The North American Carbon Cycle from the Atmospheric Point of View

Scott Denning, Arlyn Andrews, Martha Butler, Kathy Corbin, Kenneth J. Davis, Timothy Hilton, Andy Jacobson, Anna Michalak, Sharon Gourdji, Natasha Miles, Scott Richardson, Andrew Schuh, Ravi Lokupitiya, Steven Wofsy, Erandi Lokupitiya, Nick Parazoo, Marek Uliasz, and Dusanka Zupanski

U.S. Global Change Research Program
Carbon Cycle Science Program
An Interagency Partnership

US Climate Change Science Program
www.climatescience.gov

USGS
science for a changing world

USDA

NIST

NASA

NOAA

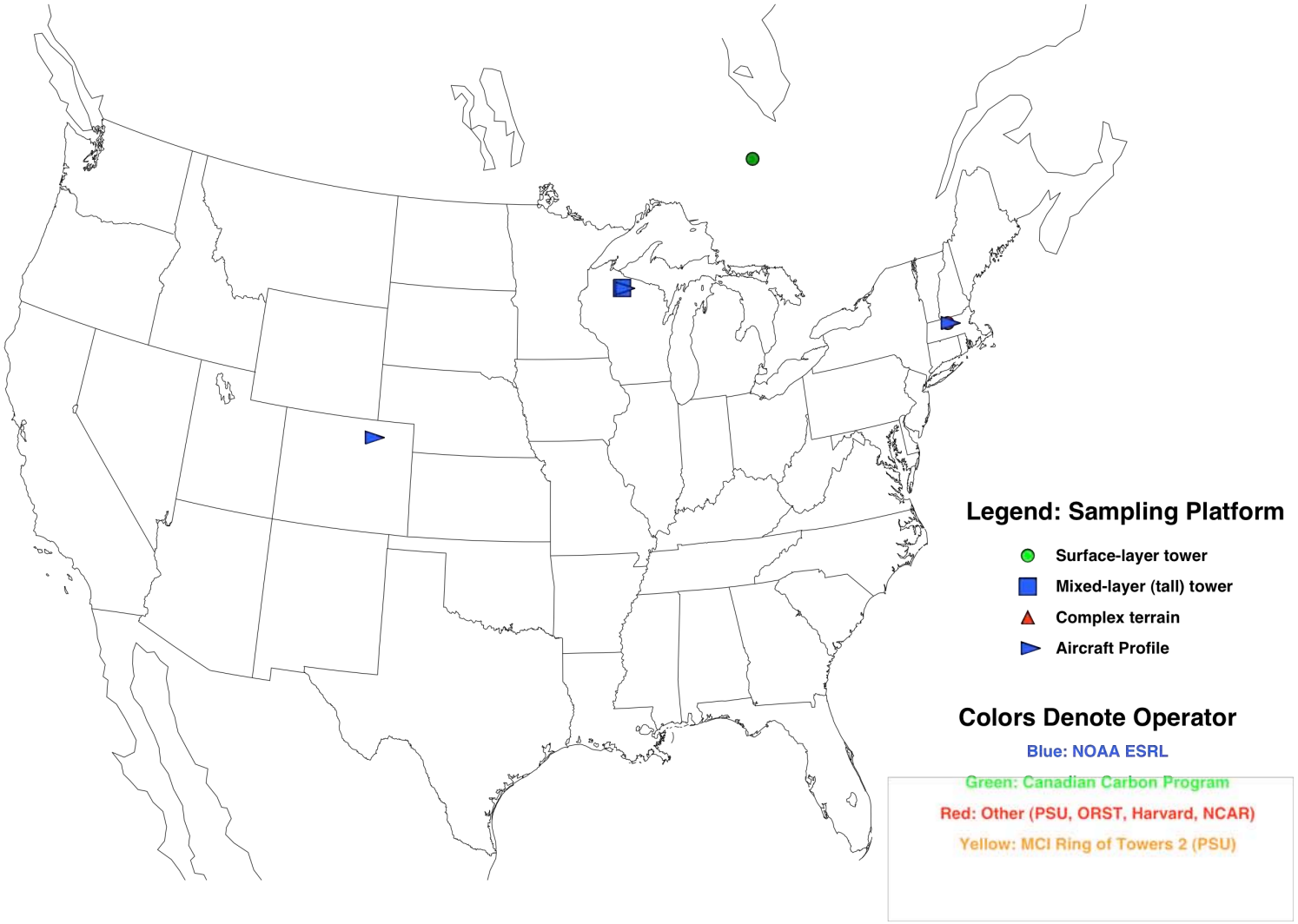
Outline

1. Dramatic growth of the atmospheric observing network under NACP
2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)
3. Variations in the carbon cycle of North America are driven by climate and people
4. A new view of atmospheric CO_2

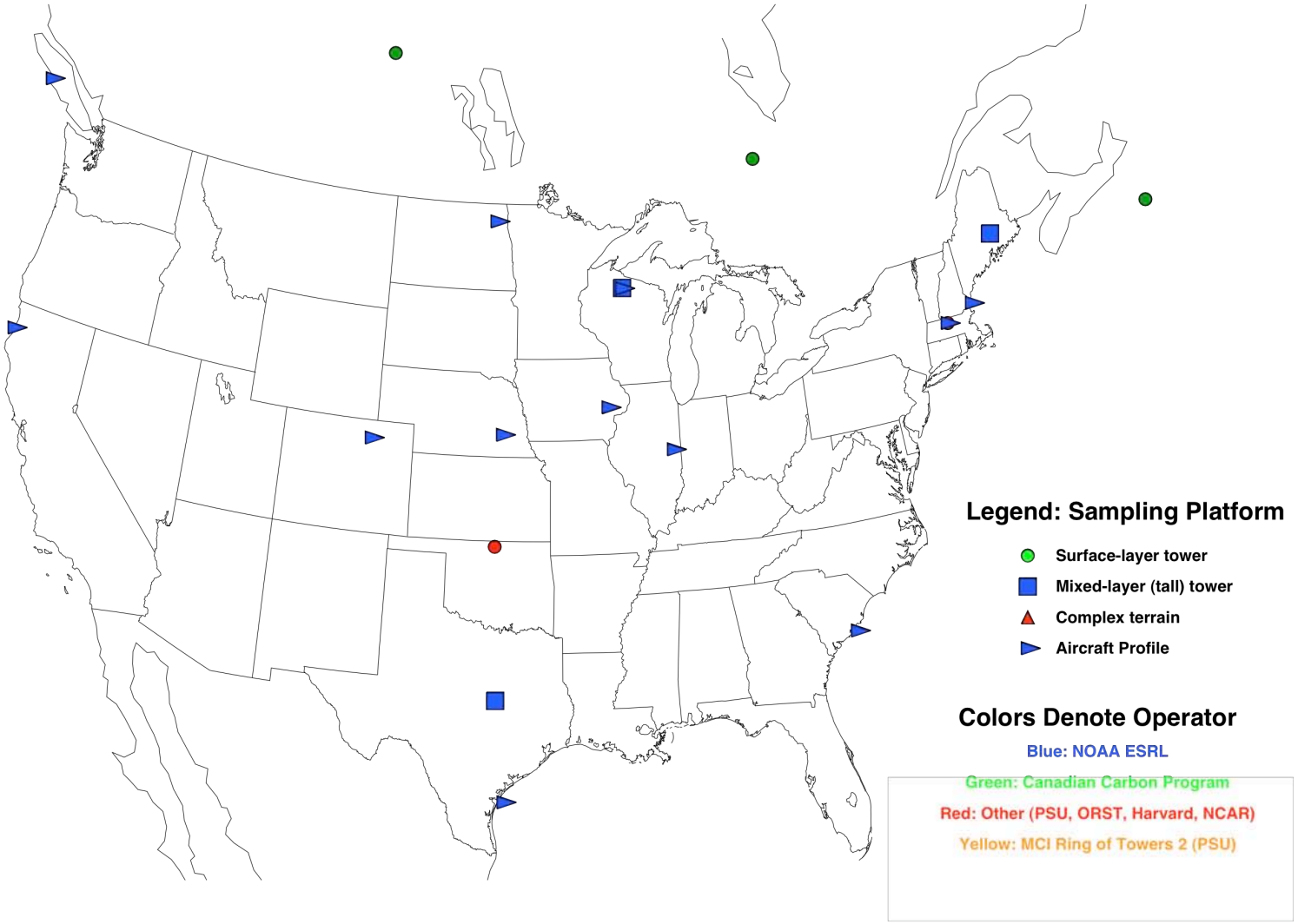
Outline

1. **Dramatic growth of the atmospheric observing network under NACP**
2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)
3. Variations in the carbon cycle of North America are driven by climate and people
4. A new view of atmospheric CO2

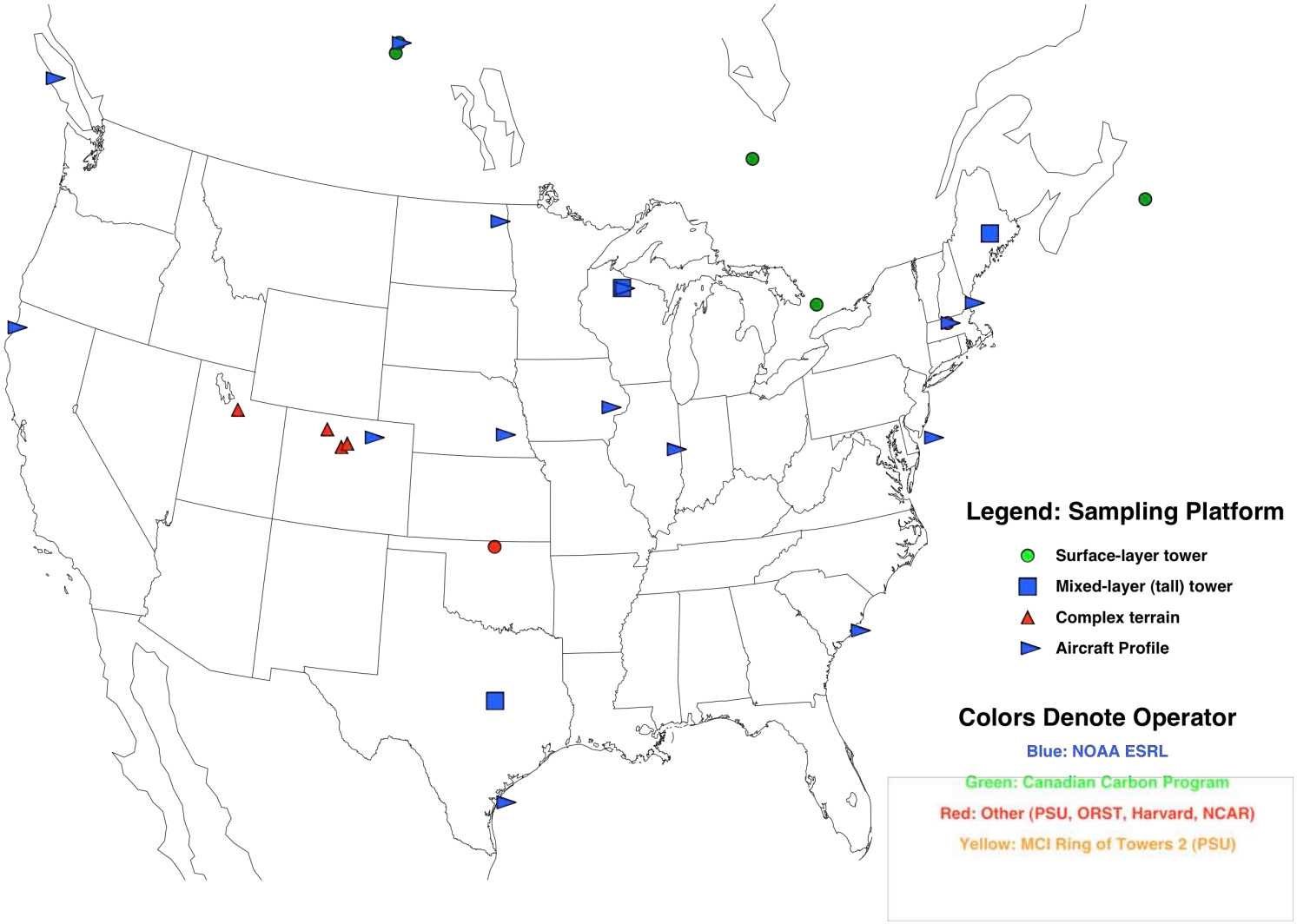
CO_2 Concentration Network: 2000



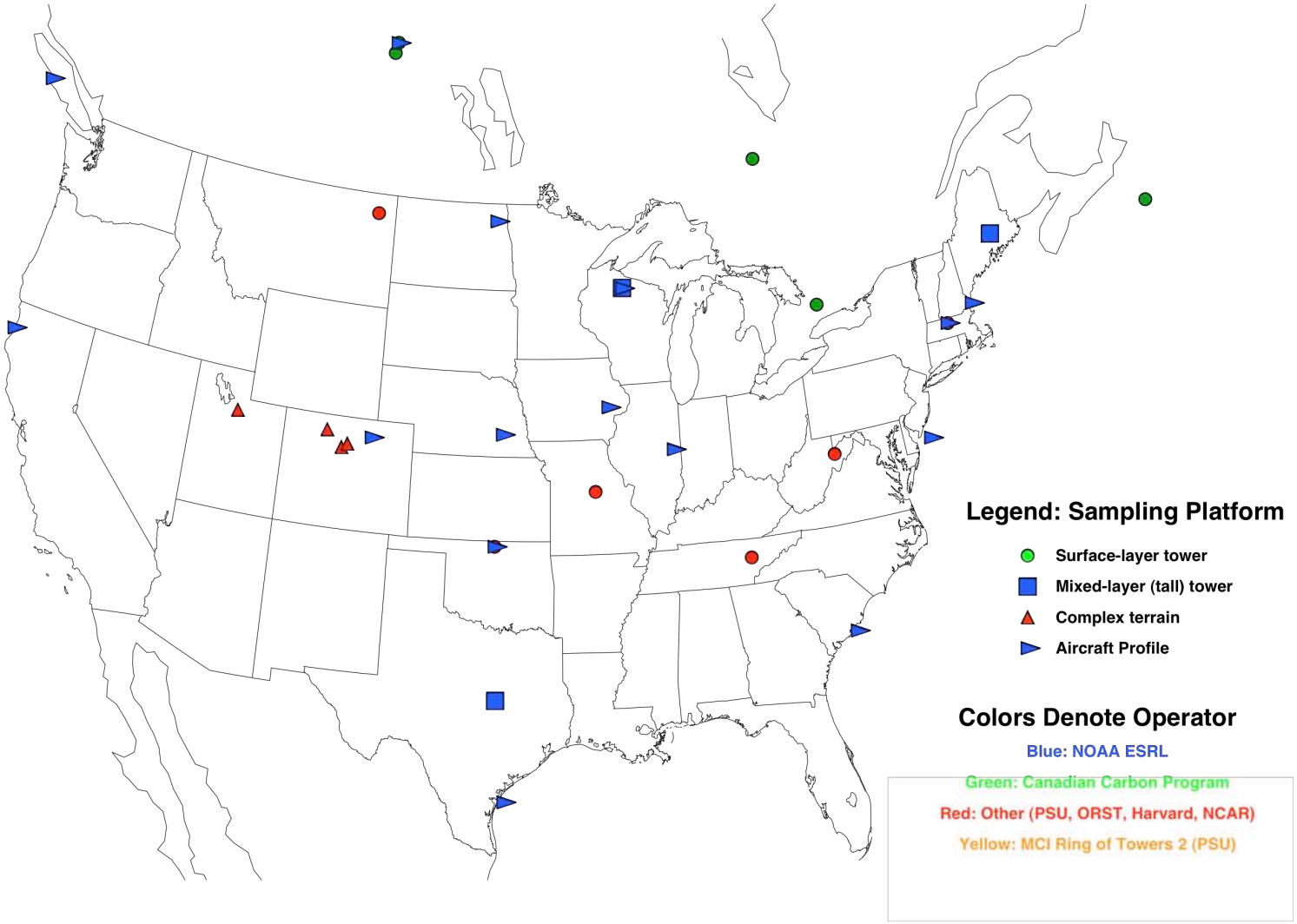
CO_2 Concentration Network: 2004



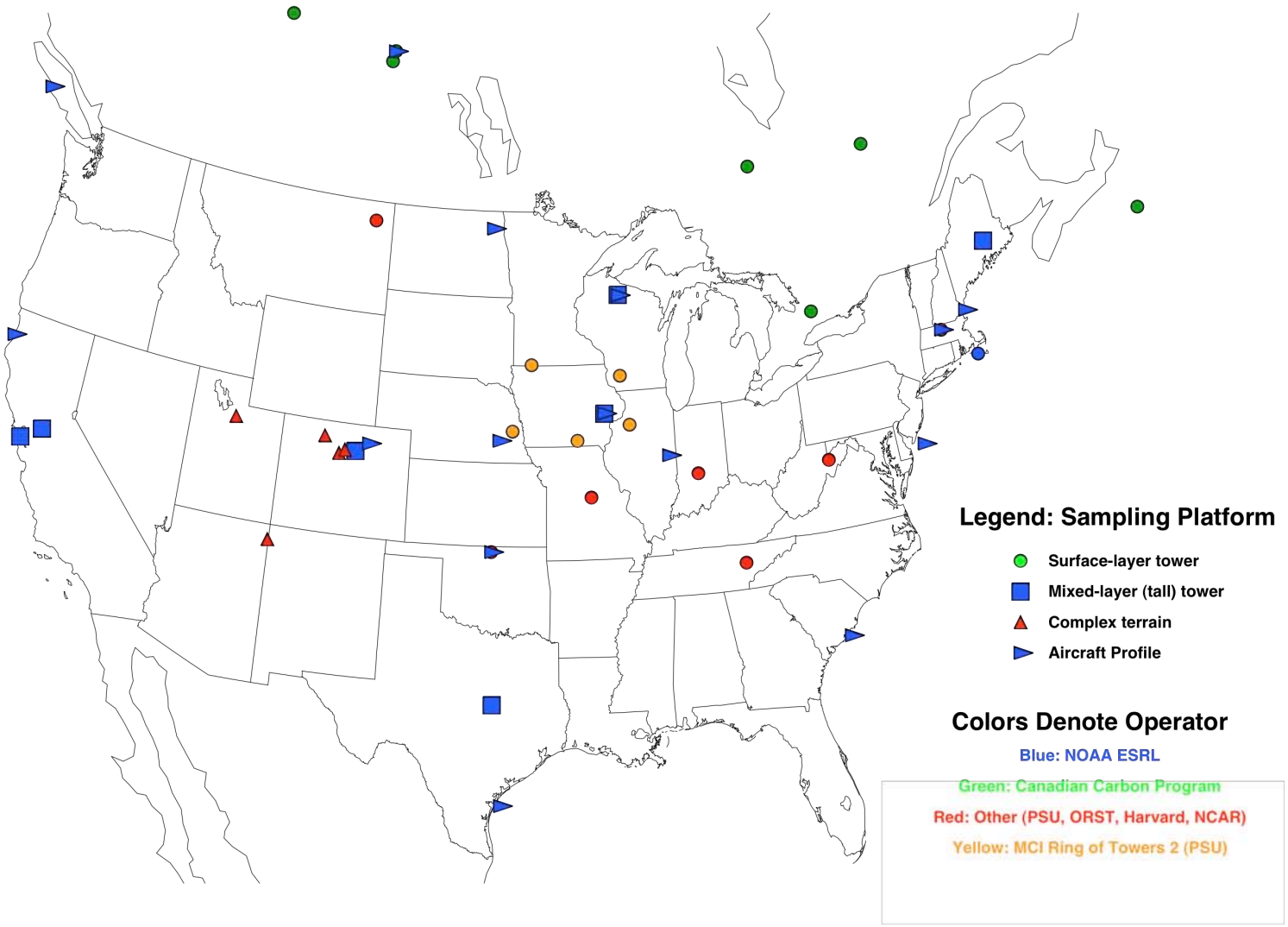
CO_2 Concentration Network: 2005



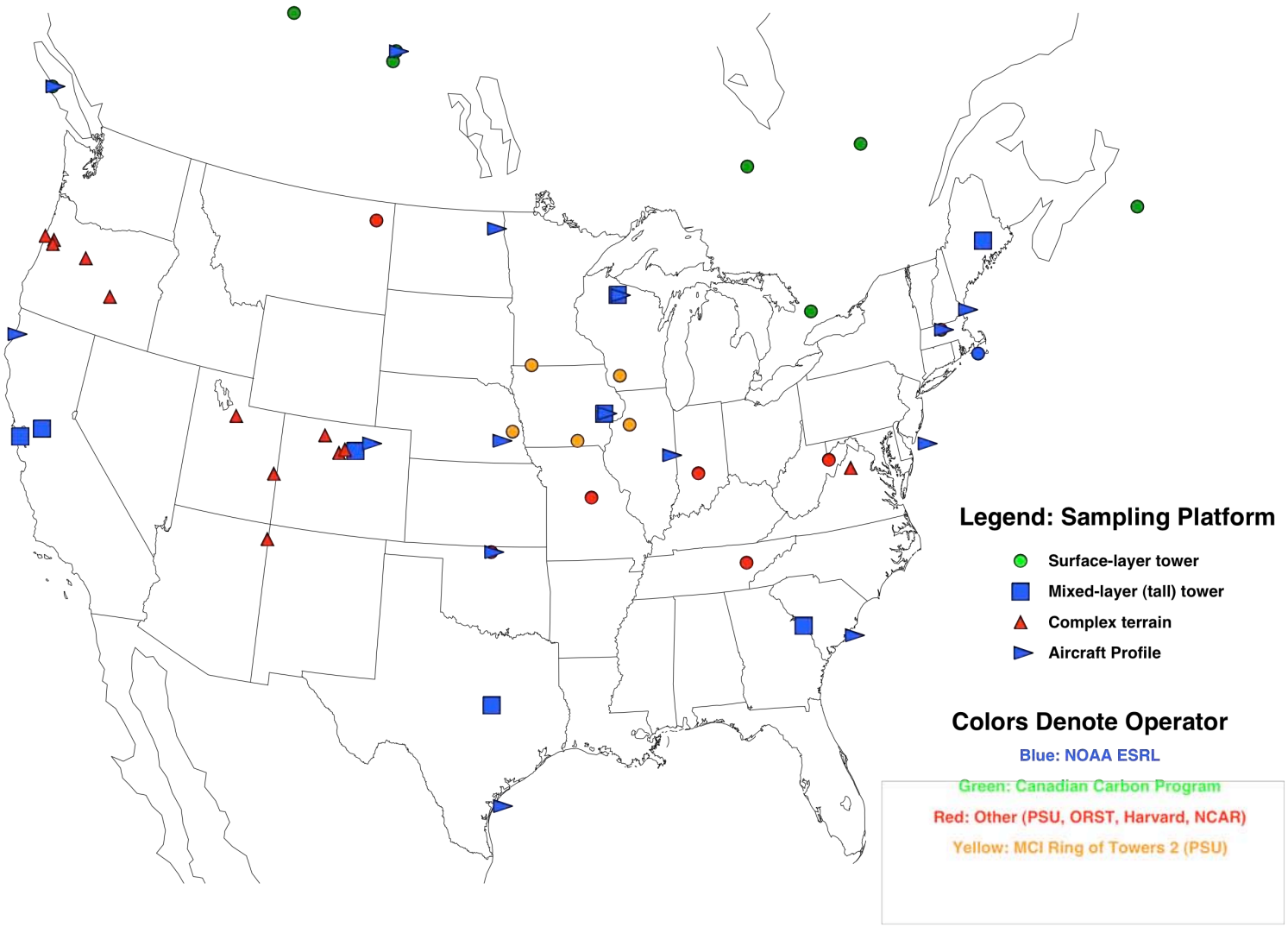
CO_2 Concentration Network: 2006



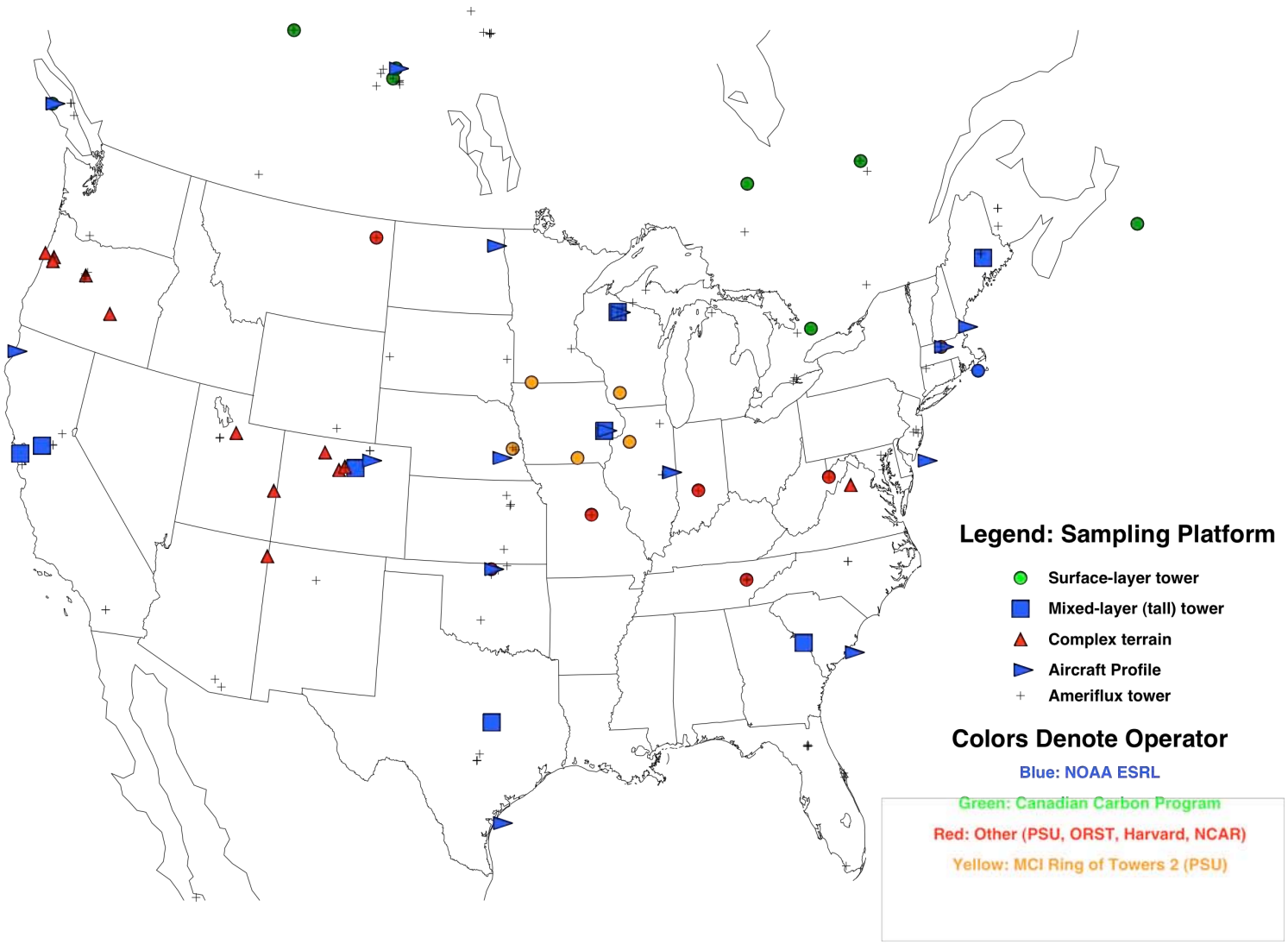
CO_2 Concentration Network: 2007

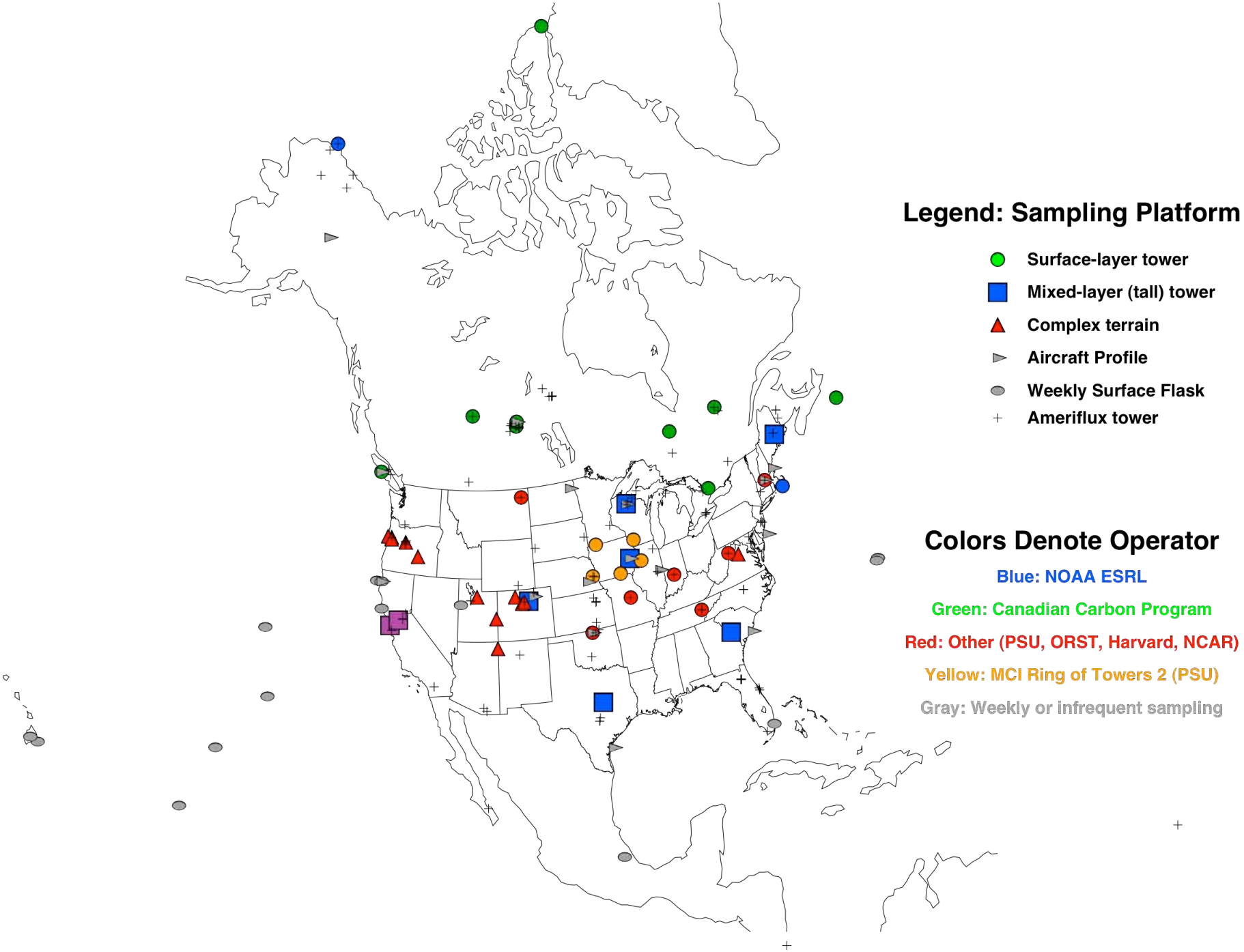


CO_2 Concentration Network: 2008



CO_2 Concentration Network: 2008

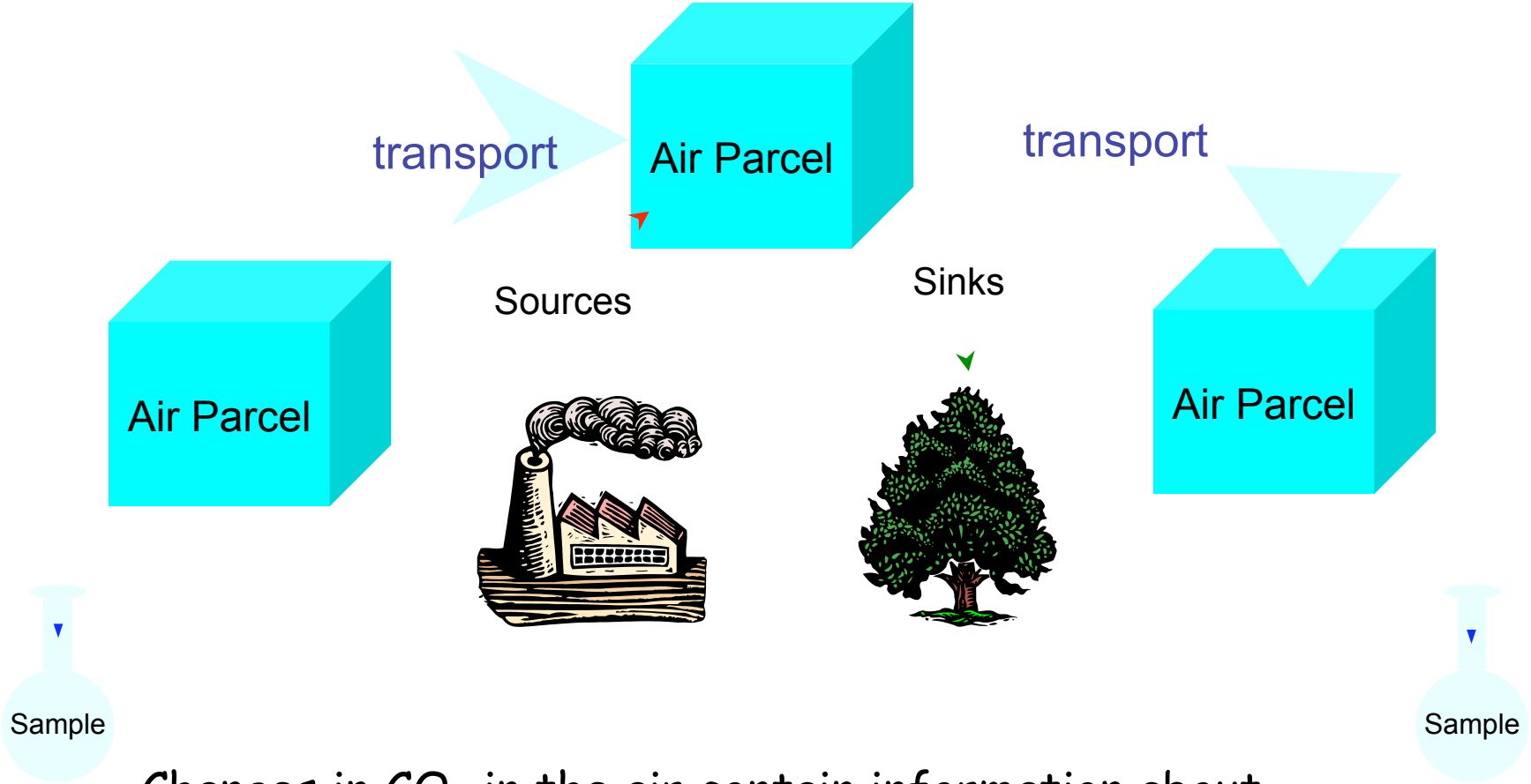



Legend: Sampling Platform
Surface-layer tower
Mixed-layer (tall) tower
Complex terrain
Aircraft Profile
Weekly Surface Flask
Ameriflux tower
Colors Denote Operator
Blue: NOAA ESRL
Green: Canadian Carbon Program
Red: Other (PSU, ORST, Harvard, NCAR)
Yellow: MCI Ring of Towers 2 (PSU)
Gray: Weekly or infrequent sampling

Outline

1. Dramatic growth of the atmospheric observing network under NACP
2. **Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)**
3. Variations in the carbon cycle of North America are driven by climate and people
4. A new view of atmospheric CO_2

Regional Carbon Budgeting from Atmospheric CO_2

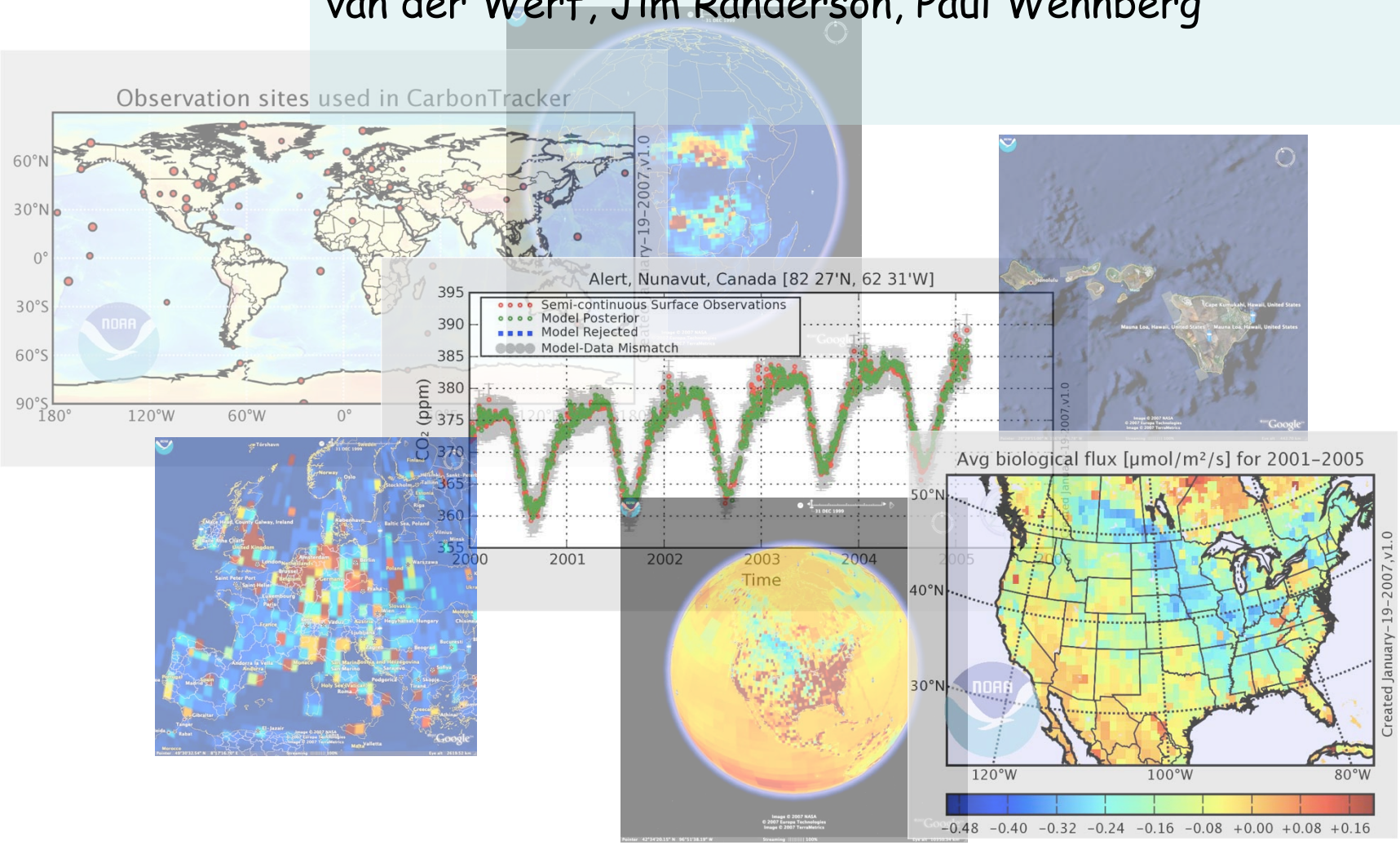


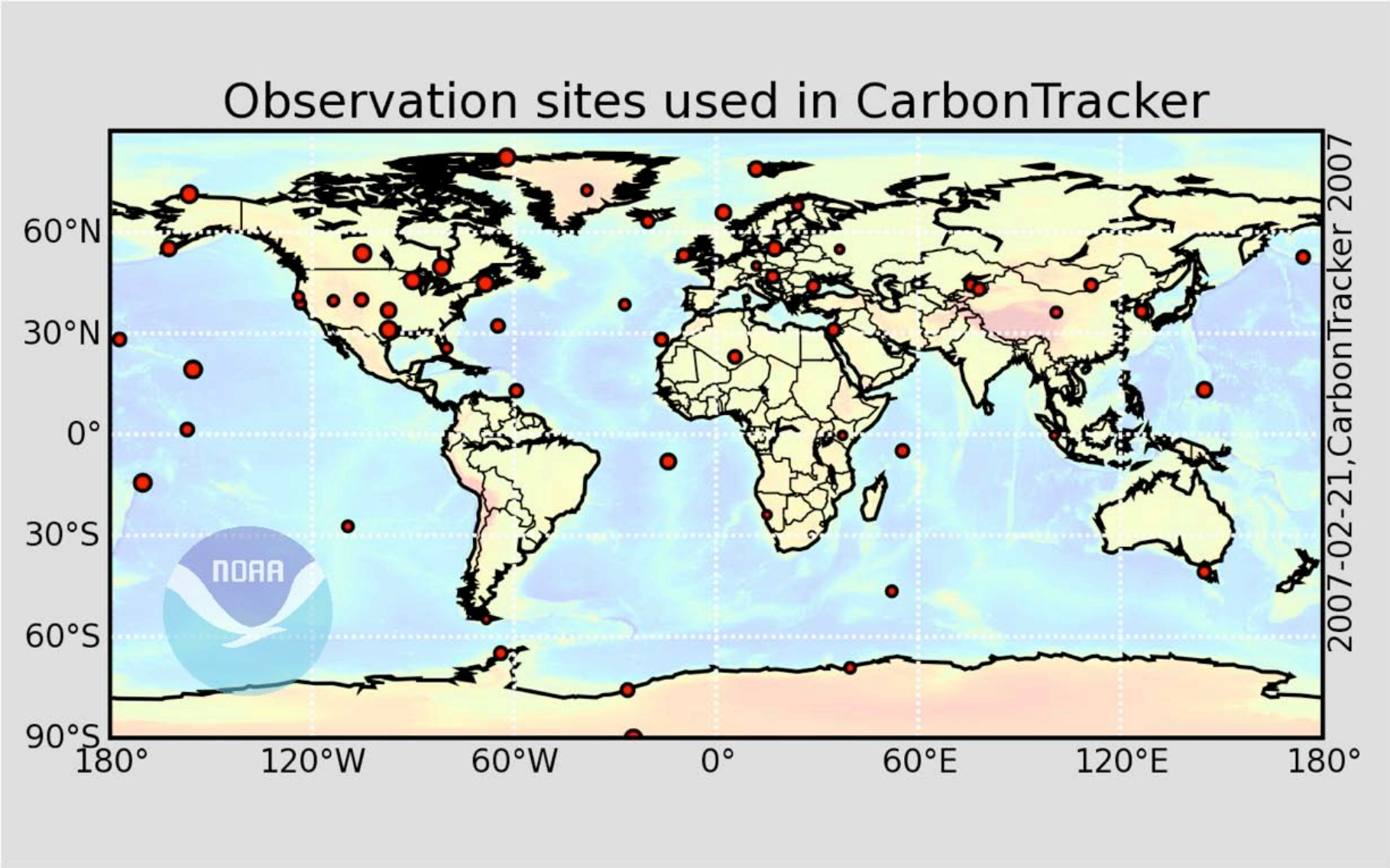
Changes in CO_2 in the air contain information about all sources and sinks encountered along the way

Requires: observations, accurate accounting for transport!

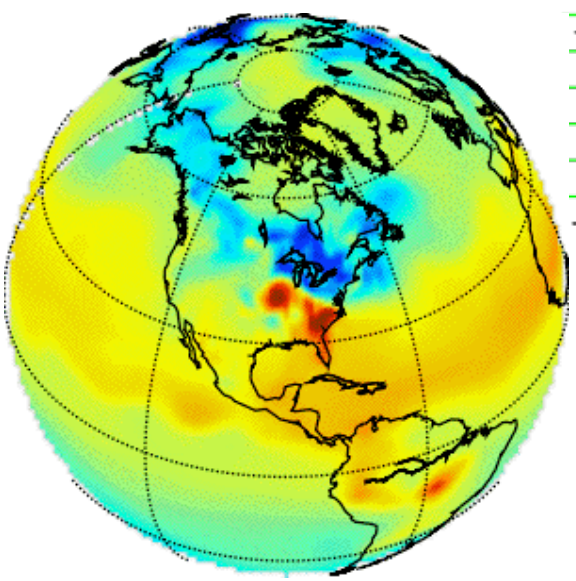
CarbonTracker

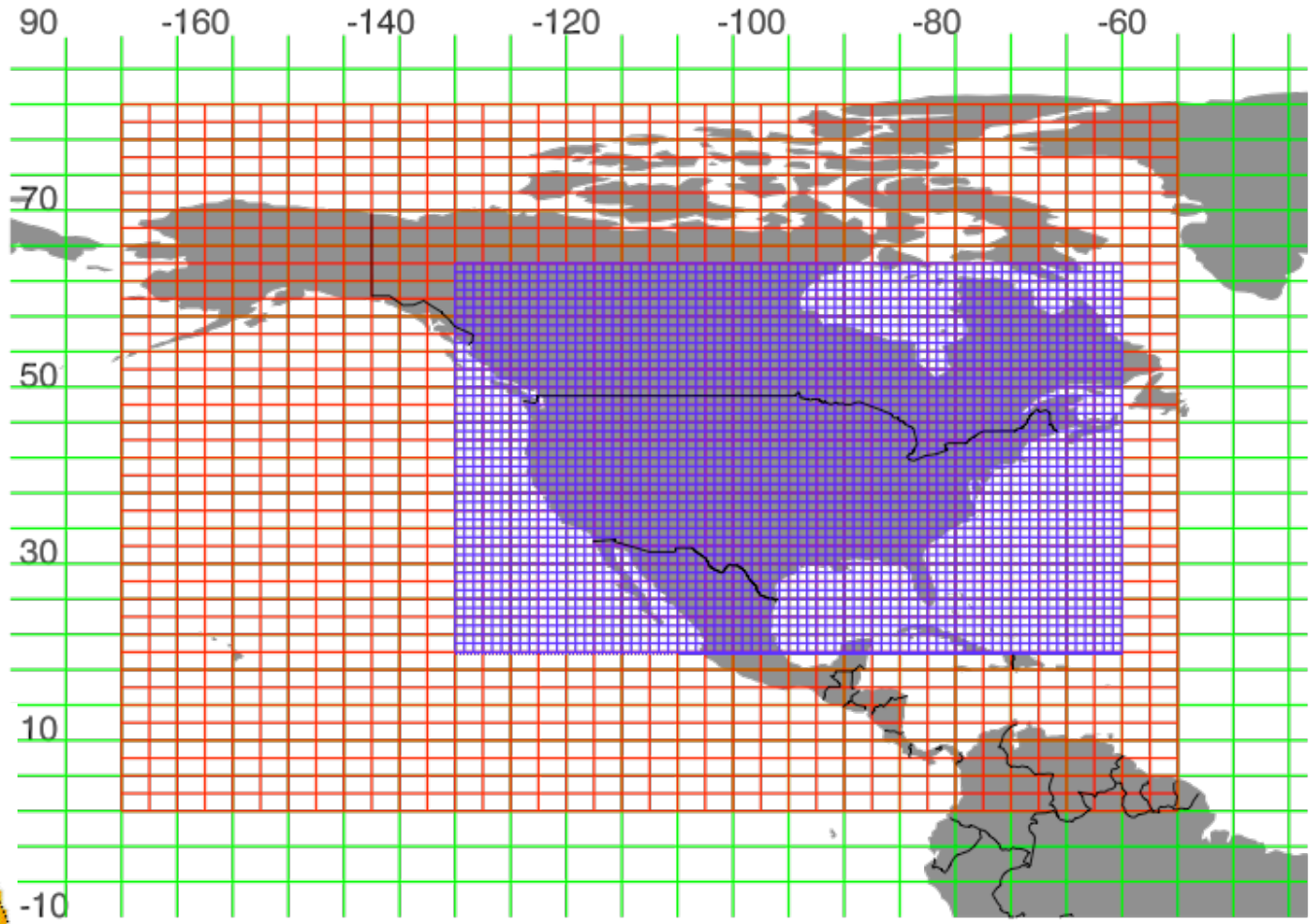
- Wouter Peters, Andy Jacobson, Ken Masarie, Pieter Tans, Colm Sweeney, Arlyn Andrews, Lori Bruhwiler, John Miller, Gaby Pétron, Adam Hirsch, Tom Conway, Maarten Krol, Guido van der Werf, Jim Randerson, Paul Wennberg




Observation sites used in CarbonTracker
60°N
30°N
0°
30°S
60°S
90°S
180°
120°W
60°W
0°
60°E
120°E
180°
2007-02-21,CarbonTracker 2007
NOAA

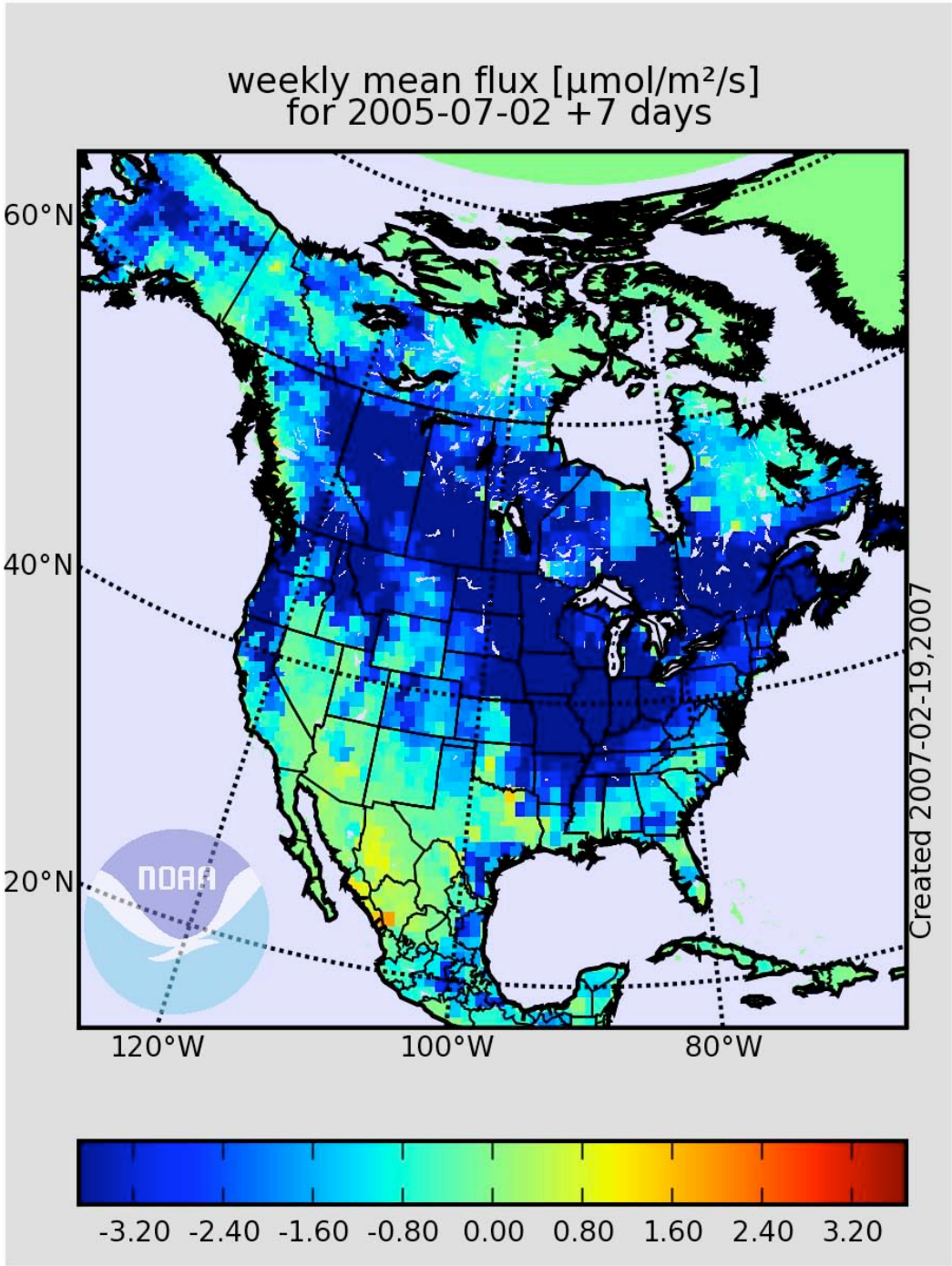
TM5





Global 6x4 North America 3x2 US 1x1

- Global Chemistry Transport Model
- Driven by ECMWF meteorology
- Two-way nested zoom

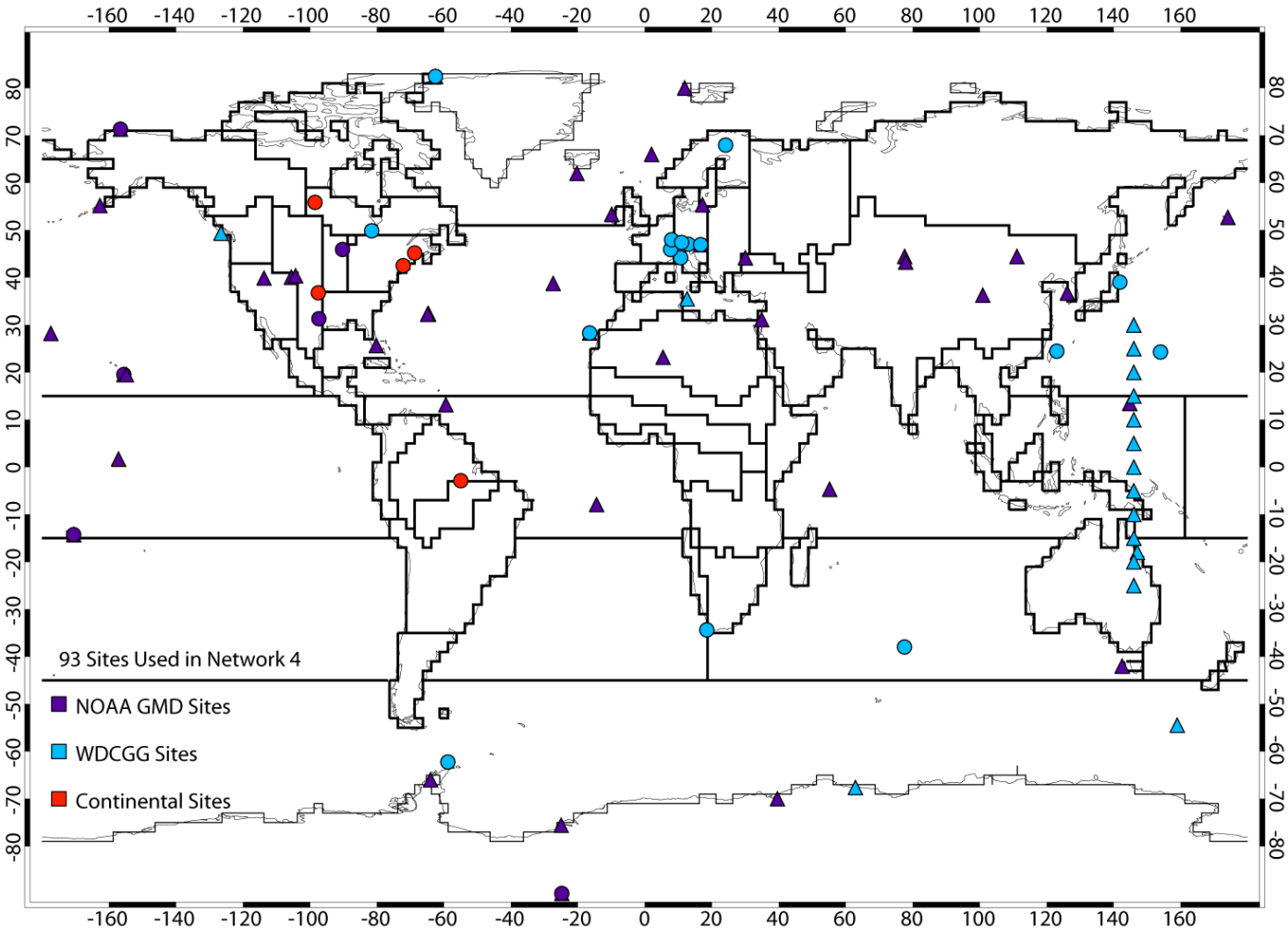


CarbonTracker Result

Weekly gridded product at 1x1 degree with error estimate, freely available on web with code, data, docs

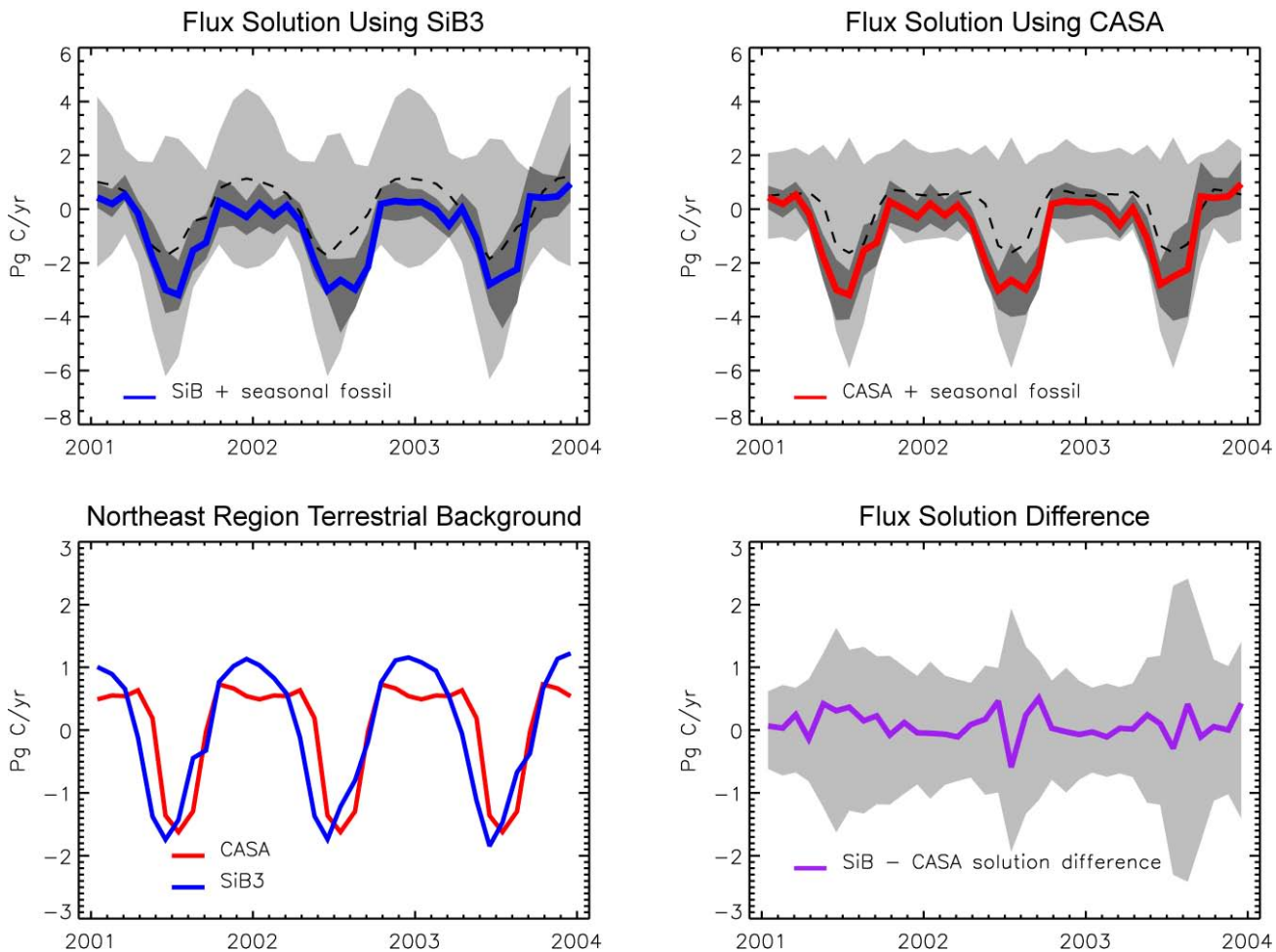
Highlights from an Atmospheric Inversion Experiment

Surface fluxes of carbon are inferred for 2001-2003 for each region shown by adjusting modeled fluxes (terrestrial, ocean, fossil emissions, and biomass burning) using atmospheric observations from this network, which includes flux tower sites (in **red**) with well-calibrated carbon dioxide measurements.



mpbutler@met.psu.edu

Sensitivity to Choice of Terrestrial Flux Model



For this well-constrained region, the inferred fluxes are not significantly different when using terrestrial flux models which vary in:

-Time resolution (hourly with interannual variability vs. monthly mean climatology)

- Amplitude of seasonal cycle

-Timing of seasonal cycle

PENNSTATE

Geostatistical inversions
(Michalak et al, U of Michigan)

- Data-driven approach eliminating use of explicit prior estimates
- Takes advantage of spatial autocorrelation in flux distribution
- Incorporates auxiliary variables related to flux processes in a manner analogous to multi-linear regression
- Objective function and flux estimates:

$$L_{\mathbf{s},\beta} = \frac{1}{2}(\mathbf{y} - \mathbf{Hs})^T \mathbf{R}^{-1}(\mathbf{y} - \mathbf{Hs}) + \frac{1}{2}(\mathbf{s} - \mathbf{X}\beta)^T \mathbf{Q}^{-1}(\mathbf{s} - \mathbf{X}\beta)$$

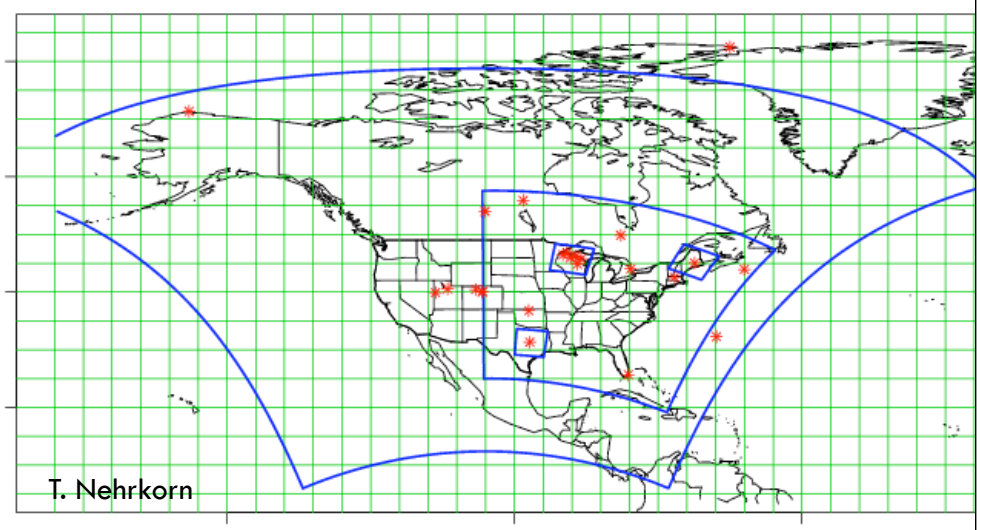
$$\hat{\mathbf{s}} = \mathbf{X}\hat{\boldsymbol{\beta}} + \mathbf{Q}\mathbf{H}^T \boldsymbol{\xi}$$

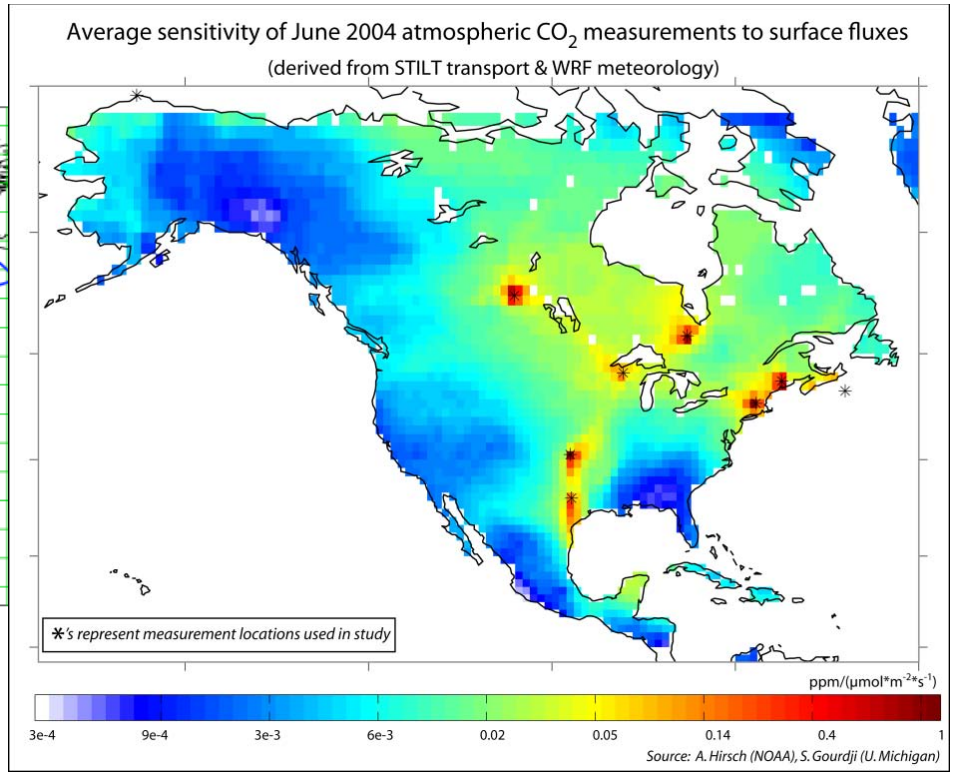
Deterministic component

Stochastic component

North American geostatistical inversion

- U. of Michigan NACP project in collaboration with NOAA
- 1°x1° North American fluxes estimated for 2004 and 2006 using continuous & weekly flask atmospheric measurements, a Lagrangian atmospheric particle-tracking model (STILT), and high-resolution meteorology (WRF)
- *Met fields will be available from: http://data.engin.umich.edu/michalak*





Treatment of Variations for Inversion

$$F_{CO2}(x,y,t) = \underbrace{\beta_R(x,y)}_{\text{unknown!}} \overbrace{R(x,y,t)}^{\text{SiB}} - \underbrace{\beta_{GPP}(x,y)}_{\text{unknown!}} \overbrace{GPP(x,y,t)}^{\text{SiB}}$$

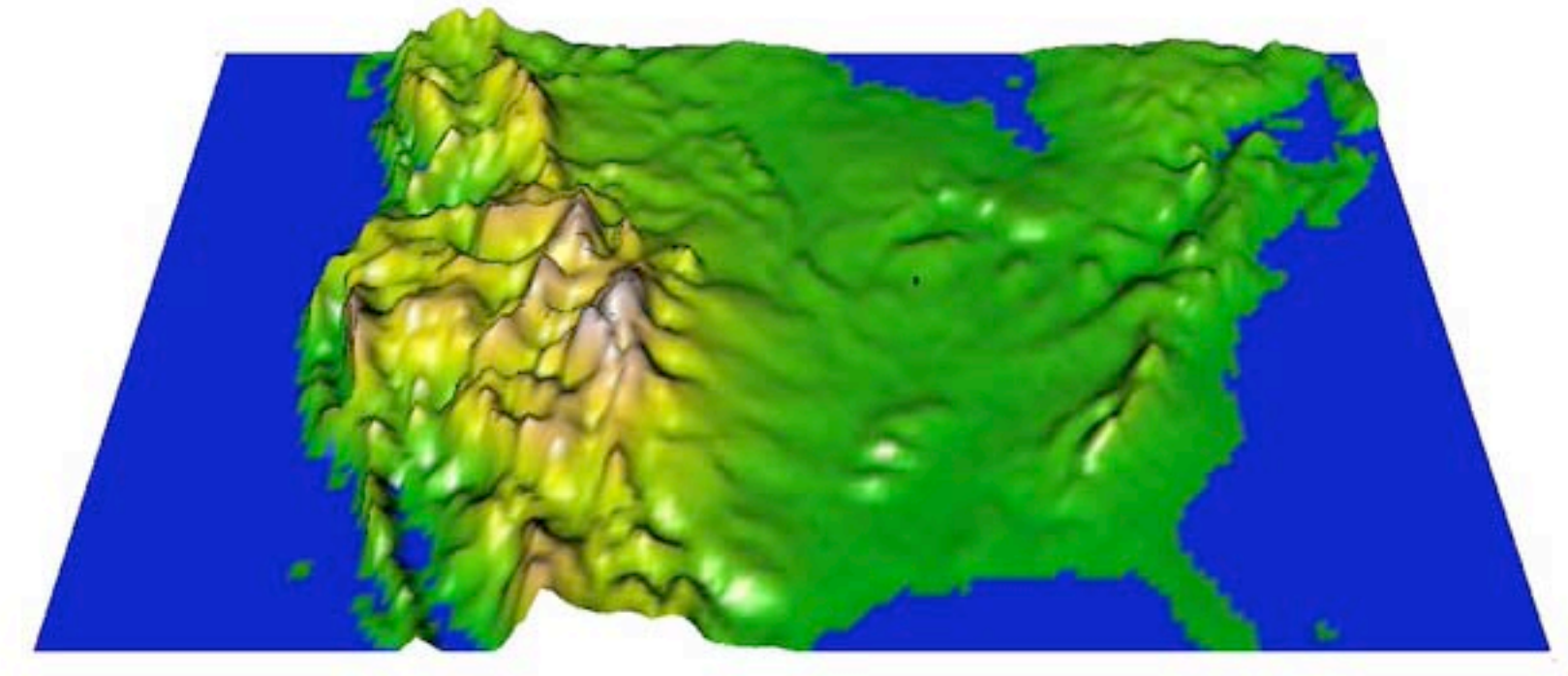
- Fine-scale variations (hourly, pixel-scale) from weather forcing, MODIS, as processed by forward model logic (SiB-RAMS)
- Multiplicative biases (caused by "slow" BGC that's not in the model) derived by from observed hourly [CO_2]

$$C_{k,m} = \sum_{i,j,n} \left(\beta_{R,i,j} R_{i,j,n} C^*_{Rk,m,i,j,n} + \beta_{A,i,j} A_{i,j,n} C^*_{Ak,m,i,j,n} \right) \Delta t_f \Delta x \Delta y + C_{IN}$$

Flux-convolved influence functions derived from SiB-RAMS

Back-Trajectories from WLEF Tower
(400 m TV tower near Park Falls, WI)

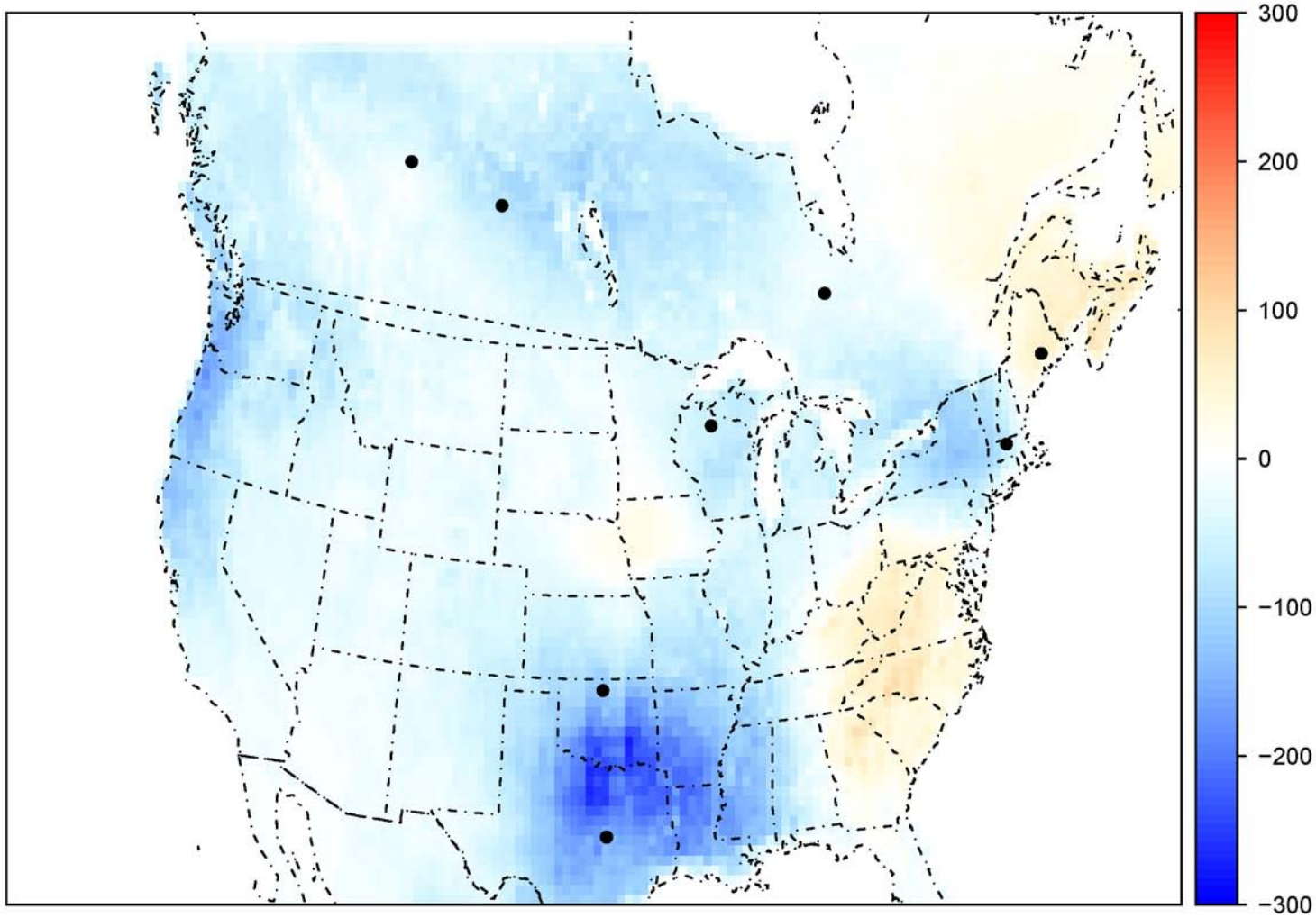
SiB-RAMS-LPDM



20 days of “upstream” transport in 50 seconds

Black: air parcels in contact with surface
Red: air parcels reach lateral boundaries

Result: Estimated 2004 Net Ecosystem CO_2 Exchange



g C m^{-2} yr^{-1}

COBRA-2003§ flight region and footprints

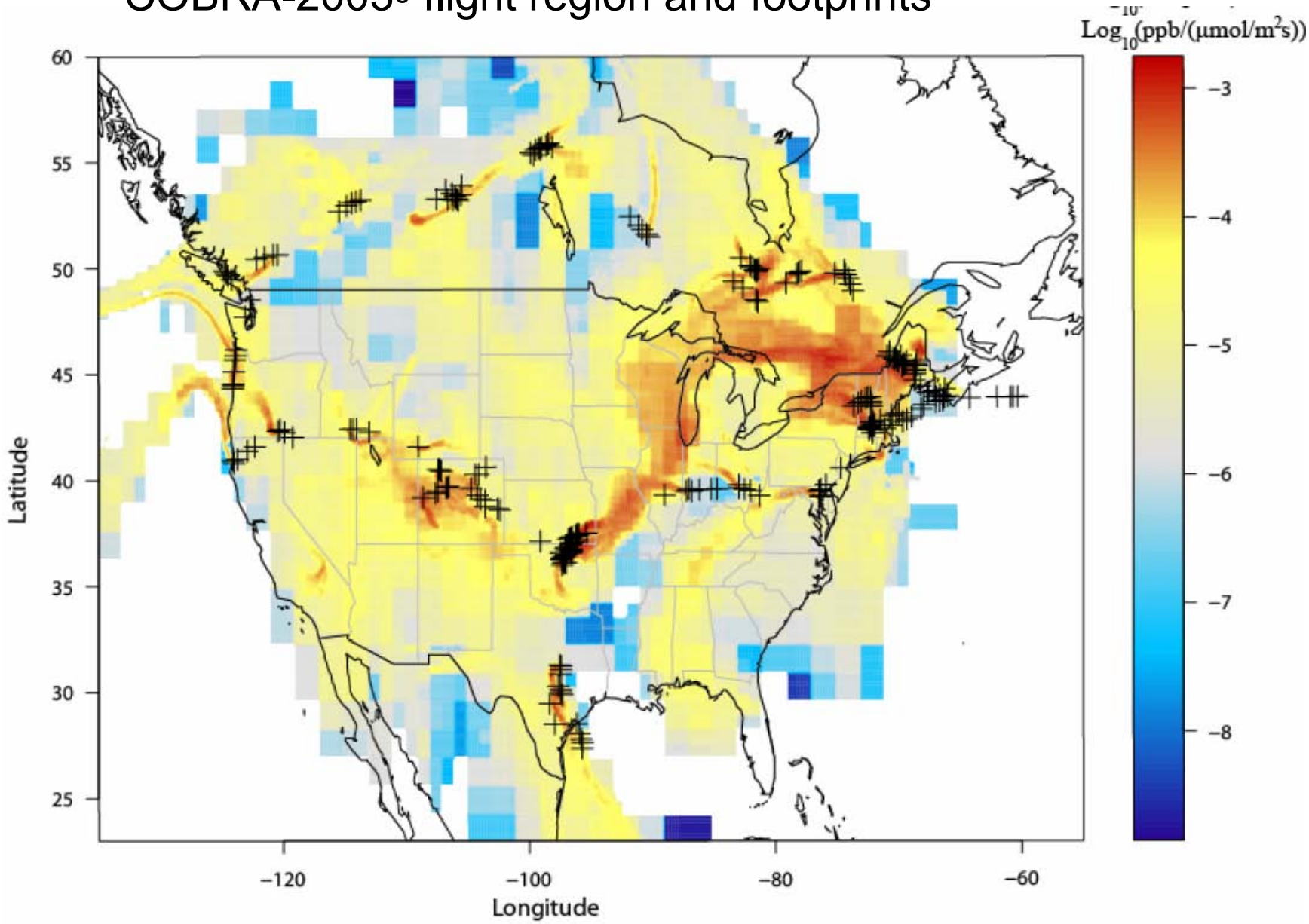
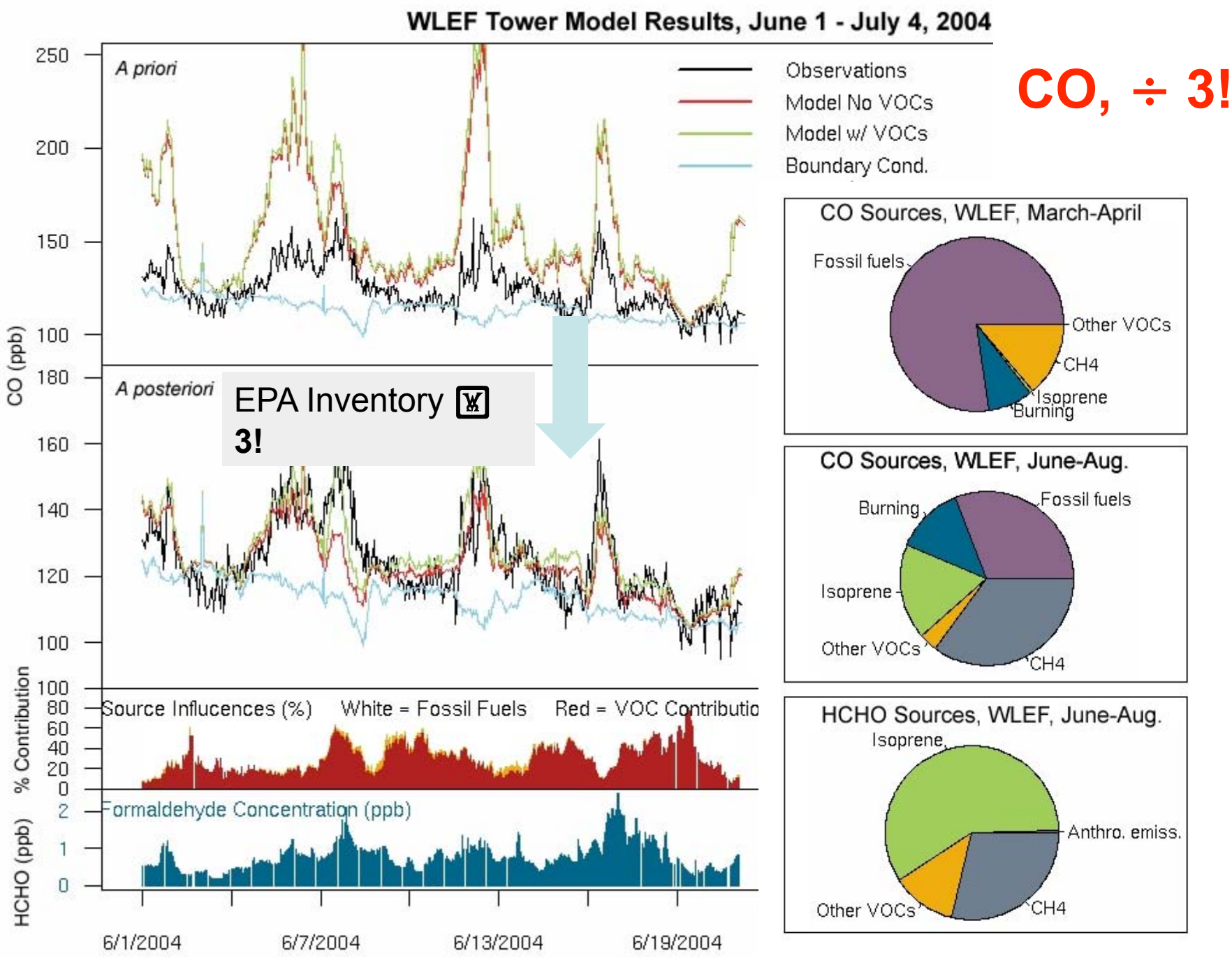


Figure 1: Plus markings indicate locations of airborne flask collection. The average footprint from all the flasks is shown, indicating regions to which our measurements are most sensitive.

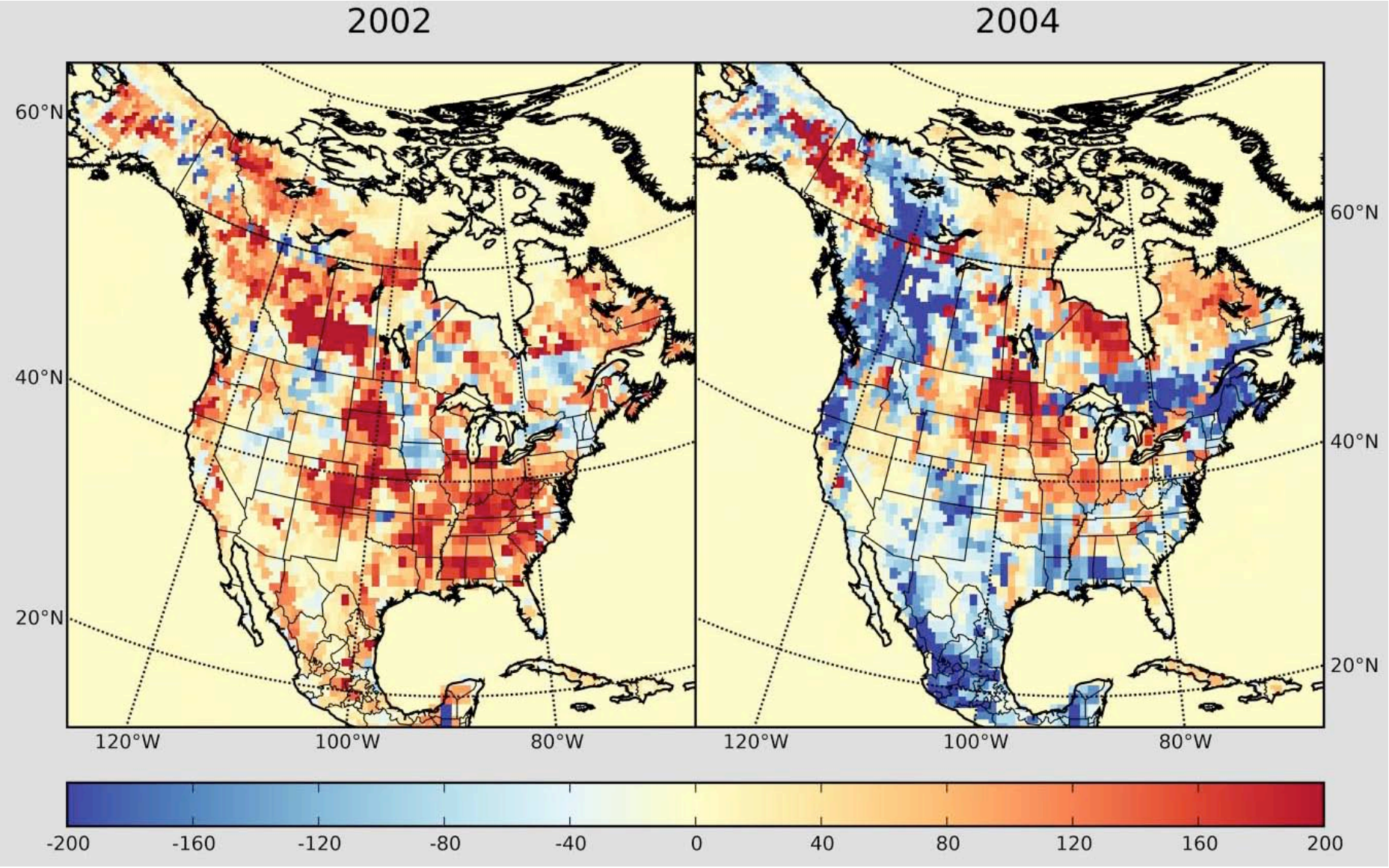
§a **CCE** (LBA !) project


WLEF Tower Model Results, June 1 - July 4, 2004
A priori
A posteriori
Observations
Model No VOCs
Model w/ VOCs
Boundary Cond.
CO (ppb)
EPA Inventory ÷ 3!
Source Influences (%)
White = Fossil Fuels
Red = VOC Contributio
% Contribution
Formaldehyde Concentration (ppb)
HCHO (ppb)
6/1/2004
6/7/2004
6/13/2004
6/19/2004
CO, ÷ 3!
CO Sources, WLEF, March-April
Fossil fuels
Other VOCs
CH4
Isoprene
Burning
CO Sources, WLEF, June-Aug.
Burning
Fossil fuels
Isoprene
Other VOCs
CH4
HCHO Sources, WLEF, June-Aug.
Isoprene
Anthro. emiss.
Other VOCs
CH4

Outline

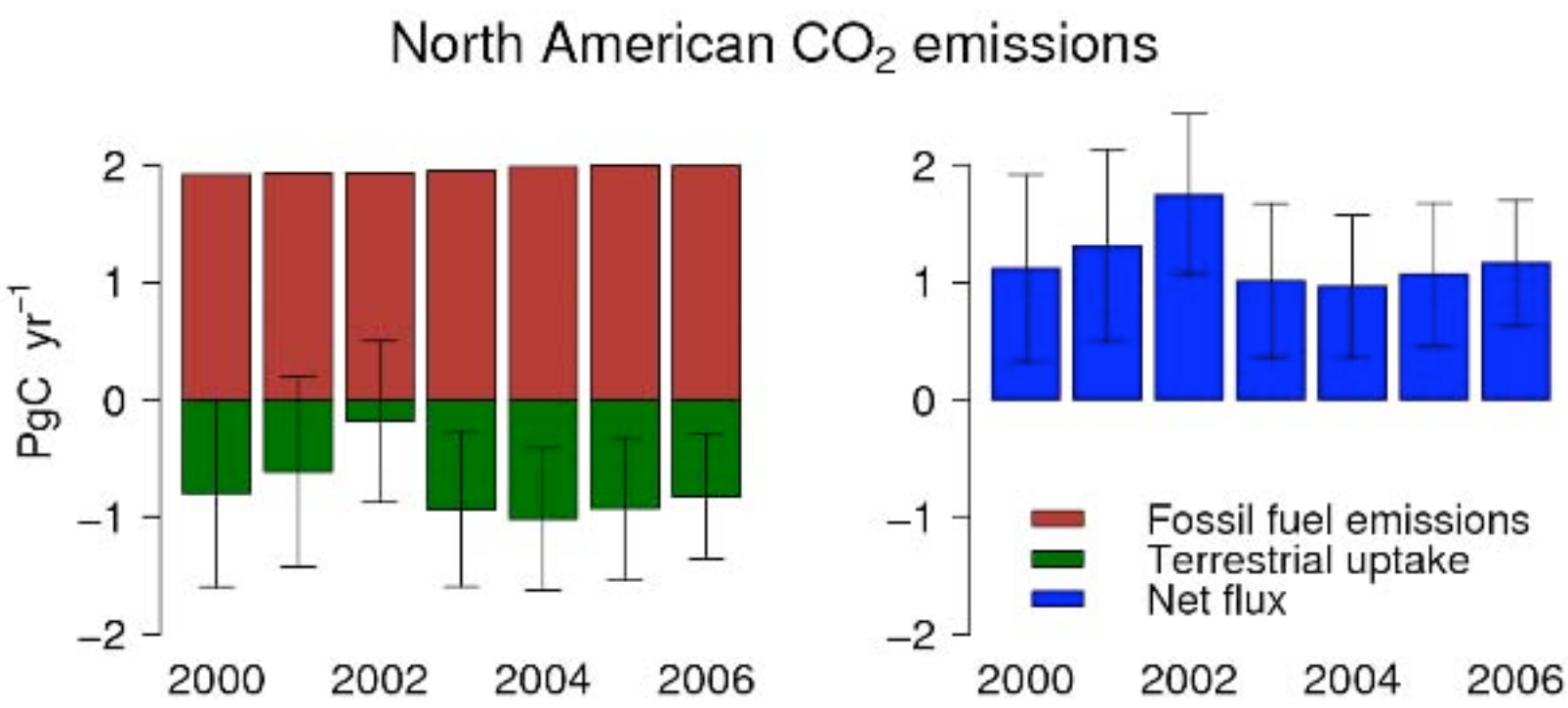
1. Dramatic growth of the atmospheric observing network under NACP
2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)
3. **Variations in the carbon cycle of North America are driven by climate and people**
4. A new view of atmospheric CO_2

CarbonTracker Estimated C Source/Sink



CarbonTracker Inversion Model, Net Terrestrial Summer Flux (gC/m2/yr)
www.esrl.noaa.gov/gmd/ccgg/carbontracker/

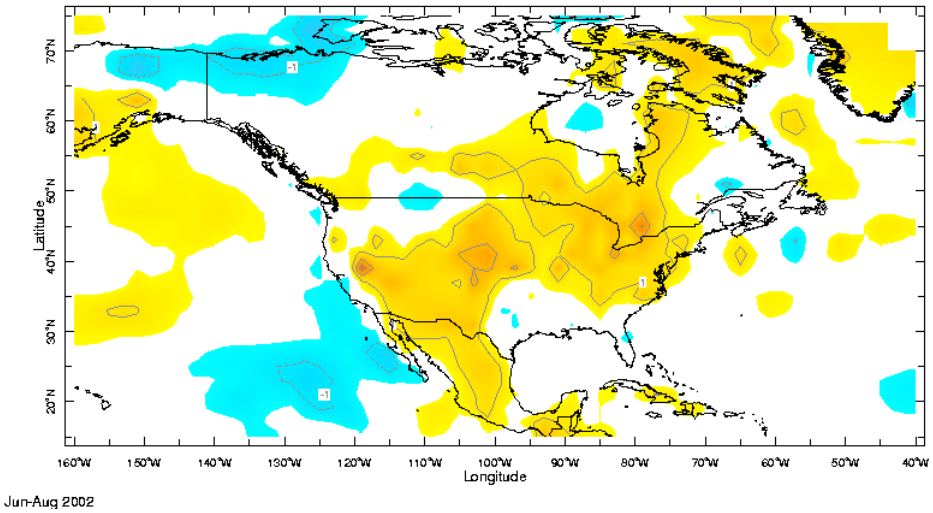
CarbonTracker Results

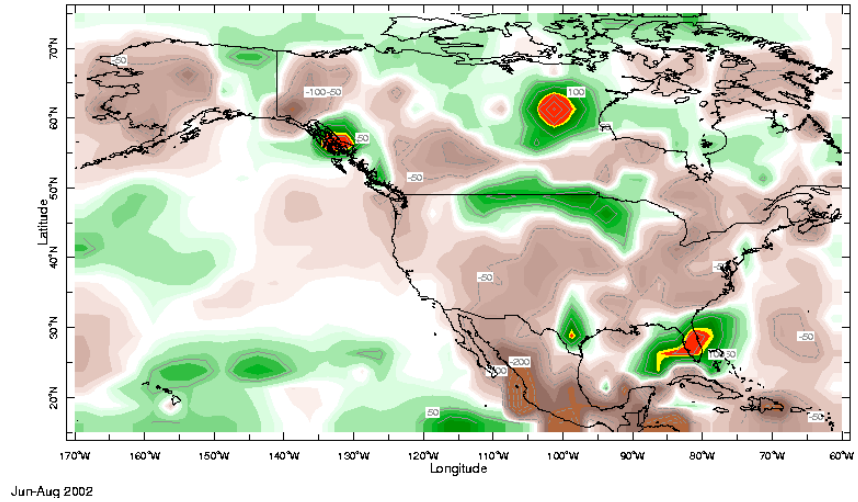


Climate Anomalies

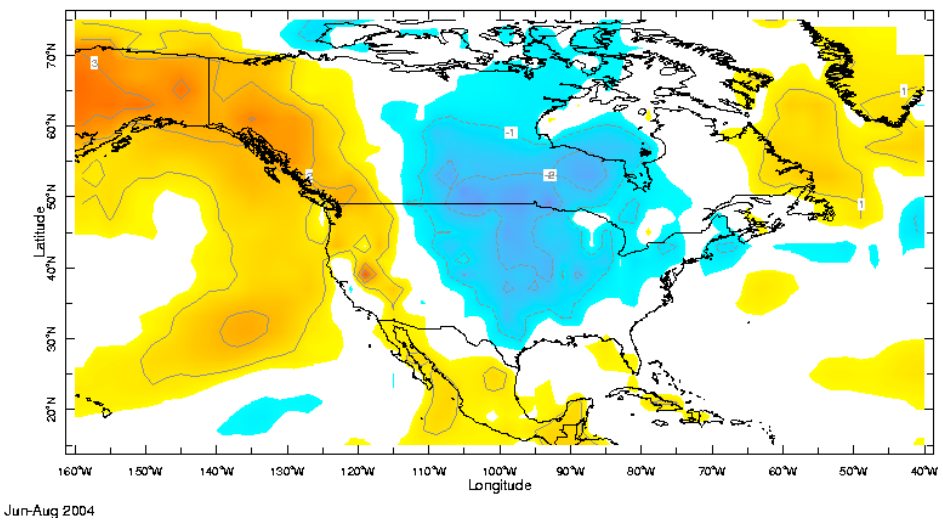
(NOAA NCDC)

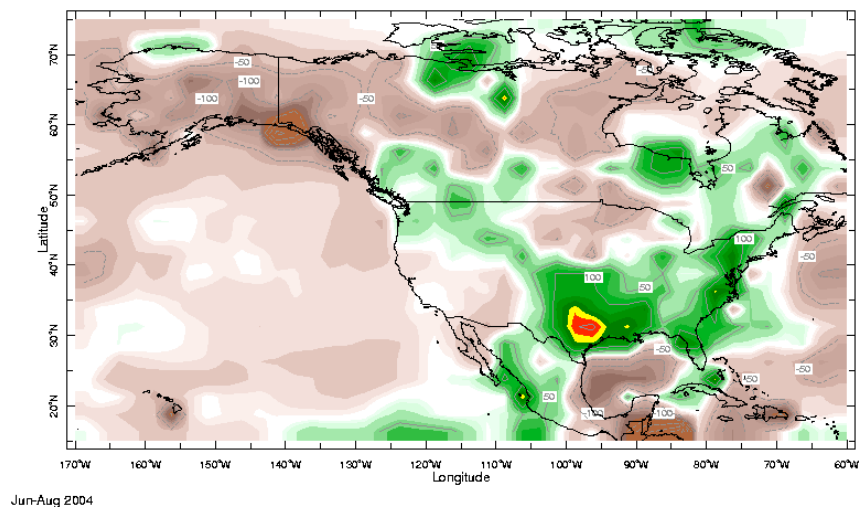
Summer Temperature 2002 Summer Precipitation



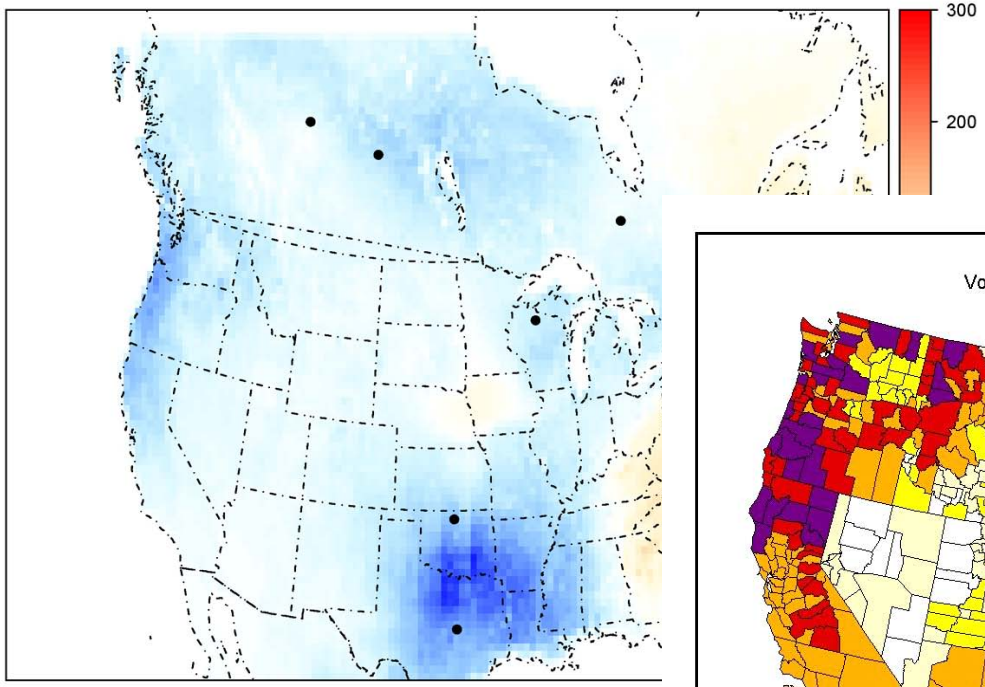


2004



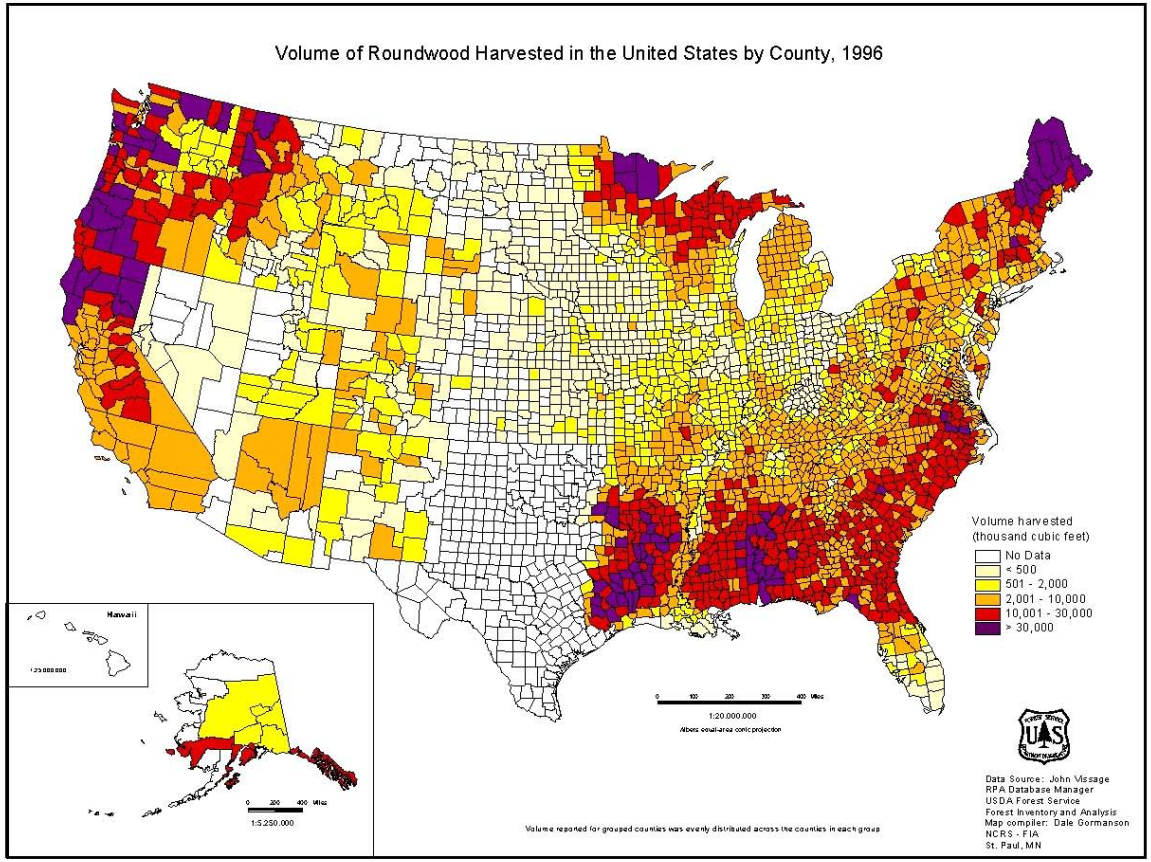


Result: Estimated 2004 Net Ecosystem CO_2 Exchange



Schuh et al, in prep

Forest Harvest



Temporal and spatial variability in regional-scale CO_2 mixing ratios as measured during the Mid-Continental Intensive study

Natasha Miles, Scott Richardson, Ken Davis, and Eric Crosson

American Geophysical Union Annual Meeting 2008: 17 Dec 2008

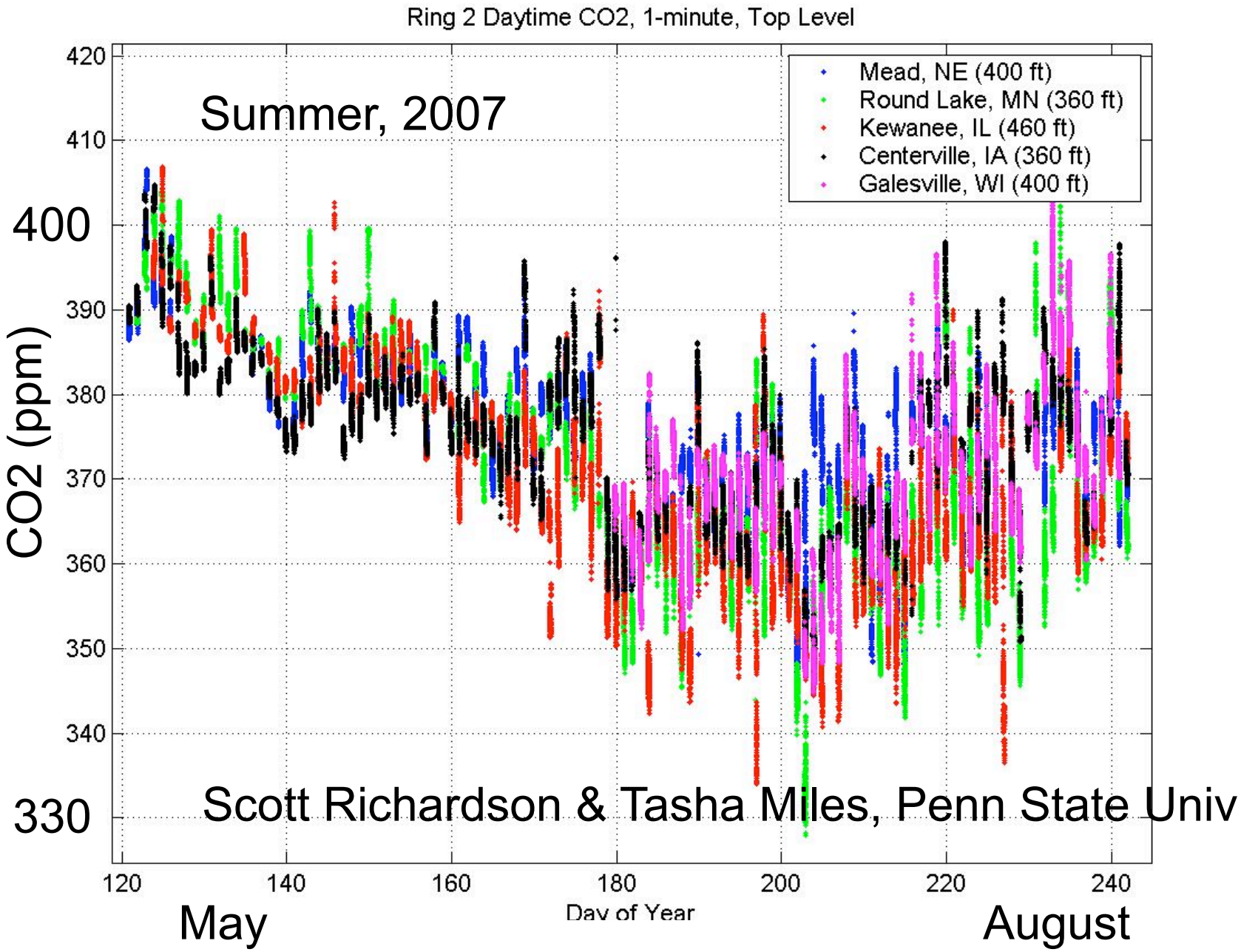
RING 2

ring2.psu.edu

PENNSTATE 1855

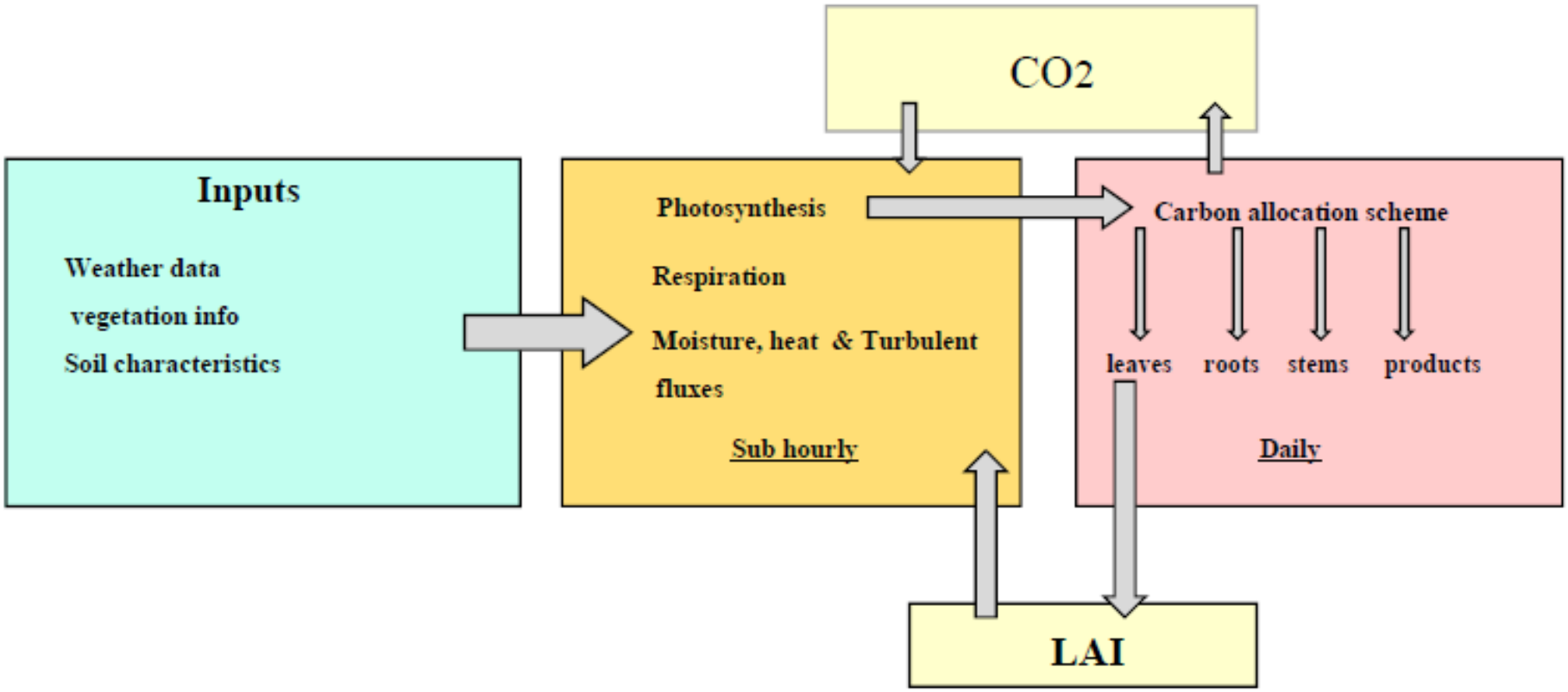
PICARRO

Corn, as seen from 100 m

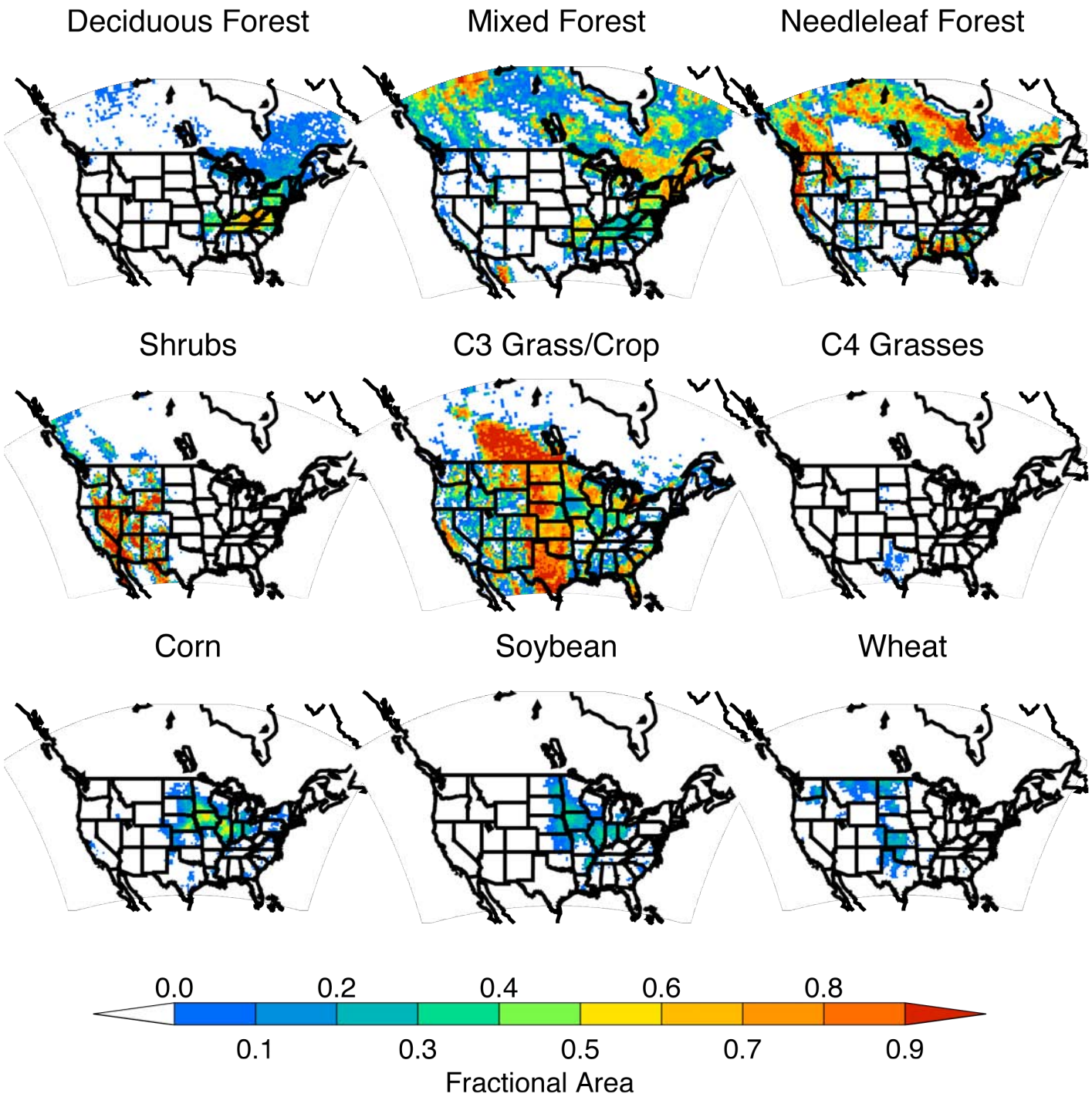


Scott Richardson & Tasha Miles, Penn State Univ

Crop Physiology Model (SiBCrop)



Erandi Lokupitiya (*Biogeosciences*) see Poster!

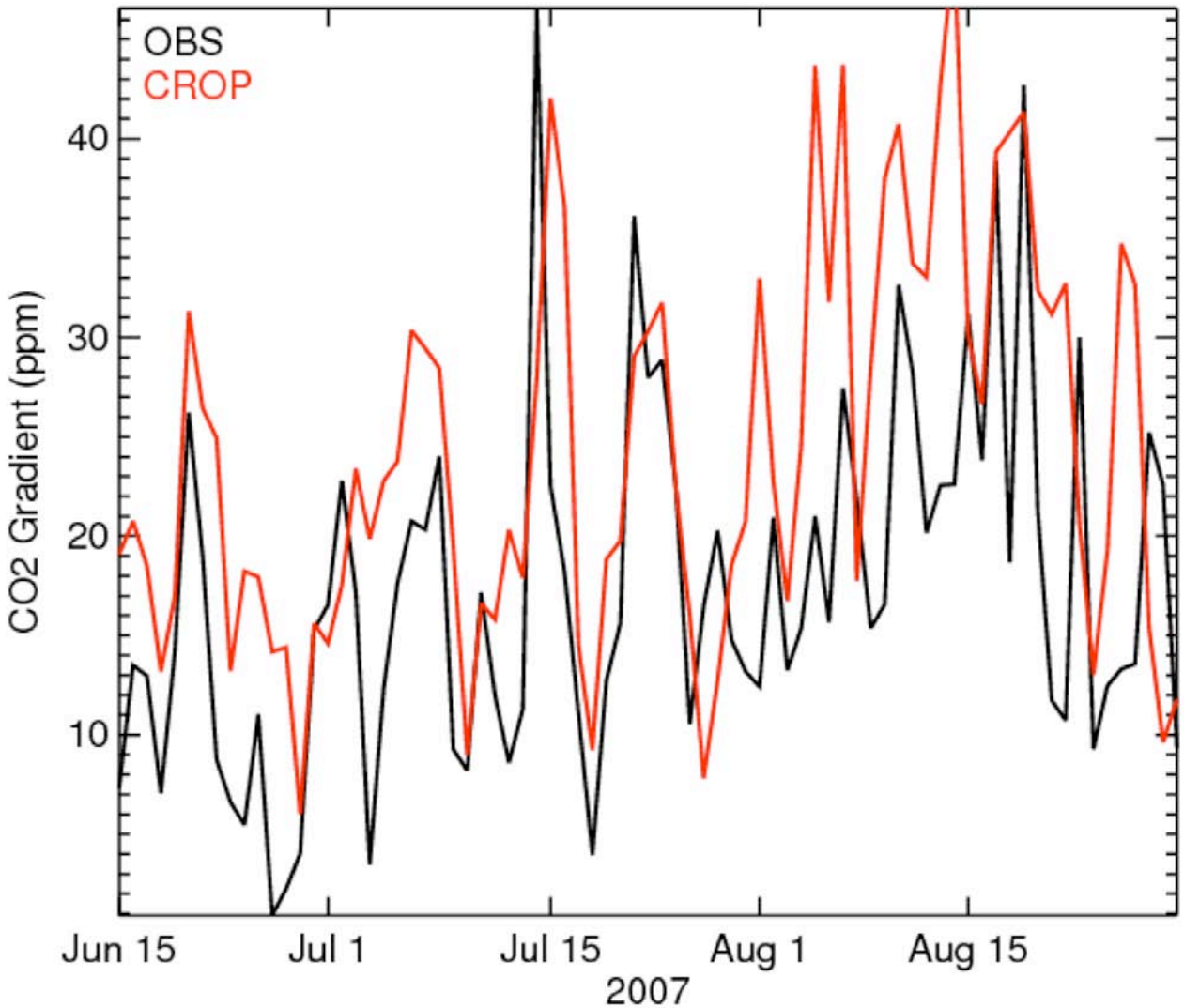


Fractional Vegetation Distribution (subgrid-scale tiles)

Multiple instances of SiB run in each 40-km RAMS cell

Fluxes are weighted by fractional area

CO_2 Gradients Across Ring2

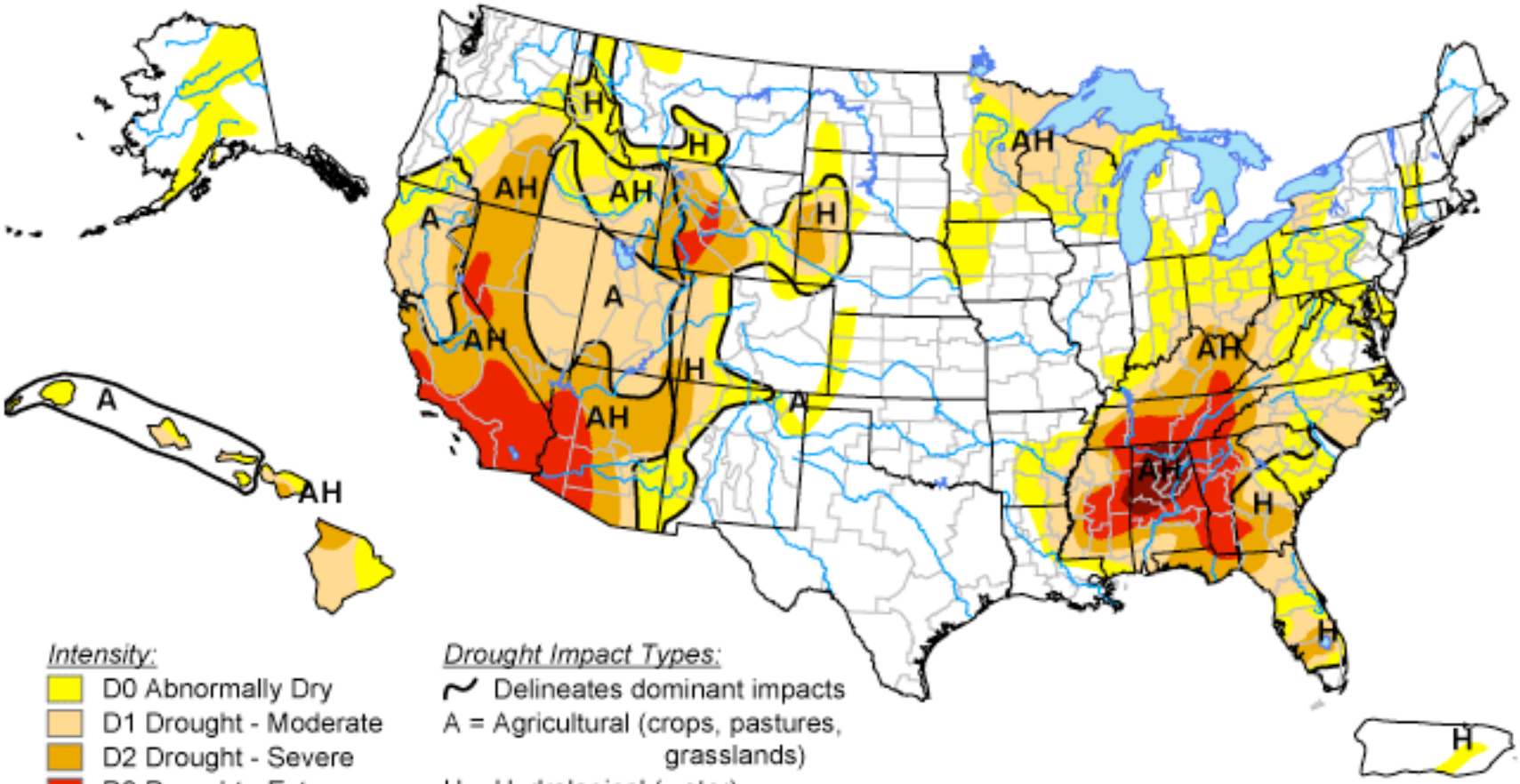


- Maximum daytime difference in CO_2 at 120 m above ground level for each day during summer 2007, as observed by the Ring2 towers and as simulated by SIB-RAMS

Corbin et al, in prep

U.S. Drought Monitor

July 3, 2007
Valid 8 a.m. EDT



Intensity:

- D0 Abnormally Dry
- D1 Drought - Moderate
- D2 Drought - Severe
- D3 Drought - Extreme
- D4 Drought - Exceptional

Drought Impact Types:

Delineates dominant impacts
A = Agricultural (crops, pastures, grasslands)
H = Hydrological (water)

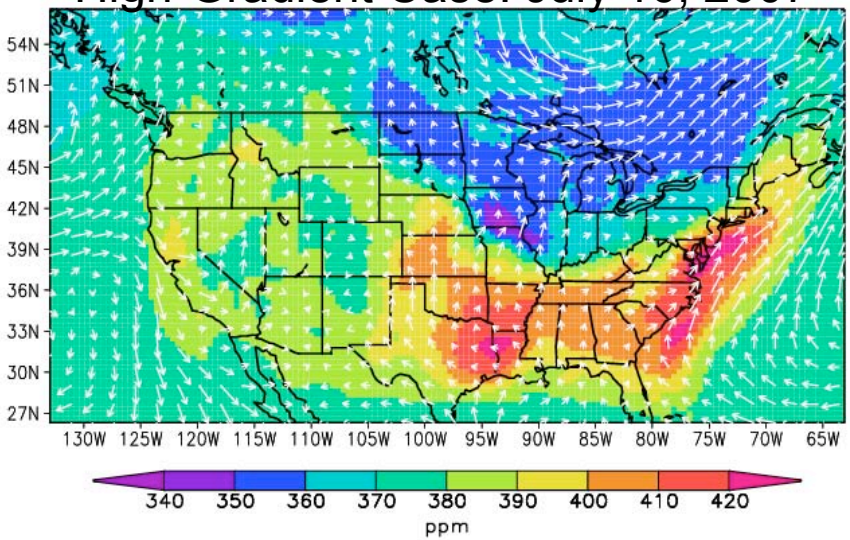
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

http://drought.unl.edu/dm

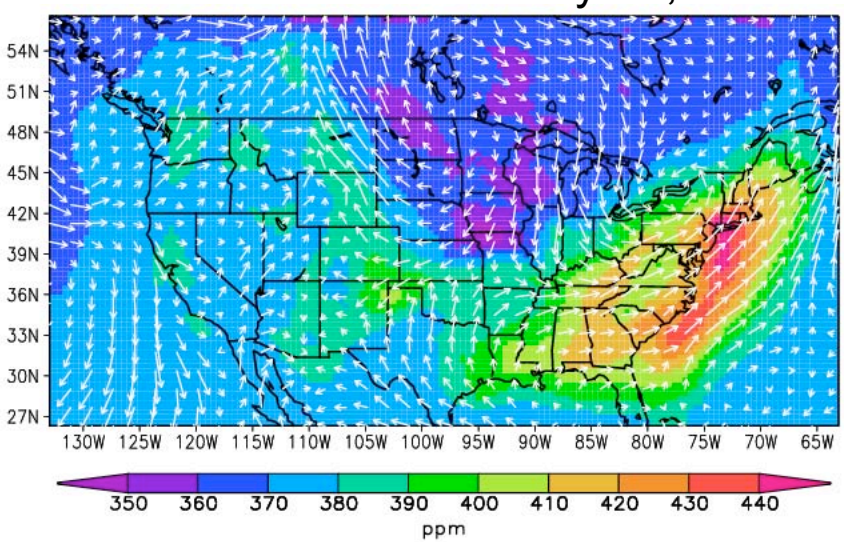
Released Thursday, July 5, 2007
Author: Douglas Le Comte, CPC/NOAA

Synoptic Controls of CO_2 Gradient
(Simulated CO2 and winds at 120 m agl)

High-Gradient Case: July 16, 2007



Low-Gradient Case: July 19, 2007

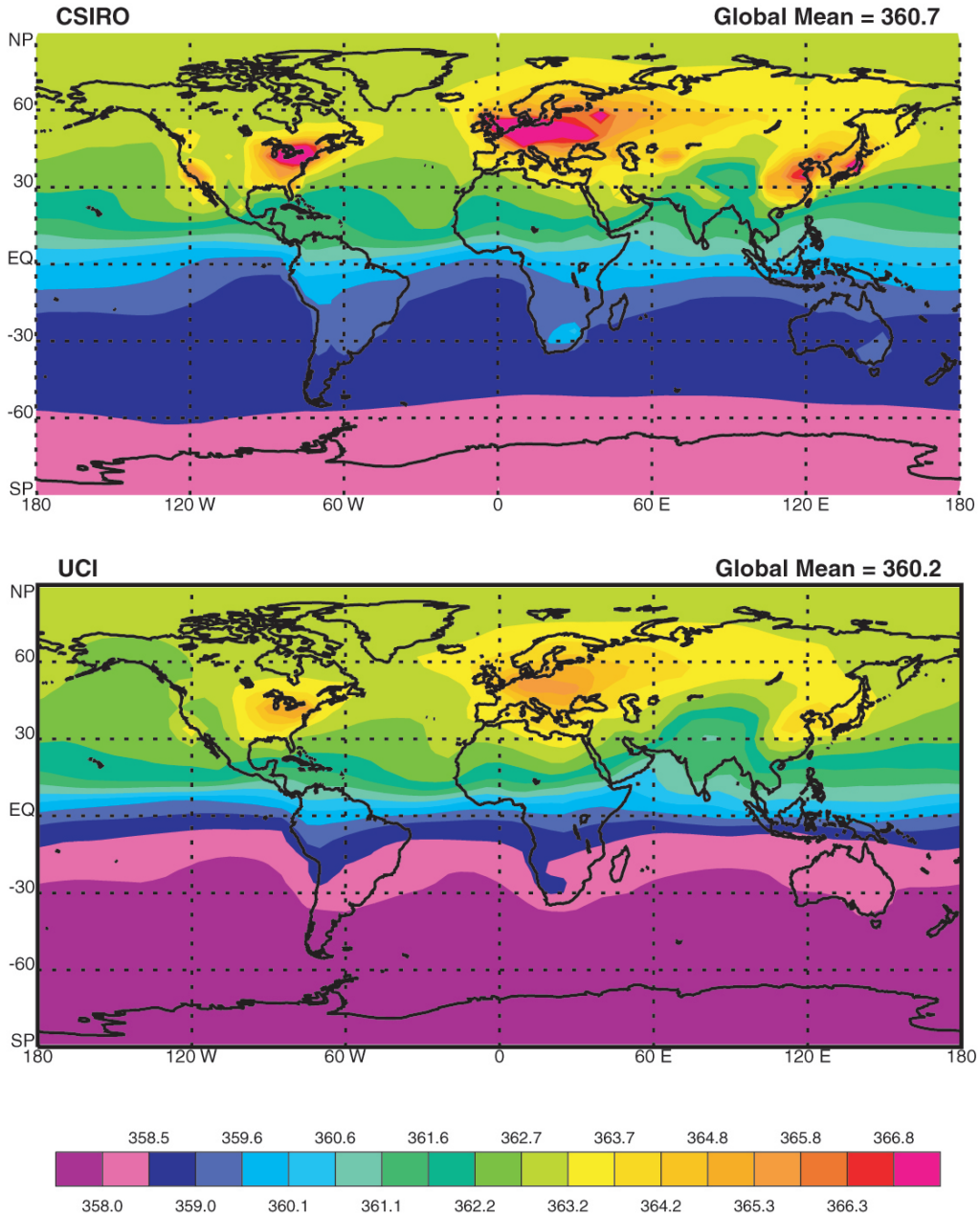


- Contrast between midwest agriculture uptake with exceptional SE drought !
- Synoptic "sloshing": Ecology meets advection
- Southerly flow from Gulf of Mexico on 7/16 enhances gradient across ring
- Northerly flow on 7/19 relaxes gradient across ring

Outline

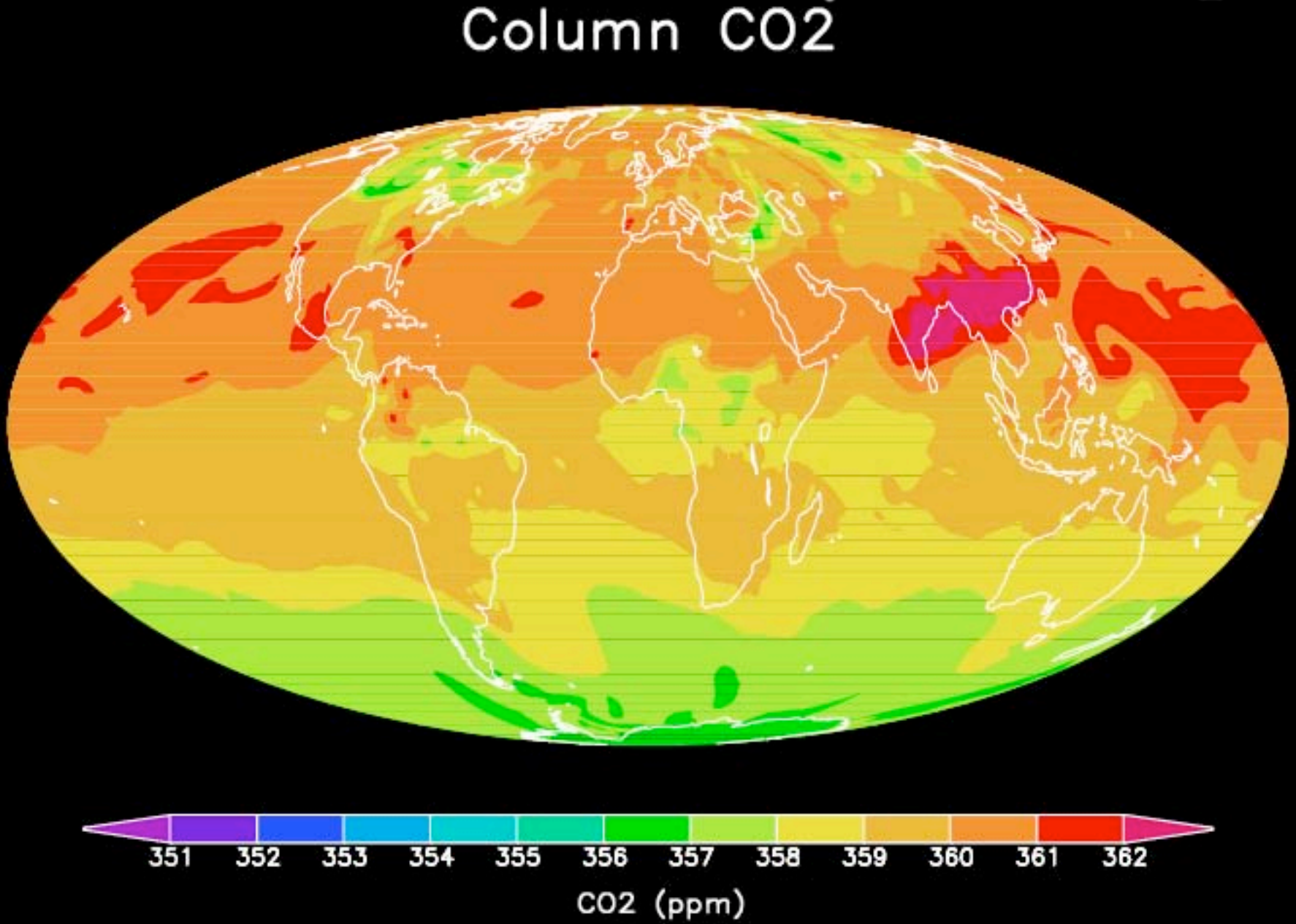
1. Dramatic growth of the atmospheric observing network under NACP
2. Diversity of measuring and inversion analysis methods (incl CO & CH4 & COS)
3. Variations in the carbon cycle of North America are driven by climate and people
4. **A new view of atmospheric CO_2**

Old View of Atmospheric CO_2



- TransCom-era simulations of annual mean gradients due to fossil fuel emissions
- State-of-the-art in 2002
- Source regions identified by gradients of less than 2 ppm
- Precision of measurements and models limit analysis

New View of Atmospheric CO_2



Conclusions

- The CO_2 observing network has grown dramatically under NACP and gives us new eyes with which to see the carbon cycle
- A diverse suite of approaches to analysis has emerged to interpret the new data
- The NA Carbon Cycle is dynamic and variable in time and space, responding to variations in climate and management
- Our new eyes have provided the first "synoptic" view of CO_2: there are huge gradients, waves, vortices and fronts
- Next week we'll take a giant leap with OCO launch!