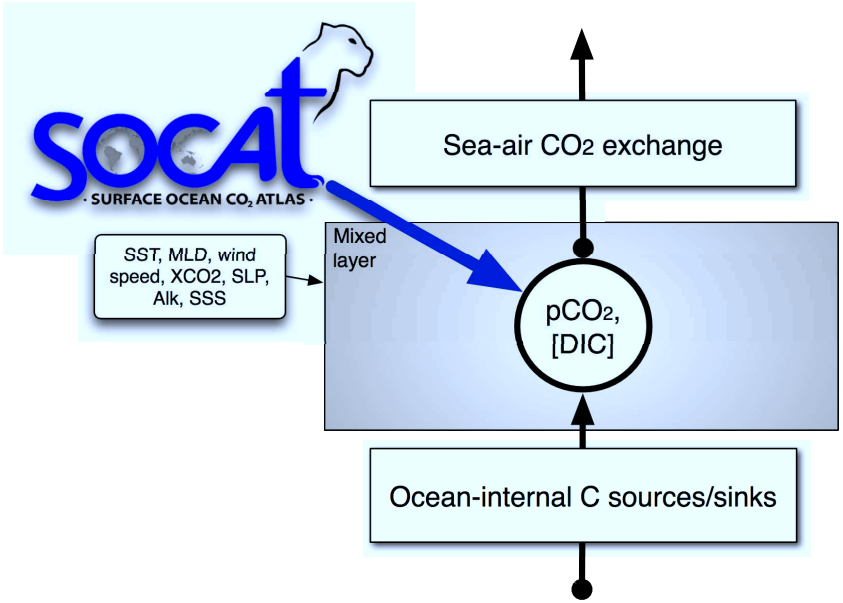
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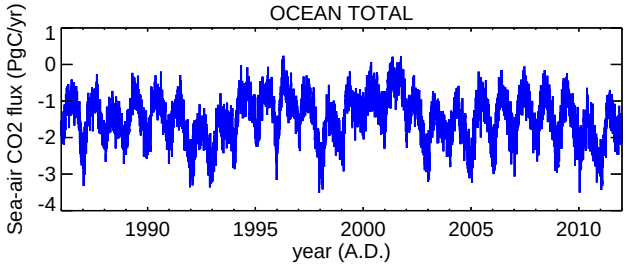
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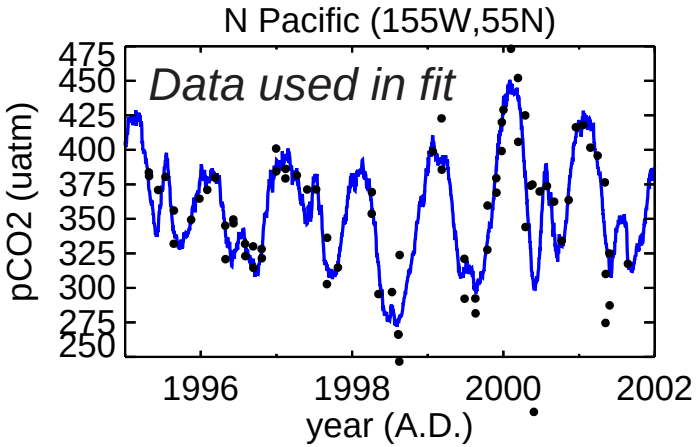
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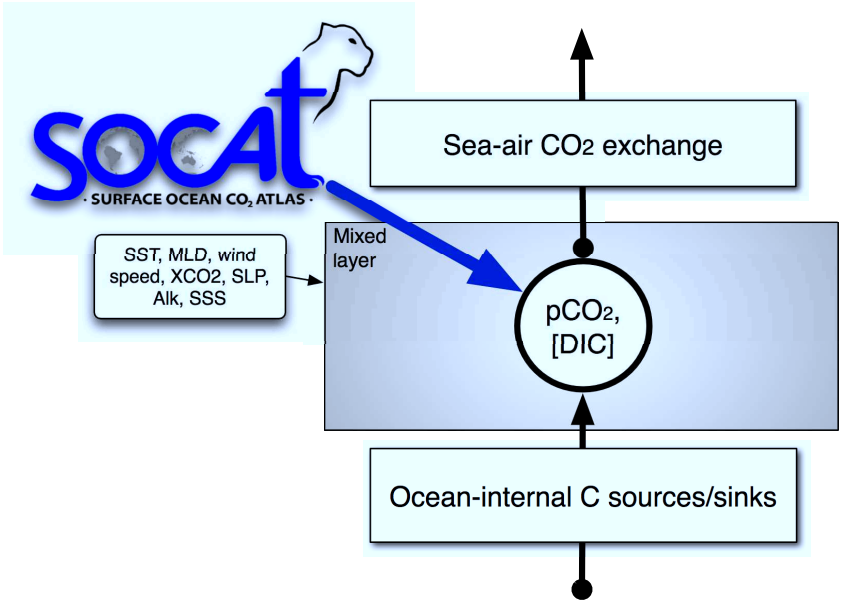
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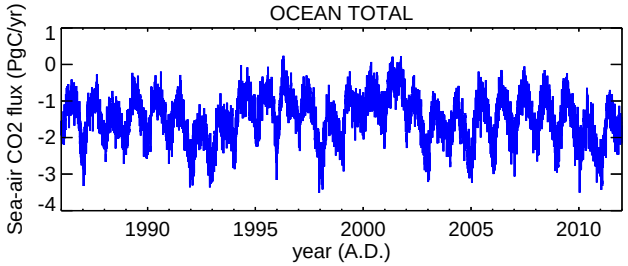
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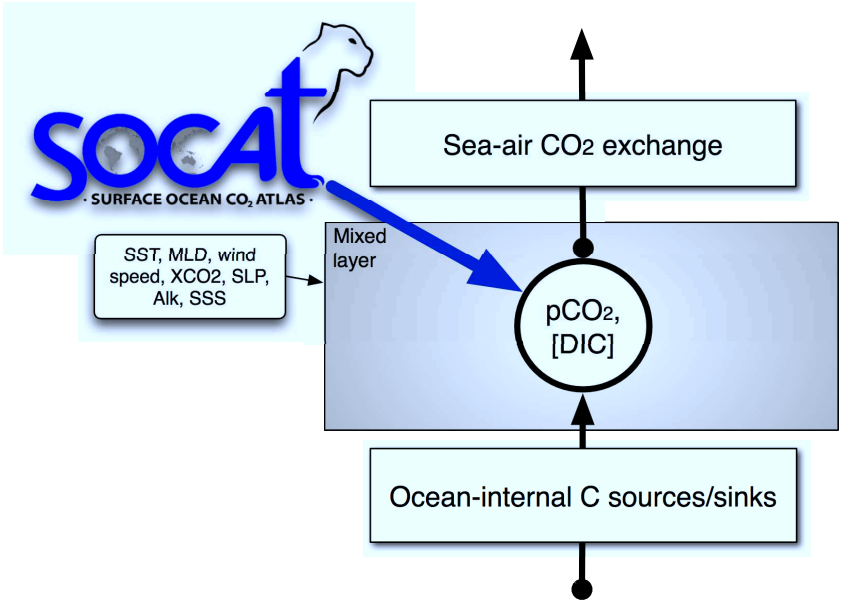
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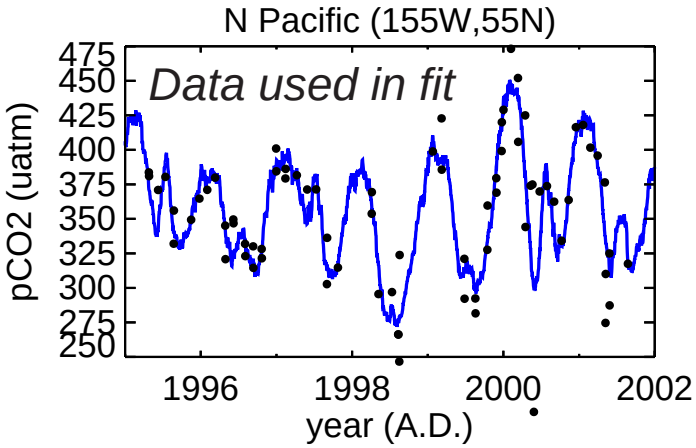
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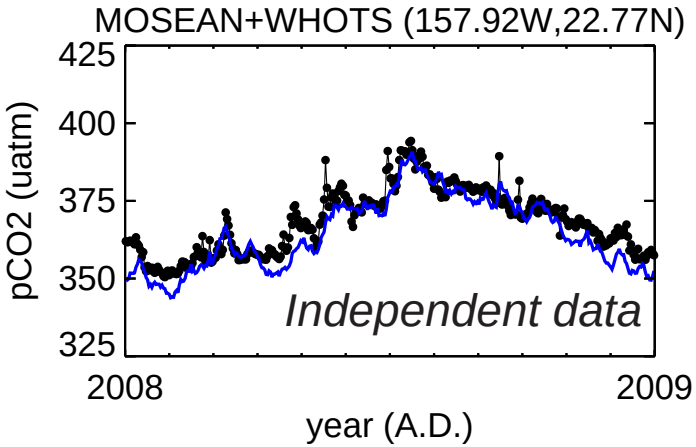
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Independent data
pCO2 (uatm)
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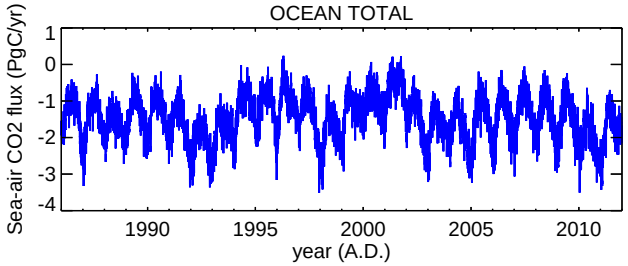
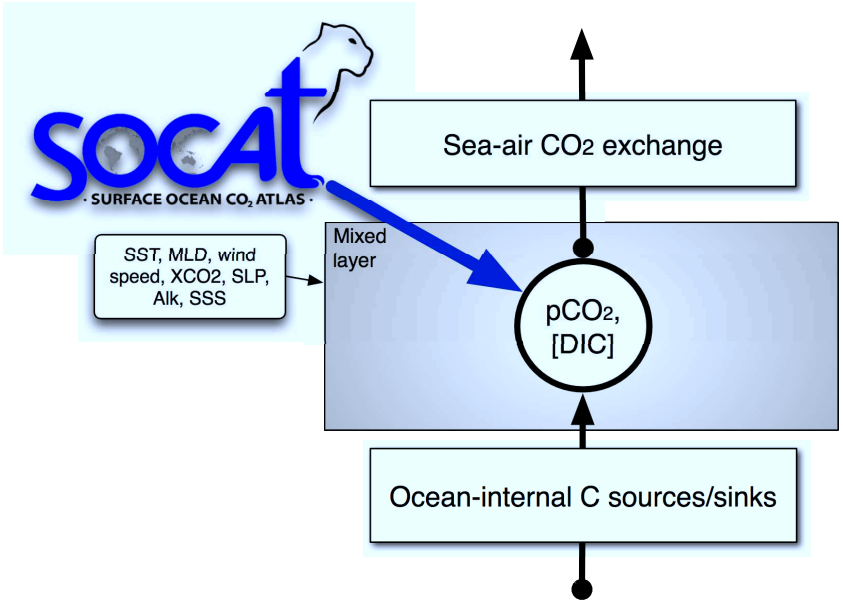
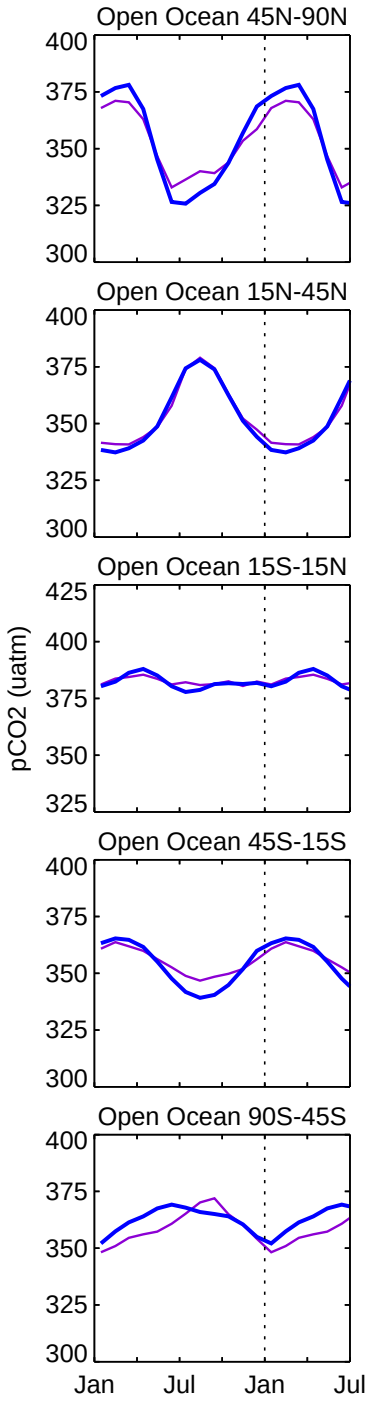
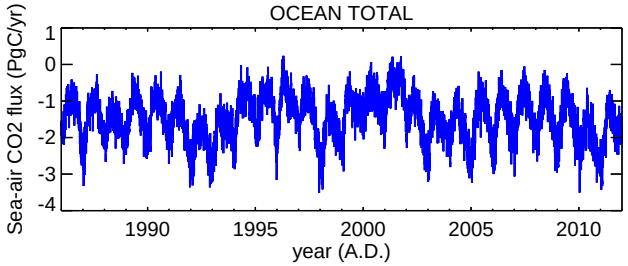






Takahashi climatology



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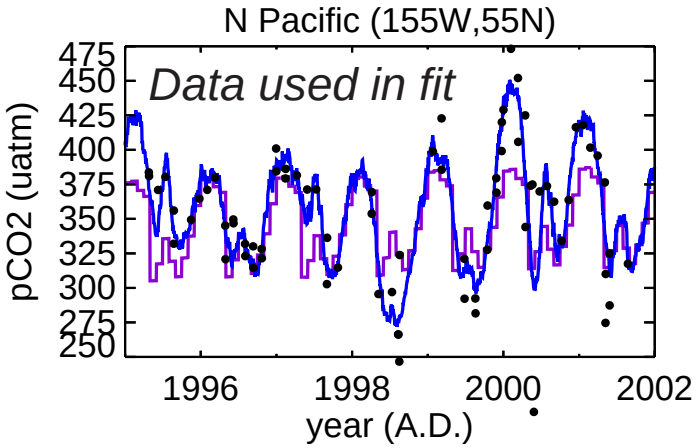
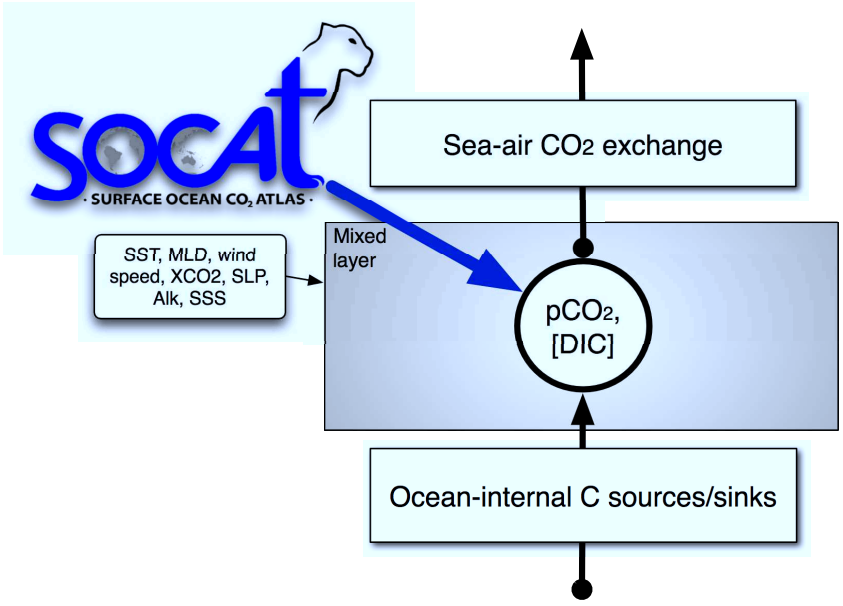
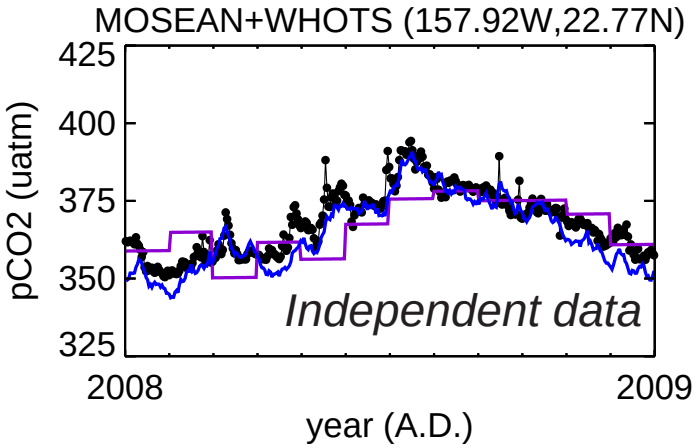
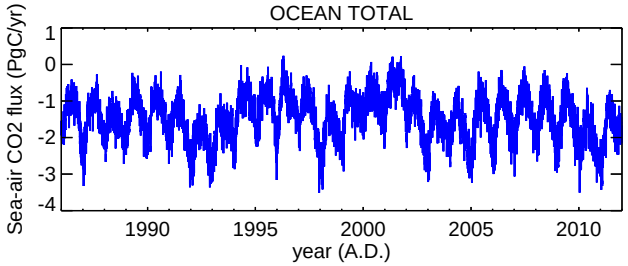








SOCAT · SURFACE OCEAN CO_2 ATLAS ·

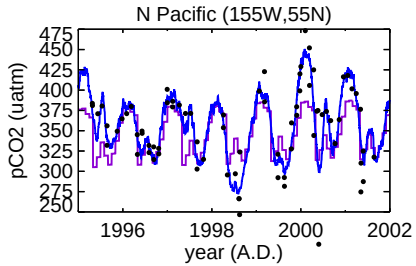
Sea-air CO_2 exchange

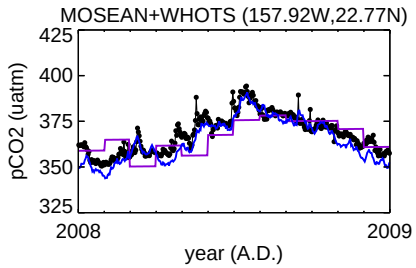
SST, MLD, wind speed, XCO2, SLP, Alk, SSS

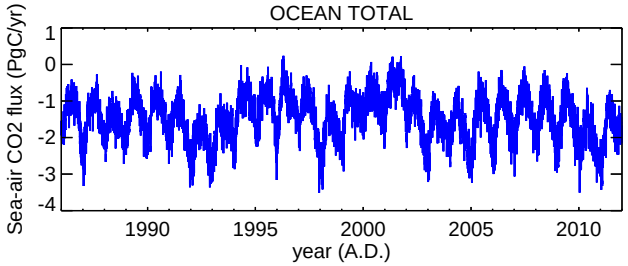
Mixed layer

pCO_2, [DIC]

Ocean-internal C sources/sinks







SOCAT · SURFACE OCEAN CO_2 ATLAS ·

Sea-air CO_2 exchange

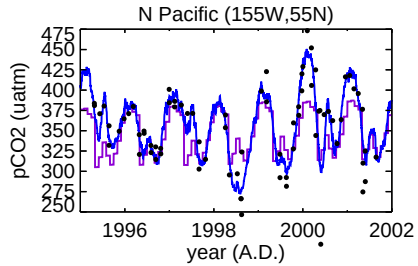
SST, MLD, wind speed, XCO2, SLP, Alk, SSS

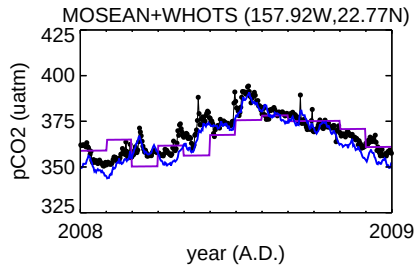
Mixed layer

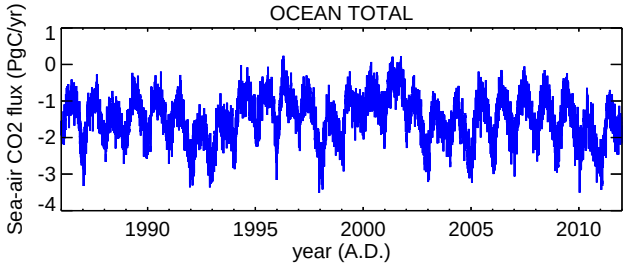
$[PO_4]$

pCO_2, [DIC]

Ocean-internal sources/sinks



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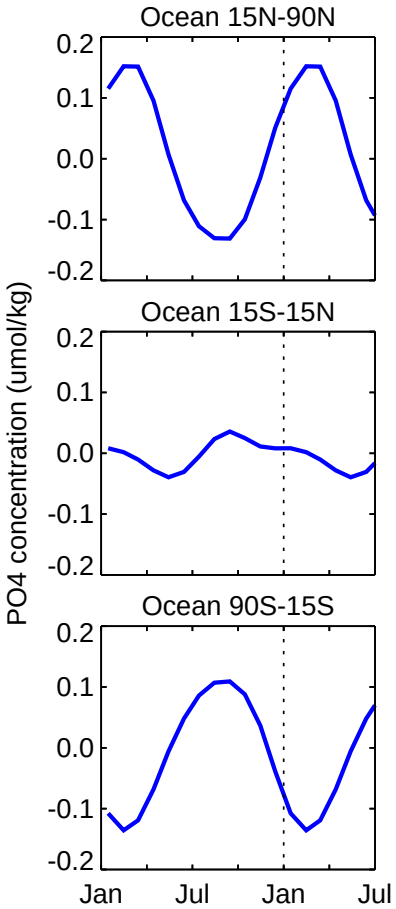
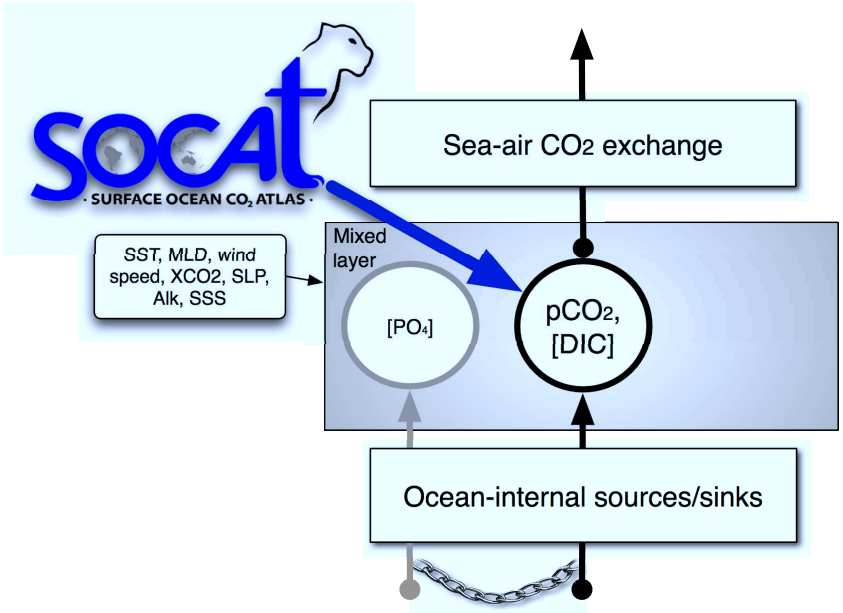

Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
0.2
0.1
0.0
-0.1
-0.2
Jan
Jul
Jan
Jul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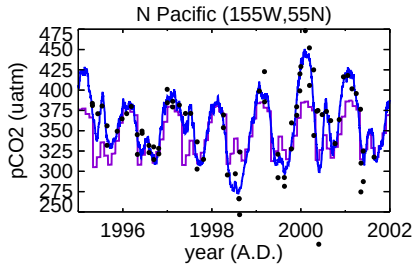
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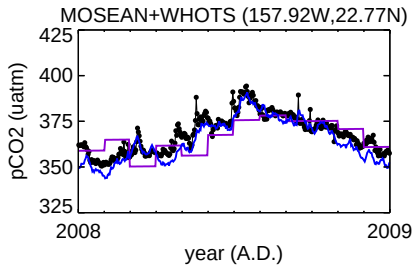
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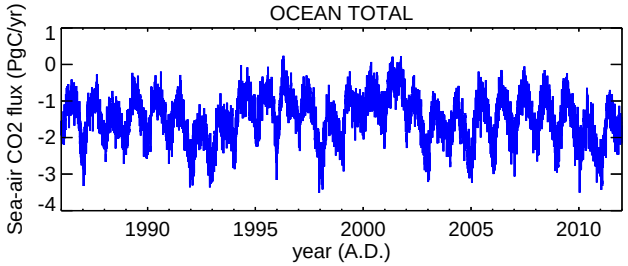
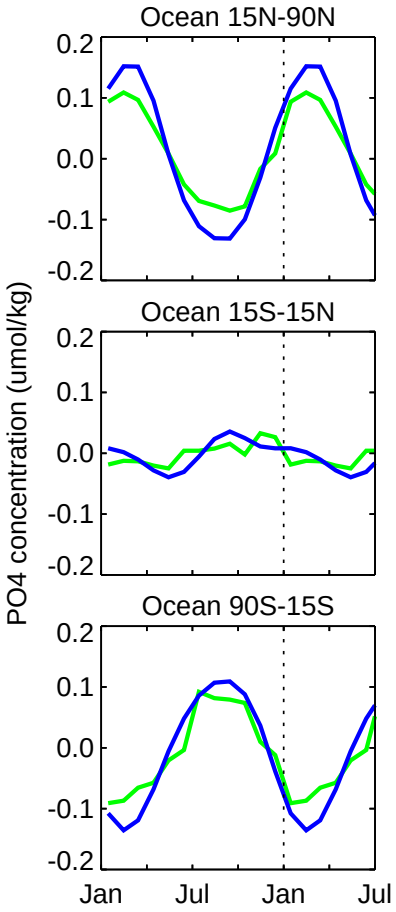
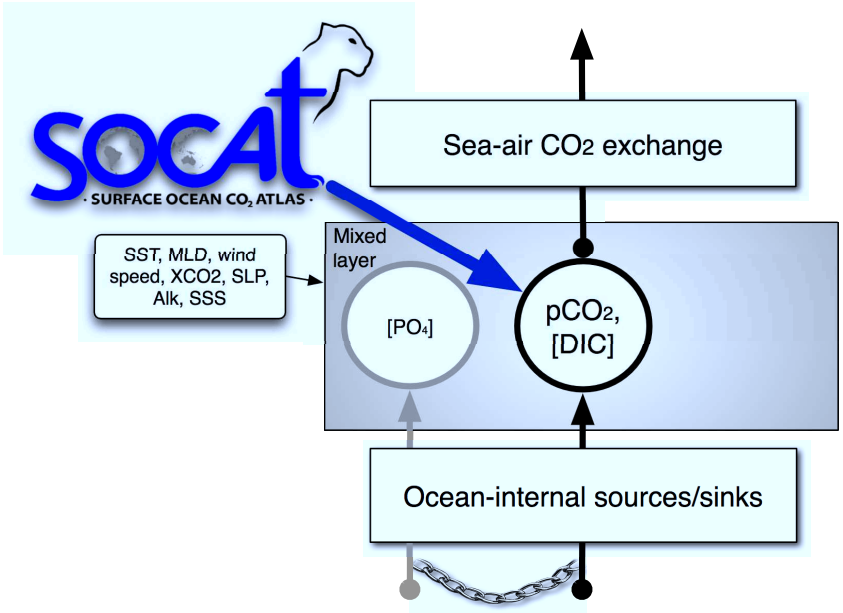
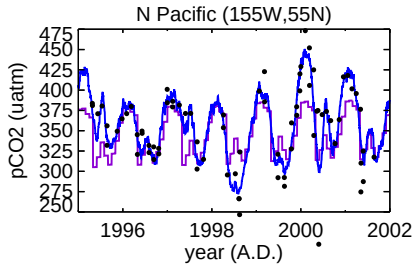
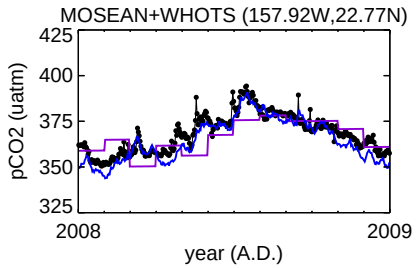


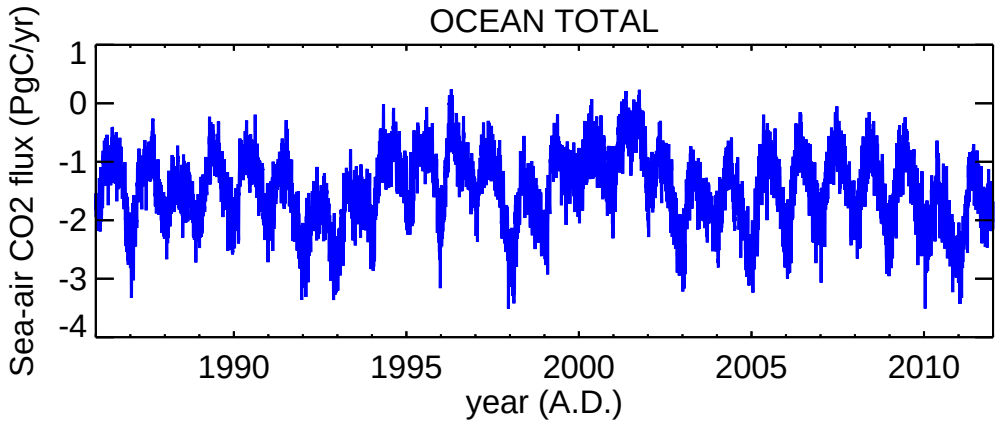
WOA nutrient climatology







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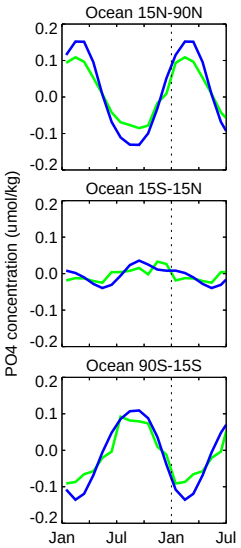
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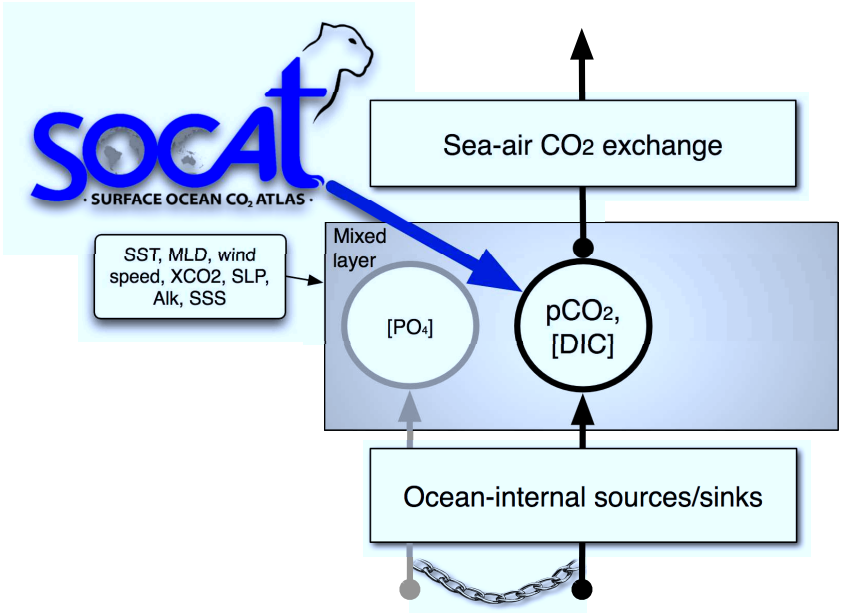
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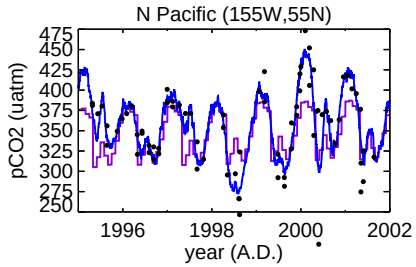
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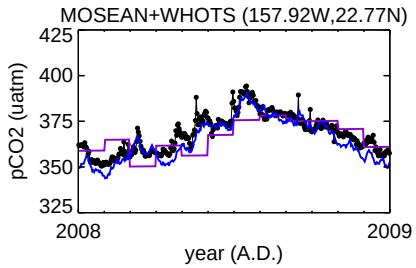
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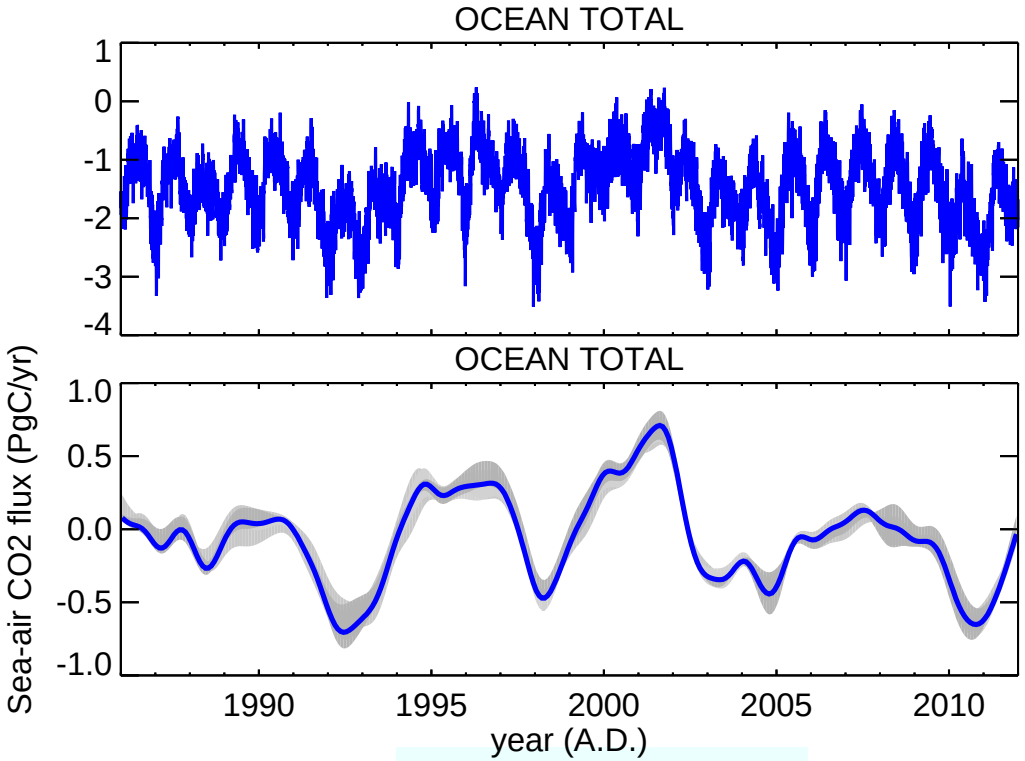
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OCEAN TOTAL
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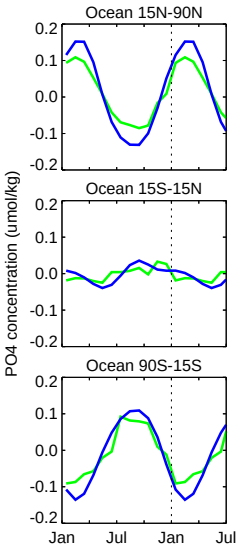
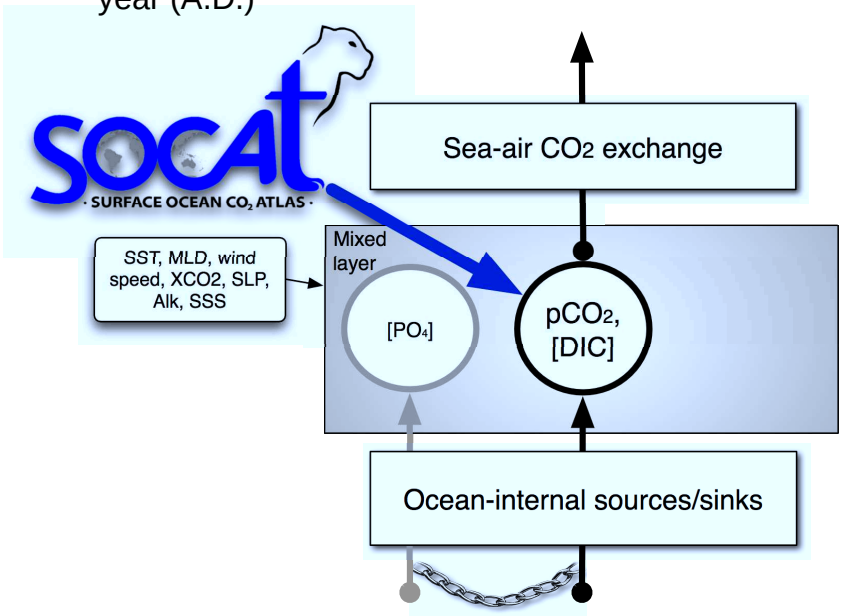
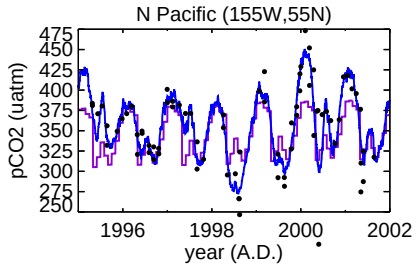
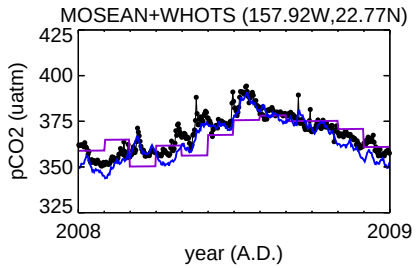
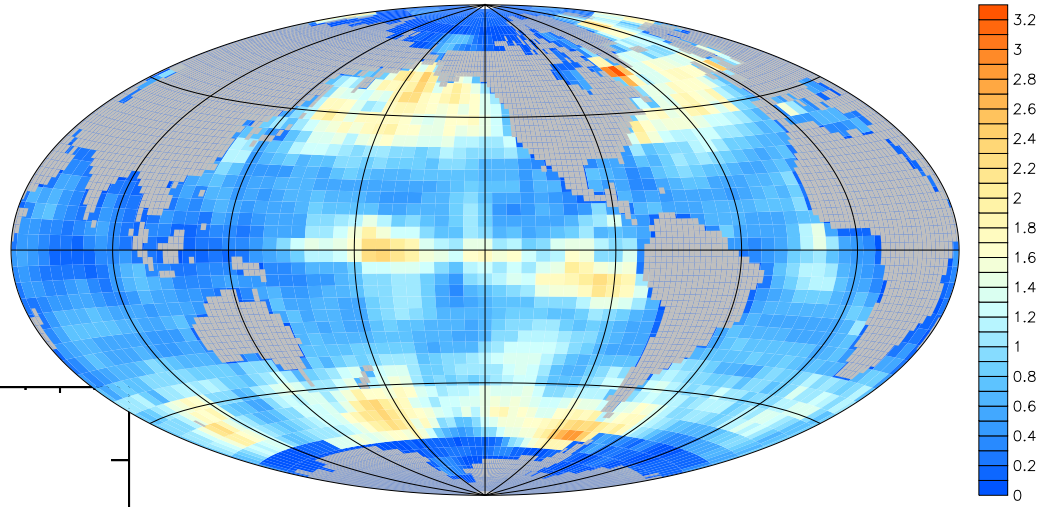
2010
year (A.D.)


Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
Jan
Jul
Jan
Jul

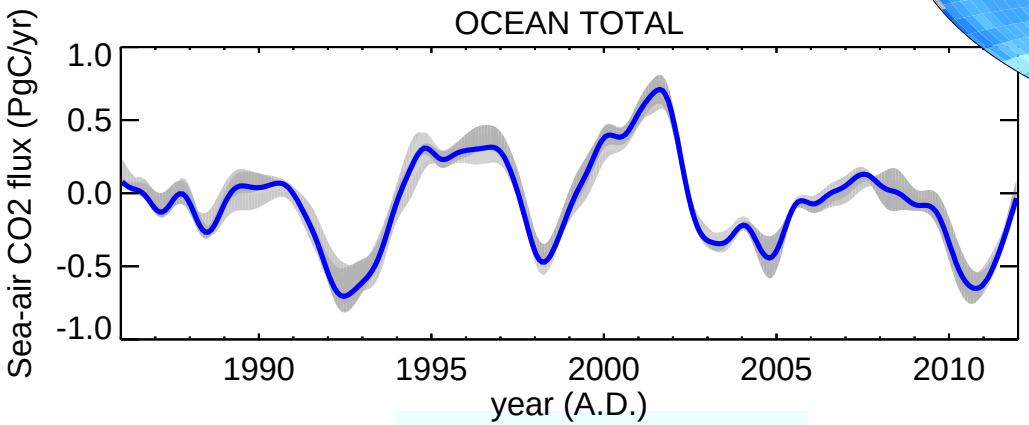

SOCAT
SURFACE OCEAN CO2 ATLAS
Sea-air CO2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
[PO4]
pCO2, [DIC]
Ocean-internal sources/sinks

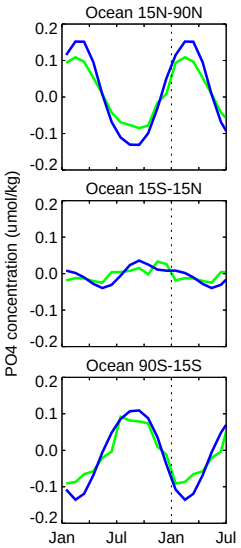

N Pacific (155W,55N)
pCO2 (uatm)
1996
1998
2000
2002
year (A.D.)

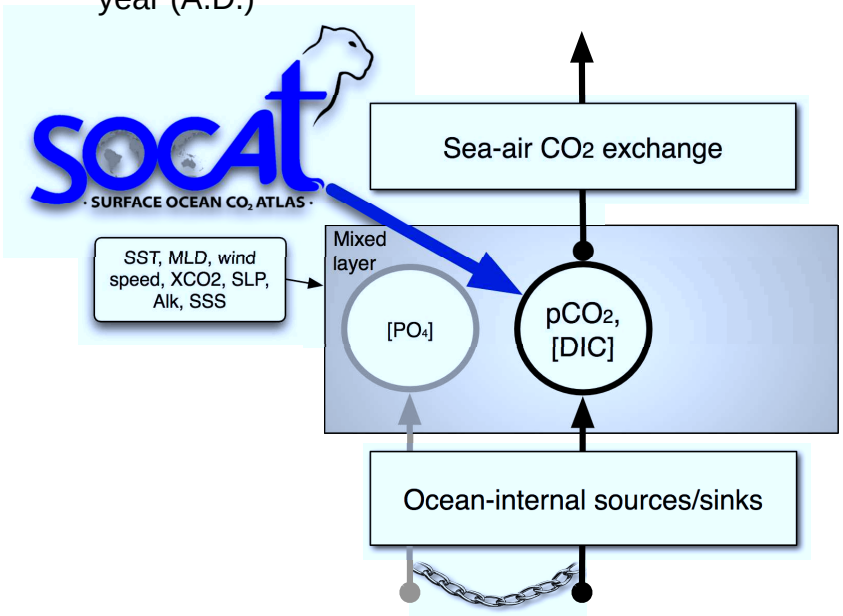

MOSEAN+WHOTS (157.92W,22.77N)
pCO2 (uatm)
2008
2009
year (A.D.)

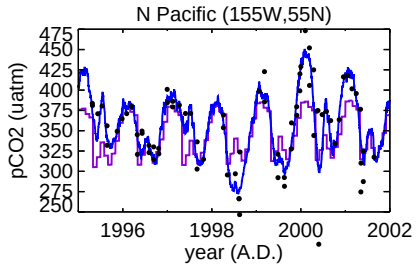


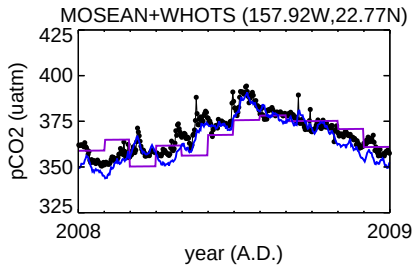
Std.dev. of flux IAV

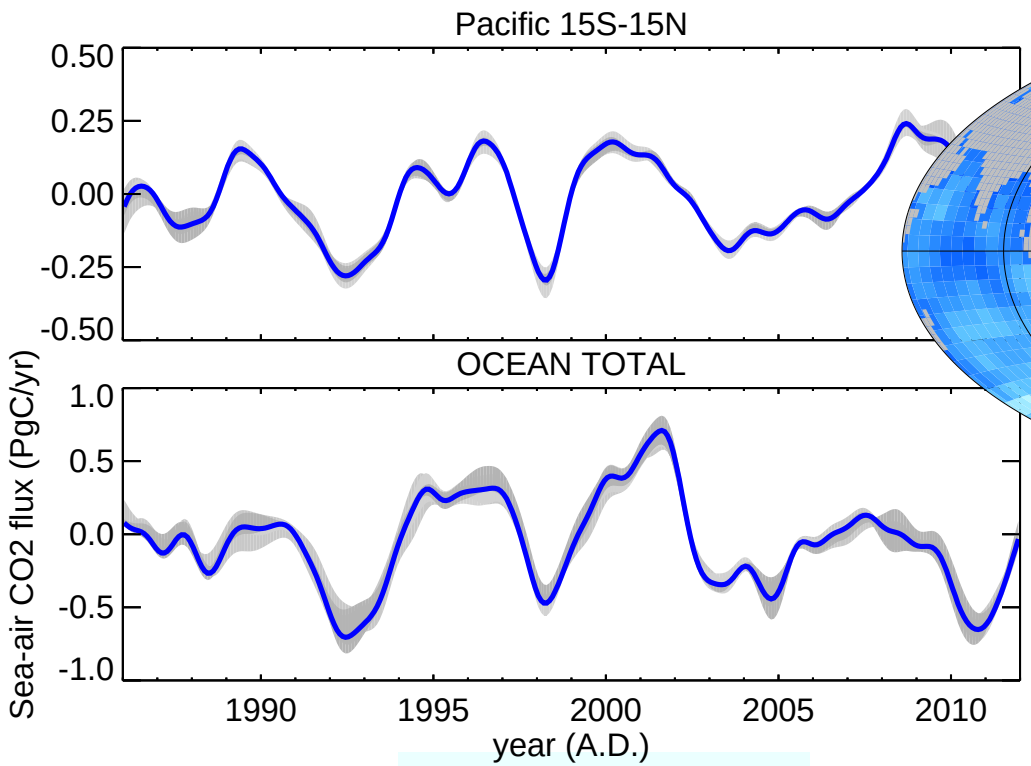


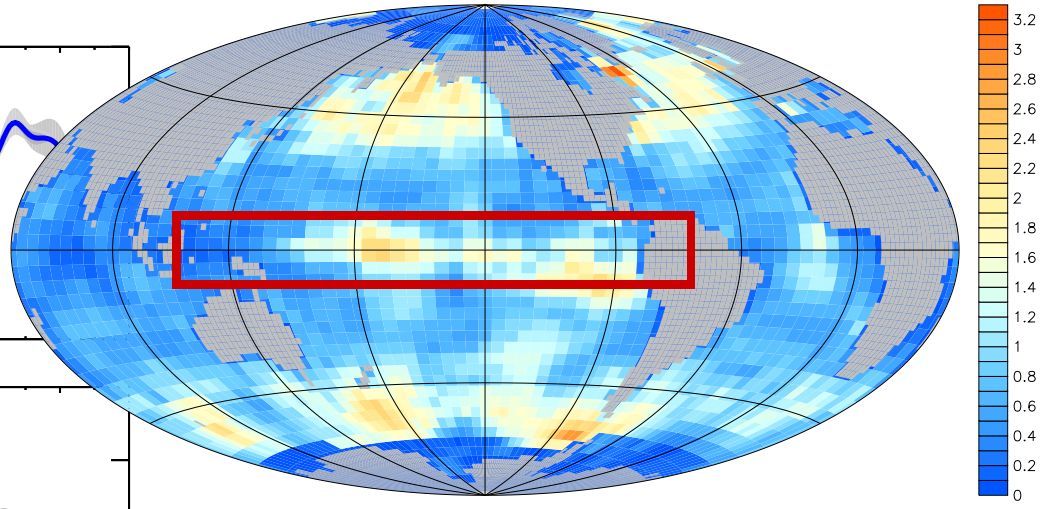




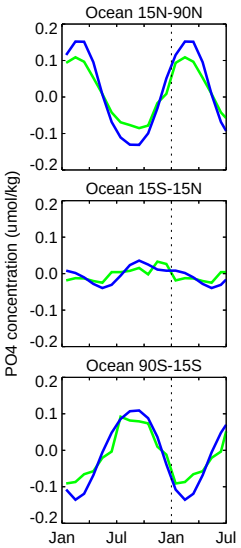


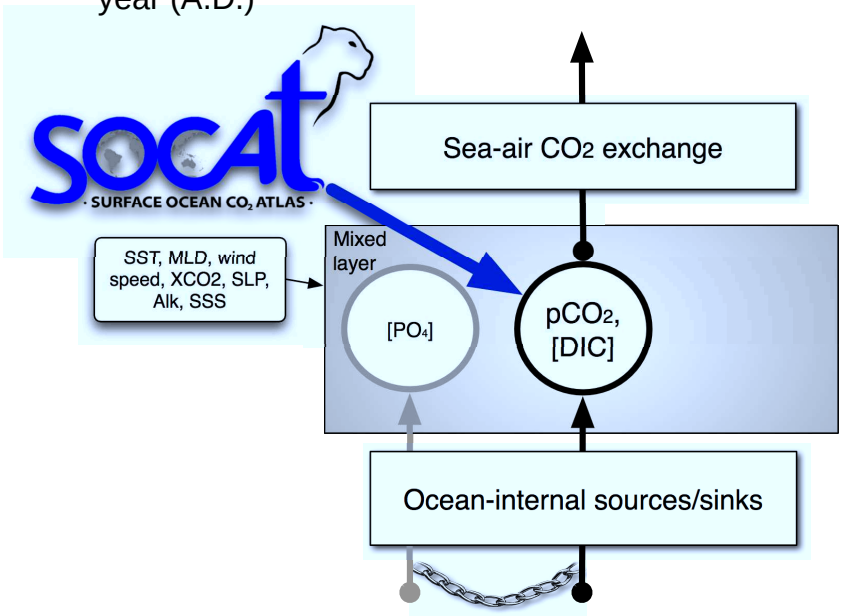


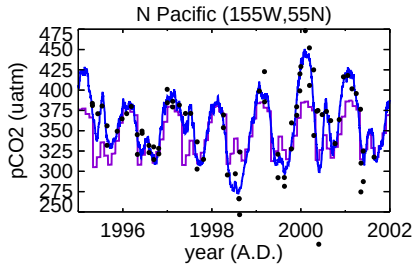


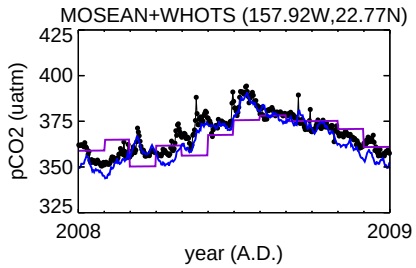


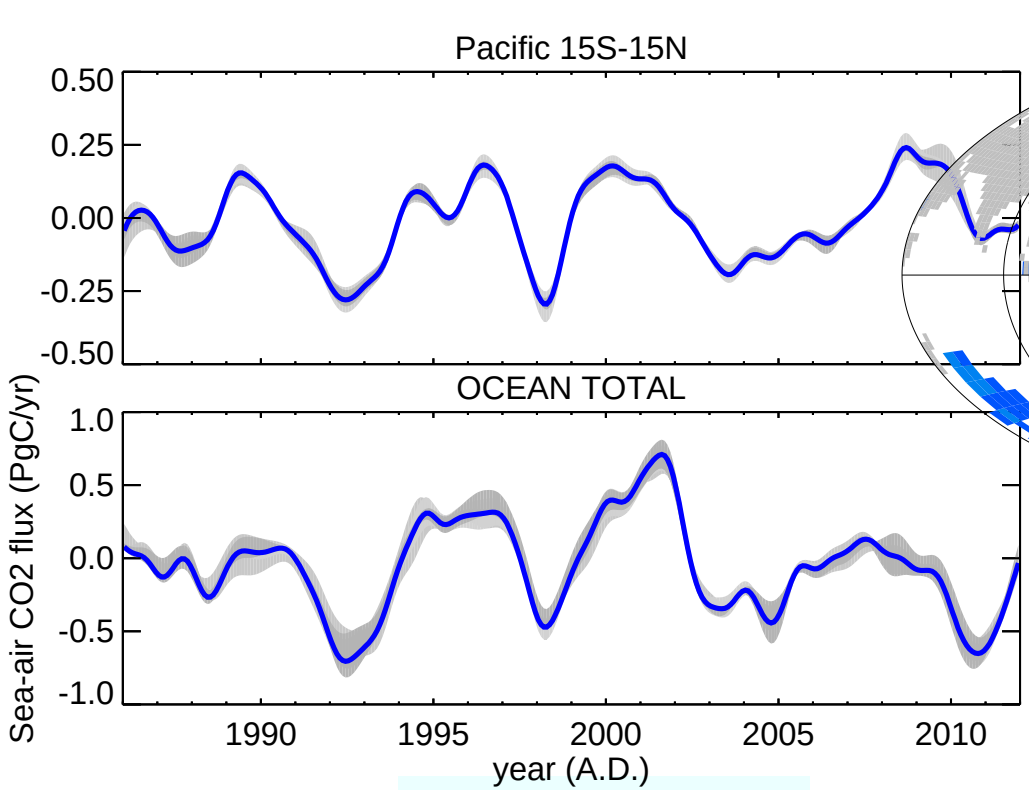
Std.dev. of flux IAV

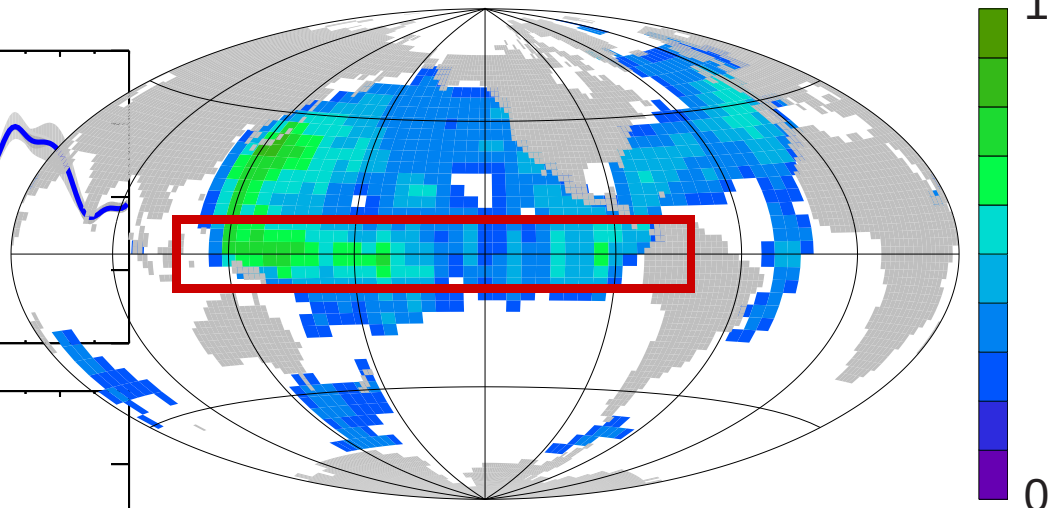






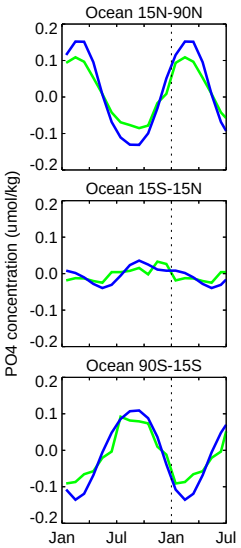


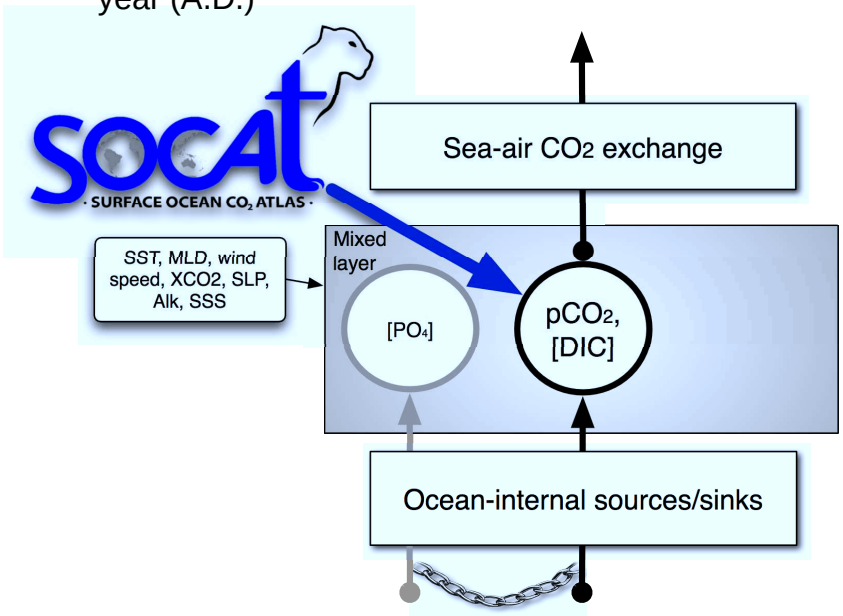


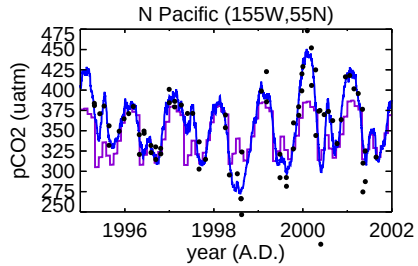


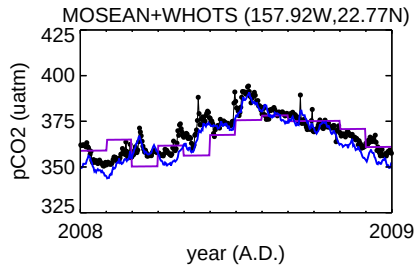
$$\left(1 - \frac{\sigma_{\text{post}}}{\sigma_{\text{pri}}}\right)$$

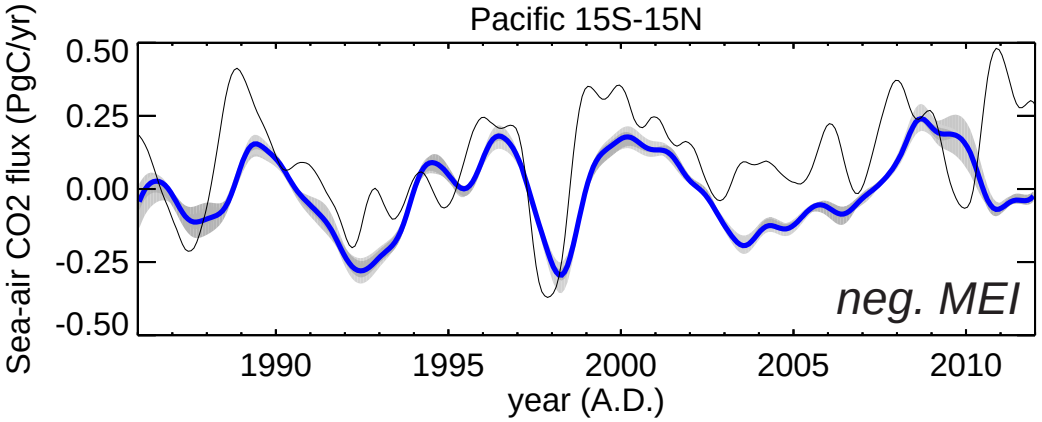
Reduction of Uncertainty of flux IAV

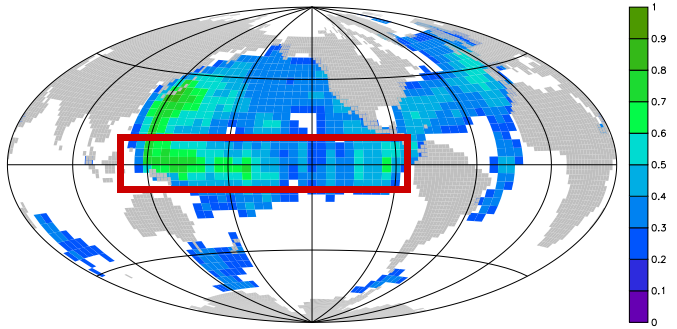


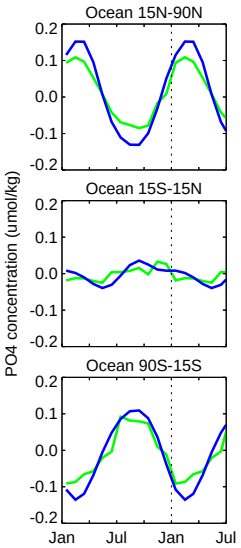


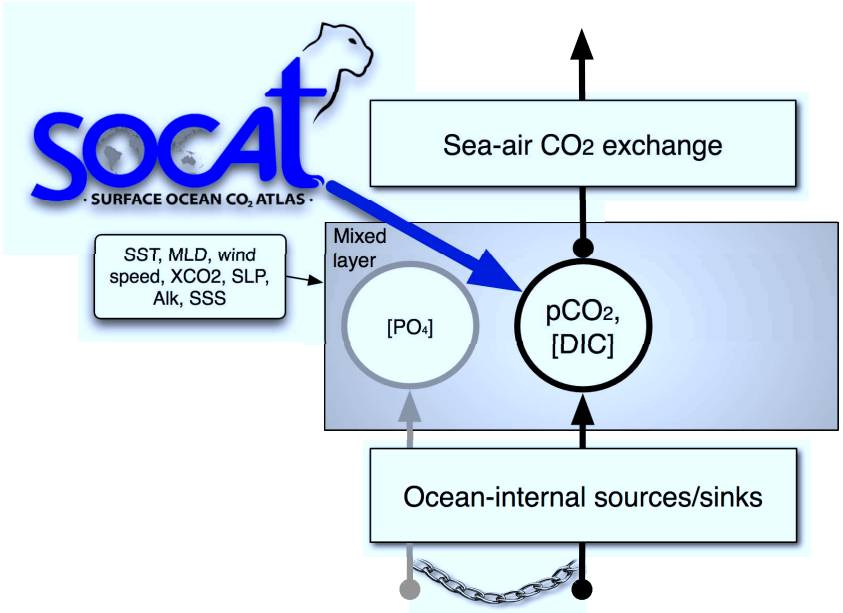


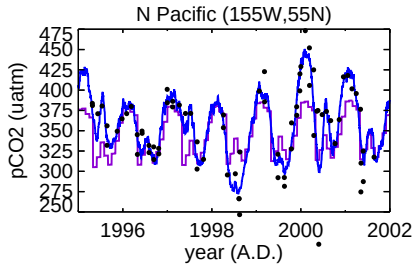


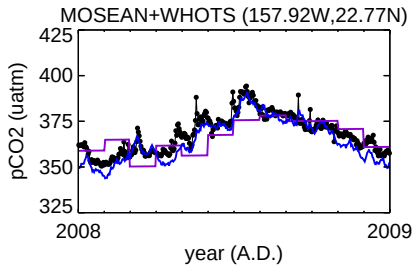

Pacific 15S-15N
Sea-air CO2 flux (PgC/yr)
0.50
0.25
0.00
-0.25
-0.50
1990
1995
2000
2005
2010
year (A.D.)
neg. MEI

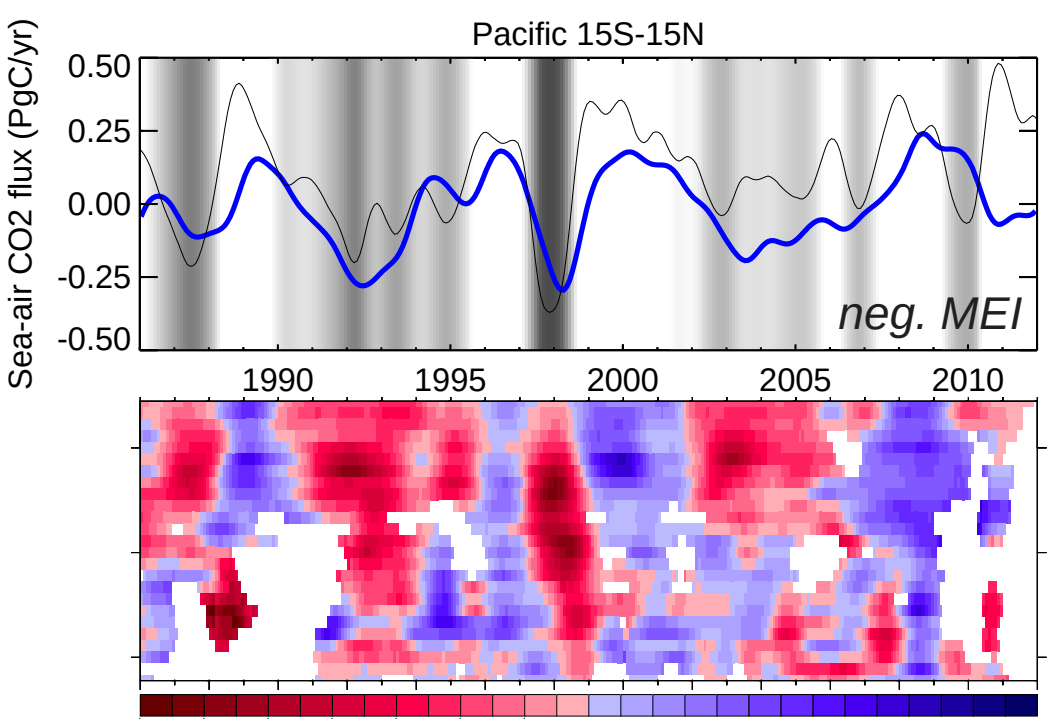

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

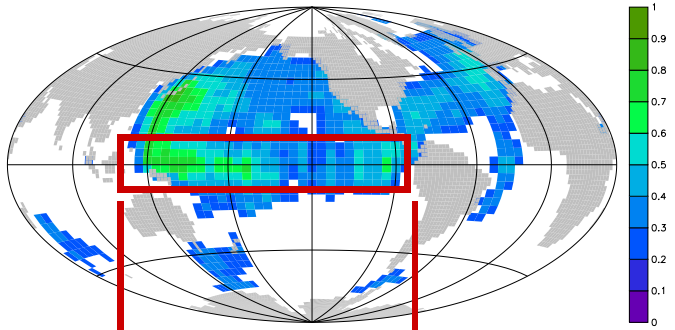

Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
0.2
0.1
0.0
-0.1
-0.2
Jan
Jul
Jan
Jul

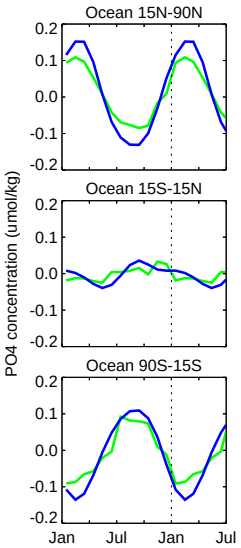

SOCAT
SURFACE OCEAN CO2 ATLAS
Sea-air CO2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
[PO4]
pCO2, [DIC]
Ocean-internal sources/sinks

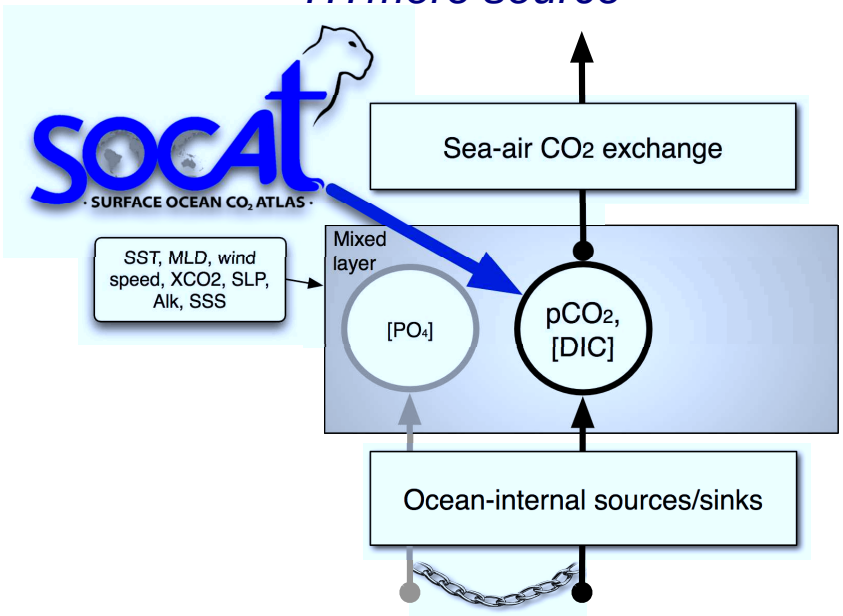

N Pacific (155W,55N)
pCO2 (uatm)
475
450
425
400
375
350
325
300
275
250
1996
1998
2000
2002
year (A.D.)

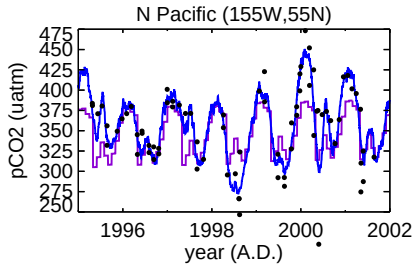

MOSEAN+WHOTS (157.92W,22.77N)
pCO2 (uatm)
425
400
375
350
325
2008
2009
year (A.D.)

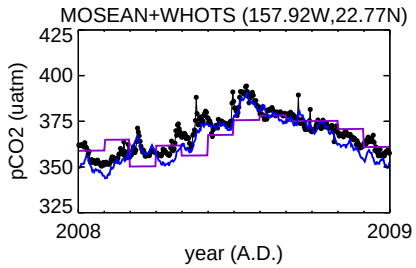

Pacific 15S-15N
Sea-air CO2 flux (PgC/yr)
0.50
0.25
0.00
-0.25
-0.50
neg. MEI
1990
1995
2000
2005
2010
180°W
90°W
More sink. . .
. . . more source

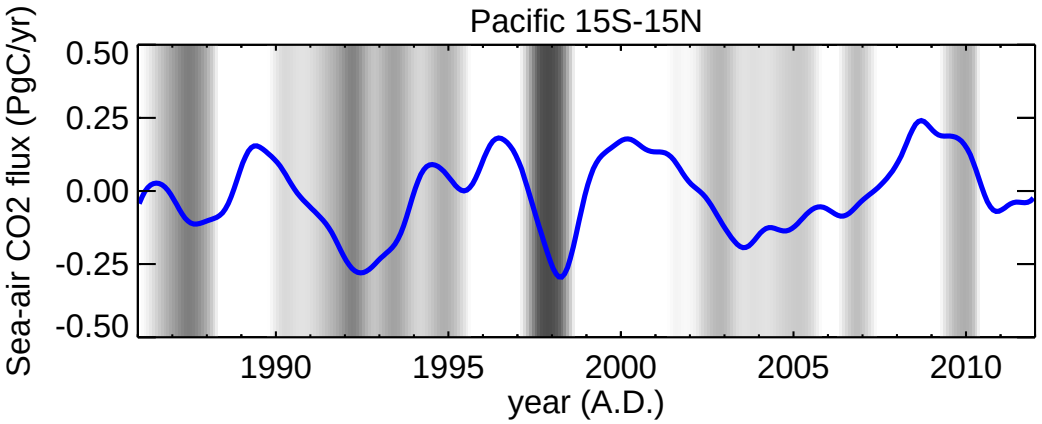


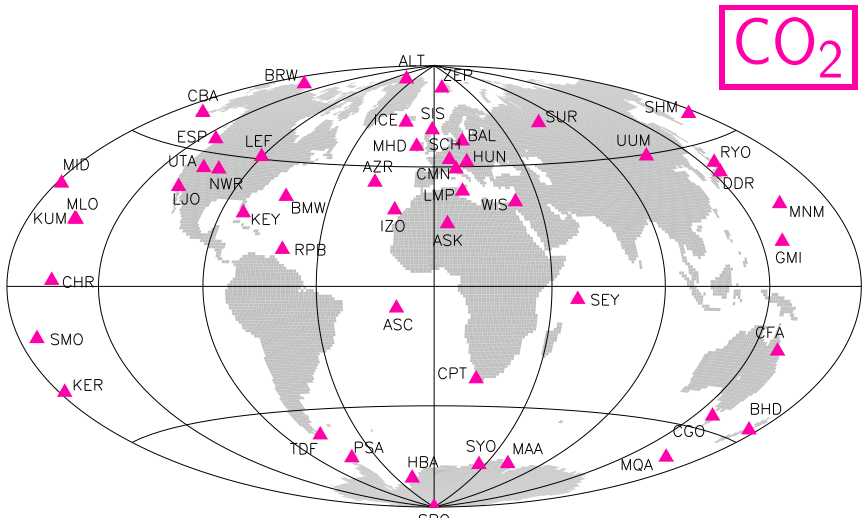

Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
Jan
Jul
Jan
Jul

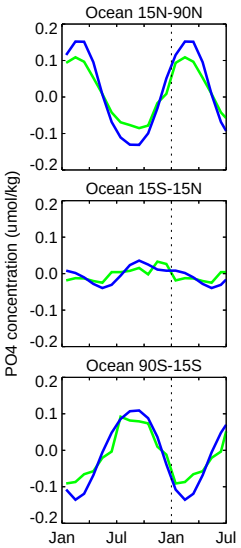

SOCAT
SURFACE OCEAN CO2 ATLAS
Sea-air CO2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
[PO4]
pCO2, [DIC]
Ocean-internal sources/sinks

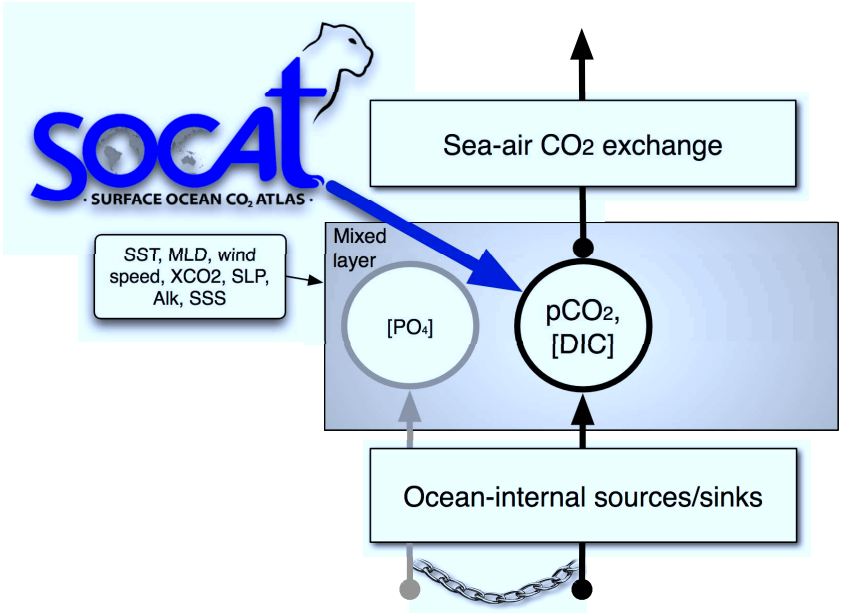

N Pacific (155W,55N)
pCO2 (uatm)
1996
1998
2000
2002
year (A.D.)

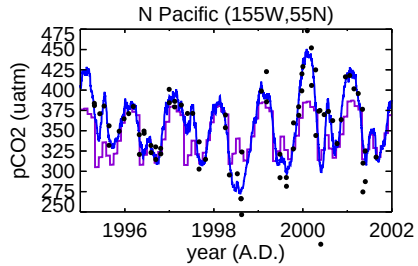

MOSEAN+WHOTS (157.92W,22.77N)
pCO2 (uatm)
2008
2009
year (A.D.)

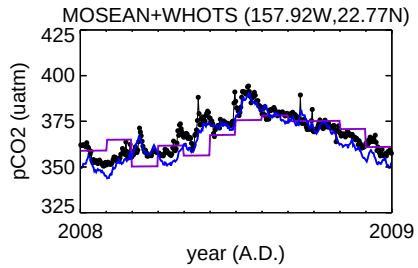

Pacific 15S-15N
Sea-air CO2 flux (PgC/yr)
0.50
0.25
0.00
-0.25
-0.50
1990
1995
2000
2005
2010
year (A.D.)

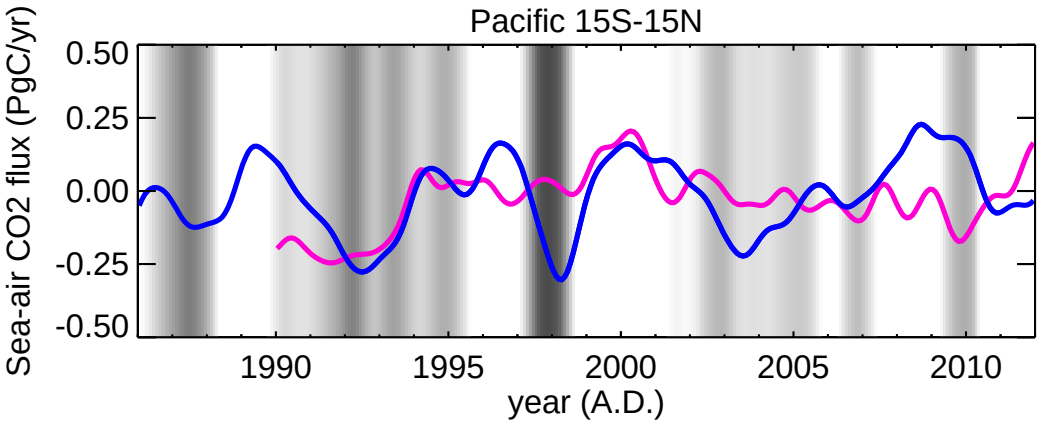

CO_2
ALT
BRW
ZEP
CBA
SIS
ICE
SUR
SHM
ESP
LEF
BAL
MHD
SCH
UUM
RYO
HUN
MID
UTA
AZR
CMN
DDR
NWR
LMP
MNM
LJO
WIS
MLO
BMW
KUM
KEY
IZO
ASK
GMI
RPB
CHR
SEY
ASC
SMO
CFA
CPT
KER
BHD
CGO
TDF
PSA
SYO
MAA
HBA
MQA


Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
0.2
0.1
0.0
-0.1
-0.2
Jan
Jul
Jan
Jul

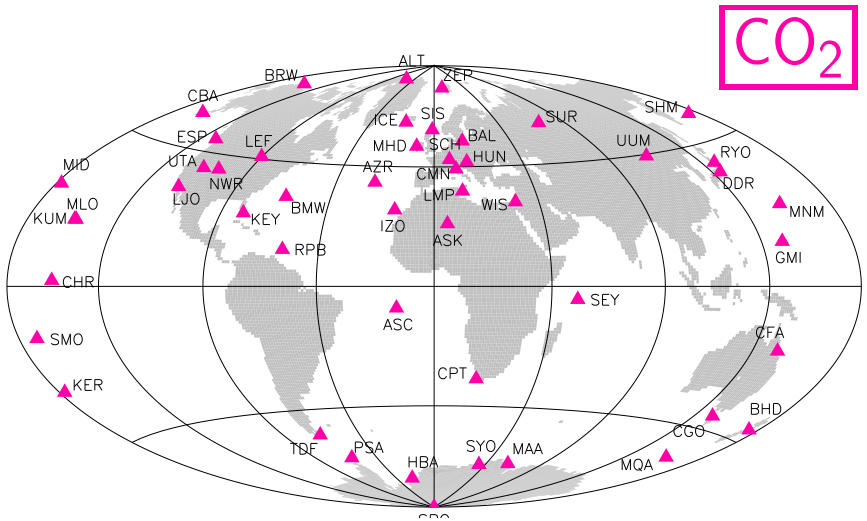

SOCAT
SURFACE OCEAN CO_2 ATLAS
Sea-air CO_2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
$[PO_4]$
pCO_2, [DIC]
Ocean-internal sources/sinks

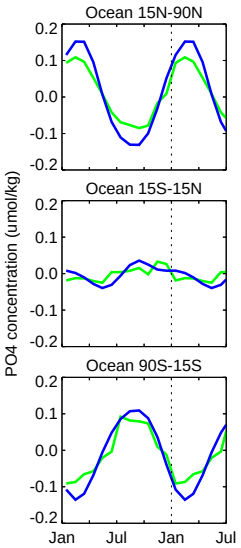

N Pacific (155W,55N)
pCO2 (uatm)
475
450
425
400
375
350
325
300
275
250
1996
1998
2000
2002
year (A.D.)

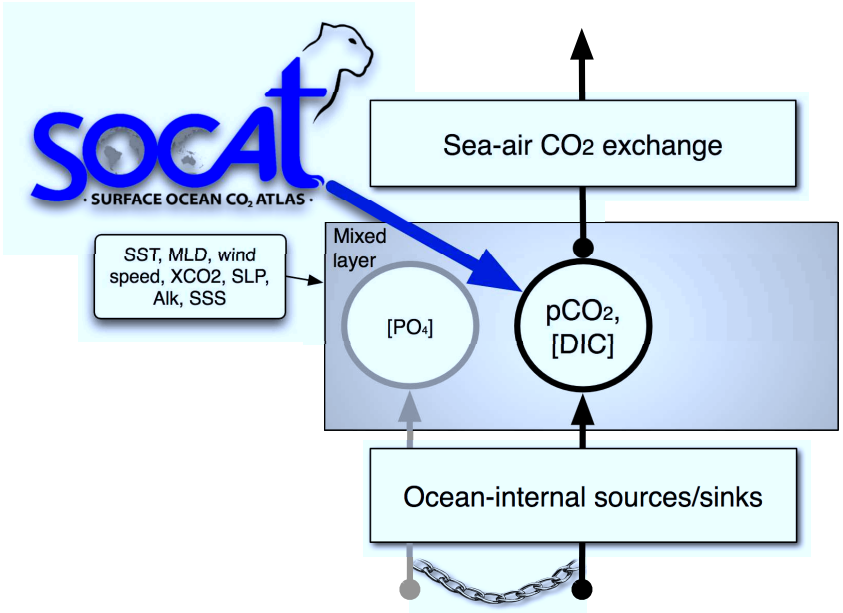

MOSEAN+WHOTS (157.92W,22.77N)
pCO2 (uatm)
425
400
375
350
325
2008
2009
year (A.D.)

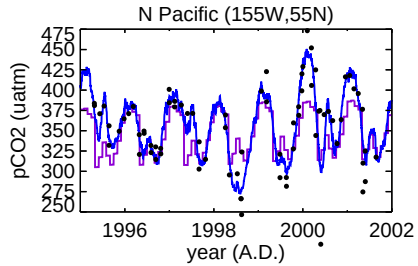


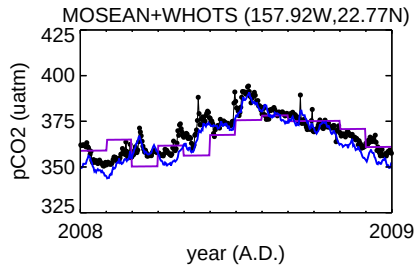
Atmospheric CO_2 inversion

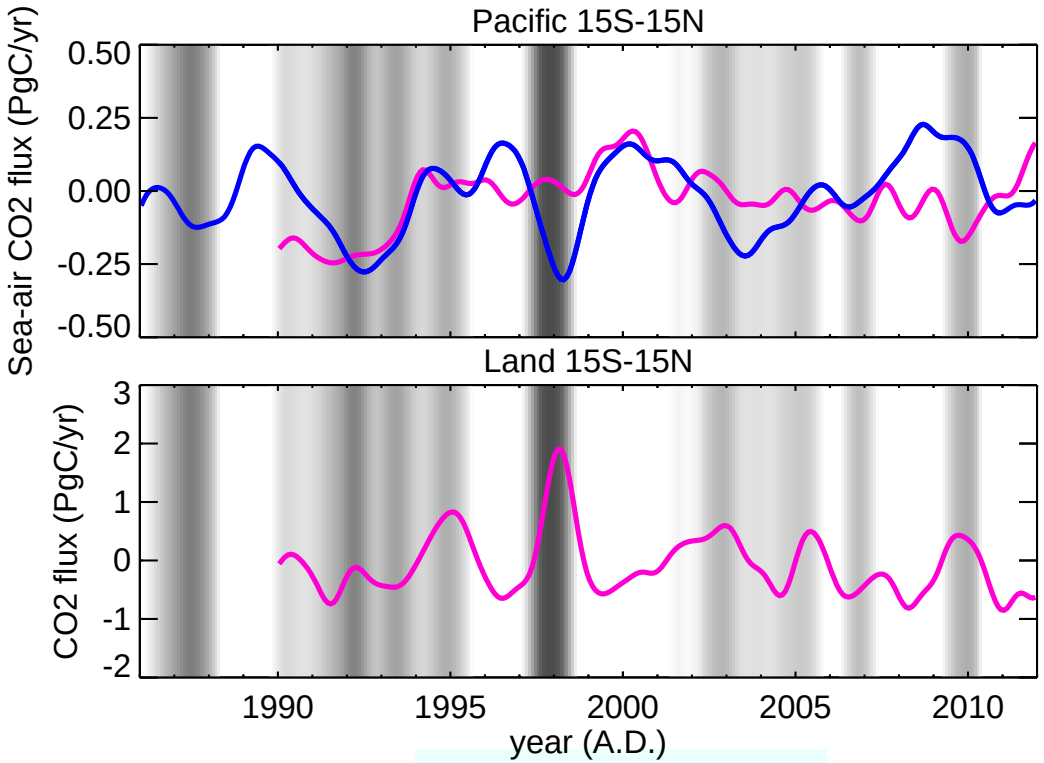


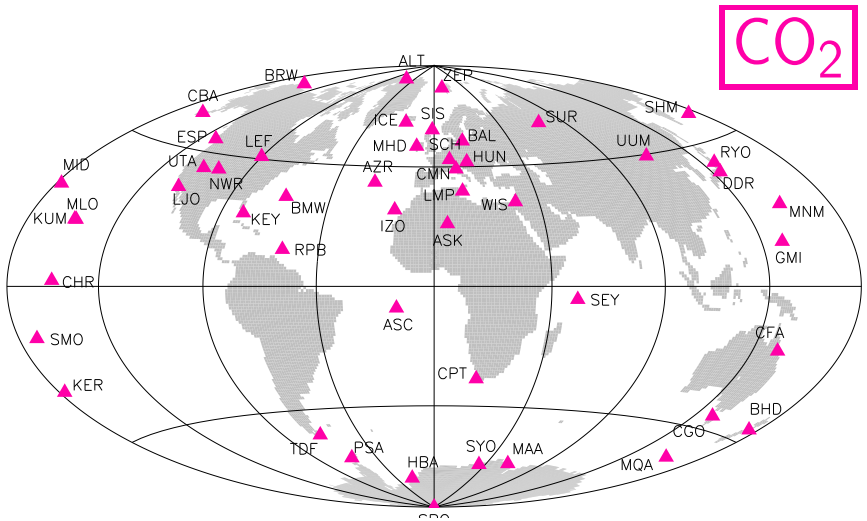


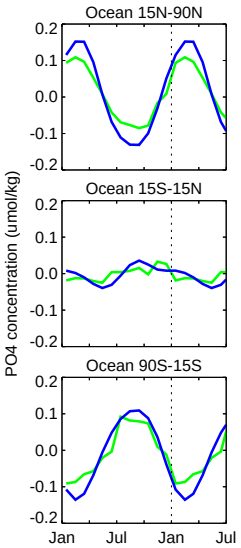


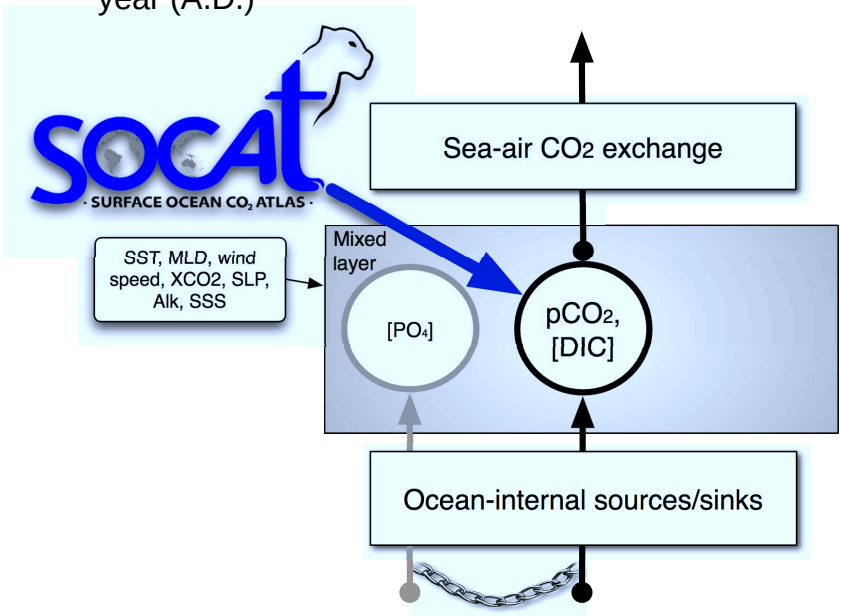


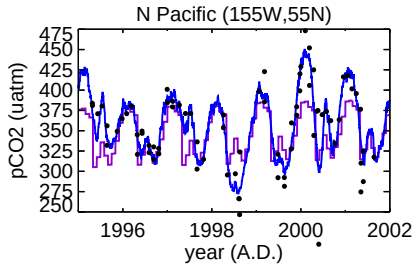


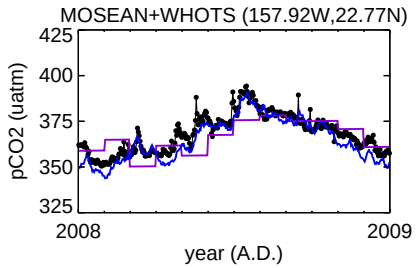

Pacific 15S-15N
Sea-air CO2 flux (PgC/yr)
0.50
0.25
0.00
-0.25
-0.50
Land 15S-15N
CO2 flux (PgC/yr)
3
2
1
0
-1
-2
1990
1995
2000
2005
2010
year (A.D.)

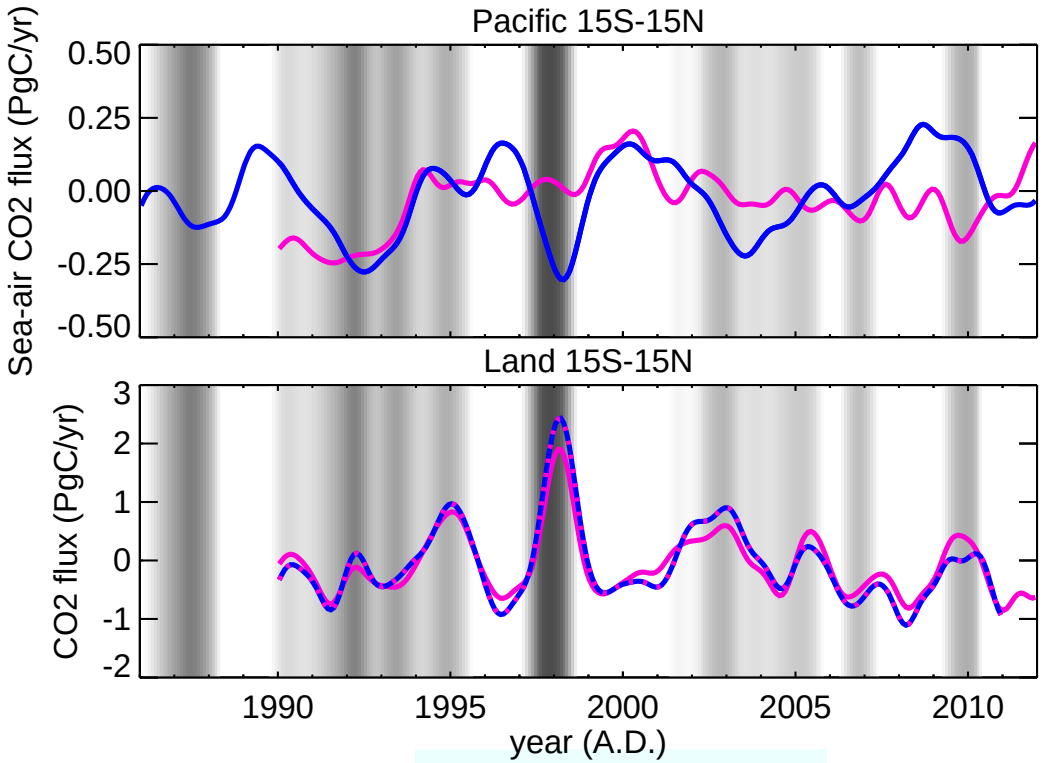

CO2
ALT
BRW
ZEP
CBA
SIS
ICE
SUR
SHM
ESP
LEF
MHD
SCH
BAL
UUM
RYO
MID
UTA
HUN
AZR
CMN
DDR
NWR
LMP
WIS
MNM
LJO
MLO
KUM
BMW
KEY
IZO
ASK
RPB
GMI
CHR
SEY
ASC
CFA
SMO
CPT
KER
BHD
CGO
TDF
PSA
SYO
MAA
HBA
MQA

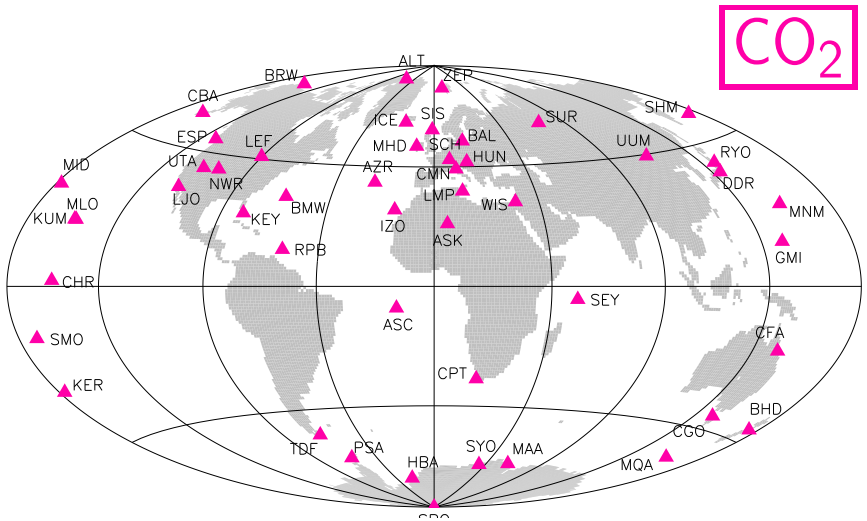

Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
0.2
0.1
0.0
-0.1
-0.2
Jan
Jul
Jan
Jul

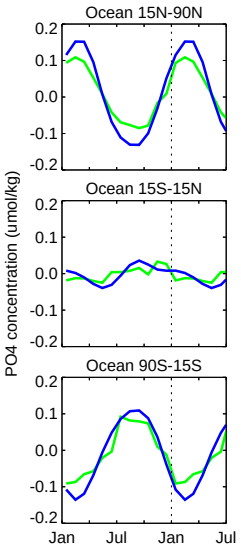

SOCAT
SURFACE OCEAN CO2 ATLAS
Sea-air CO2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
[PO4]
pCO2, [DIC]
Ocean-internal sources/sinks

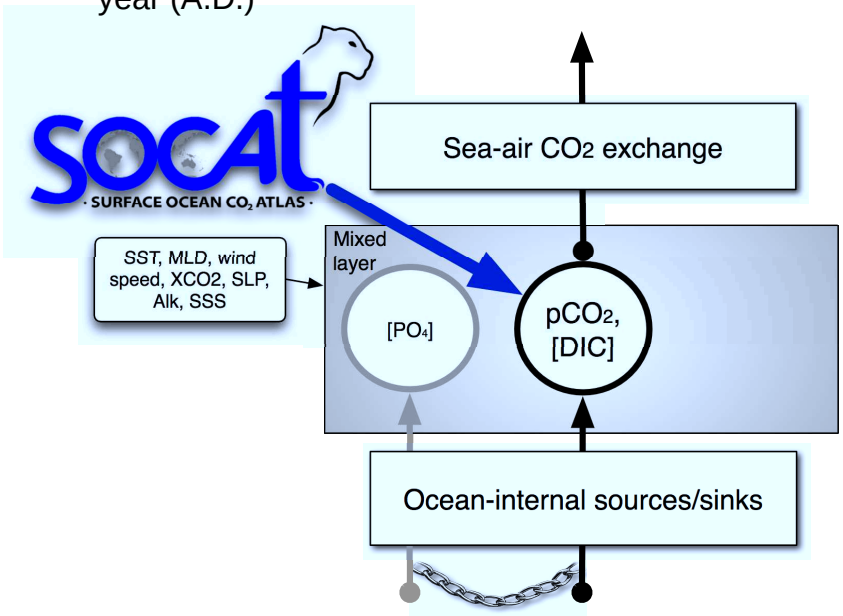

N Pacific (155W,55N)
pCO2 (uatm)
475
450
425
400
375
350
325
300
275
250
1996
1998
2000
2002
year (A.D.)

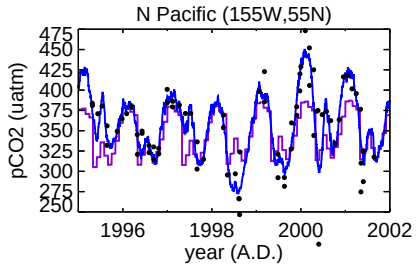

MOSEAN+WHOTS (157.92W,22.77N)
pCO2 (uatm)
425
400
375
350
325
2008
2009
year (A.D.)


Pacific 15S-15N
Sea-air CO2 flux (PgC/yr)
0.50
0.25
0.00
-0.25
-0.50
Land 15S-15N
CO2 flux (PgC/yr)
3
2
1
0
-1
-2
1990
1995
2000
2005
2010
year (A.D.)


CO2
ALT
BRW
ZEP
CBA
SIS
ICE
SUR
SHM
ESP
LEF
MHD
SCH
BAL
UUM
RYO
MID
UTA
AZR
HUN
CMN
DDR
NWR
LMP
WIS
MNM
LJO
MLO
KUM
BMW
KEY
IZO
ASK
RPB
GMI
CHR
SEY
ASC
CFA
SMO
CPT
KER
BHD
CGO
TDF
PSA
SYO
MAA
HBA
MQA


Ocean 15N-90N
Ocean 15S-15N
Ocean 90S-15S
PO4 concentration (umol/kg)
0.2
0.1
0.0
-0.1
-0.2
Jan
Jul
Jan
Jul


SOCAT
SURFACE OCEAN CO2 ATLAS
Sea-air CO2 exchange
SST, MLD, wind speed, XCO2, SLP, Alk, SSS
Mixed layer
[PO4]
pCO2, [DIC]
Ocean-internal sources/sinks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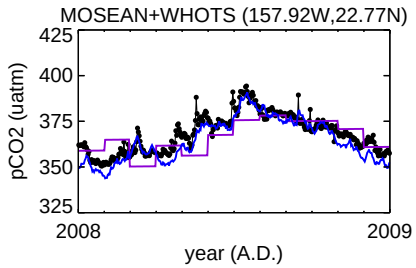
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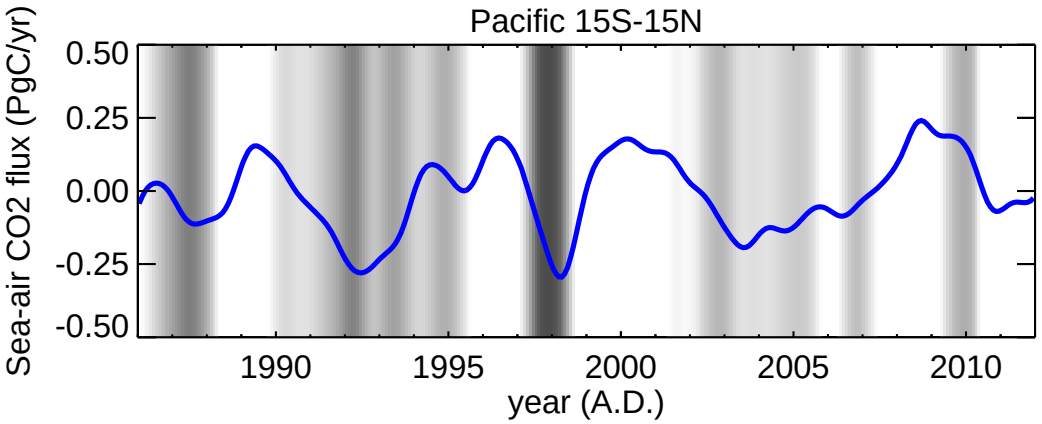
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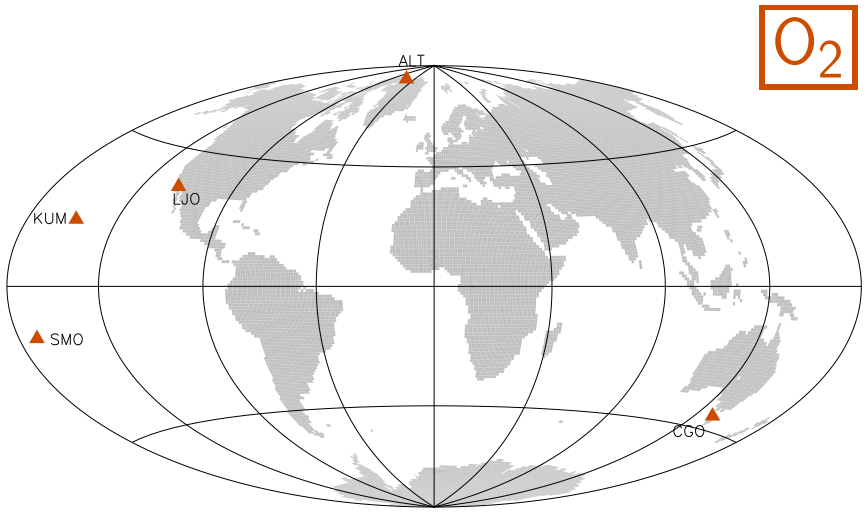
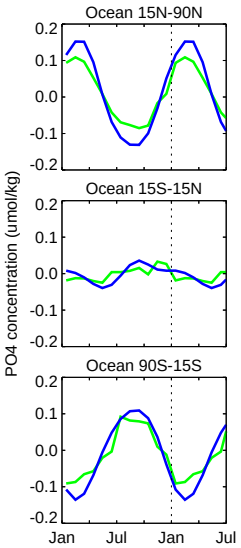

O2
ALT
LJO
KUM
SMO
CGO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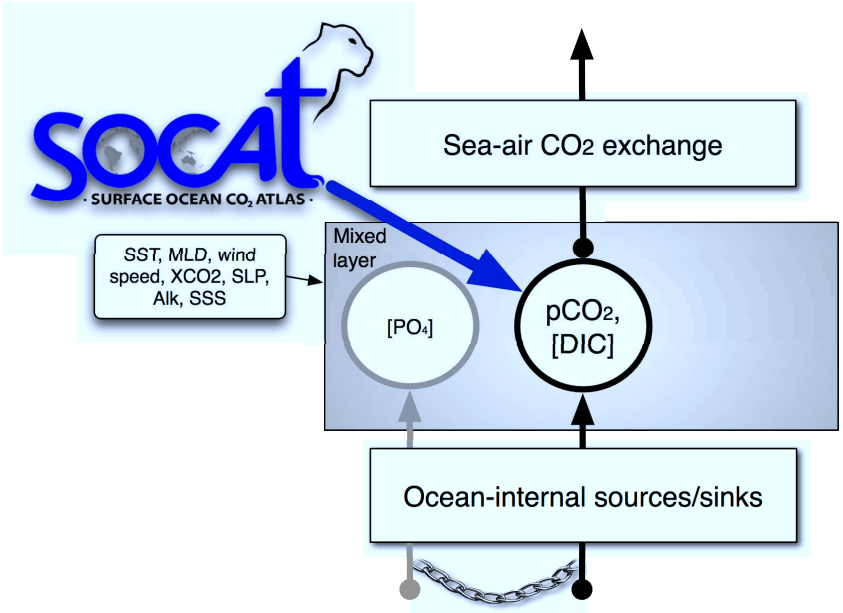
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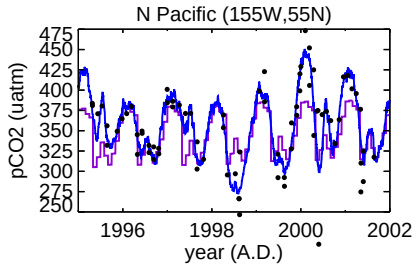
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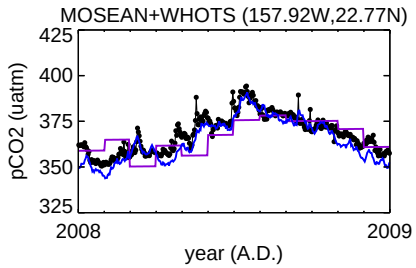
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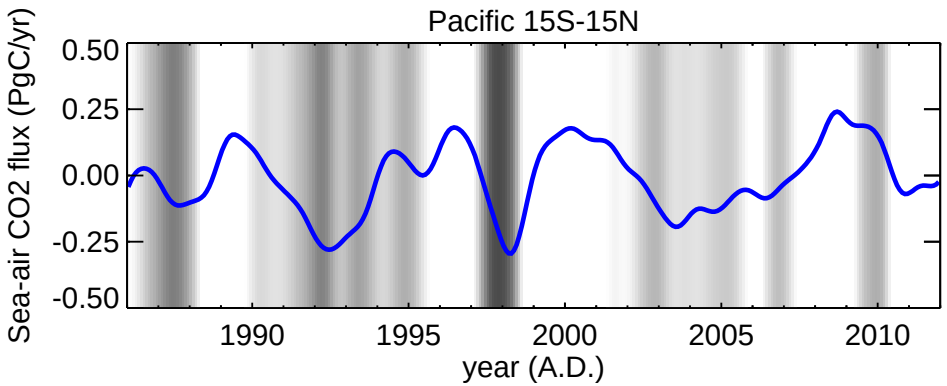
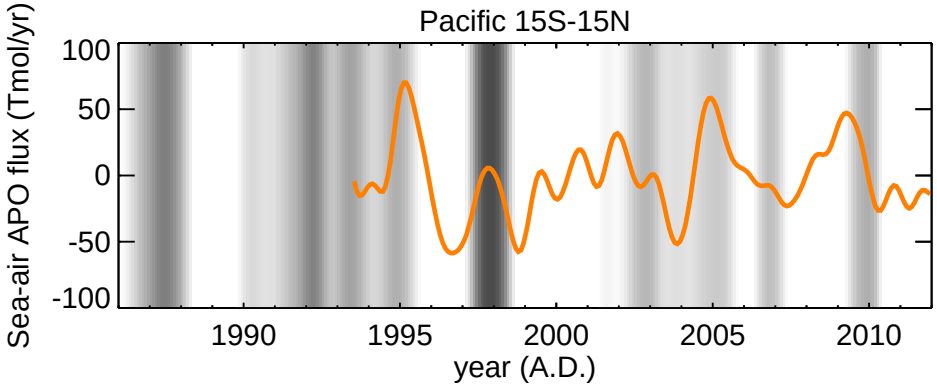
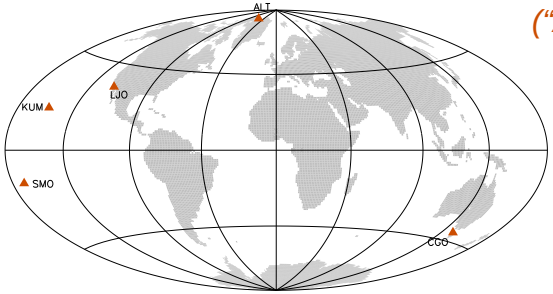
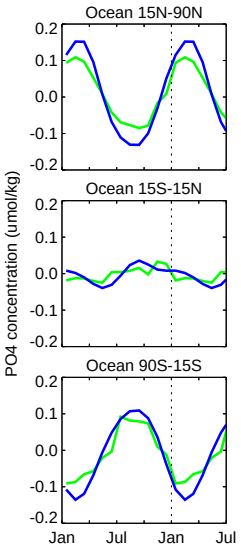


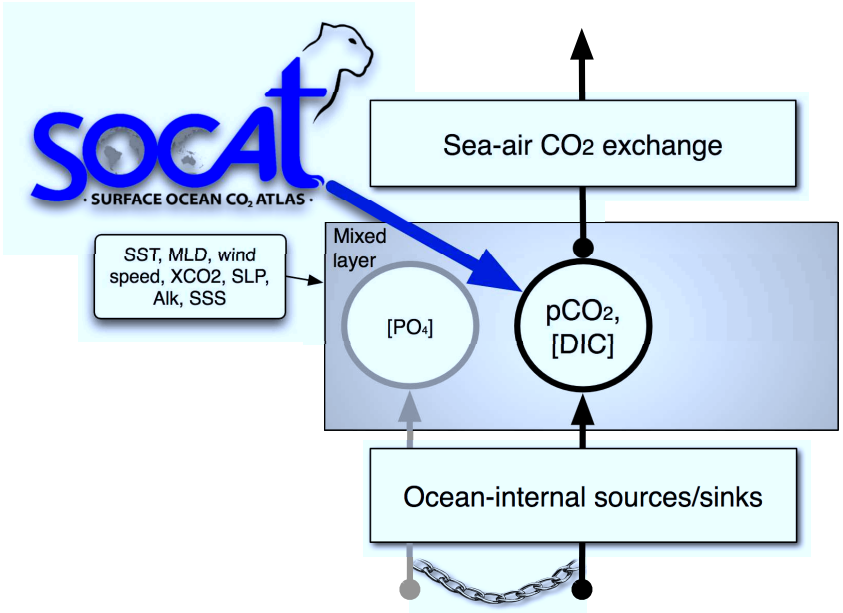


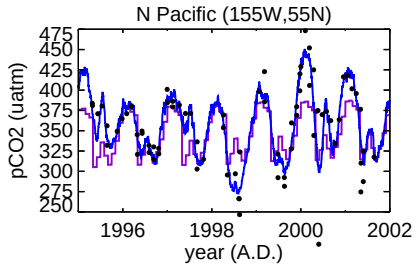
Inferred from atmospheric O_2/N_2 data

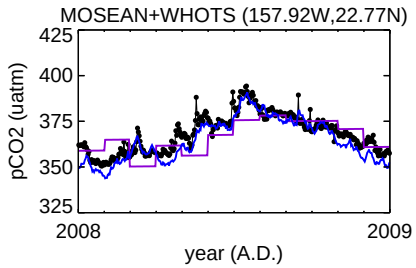
("APO inversion")

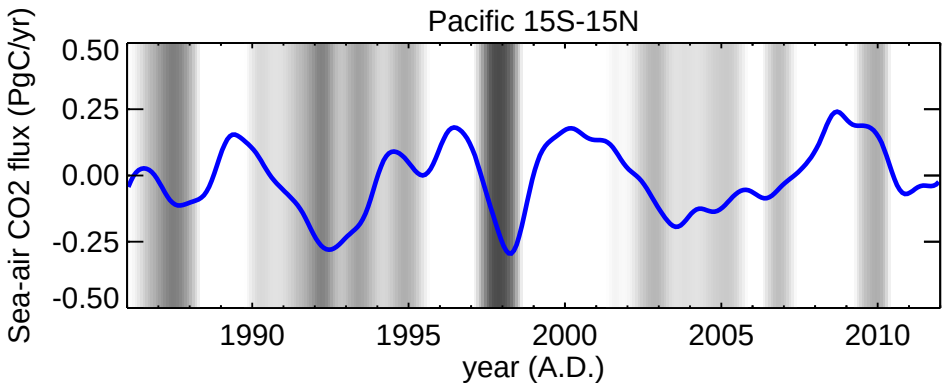


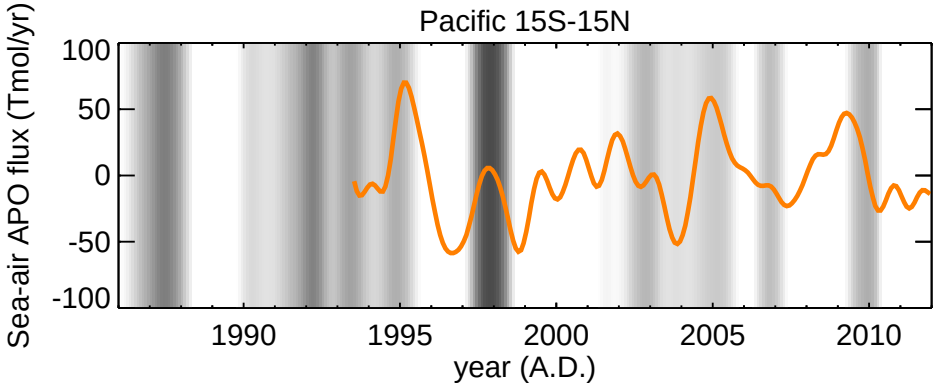






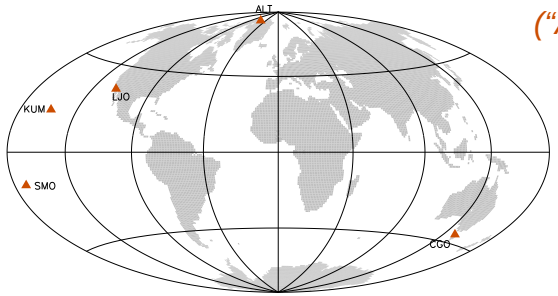


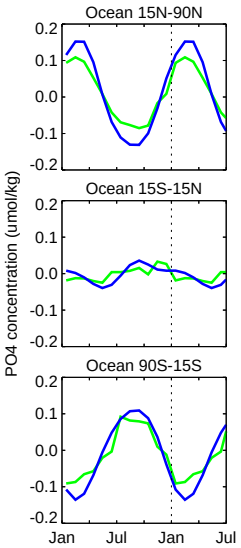


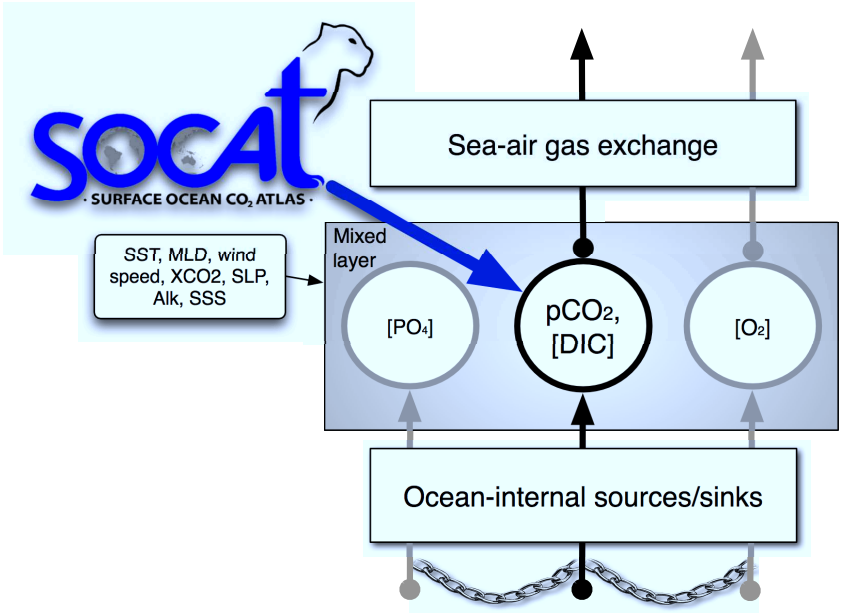


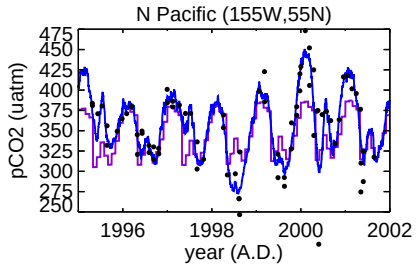
Inferred from atmospheric O_2/N_2 data

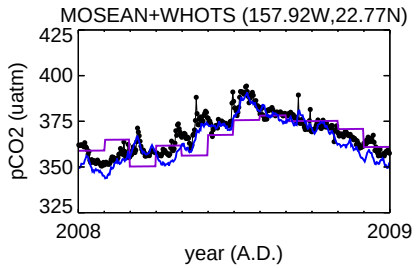
("APO inversion")

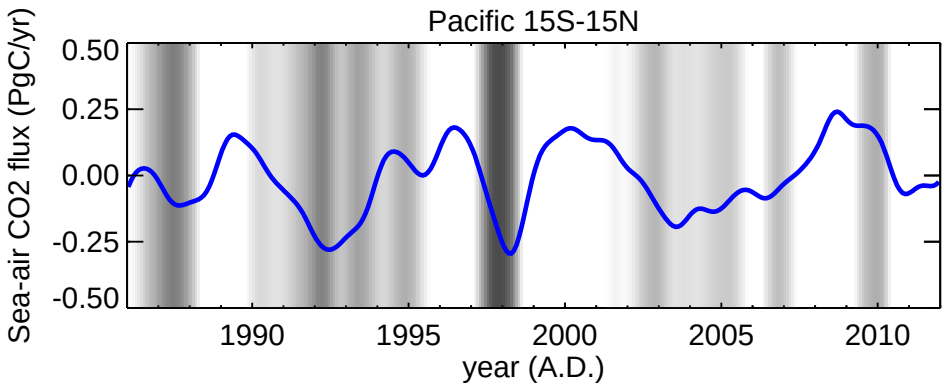


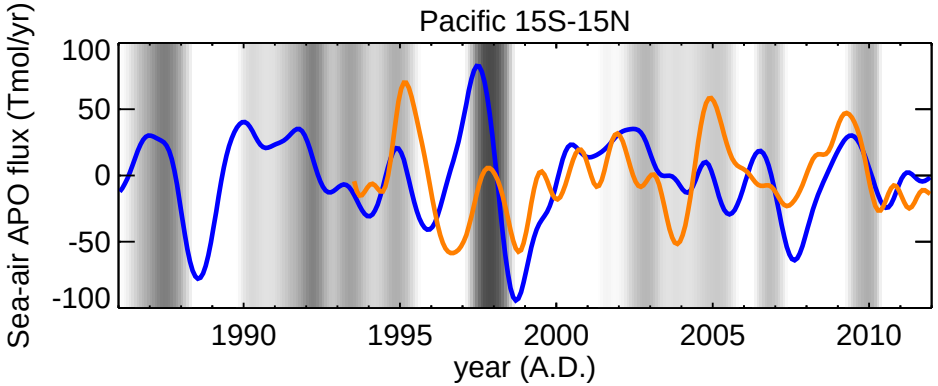






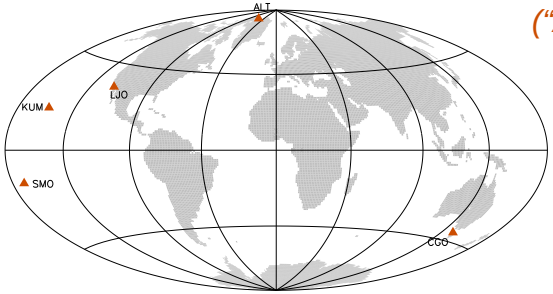


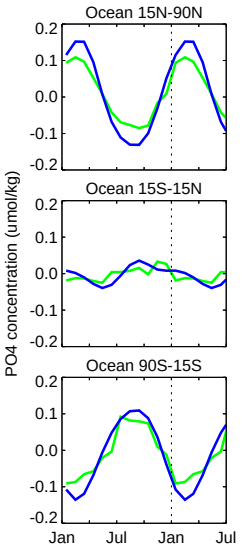


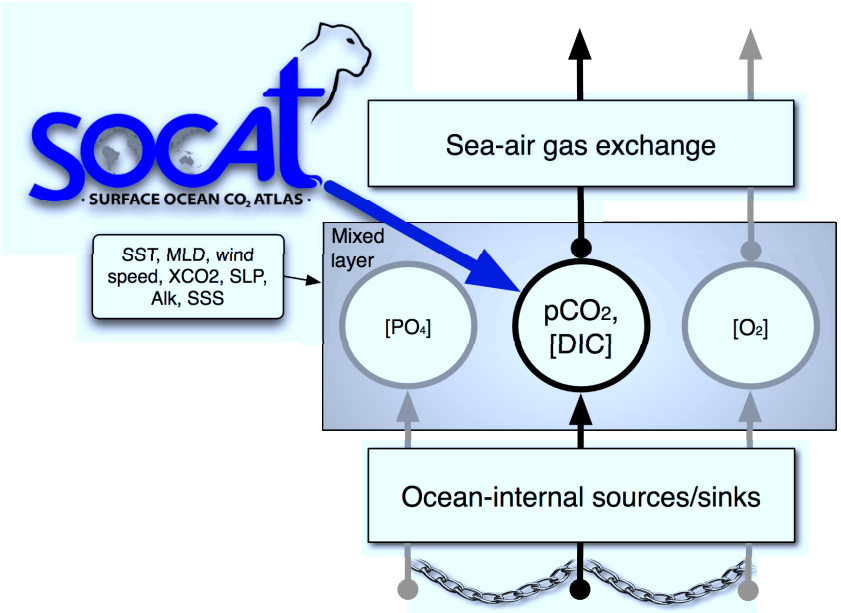


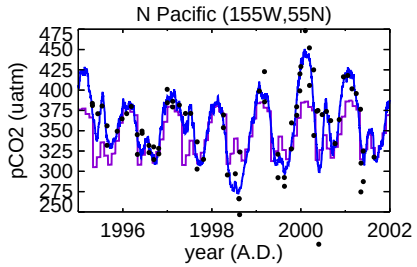
Inferred from atmospheric O_2/N_2 data

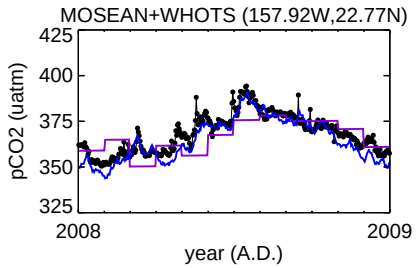
("APO inversion")



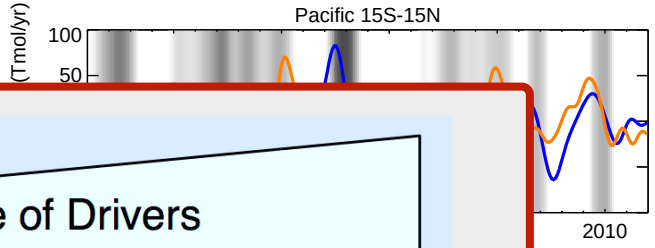


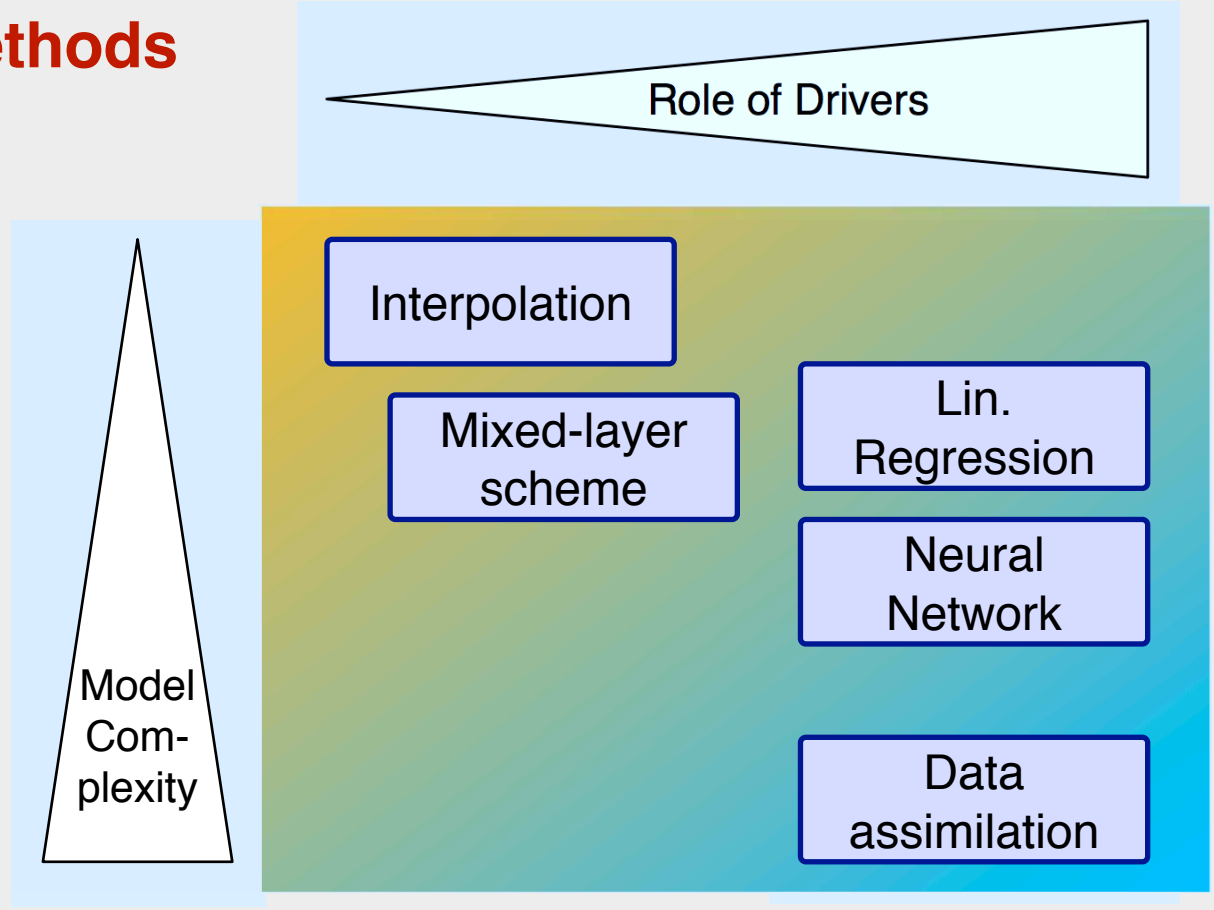


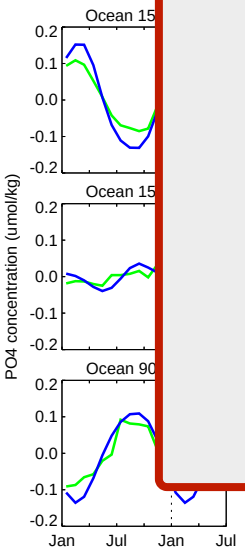


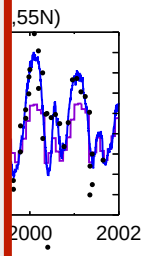


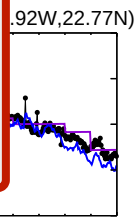
Mapping methods

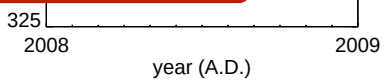


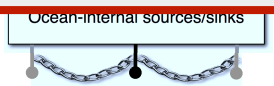


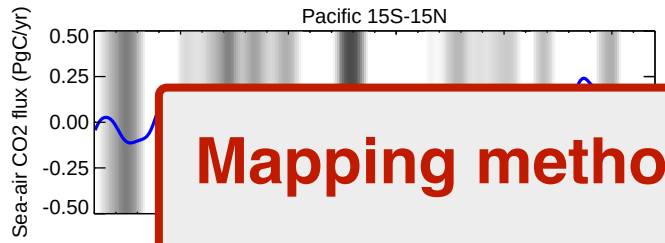


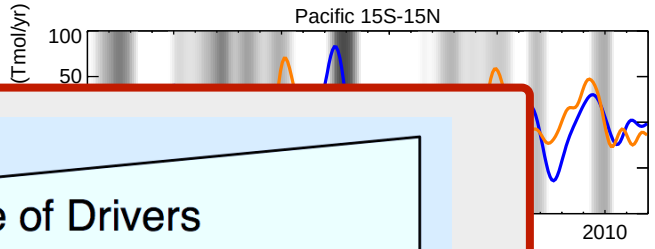












Mapping methods

Role of Drivers

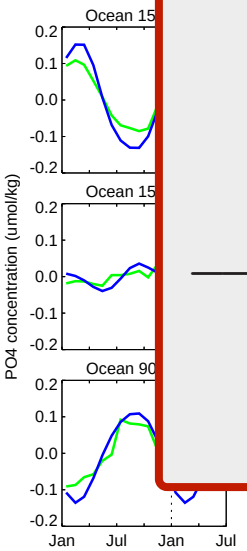
Direct data signals

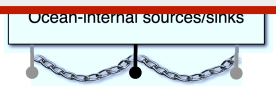
Model Com-plexity

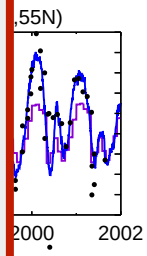
- Interpolation
- Mixed-layer scheme
- Lin. Regression
- Neural Network
- Data assimilation

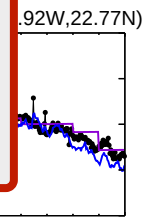
Bridging data gaps

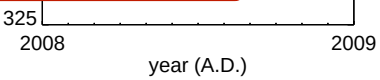
⟶ **Interesting complementarity**











Mapping methods

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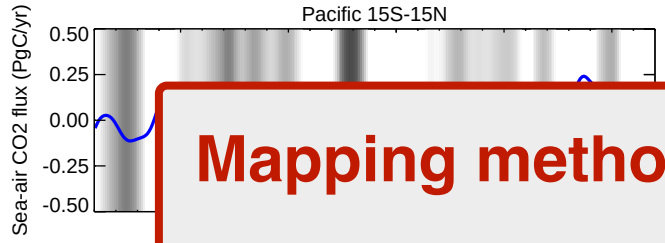
- Interpolation
- Mixed-layer scheme
- Lin. Regression
- Neural Network
- Data assimilation

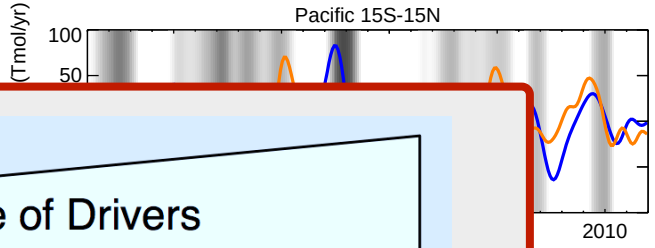
Bridging data gaps

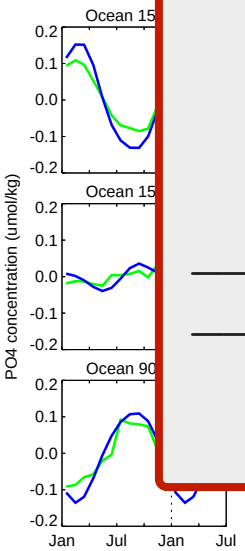
⟶ **Interesting complementarity**

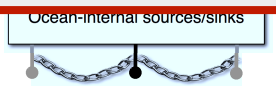
⟶ **SOCOM – Surface Ocean pCO2 Mapping intercomparison**

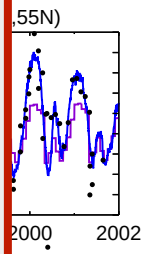
- *1st submissions by Oct 31, 2013*
- *open to further data-based products*

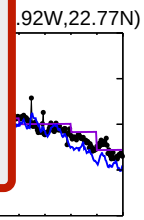


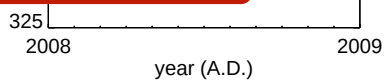


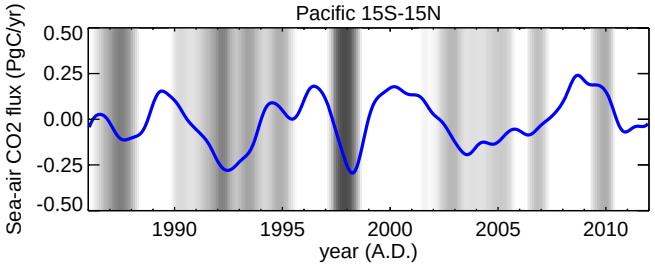


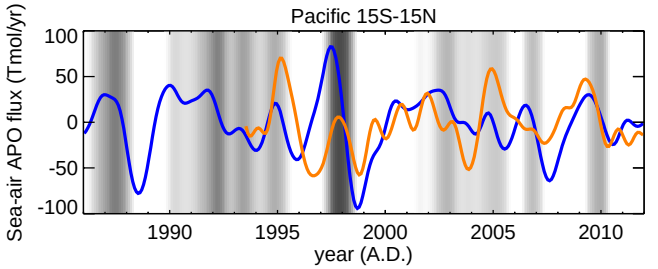




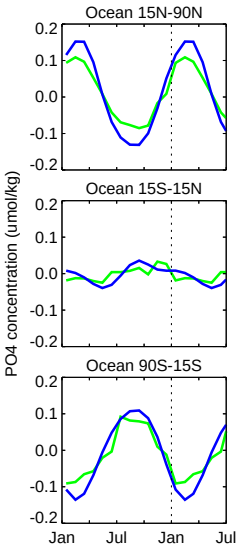


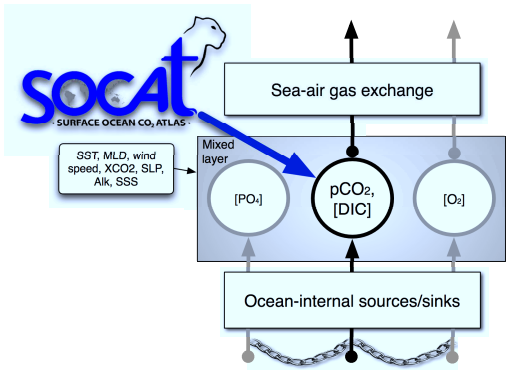


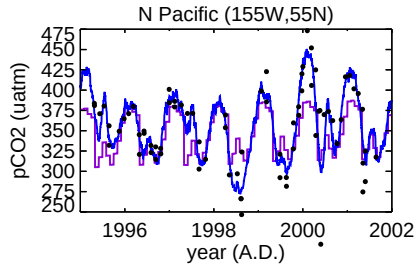


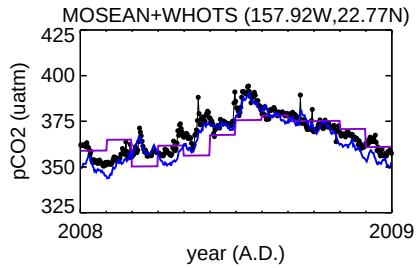


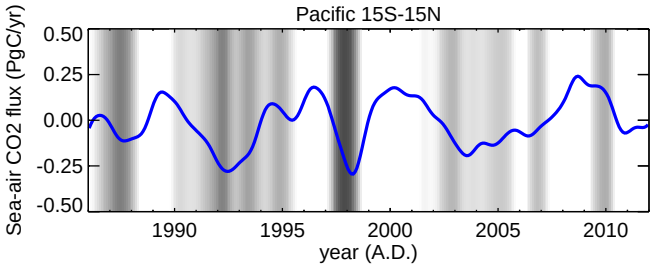
Conclusion: • Data-driven sea-air CO_2 flux estimates:
seasonality, **IAV**, day-to-day variability

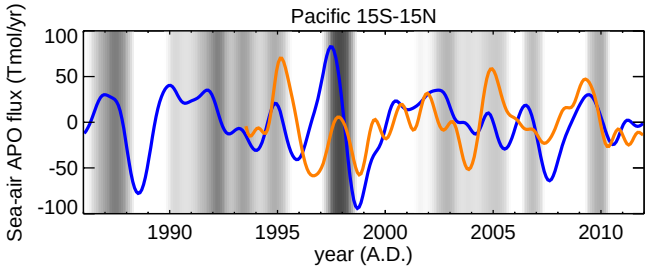












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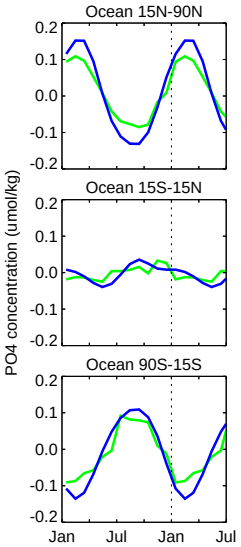

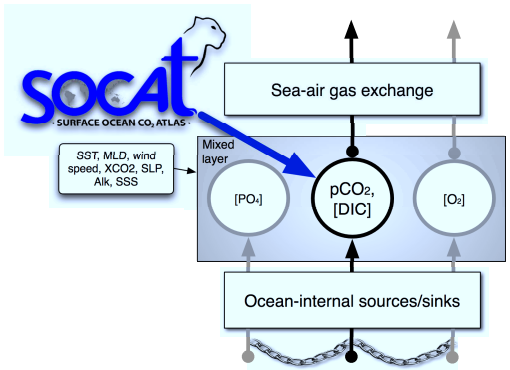

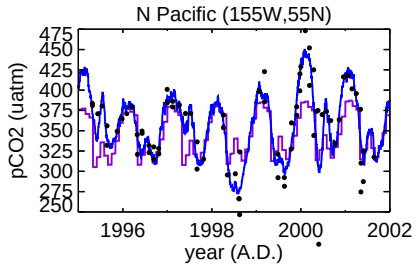

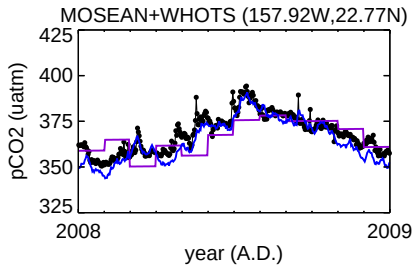

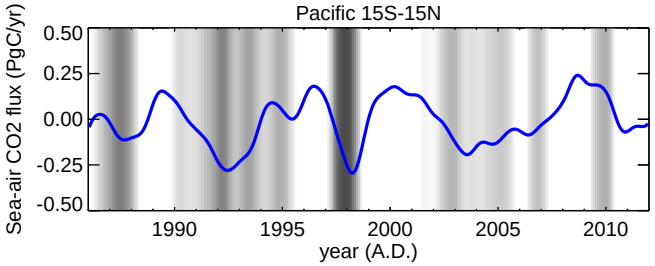

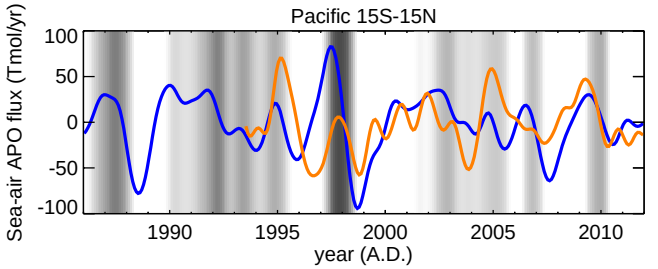

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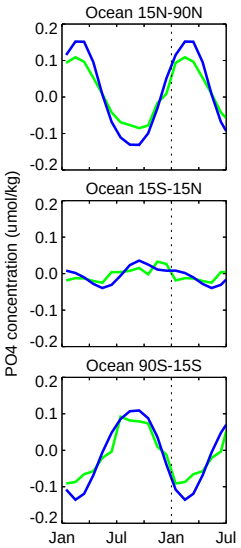

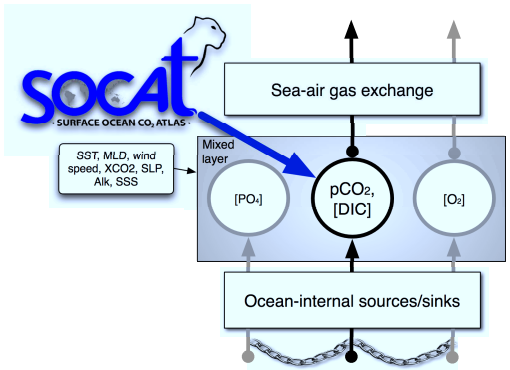

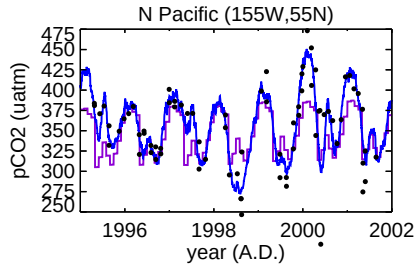

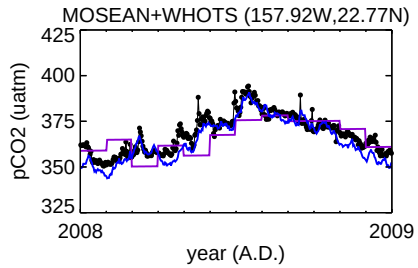

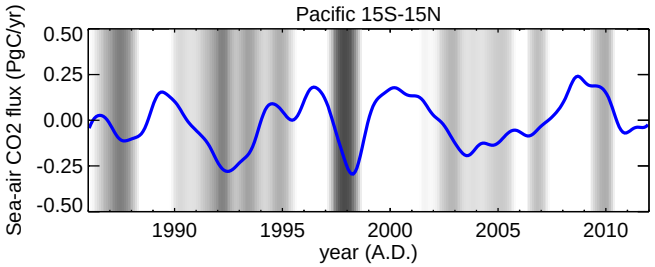

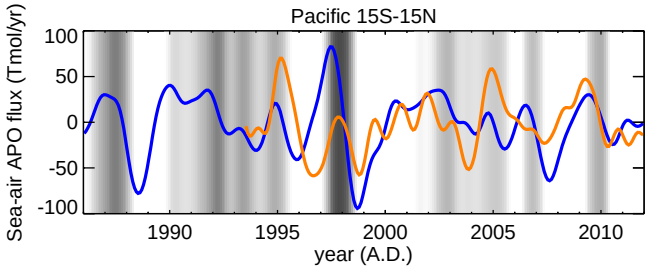

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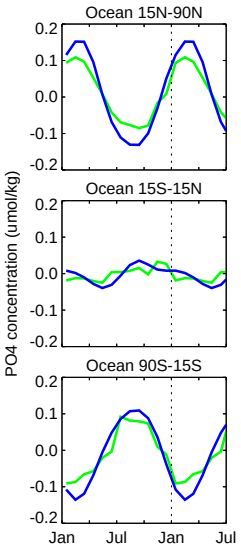

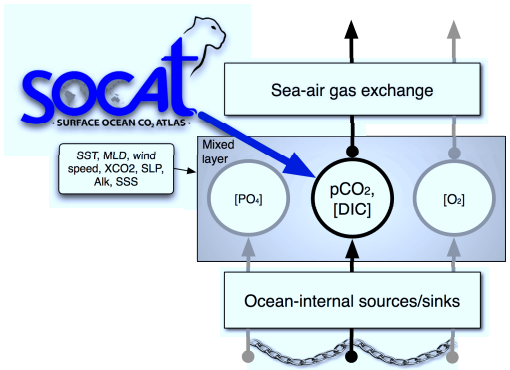

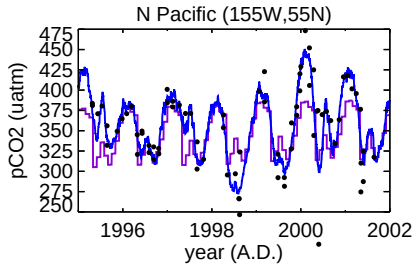

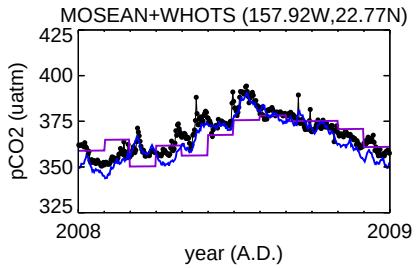

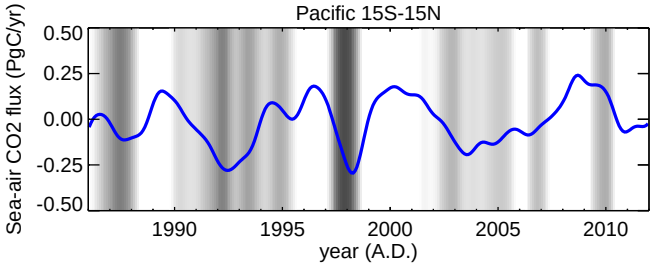

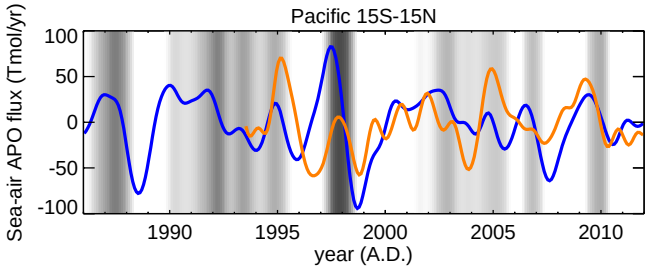

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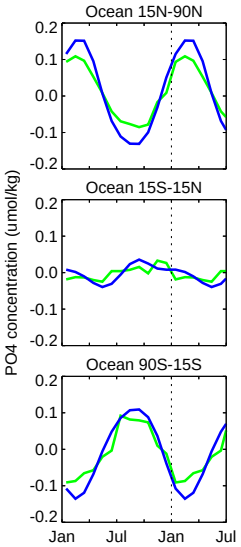

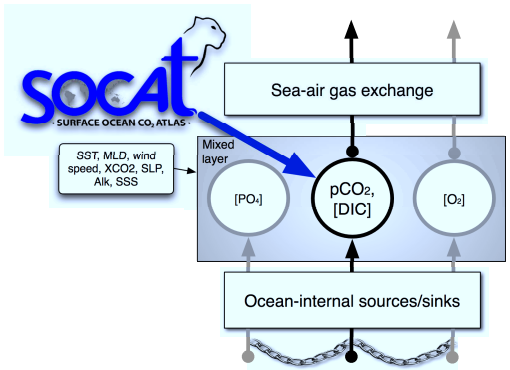

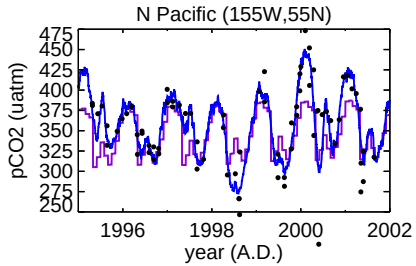

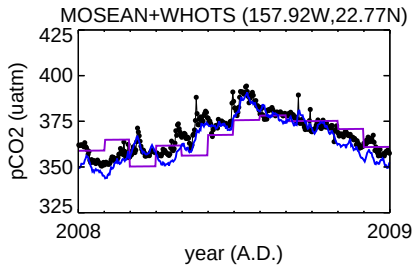

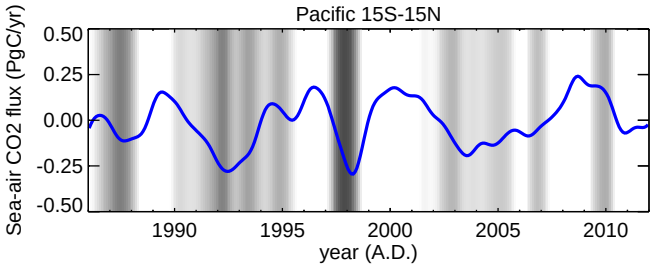

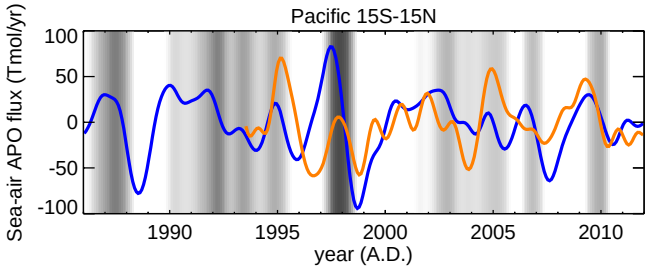

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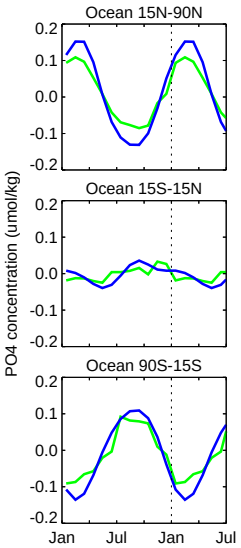

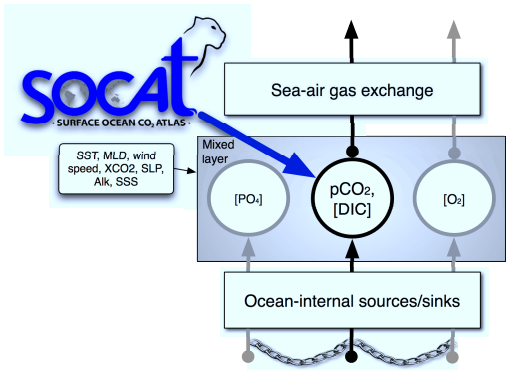

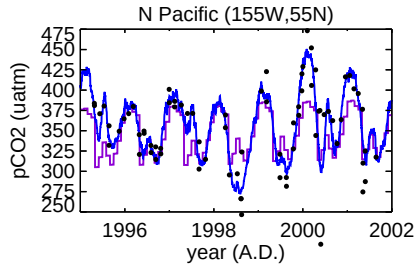

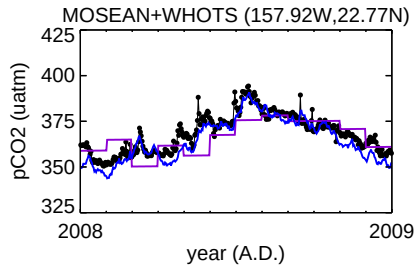

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$$\left(1 - \frac{\sigma_{\mathrm{post}}}{\sigma_{\mathrm{pri}}}\right)$$

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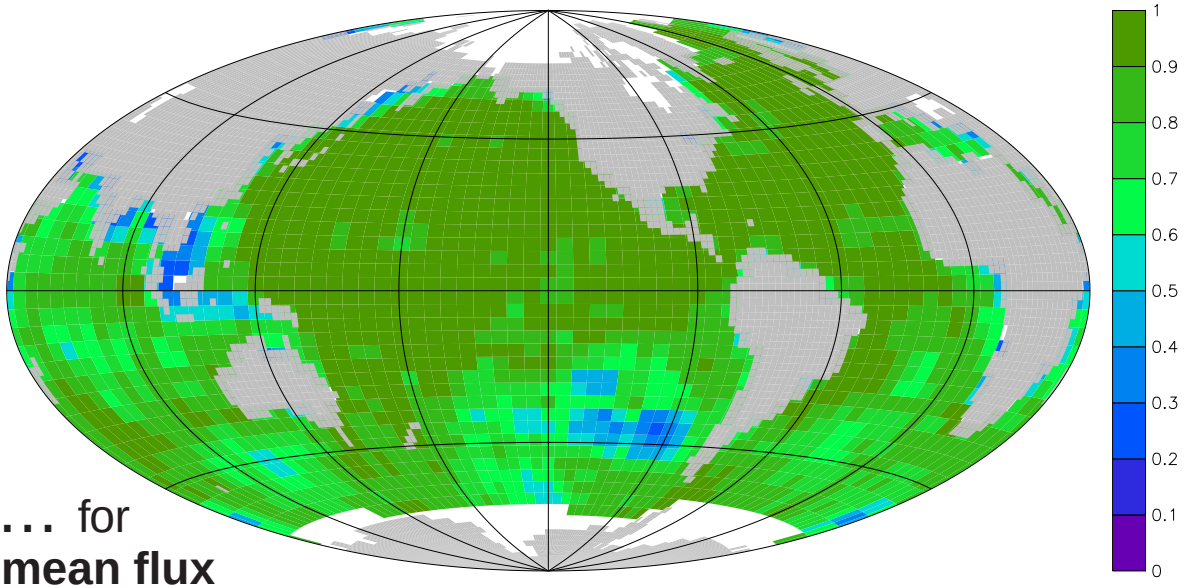
1990–2006



. . . for
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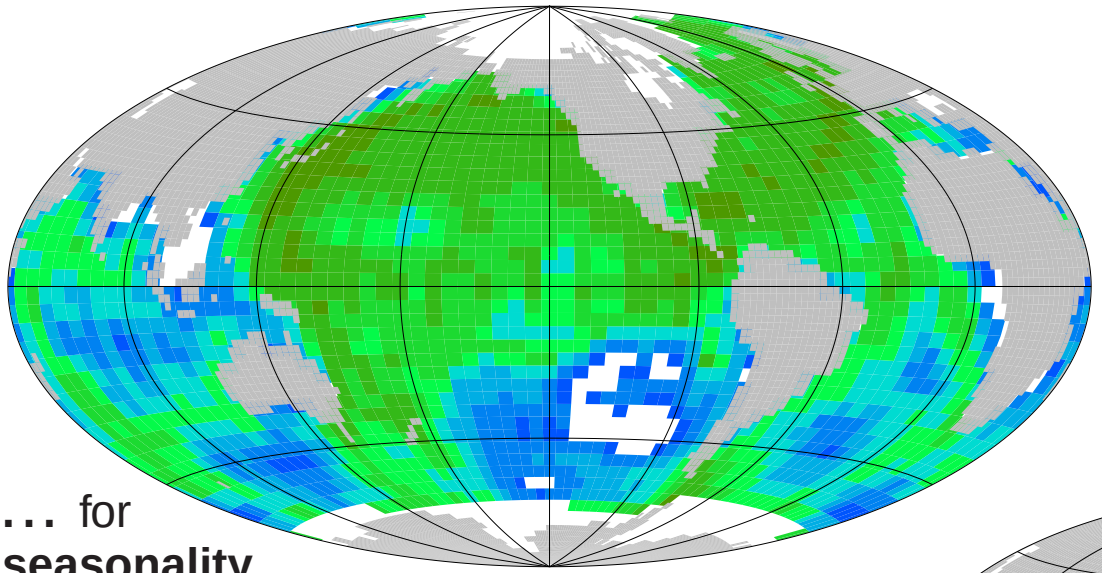

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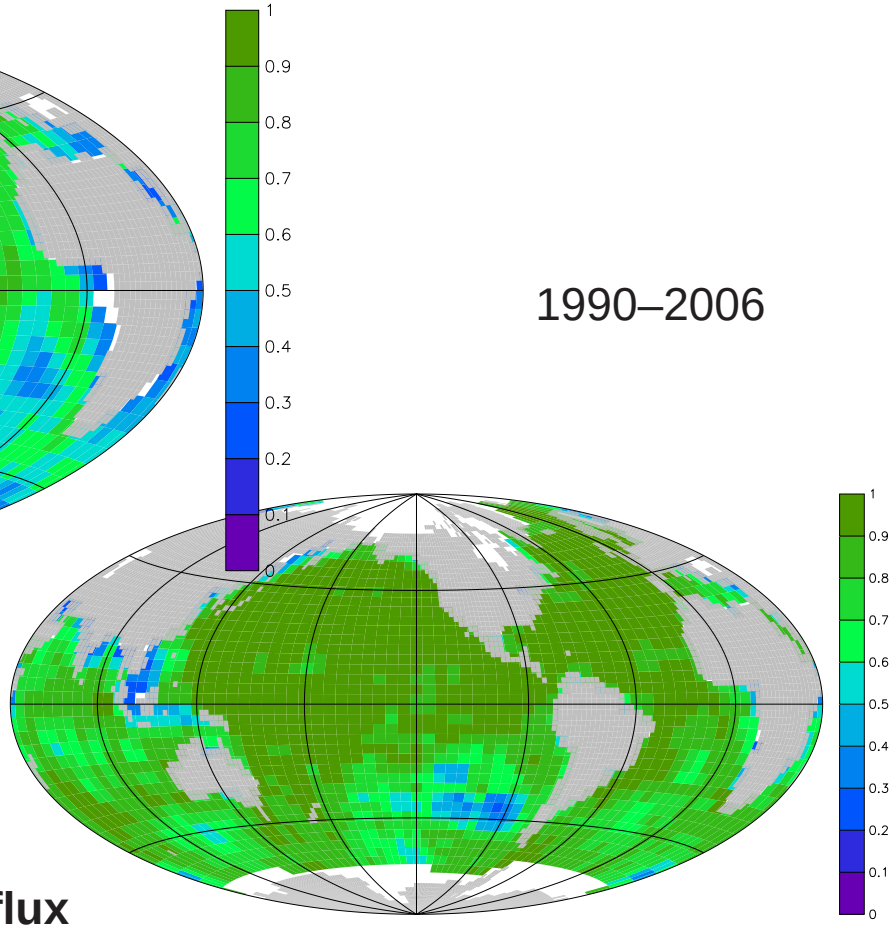

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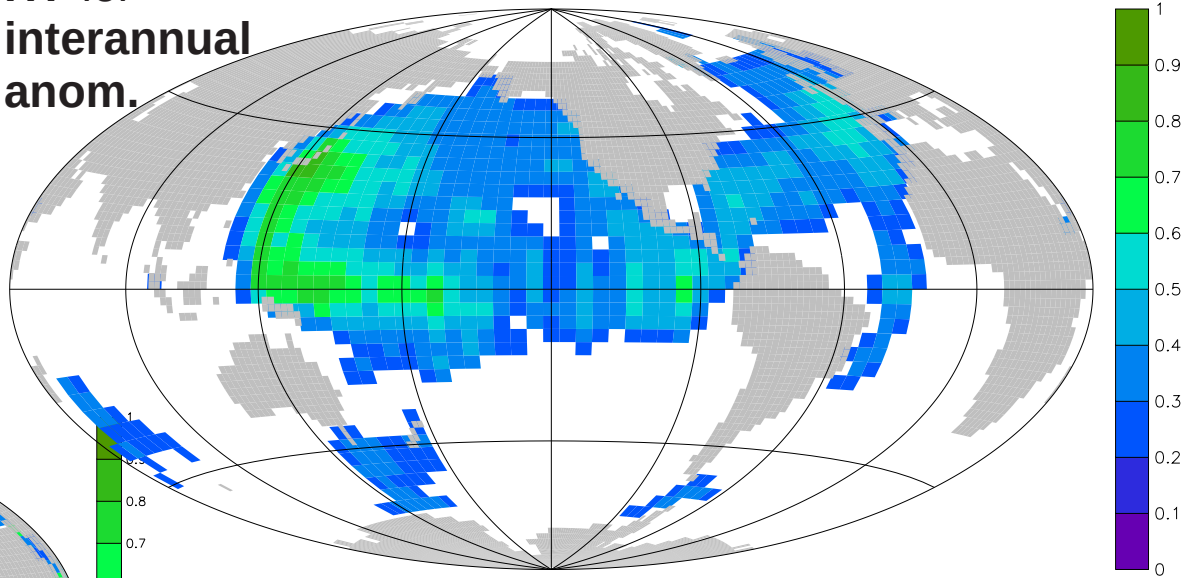

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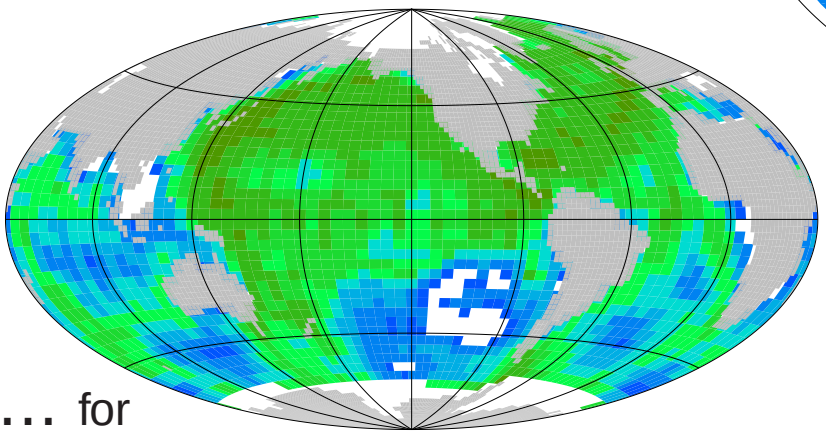

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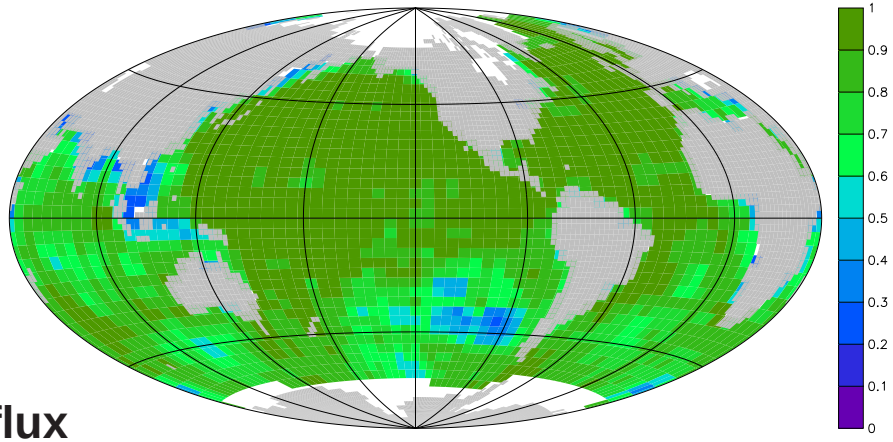

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Tropical Pacific sea–air CO_2 flux variability

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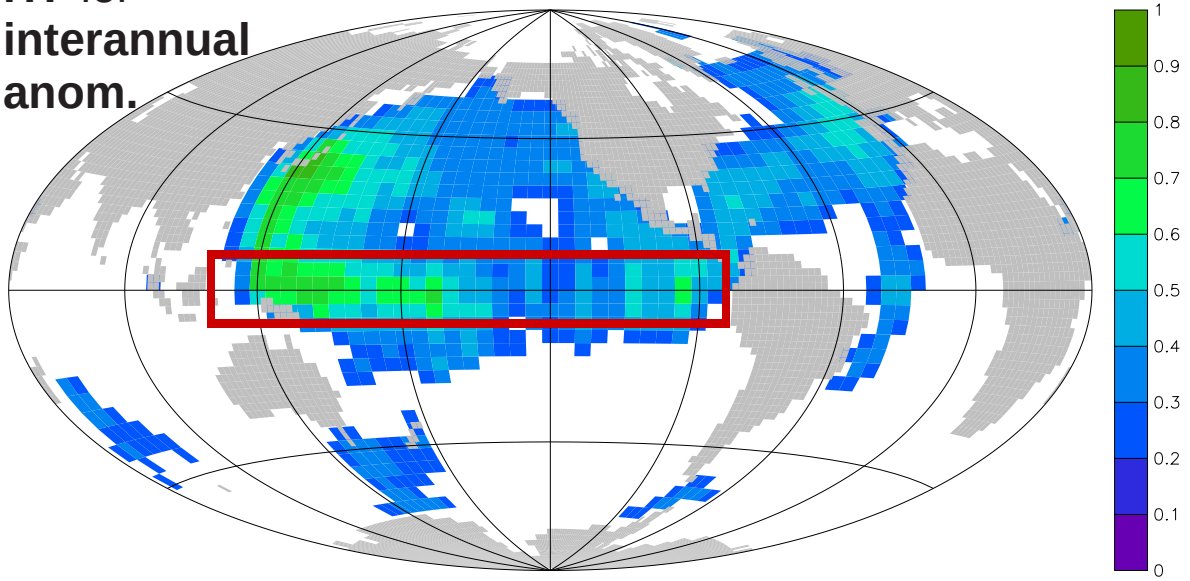

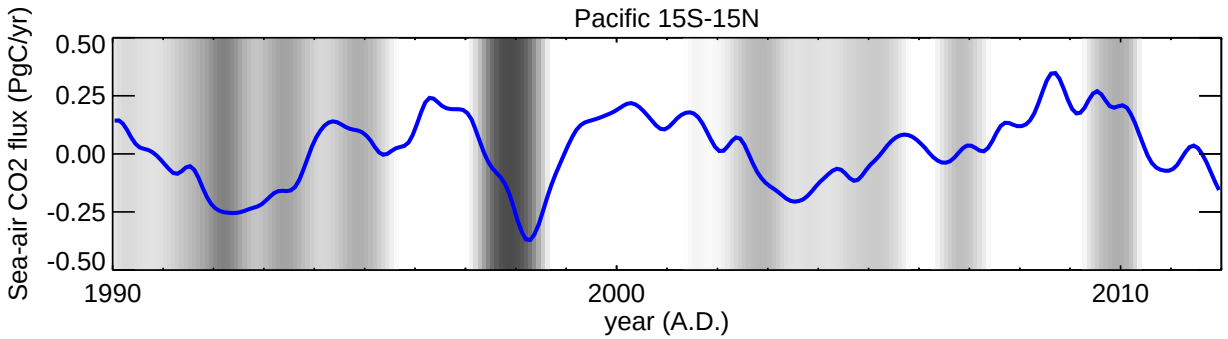

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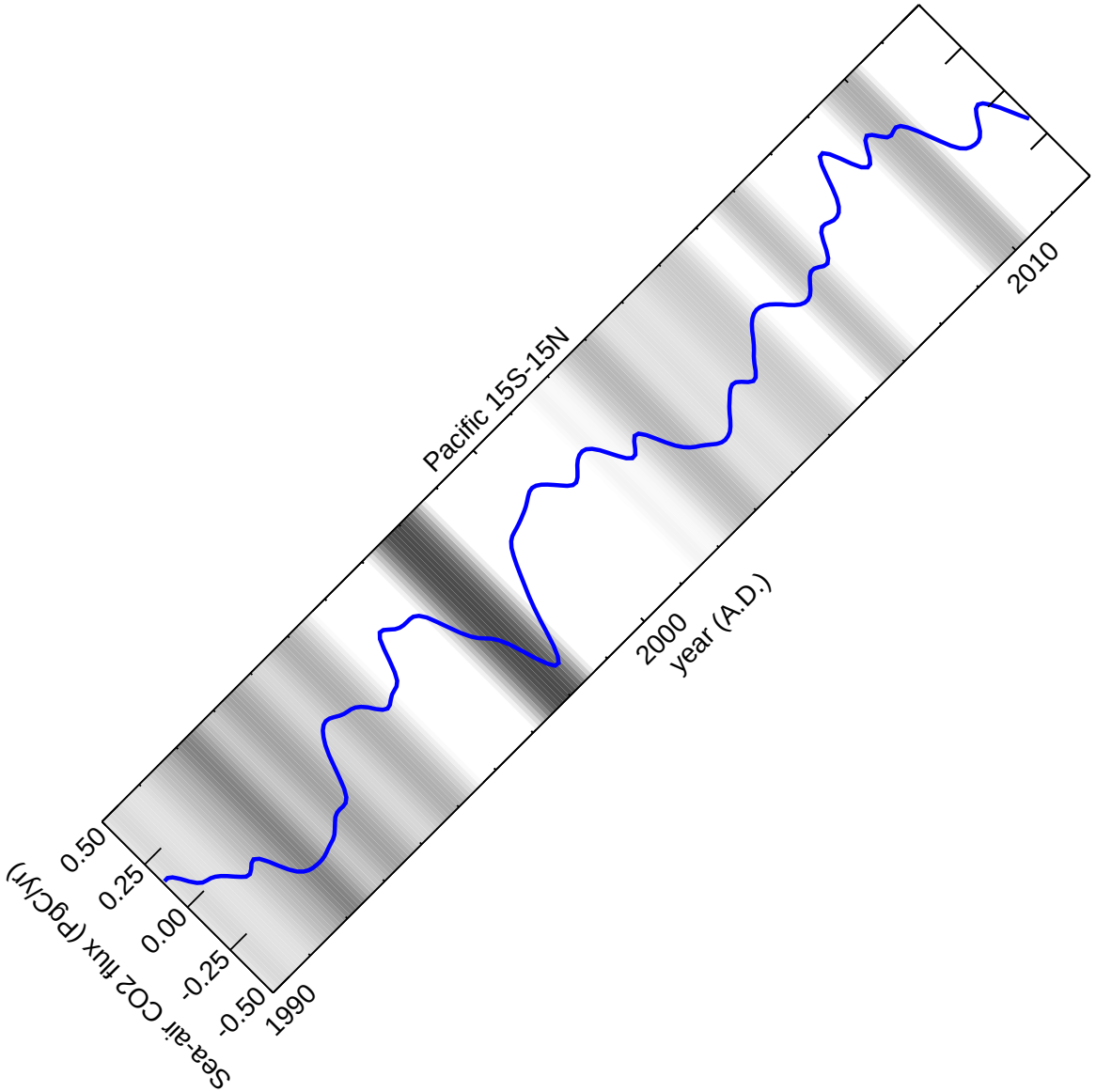

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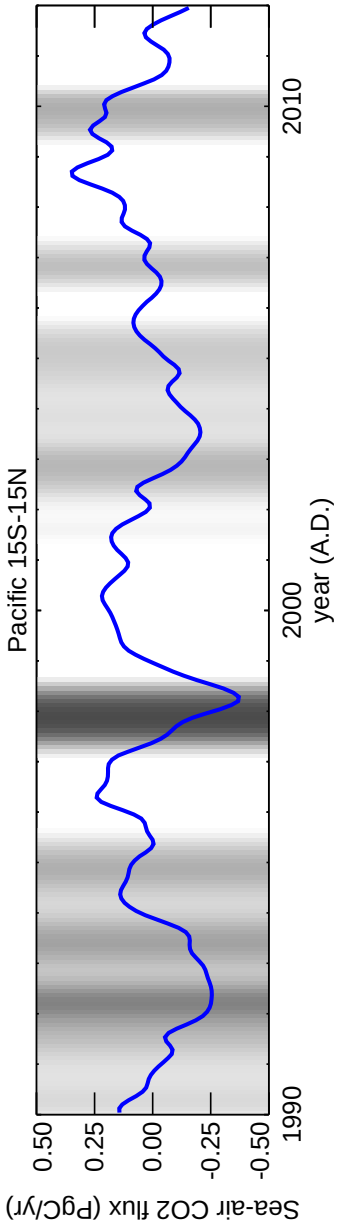

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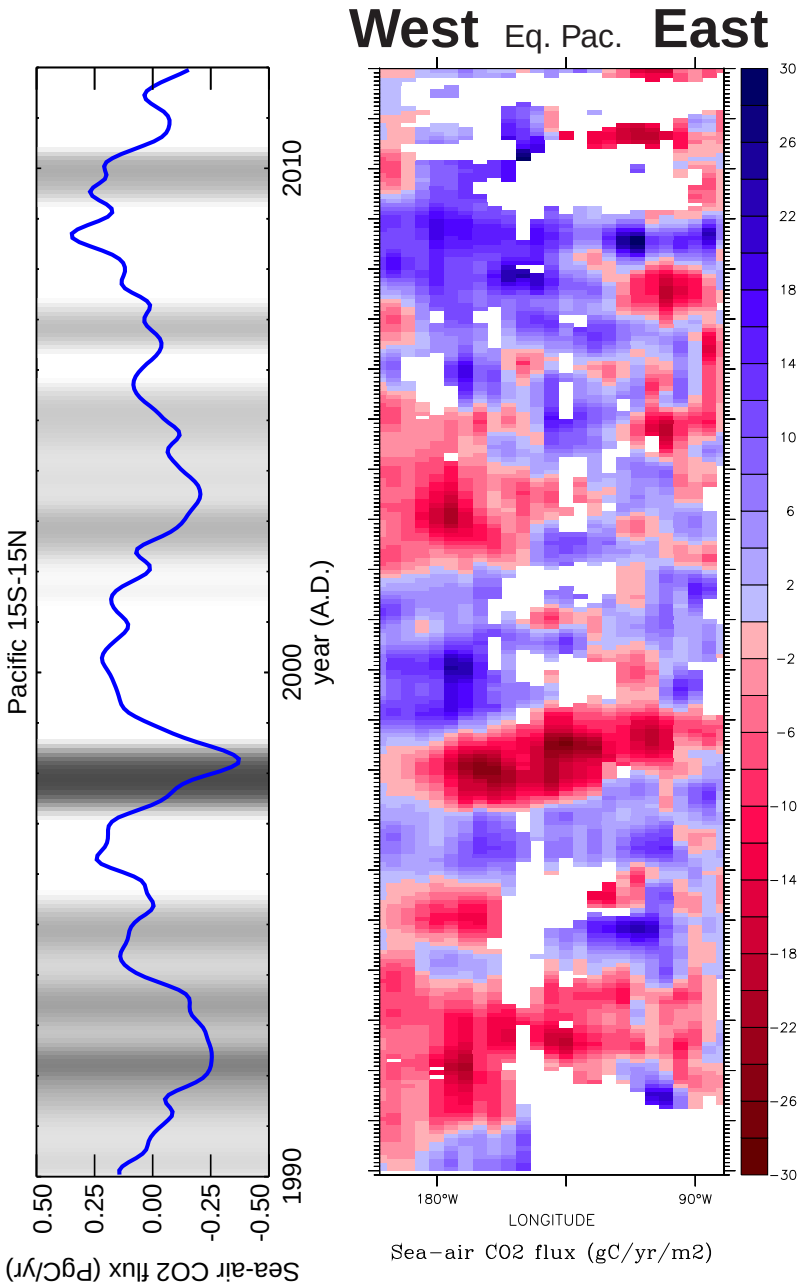
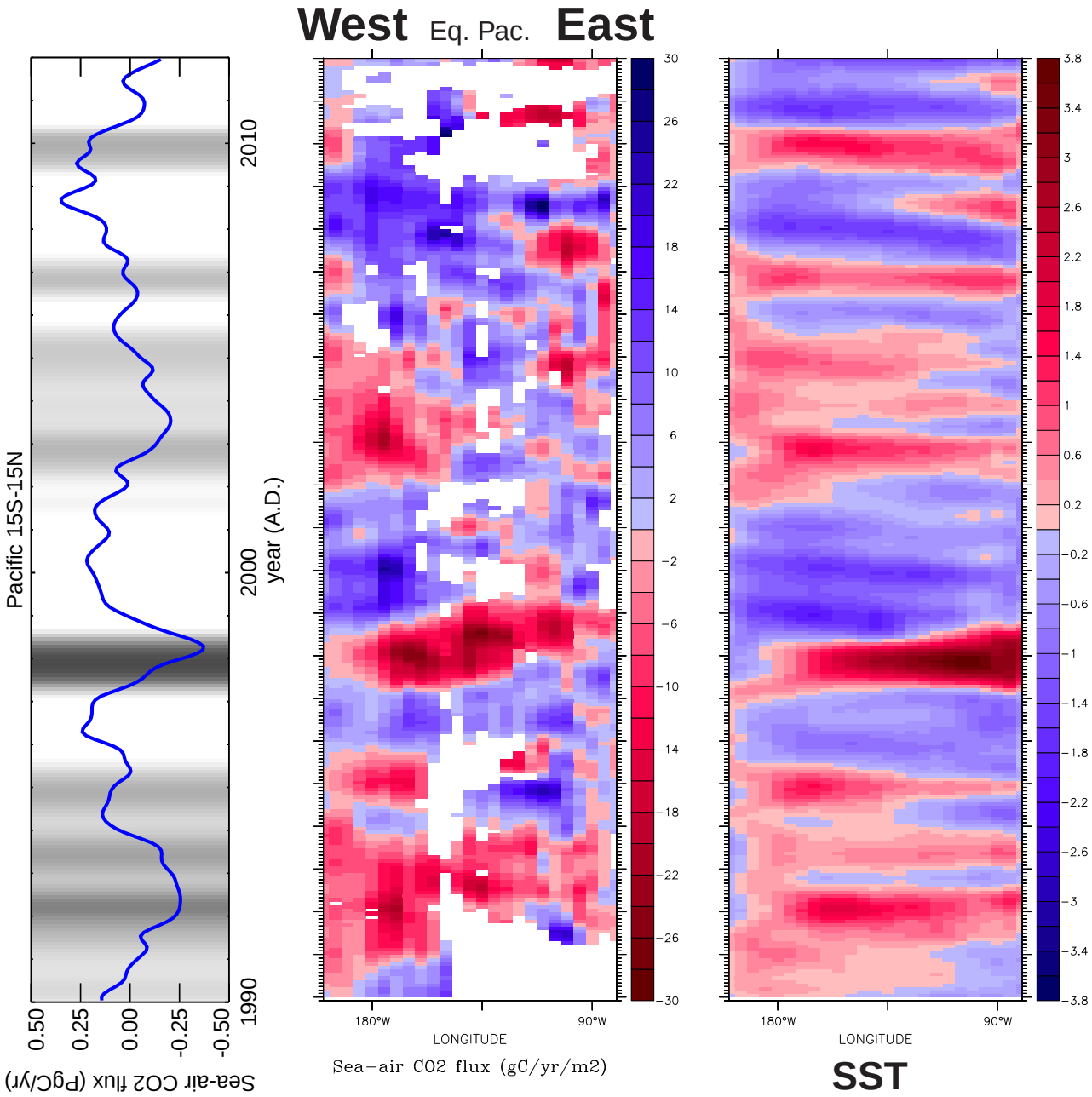
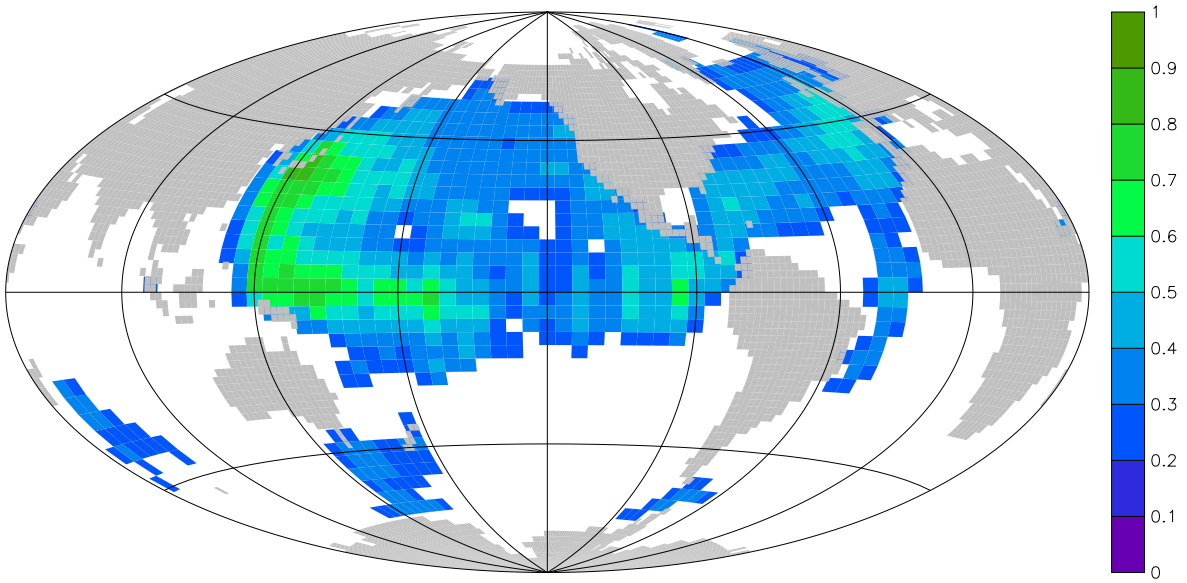


Tropical Pacific sea–air CO_2 flux variability



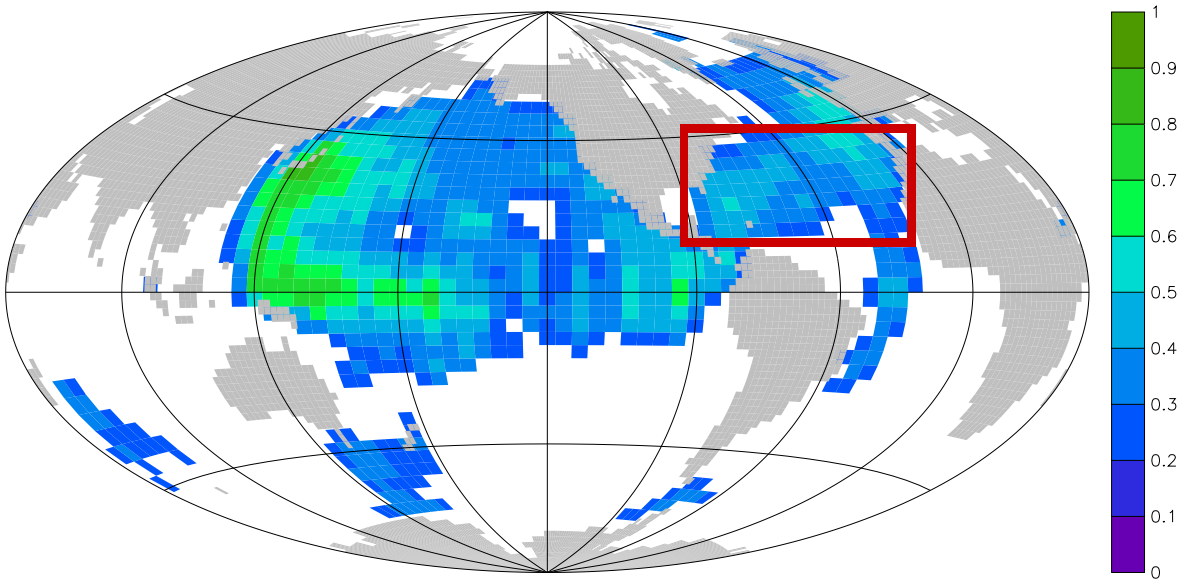
(Poster #60)

North Atlantic constraint

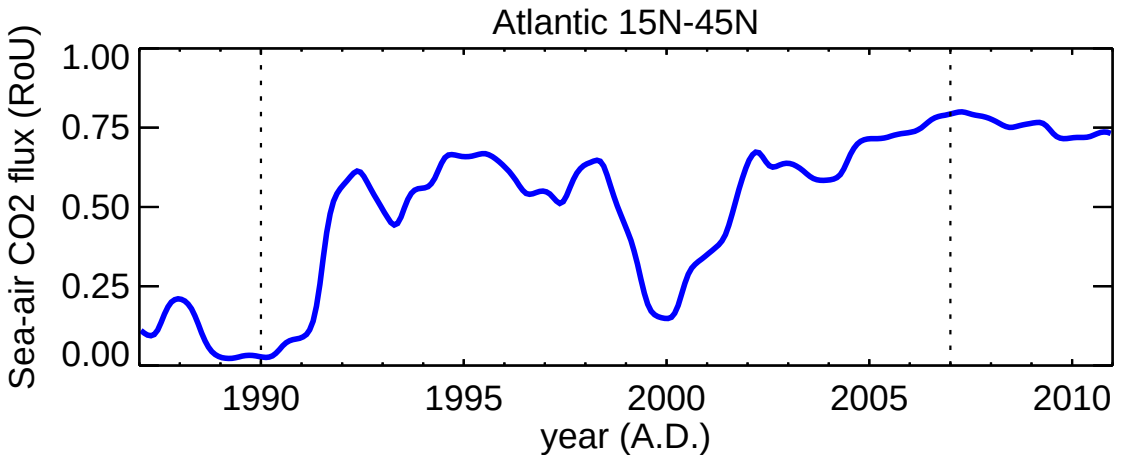


1990–2006

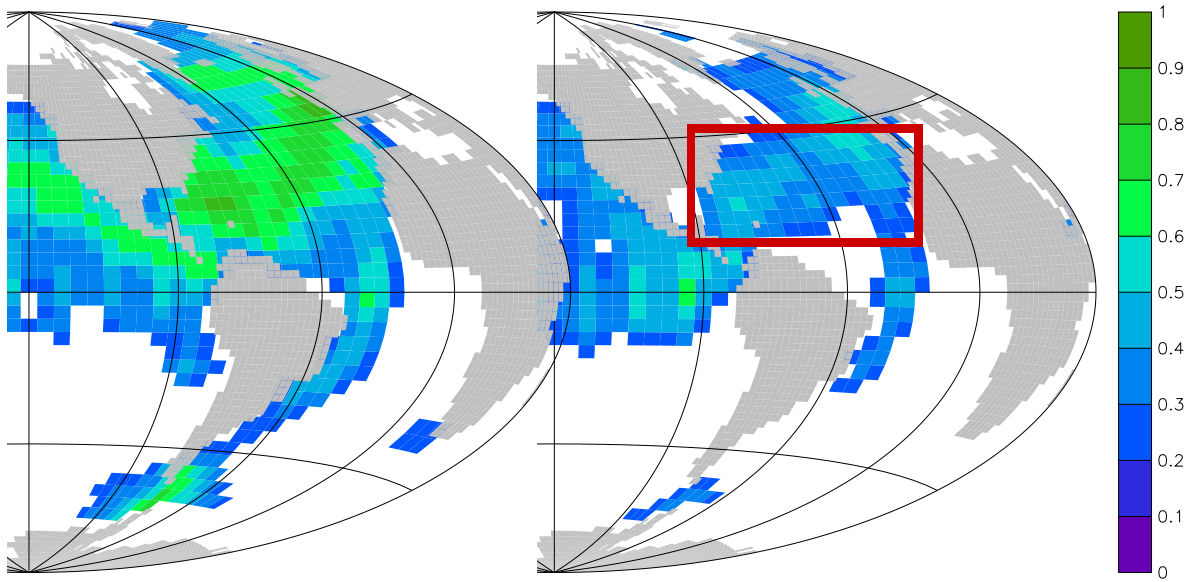
North Atlantic constraint



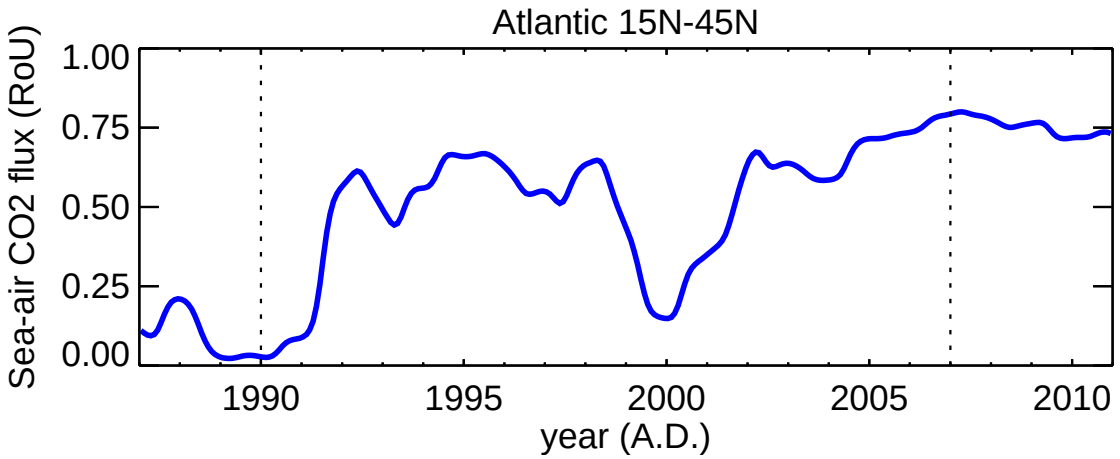
1990–2006



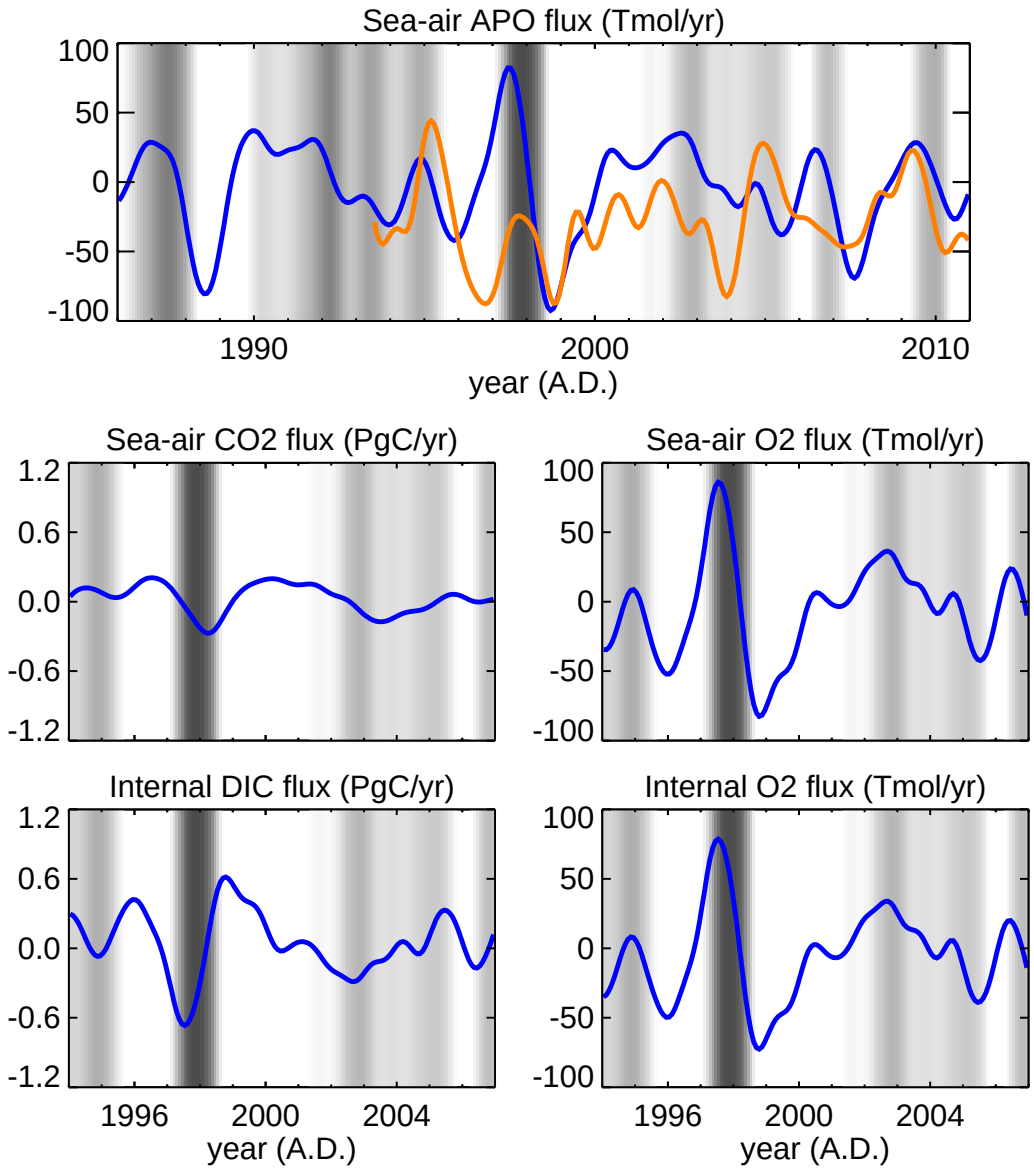
North Atlantic constraint



2003–2010 1990–2006



Comparison to atmospheric oxygen data



Tropical Pacific (15S–15N)

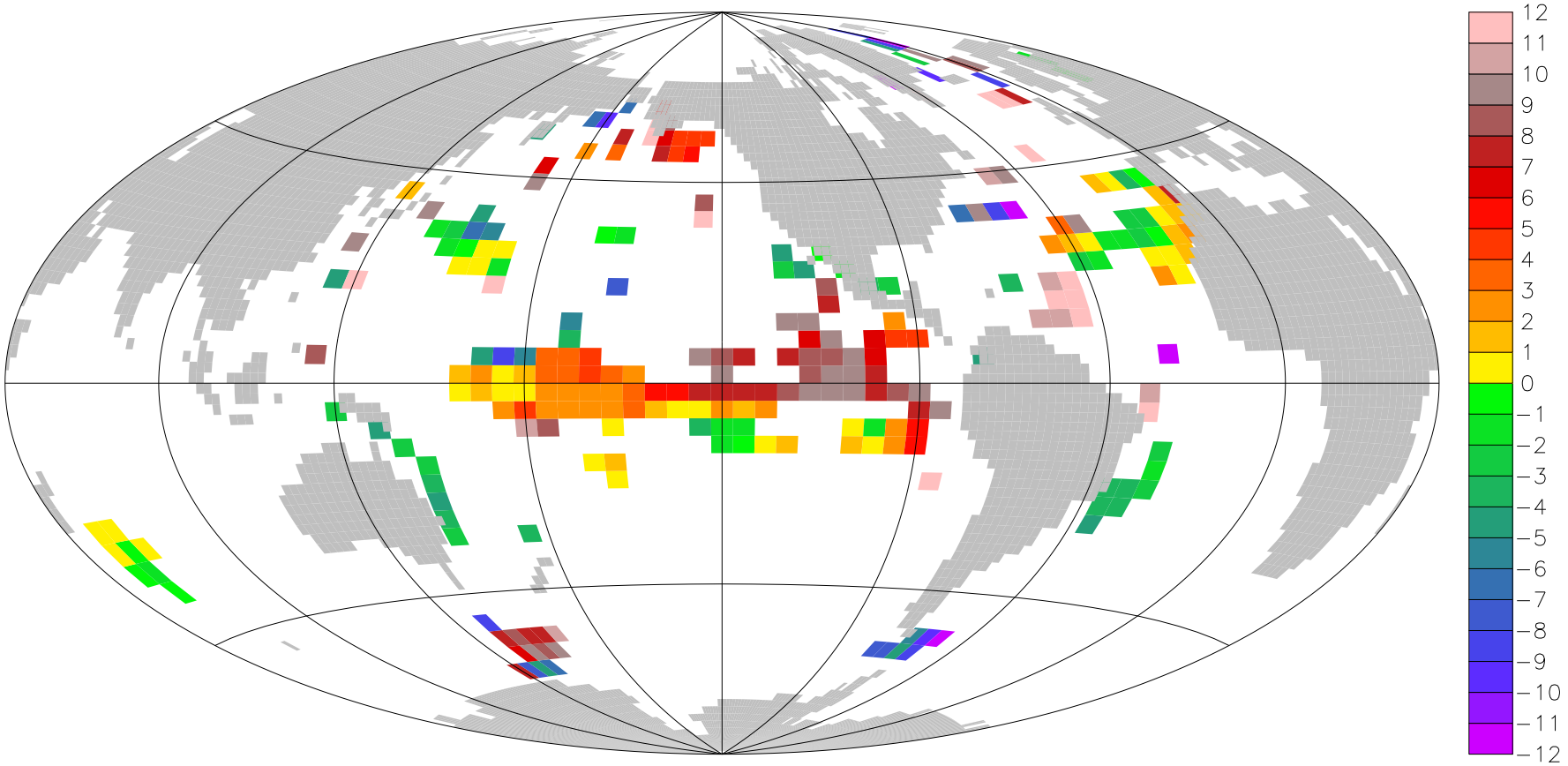
- inferred from SOCAT (blue)
- independently estimated from atmospheric O_2/N_2 ratios and CO_2 mixing ratios (atmospheric APO inversion, Rödenbeck et al., 2008, updated).

Backgound shading: El Niño (MEI index).
Identical vertical range on a molar basis.

Correlation: Sea–air CO_2 flux vs. SST

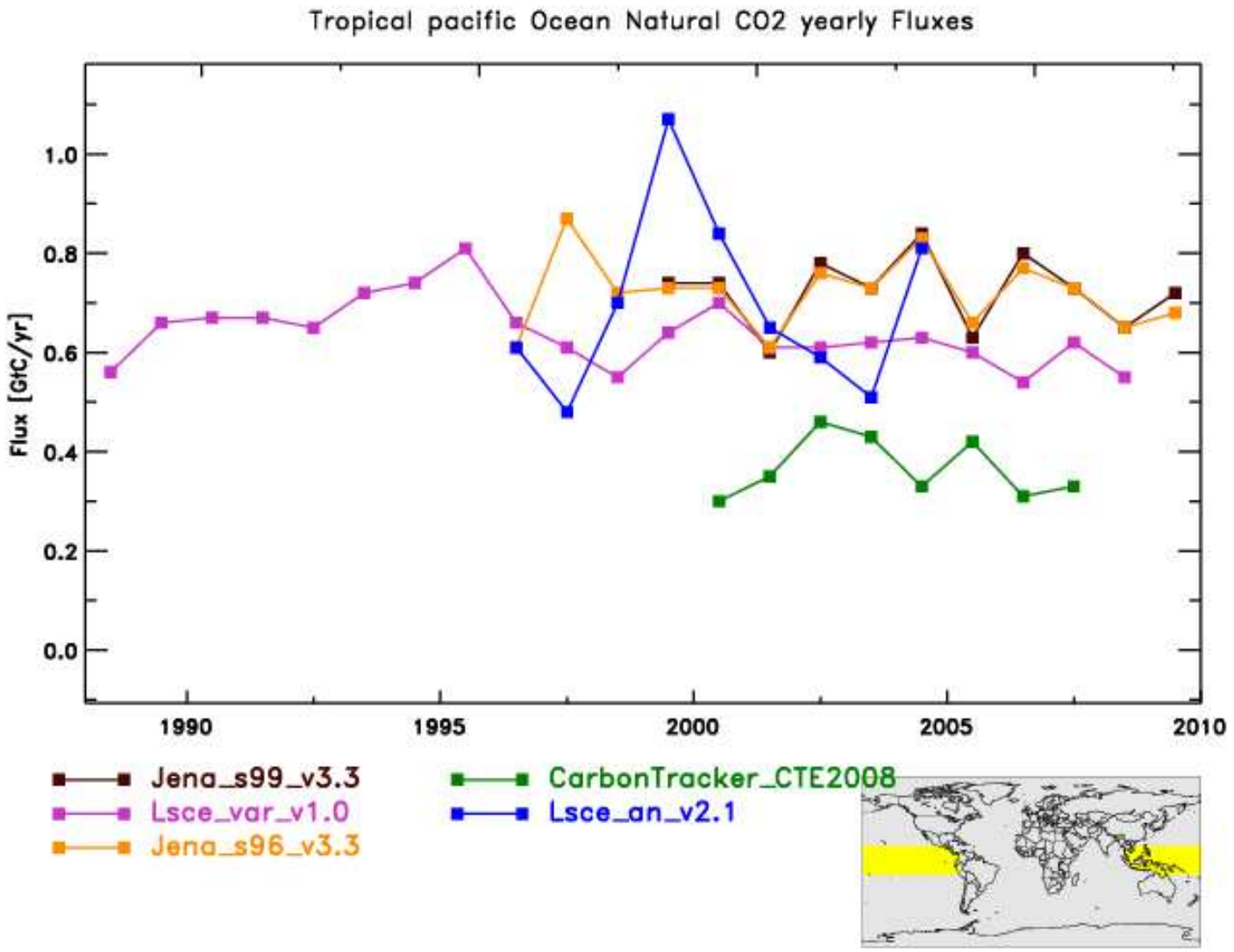
Lag of interannual anomalies (1992-2007):

Flux **later** than SST



Flux **earlier** than SST

Atmospheric CO_2 inversions



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