Assessing the utility of ACOS v2.10 GOSAT column CO_2 retrievals by comparing to independent CO_2 measurements

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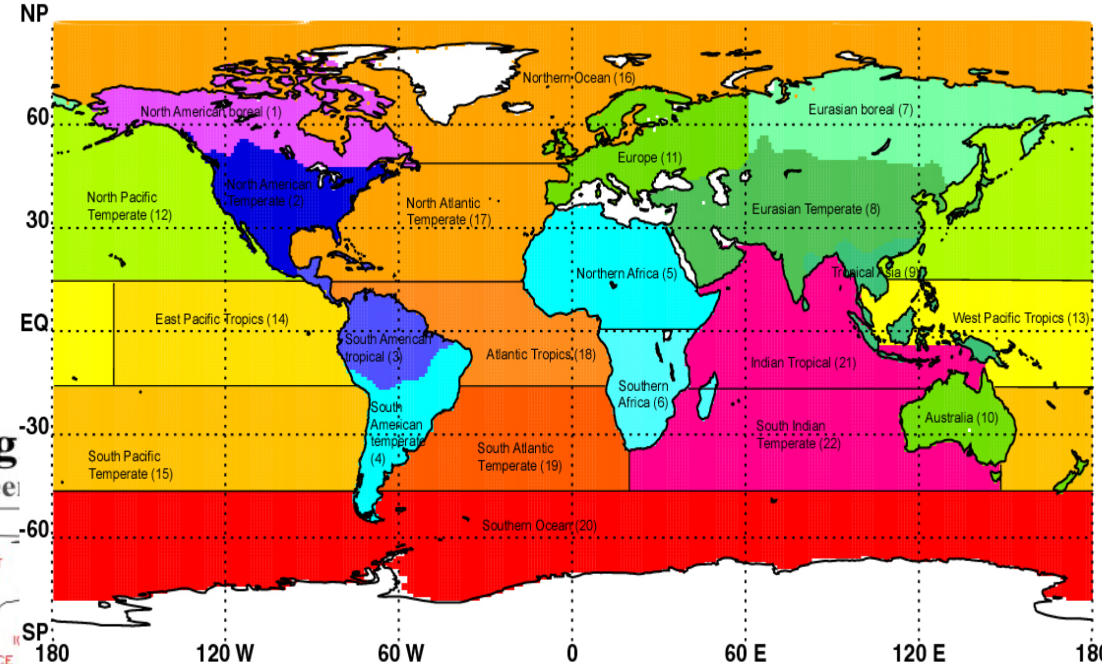
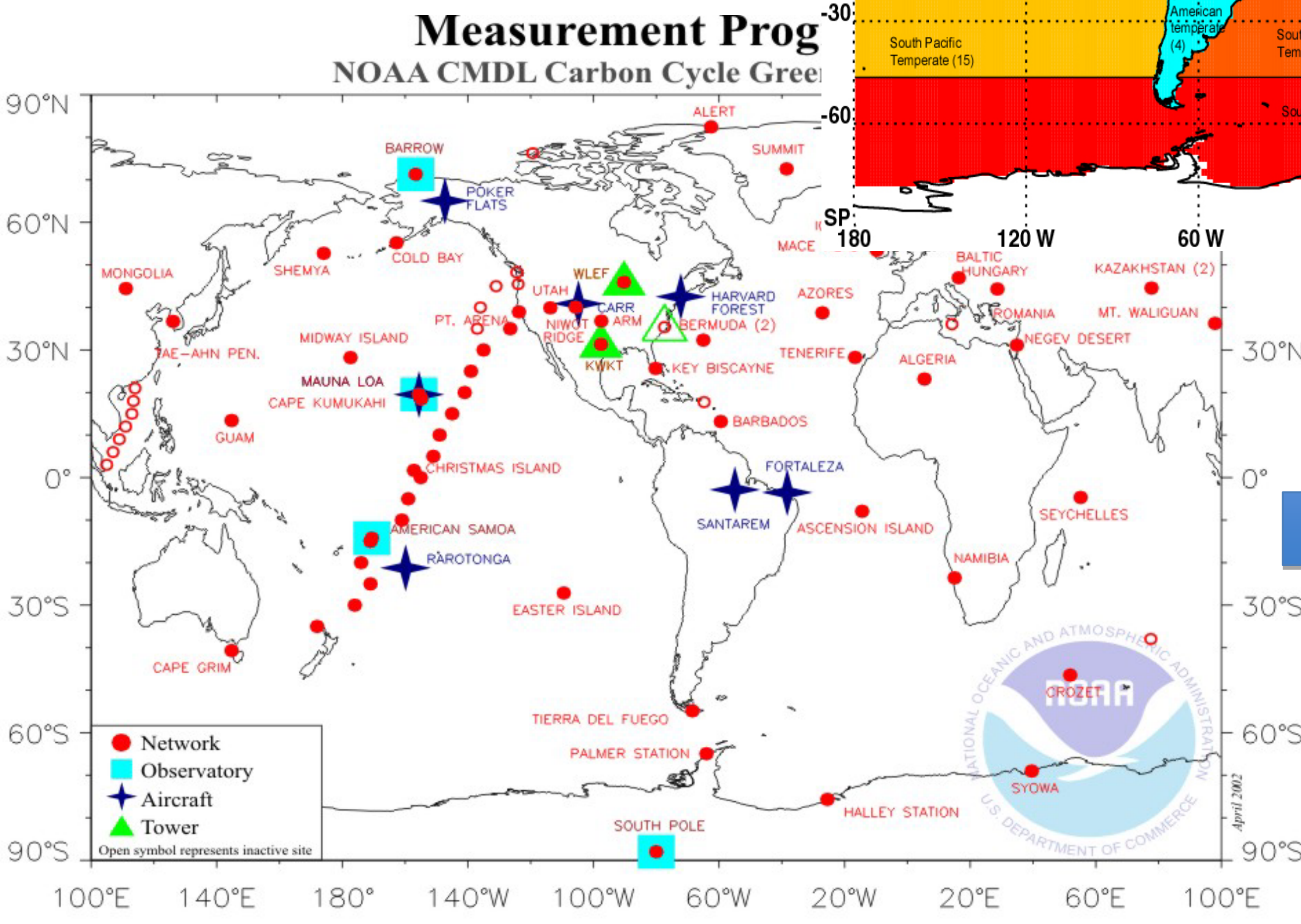
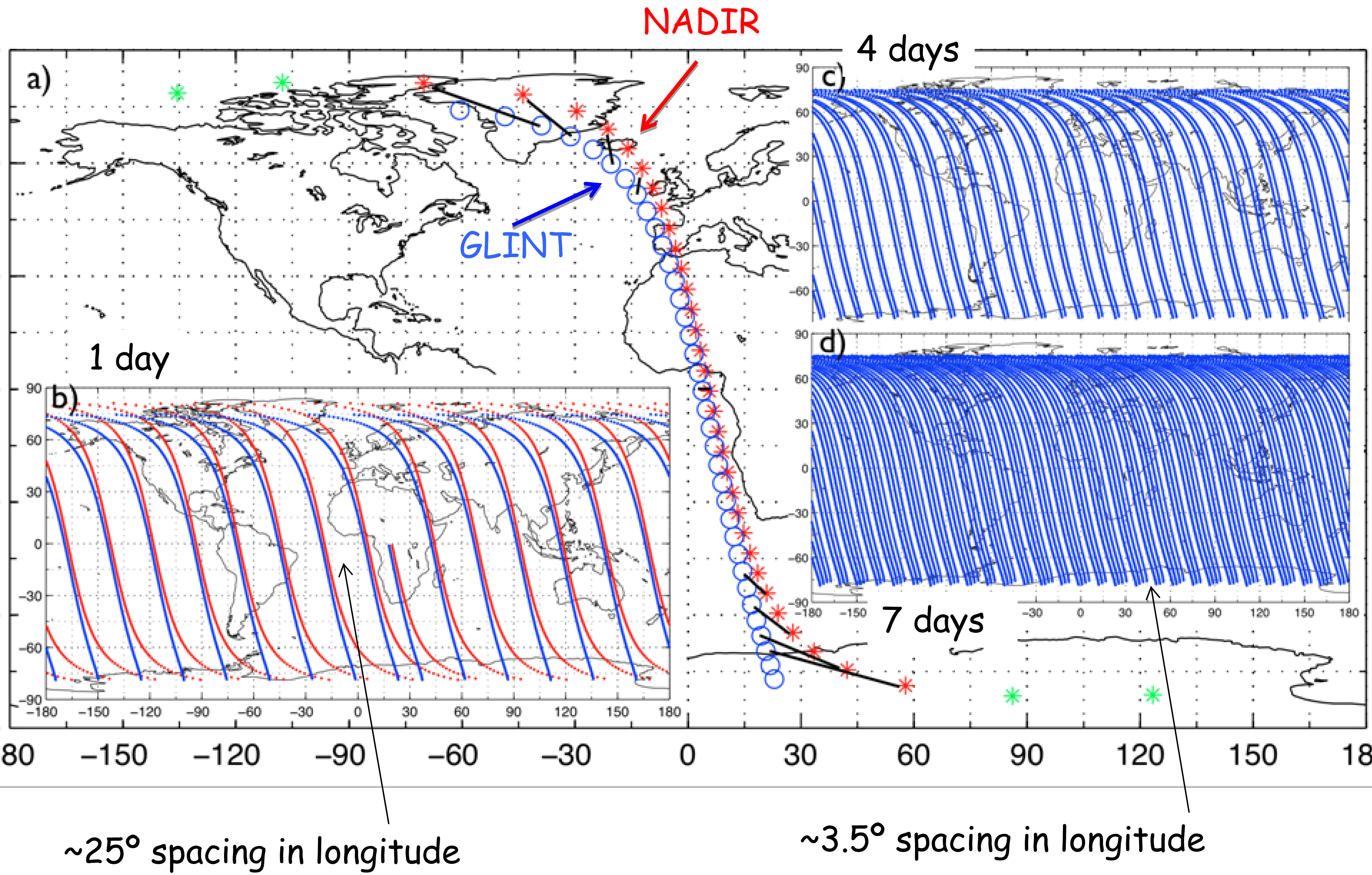

NP
60
30
EQ
-30
-60
SP
180
120 W
60 W
0
60 E
120 E
180
North American boreal (1)
North American Temperate (2)
South American tropical (3)
South American temperate (4)
Northern Africa (5)
Southern Africa (6)
Eurasian boreal (7)
Eurasian Temperate (8)
Tropical Asia (9)
Australia (10)
Europe (11)
North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


Measurement Prog
NOAA CMDL Carbon Cycle Gree
ALERT
BARROW
SUMMIT
POKER FLATS
COLD BAY
SHEMYA
MONGOLIA
TAE-AHN PEN.
MIDWAY ISLAND
MAUNA LOA
CAPE KUMUKAHI
GUAM
CHRISTMAS ISLAND
AMERICAN SAMOA
RAROTONGA
CAPE GRIM
EASTER ISLAND
TIERRA DEL FUEGO
PALMER STATION
SOUTH POLE
HALLEY STATION
SYOWA
CROZET
NAMIBIA
SEYCHELLES
ASCENSION ISLAND
SANTAREM
FORTALEZA
BARBADOS
KEY BISCAYNE
BERMUDA (2)
HARVARD FOREST
WLEF
UTAH
CARR
NIWOT RIDGE
ARM
KWKT
PT. ARENA
AZORES
TENERIFE
ALGERIA
MACE
BALTIC
HUNGARY
ROMANIA
NEGEV DESERT
KAZAKHSTAN (2)
MT. WALIGUAN
90°N
60°N
30°N
0°
30°S
60°S
90°S
100°E
140°E
180°
140°W
100°W
60°W
20°W
20°E
60°E
100°E
Network
Observatory
Aircraft
Tower
Open symbol represents inactive site
April 2002

Typical coverage for a sun-synchronous satellite



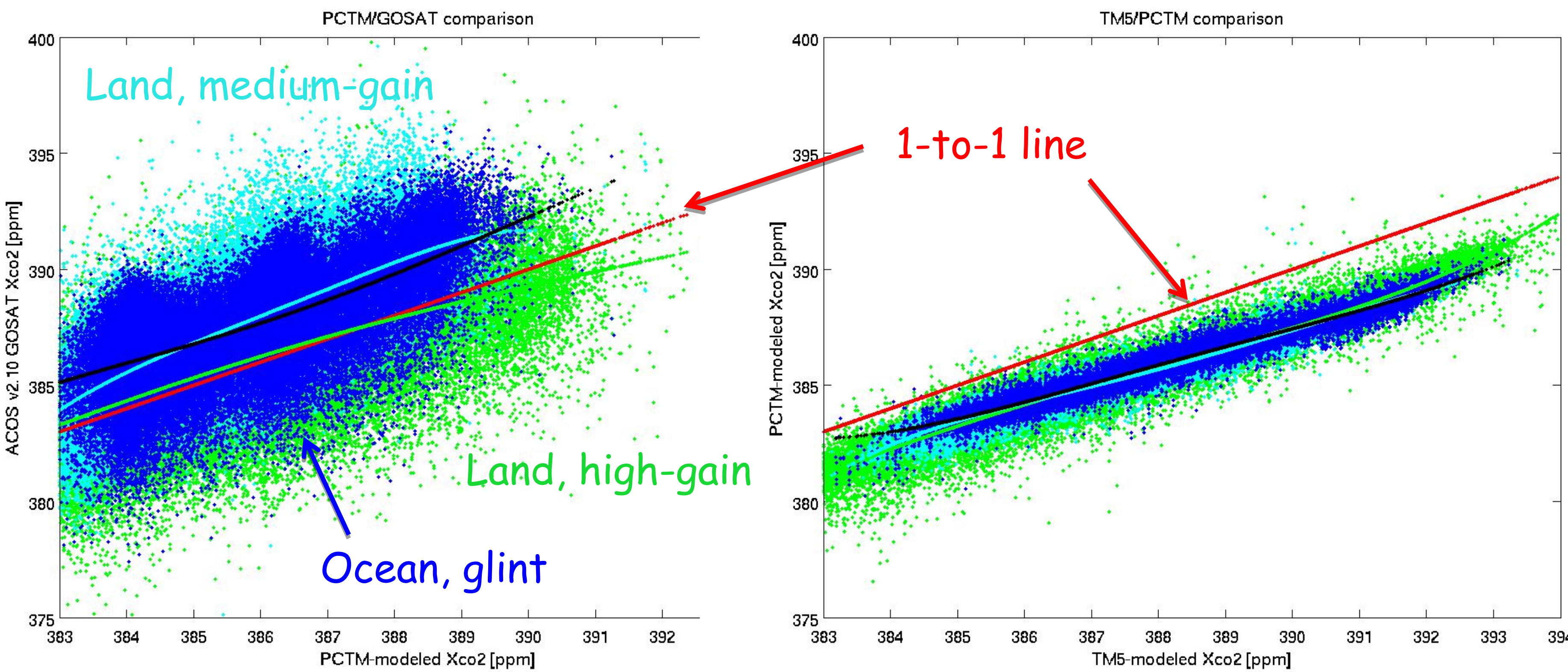
Outline

- Satellite data promise a new view: a move from the continental scale to the “regional” scale
- Things needed, first:
  - Efficient numerical methods for the flux inversion
  - Understanding of spatial and temporal correlations of fluxes and column concentrations along orbit
  - Way to remove systematic errors from the satellite retrievals
- Here: an attempt at removing systematic errors from satellite retrievals

Is it real or a bias in the satellite retrieval?

GOSAT comparison to CO_2 forward models

- Compare satellite data to a suite of forward model runs:
  - CT fluxes → TM5 Standard CT release
  - CT fluxes → PCTM ½°x ⅔° resolution (lat/lon)
  - CSU fluxes → PCTM SiB + Doney ocean
  - CSU fluxes → TM5 Just now being run
- Sample model at same time/place with same vertical weighting as the actual measurements
- Take the obs - model difference
- If the differences are all similar, blame it on retrieval errors



Obs versus model
(GOSAT vs. CT+PCTM)

Model versus model
(CT+TM5 vs. CT+PCTM)

Different forward model X_{CO2} values are closer to each other than any are to the GOSAT-retrieved values

Blame GOSAT-model differences on GOSAT retrieval errors (mostly)

Some Filters (land H)

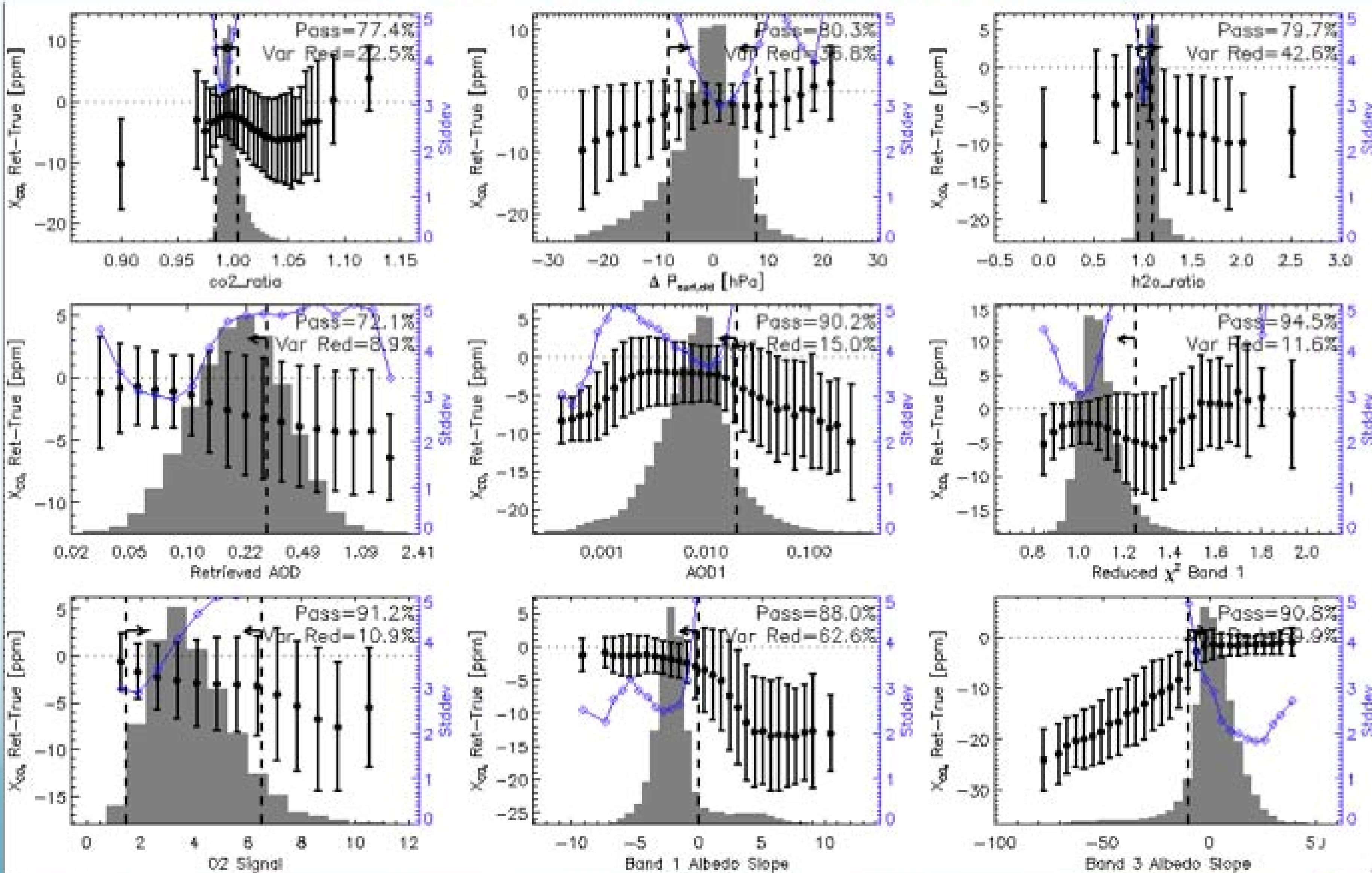


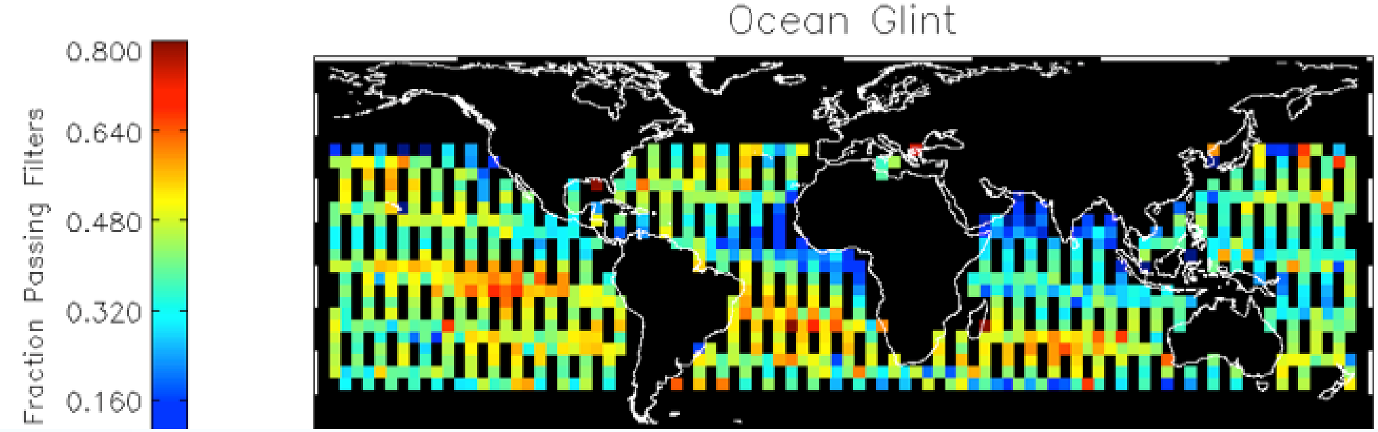
Figure courtesy of Chris O'Dell, CSU

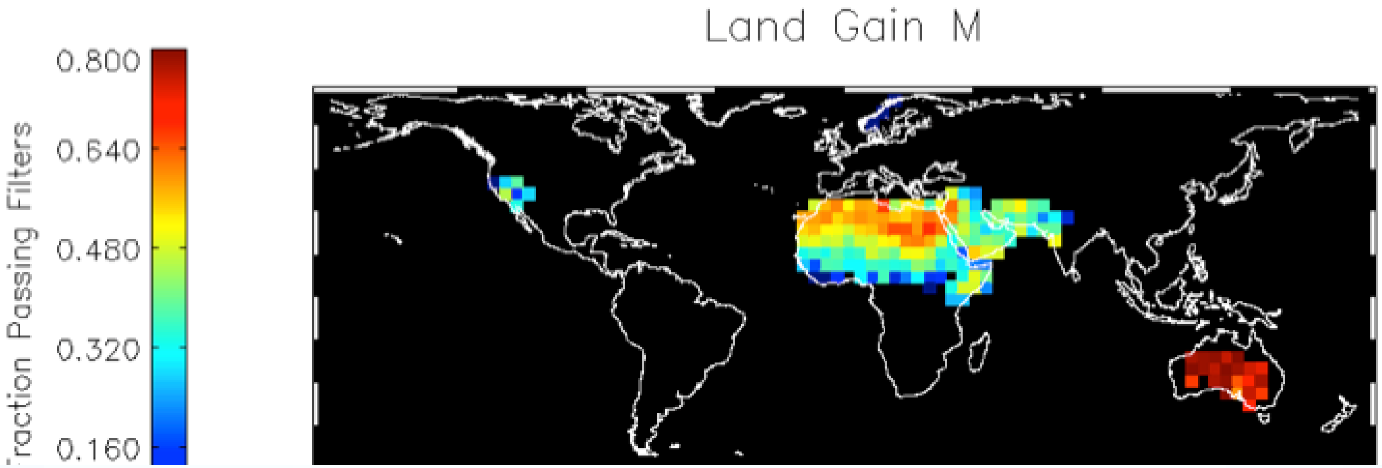
Filters Summary

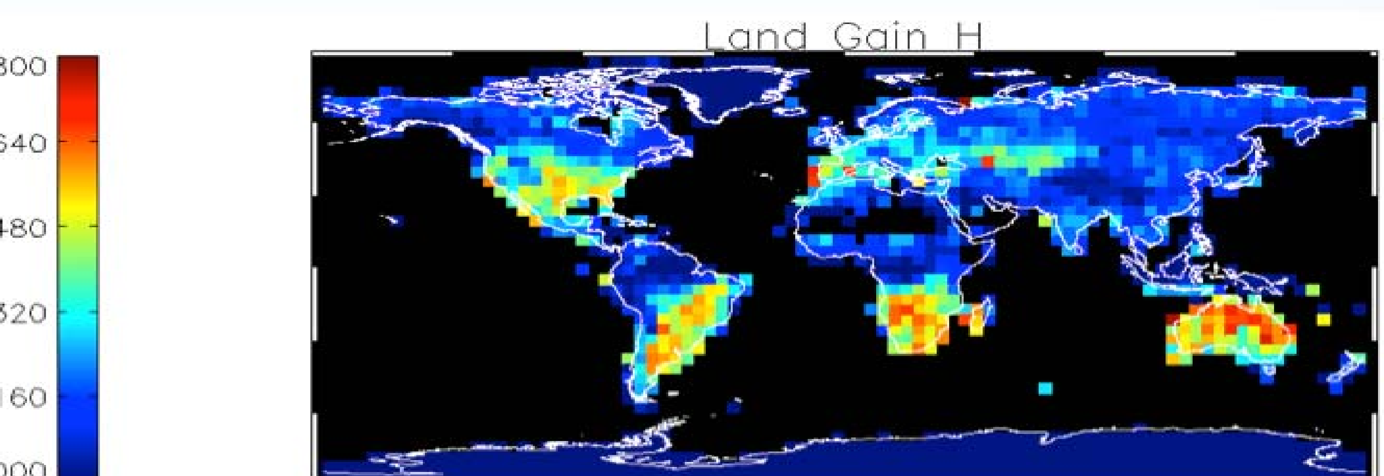
Variable	Allowed Range		
	Glint	Land H	Land M
outcome_flag	*	1 or 2	*
AOD Total	*	< 0.3	*
AOD Water Cloud	*	< 0.15	*
Diverging Steps	*	<= 2	*
altitude_sd [m]	*	< 200	*
CO2_ratio	*	0.985 to 1.005	0.985 to 1.01
H2O_ratio	*	0.96 to 1.10	0.98 to 1.08
$\Delta P_{s,cld}$ [hPa]	*	−8 to 8	−10 to 10
AOD Ice Cloud	*	< 0.02	0.004 to 0.04
Reduced χ^2	< (1.5, 1.8, 2.0)	< (1.25, 1.6, 2.0)	< (1.5, 1.6, 2.0)
X_{CO2} Error [ppm]	< 1.5	< 2.0	*
Albedo Slope 3	> 1.2e-5	> -1e-4	*
ΔP_s [hPa]	-10 to 10	-10 to 7	-12 to 2
Albedo Slope 1	< 4e-6	< 0	
Albedo Slope 2	-7e-6 to -5e-7		
ΔT offset [K]	> -1		
Band 1 Offset • 10^7	< 5.0		
Band 3 Albedo	> 0.01		
Blended Albedo		< 0.8	*
Signal_O2 • 10^7		1.5 to 6.5	

** Same as Land H*

Figure courtesy of Chris O'Dell, CSU







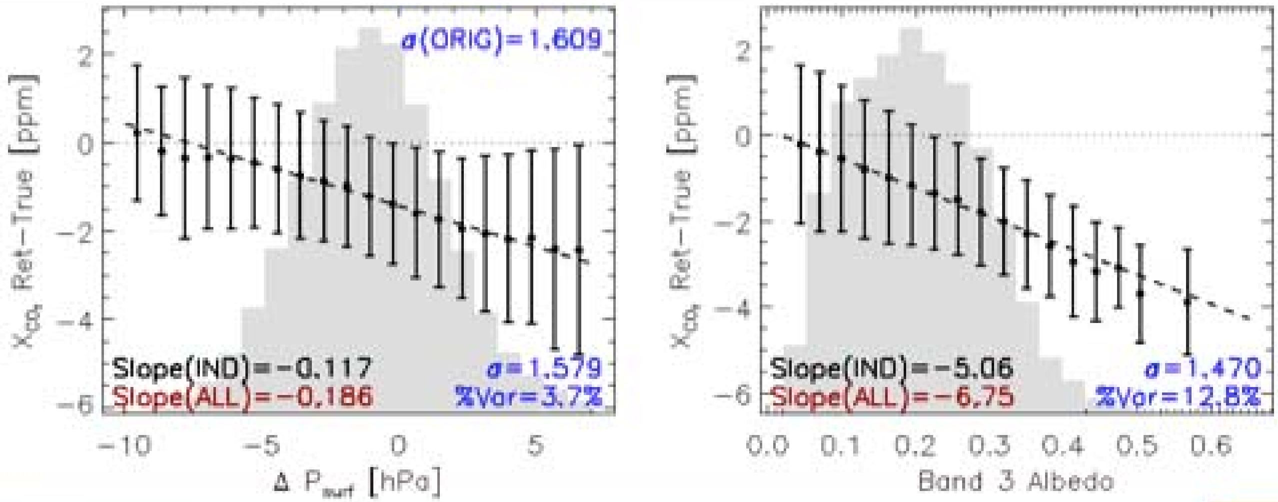
Fraction of GOSAT shots passing Chris' filters

Number of shots remaining, 2009-2010:

Ocean: 76 K
M-Land: 48 K
H-land: 73 K

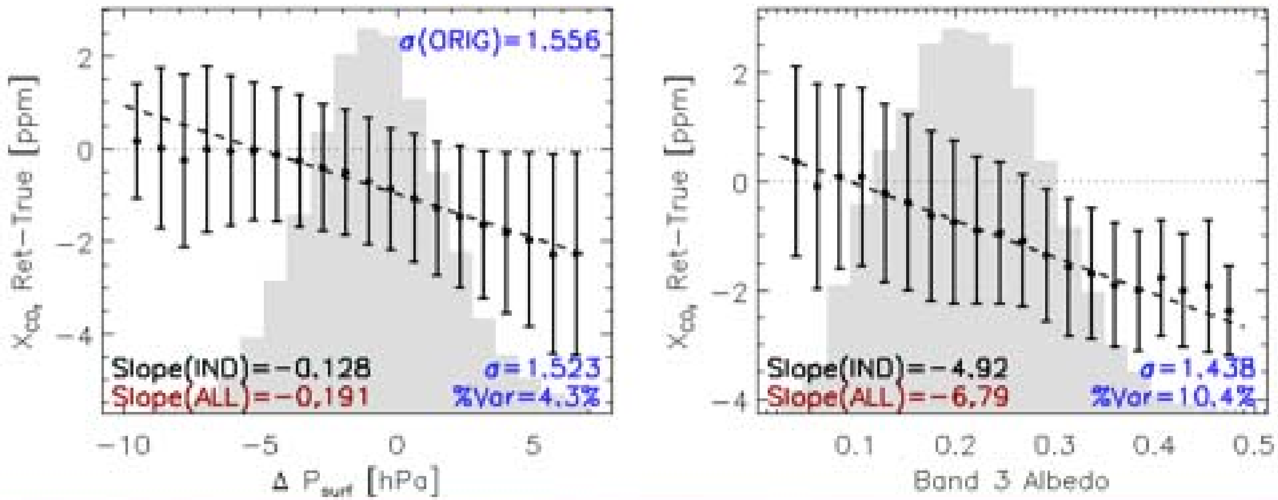
Figures courtesy of Chris O'Dell, CSU

Post-hoc correction (land H)



Multi-Model Mean
(bias = -1.25 ppm)

~15% of variance explained



Southern Hemisphere
Approximation

Figure courtesy
of Chris O'Dell, CSU

Proposed Corrections

Obs – model difference (1σ) after fit:

- Land, Gain H: 1.55 ppm

$$X'_{CO2} = X_{CO2} + 0.19 \cdot (\Delta P_S + 1.0 \text{ hPa}) + 7.0 \cdot (\text{Alb}_3 - 0.20) + 1.2 \text{ [ppm]}$$

- Land, Gain M: 1.4 ppm

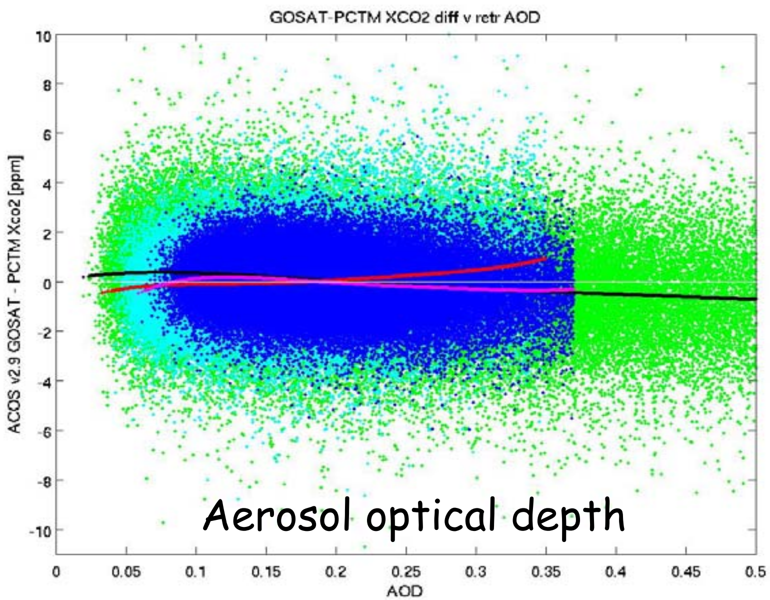
$$X'_{CO2} = X_{CO2} + 0.17 \cdot (\Delta P_S + 5.5 \text{ hPa}) + 7.0 \cdot (\text{Alb}_3 - 0.5) \text{ [ppm]}$$

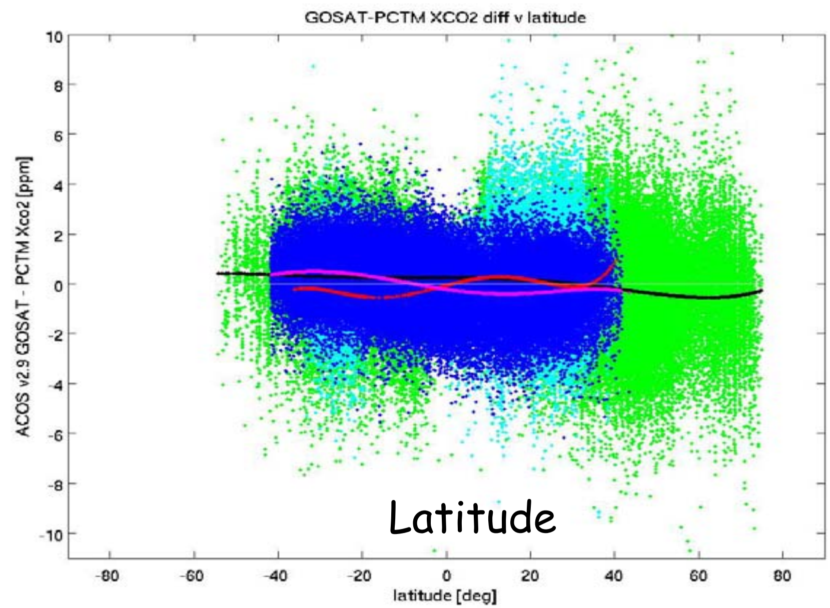
- Ocean Glint: 1.0 ppm

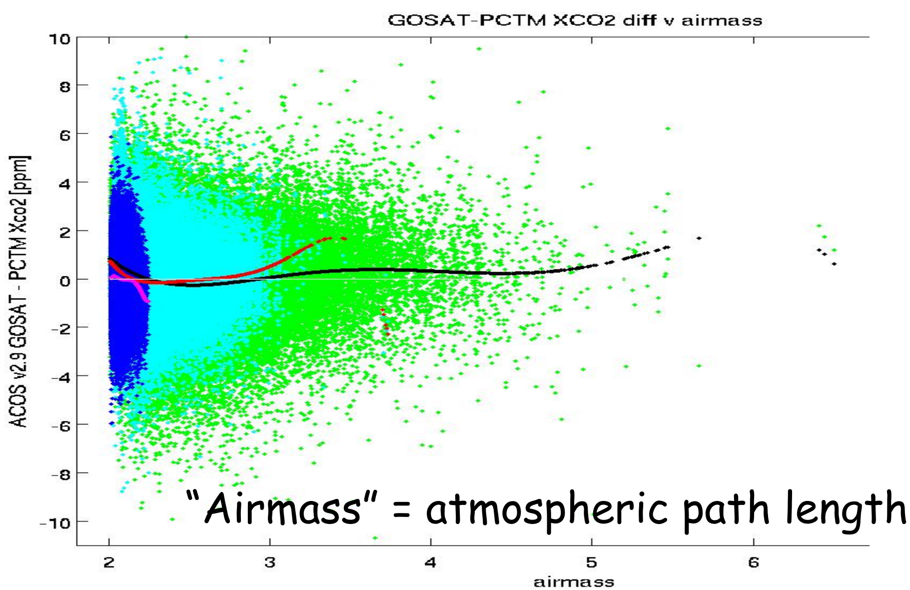
$$X'_{CO2} = X_{CO2} + 0.35 \cdot (\Delta P_S + 1 \text{ hPa}) + 6.8 \cdot (\text{AOD} - 0.2) + 0.45 \cdot \min(\text{Offset}_{Band1} \cdot 10^7, 2.0) + 0.2 \text{ [ppm]}$$

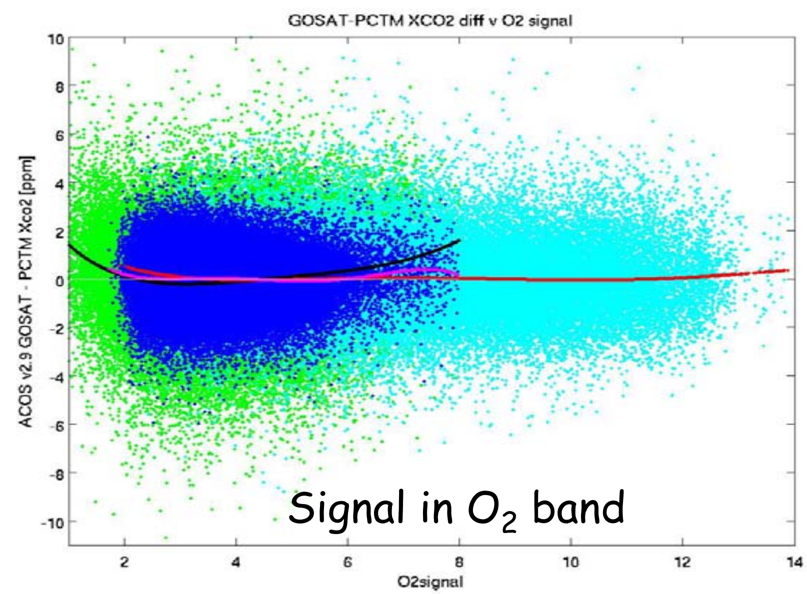
Slide courtesy of Chris O'Dell, CSU

Systematic differences (errors?) left after bias correction









Time-dependence of concentrations on fluxes

$$
\left|\begin{array}{ccc:cccccccc}
\mathbf{H}_1^{-2} & \mathbf{H}_1^{-1} & \mathbf{H}_1^{0} & \mathbf{H}_1^{1} & & & & & & & \\
 & \mathbf{H}_2^{-1} & \mathbf{H}_2^{0} & \mathbf{H}_2^{1} & \mathbf{H}_2^{2} & & & & \mathbf{0} & & \\
 & & \mathbf{H}_3^{0} & \mathbf{H}_3^{1} & \mathbf{H}_3^{2} & \mathbf{H}_3^{3} & & & & & \\
 & & & \mathbf{H}_4^{1} & \mathbf{H}_4^{2} & \mathbf{H}_4^{3} & \mathbf{H}_4^{4} & & & & \\
 & & & & \mathbf{H}_5^{2} & \mathbf{H}_5^{3} & \mathbf{H}_5^{4} & \mathbf{H}_5^{5} & & & \\
 & & & & & \ddots & \ddots & \ddots & \ddots & & \\
 & & \mathrm{H}_\infty & & & & \mathbf{H}_{M-1}^{M-4} & \mathbf{H}_{M-1}^{M-3} & \mathbf{H}_{M-1}^{M-2} & \mathbf{H}_{M-1}^{M-1} & \\
 & & & & & & & \mathbf{H}_{M}^{M-3} & \mathbf{H}_{M}^{M-2} & \mathbf{H}_{M}^{M-1} & \mathbf{H}_{M}^{M}
\end{array}\right|
\left|\begin{array}{c}
\mathbf{x}_{-2} \\ \mathbf{x}_{-1} \\ \mathbf{x}_{0} \\ \hdashline \mathbf{x}_{1} \\ \mathbf{x}_{2} \\ \mathbf{x}_{3} \\ \mathbf{x}_{4} \\ \mathbf{x}_{5} \\ \vdots \\ \mathbf{x}_{M-1} \\ \mathbf{x}_{M}
\end{array}\right|
=
\left|\begin{array}{c}
\mathbf{z}_{1} \\ \mathbf{z}_{2} \\ \mathbf{z}_{3} \\ \mathbf{z}_{4} \\ \mathbf{z}_{5} \\ \\ \mathbf{z}_{M-1} \\ \mathbf{z}_{M}
\end{array}\right|
$$

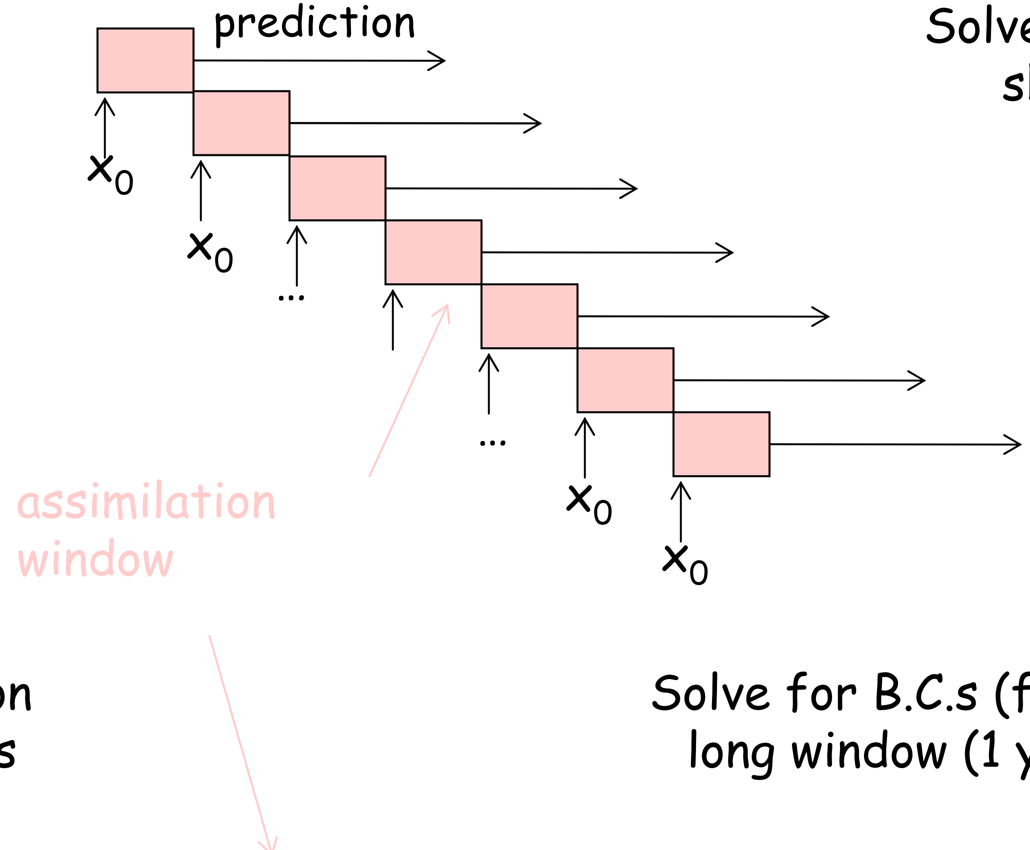
Transport basis functions

fluxes

concentrations

4D-Var: NWP vs. carbon flux estimation

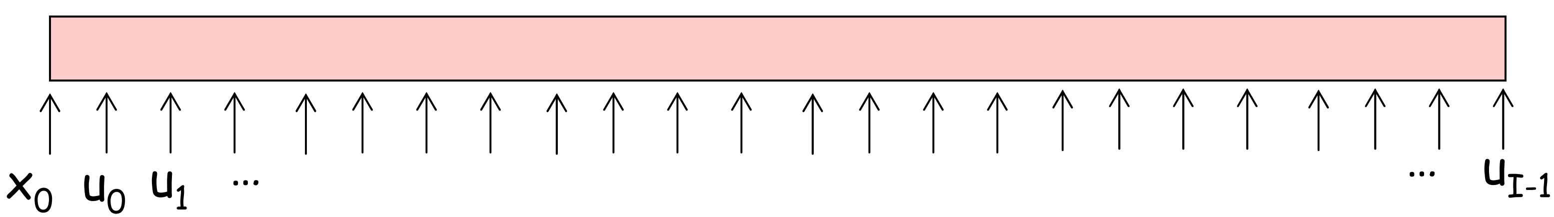
NWP



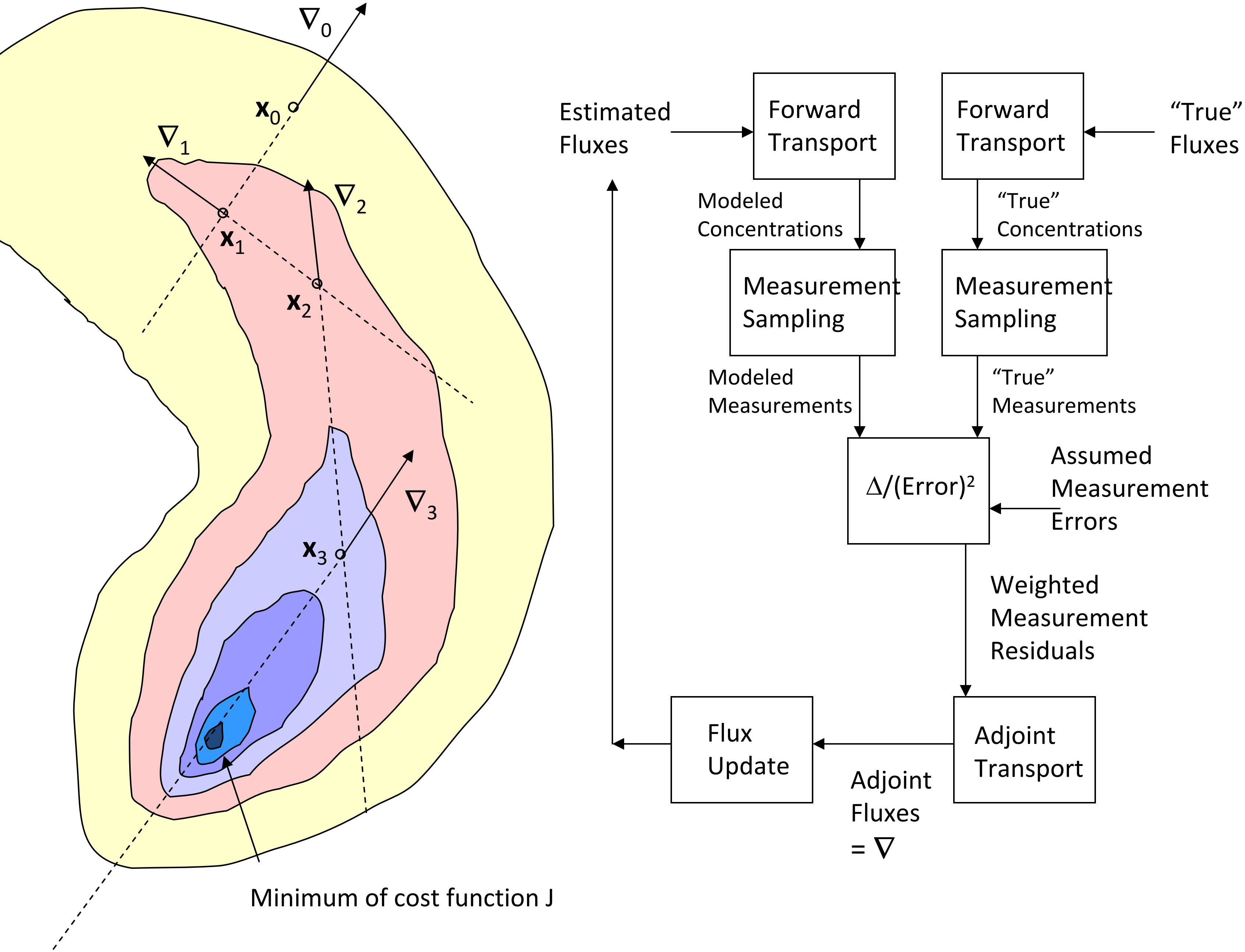
Solve for I.C.s over multiple short windows (6 hours): driven by the need to update predictions

Carbon fluxes

Solve for B.C.s (fluxes) and I.C.s over long window (1 year +): retrospective



4-D Var Iterative Optimization Procedure



CO_2 flux estimation approach using GOSAT X_{CO2}

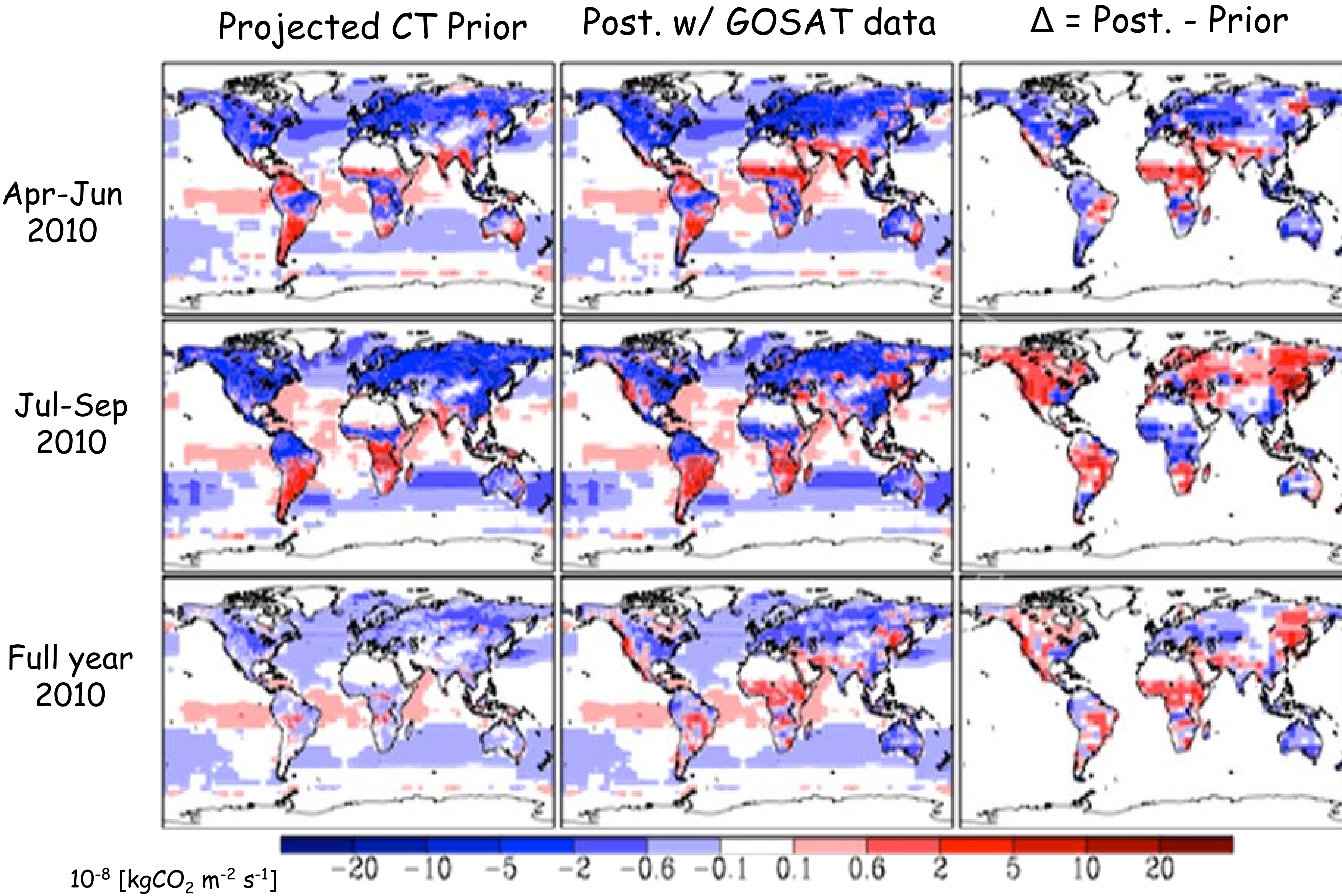
- Variational carbon data assimilation system
- Optimize weekly CO_2 fluxes for 2010 at 4½°x6° (lat/lon)
- Prior fluxes, a CarbonTracker "projection" (Jacobson):
  - fossil fuel from preliminary 2010 statistics (CDIAC)
  - "climatological" fluxes for land biosphere and ocean (average of 2000-2009 values from CT 2010)
  - NOT optimized against in situ data for 2010
- PCTM off-line atmospheric transport model, driven by GEOS5 analyzed meteorology fields
  - CT fluxes run thru at ½°x⅔° (lat/lon) to get prior [CO2]
  - Flux corrections estimated at 4½°x6° (lat/lon)

4DVar flux inversion cases

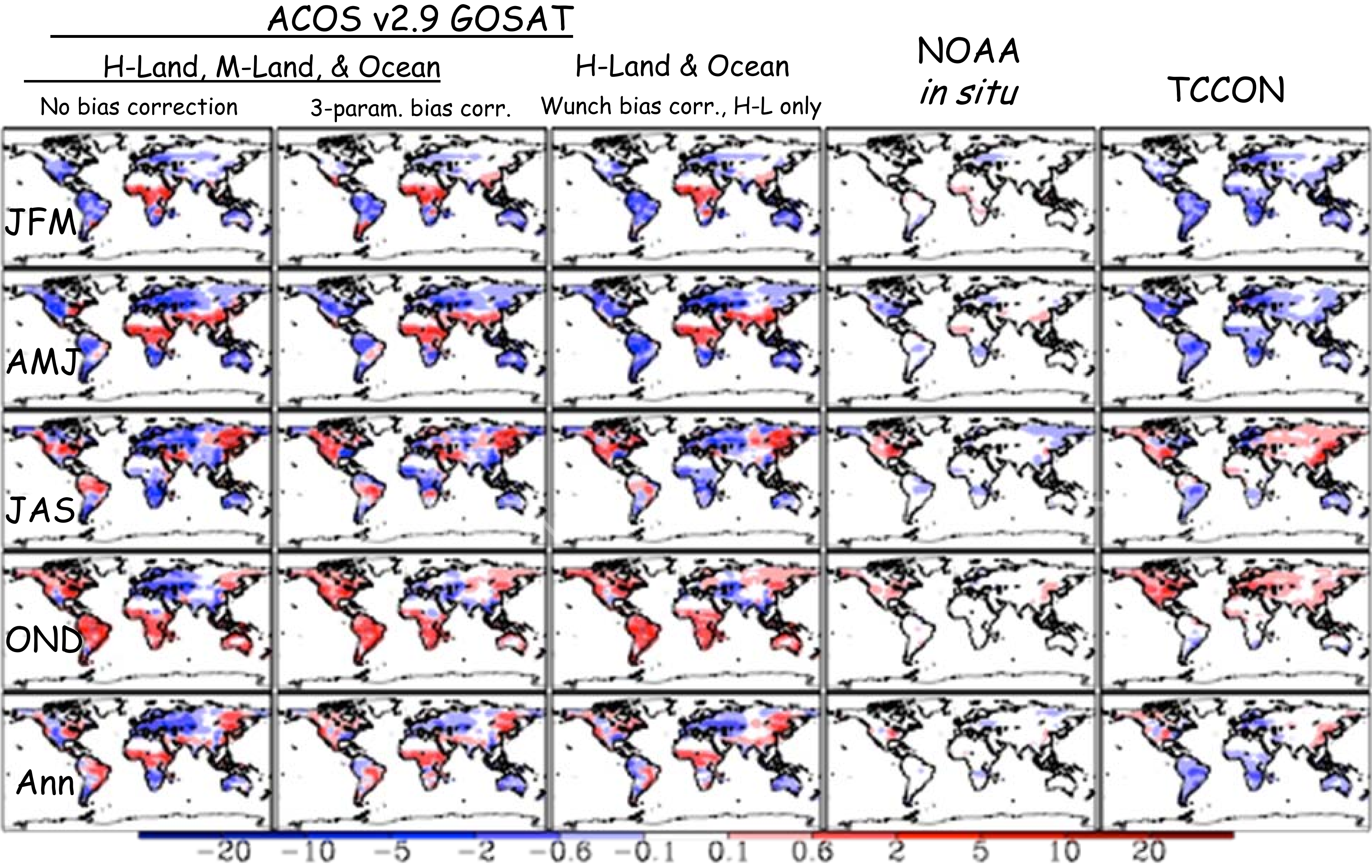
Seven flux inversions cases for 2010 using:

- NOAA *in situ*: 62 weekly flask sites, 4 continuous sites, 8 tall towers (daily)
- TCCON columns, 14 sites
- Screened ACOS ver. 2.9 GOSAT X_{CO2}:
  - No bias correction
  - a separate 3-parameter bias correction for ocean and high- and medium-gain land data
  - Three bias corrections of Wunch, et al (2011)

4DVar CO_2 Flux Estimates w/ ACOS v.2.9 GOSAT X_{CO2}



CO_2 flux corrections to the CT-PCTM prior $[10^{-8}\ kgCO_2\ m^{-2}\ s^{-1}]$ when assimilating only:



Evaluation of a posteriori CO_2 fields against independent data

1σ error [ppm] between optimized model and TCCON (in 2-hr bins)

Prior		1.307
GOSAT, H+M+Ocn, no bias corr.		1.204
GOSAT, H+M+Ocn, 3-param.	“	1.172
GOSAT, H+Ocn, Wunch #1	“	1.219
GOSAT, H+Ocn, Wunch #2	“	1.219
GOSAT, H+Ocn, Wunch #3	“	1.213
NOAA *in situ*		1.268
TCCON		1.054

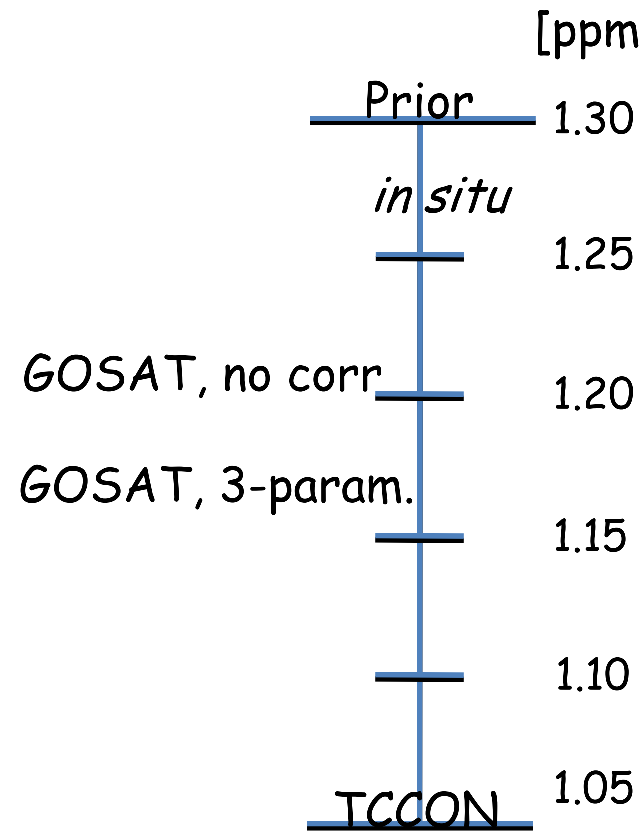
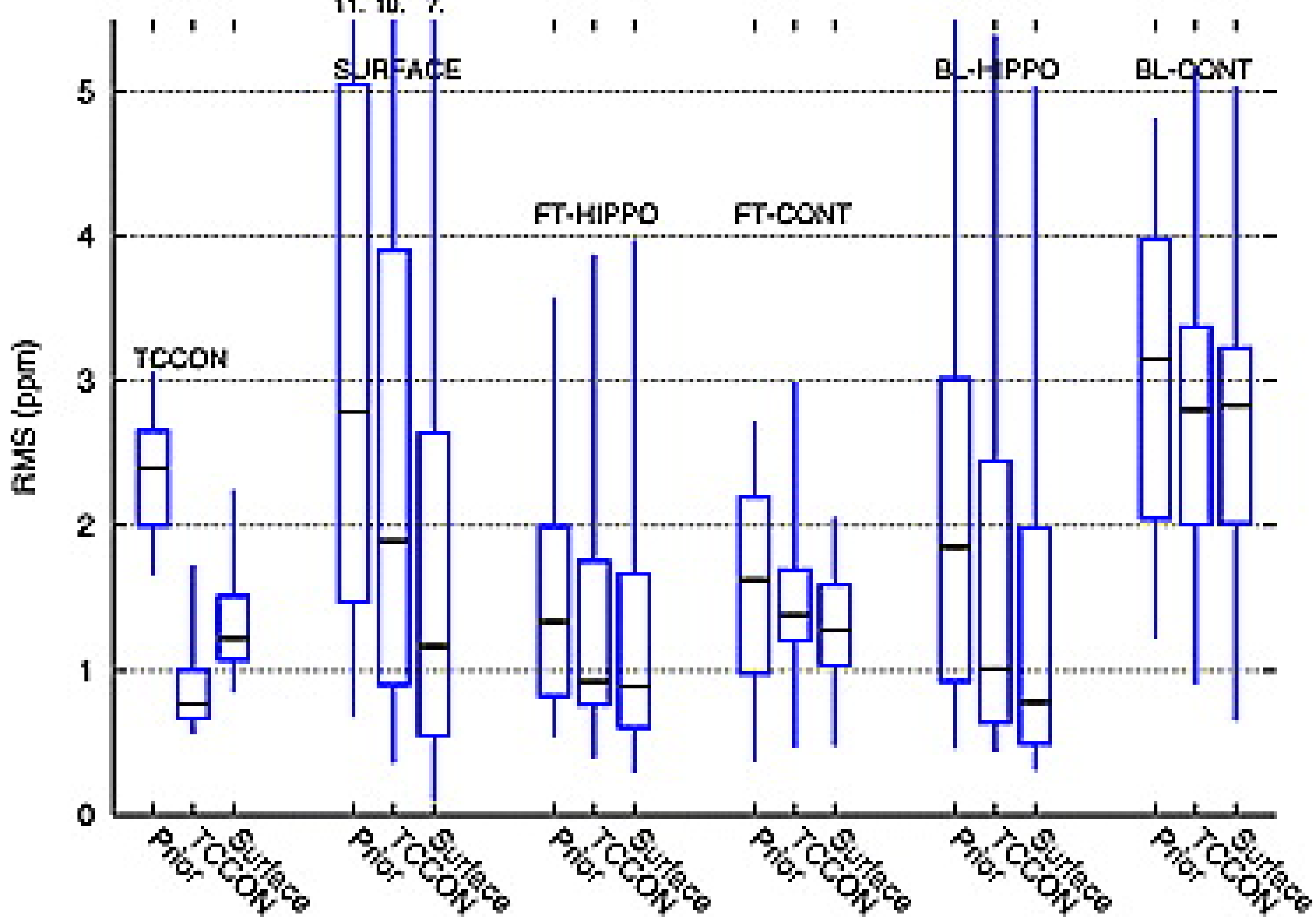


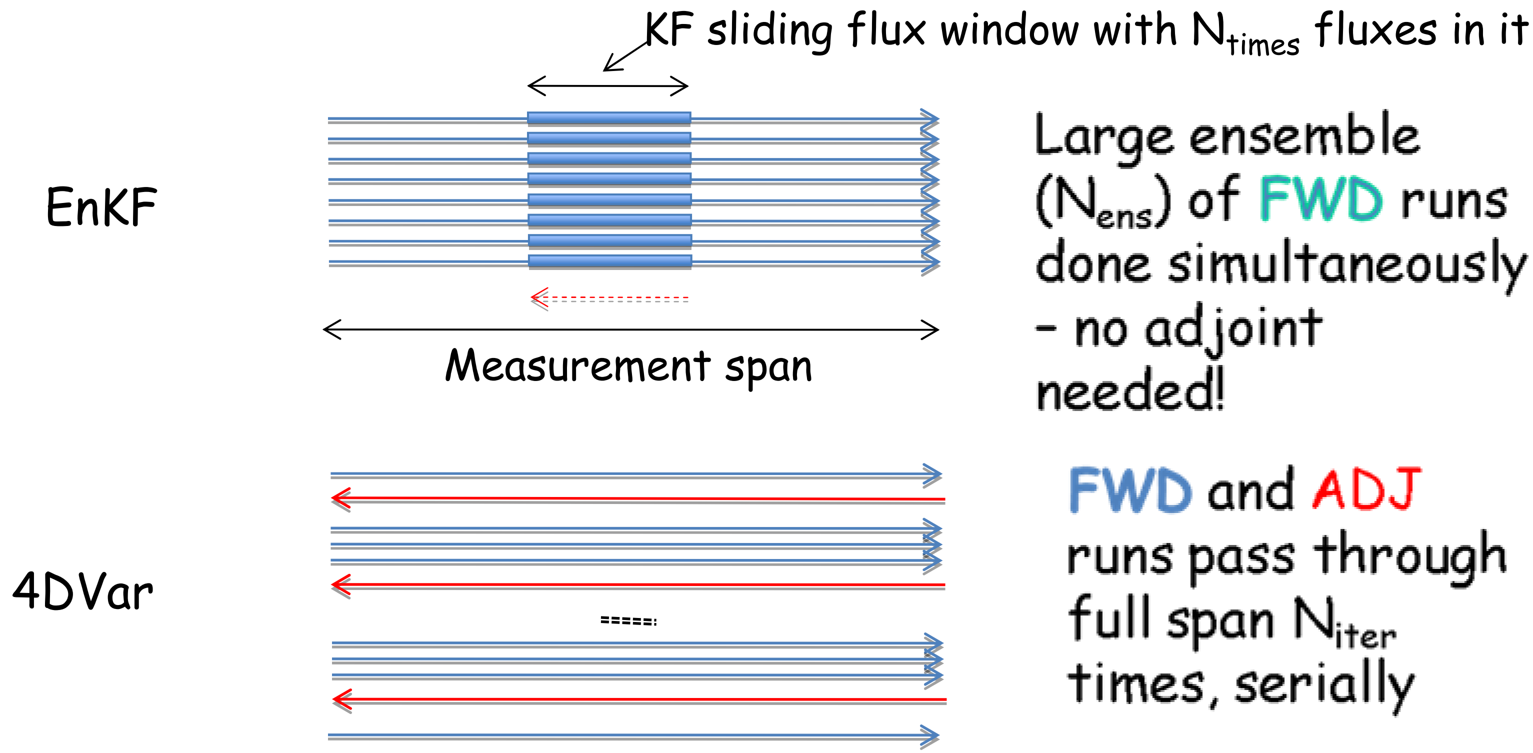
Figure 3 from Chevallier, et al (2011) TCCON inversion paper.



Next: make a similar plot for inversions / data comparisons using:

- *ACOS GOSAT XCO2*
- NOAA surface *in situ* data
- NOAA routine aircraft profiles
- TCCON XCO2
- HIPPO, AIRS, TES, AirCore, etc

EnKF & 4DVar



Large ensemble (N_{ens}) of FWD runs done simultaneously – no adjoint needed!

FWD and ADJ runs pass through full span N_{iter} times, serially

Computational work:

- N_{times}*N_{ens} for EnKF (in parallel)
- 4*N_{iter} for 4DVar (serial)

Columns in C, where $P=CC^T$:
N_{ens} for EnKF
2*N_{iter} for 4DVar

Backward propagation of information:
For EnKF, depends on time width of window – shorter spans give poorer constraints at larger time/space scales