The Global Carbon Cycle as Seen by the Atmosphere

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

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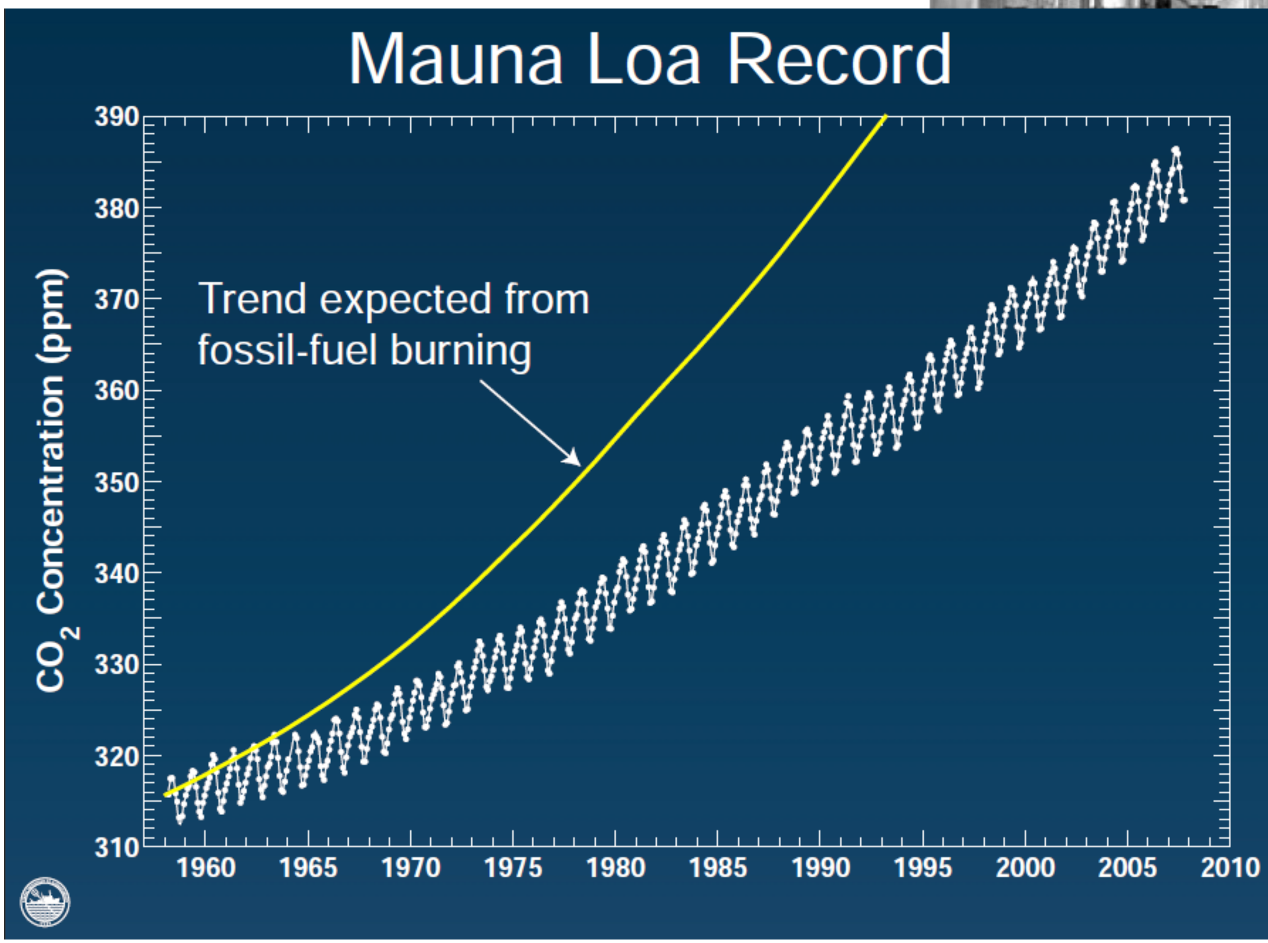
ASP Colloquium on Carbon-climate Connections in the Earth System

Carbon cycle science as a field began with the careful observational work of Dave Keeling



Atmospheric CO_2 "Features"

- Long-term trends
- Interannual variations
- Seasonal cycle
- Spatial gradients
- Synoptic variations
- Diurnal cycle

Keeling, C.D., Rewards and penalties of monitoring the earth, *Annu. Rev. Energy Environ.*, 23, 25-82, 1998.

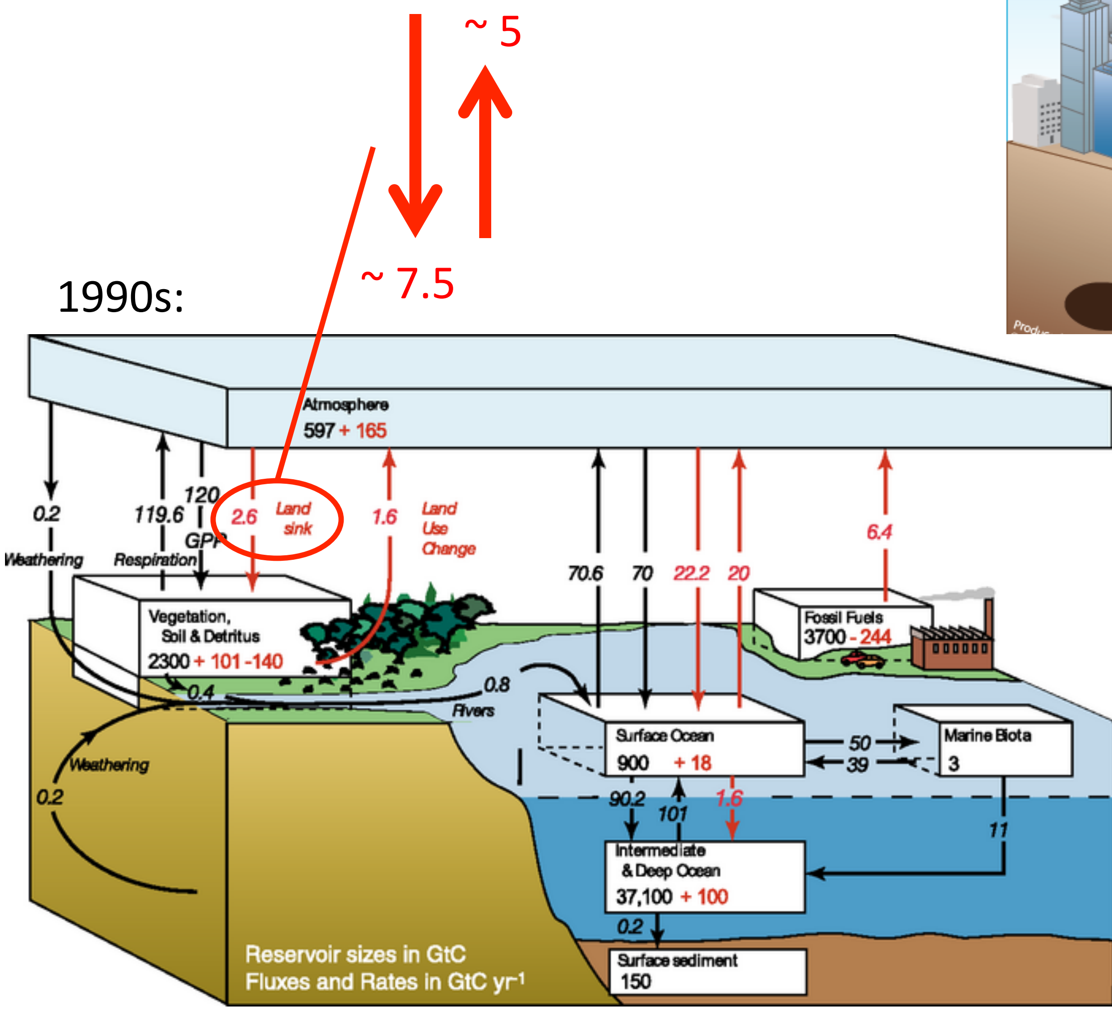
Outline

1. Global carbon budget
2. Atmospheric CO_2 measurements
3. Latitudinal distribution of fluxes
4. Interannual variability
5. Long-term transitions
6. Seasonal cycle
7. The model-observation divide

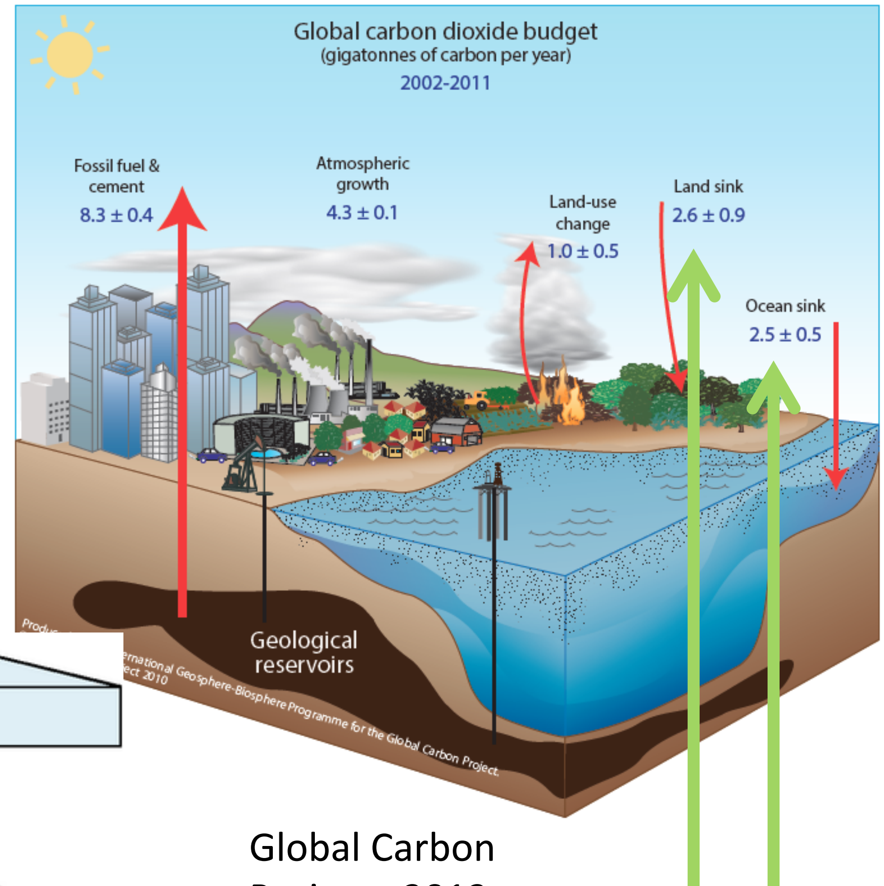
1. The Global Carbon Budget

Annual land flux is the difference between larger seasonal fluxes which themselves are residuals of much larger gross fluxes. The atmosphere is a great integrator.

1990s:

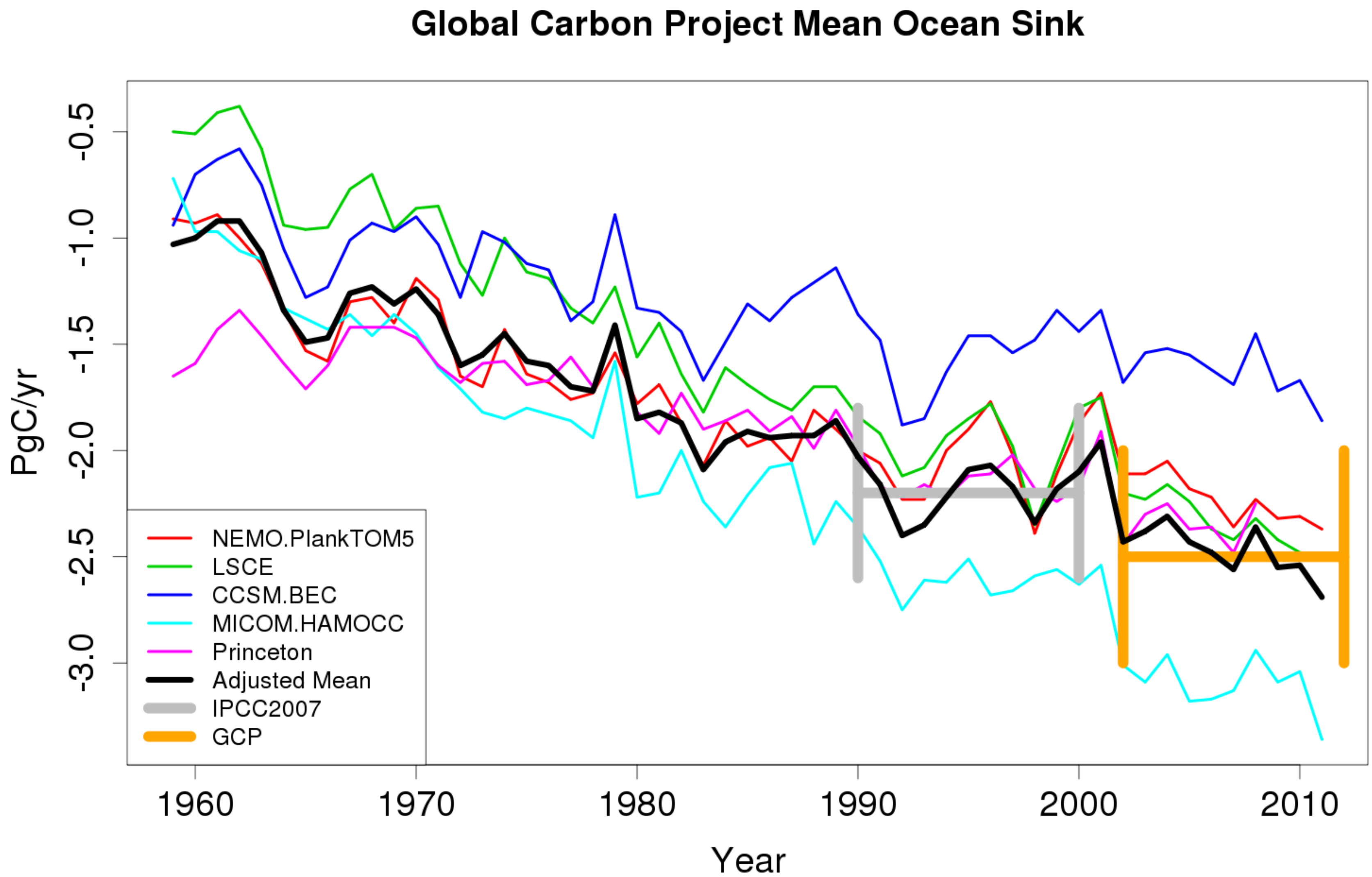


IPCC, 2007



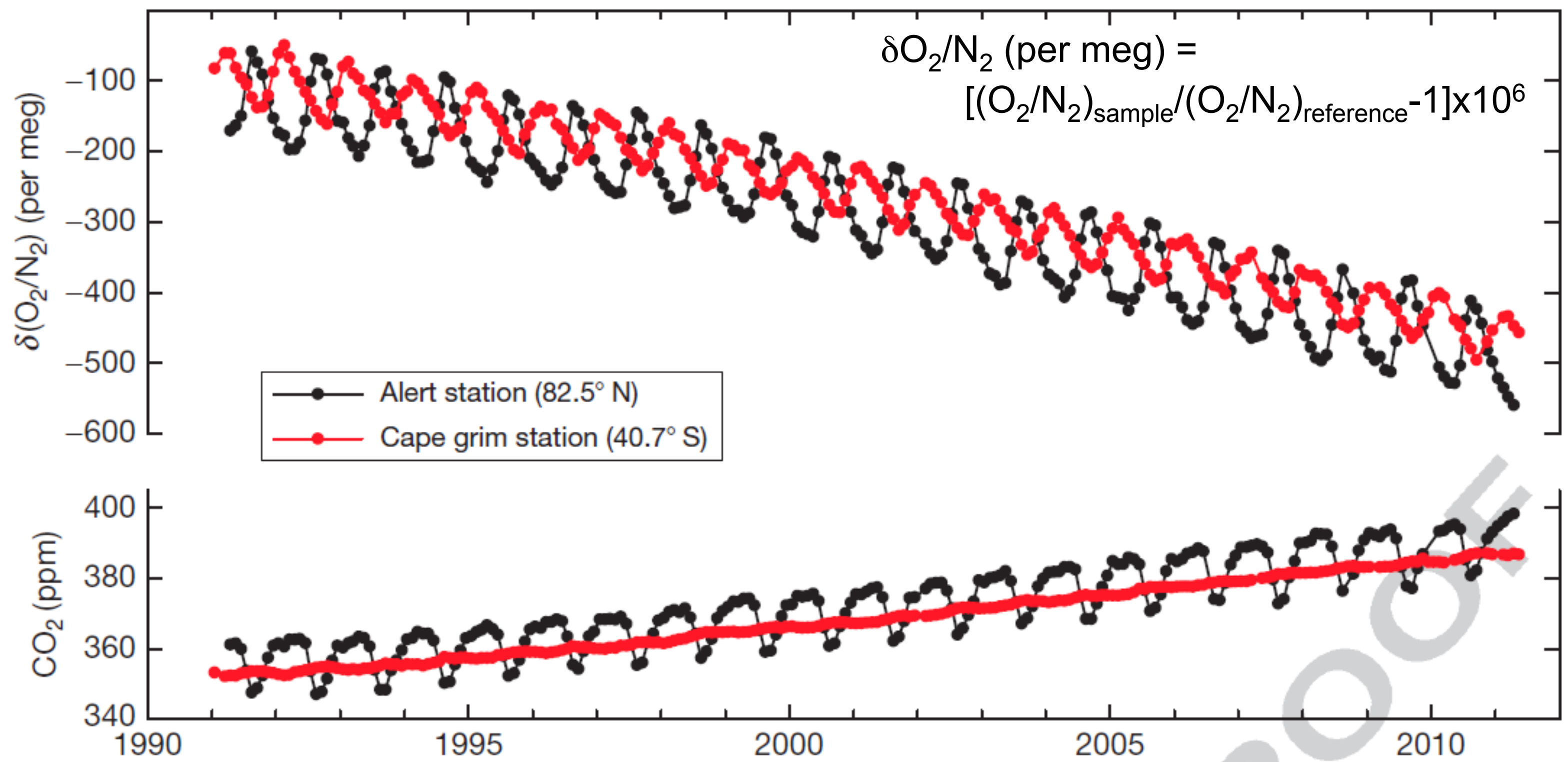
Global Carbon Project, 2012

Where do these numbers come from?



Data from Le Quéré et al., ESSD-D, 2013 supplement

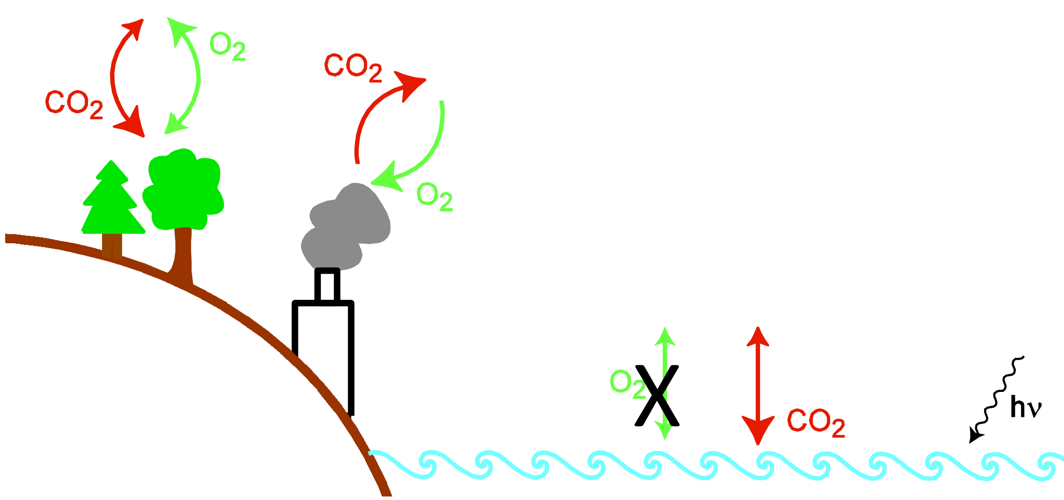
IPCC2007 numbers come from 3 methods: atmospheric O_2, ocean CFC, ocean inversion



Studies of Recent Changes in Atmospheric O_2 Content

RF Keeling, Scripps Institution of Oceanography, UCSD, La Jolla, CA, USA
AC Manning, University of East Anglia, Norwich, UK

Treatise in Geochemistry 2nd Edition

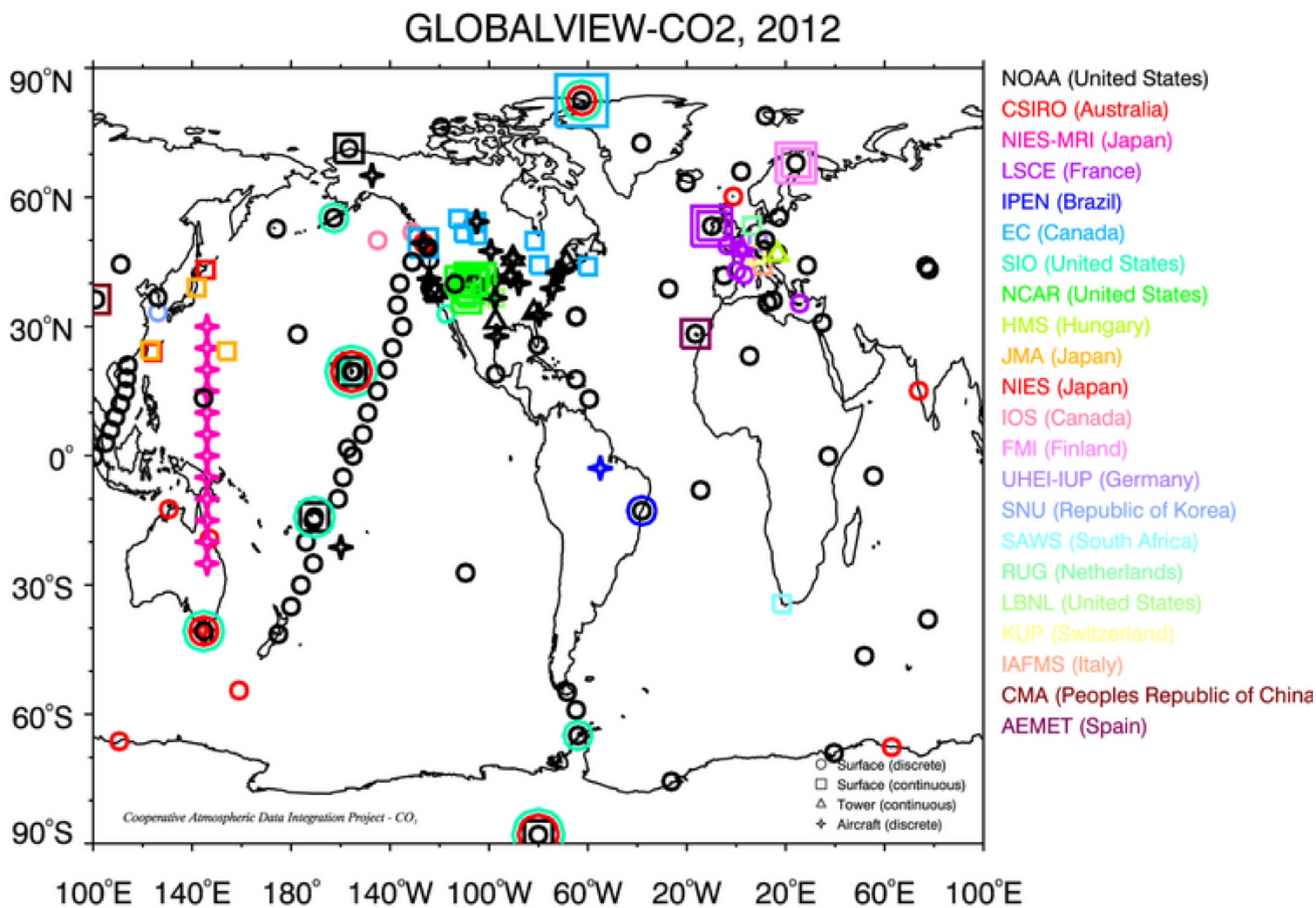


$$\Delta C = F + B + O$$

$$\Delta O = \alpha_f F + \alpha_b B$$

CO_2 is increasing more slowly than O_2 is decreasing because of net ocean sink

2. Atmospheric CO_2 Measurements

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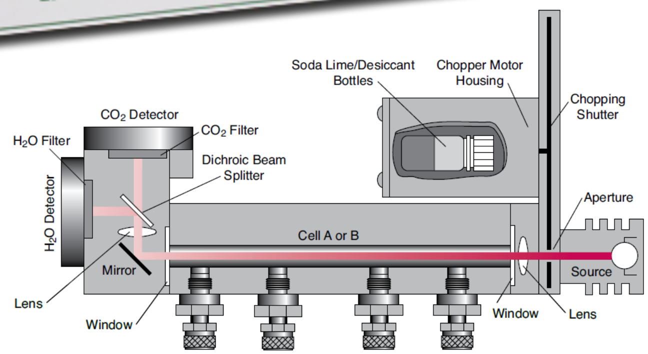
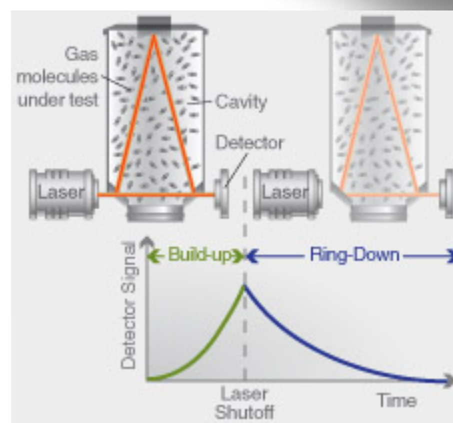
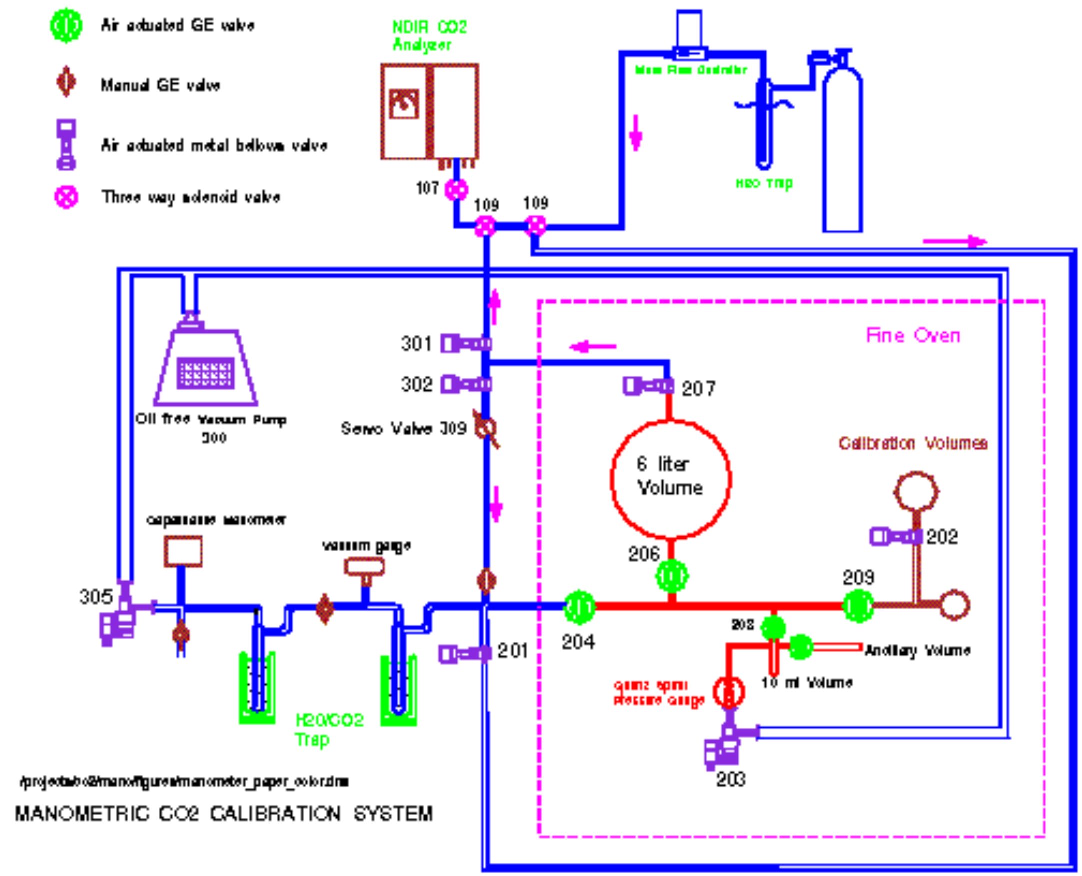




Cavity-enhanced laser aborption spectroscopy

Absolute Measurement Techniques: Manometric and Gravimetric

NOAA/CMDL Manometer:



Reproducibility of 0.03 ppm for *dry mole fraction of* CO_2

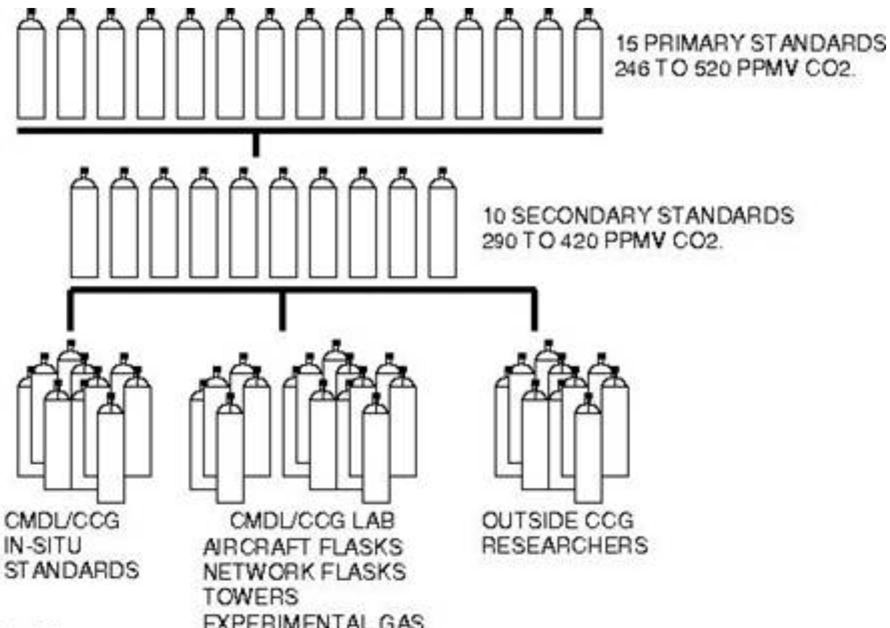
(C. Zhao *et al.*, 1997)

Relative measurements require calibration gases tied to a common scale

NOAA/CMDL scheme for propagation of WMO CO_2 scale:

For NDIR, generally 4 points needed for 0.1 ppm comparability

Recalibration needed ~ every 3 years due to possible drift



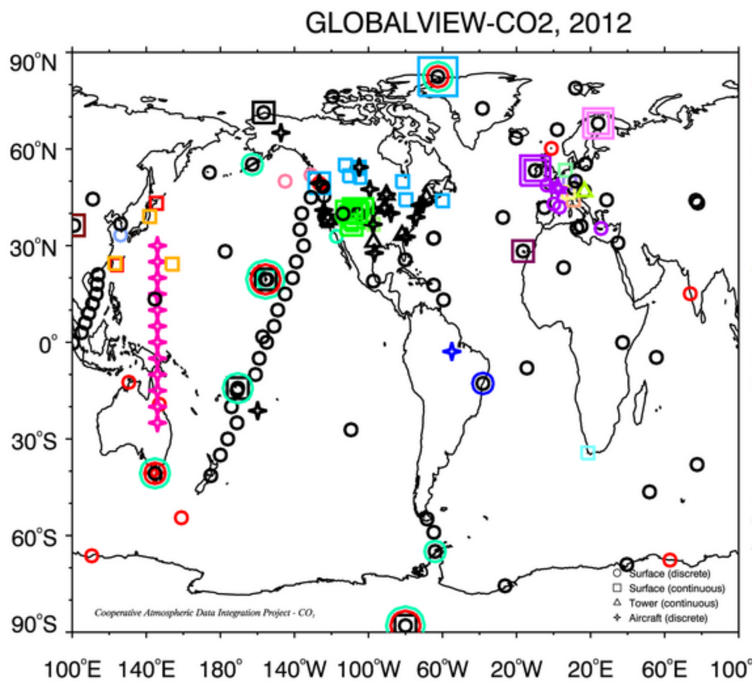
For CO2:
CALIBRATION PRECISION; 0.014 µmol/mol [1 sd of calibrations < 6 months apart].
precision for < 325 approx. 0.1
precision for > 425 approx. 0.25

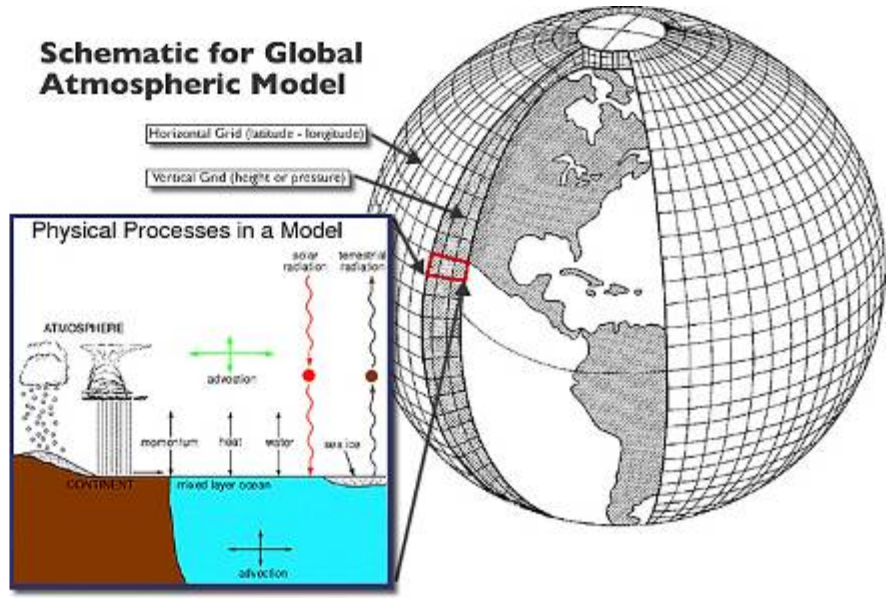
Absolute Uncertainty; 0.1 µmol/mol
Internal consistency [325-425 µmol/mol]; 0.04 µmol/mol [2 sigma] [< 2 years]

Figure 4. Primary standards are used to calibrate a smaller secondary set which in turn is used as reference for all other concentrations. A subset of the secondaries is used to bracket the standards to be calibrated.

Global atmospheric inverse models and surface data can be used to make regional flux estimates

Forward: **Flux + Transport = [CO_2]**

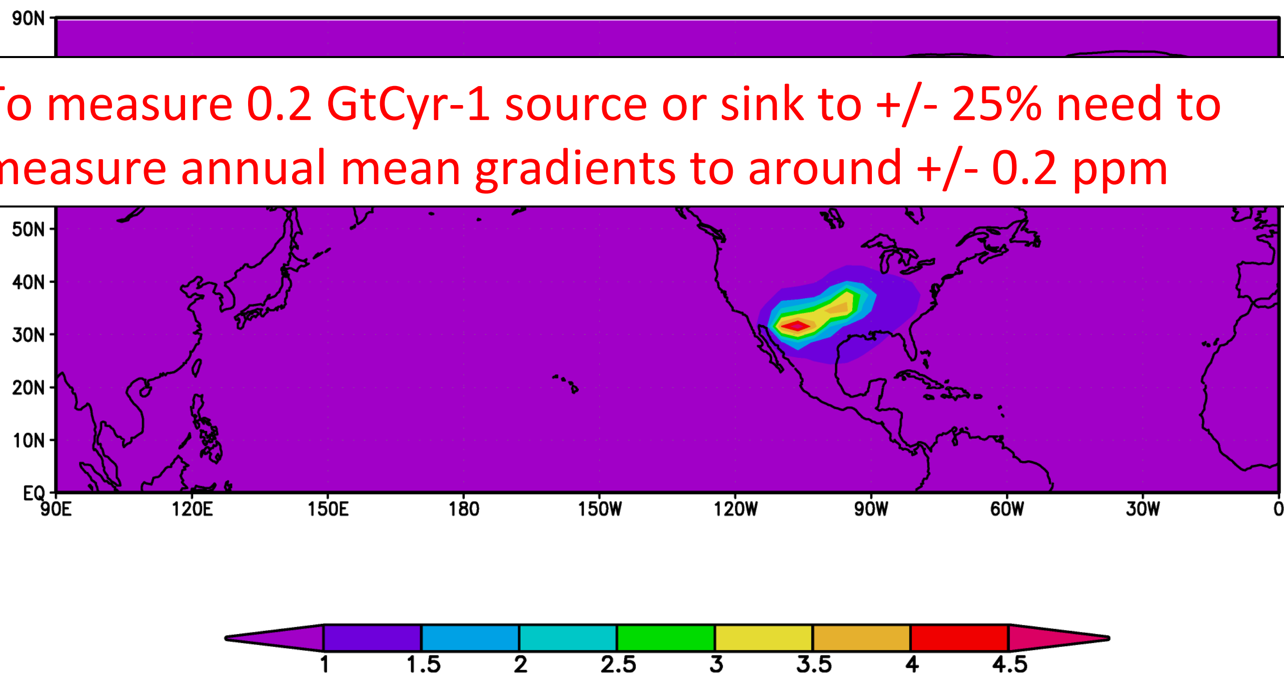




Inverse: **[CO_2] – Transport = Flux**

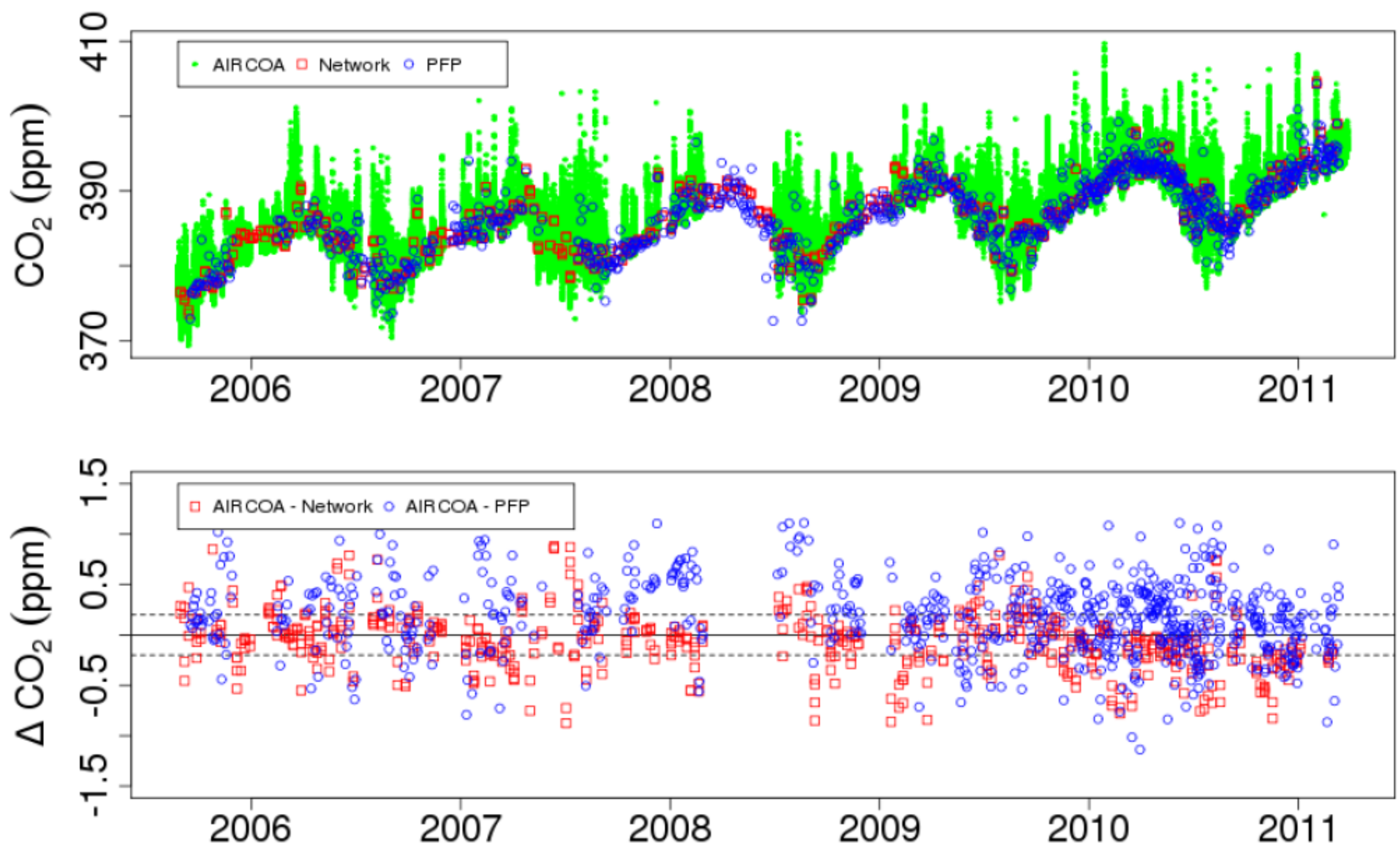
Using high frequency data makes signals bigger, but the annual-mean signals are still very small:

To measure 0.2 GtCyr-1 source or sink to +/- 25% need to measure annual mean gradients to around +/- 0.2 ppm



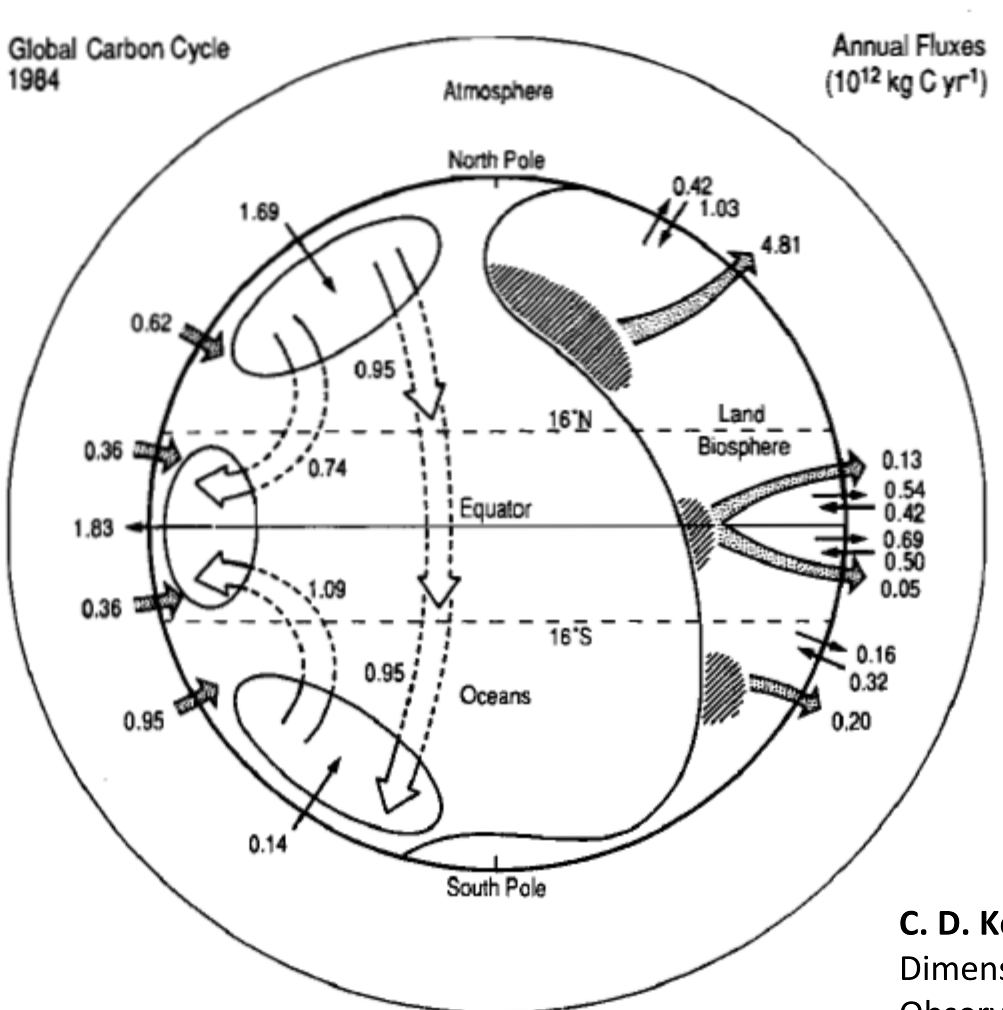
Flux footprint, in ppm($GtCyr^{-1}$)$^{-1}$, for a 10^6 km^2 chaparral region in the U.S. Southwest (Gloor et al., 1999).

Intra- and Inter-laboratory agreement still not better than 0.2 ppm



NCAR and NOAA measurements from Niwot Ridge, CO (Stephens et al., AMT, 2011)

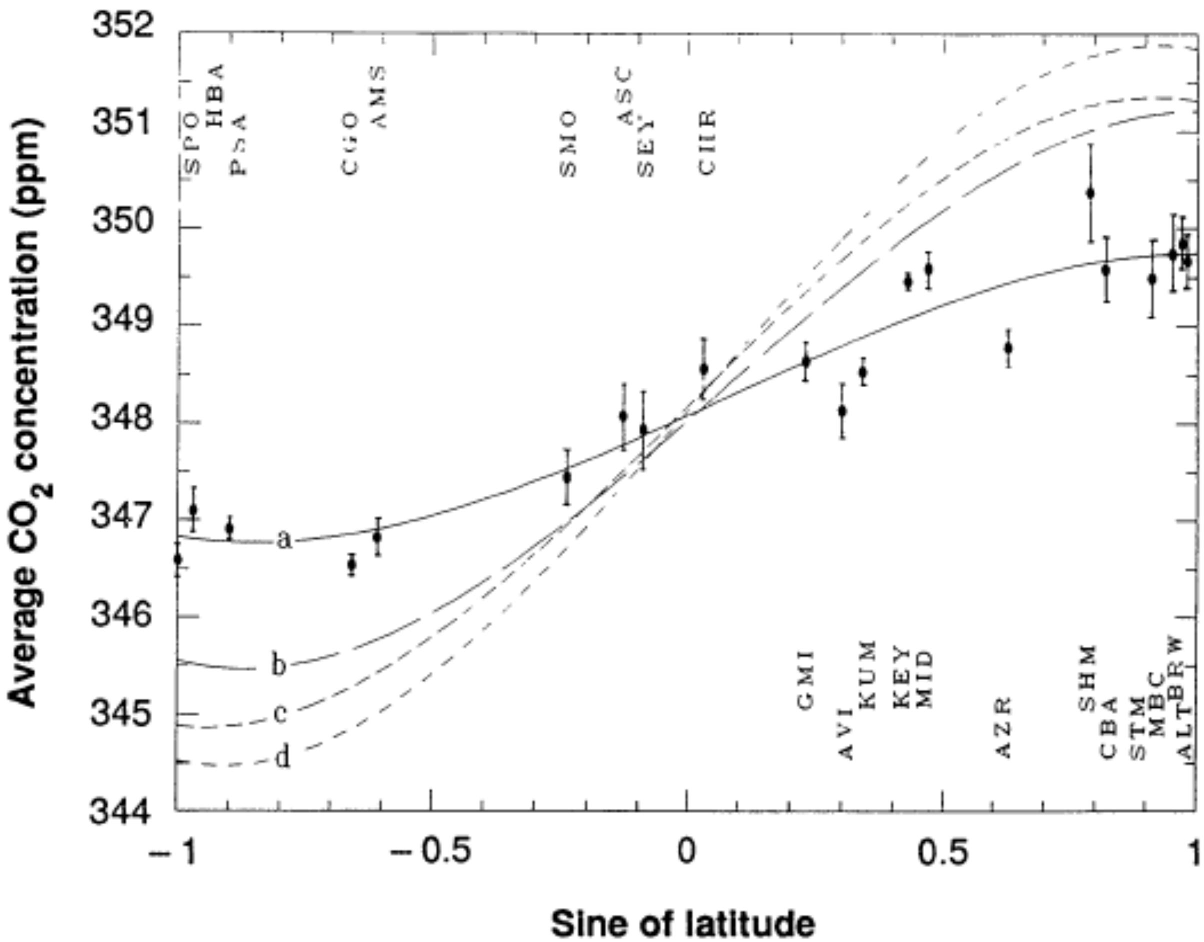
3. Latitudinal distribution of fluxes



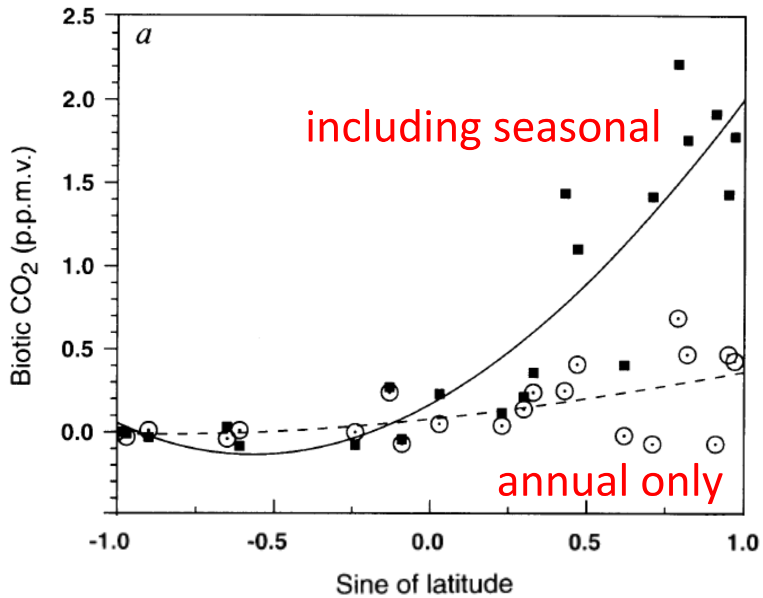
An early 3-D atmospheric inversion gave 1.7 PgC/yr into northern oceans and only 0.6 PgC/yr into northern land for 1984

C. D. Keeling, S. C. Piper, and M. Heimann, A Three Dimensional Model of Atmosperhic CO_2 Transport Based on Observed Winds: 4. Mean Annual Gradients and Interannual Variations, in *Aspects of Climate Variability in the Pacific and the Western Americas*, edited by D. H. Peterson, American Geophysical Union, Washington, D.C., pp. 305-363, 1989.

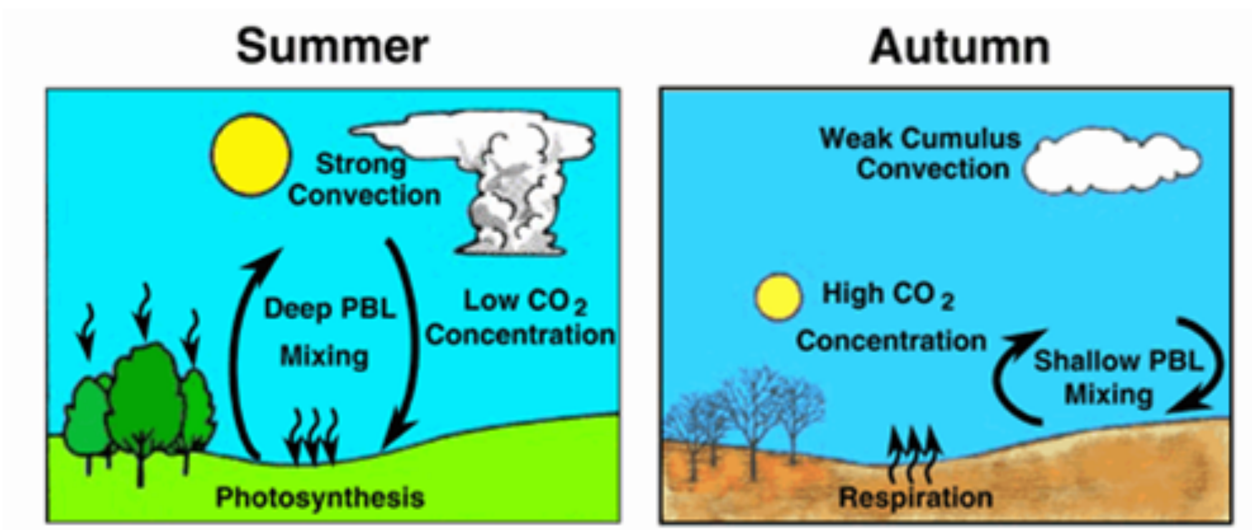
Global pCO_2 data set implies a northern land sink of 2.0-3.4 PgC/yr for 1981-1987



Tans, Fung, Takahashi, Science, 1990



Seasonal covariance between fluxes and transport imply an even larger sink in northern mid-high latitudes



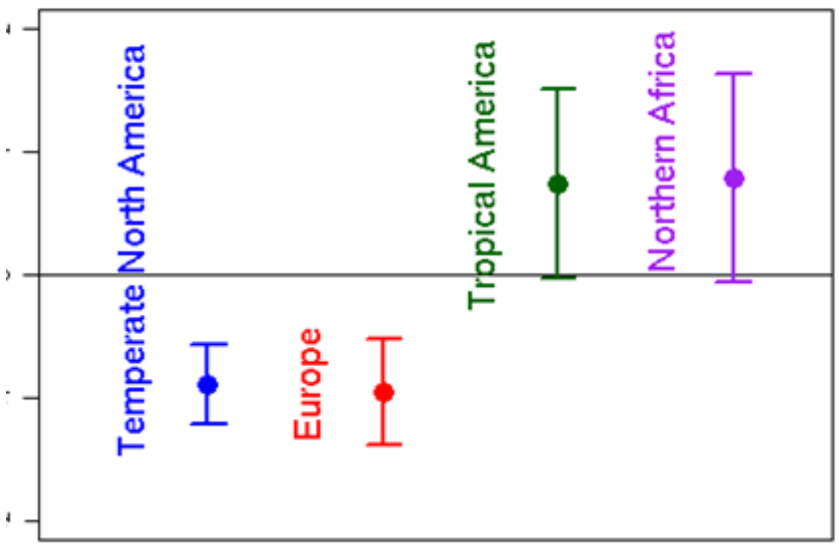
Denning et al., Nature, 1995

TransCom3 Atmospheric Inverse Model Intercomparison Study

All model average and standard deviations:

Northern Land = -2.4 ± 1.1 $PgCyr^{-1}$

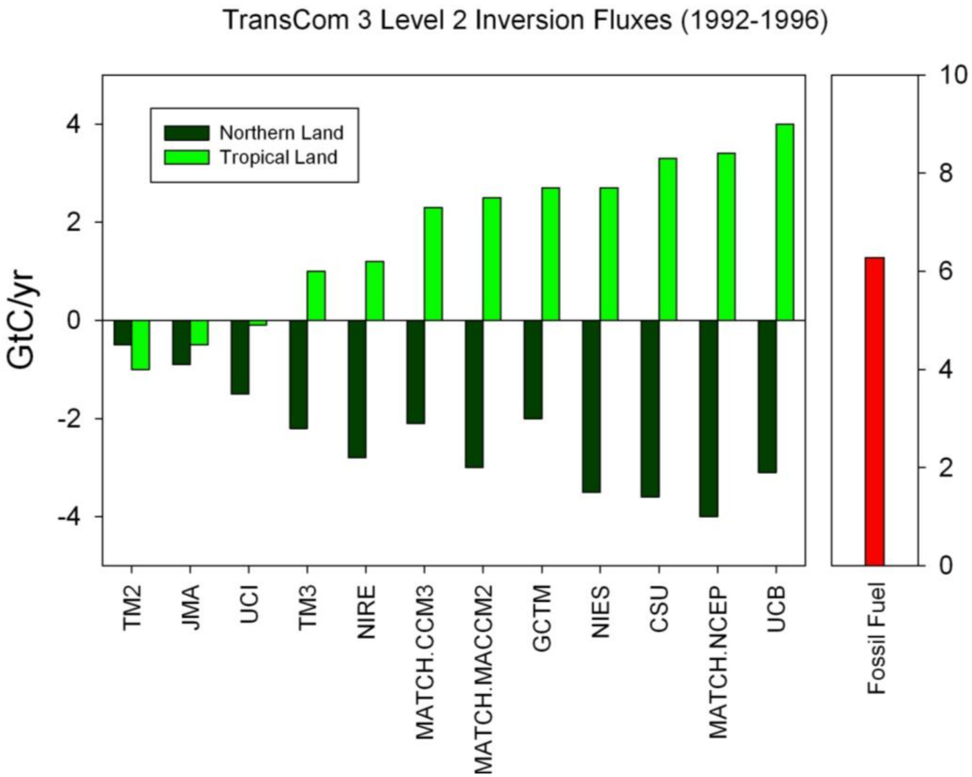
Tropical Land = +1.8 ± 1.7 $PgCyr^{-1}$

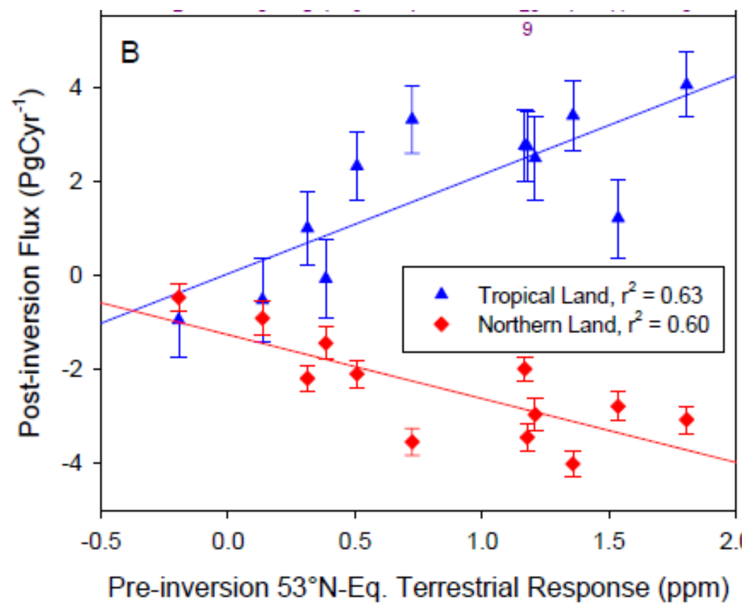


"For most regions, the between-model uncertainties are of similar or smaller magnitude than the within-model uncertainties. This suggests that the choice of transport model is not the critical determinant of the inferred fluxes."

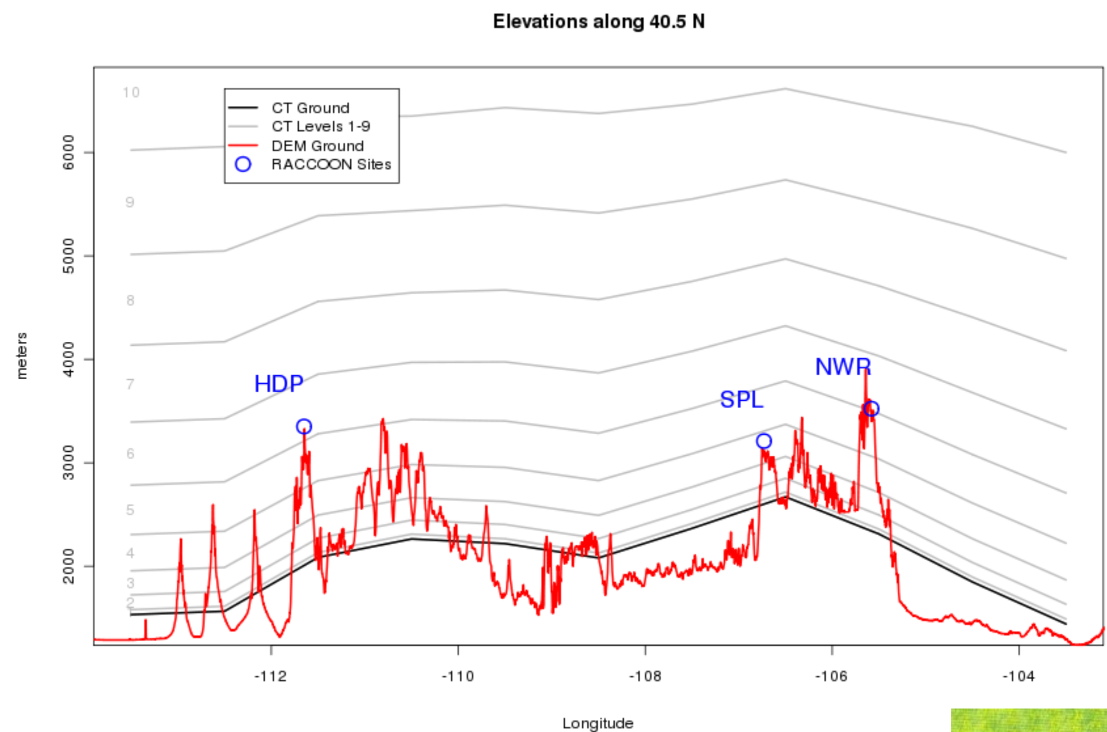
Gurney et al, *Nature*, 2002

But in fact, choice of transport model was the critical determinant of the inferred fluxes





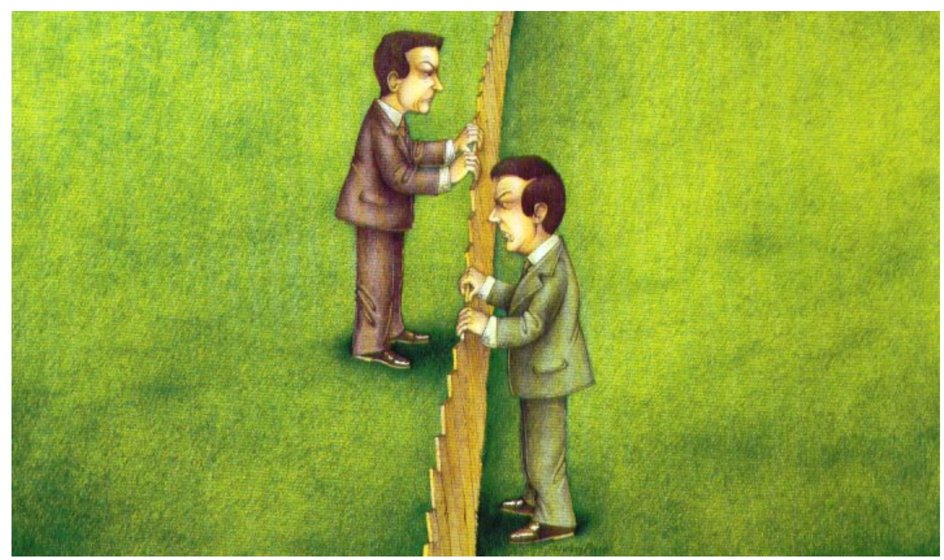
Representativeness



1. Models often don't predict something that can be measured
2. Observations don't measure something that can be predicted
3. A cultural divide

Measurement uncertainty ≈ 0.2 ppm

TransCom3 continental site "Data error" ≈ 2.2 ppm



Model results are also correlated with vertical CO_2 gradients, which can be measured

- 3 models that most closely reproduce the observed annual-mean vertical CO_2 gradients (4, 5, and C):

Northern Land

Tropical Land

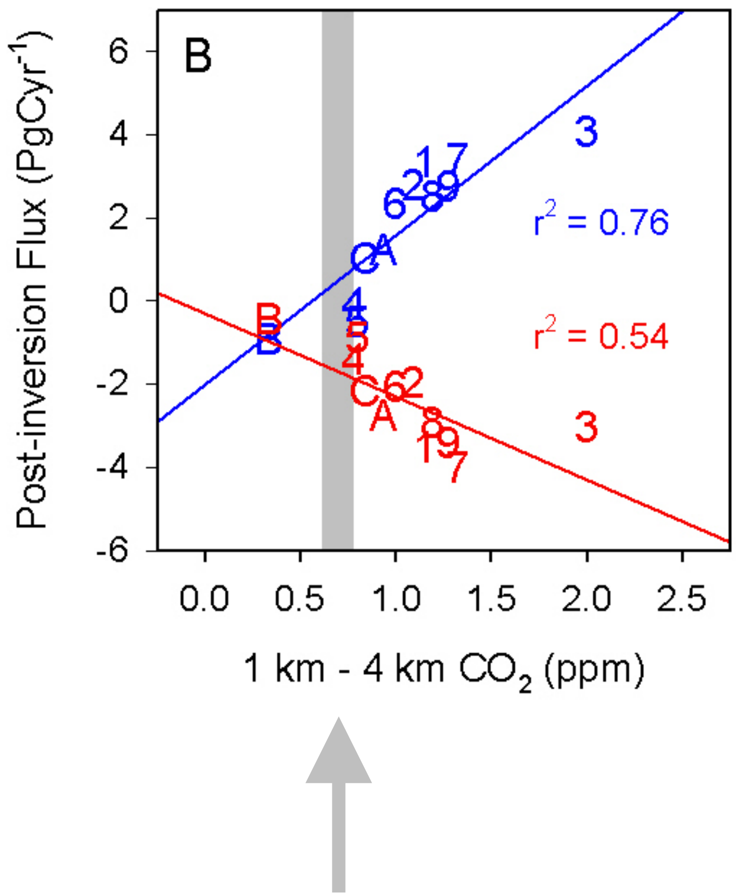
  Northern Land = -1.5 ± 0.6 $PgCyr^{-1}$

  Tropical Land = +0.1 ± 0.8 $PgCyr^{-1}$

- All model average:

  Northern Land = -2.4 ± 1.1 $PgCyr^{-1}$

  Tropical Land = +1.8 ± 1.7 $PgCyr^{-1}$

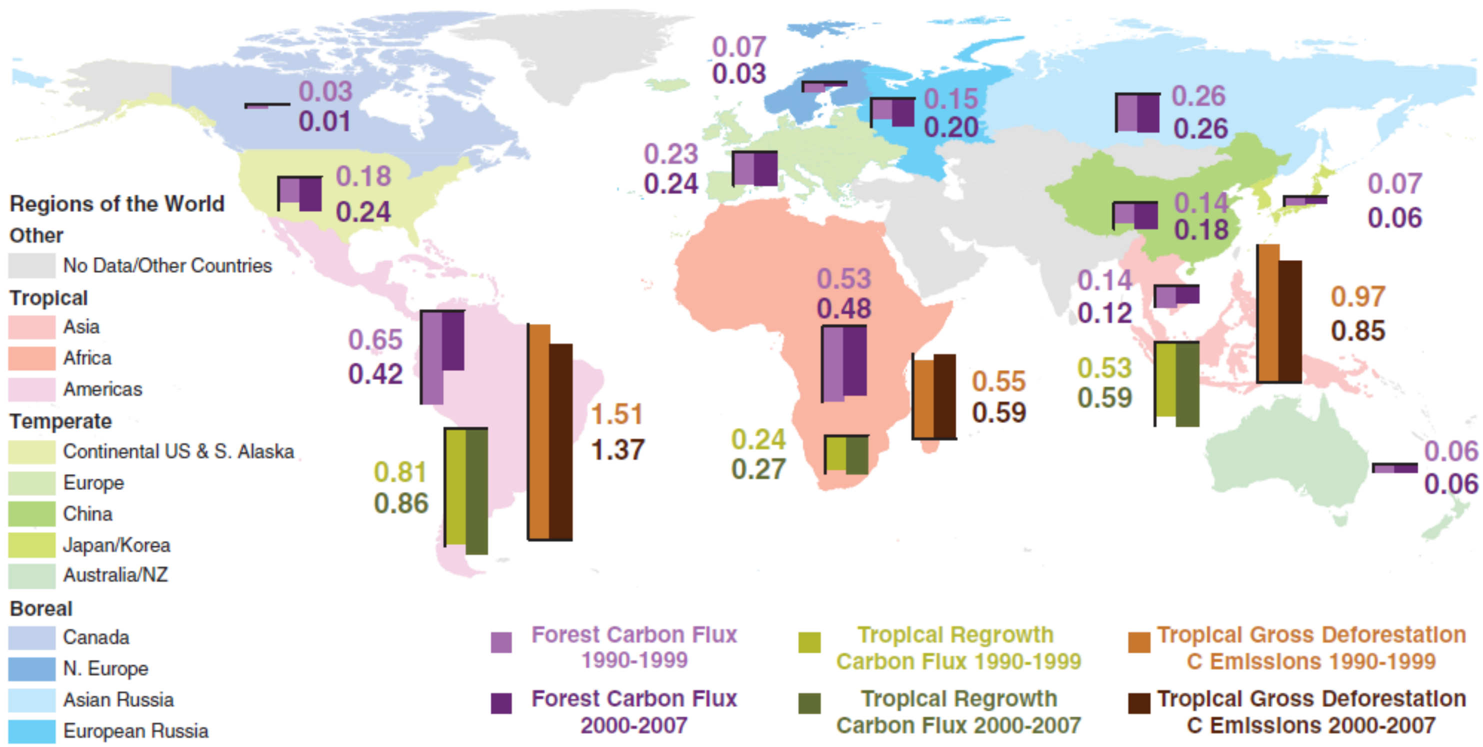


Observed value

Most of the models overestimate the annual-mean vertical CO_2 gradient

Stephens et al., Science, 2007

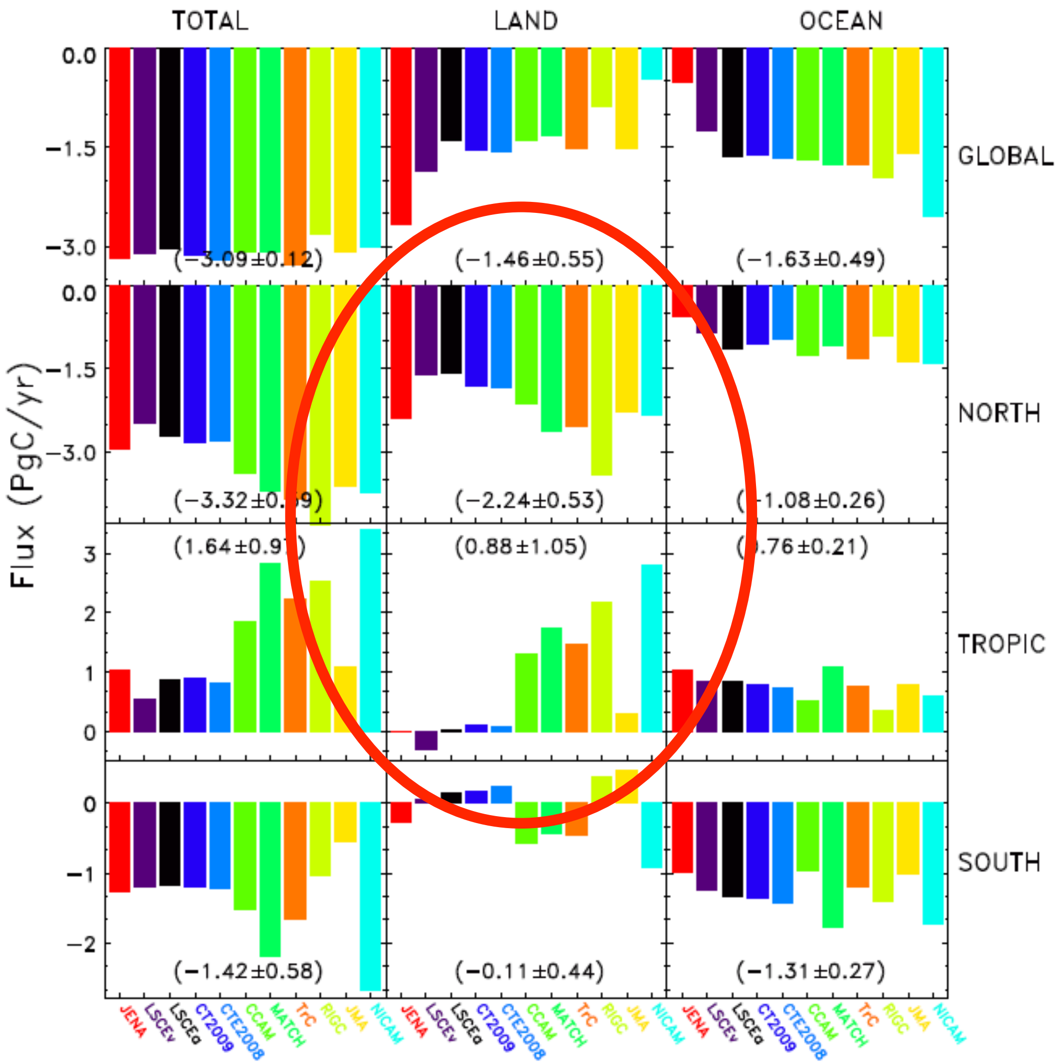
Similar results from bottom up studies



Temperate and boreal forests = -1.2 +/- 0.1
Tropical forests = +0.1 +/- 0.8

Pan et al., Science, 2011

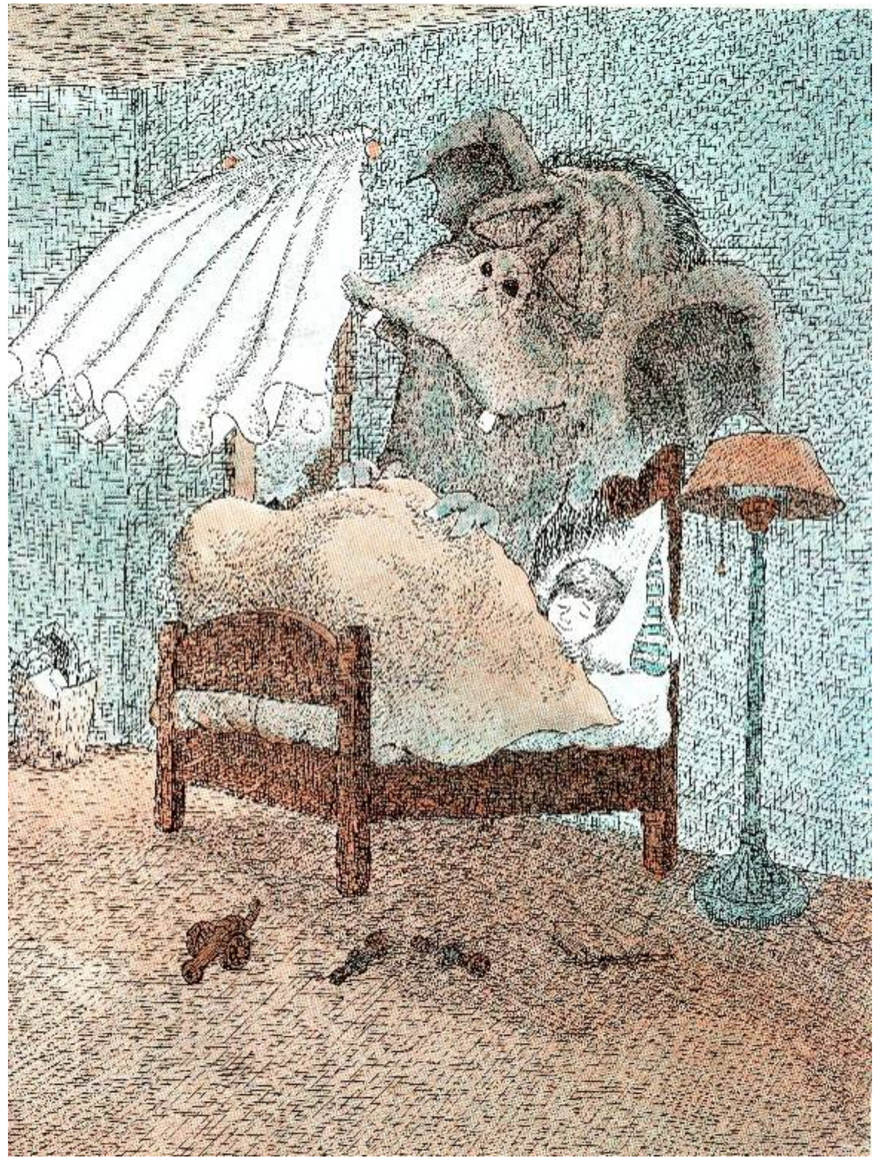
RECCAP Atmospheric Inverse Model Intercomparison Study



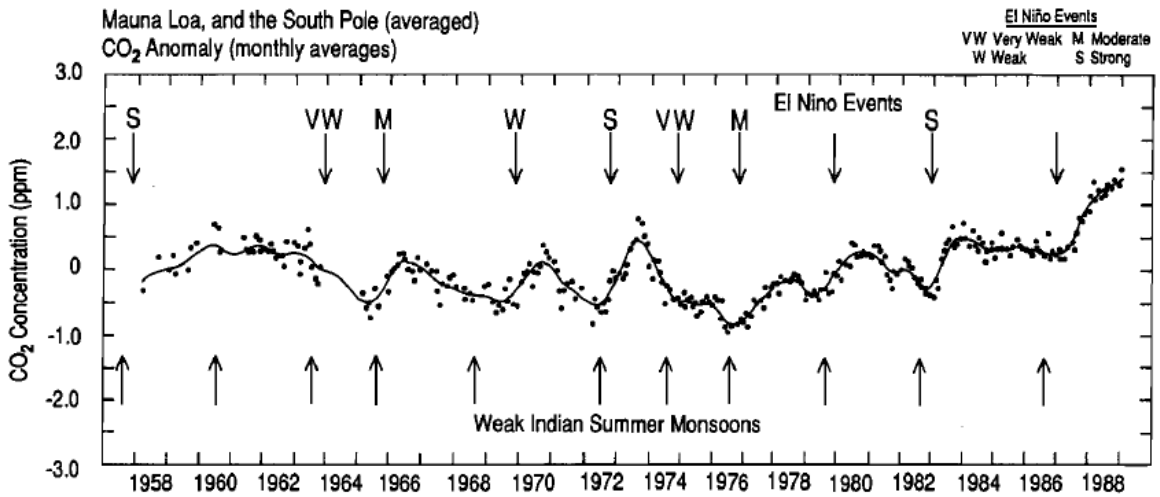
Who should be comparing model results to data and diagnosing intermodel disagreements?

Peylin et al., BGD, 2013

Your choice:

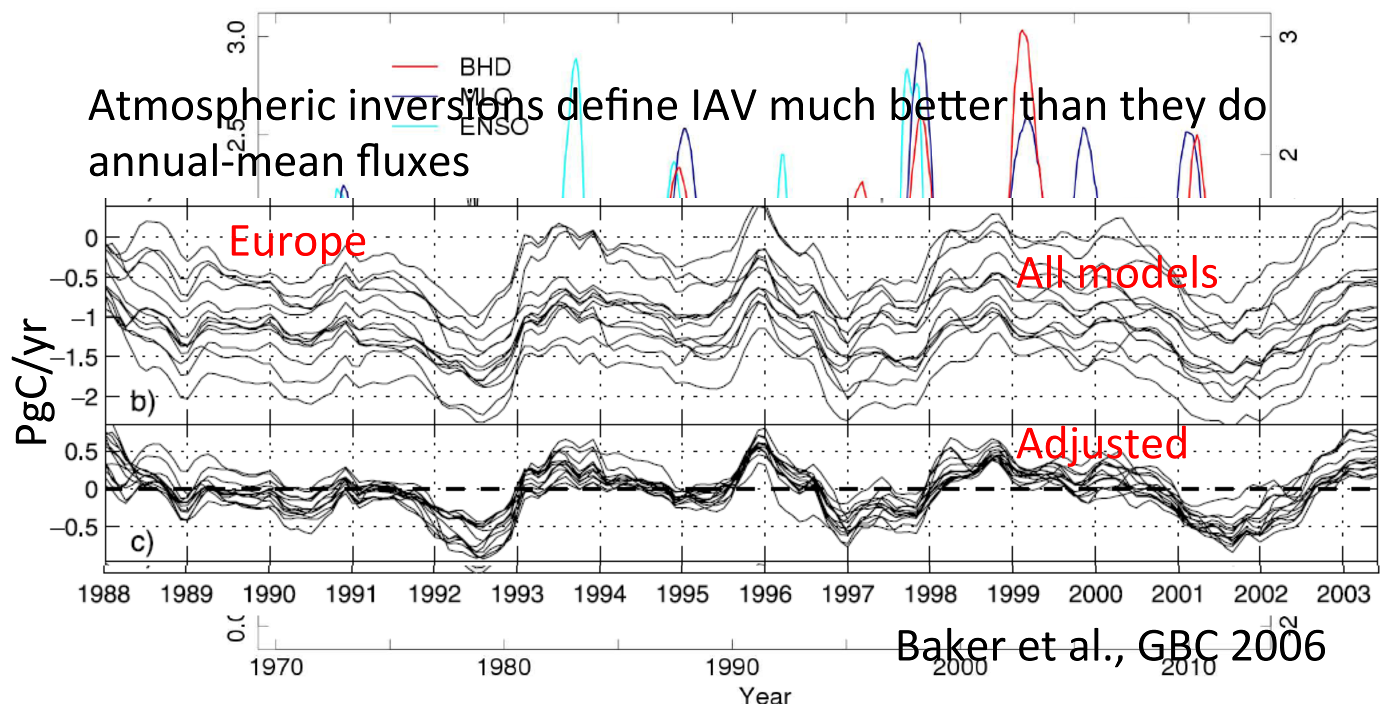


4. Interannual Variability



Bacastow, Nature, 1976
Keeling et al., AGU, 1989

Atmospheric inversions define IAV much better than they do annual-mean fluxes

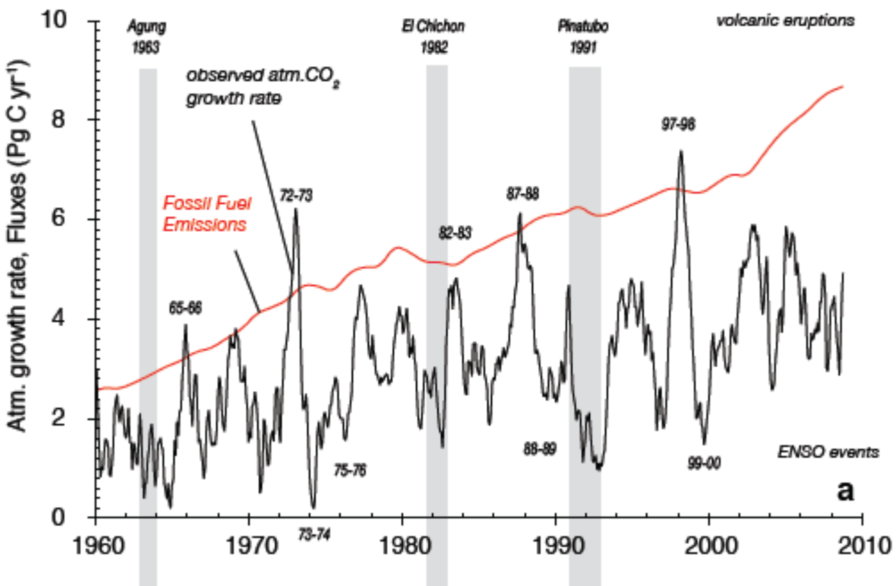


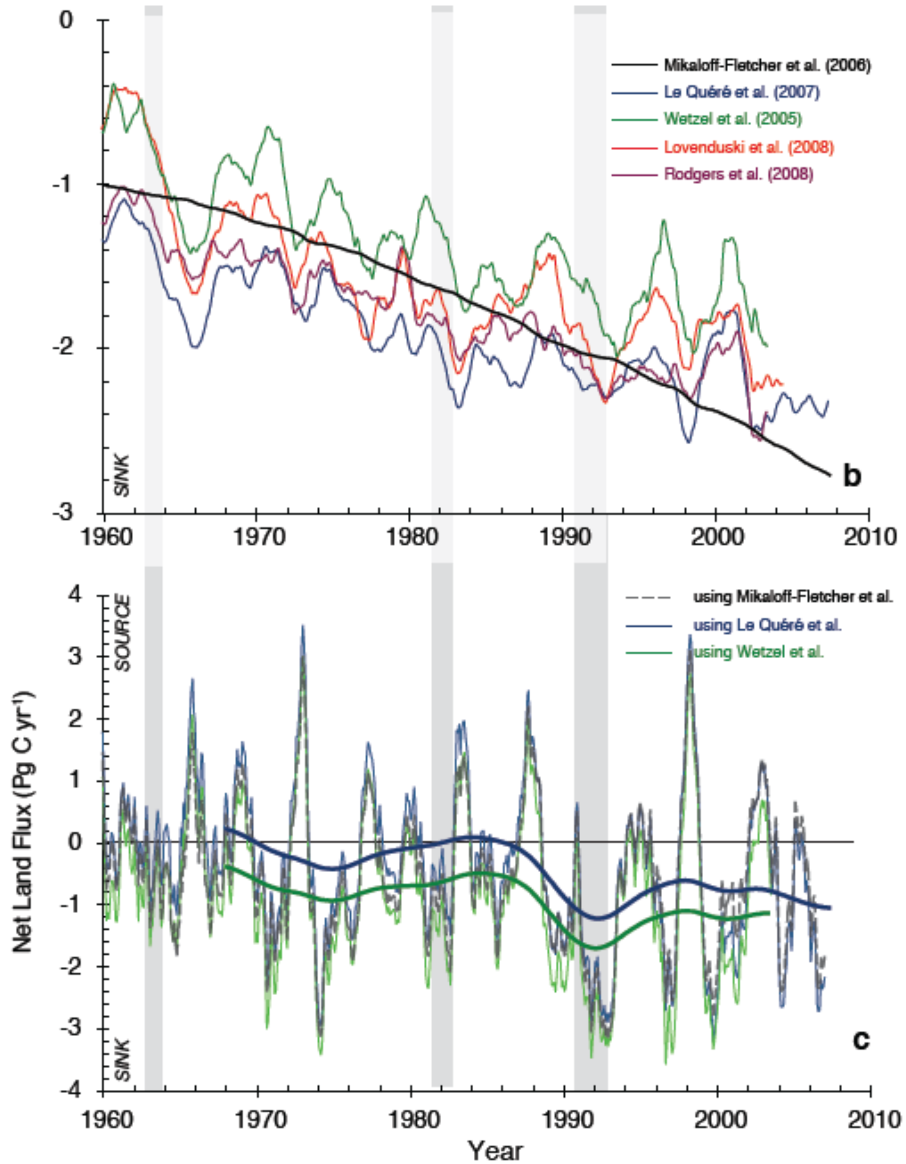
- Temperature
- Precipitation
- Fires
- Volcanoes

Baker et al., GBC 2006

Stephens et al., BG, 2013

5. Long-term transitions



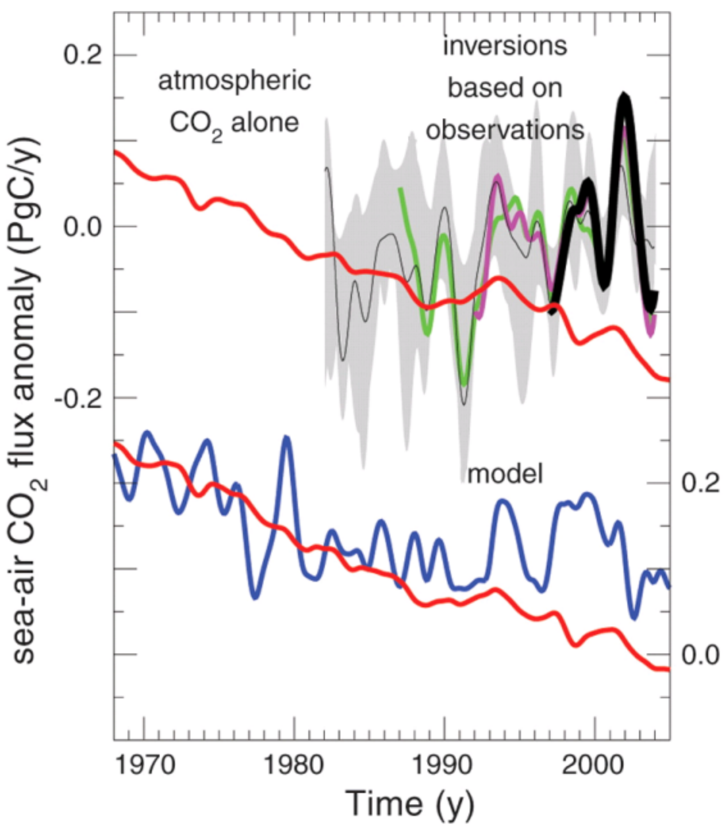


Shift of -1 PgC/yr in land fluxes around 1989?

Sarmiento et al., BG, 2010

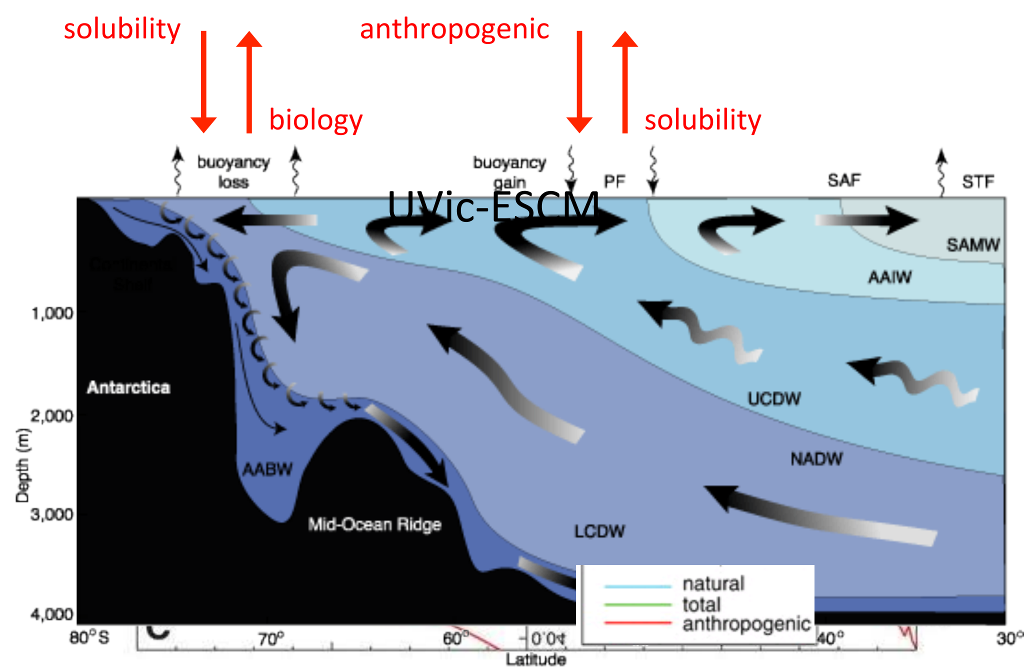
Decrease in the efficiency of Southern Ocean anthropogenic CO_2 uptake?

Atmospheric inversion using TM3 and forward ocean model (ORCA-PISCES-T)



Le Quéré et al., Science 2007

Southern Ocean Air-Sea CO_2 Fluxes

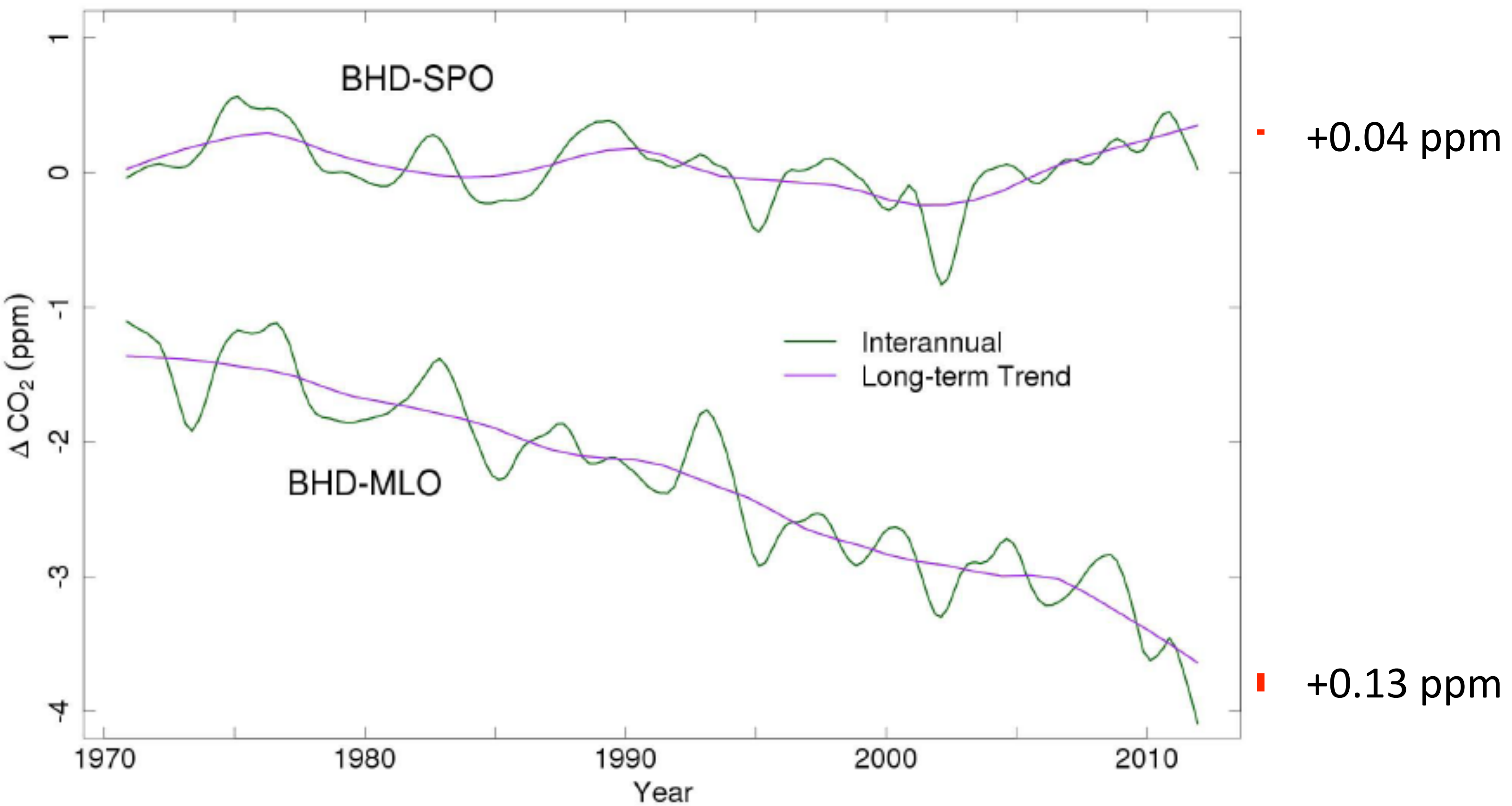


[Speer et al., 2000; provided by the International CLIVAR Project Office]

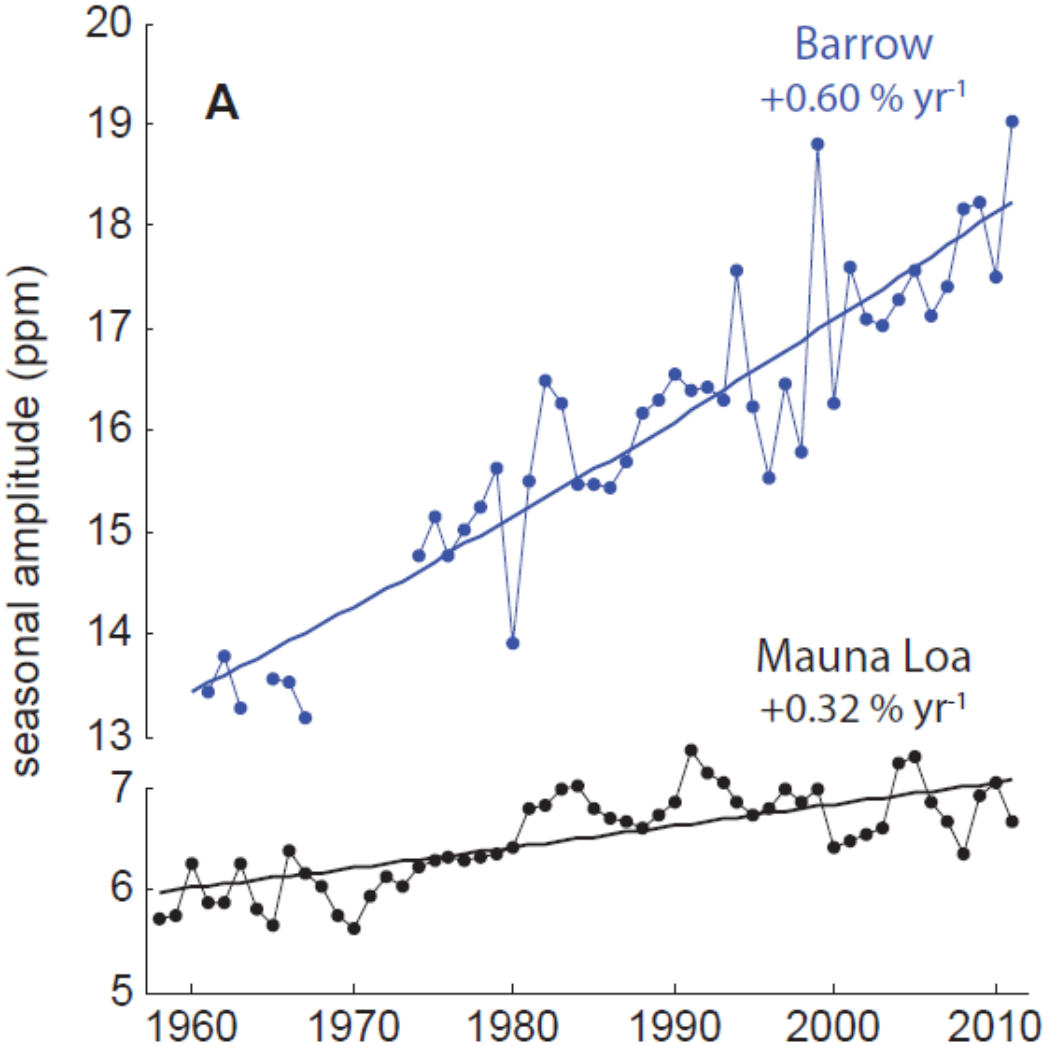
[Zickfeld et al., Science 2008]

Expected changes in atmospheric CO_2 gradients are extremely small

+0.1 PgC/yr change in Southern Ocean sink over 1985–2005



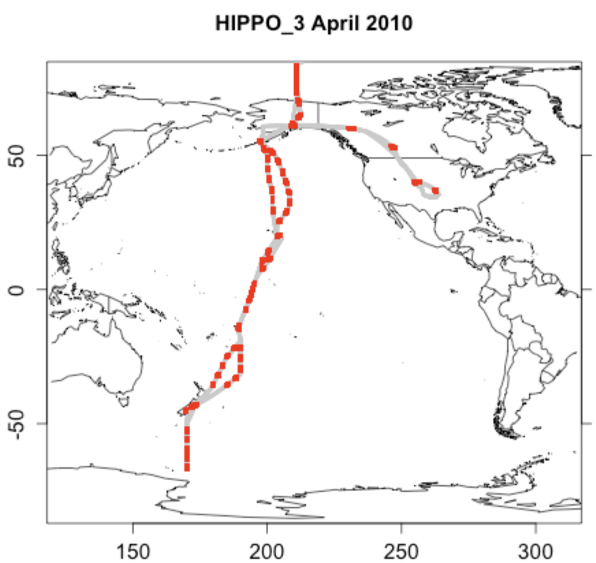
6. Seasonal Cycle

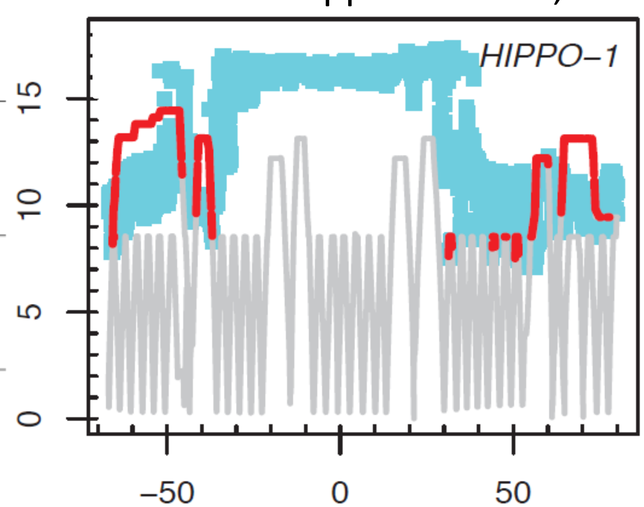


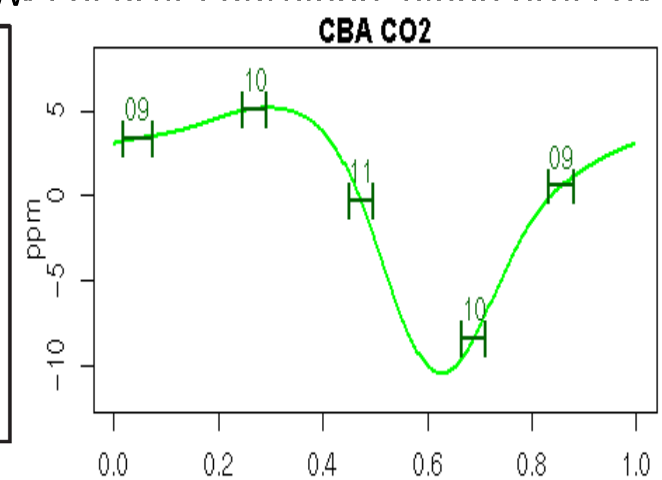
Keeling et al., Nature, 1996 ; Randerson et al., GBC, 1997; Graven et al., accepted to Science, 2013

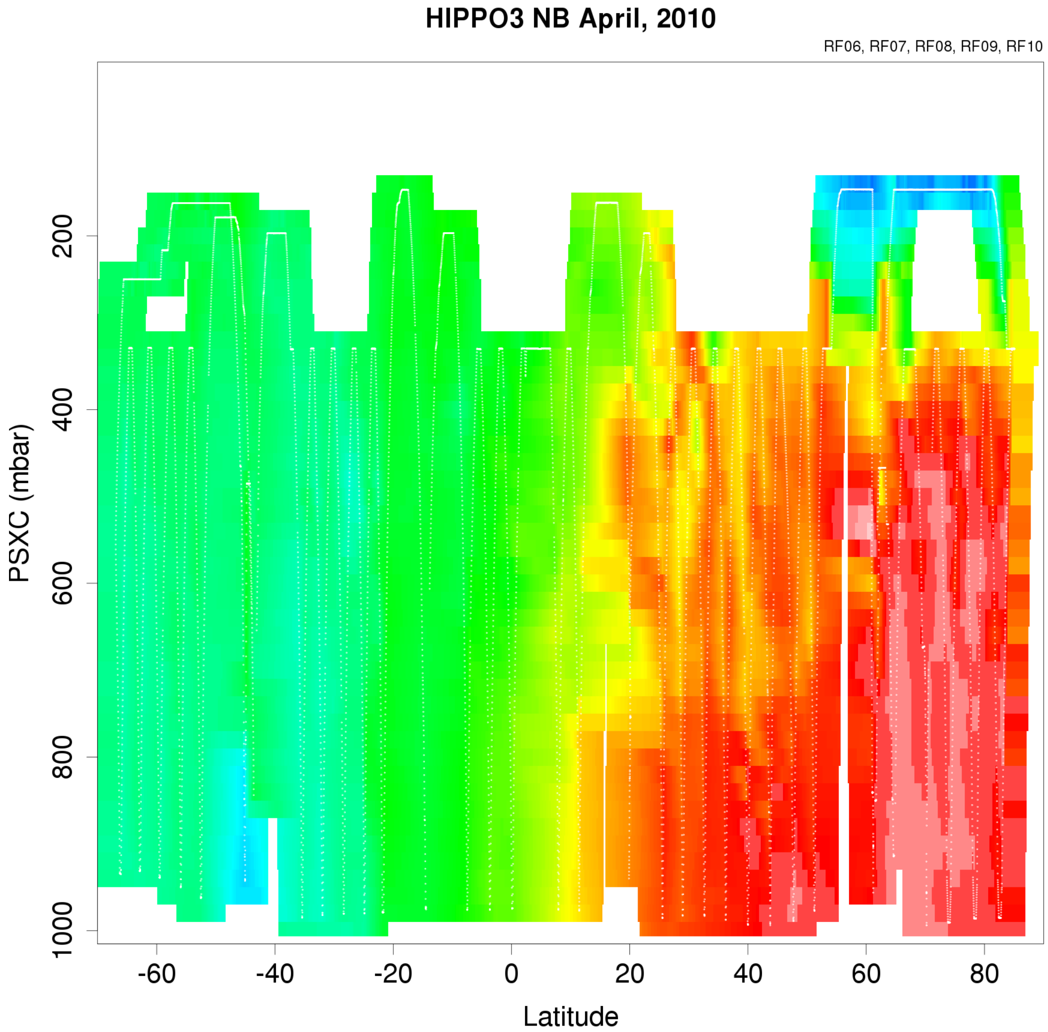
HIAPER
Pole-to-Pole Observations

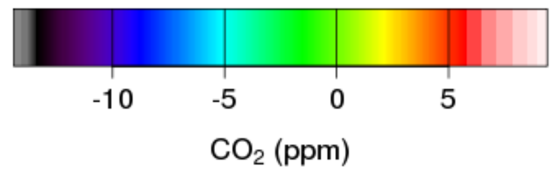
- PIs: Harvard, NCAR, Scripps, NOAA
- Global and seasonal survey of CO_2, O_2, CH_4, CO, N_2O, H_2, SF_6, COS, CFCs, HCFCs, O_3, H_2O, CO_2 isotopes, Ar, black carbon, and hydrocarbons (over 90 species).
- NSF / NCAR Gulfstream V
- Five 3-week campaigns over 3 years, across Pacific between 87 N and 67 S
- Continuous profiling between surface and 10-14 km
- 64 flights, 787 profiles, 434 hours in situ data + 4235 flasks
- hippo.ucar.edu, www.eol.ucar.edu/hippo, hippo.ornl.gov



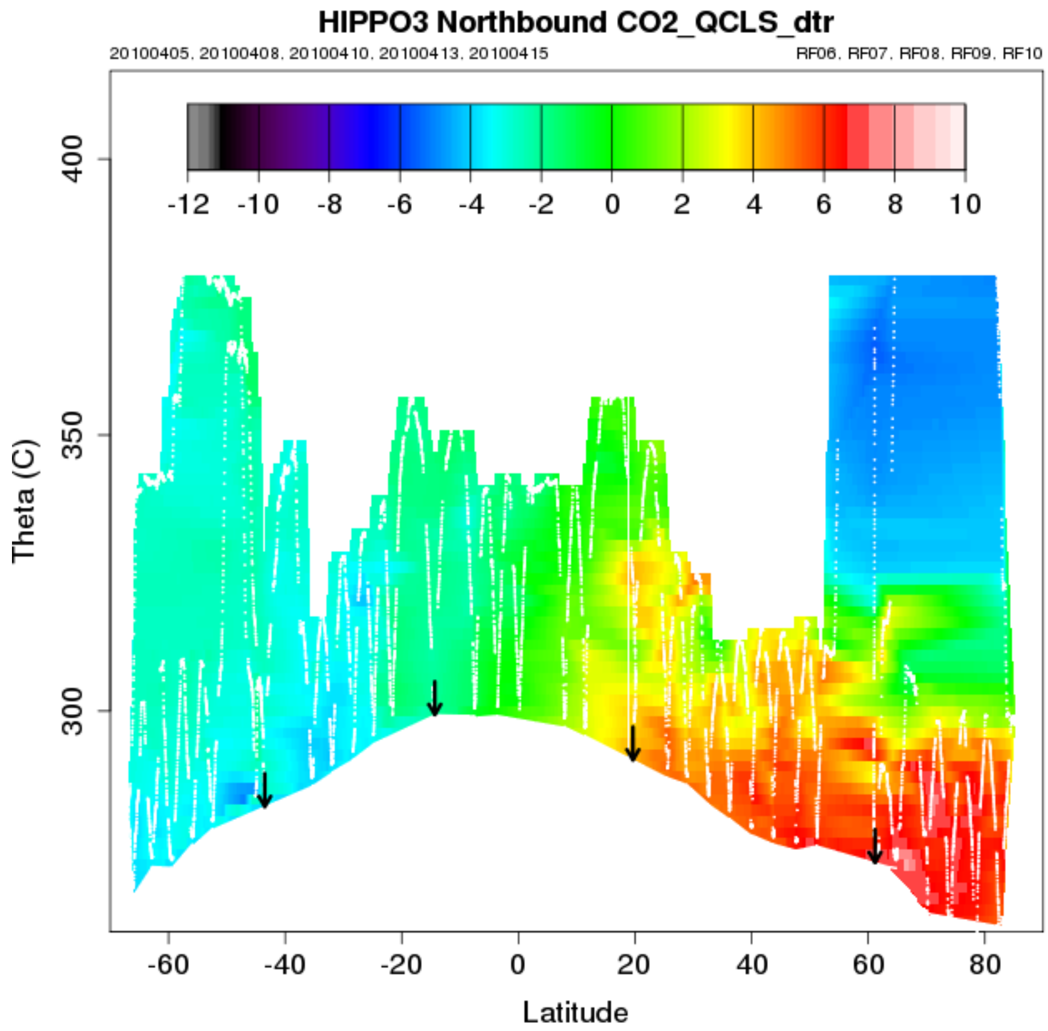








Northern Hemisphere seasonal progression: Jan 2009, Mar 2010, Apr 2010, Jun 2011, Jul 2011, Aug 2011, Sep 2011, Oct 2009, Nov 2009



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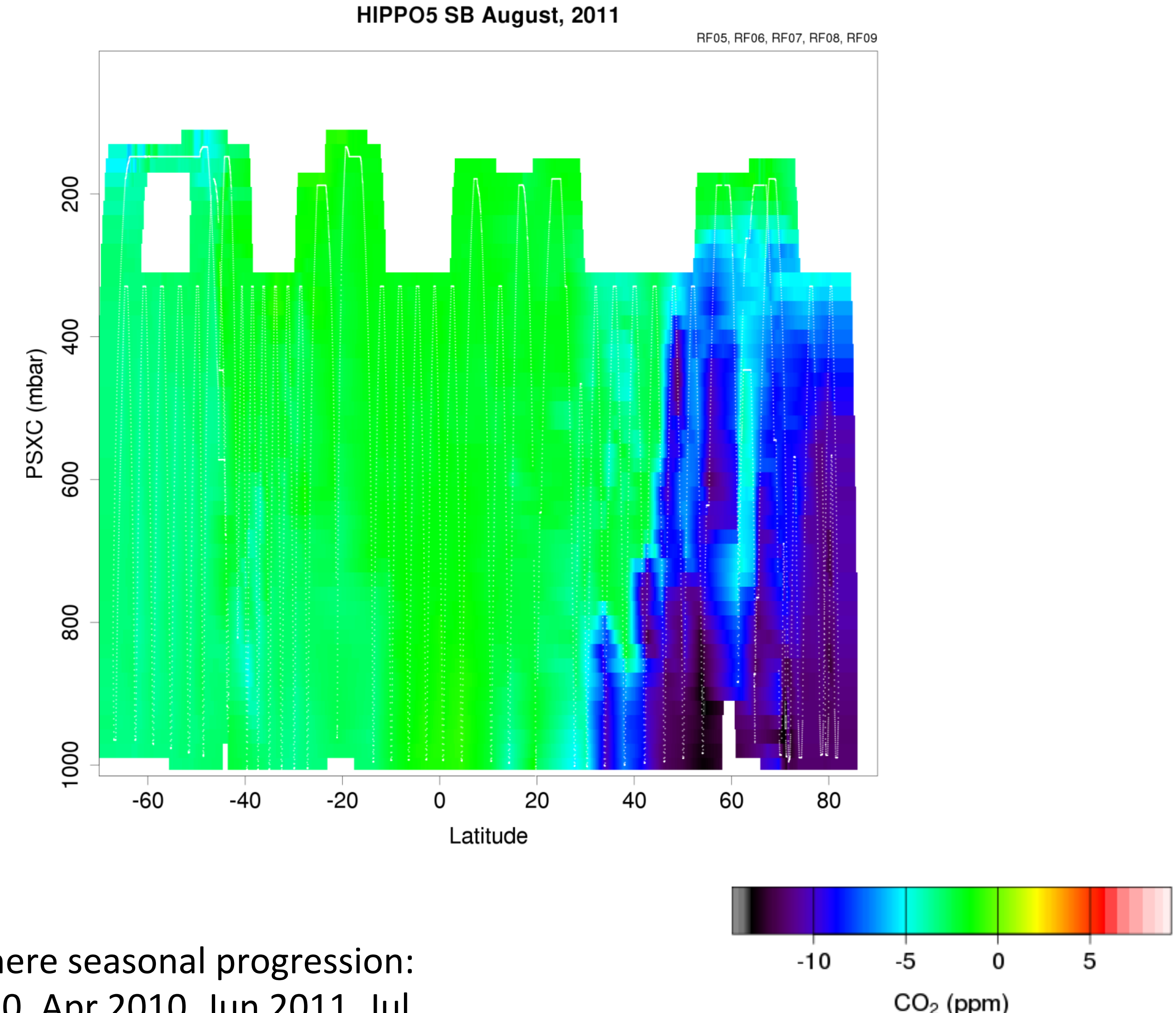

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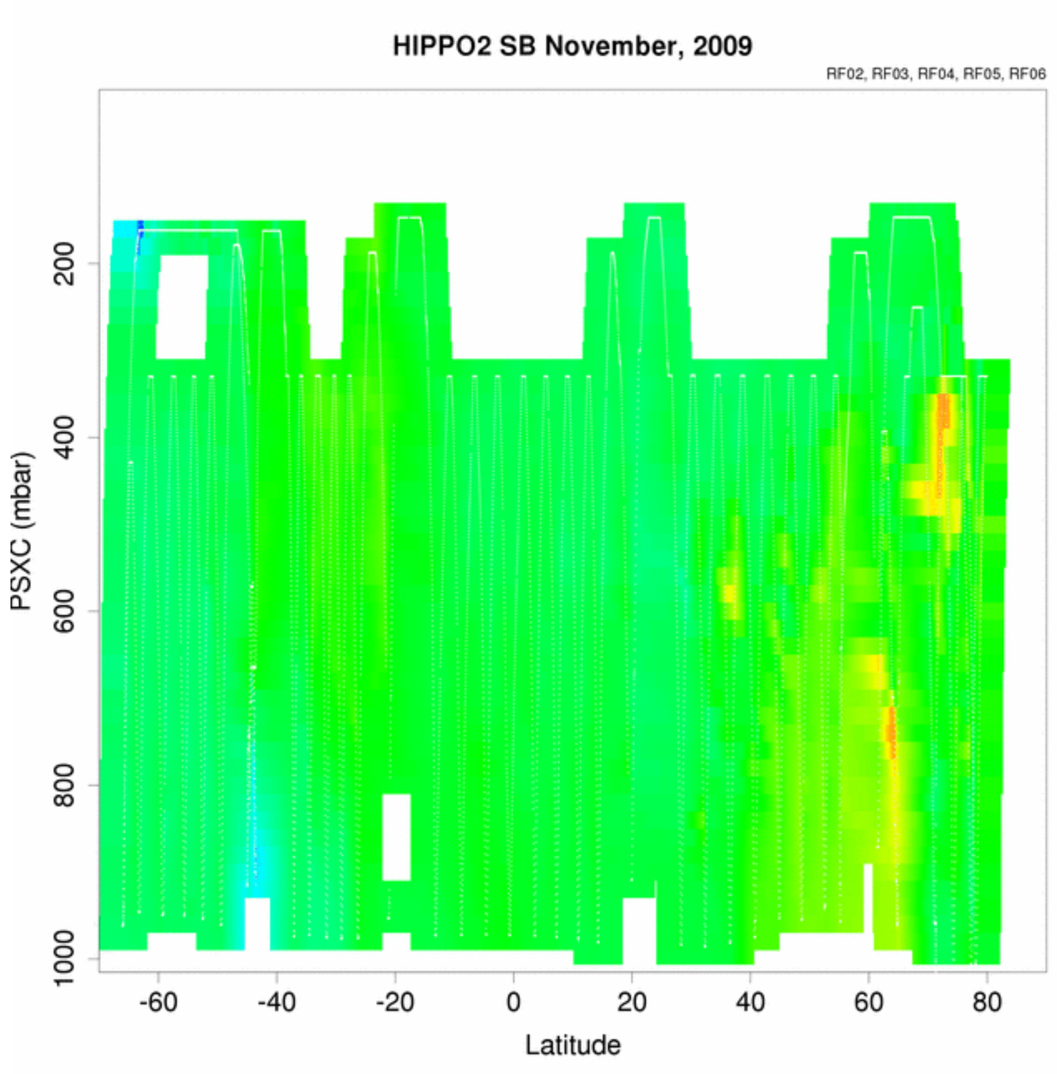
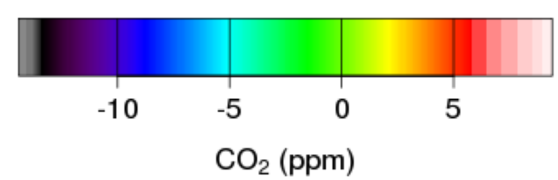
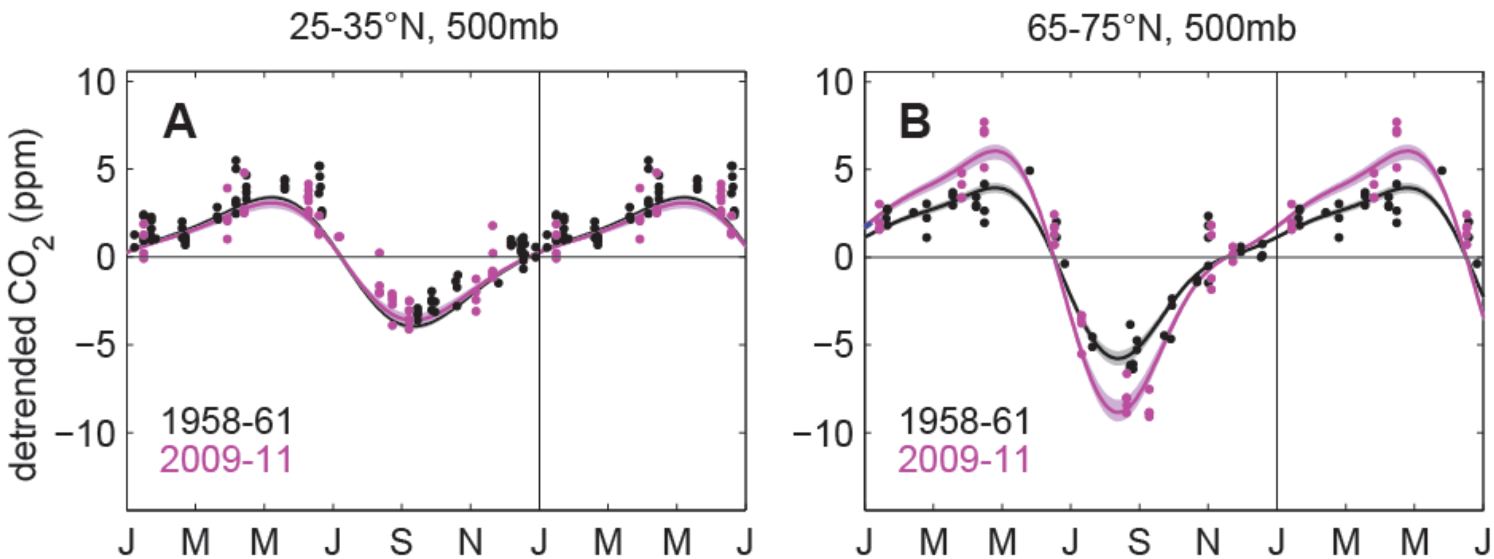
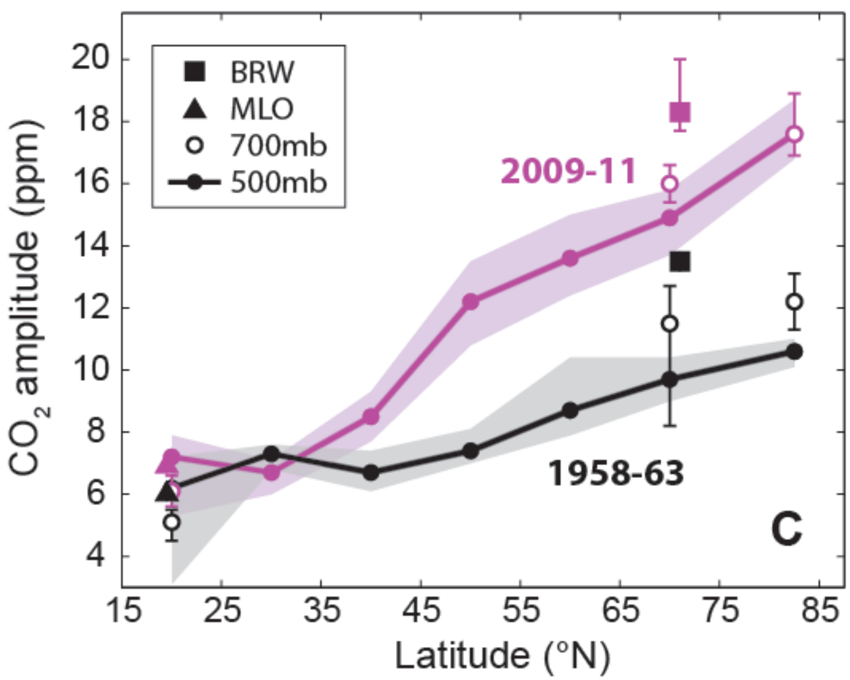


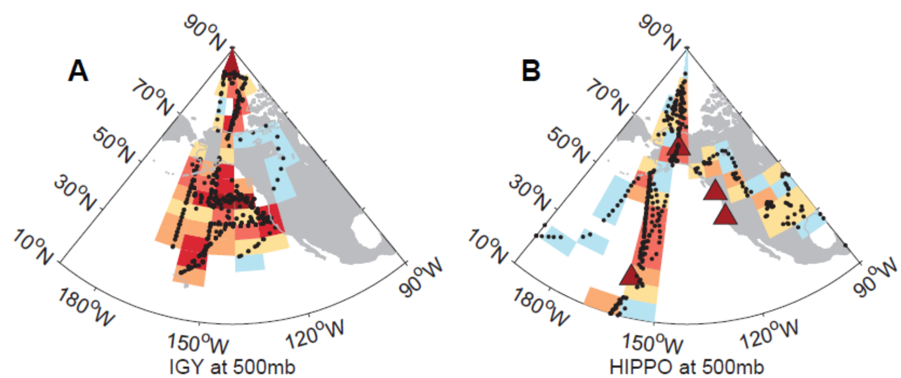


Northern Hemisphere seasonal progression: Jan 2009, Mar 2010, Apr 2010, Jun 2011, Jul 2011, Aug 2011, Sep 2011, Oct 2009, Nov 2009

HIPPO Comparison to IGY

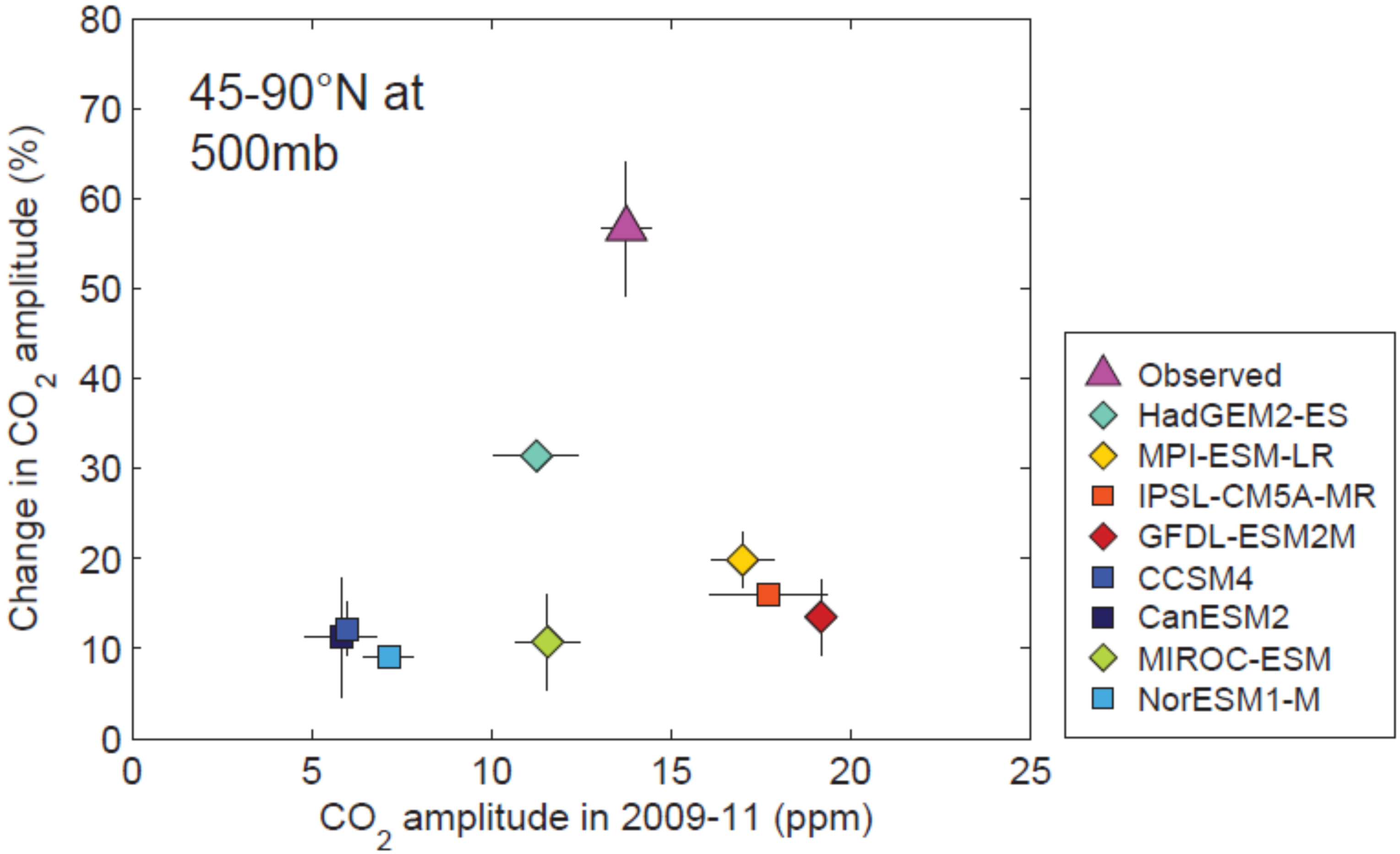






Graven et al., accepted to Science, 2013

HIPPO-IGY observations compared to CMIP5 models



Graven et al., accepted to Science, 2013

Conclusions

- Atmosphere contains a wealth of information on global carbon fluxes on all time and space scales
- To make efficient and maximum use of this information, modelers and observationalists need to work very closely together (or fuse into one)
- Inverse / DA calculations need to look at residuals, archive posterior concentrations to do this, esp. in model intercomparison studies
- Many open global carbon cycle questions remain: annual mean terrestrial sink, interannual variability, growth in seasonal cycle are all very well observed and still demand explanations