NASA Carbon Flux System

NASA CMS team:

Kevin Bowman, Junjie Liu, Meemong Lee, Dimitris Menemenlis, Holger Brix, Joshua Fisher, Aaron Polhamus, Annmarie Eldering, Michael Gunson

Jet Propulsion Laboratory, California Institute of Technology

Joint Institute for Regional Earth System Science and Technology, University of California, Los Angeles

Steven Pawson, Lesley Ott, James Collatz, Watson Gregg, Zhengxin Zhu, Randy Kawa, Cecile Rousseaux

NASA Goddard Space Flight Center

Christopher Potter, Steve Klooster

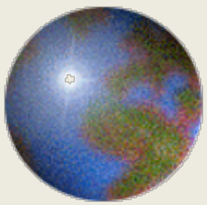
NASA Ames Research Center

Chris Hill, Mick Follows, Stephanie Dutkiewicz

MIT

Ken Jucks

NASA Headquarters



GEOS-Chem developers:

Daven Henze

University of Colorado, Boulder

Ray Nassar

Environment Canada

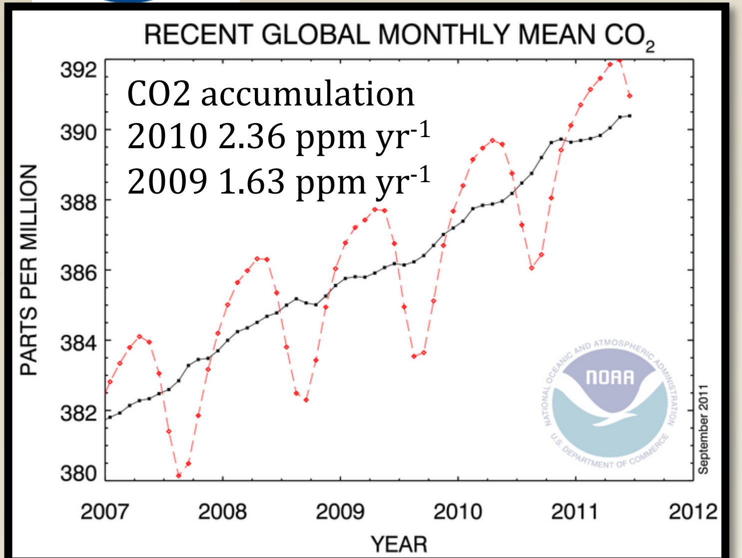
Dylan Jones

University of Toronto

P. Suntharalingam

University of East Anglia

Attribution of climate forcing

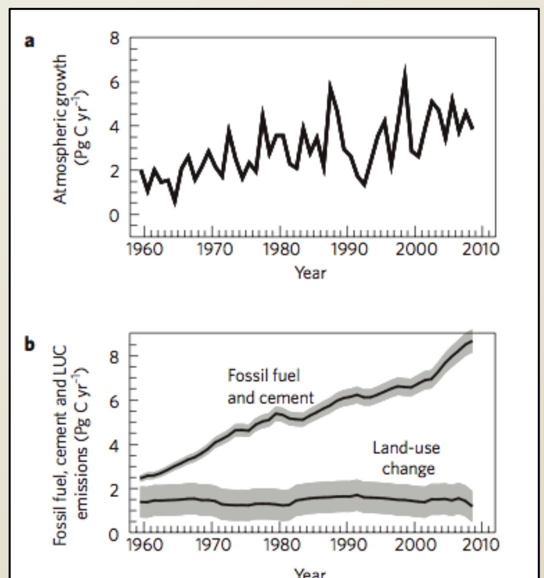


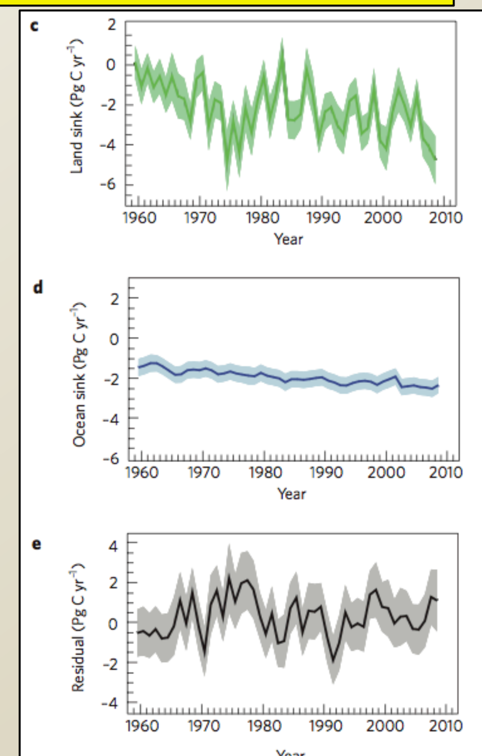
nature geoscience
FOCUS | PROGRESS ARTICLES
PUBLISHED ONLINE: 17 NOVEMBER 2009 | DOI: 10.1038/NGEO689

Trends in the sources and sinks of carbon dioxide

Corinne Le Quéré, Michael R. Raupach, Josep G. Canadell, Gregg Marland *et al.**

"major gaps remain….in our ability to link anthropogenic CO_2 emissions to atmospheric CO_2 concentration on a year-to-year basis…. and adds uncertainty to our capacity to quantify the effectiveness of climate mitigation policies.",





2010 Carbon Budget

Atmospheric 5.0±0.2 PgC y^{-1}

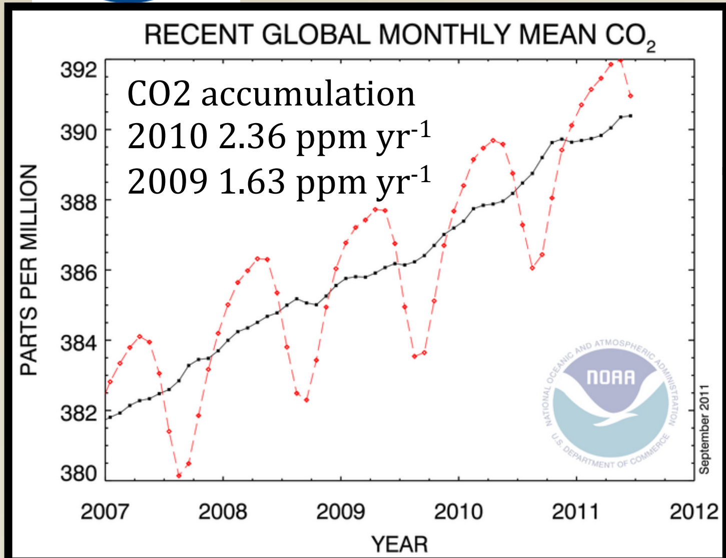
Terrestrial 2.6±1.0 PgC y^{-1}
Calculated as the residual of all other flux components

Oceanic 2.4±0.5 PgC y^{-1}
Average of 5 models

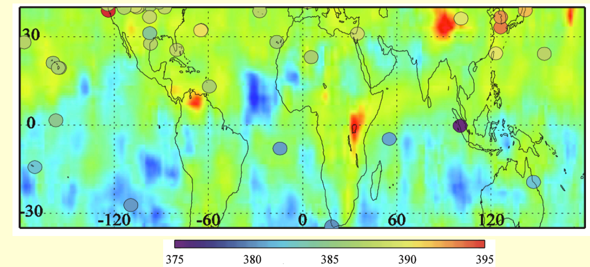
Global Carbon Project

http://www.globalcarbonproject.org

Attribution of climate forcing

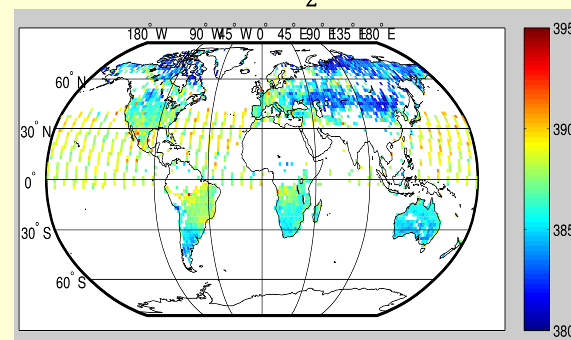


TES/AIRS (IR) free tropospheric CO_2

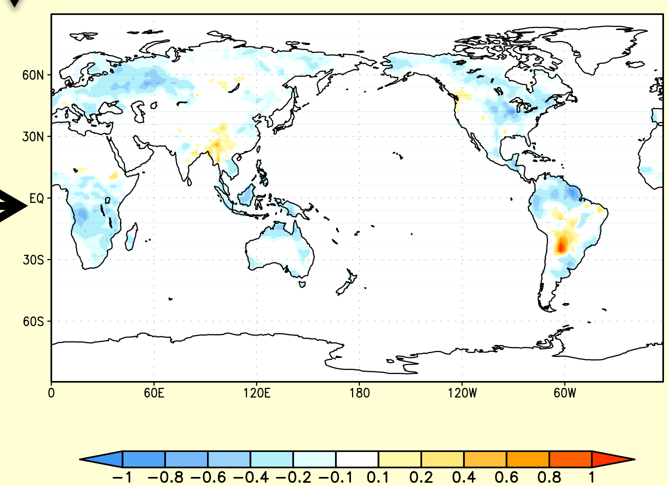


Kulawik *et al*, 2010 ACP

ACOS GOSAT CO_2 columns



Spatially resolved emissions



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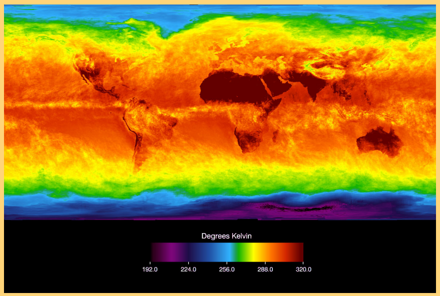
Global Carbon Project

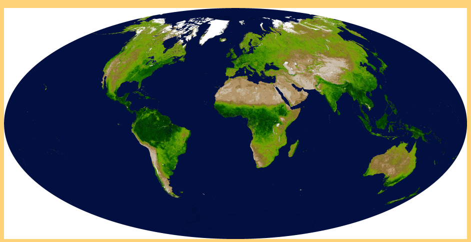
http://www.globalcarbonproject.org

NASA Carbon Flux System

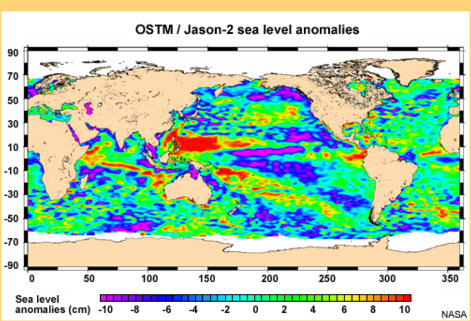
NASA satellites



T, q, p,.. (AIRS)



EVI, FPAR,.. (MODIS)



chlorophyll, altimetry, … (MODIS, JASON)

NASA models/ assimilation

Atmos
GEOS-5

winds (u,v)

Terrestrial
CASA/ CASA-GFED

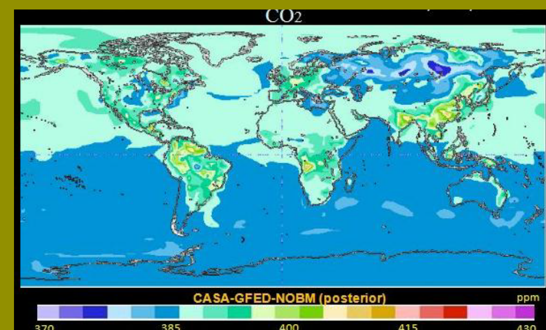
NEE

Ocean
NOBM/ JPL-MIT ECCO2

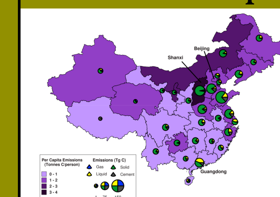
Air/sea CO2 exchange

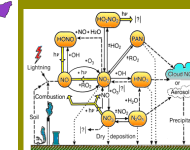
NASA inverse modeling

Inverse
GEOS-Chem



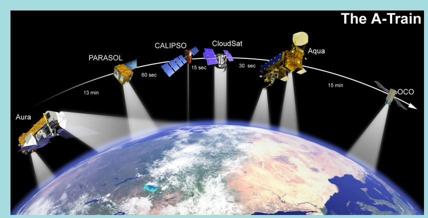
Anthropogenic





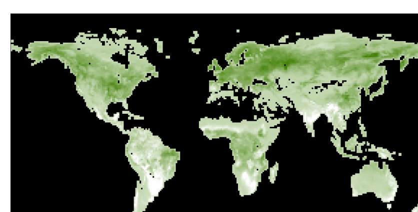
FF, biofuel, chemical production

$$\min_{\mathbf{x}_0} C(\mathbf{x}) = \left\{ \sum_i (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x}))^\top (\mathbf{S}_n^i)^{-1} (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x})) + (\mathbf{x}_0 - \mathbf{x}_a)^\top \mathbf{S}_a^{-1} (\mathbf{x}_0 - \mathbf{x}_a) \right\}$$

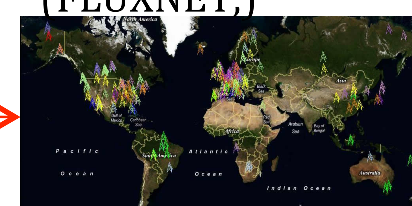


Satellite CO2 sensors (GOSAT, TES, AIRS)

Optimal flux (gC/m^2/day)

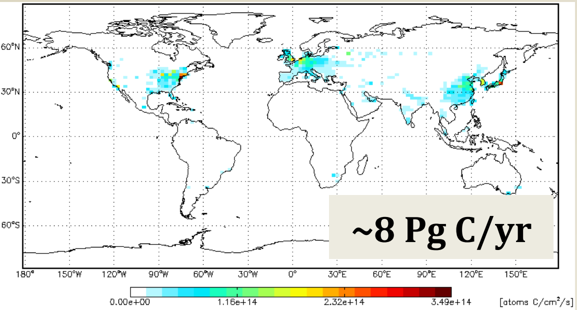


Independent tests (FLUXNET,)



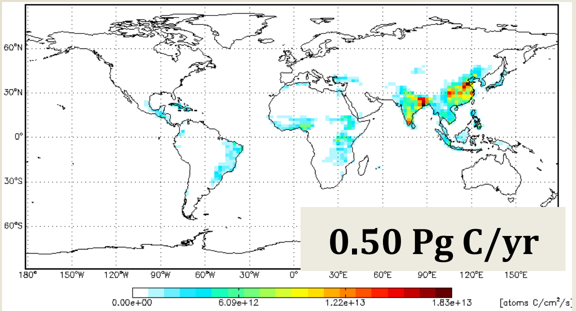
CO_2 3-D and shipping emissions

Fossil Fuel

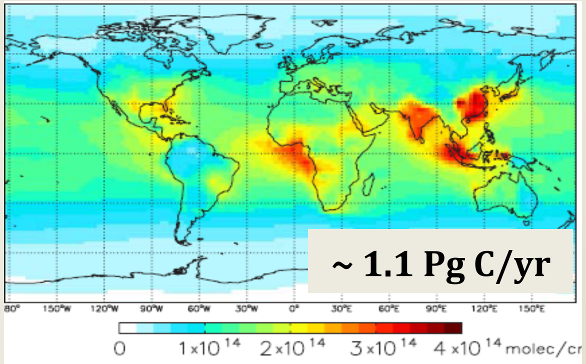


Andres et al. (2010), CDIAC
monthly 1950-2006

Biofuel

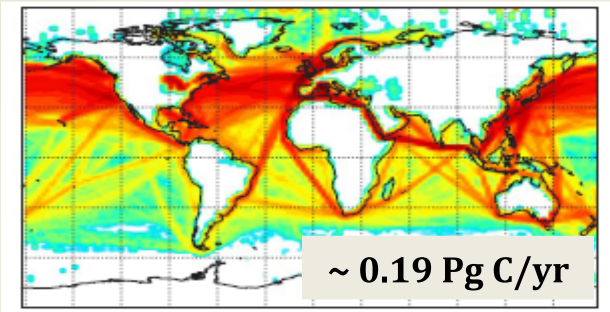


CASA-GFED3
2009-2010



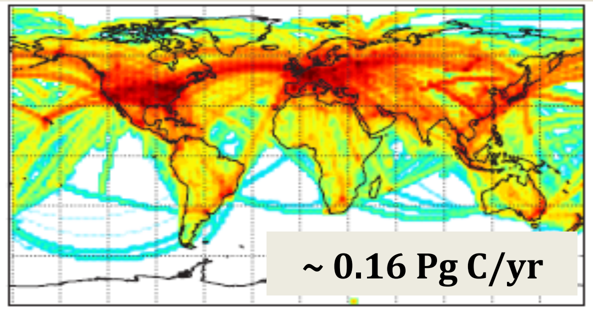
GEOS-Chem CO_2 production from oxidation of CO, CH_4, NMVOCs

International Shipping



ICOADS (*Corbett & Koehler*, 2003; 2004)

Aviation (3-D)



AEAP (*Friedl*, 1997) and SAGE (*Kim et al.*, 2007)

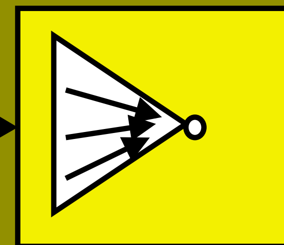
Nassar et al. (2010) Geoscientific Model Development

Hybrid 3D-var/4D-var assimilation approach

GEOS-Chem adjoint

$$\lambda = \nabla_{\mathbf{x}_0} C(\mathbf{x}) = \left(\frac{\partial C(\mathbf{x})}{\partial \mathbf{x}_0}\right)^\top$$

$$\left(\frac{\partial \mathbf{x}^i}{\partial \mathbf{x}^0}\right)^\top = \left(\frac{\partial \mathbf{M}_0}{\partial \mathbf{x}_0}\right)^\top \cdots \left(\frac{\partial \mathbf{M}_{i-1}}{\partial \mathbf{x}_{i-1}}\right)^\top \rightarrow$$



- Initial conditions derived from 3D-var
- Independent monthly fluxes
- Estimate of terrestrial flux **only**

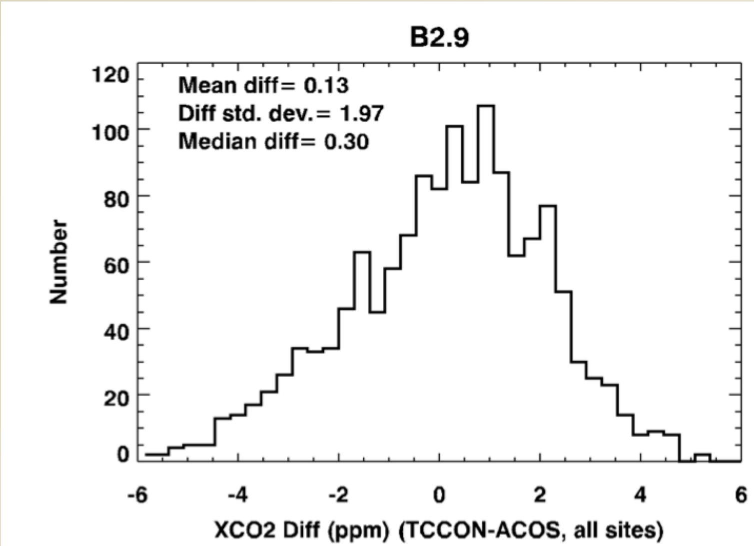
Seq 3D-var	Parallel 4D-var	
CO_2 July 1st	July 2009	ECO_2 (GtC/month)
CO_2 Aug 1st	Aug 2009	ECO_2 (GtC/month)
CO_2 ••••	••••	ECO_2 (GtC/month)
CO_2 June 1st	June 2010	ECO_2 (GtC/month)

3D-var
x: CO2 initial conditions
$[\mathbf{S}_a]_{ii}$ = 50%
$\mathbf{S}_n$ = Observational error from ACOS. No transport error or horizontal correlation error.

4D-var
x: monthly scale factor
$[\mathbf{S}_a]_{ii}$ = 10% and 50%
$\mathbf{S}_n$ = Observational error from ACOS. No transport error or horizontal correlation error.

GOSAT-ACOS v2.9 xCO2

v2.9 validation against TCCON



JAXA GOSAT observations are processed through the JPL ACOS retrieval algorithm v2.9 from July 2009-June 2010.

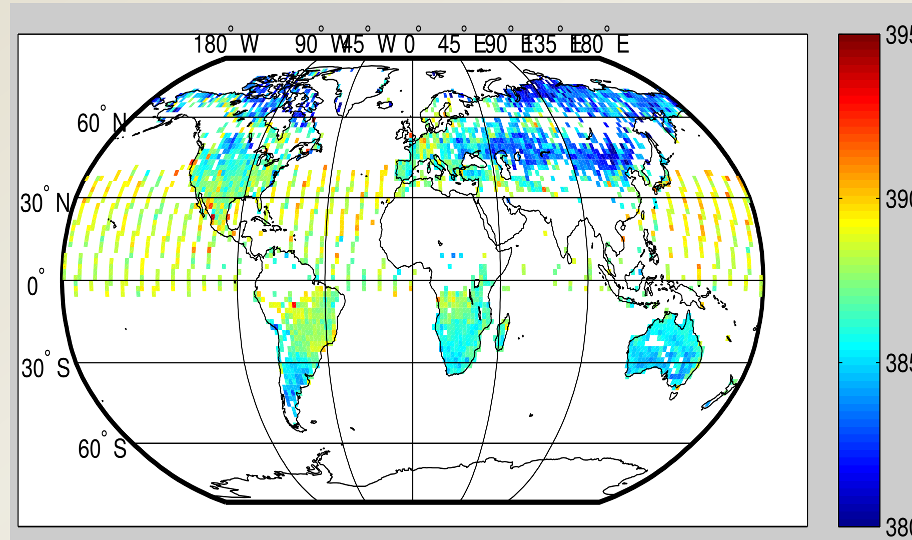
Data: xCO2 columns in both nadir and glint mode under high gain settings.

Observations are filtered by flags recommended in the ACOS Level 2 Standard Product Data User's Guide, v2.9

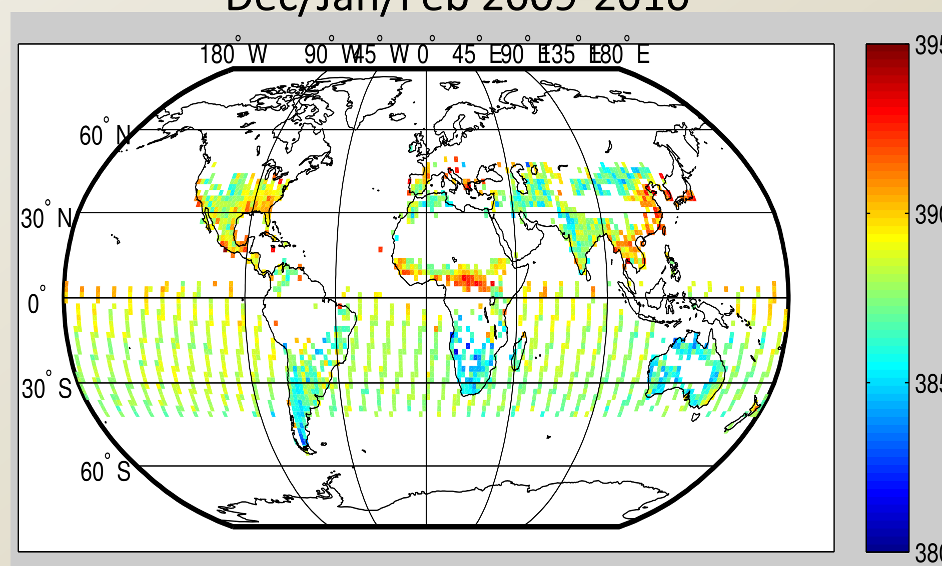
Observation operator: xCO2 averaging kernels, a priori, and measurement error

Bias correction applied based on Wunch *et al*, ACPD, 2011

June/July/August 2009



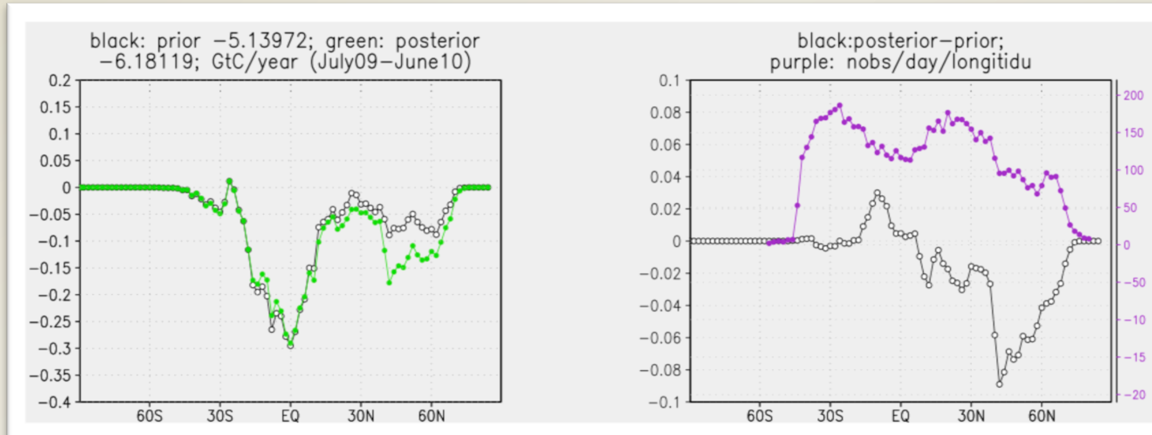
Dec/Jan/Feb 2009-2010

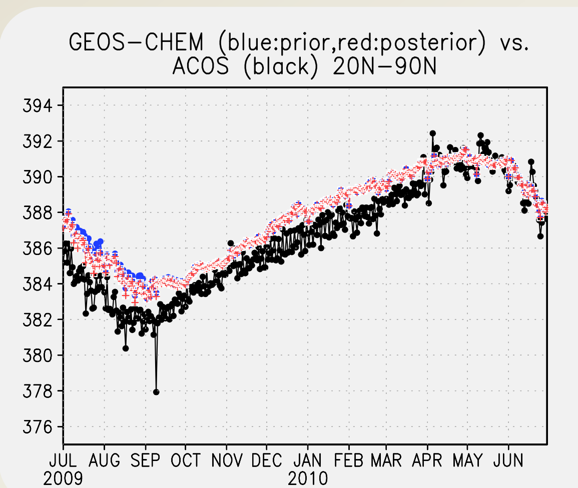


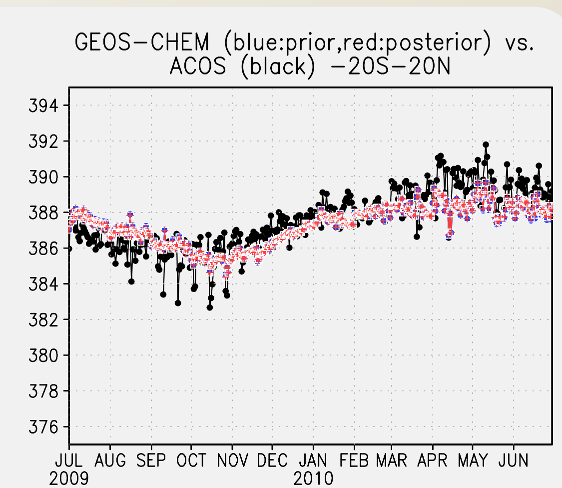
Courtesy Christian Frankenberg

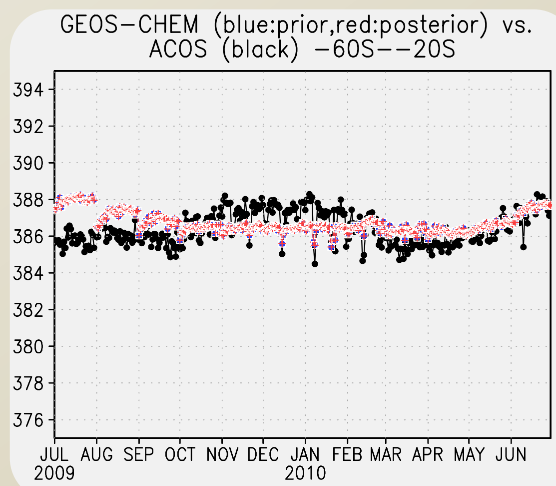
Flux estimates with 10% uncertainty

- GOSAT has reasonably
high throughput
- Zonal, annual average shows increased NH sink: consequence of high initial conditions.
- Tropical high bias in summer/fall.
- Tropical low bias in winter/spring
- SH high bias→indicative of weak oceanic sink.
- SH seasonal variation of 2ppm xCO2 not captured.
- 3D-var compensates for some but not all initial conditions all



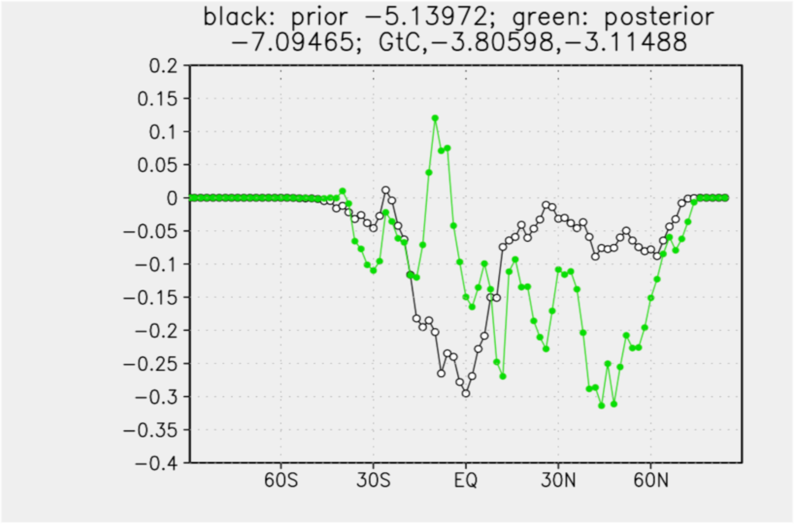


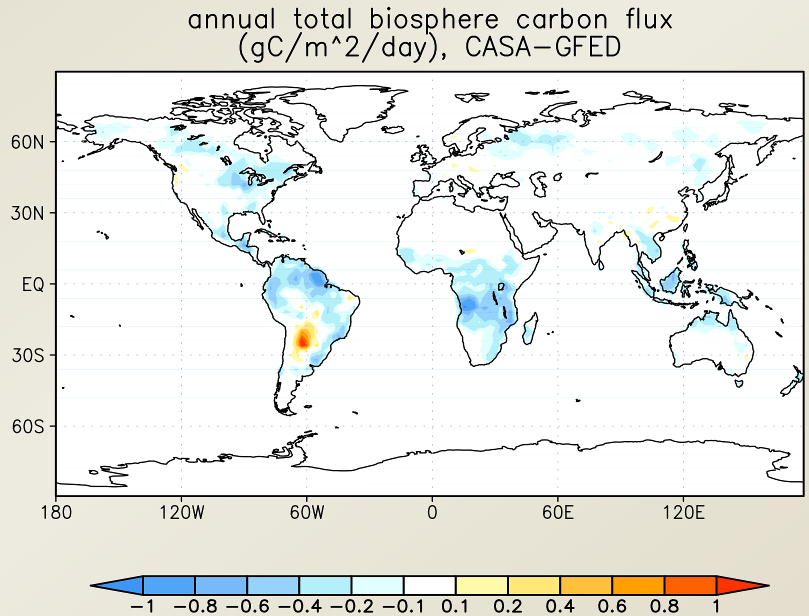


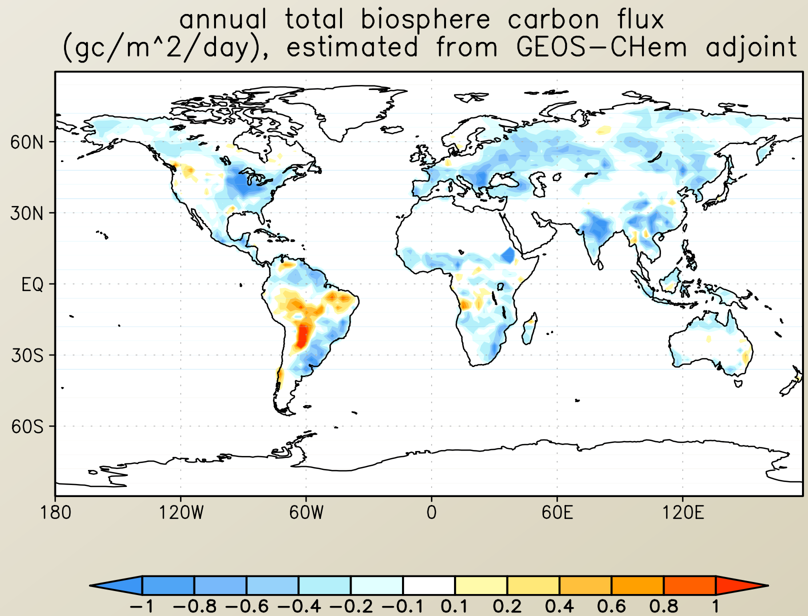


Flux estimate 50% a priori uncertainty

- Dramatic increase in NH sink in both Eurasia and North America
- Strong tropical source in South America
- Weakening of tropical sink in sub-Saharan Africa
- Increase of tropical sink in India and Southeast Asia







Flux Time series

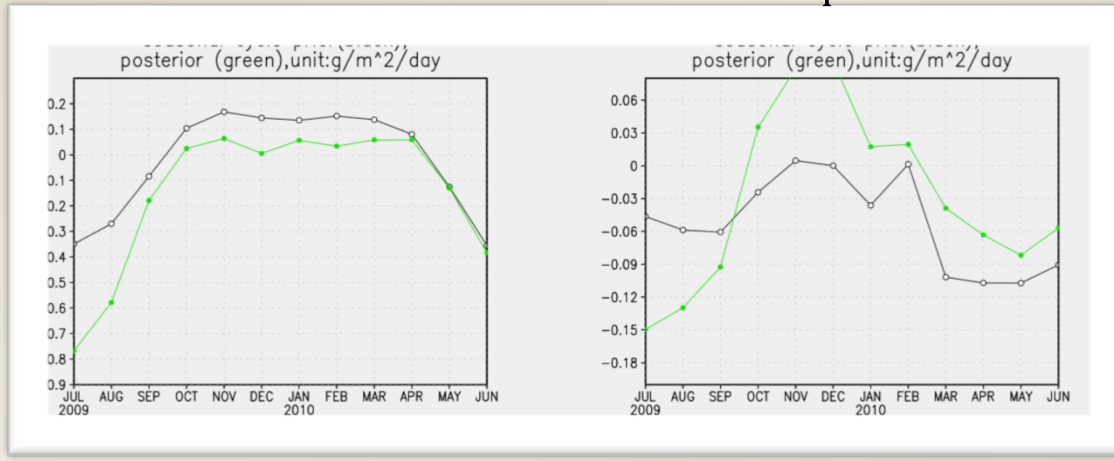
NH monthly mean fluxes decrease by 0.15 gC/m^2/day from Fall through Spring.

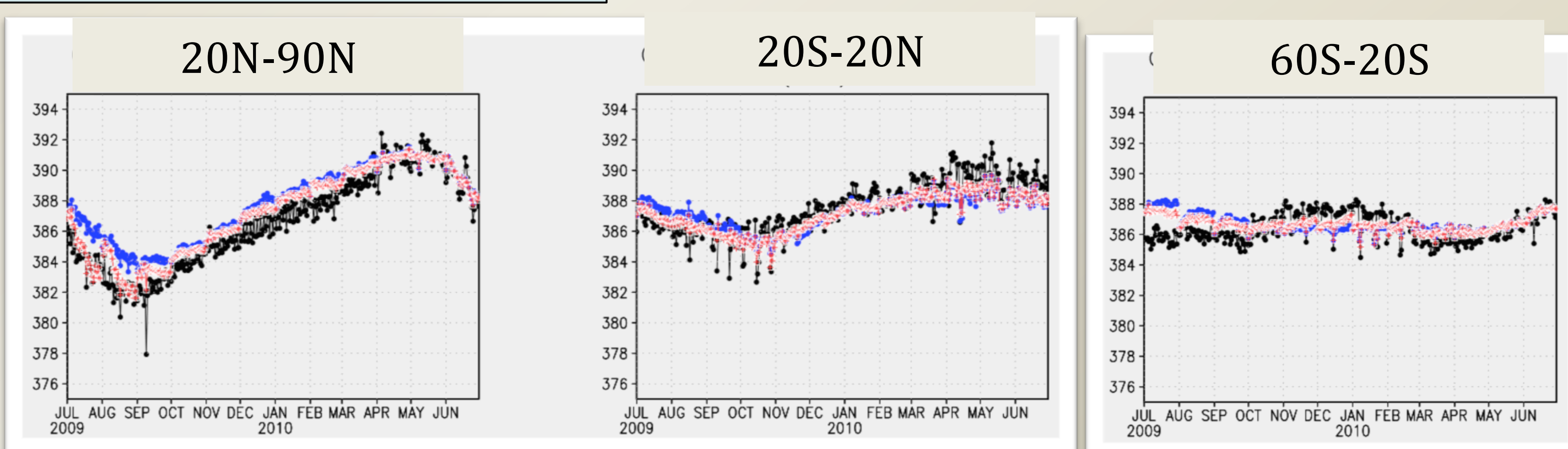
Significantly better agreement with GOSAT, but overestimate of of winter time accumulation

Big increase in tropical fluxes, but still an underestimate relative to observations

Black: a priori flux Green: posterior

NH mid-latitude Tropics





Summary

- The total anthropogenic emissions is consistent with the Global Carbon Project, ~10 GtC/yr
- The net sink is slightly higher at 5.6 GtC/yr
  - Based on 50% a priori uncertainty
  - Increase in sink in part due to initial conditions
- The total airborne fraction, ~.44, is reasonable.
- Oceanic sink is too weak
  - Consequence of chlorophyll assimilation strategy

Control parameter limited to terrestrial update

- 4D-var system attributes fluxes from oceans and other sources in order to match observations
- However, tropical and SH seasonal variation in xCO2 suggests tropical flux too low→ underestimate of biomass burning?

The NASA Carbon Flux System has integrated a suite of ocean, terrestrial, atmospheric models and observations to attribute atmospheric CO2 to spatially resolved sources/sinks.

Emission	Annual GtC/yr
Fossil fuel (Andres 2011)	8.13
Biofuel (GFED3)	0.5
Shipping (ICOADS)	0.19
Aviation (APEAP-SAGE)	0.16
Chemical source (Nassar 2010)	1.05
Total	**10.03**
Biosphere (NASA CFS)	-7.09
Biomass Burning (GFED3)	1.73
Oceans (NOBM)	-0.24
Total Sink	**5.60**
Accumulation	**4.43**

BACKUP

4D-var assimilation approach

$$\min_{\mathbf{x}_0} C(\mathbf{x}) = \left\{ \sum_i (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x}))^\top (\mathbf{S}_n^i)^{-1} (\mathbf{y}_i - \mathbf{F}_i(\mathbf{x})) + (\mathbf{x}_0 - \mathbf{x}_a)^\top \mathbf{S}_a^{-1} (\mathbf{x}_0 - \mathbf{x}_a) \right\}$$

$$\text{subject to } \mathbf{x}_{i+1} = \mathbf{M}_i(\mathbf{x}_i, \mathbf{p}_i)$$

- Short spin-up from Jan 2009 to June 2009 driven by CASA-GFED3 and NOBM inventories
- ACOS xCO_2 is assimilated into GEOS-Chem in 3D-var mode from July-2009 to June 2010.
- Assimilated fields are used as initial conditions for each month
- Fluxes are estimated for each month independently
- Only terrestrial eco-system fluxes are estimated

3D-var
x: CO_2 initial conditions
$[\mathbf{S}_a]_{ii}$ = 50%
$\mathbf{S}_n$ = Observational error from ACOS. No transport error or horizontal correlation error.

4D-var
x: monthly scale factor
$[\mathbf{S}_a]_{ii}$ = 10% and 50%
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