Carbon Cycle Modelling and Measurements – Robust Flux Estimation

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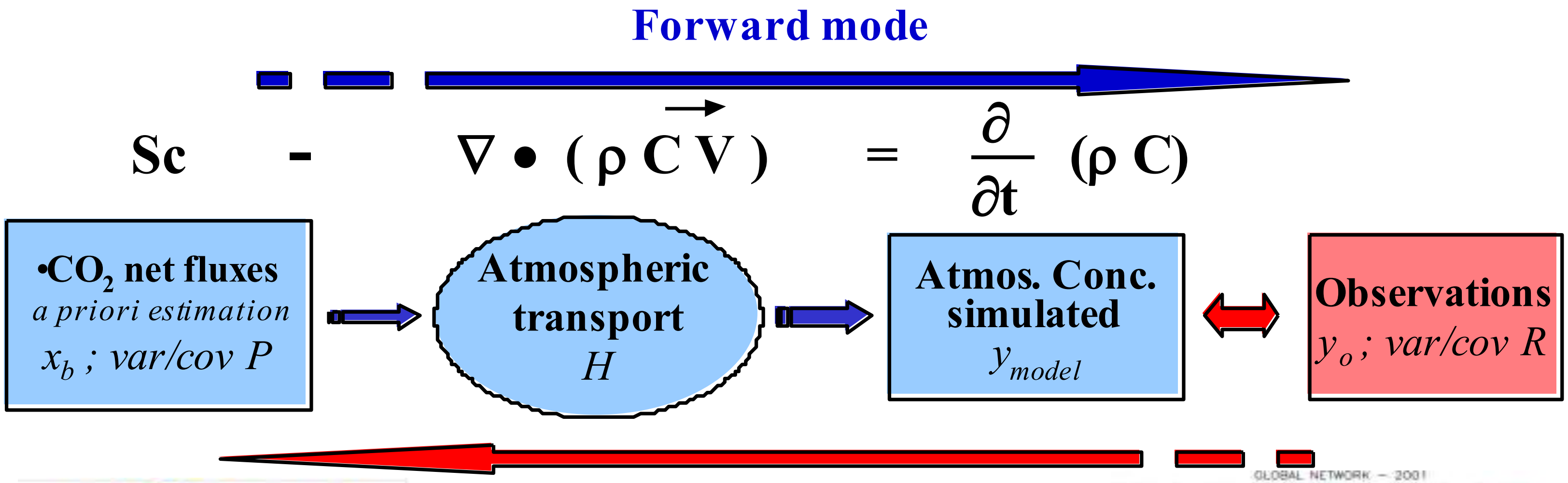
Recent Advances in CO2 Capture Technologies
and Sectoral Applications, Delhi, 1 Sep. 2018

- India’s COP 21 commitments (by 2030)
- 33-35 % improvement in energy intensity from 2005 levels
- 2.5 – 3 GTCO2 (0.6 – 0.8 GTC) additional forest sink
- Question: How do we quantify this?
- Bottom-up and Top-down approaches

Atmospheric transport model



Forward mode

$$Sc \quad - \quad \nabla \bullet (\rho C \vec{V}) \quad = \quad \frac{\partial}{\partial t} (\rho C)$$

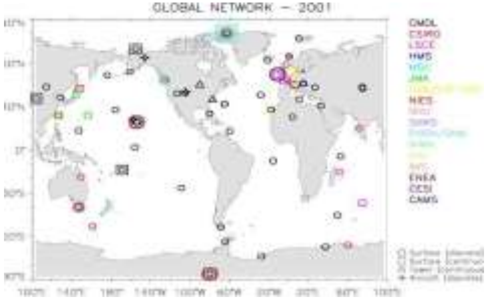
•CO_2 net fluxes
a priori estimation
x_b ; var/cov P

Atmospheric transport
H

Atmos. Conc. simulated
y_{model}

Observations
y_o; var/cov R

Inverse mode

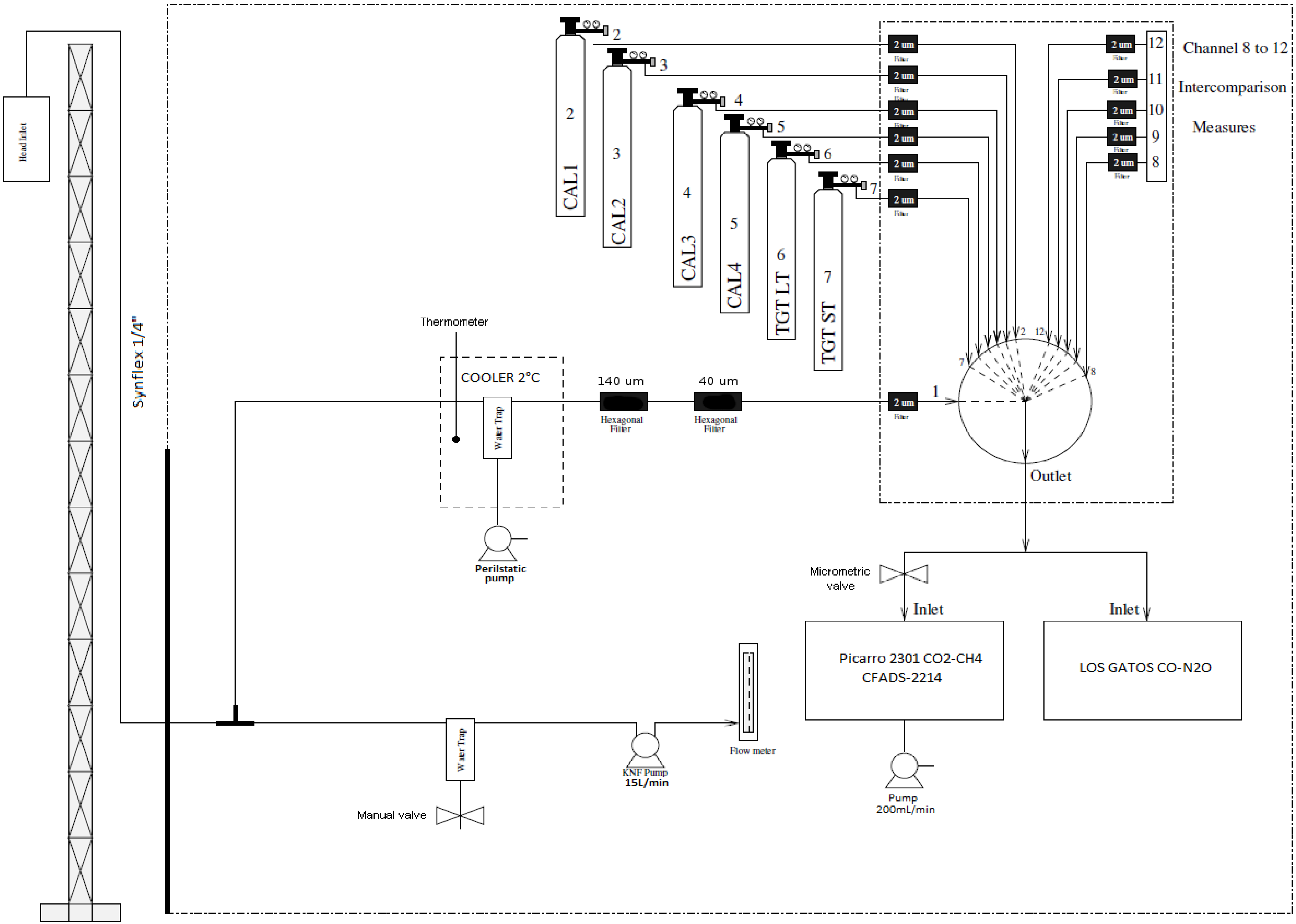


MOZART Transport model
Bayesian Inversion

- Need very accurate measurements traceable to WMO-NOAA primary standards
- A good density of measurements
- A procedure to assimilate measurements into models to yield robust flux estimates

Reference Station set up in Hoskote near Bangalore

Schematic diagram of the station




ZAR

Calibration with NOAA primary

- Calibration of Secondary (working) standards
  - NOAA cylinders are connected in the sequence and the calibration is carried out with three cycles of NOAA and secondary cylinders in succession
  - Each cylinder gas goes through the instruments Picarro and LGR for 20 minutes
  - Calibration curve is fitted and with the parameters a0 and a1 in the equation $y=a0 + a1x$, the values are corrected on the secondary cylinders
  - Using these corrected secondary cylinder values, further the measurements are corrected

Compositions of NOAA and Secondary cylinders

- **NOAA cylinders**:

TANK	CO2 ppm	CH4 ppm	CO ppb	N2O ppb
CAL 1	341.95	1.6335	66.1	300.63
CAL 2	74.15	1.7839	108.1	313.75
CAL 3	396.95	1.939	152.4	328.12
CAL 4	429.0	2.087	163.8	332.01
CAL 5	464.0	2.3424	286.3	341.28
CAL 6	503.18	2.6107	470.7	350.61

- **Secondary cylinders**:

TANK	CO2 ppm	CH4 ppm	CO ppb	N2O ppb
CAL 1	370.0	1.805	50	310.3
CAL 2	400.1	1.899	100.2	330
CAL 3	420.4	2.099	250	335.8
CAL 4	480	2.400	500.4	351.6
TGT ST	400.2	1.901	150	330.7
TGT LG	460	2.301	500.3	342.2

CO2 Result: (Picarro)

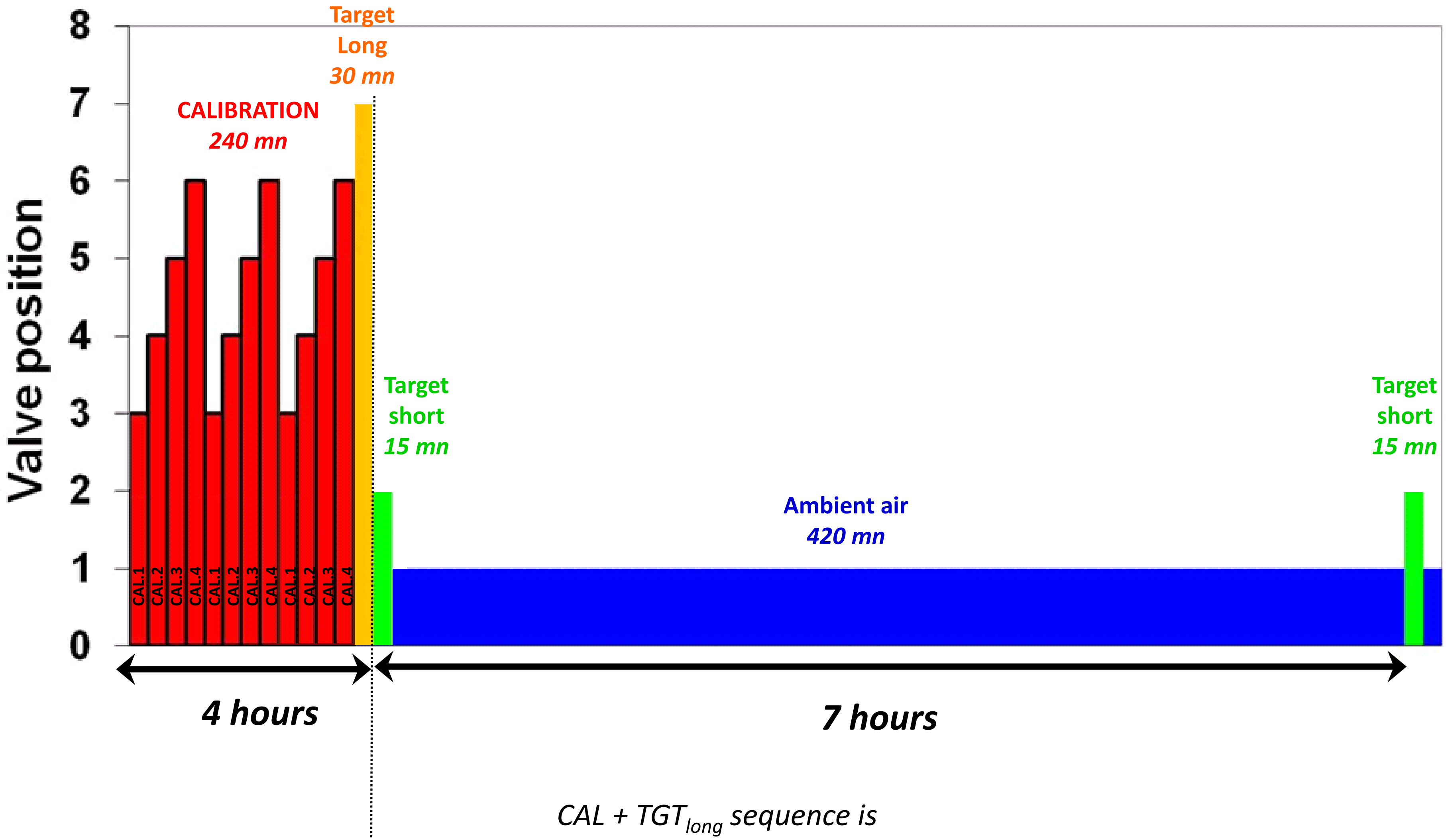
- NOAA cylinders:

- **ao= -0.473292345073   a1= 0.994806213121**

NOAA values (ppm)	Calibration Means (ppm)
341.95	339.68855151 ± 0.0157976113582
374.15	371.72446246 ± 0.0130839226625
396.95	394.4407502 ± 0.0145592964574
429.0	426.31756892 ± 0.0172201473859
464.0	461.09896705 ±0.0174353596751
503.18	500.08126644 ±0.0201042624759

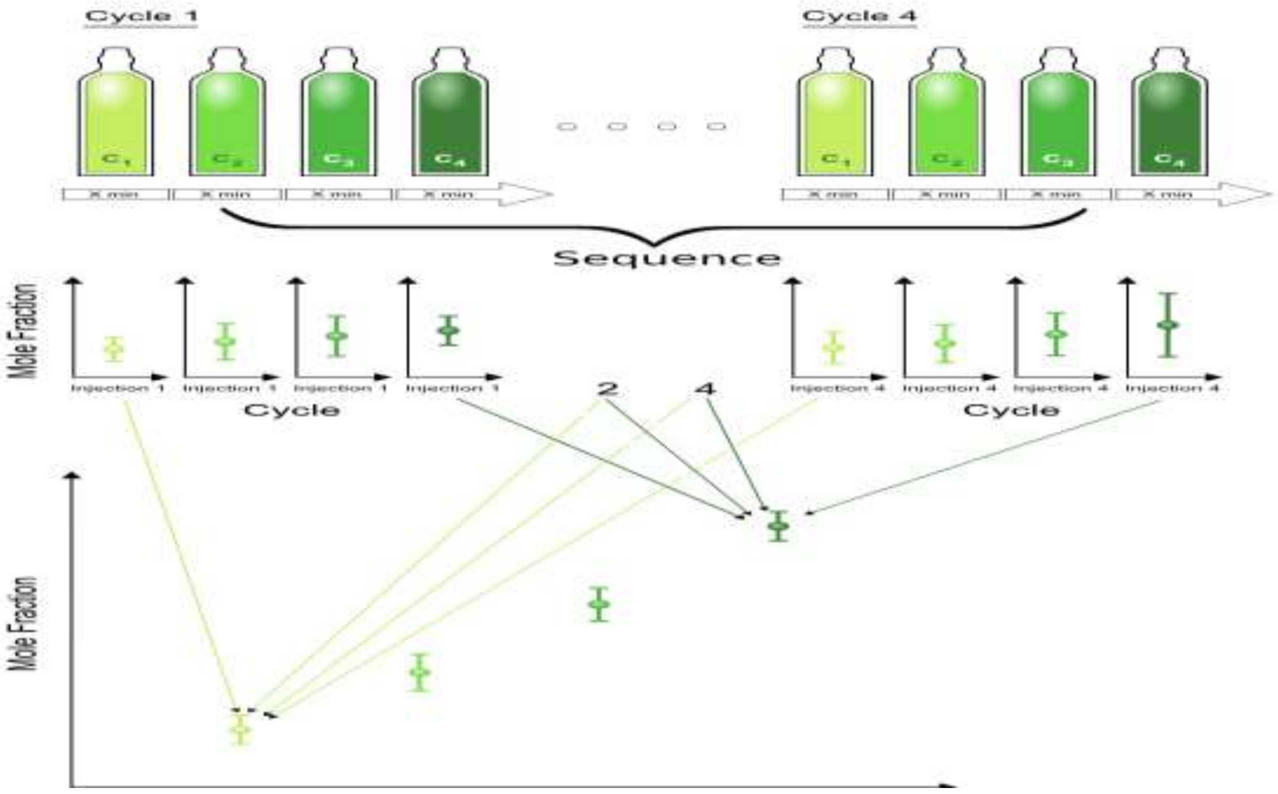
11.91 °*N* -79.81 °*E*

PICARRO SEQUENCE - PONDICHERRY



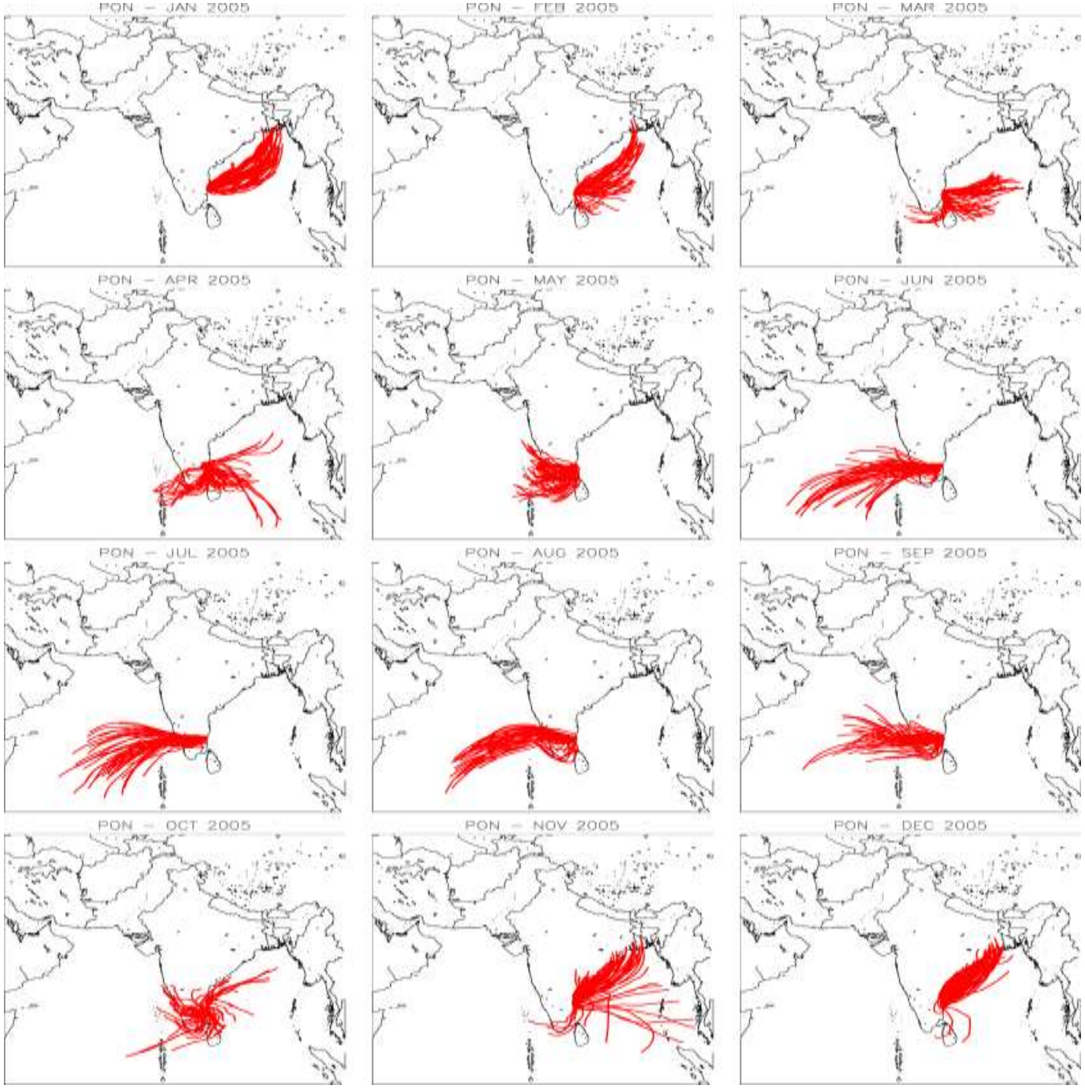
CAL + TGT_{long} sequence is repeated every 15 days

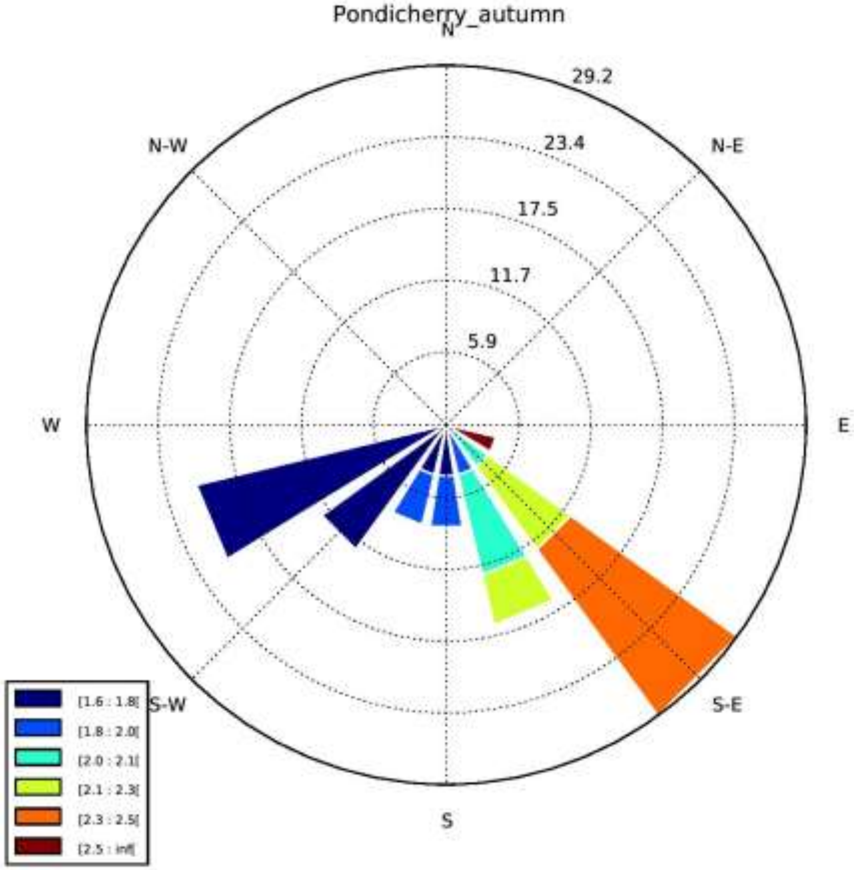
Calibration computing

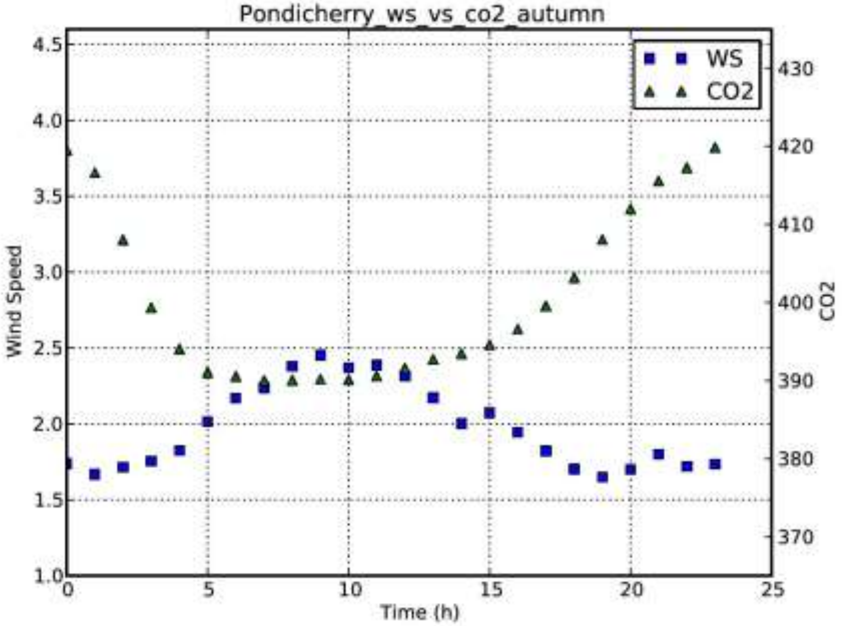


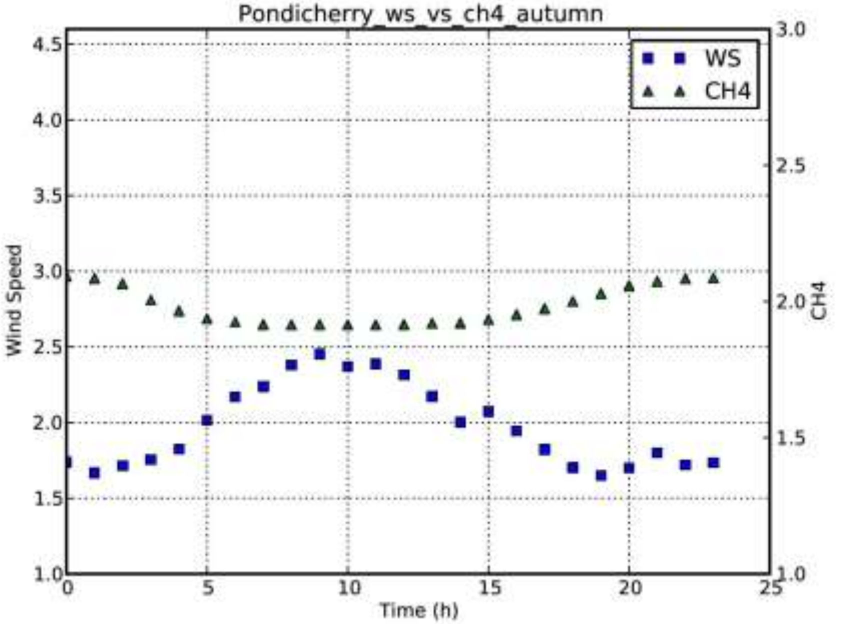
Standard Concentration

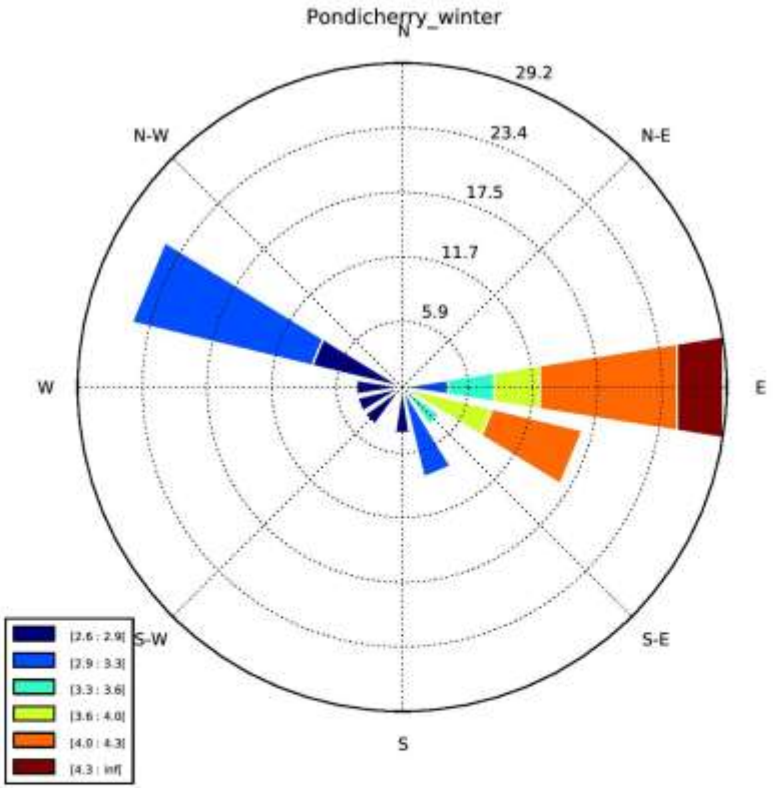
Pondichery (PON)

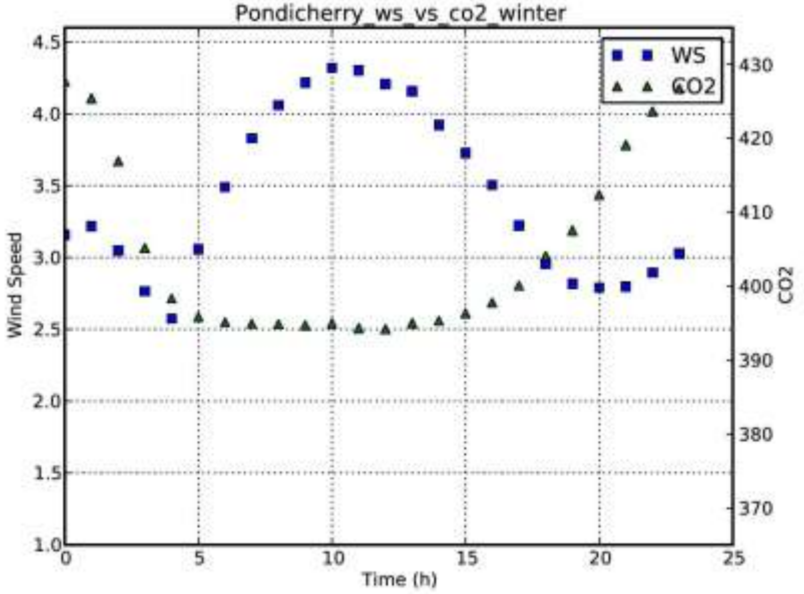


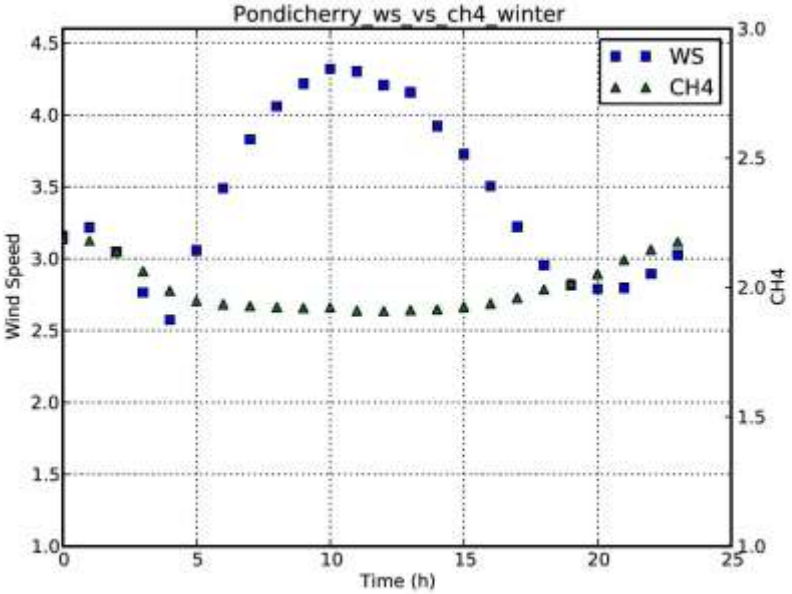

Pondicherry_autumn
N
N-E
E
S-E
S
S-W
W
N-W
29.2
23.4
17.5
11.7
5.9
[1.6 : 1.8[
[1.8 : 2.0[
[2.0 : 2.1[
[2.1 : 2.3[
[2.3 : 2.5[
[2.5 : inf[

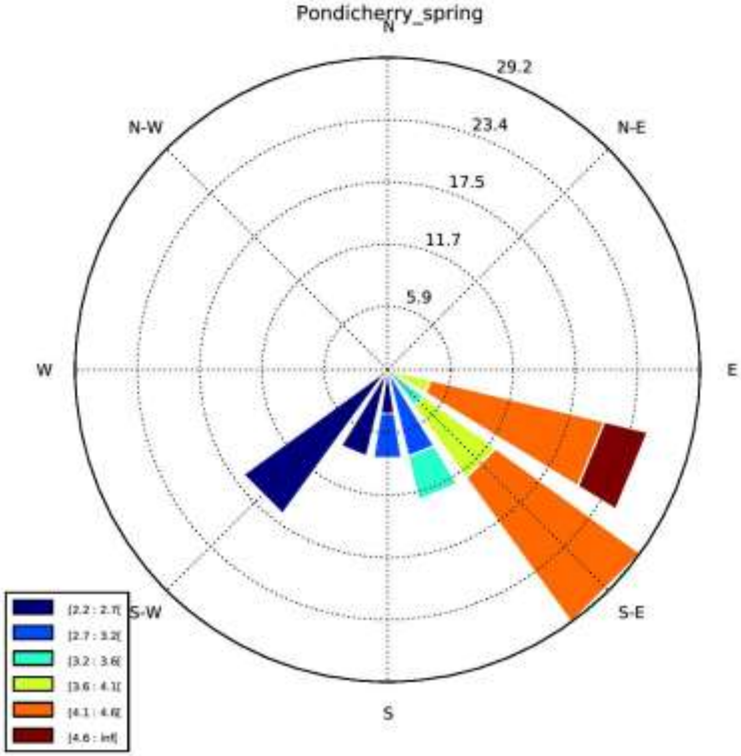

Pondicherry_ws_vs_co2_autumn
WS
CO2
Wind Speed
CO2
Time (h)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
370
380
390
400
410
420
430
0
5
10
15
20
25

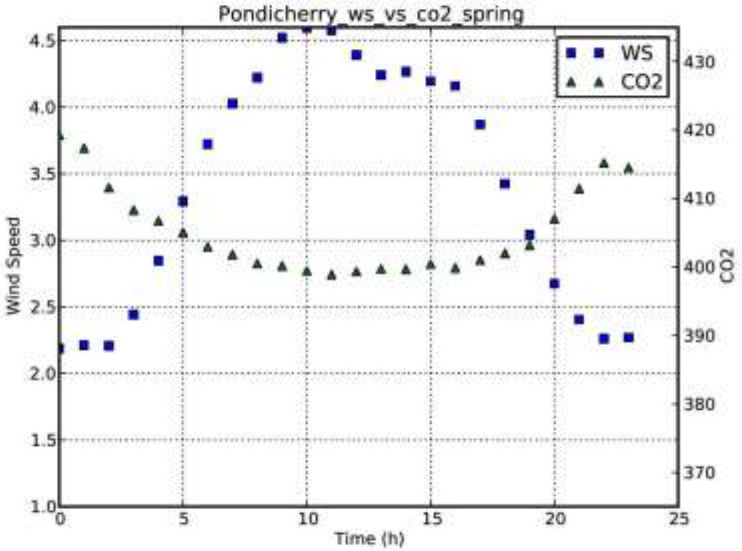

Pondicherry_ws_vs_ch4_autumn
WS
CH4
Wind Speed
CH4
Time (h)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
25

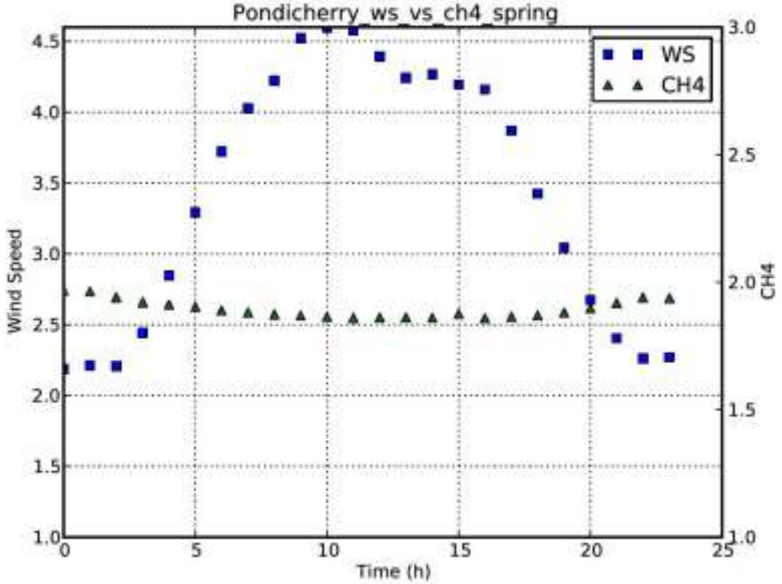

Pondicherry_winter
N
N-E
E
S-E
S
S-W
W
N-W
5.9
11.7
17.5
23.4
29.2
[2.6 : 2.9[
[2.9 : 3.3[
[3.3 : 3.6[
[3.6 : 4.0[
[4.0 : 4.3[
[4.3 : inf[

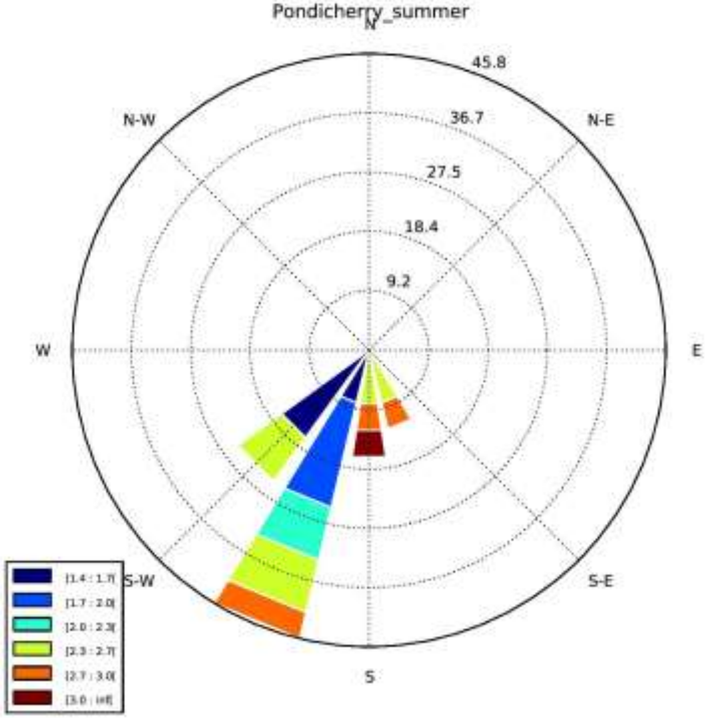

Pondicherry_ws_vs_co2_winter
WS
CO2
Wind Speed
CO2
Time (h)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
370
380
390
400
410
420
430
0
5
10
15
20
25

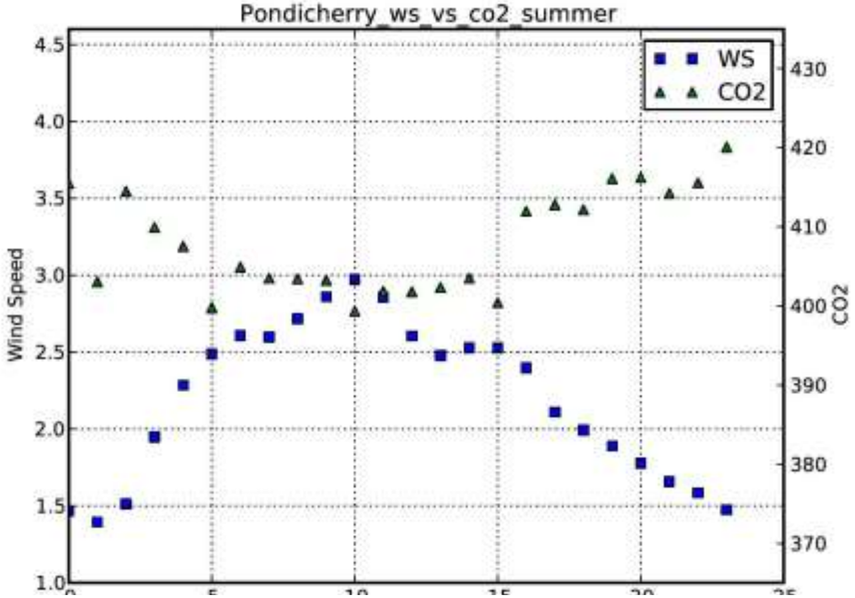

Pondicherry_ws_vs_ch4_winter
WS
CH4
Wind Speed
CH4
Time (h)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
25

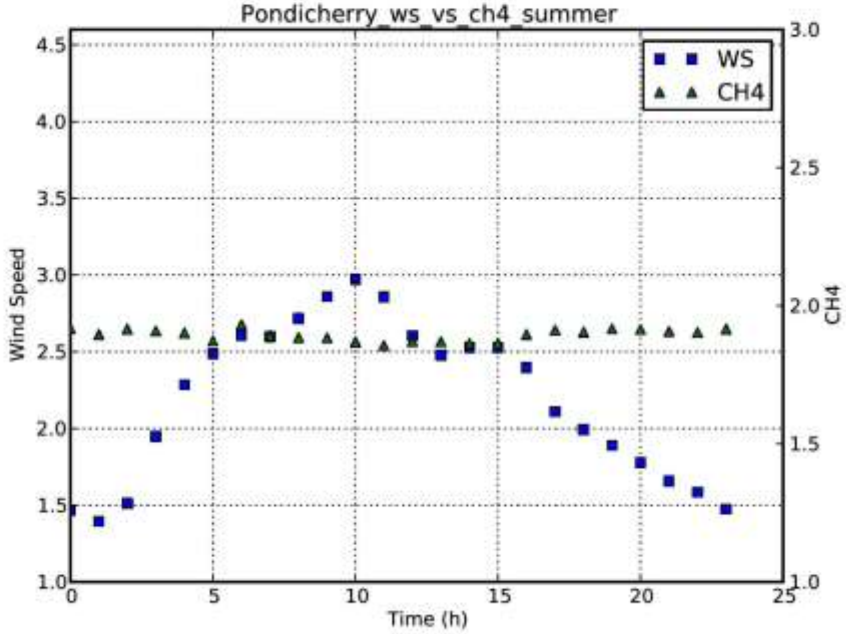

Pondicherry_spring
N
N-E
E
S-E
S
S-W
W
N-W
5.9
11.7
17.5
23.4
29.2
[2.2 : 2.7[
[2.7 : 3.2[
[3.2 : 3.6[
[3.6 : 4.1[
[4.1 : 4.6[
[4.6 : inf[


Pondicherry_ws_vs_co2_spring
WS
CO2
Wind Speed
CO2
Time (h)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
370
380
390
400
410
420
430
0
5
10
15
20
25


Pondicherry_ws_vs_ch4_spring
WS
CH4
Wind Speed
CH4
Time (h)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1.0
1.5
2.0
2.5
3.0
0
5
10
15
20
25

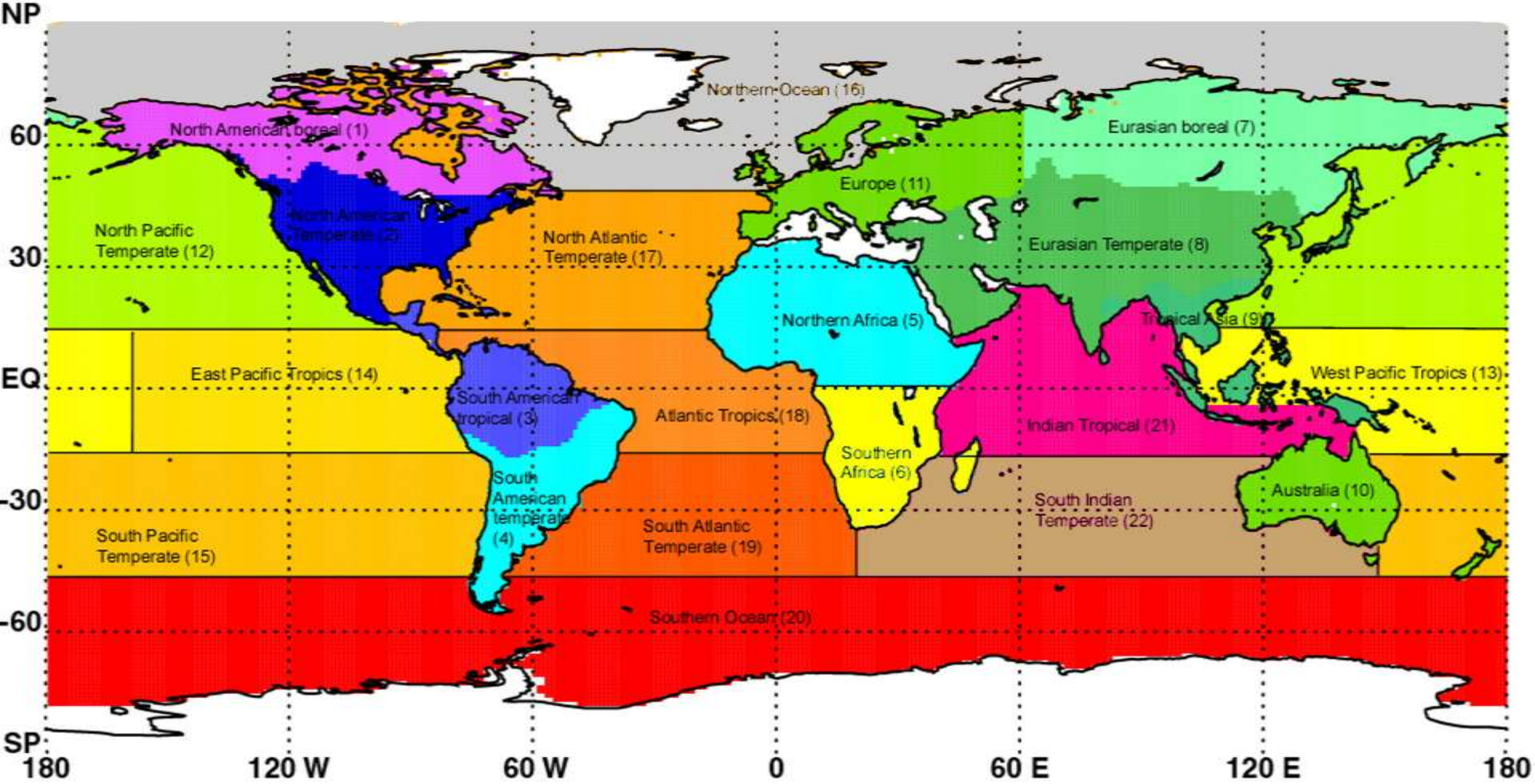

Pondicherry_summer
N
N-E
E
S-E
S
S-W
W
N-W
9.2
18.4
27.5
36.7
45.8
[1.4 : 1.7[
[1.7 : 2.0[
[2.0 : 2.3[
[2.3 : 2.7[
[2.7 : 3.0[
[3.0 : inf[


Pondicherry_ws_vs_co2_summer
Wind Speed
CO2
WS
CO2
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
370
380
390
400
410
420
430


Pondicherry_ws_vs_ch4_summer
Wind Speed
CH4
WS
CH4
Time (h)
0
5
10
15
20
25
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1.0
1.5
2.0
2.5
3.0

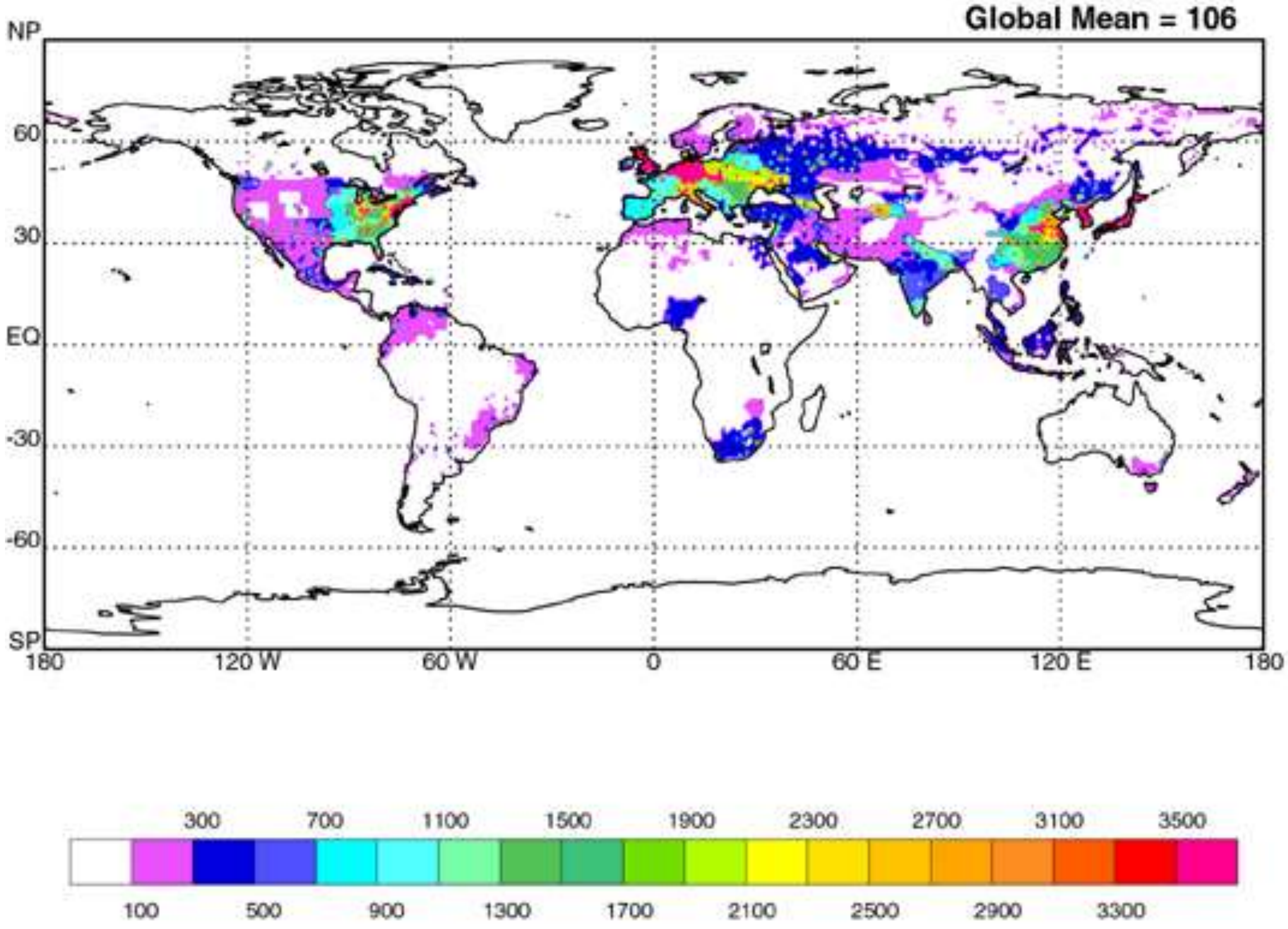
Flux Estimations - Transcom Setup

- 11 Land and 11 Ocean Regions
- Repeating 1996 NCEP winds
- Presubs: FF90 and FF95, NEP and Ocean
- Green’s Functions: Monthly unit emissions tracked for 36 months.
- Transport code: MOZART T-42 resolution (128*64*28)
- Cyclostationary case with TDI inversion
- Station data 71
- Priors based on L3 case


NP
60
30
EQ
-30
-60
SP
180
120 W
60 W
0
60 E
120 E
180
Northern Ocean (16)
North American boreal (1)
Eurasian boreal (7)
Europe (11)
North American Temperate (2)
North Pacific Temperate (12)
North Atlantic Temperate (17)
Eurasian Temperate (8)
Northern Africa (5)
Tropical Asia (9)
East Pacific Tropics (14)
West Pacific Tropics (13)
South American tropical (3)
Atlantic Tropics (18)
Indian Tropical (21)
Southern Africa (6)
South American temperate (4)
Australia (10)
South Indian Temperate (22)
South Pacific Temperate (15)
South Atlantic Temperate (19)
Southern Ocean (20)

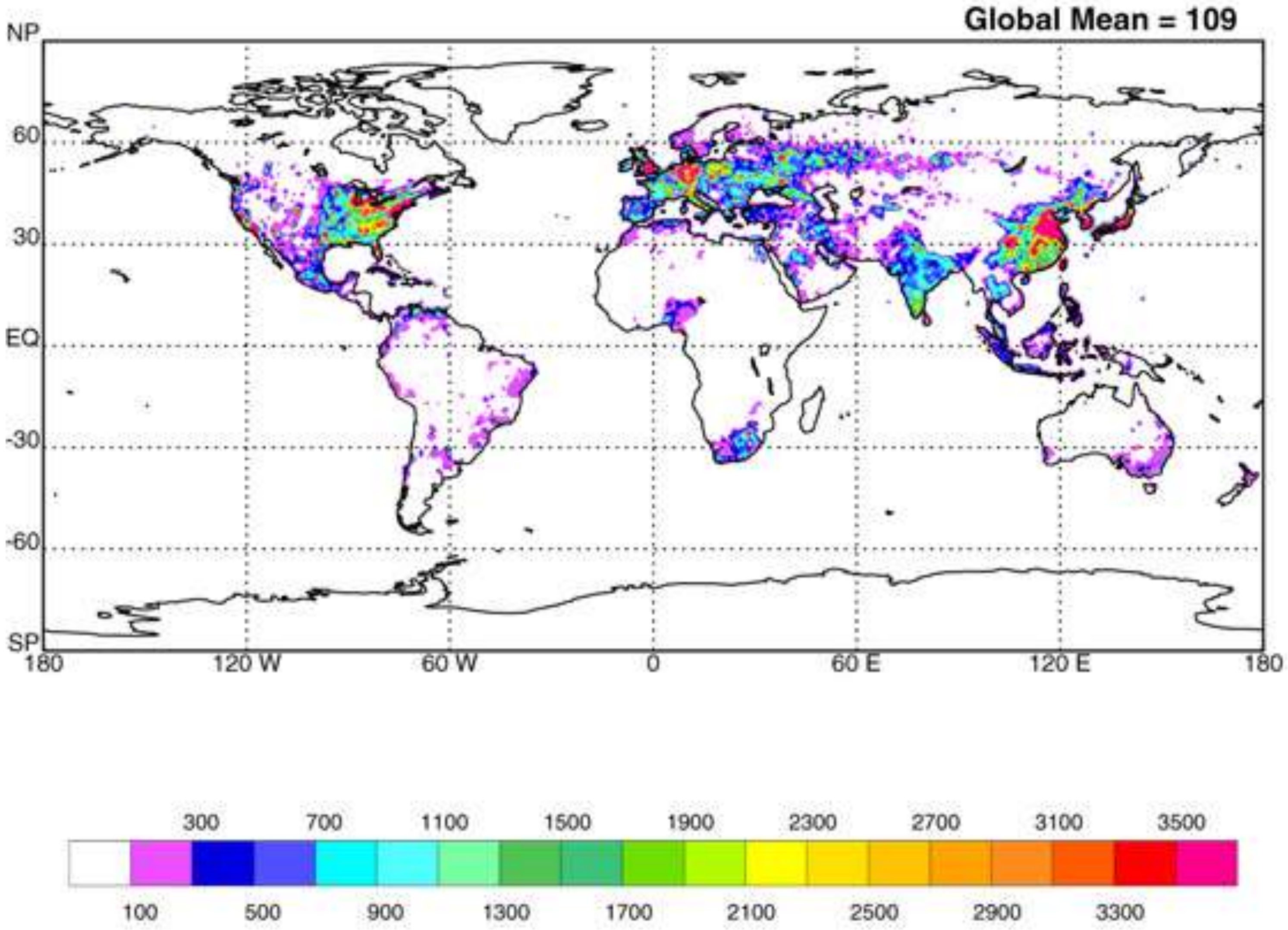
1990 carbon emissions

1000 tonnes C/grid cell



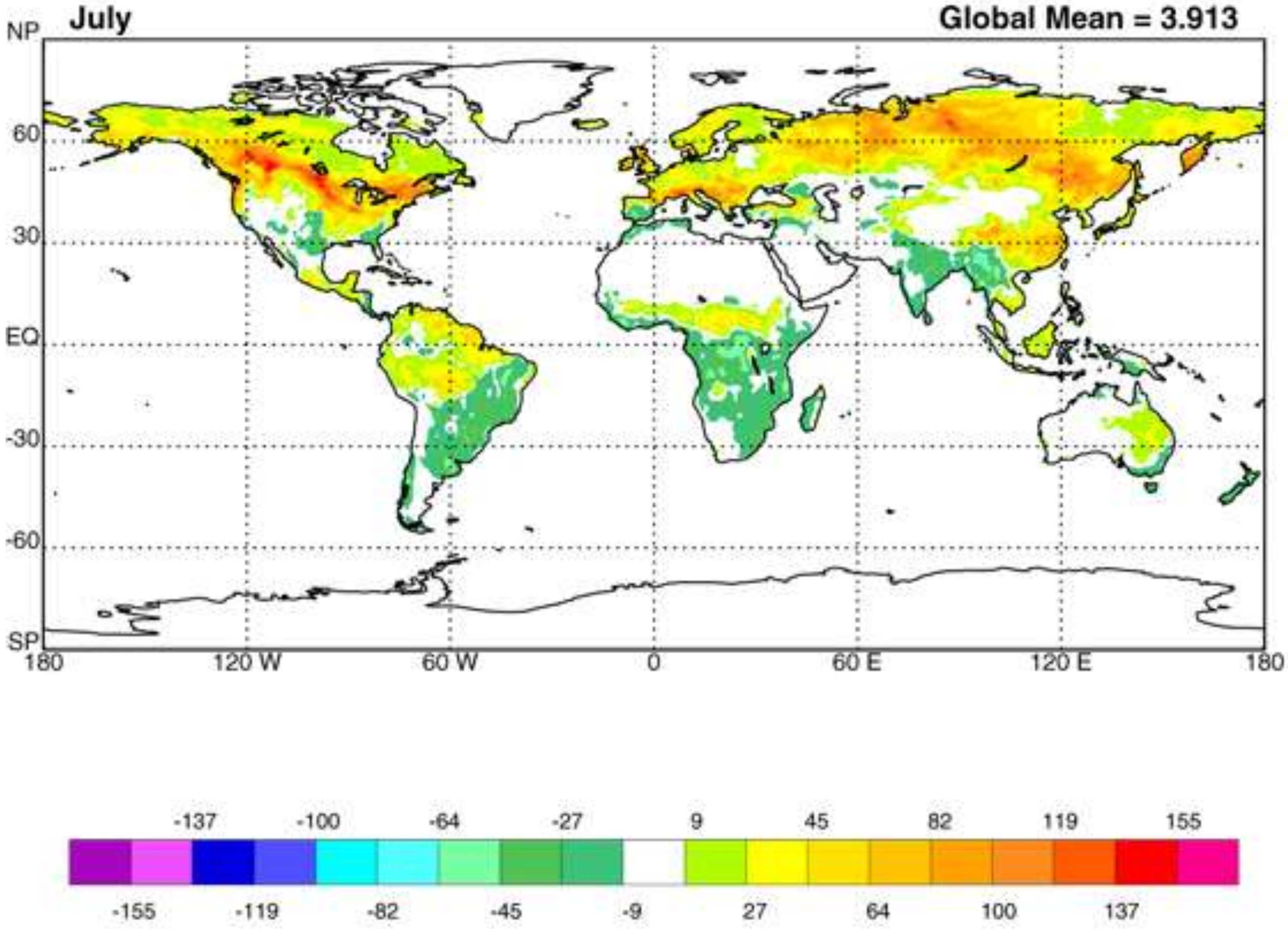
1995 carbon emissions

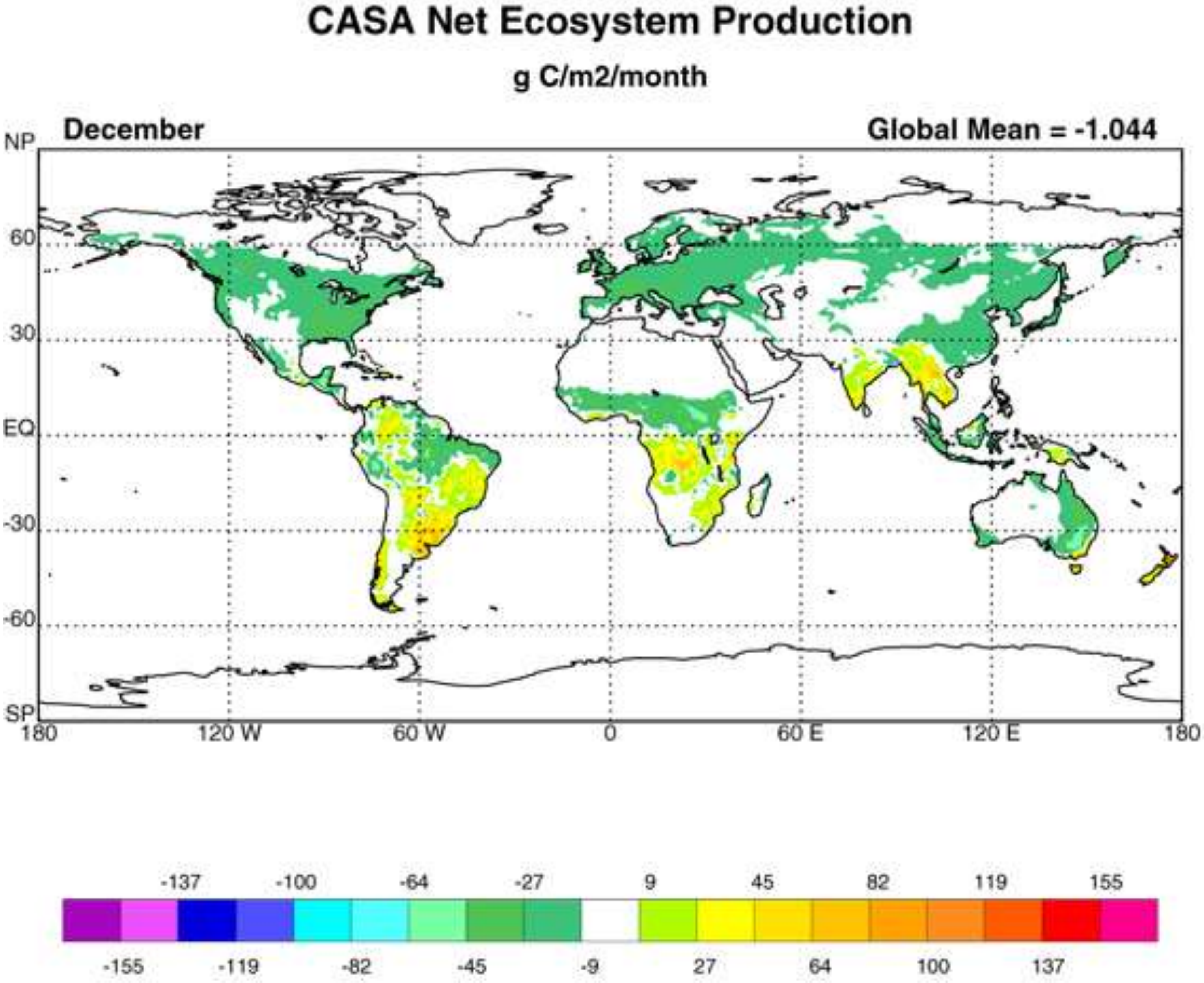
1000 tonnes C/grid cell



CASA Net Ecosystem Production

g C/m2/month





CASA Net Ecosystem Production

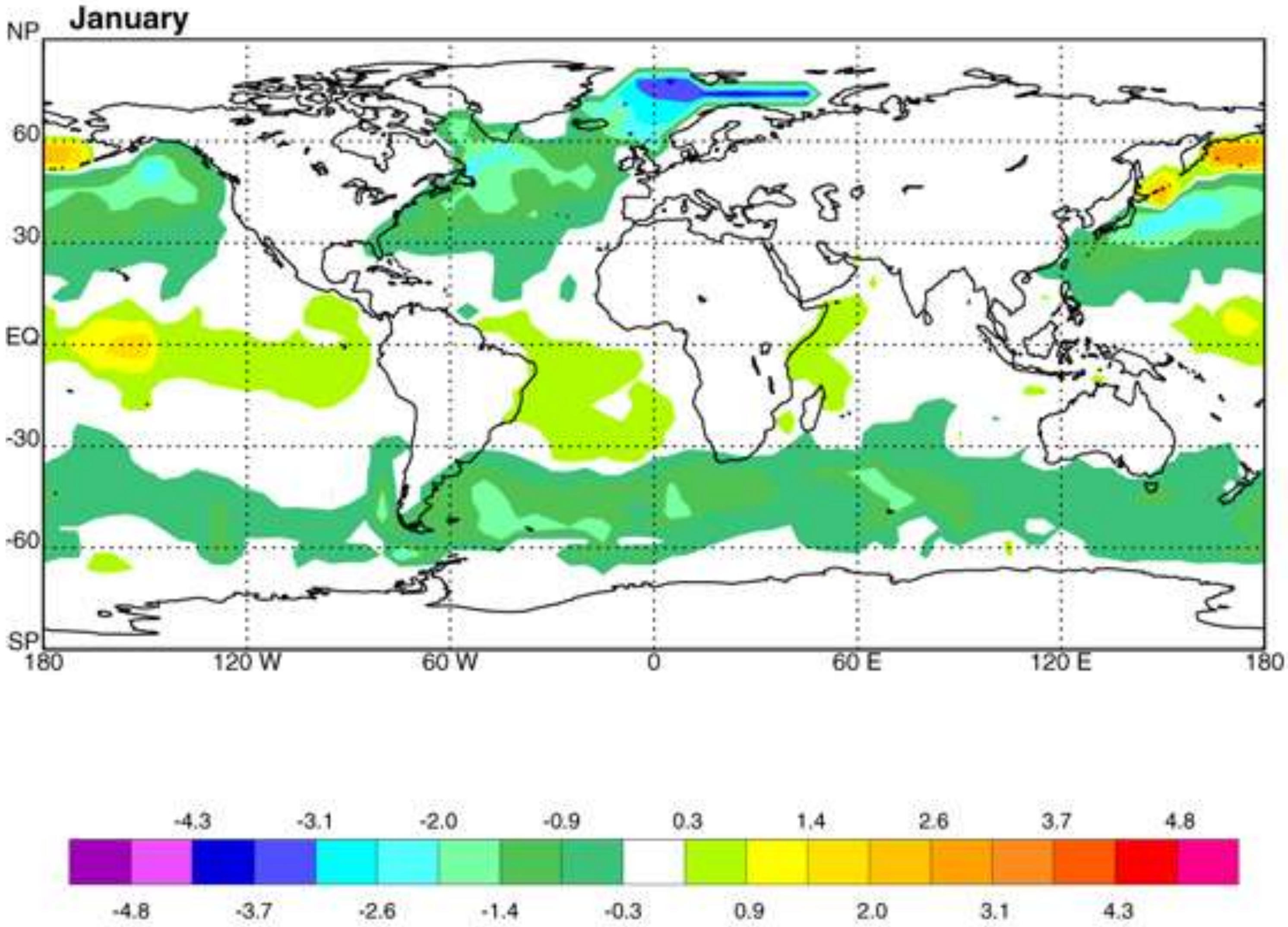
g C/m2/month

December

Global Mean = -1.044

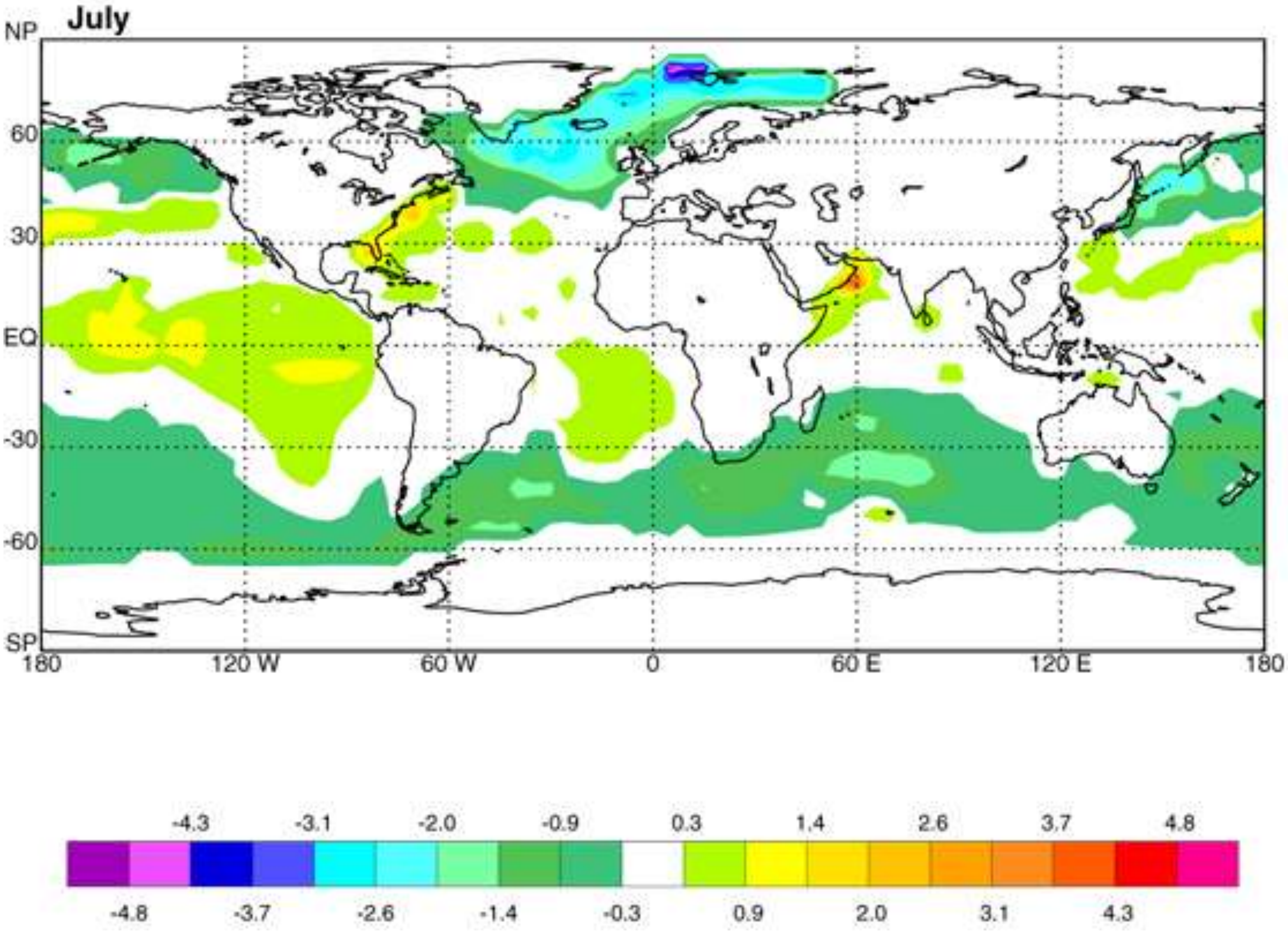
Takahashi CO2 flux

kg C/m2/second x 10^{-9}



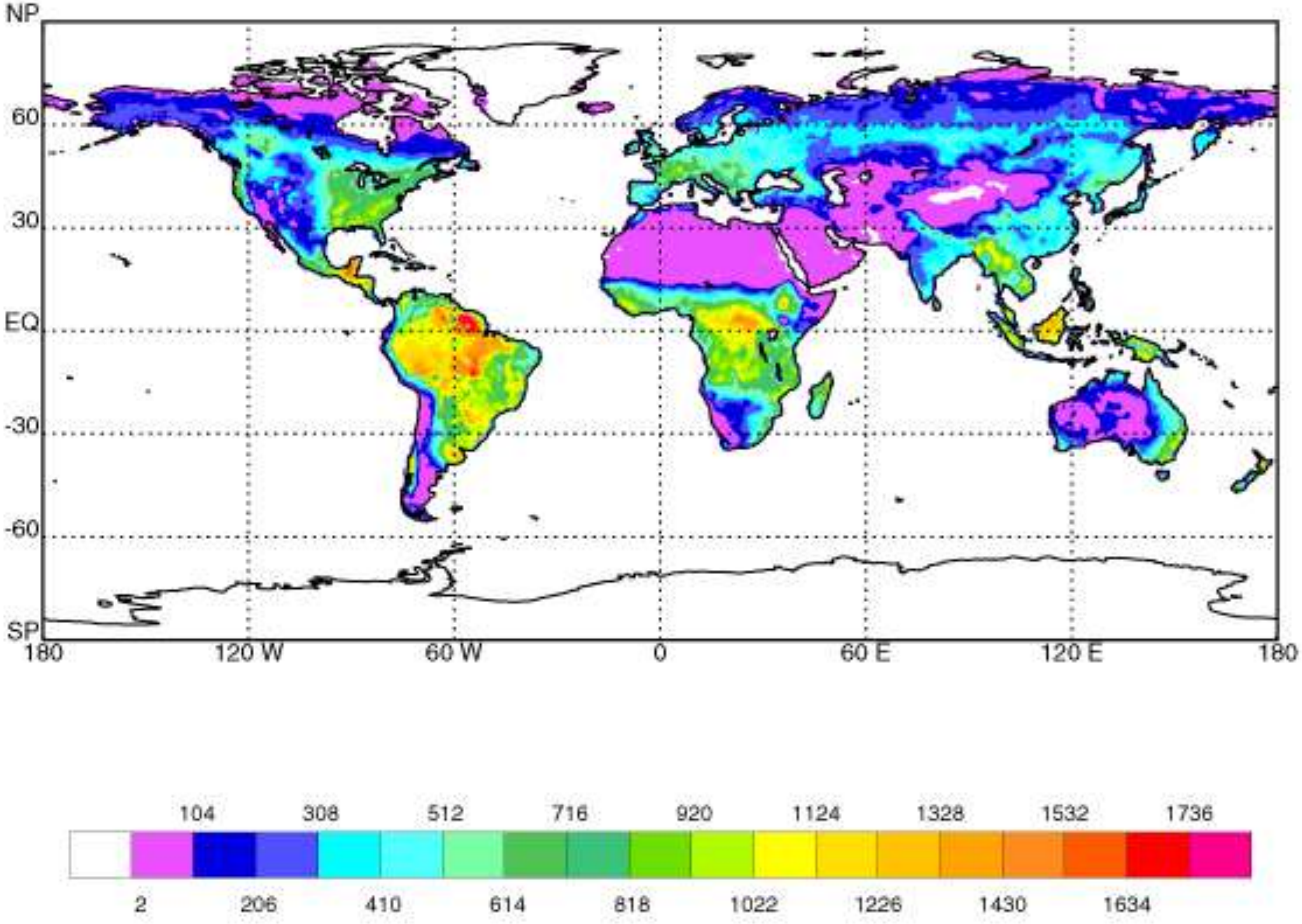
Takahashi CO2 flux

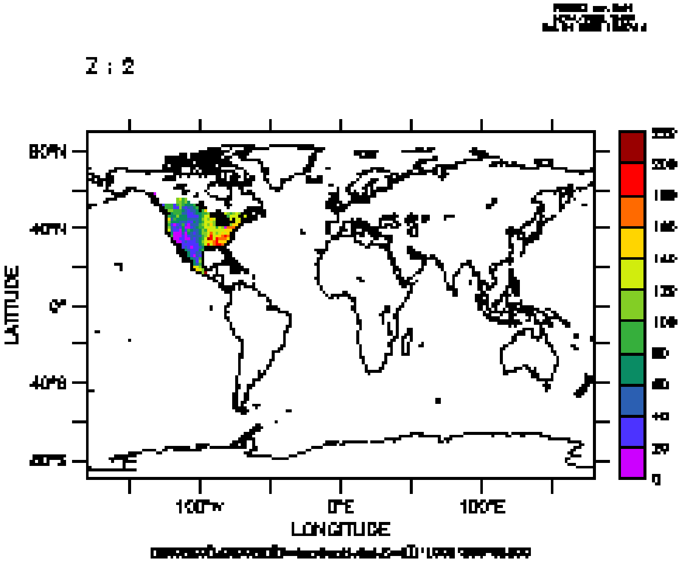
kg C/m2/second x 10^{-9}

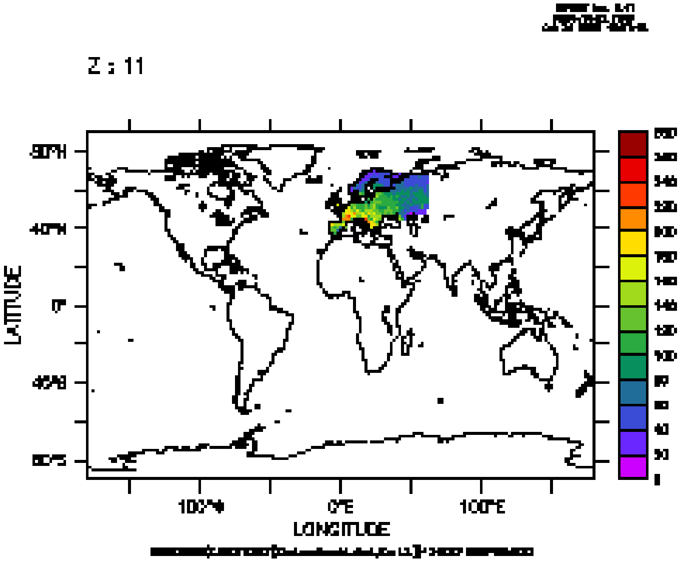


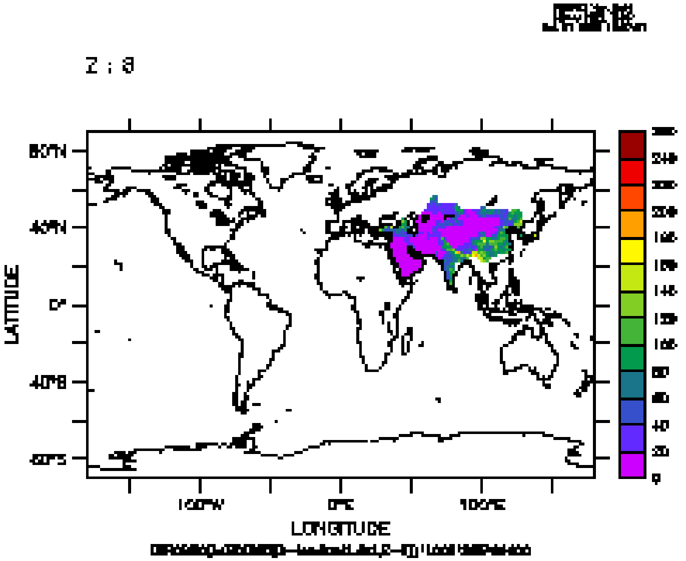
CASA NPP

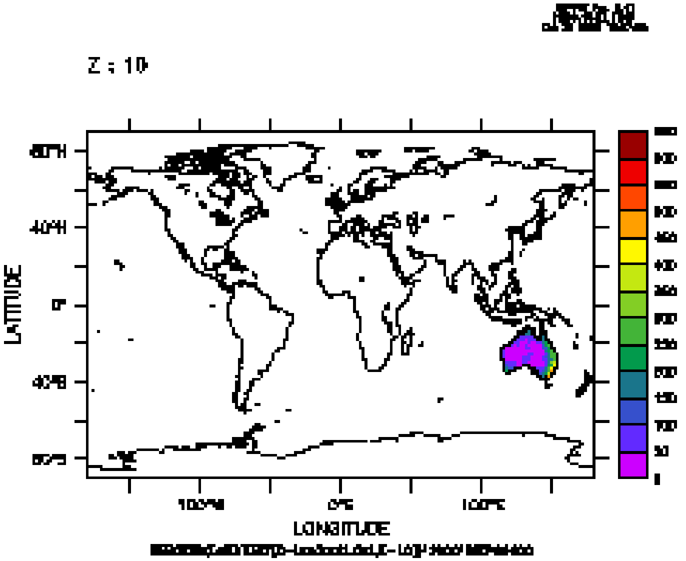
g C/m2/second




Z : 2
80°N
40°N
0°
40°S
80°S
LATITUDE
100°W
0°E
100°E
LONGITUDE

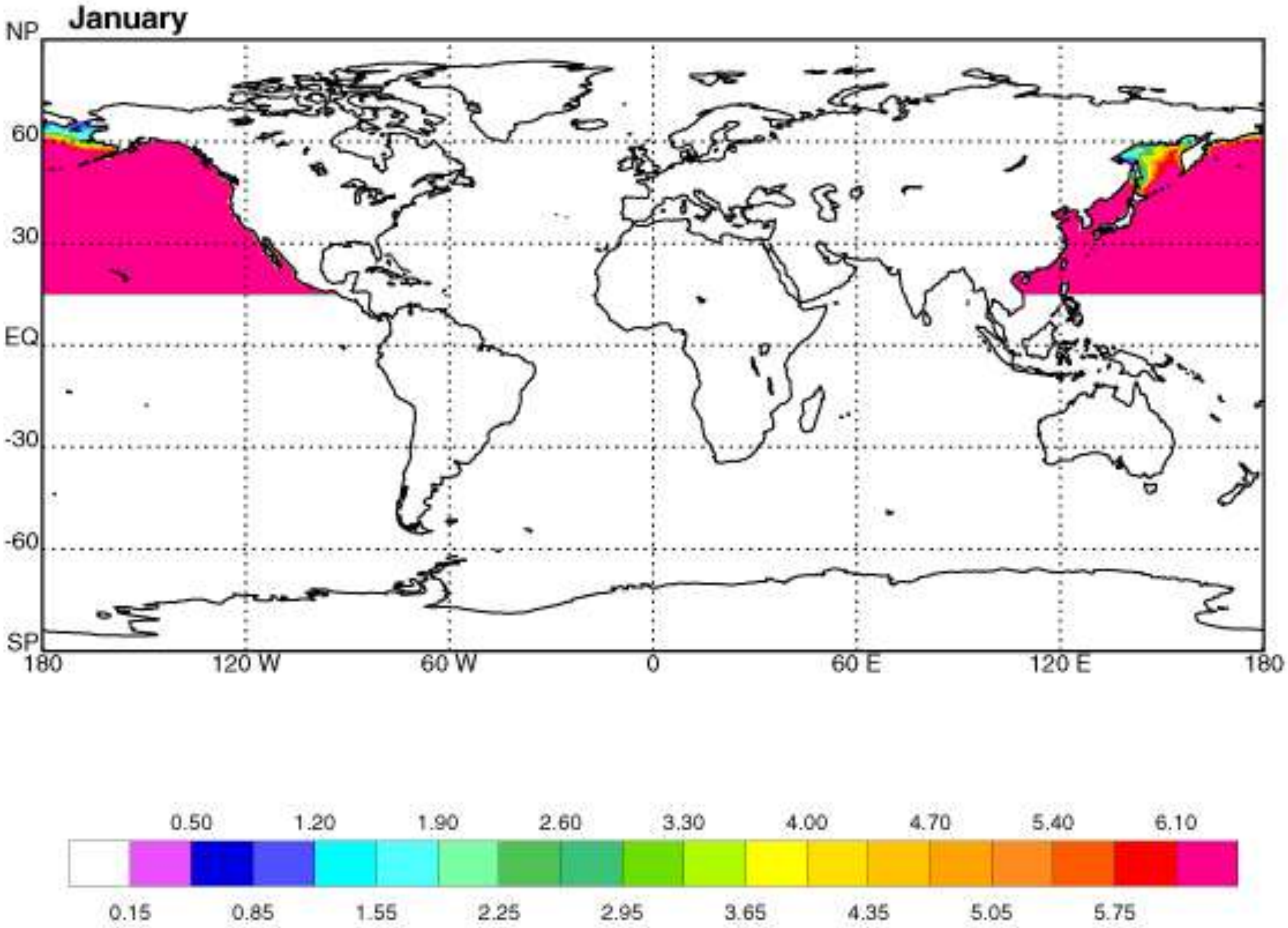

Z : 11
80°N
40°N
0°
40°S
80°S
LATITUDE
100°W
0°E
100°E
LONGITUDE

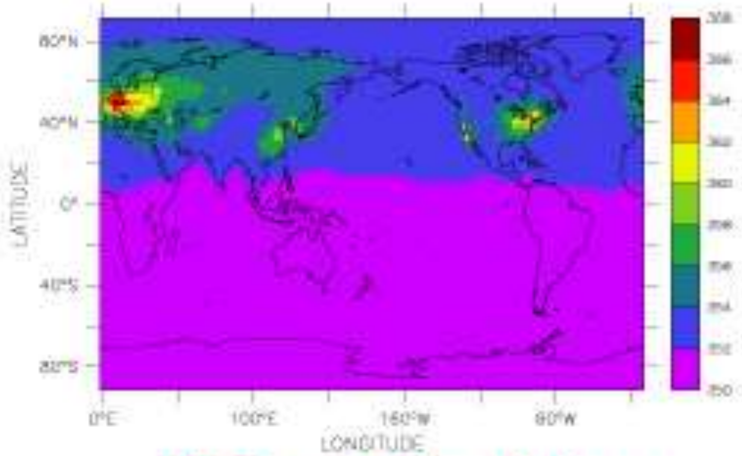

Z : 8
80°N
40°N
0°
40°S
80°S
LATITUDE
100°W
0°E
100°E
LONGITUDE


Z : 10
80°N
40°N
0°
40°S
80°S
LATITUDE
100°W
0°E
100°E
LONGITUDE

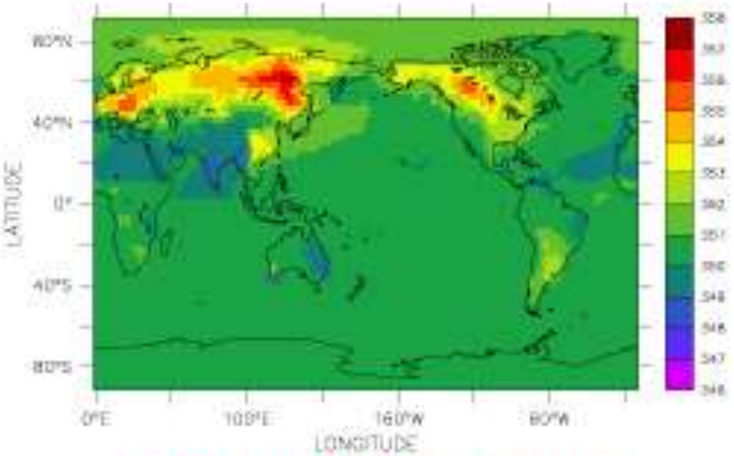
North Pacific Temperate basis function

kg C/m^{2}/second x 10^{-10}

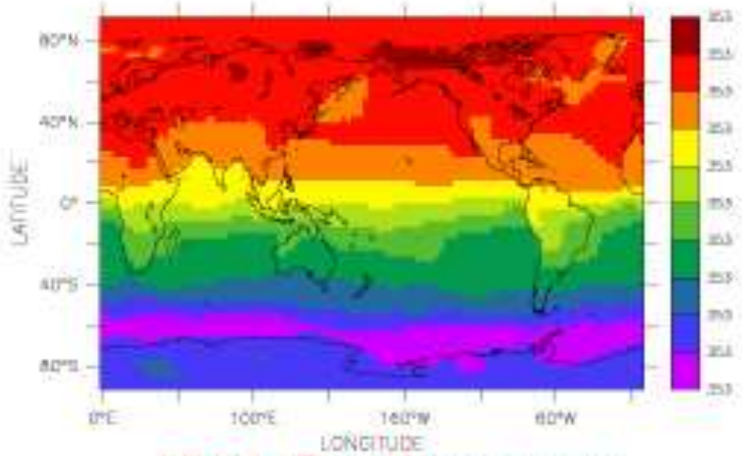




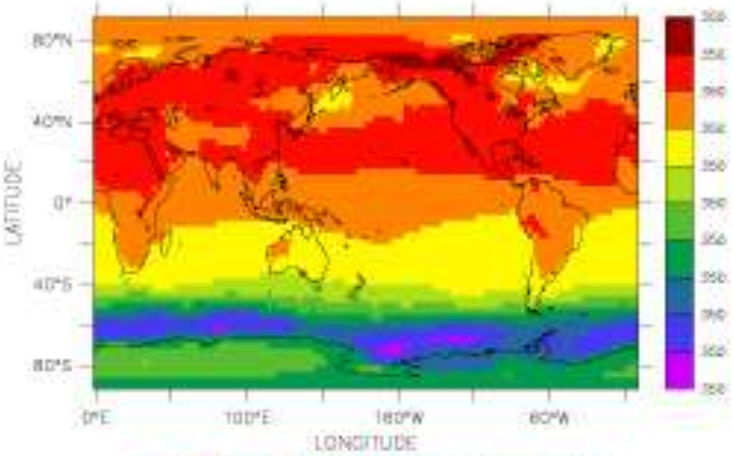
FF90 year of emission



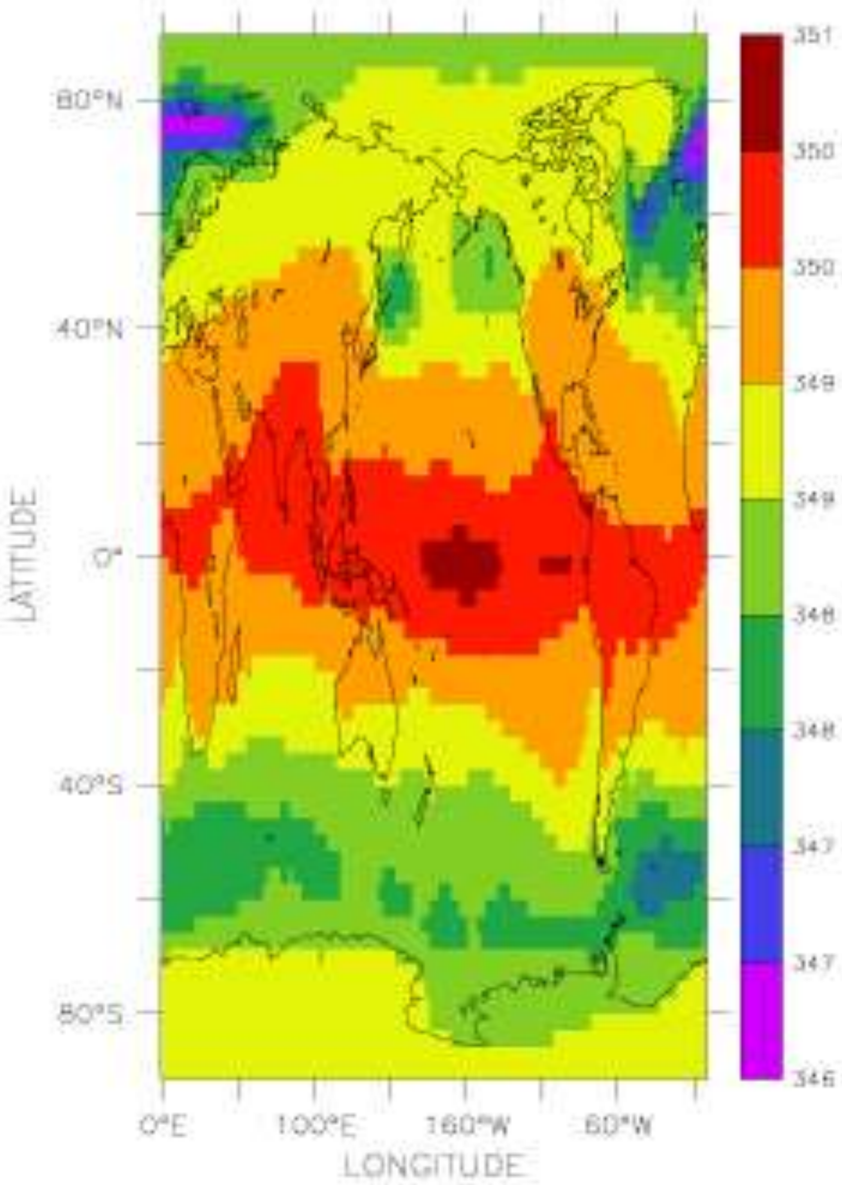
NEP year of emission



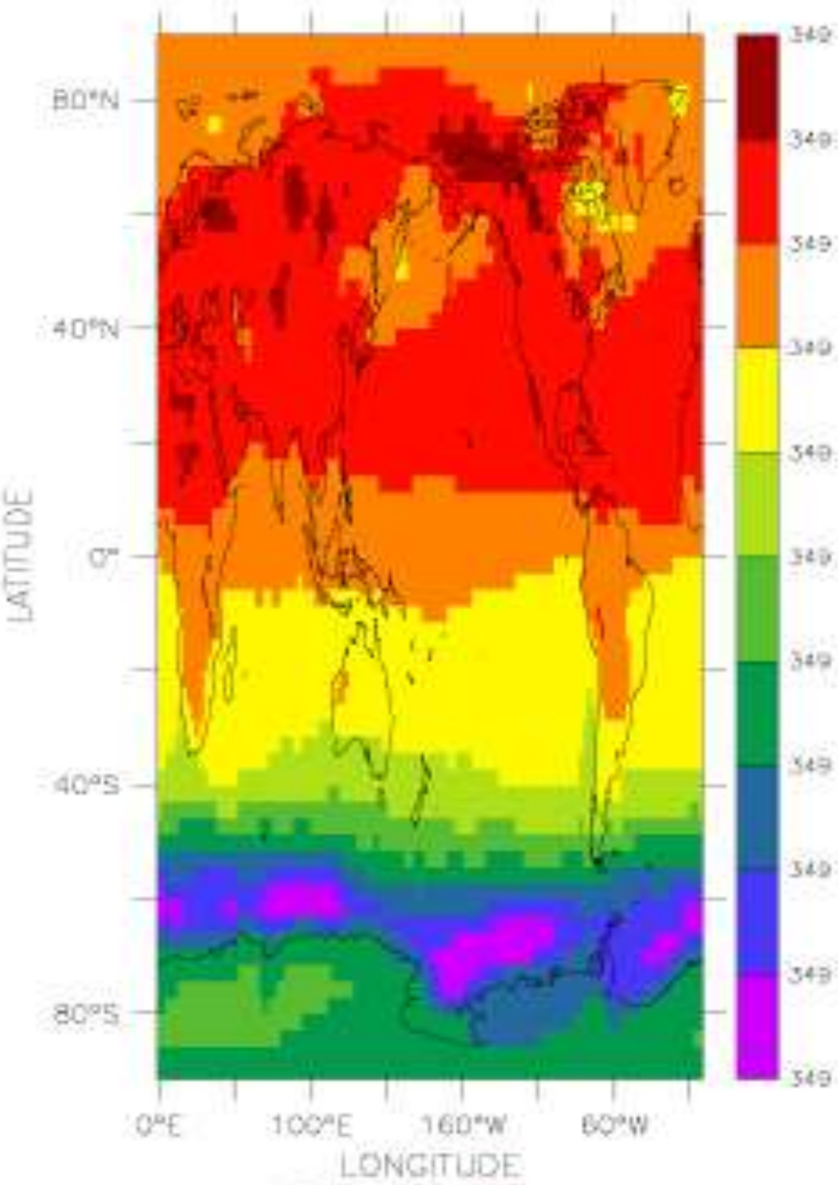
FF90 after three years



NEP after three years

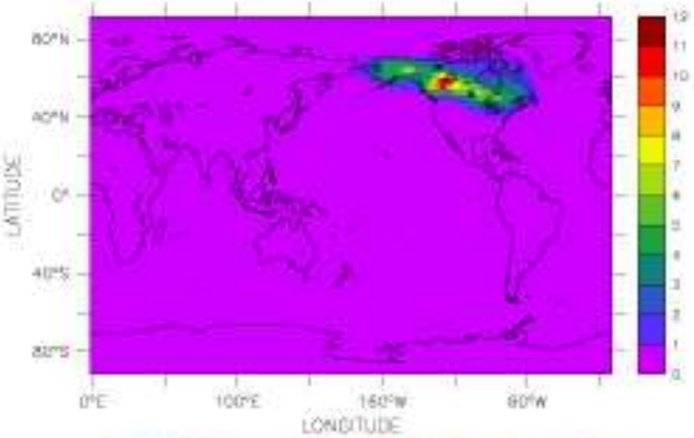


Ocean Fluxes
year of emission

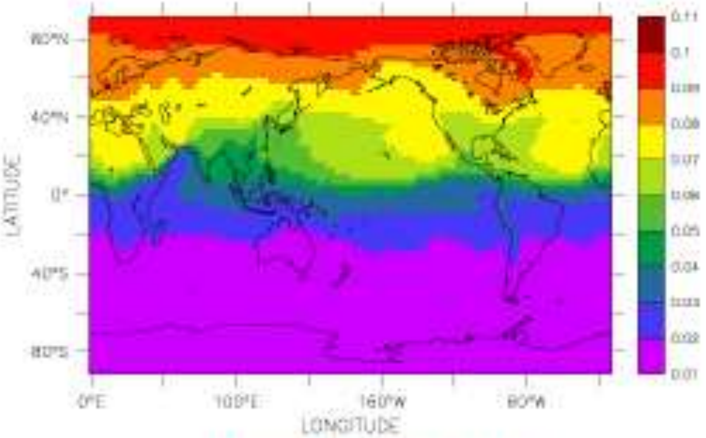


Ocean Fluxes
after three years

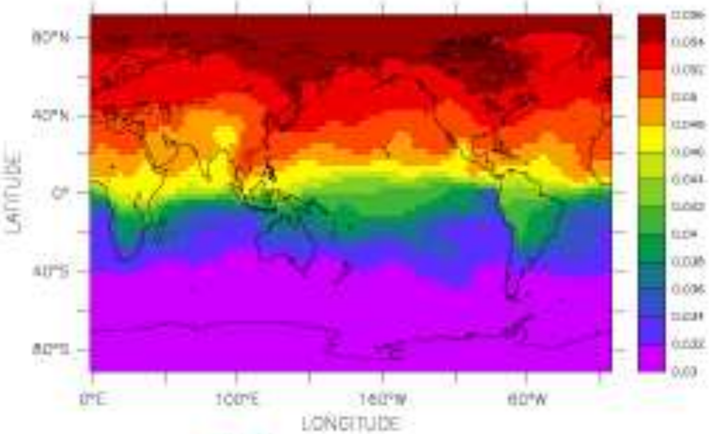
Horizontal Mixing and Trasport



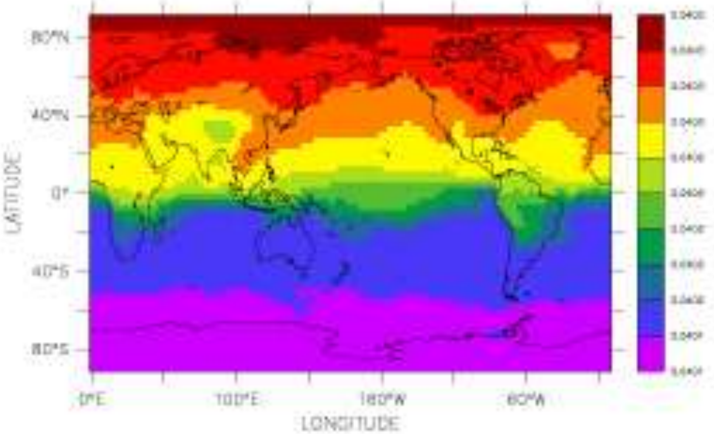
First month of emission



After Six months

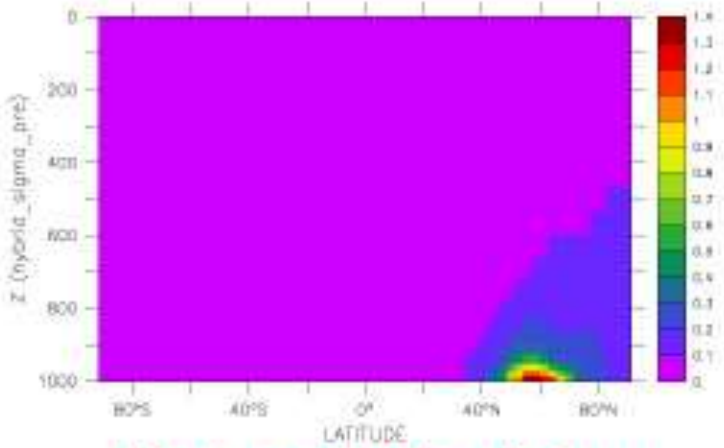


After one year

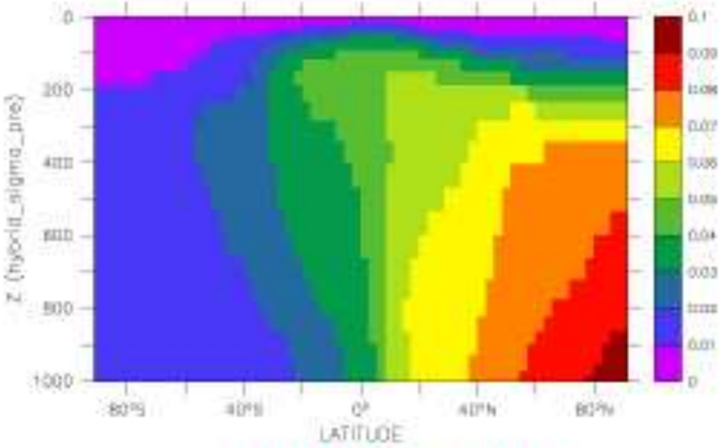


After three years

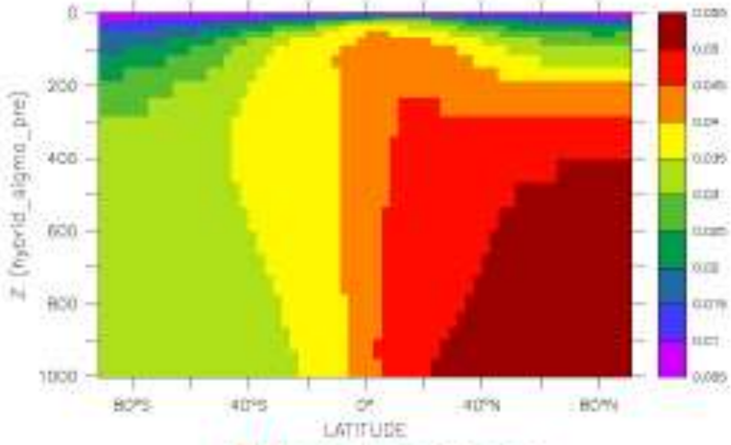
Vertical mixing and transport over boreal North America



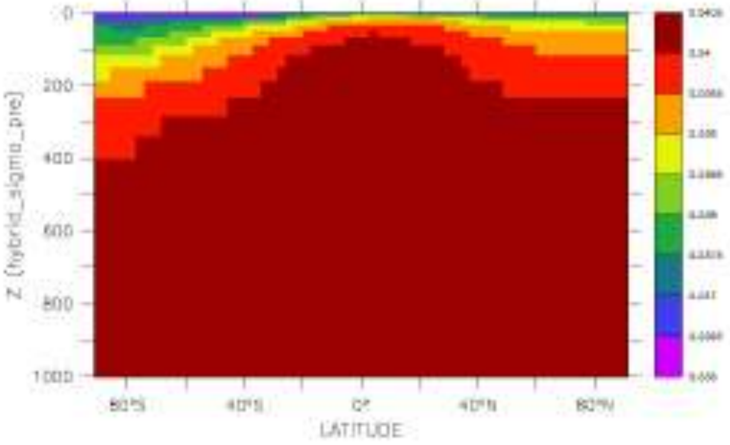
First month of emission



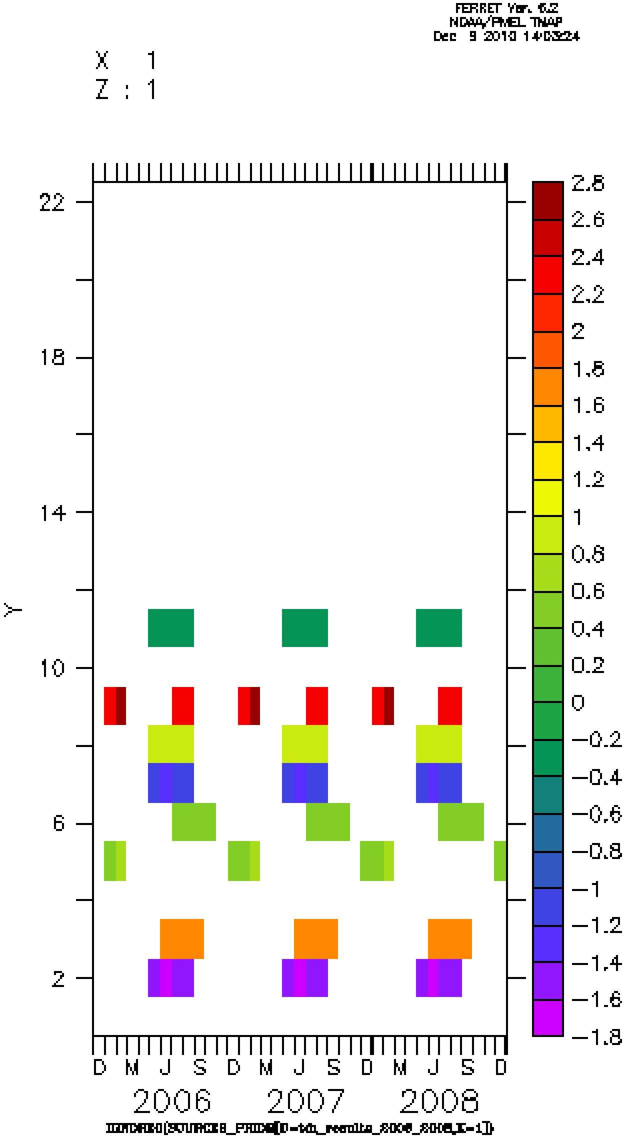
After six months



After one year



After three years


FERRET Ver. 6.2
NOAA/PMEL TMAP
Dec 9 2010 14:03:24
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18
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D M J S D M J S D M J S D
2006
2007
2008
2.8
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2
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1
0.8
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−0.2
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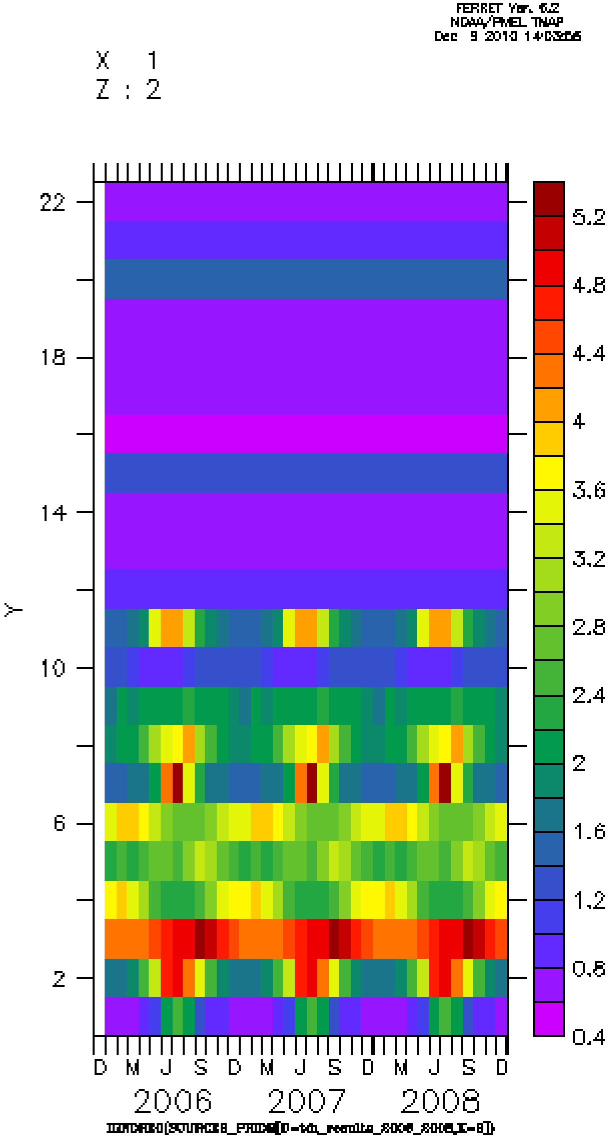
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D M J S D M J S D M J S D
2006
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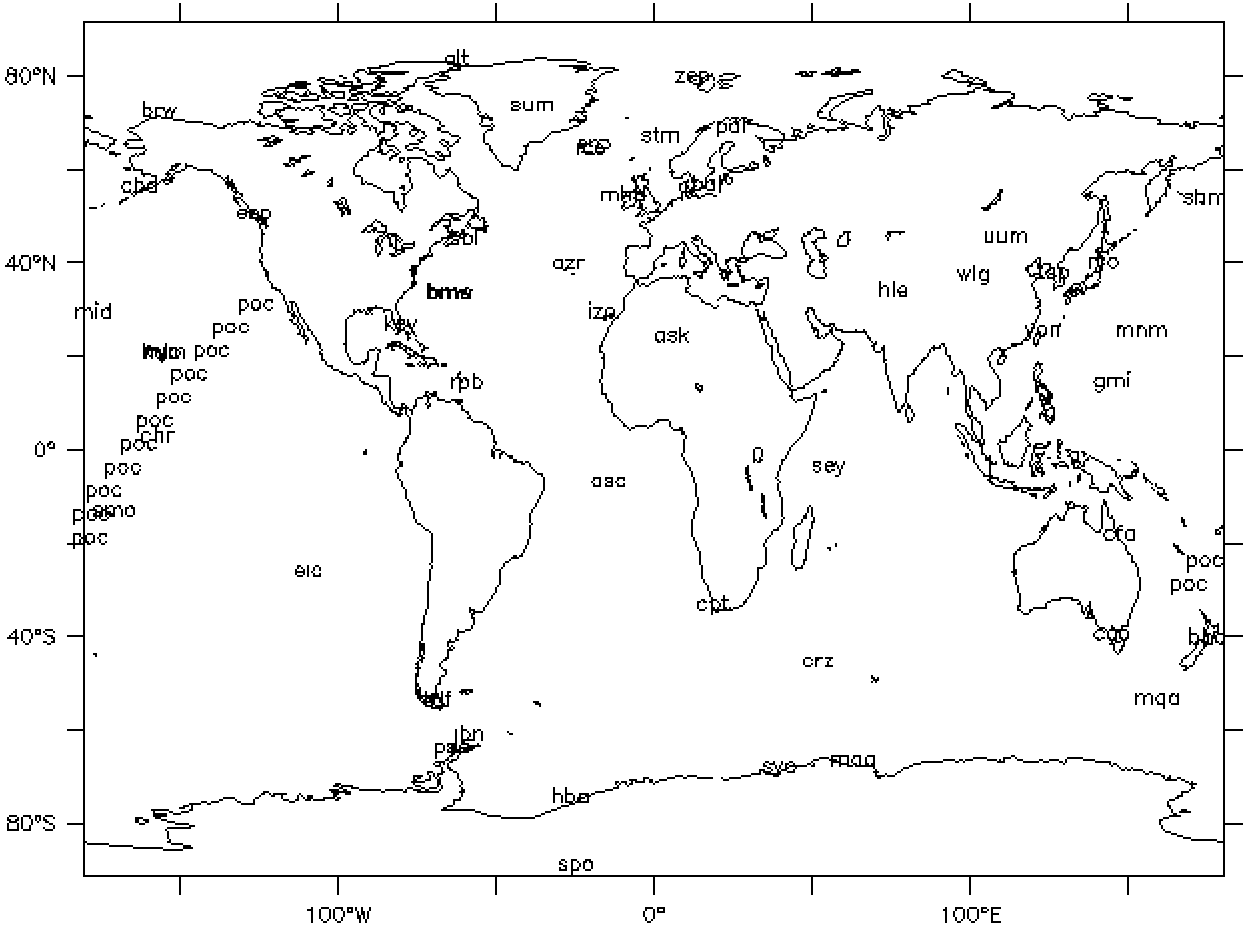
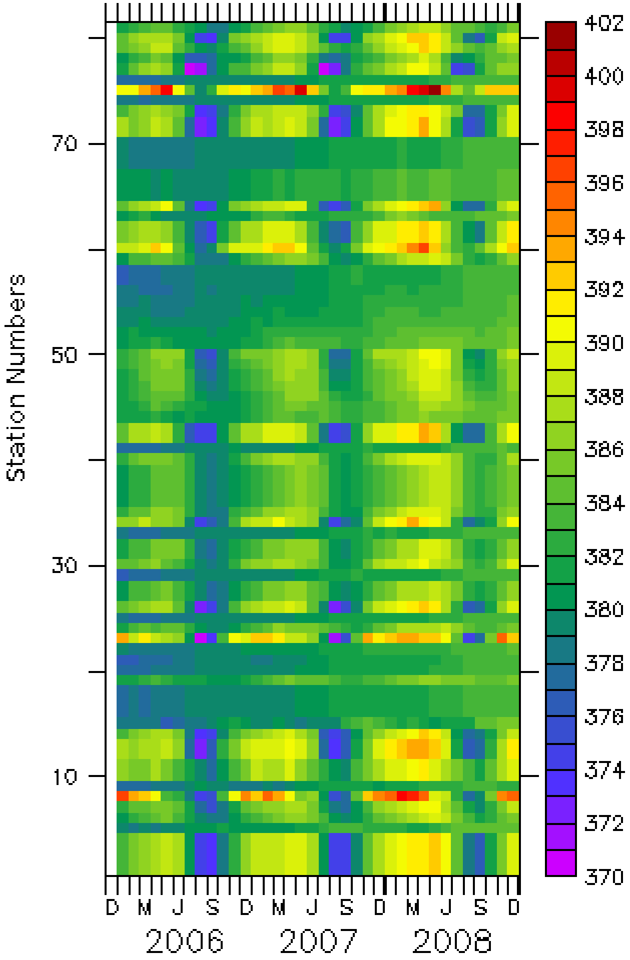


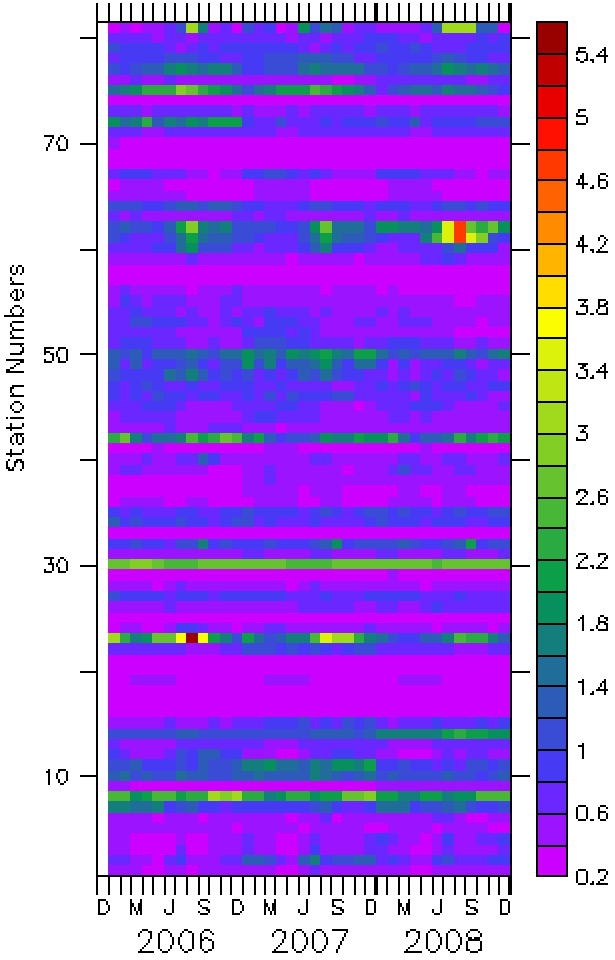
Stations used

Bayesian Inversion

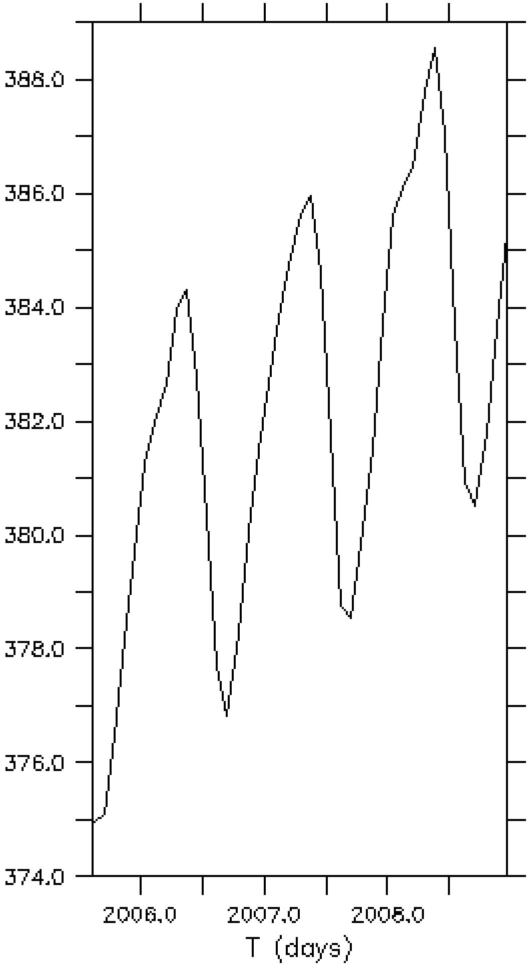
- $D = JS$
- $Z = (S-S_0)^T C(S_0)^{-1}(S-S_0) + (D-JS_0)^T C(D)^{-1}(D-JS_0)$
- $S = S_0 + (C(S_0)^{-1} + J^T C(D)^{-1} J)^{-1}(D-JS_0)$
- $C(S)^{-1} = C(S_0)^{-1} + J^T C(D)^{-1} J$



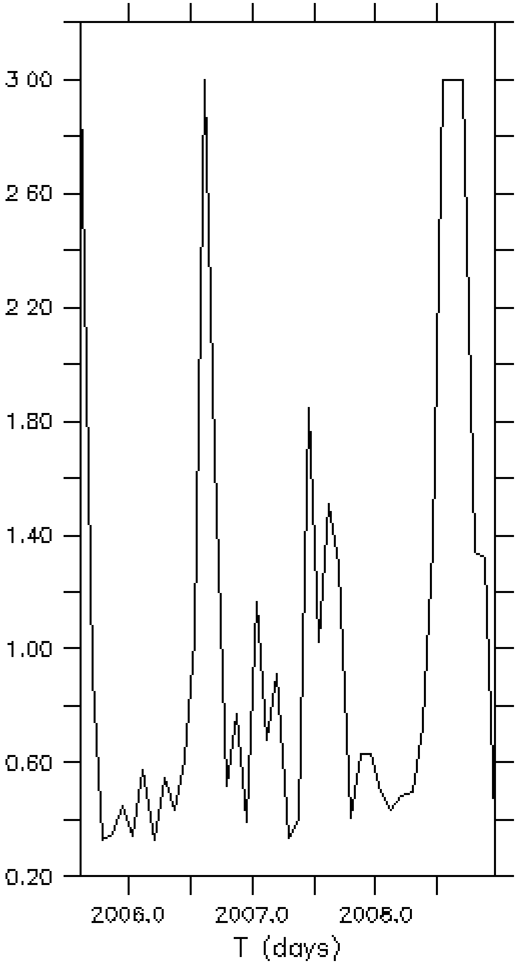
CO2 data (ppm)



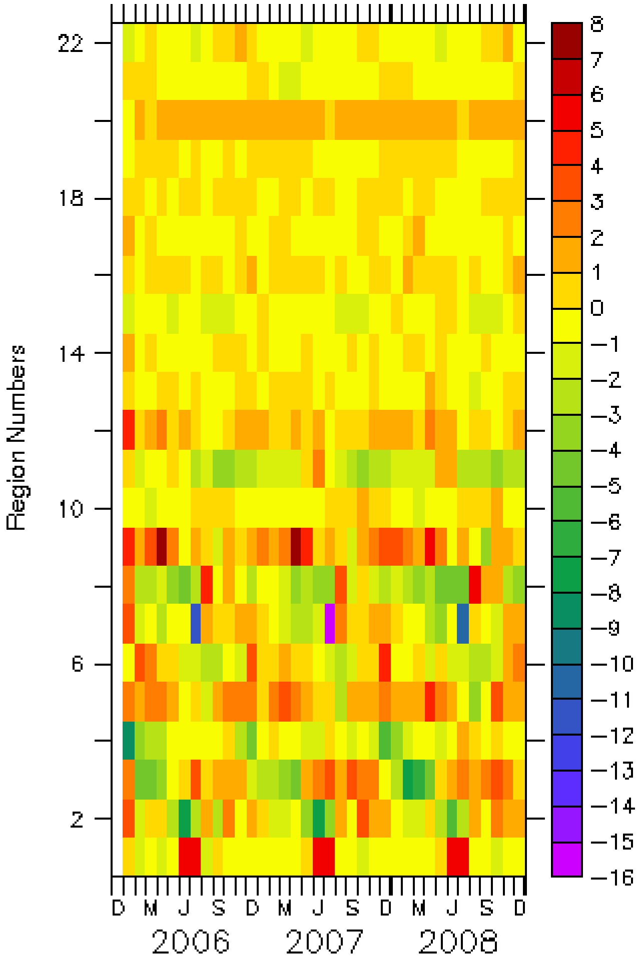
uncertainty (ppm)



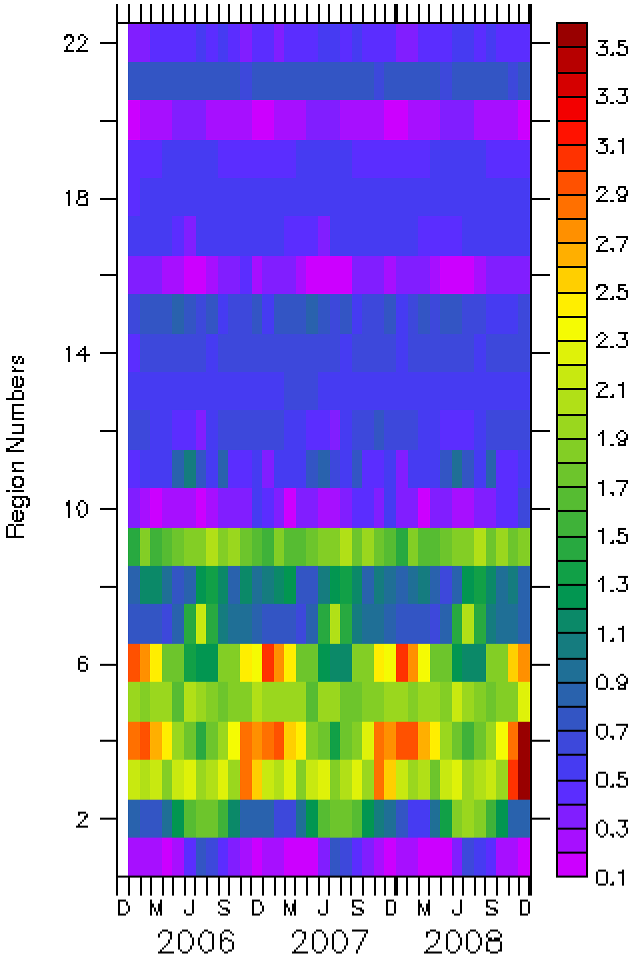
CO2 (ppm)



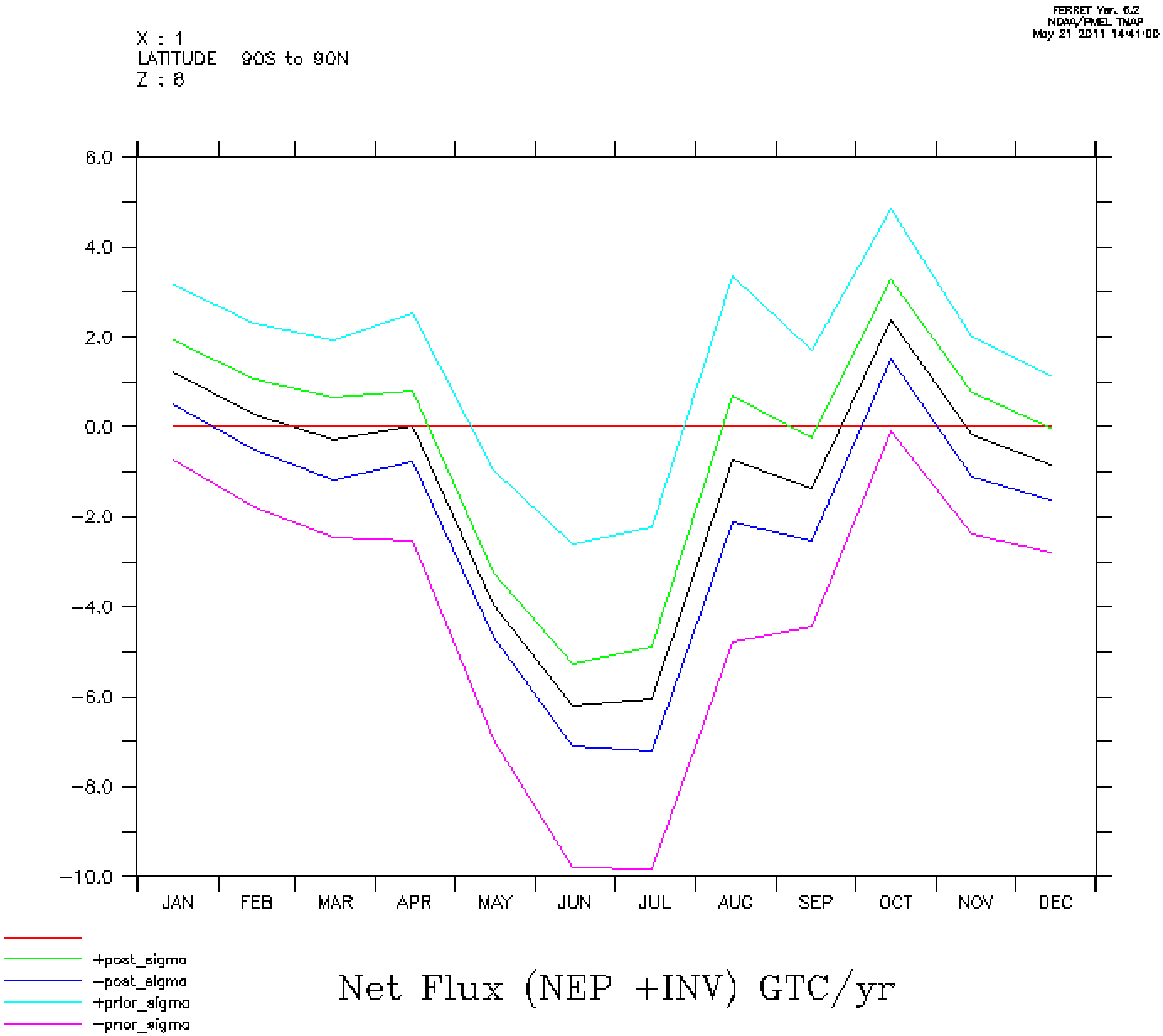
uncertainty (ppm)



a-posteriori flux (GTC/yr)



a-posteriori uncertainty (GTC/yr)



Net Flux (NEP +INV) GTC/yr

No	Name	Prior	Post	Prior Unc	Post Unc	FF/O	Res	Total	Robust
1	Boreal N. America	0.000	0.401	1.199	0.319	0.04	0.929	0.401	Y
2	Temp. N America	-0.534	-0.681	2.890	1.190	1.92	0.831	-0.681	Y
3	Trop. N America	0.547	-0.137	4.633	2.198	0.23	0.775	-0.137	Y
4	South America	0.000	-1.321	3.024	2.312	0.14	0.415	-1.321	N
5	North Africa	0.152	1.314	2.667	1.902	0.16	0.491	1.314	N
6	Southern Africa	0.148	-0.122	3.215	2.005	0.11	0.610	-0.122	Y
7	Bor. Eurasia	-0.396	-1.161	2.404	1.045	0.21	0.810	-1.161	Y
8	Temp. Asia	0.297	-1.485	2.741	1.018	2.38	0.862	-1.485	Y
9	Trop. Asia	0.806	1.887	2.091	1.776	0.64	0.278	1.187	N
10	Australia	0.000	-0.058	1.109	0.333	0.11	0.910	-0.058	Y
11	Europe	-0.100	-1.518	2.411	0.603	1.92	0.94	-1.518	Y
12	North Pac.	0.000	1.003	0.960	0.583	-0.50	0.631	0.500	Y
13	Eq. W Pac.	0.000	-0.042	0.710	0.558	0.15	0.381	0.111	N
14	Eq. E Pac.	0.000	-0.050	0.750	0.631	0.46	0.291	0.417	N
15	South Pac.	0.000	-0.615	1.320	0.686	0.23	0.730	0.845	Y
16	Arctic Ocean	0.000	0.352	0.560	0.270	-0.44	0.770	-0.086	Y
17	N Atlantic	0.000	-0.076	0.640	0.521	-0.29	0.338	-0.368	N
18	Eq. Atlantic	0.000	0.036	0.640	0.557	0.13	0.24	0.165	N
19	S Atlantic	0.000	0.058	0.690	0.484	-0.13	0.508	-0.070	N
20	South Ocean	0.000	1.304	1.580	0.271	-0.90	0.971	0.417	Y
21	N Indian	0.000	-0.190	0.890	0.730	0.12	0.327	-0.072	N
22	S Indian	0.000	-0.205	0.740	0.456	-0.55	0.620	-0.759	Y
					Total	FF=7.86 O = -2.19			

Principles of Network Design

- Borrowed from geophysics

$$\mathbf{C}(\vec{S})^{-1} = \mathbf{C}(\vec{S}_0)^{-1} + \mathbf{J}^T\mathbf{C}(\vec{D})^{-1}\mathbf{J}$$

- Choose some property of $\mathbf{C}(\vec{S})$ (posterior covariance)
- Manipulate $\mathbf{J}$ e.g. choosing sampling locations
- Use nonlinear minimization to optimize

Genetic Algorithms

- Genetic Algorithms
- Gene = List of values (Potential Stations)
- Algorithm maintains population of genes
- Genes breed, mutate and compete each generation
- “Generation” = iteration of algorithm
- Competition determined by scoring function
- Two choices

  Trace of ***C(S)*** or ***C(S8)***

Life-cycle of an iteration

- Cull population, leaving only best genes
- Refill population by cloning survivors
- Breed from existing population
- Mutate existing population

Culling

- Rank genes by score and sort
- Assign a survival probability according to rank e.g. $P(n) = n/N$
- For each gene, choose uniform random number $x \in [0, 1]$ and eliminate gene i
- $P(n)$ is user-specified

Refilling

- Choose gene at random
- Choose uniform random number $x \in [0, 1]$
- If $x < P(n)$ copy gene to gap left by culling

Breeding

- Breeding probability P_B set by user
- Choose pairs of “parents” at random
- Choose uniform random $x \in [0, 1]$
- If $x < P_B$ create new gene with random combination from parents
- Children kill and replace parents

Mutation

- Mutation probability P_M set by user
- For each value in each gene choose uniform random $x \in [01]$
- If $x < P_M$ replace by random value

Summary of user inputs

- Population size
- Number of generations
- Survival probability
- Breeding probability
- Mutation probability
- Population and generations computational trade-off, others depend on probl
- Balancing converging too fast and never optimising

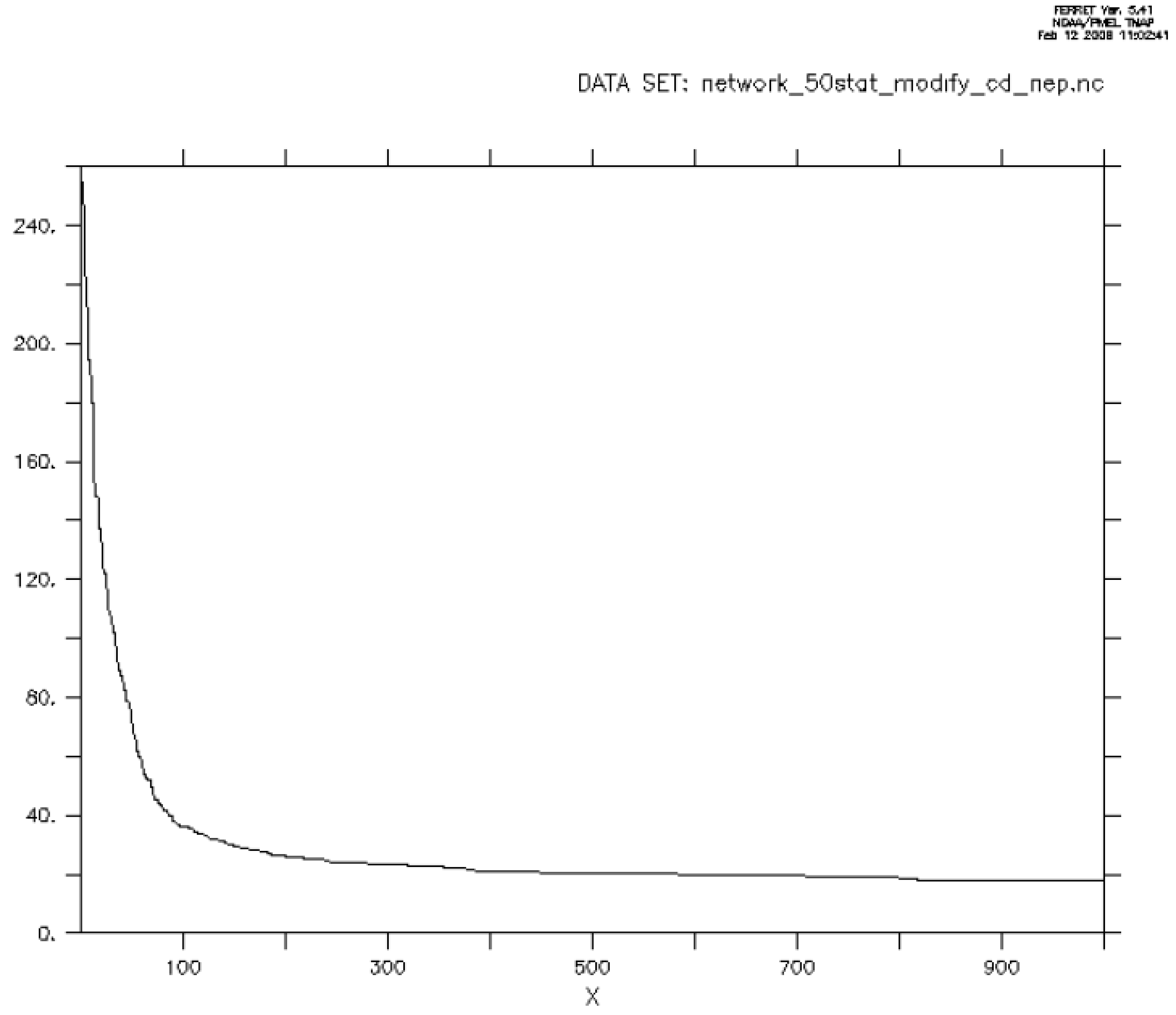
Adapting GA to the network problem

- Convert i,j,k indices of T-42 grid into a unique number
- Construct gene of a given length by randomly selecting a set of stations.
- Construct the J matrix by combining these with existing Transcom G matrix.
- Construct covariance matrix for data
- Perform Transcom inversion for each gene.
- Compute score (either trace of whole matrix or subset)
- Perform GA operations and iterate.

Set-up details

- Green's functions calculated with Mozart transport model
- Population = 200, generations =500 or 1000 (4 days on Altix)
- Test configurations of $\mathbf{C}(\vec{S}_0)$ and $\mathbf{C}(\vec{D})$.
- Test additions to current network or "ground-up" design

Testing algorithm

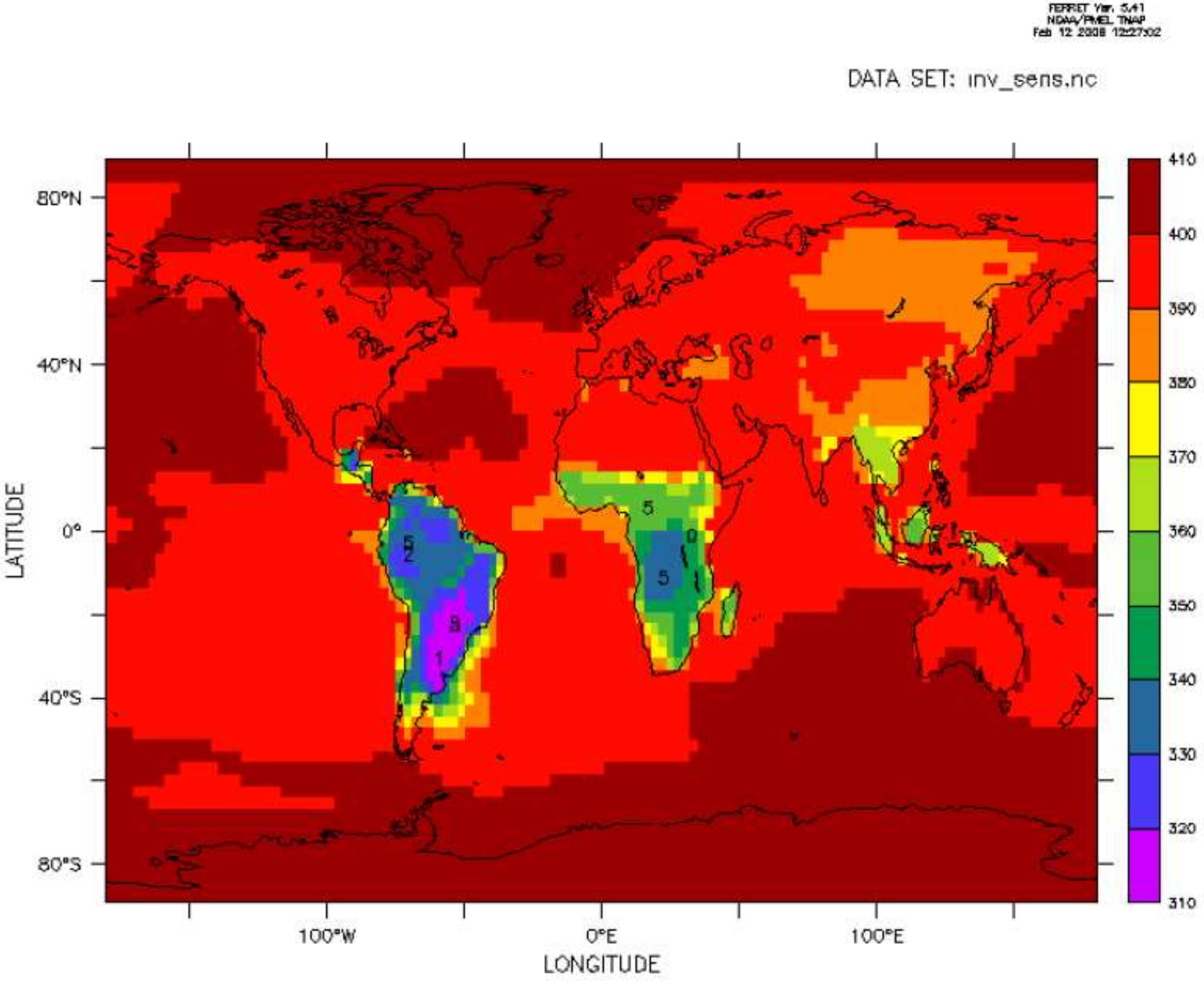


best gene scor

Tests with Known answers

- Test finding known minimum
- Add one station to current network
- Test each gridpoint in turn
- Generates map of score
- Test if GA can find this minimum

Map of score and GA attempt

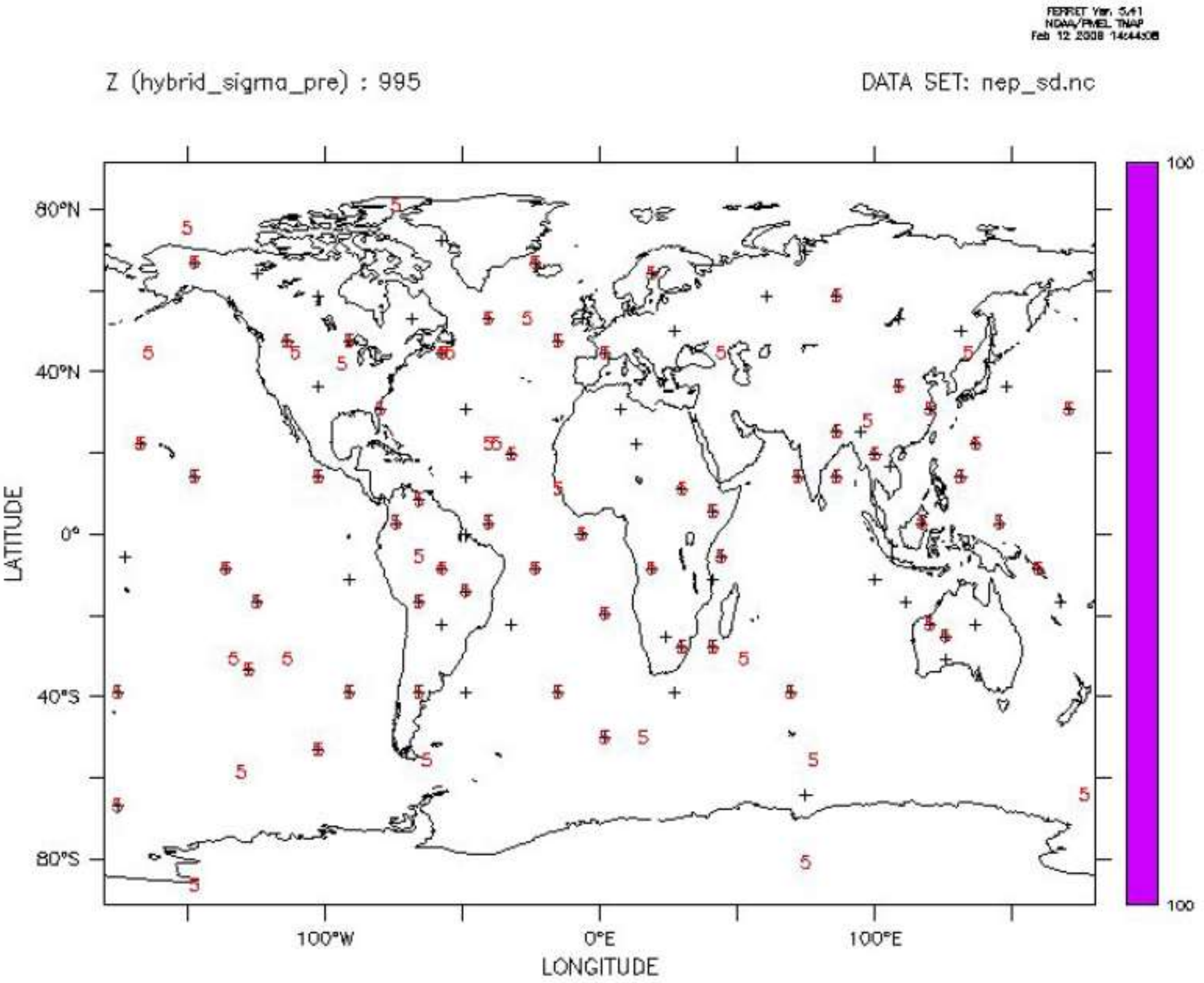


Score (GTC^2/yr^2)

Test finding preferred stations

- Choose some stations with very much lower $\mathbf{C}(\vec{D})$ than the rest
- GA should find these independent of $\mathbf{J}$.

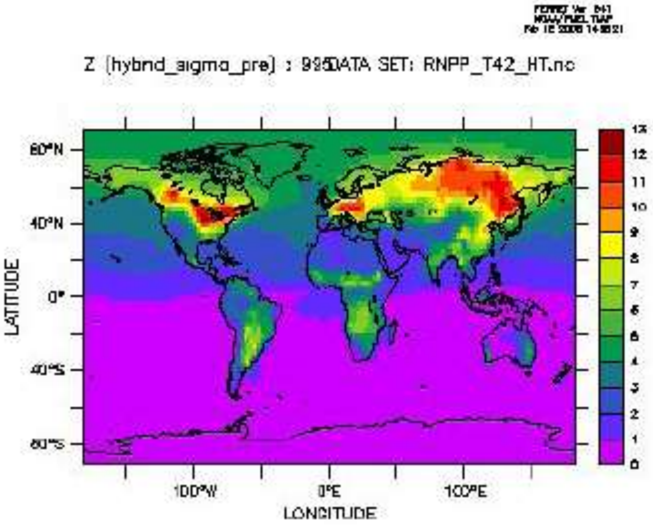
Test case with preferred stations



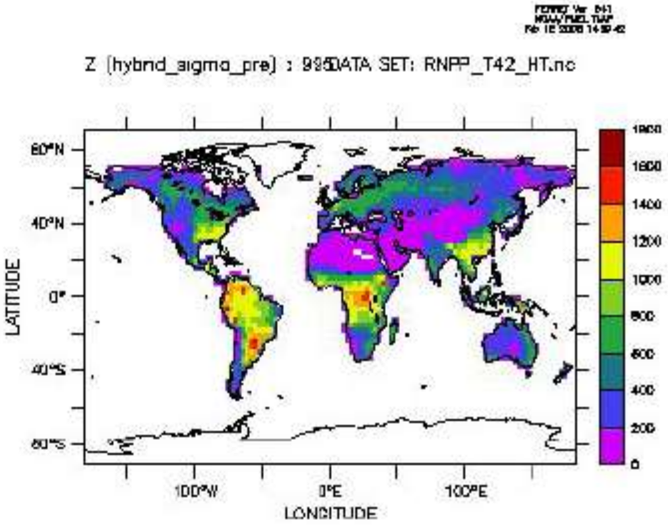
Constructing $\mathrm{C}(\vec{D})$

- Usually don't have measurements so no strict algorithm
- CO_2 measurement stations should represent model grid cell
- Should not be too variable (signal-noise)
- Most local influence terrestrial biosphere + transport
- Combine these then calibrate against real stations

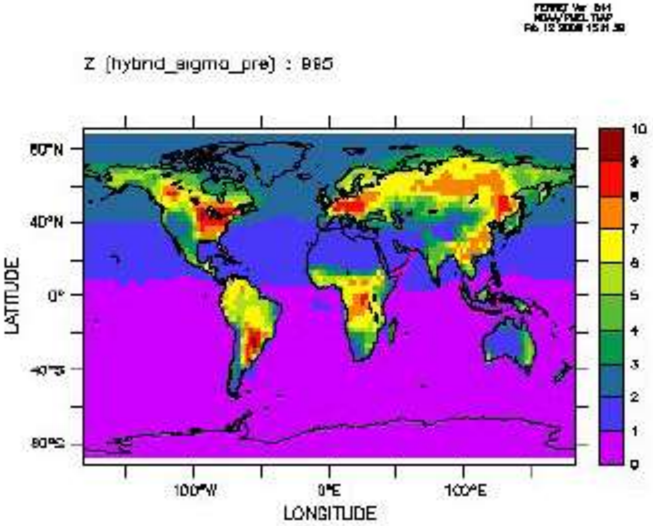
Maps of $\mathbf{C}(\vec{D})$



NEP PPM STD_DEV

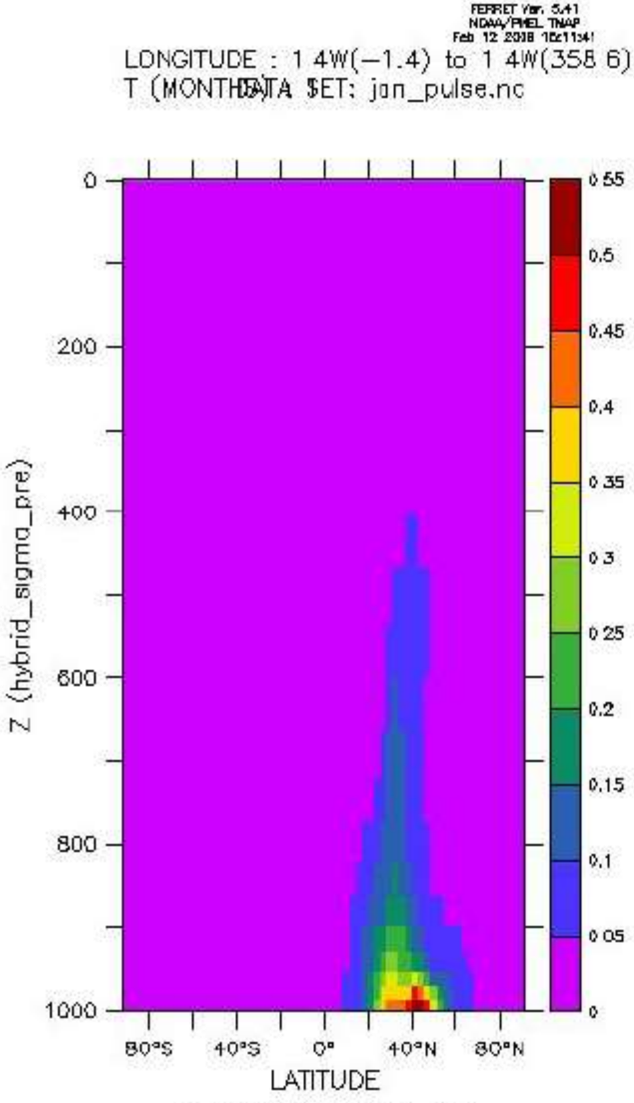


NPP STD_DEV

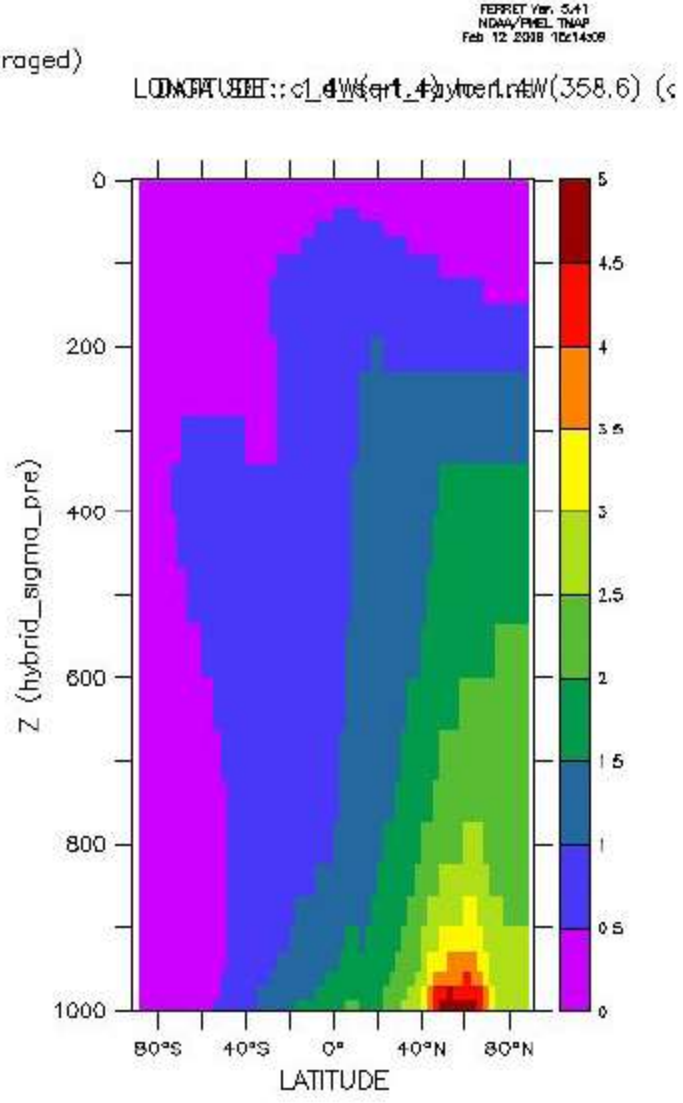


NEP + NPP

Altitude dependence of $\mathrm{C}(\vec{D})$

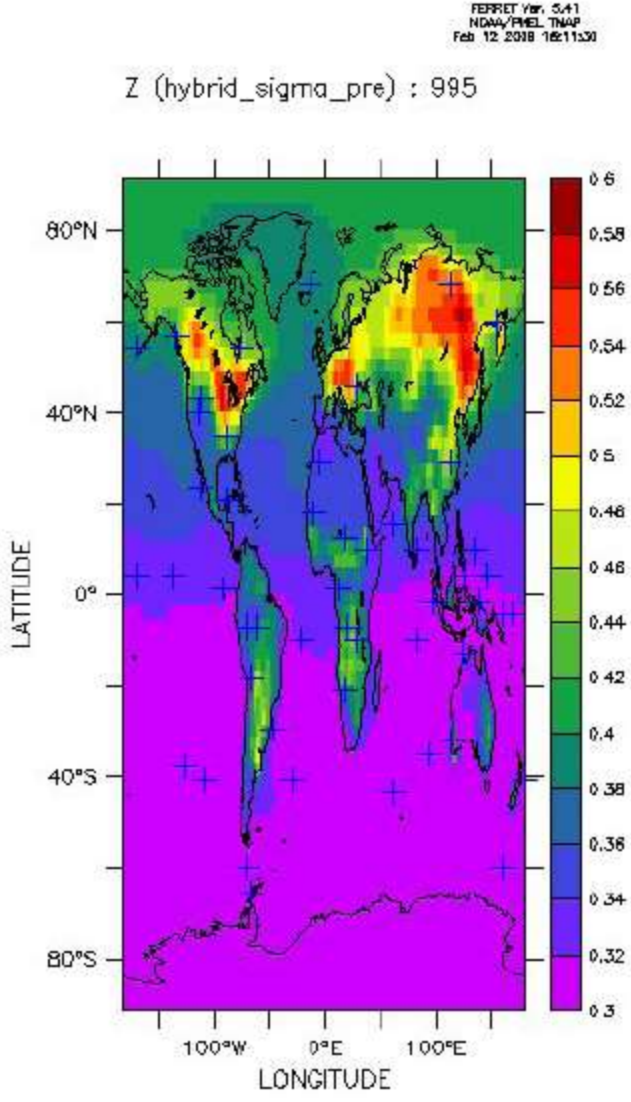


Basis function Temp. Asia

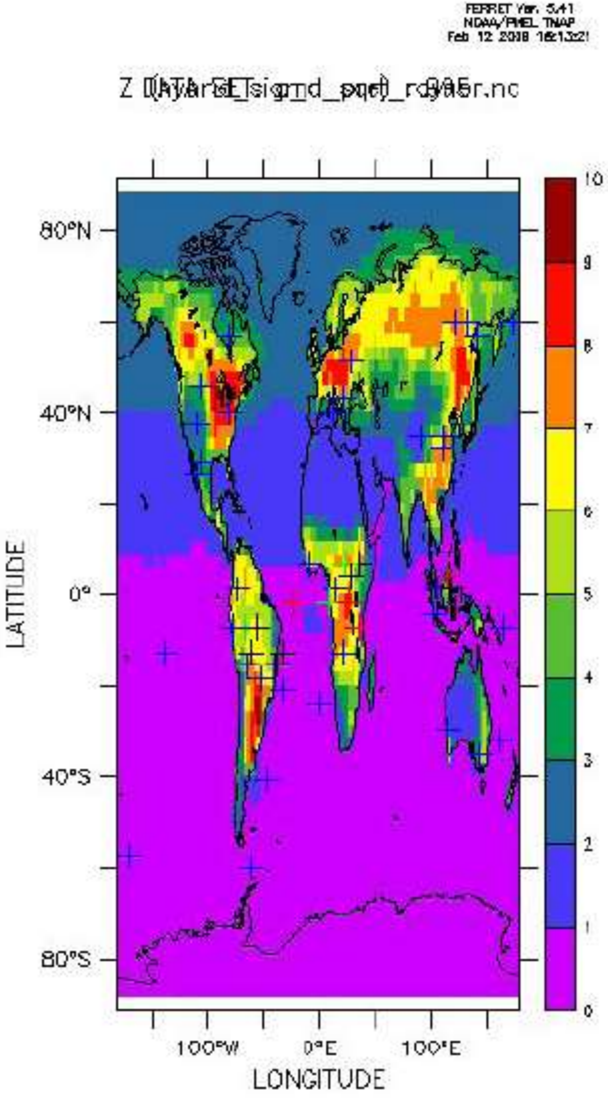


C D SQRT PPM

Optimised Networks for global observation

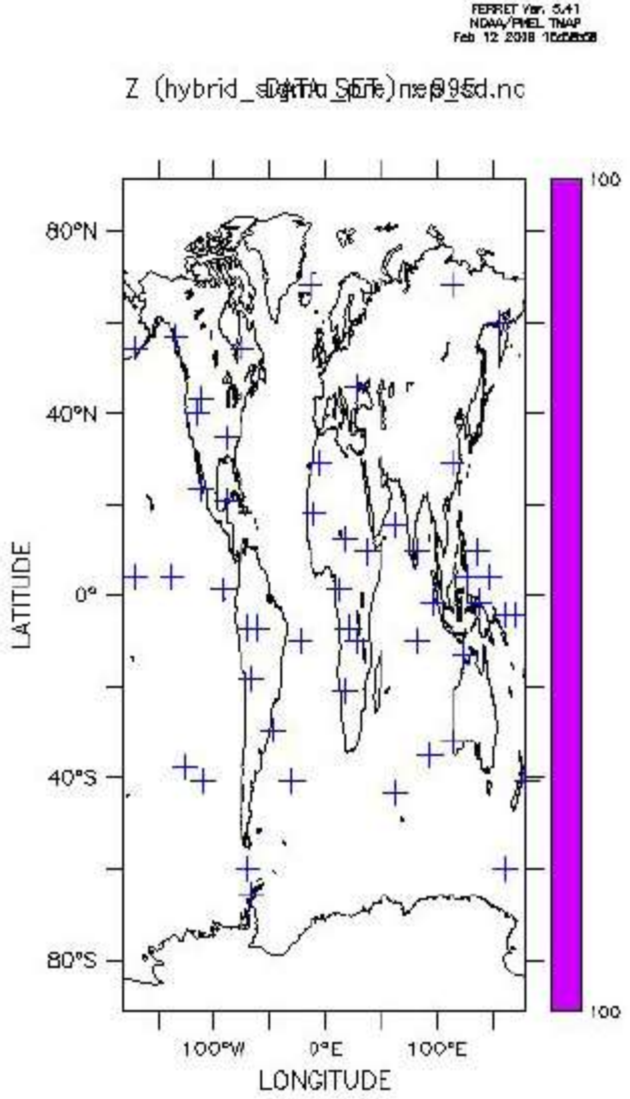


Optimistic C D

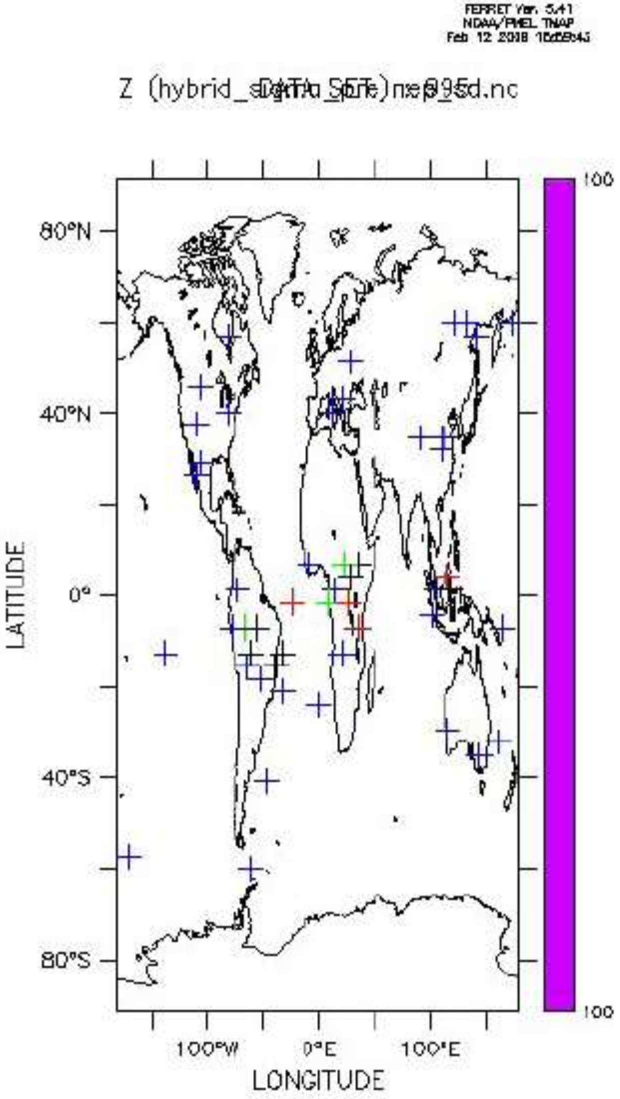


Pessimistic C D

Optimised Networks for global observation

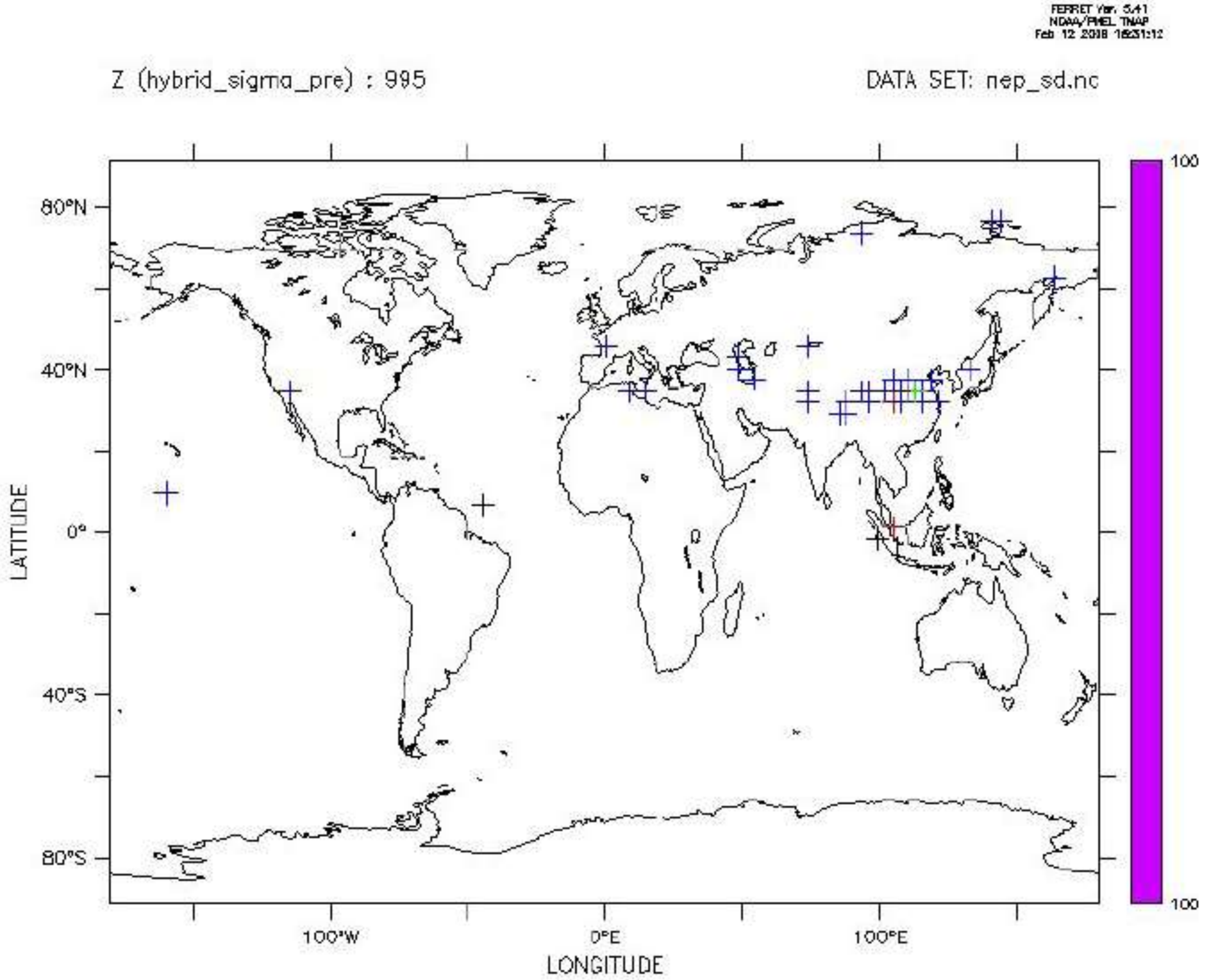


Optimistic C D



Pessimistic C D

Optimised Networks for observation of South/Central Asia



Reg. 8 case

Conclusions

- Inversions and genetic algorithms can be used in combination to design networks
- Various user inputs are crucial, e.g. choice of score and covariances
- Local noise suggests the use of airborne observations
- Targeting regional fluxes suggests dense regional network