" and now, for something completely different … "

Cloud-Scale Mass Fluxes and Tracer Transport Inversions: New Ways to Study the Global Carbon Cycle From the Air

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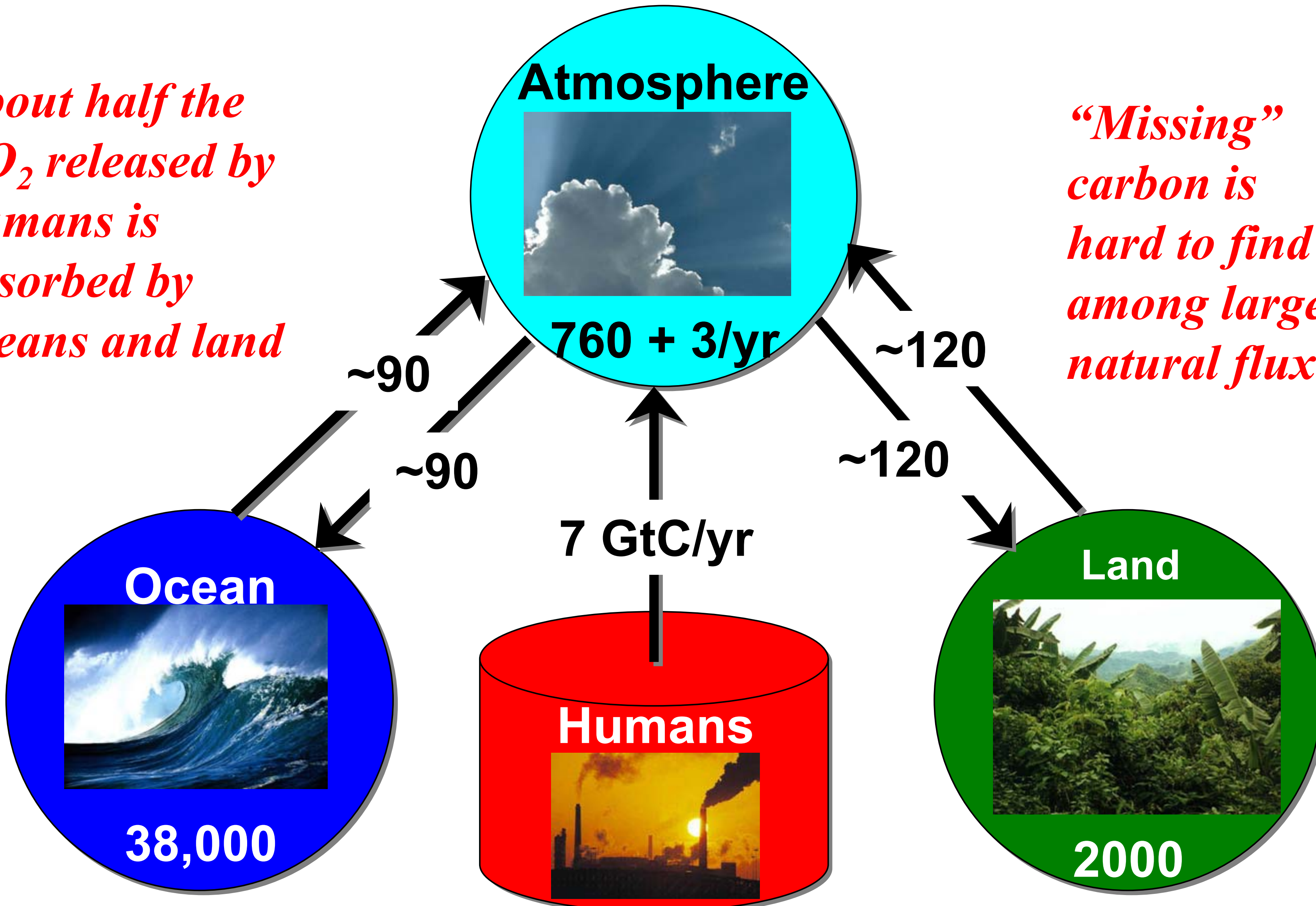
Climate Change Research Initiative

1. What aerosols are contributing factors to climate change and what is their relative contribution to climate change?
2. What are the magnitudes and distributions of North American carbon sources and sinks, and what are the processes controlling their dynamics?
3. How much of the expected climate change is the consequence of feedback processes? (clouds)

The proposed STC is well positioned to contribute substantially to every one of these highest-priority research questions!

The Global Carbon Cycle

About half the CO_2 released by humans is absorbed by oceans and land



"Missing" carbon is hard to find among large natural fluxes

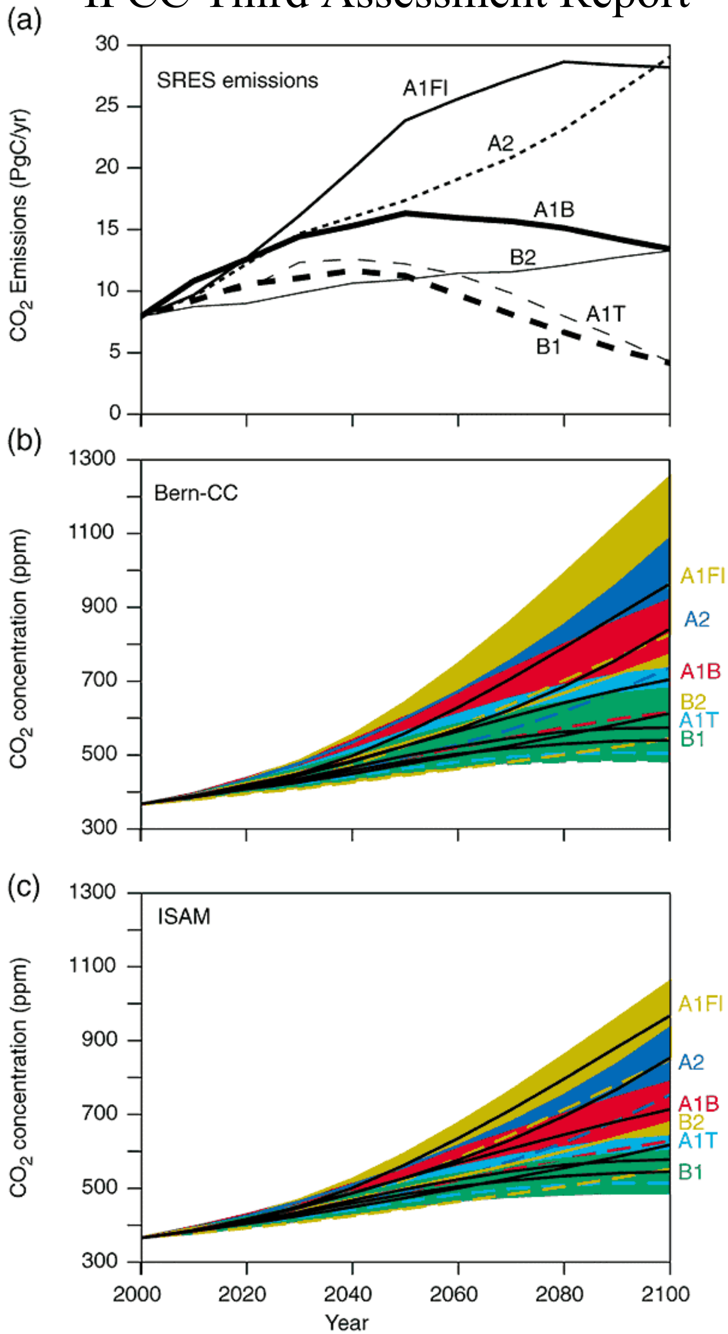
The "Missing Sink"

- Terrestrial and marine exchanges currently remove more than 3 GtC per year from the atmosphere
- This free service provided by the planet constitutes an effective 50% emissions reduction, worth at least $30 Billion per year if we had to provide it through policy changes
- Science is currently unable to quantitatively account for
  - The locations at which these sinks operate
  - The mechanisms involved
  - How long the carbon will remain stored
  - How long the sinks will continue to operate
  - Whether there is anything we can do to make them work better or for a longer time

Where Has All the Carbon Gone?

- Into the **oceans**
  - **Solubility pump** (CO_2 very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow "rain" of organic debris)
- Into the **land**
  - **CO_2 Fertilization**
    (plants eat CO2 … more is better)
    "the gift that keeps on giving"
  - **Nutrient fertilization**
    (N-deposition and fertilizers)
  - **Land-use change**
    (forest regrowth, fire suppression, woody encroachment …)
  - Response to **changing climate**
    (e.g., Boreal warming)

IPCC Third Assessment Report

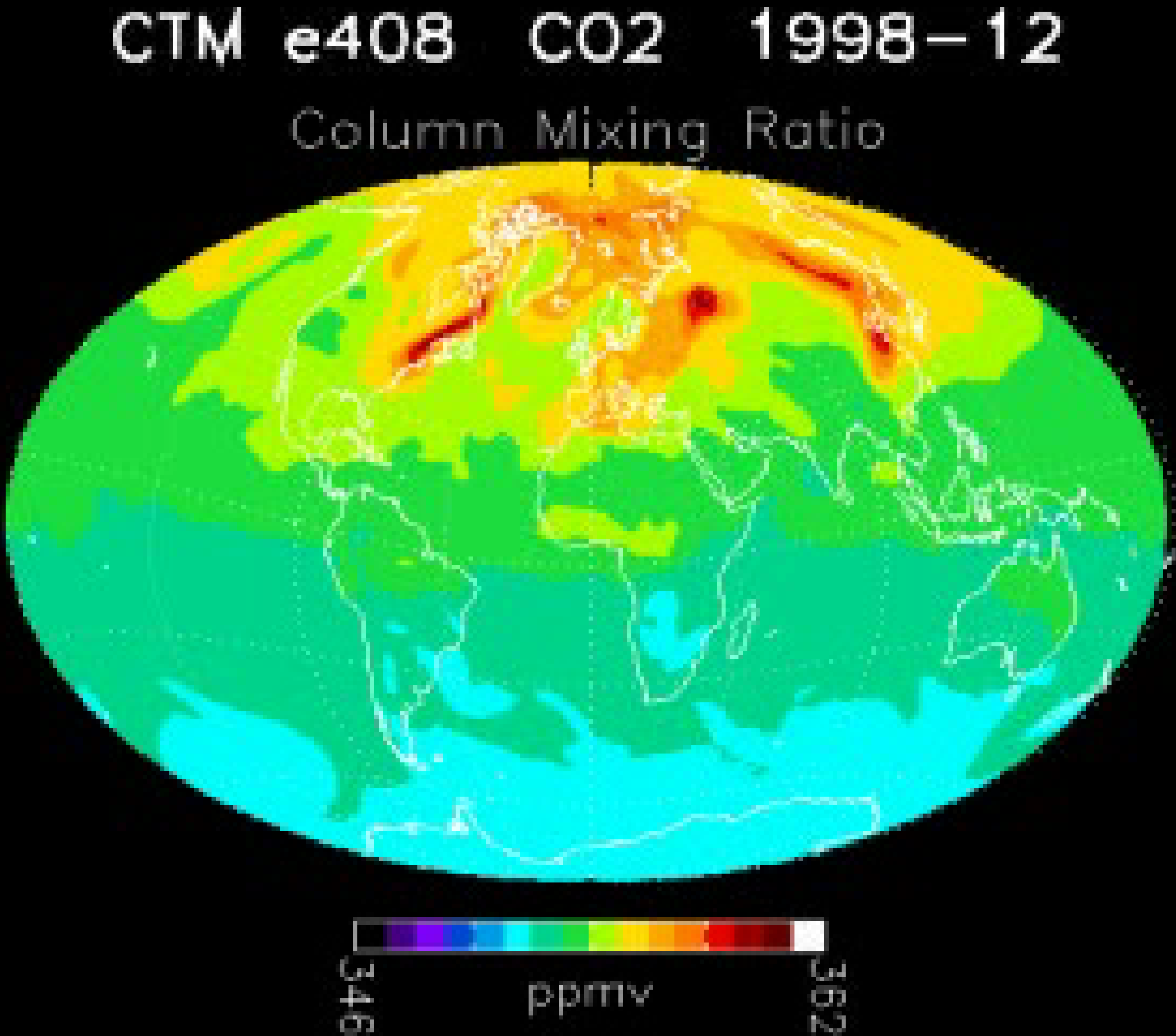


CO_2 Sensitivity

- Each carbon cycle model also produced a "high" and "low" estimate
- In Bern-CC, the high estimate assumed current sinks are not primarily driven by CO2 fertilization, so capped them at 2000 levels
- This resulted in nearly 300 ppm extra CO2 in 2100!
- Only the "central" estimates, with sinks scaling with CO_2, were used in climate scenarios

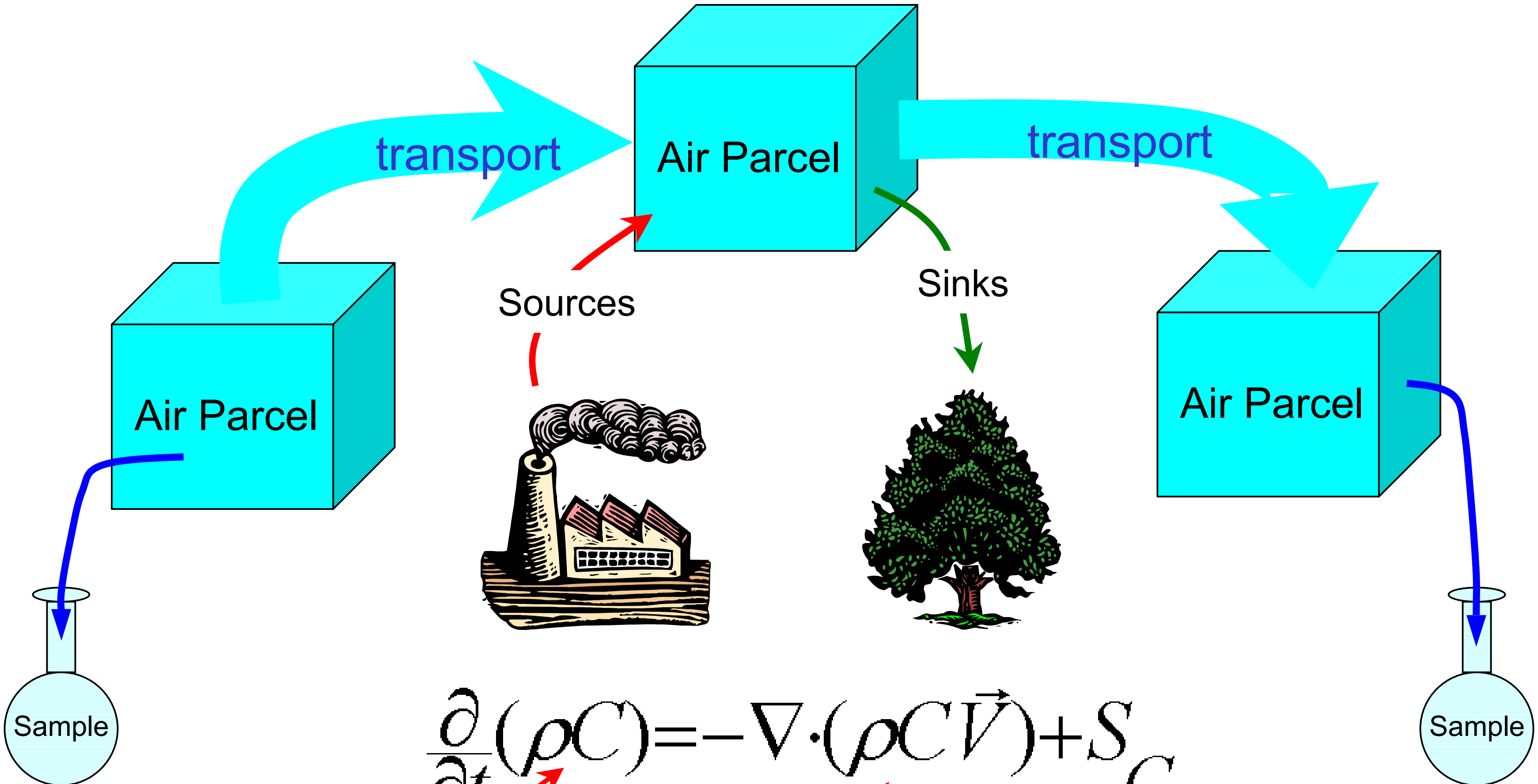
The Atmosphere as a Blurry Lens

- We use the atmosphere to help us understand carbon cycle processes that act at the surface
- From the "bottom up," we develop process-based models of sources and sinks, then test them by evaluating against atmospheric data collected at many scales
- From the "top down," we use inverse modeling and data assimilation techniques to estimate source and sink strengths by mass balance, from variations in the CO_2 mixing ratio



Randy Kawa, GSFC

Inverse Modeling of CO_2



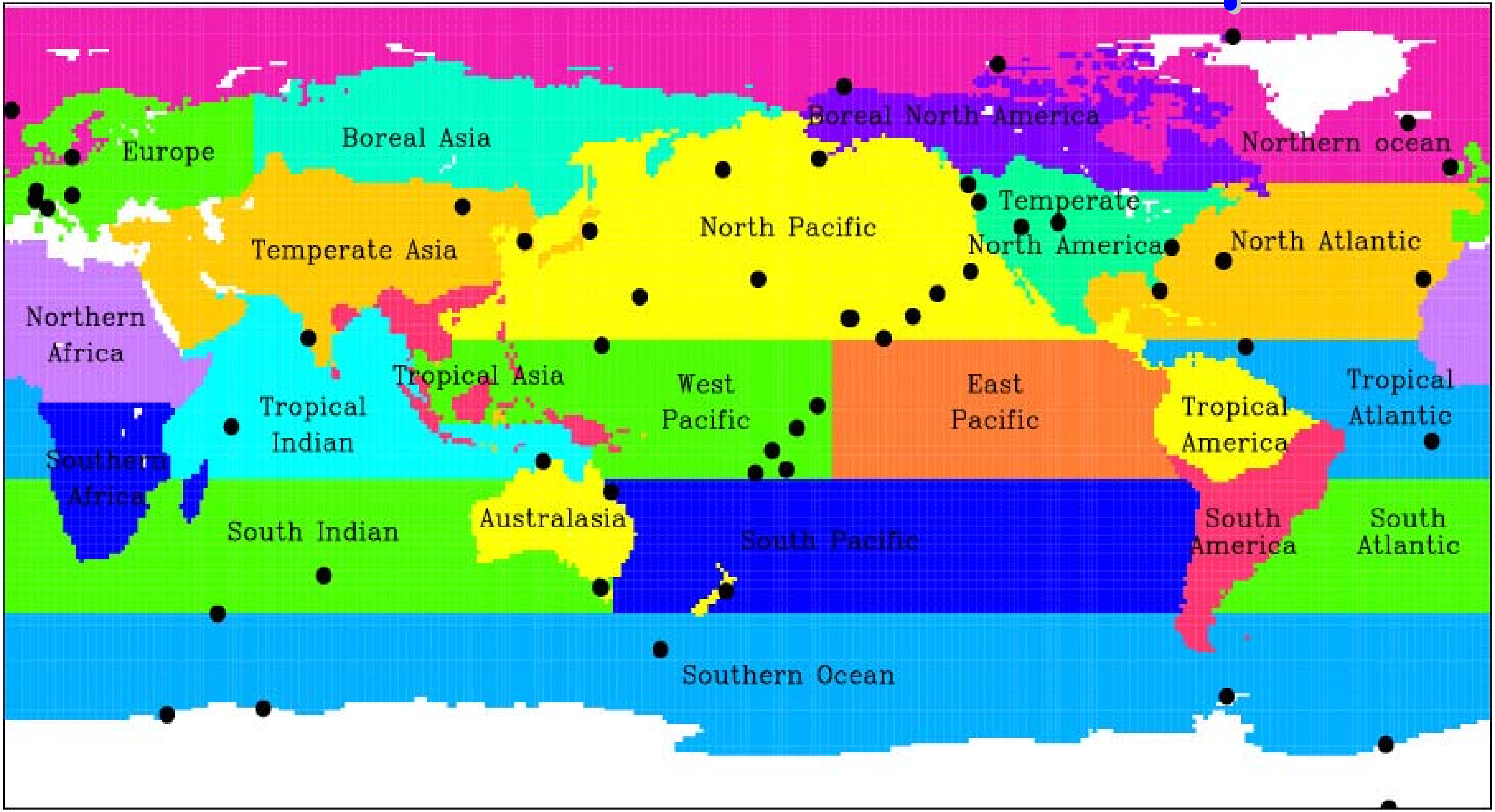
$$\frac{\partial}{\partial t}(\rho C) = -\nabla \cdot (\rho C \vec{V}) + S_C$$

concentration (observe)

transport (model)

sources and sinks (solve for)

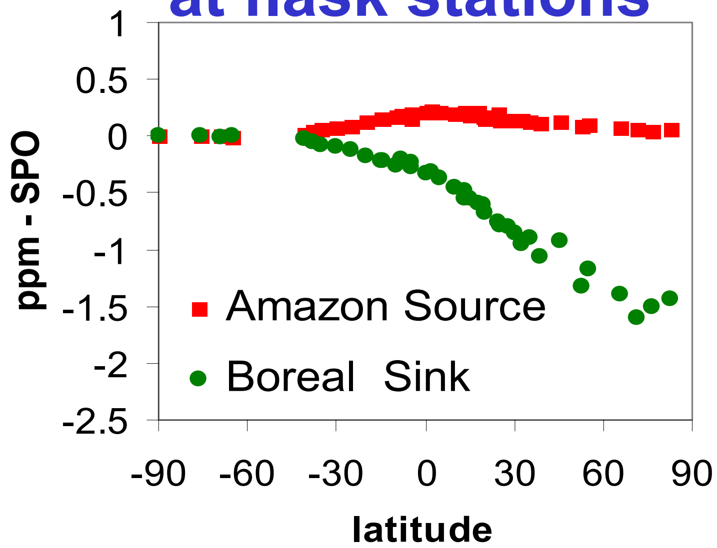
Global Inversion Setup



- Compute Green's Functions for monthly emission pulses from each of 22 regions in each of 12 months in each of 16 transport models
- Estimate monthly CO2 fluxes by optimizing to monthly observations at ~ 75 (mostly remote) sites

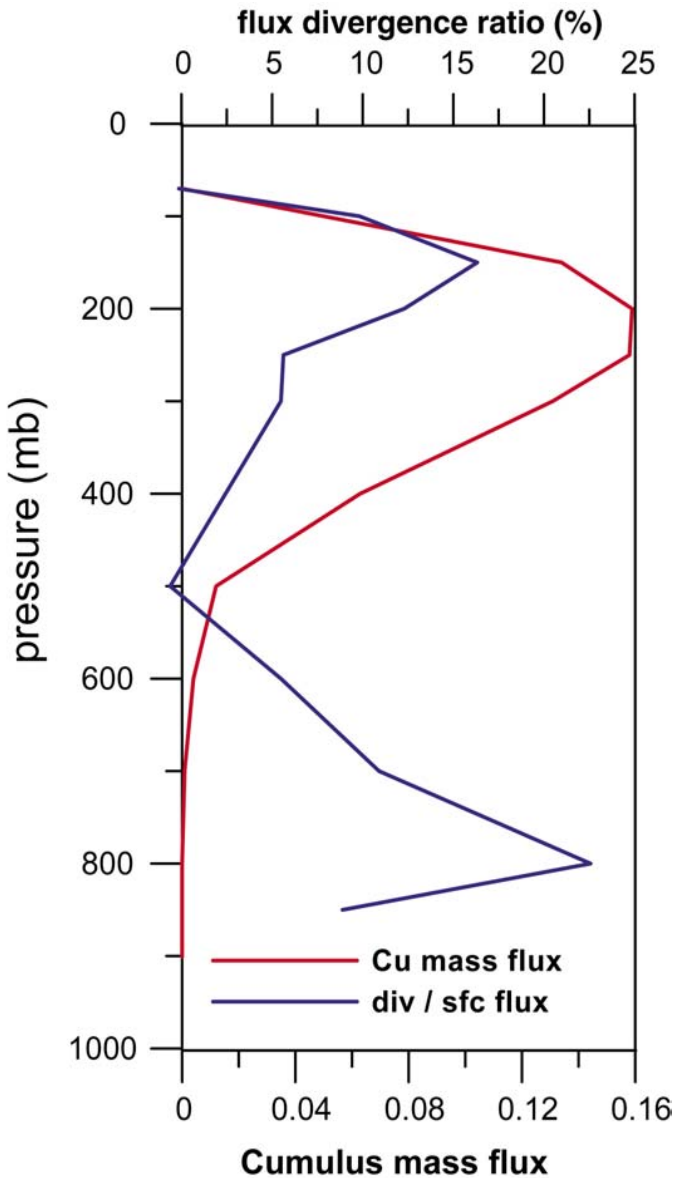
Unconstrained Tropical Fluxes

Simulated Concentrations at flask stations



- Concentration response due to a 1 GtC/yr flux in the Amazon is much weaker than response due to a 1 GtC/yr flux in boreal forest
- This weak response is also poorly sampled in near the tropical continents

Convective "Leakage"

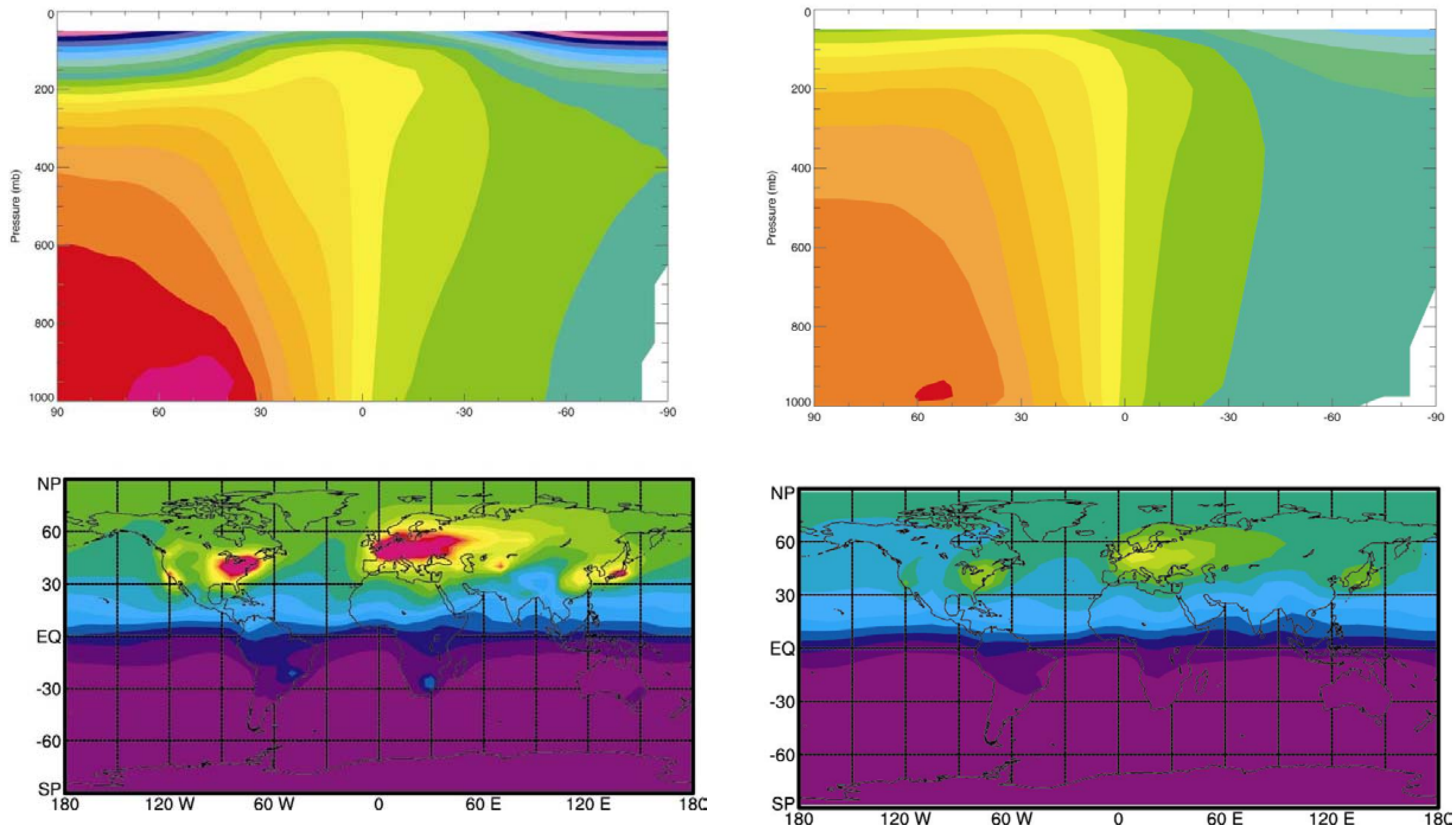


- Photosynthesis and cumulus convection are correlated in time and space in parts of the deep tropics
- Convective updrafts carry much of the "signal" of ecosystem flux aloft
- As much as 30% of the flux due to ecosystem metabolism leaves the atmospheric column in the upper troposphere, but nobody is looking there!

Two Views of the World

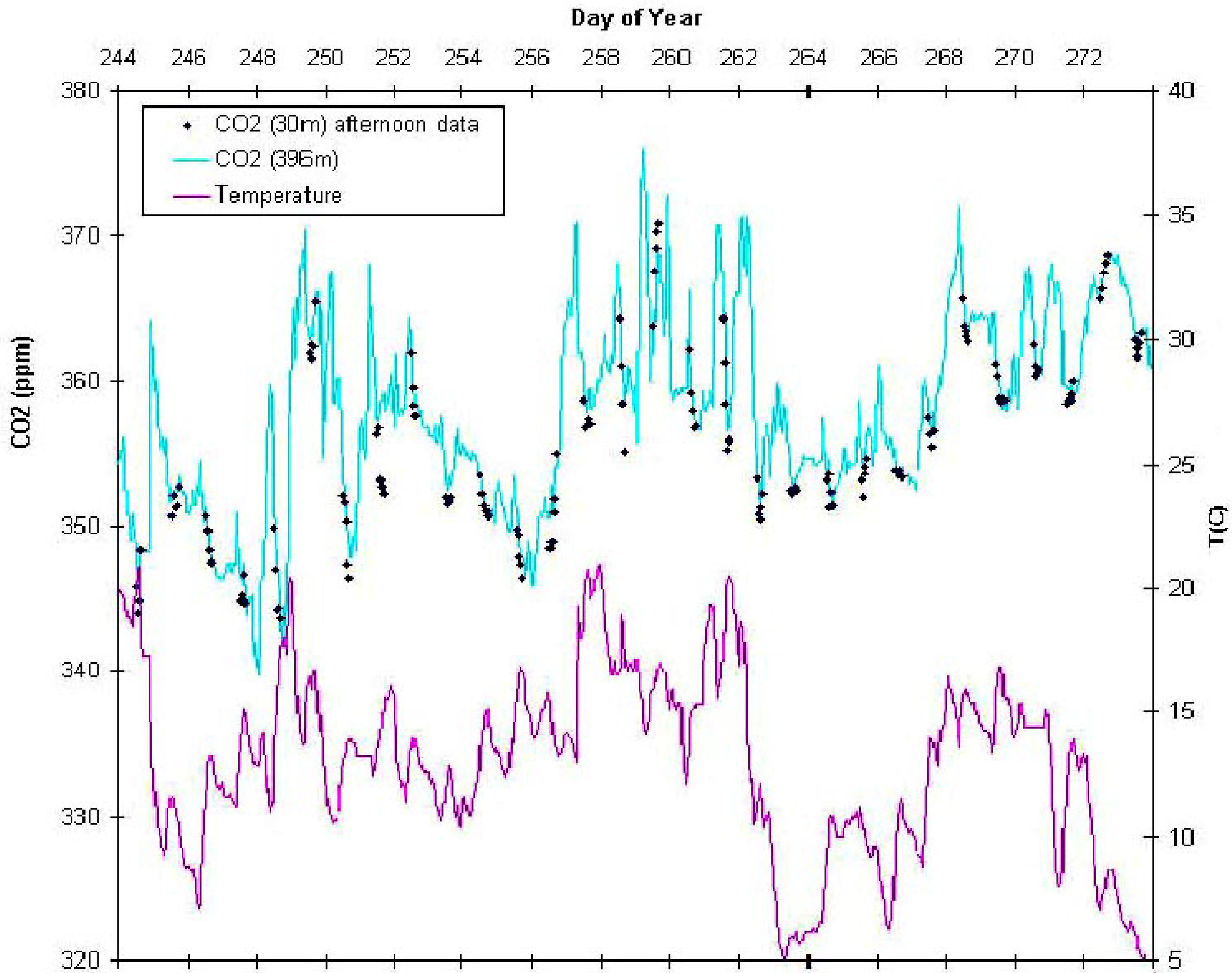
simulated annual mean SF_6

TM3 TM2

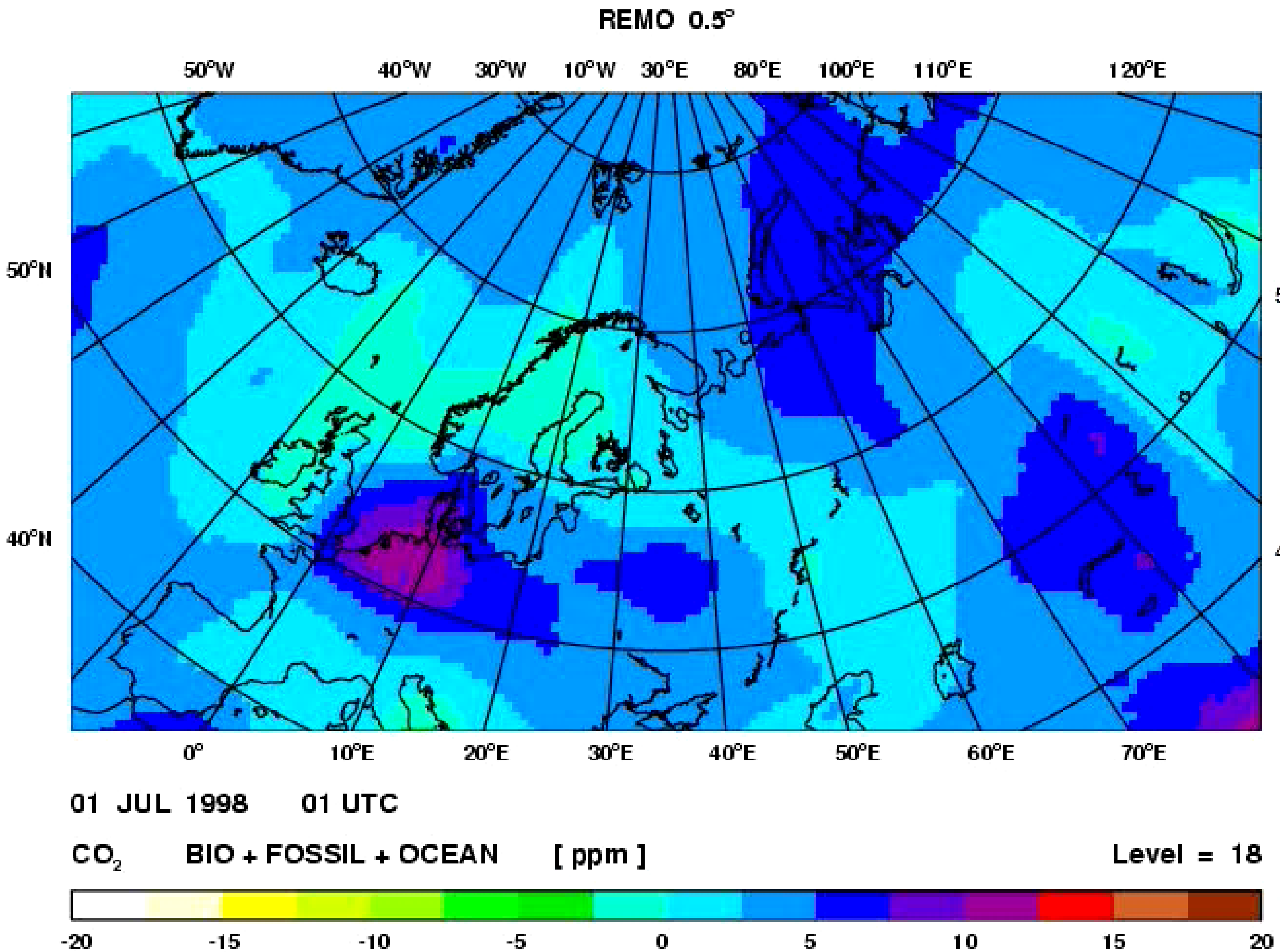


Two leading transport models using the same ECMWF winds, but different convective transport schemes

Huge Regional Signal!



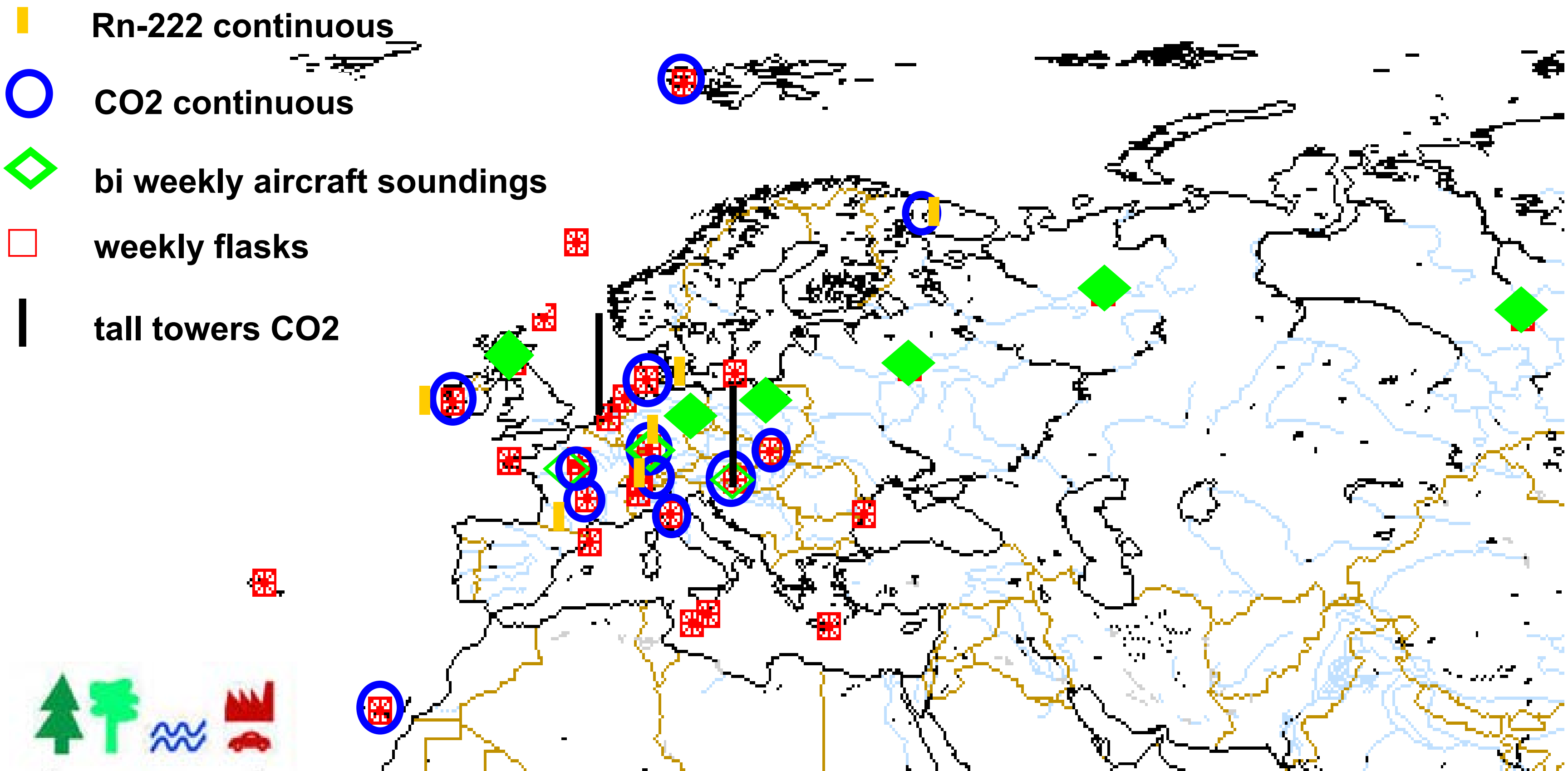
Variations of ~ 30 ppm at WLEF on synoptic time scales strongly correlated to frontal passages



TURC/NDVI Biosphere, Takahashi Ocean, EDGAR Fossil Fuel

(Ute Karstens and Martin Heimann, 2001)

European Observations of Atmospheric CO_2



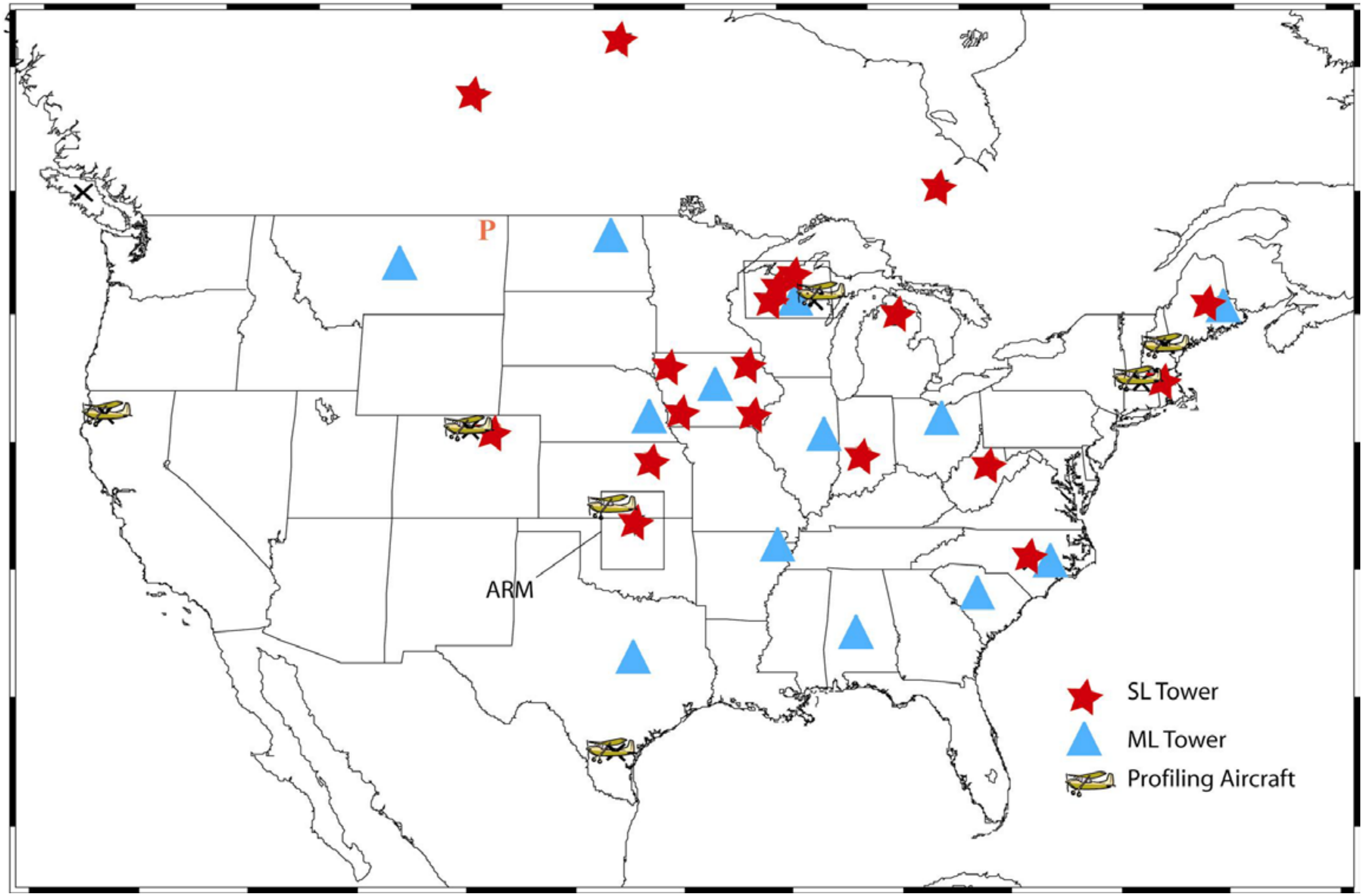
Aerocarb

** Map of European atmospheric network in 2001 (7 european labs , CMDL, CSIRO)*

North American Carbon Program

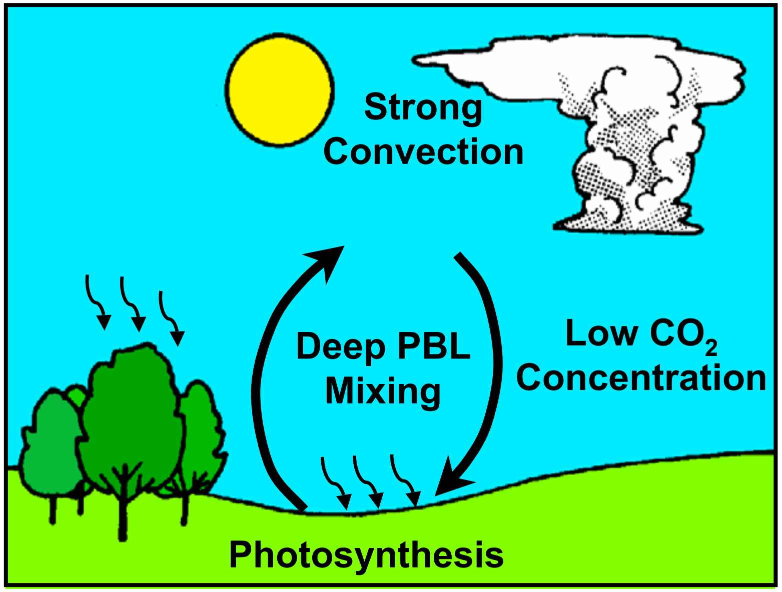
http://CarbonCycleScience.gov/nacp.pdf

North American in-situ CO_2 Observing System c. 2005

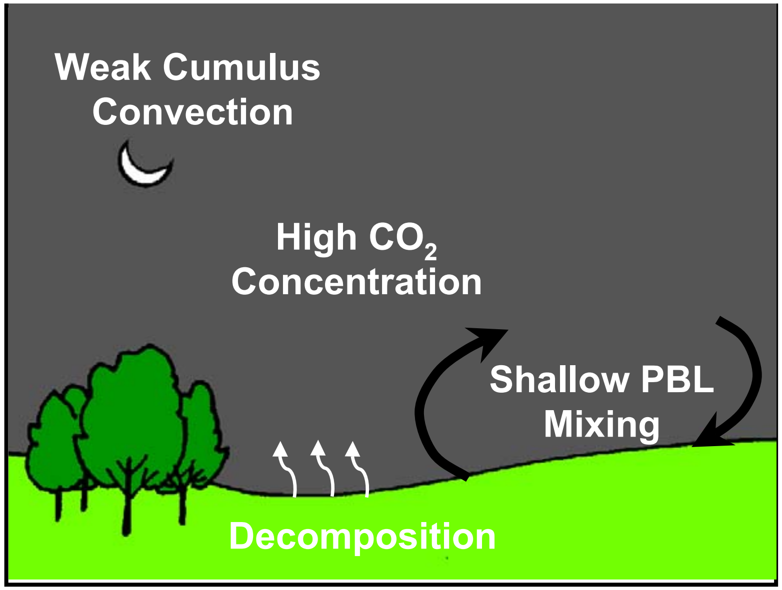


Diurnal Rectifier Forcing

Mid-day



Midnight



Dilution of photosynthesis signal through deep mixing

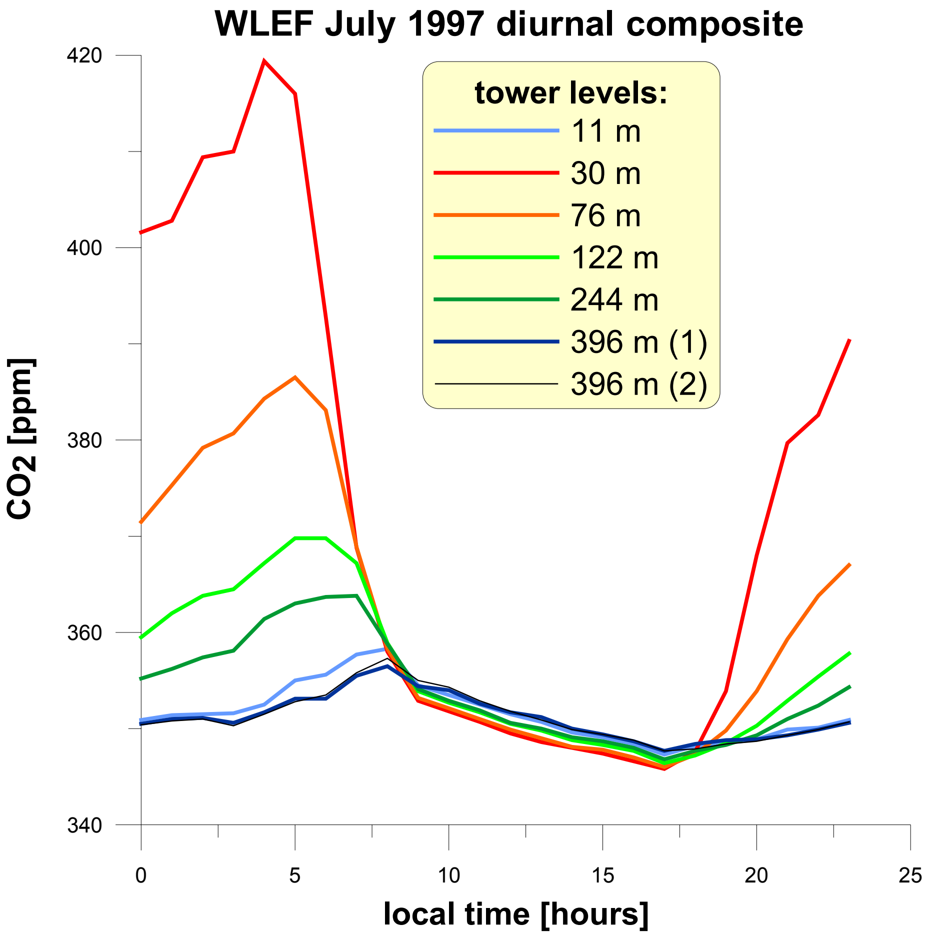
Transport of low-CO_2 air into upper troposphere

Accumulation of respiration signal near the surface

Elevated CO_2 in lower troposphere

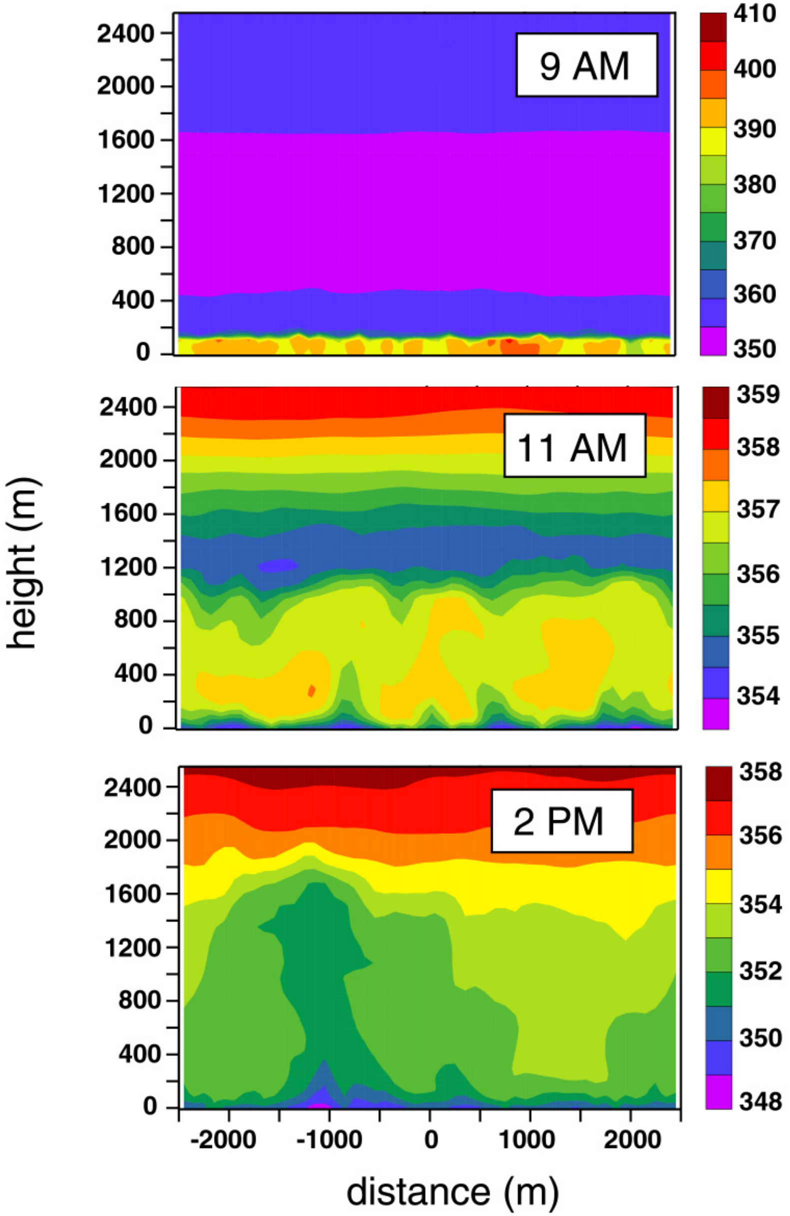
Daily mean: Accumulation of CO_2 near the ground, depletion aloft

Diurnal Cycle of CO_2 at WLEF



- Diurnal cycle of 70 ppm over an active forest is 5x as strong as seasonal cycle
- Vertical gradient at sunrise is 15x as strong as pole-to-pole gradient
- Vertical gradient reverses in daytime, much weaker
- Monthly mean [CO2] decreases upward, even though forest is a strong sink in July!

Development of a CO_2 "Mixed Layer"



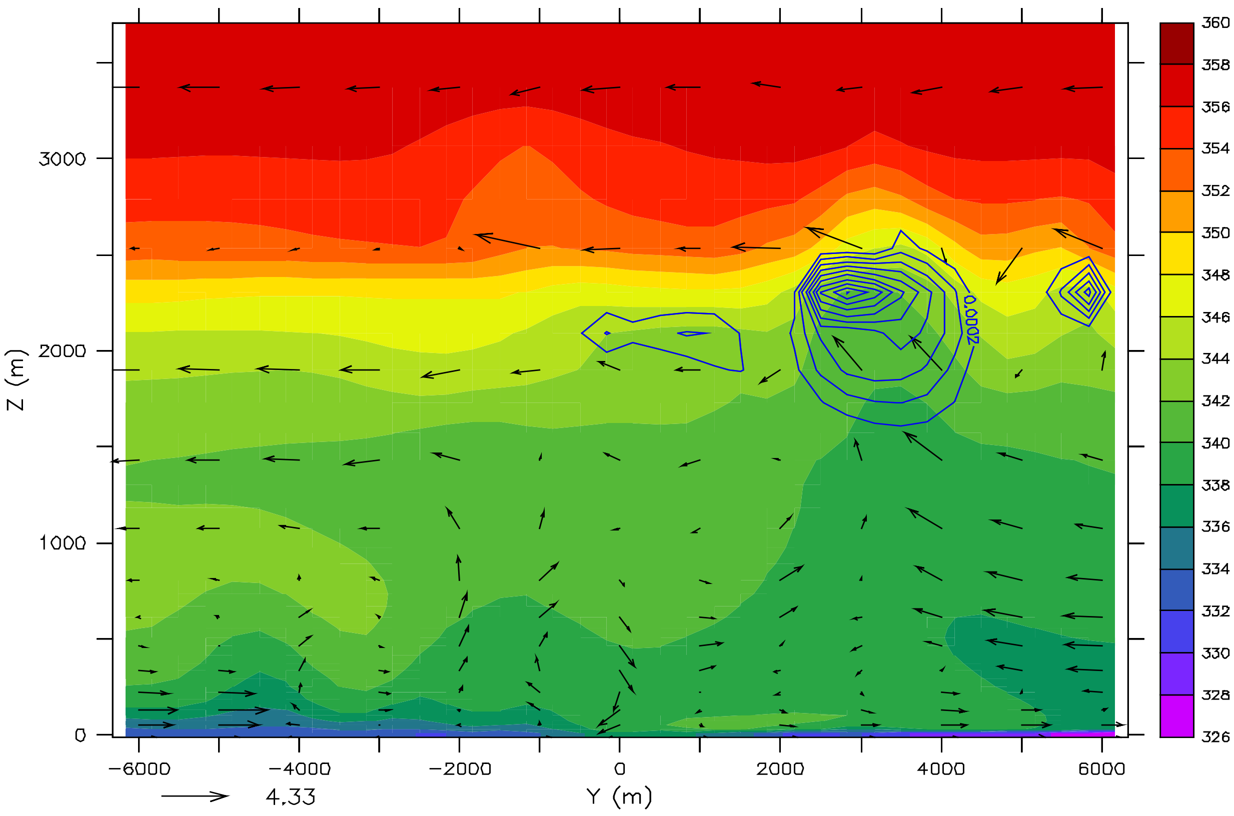
Coupled SiB-RAMS simulation

$\Delta x = 100$ m, $\Delta z=20$ m

- Nocturnal respiration produces extremely high concentrations in morning stable layer
- Surface heating and TKE generation causes entrainment of lower-CO_2 air from aloft
- Photosynthesis depletes CO_2 in surface layer
- Buoyant plumes of low-CO_2 air fill the convective boundary layer

Denning et al, 2003

Effects of PBL-top clouds



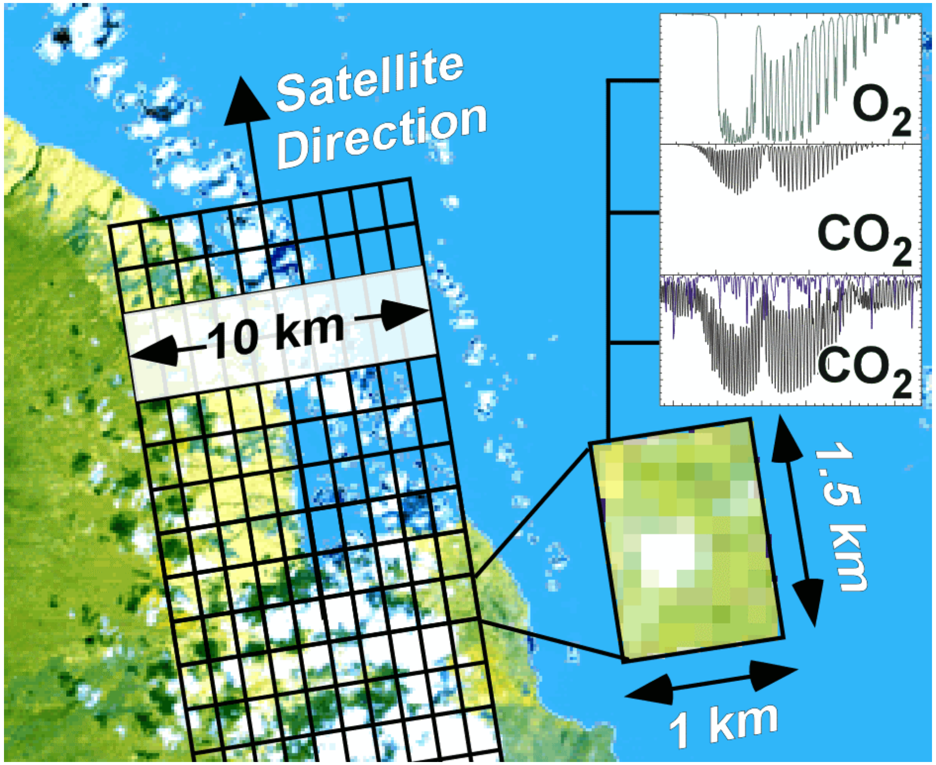
- Thermals carry forest signal to PBL top
- Clouds transports ventilate PBL into free troposphere

Color: CO_2 contours: cloud liquid water vectors: wind

Nicholls et al, 2003

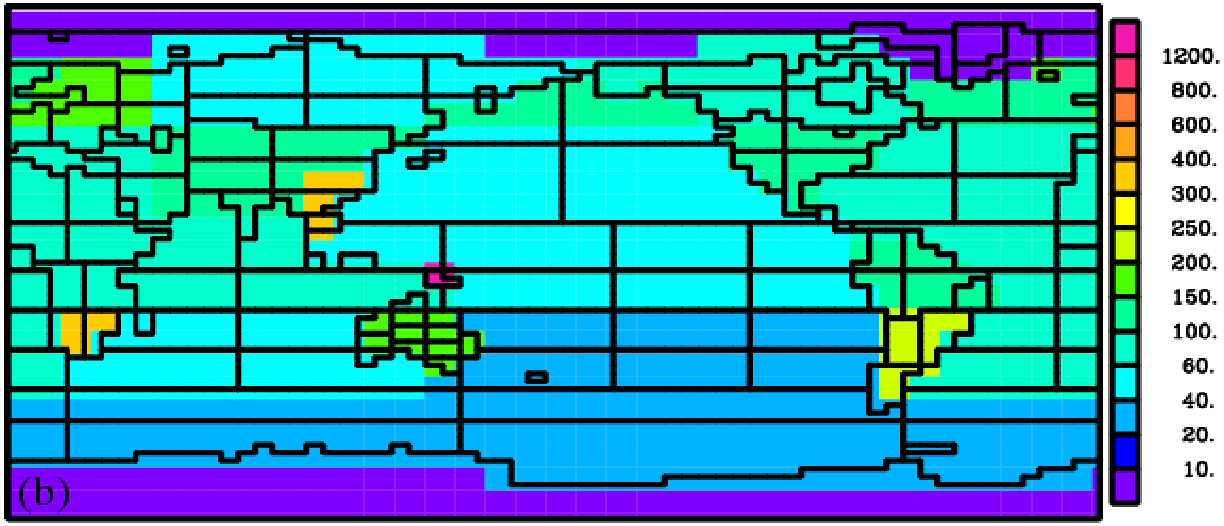
Orbiting Carbon Observatory (OCO)

2-year ESSP mission scheduled to launch in 2007



- Three bore-sighted grating spectrometers to estimate column CO_2 and O_2 (~1.6 ppm)
- Sun-synchronous, 13:30 ECT (A-train)
- 1x1.5 km IFOV to "see between clouds," 10 pixel swath
- Spatially dense CO_2 in a bright sunny world

Potential Satellite CO_2 Inversion



RMS of monthly uncertainty in flux retrieval ($g\ C\ m^{-2}\ yr^{-1}$)

- Pseudodata inversion of passive NIR retrieval
  - 8 km cloud mask (overly pessimistic)
  - 1.8 ppm uncertainty on each of 234,000 measurements
  - Invert hourly means, calculate flux uncertainties
- Result: ~ 80-150 $gC\ m^{-2}\ yr^{-1}$ over most continents
- Equivalent to ~ 1 μMol $m^{-2}\ s^{-1}$ uncertainty in regional daytime photosynthesis … powerful constraint on process models of carbon exchange!

Possible Sources of Bias in New Obs

Surface carbon exchange (biology) covaries with meteorology on many time scales!

- Diurnal cycle
- Seasonal cycle
- Cloud/clearsky bias

Unresolved atmospheric transport processes may significantly affect [CO2] mixing ratio

- PBL entrainment and diurnal pumping
- Cumulus-scale updrafts and downdrafts
- Frontal lifting

Advantages of SP for CO_2 Inversions?

- Archive grid-scale turbulent and convective mass fluxes from CSRM
- Use archived winds and mass fluxes to drive very simple offline transport model to calculate Green's functions
- Simple advection/convection model has no `IF-THEN-ELSE` constructs … self-adjoint!
- Excellent framework for fine-scale 4DVAR of carbon fluxes on model grid and time step, if observations are available

Summary (1)

- Interactions between climate and the carbon cycle are among the most important contributors to uncertainty in future climate (one of 3 highest priorities of CCRI)
- Atmospheric [CO_2] variations are an important source of information about underlying source/sink processes
- Tracer transport inversions to date have been strongly data-limited, but this is about to change dramatically!
- New sources of in-situ and remotely sensed data can potentially revolutionize the study of the carbon cycle

Summary (2)

- By 2007, we will be swimming in hourly and daily observations of atmospheric carbon
- Quantitative interpretation of the new data will be critically dependent on correct representation of
  - Vertical structure of transport by turbulence and moist convection
  - Diurnal and seasonal variations of these transports
- **The research being considered by the proposed STC could make a huge contribution to Earth System science, way beyond clouds and the hydrologic cycle!**

Earth System Data Assimilation

Carbon Cycle Science Fiction?

- *Coupled* predictions of weather, photosynthesis, transpiration, decomposition, air-sea gas exchange, wind-driven currents, thermohaline circulation, nutrients
- Develop a generalized cost function that measures the error in these predictions
  - T, q, u, clouds, ocean color, SST, currents, FPAR, veg spectral properties, tower fluxes, biomass, soil moisture, [CO_2], stable isotopes
- Optimize model state and parameters according to partial derivatives of cost function with respect to each observable
- "Memory" of slow processes helps constrain solution