Carbon Cycle Introduction

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2nd NCAR-MSRI Summer Graduate Workshop on Carbon Data Assimilation

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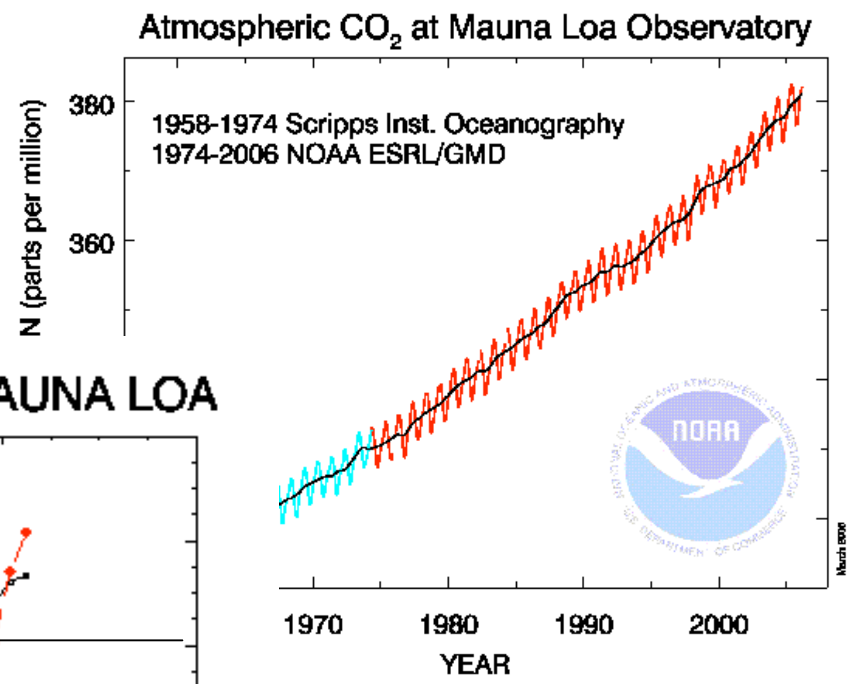
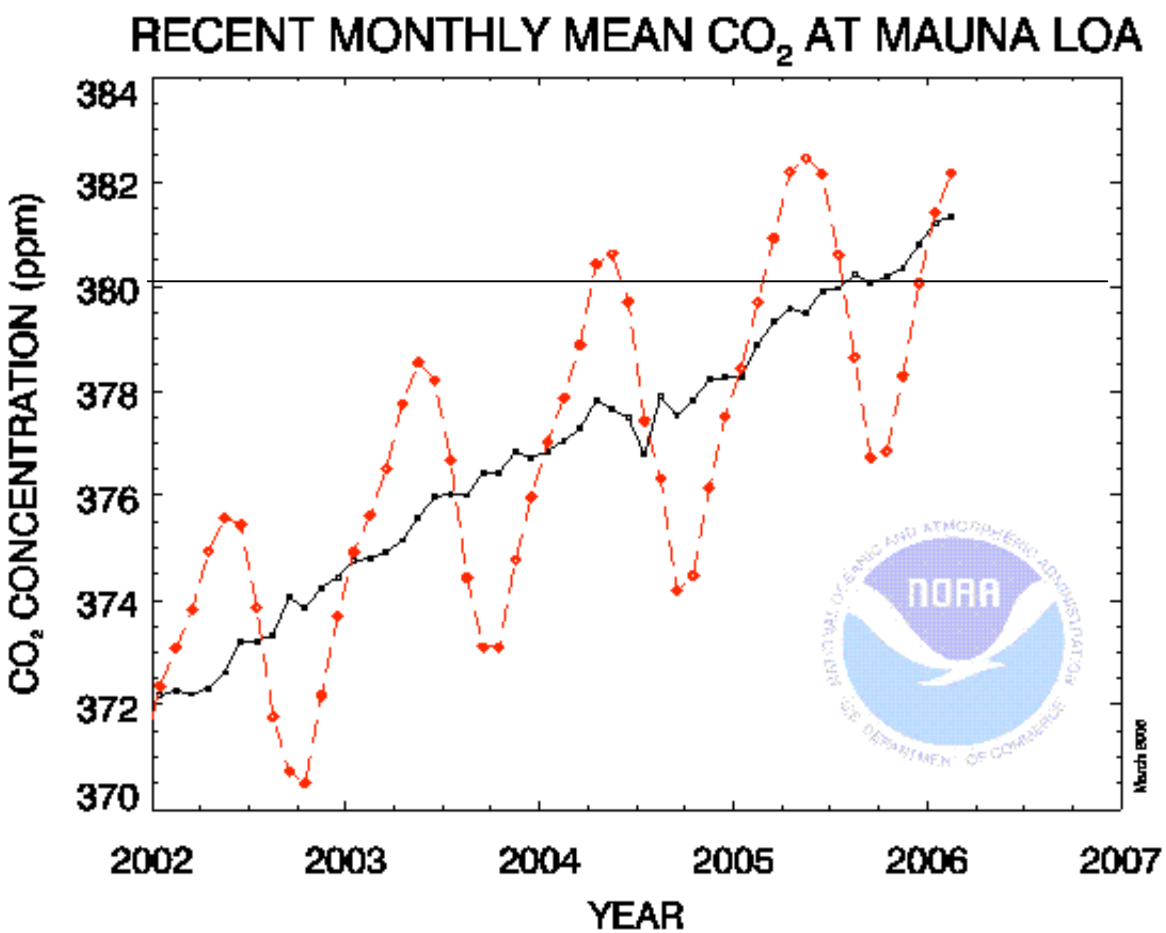
High-precision Atm CO_2: at MLO since 1958





- **180 ppmv Last Glacial Maximum**
- **280 ppmv in the preindustrial (~1800AD)**
- **380 ppmv in 2005**

Units

$$C(kgC/m^3) = \rho(kgAir/m^3) \times X(moleC/moleAir) \times (MWt_C/MWt_{air})$$

$$MWt_C = 12gm/mole; MWt_{air} = 29gm/mole$$

$$Area = \int dxdydz = 5 \times 10^{14}(m^2)$$

$$MassAtm = \int \rho dxdydz = \frac{100P_{mb}}{g}(kgAir/m^2) \times Area \sim 5 \times 10^{18} kgAir$$

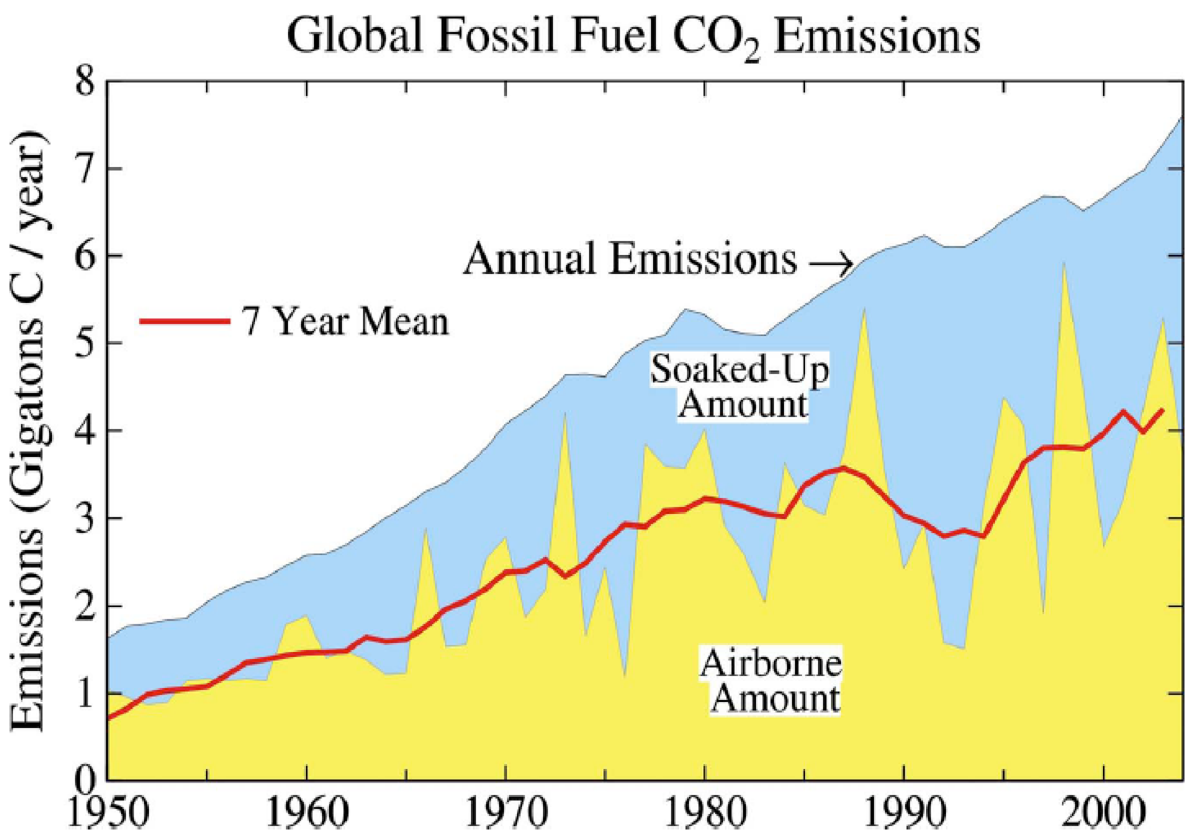
$$MassC(300\,ppmv) = MassAtm \times (300\,x10^{-6}) \times ({}^{12}\!/_{29})$$

$$\sim 600 \times 10^{12} kg = 600\,PgC = 600GtC$$

$$1PgC \rightarrow 0.5\,ppmv(mixed\_entireAtm)$$

Outstanding Questions

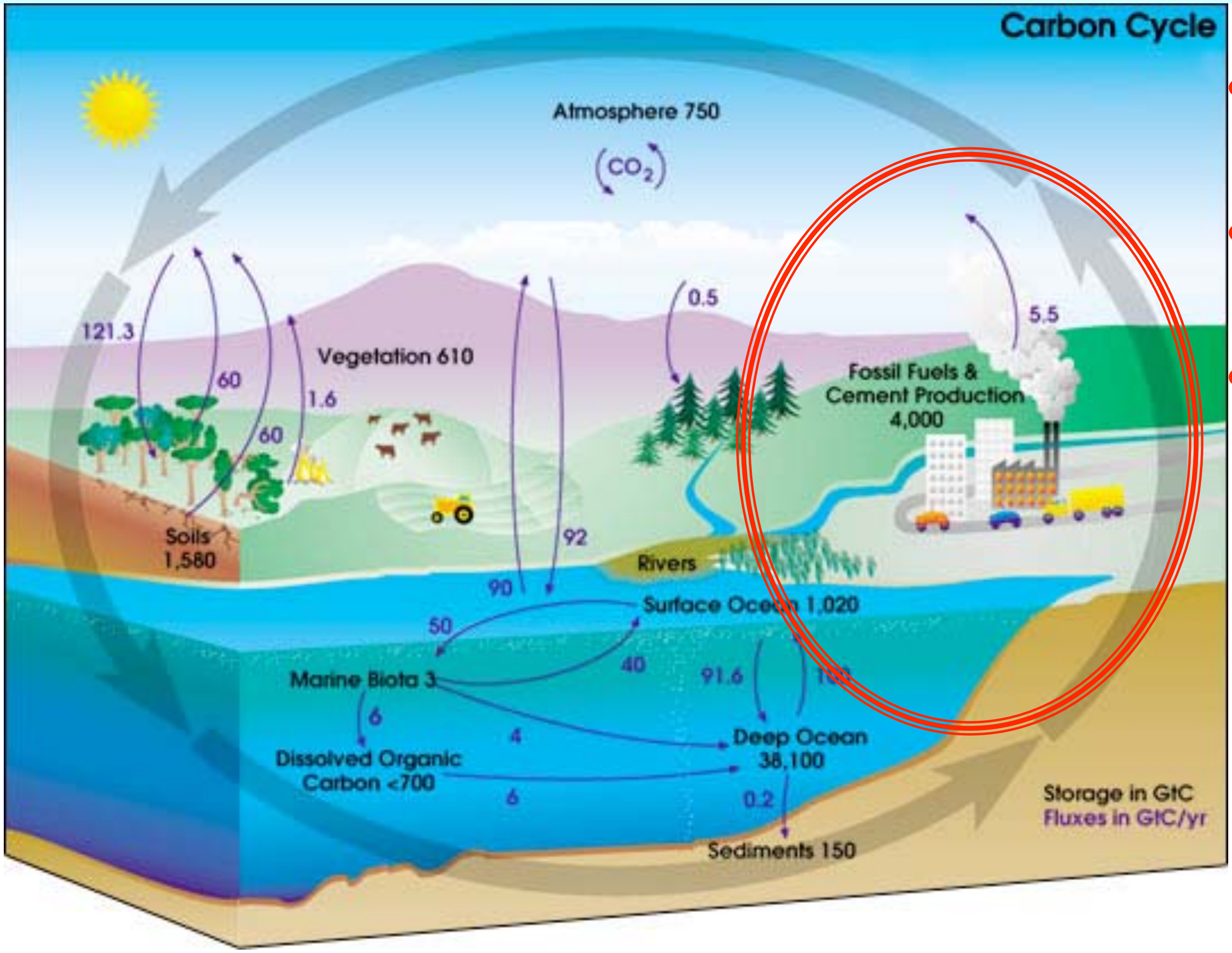
- Only half of the CO_2 produced by human activities is remaining in the atmosphere
- Where are the ***sinks*** that are absorbing over 40% of the CO_2 that we emit?
  - Land or ocean?
  - Eurasia/North America?
- Why does CO_2 buildup vary dramatically with nearly uniform emissions?
- How will CO_2 sinks respond to climate change?



Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land.

Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

Continuous Carbon Cycling



- **Fluxes PgC/yr**
- **Inventory PgC**
- **Turnover time = Inventory/Flux**

- Atm CO2 --> inventory
- Land: turnover time 10^1-10^2 yrs. Ocean: turnover time 10^2-10^3 yrs
- Difficult (time consuming and expensive) to measure changes in land and ocean inventories. Focus on fluxes

Conservation of Carbon in Atm

$$\frac{\partial C}{\partial t} + \underbrace{\Im(C)}_{Atm\_transport+mixing} = \underbrace{S\Big|_{z=0}}_{SourcesSinks} + \cancel{\underbrace{P}_{Chem\ Prod}}$$

$$S = FF + LandUse + (F_{oa} - F_{ao}) + (F_{ba} - F_{ab})$$

Separate out background (pre-industrial) from the perturbation (last 200 years) carbon cycle:

$$C = \overline{C} + C'$$

Pre-industrial: $\Im(\overline{C}) = (\overline{F_{oa}} - \overline{F_{ao}}) + (\overline{F_{ba}} - \overline{F_{ab}})$

Conservation of Perturbation Carbon in Atm

$$\frac{\partial C}{\partial t} + \underbrace{\Im(C)}_{Atm\_transport+mixing} = \underbrace{S\big|_{z=0}}_{SourcesSinks} + \cancel{\underbrace{P}_{Chem\,Prod}}$$

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In later lectures, the conservations equation may appear as:

Kalnay: $\boxed{T_b(t_{i+1}) = M[T_a(t_i)]}$

Nychka: $\boxed{x_{i+1} = \Phi(x_i) + G(u)}$

Conservation of Perturbation Carbon in Atm

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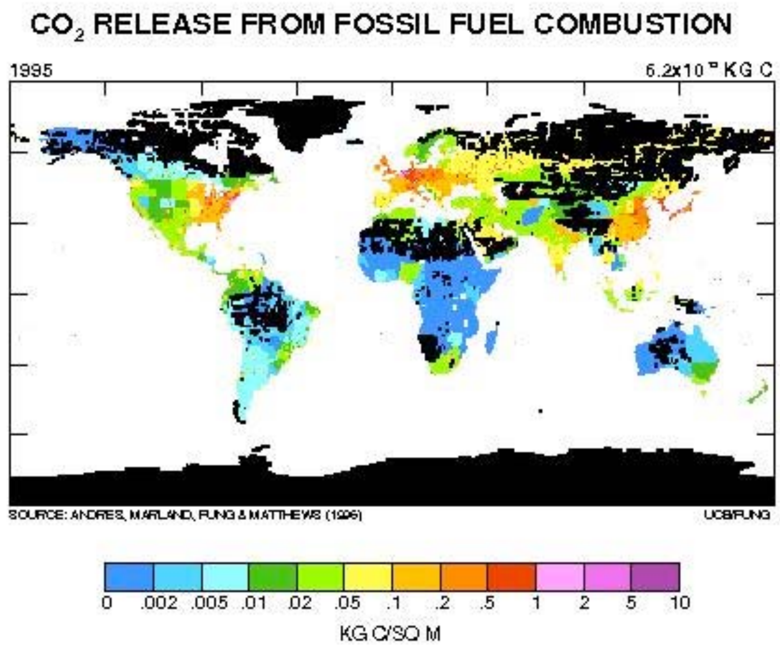
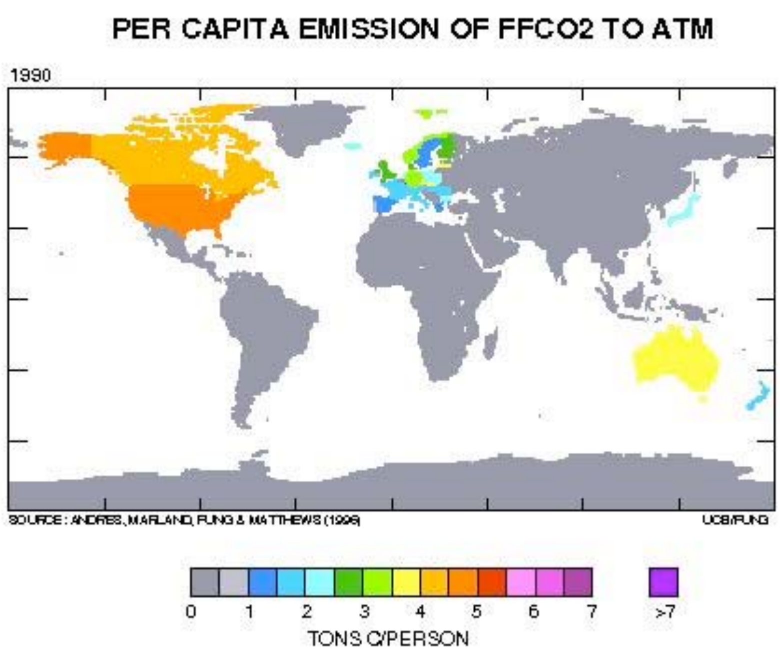
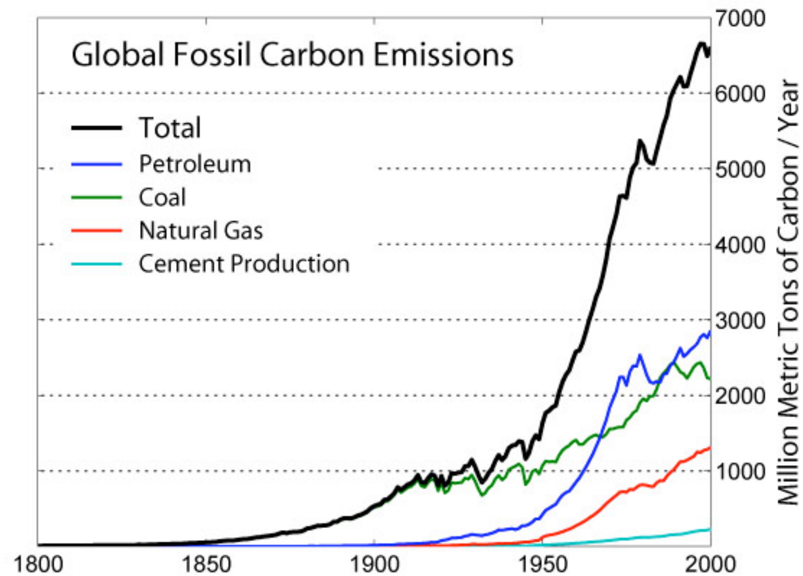
Fossil Fuel Emission

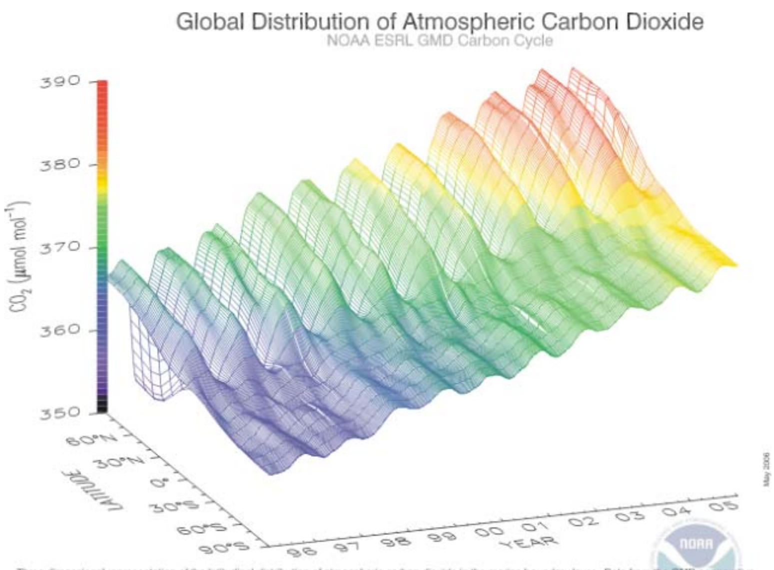




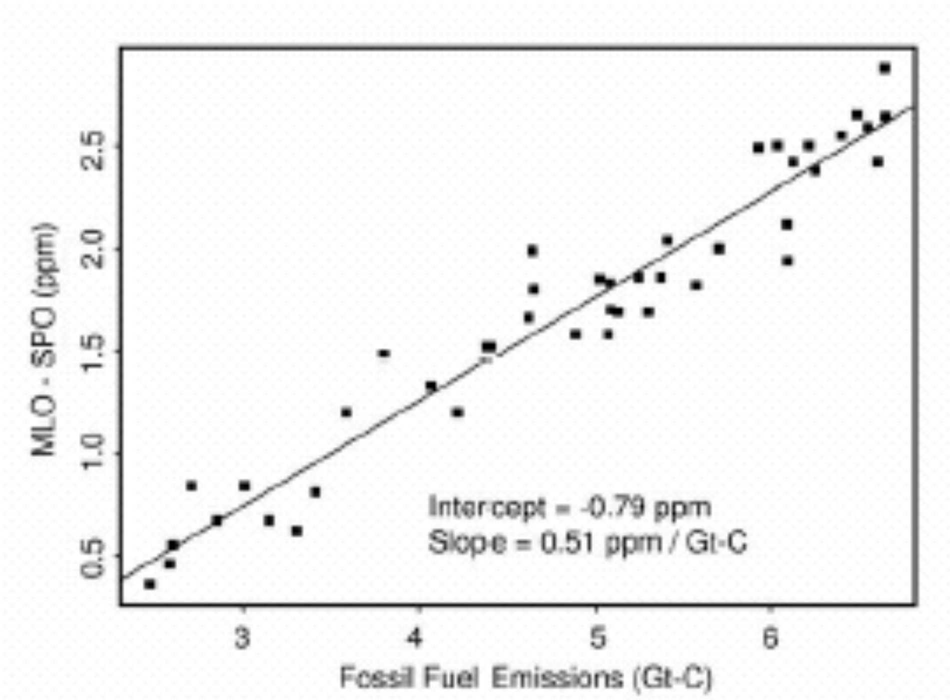


>95% emission in Northern Hemisphere

Atm CO2 Signature of Fossil Fuel Emission: N-S gradient



Three dimensional representation of the latitudinal distribution of atmospheric carbon dioxide in the marine boundary layer. Data from the GMD cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Pieter Tans and Thomas Conway, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).



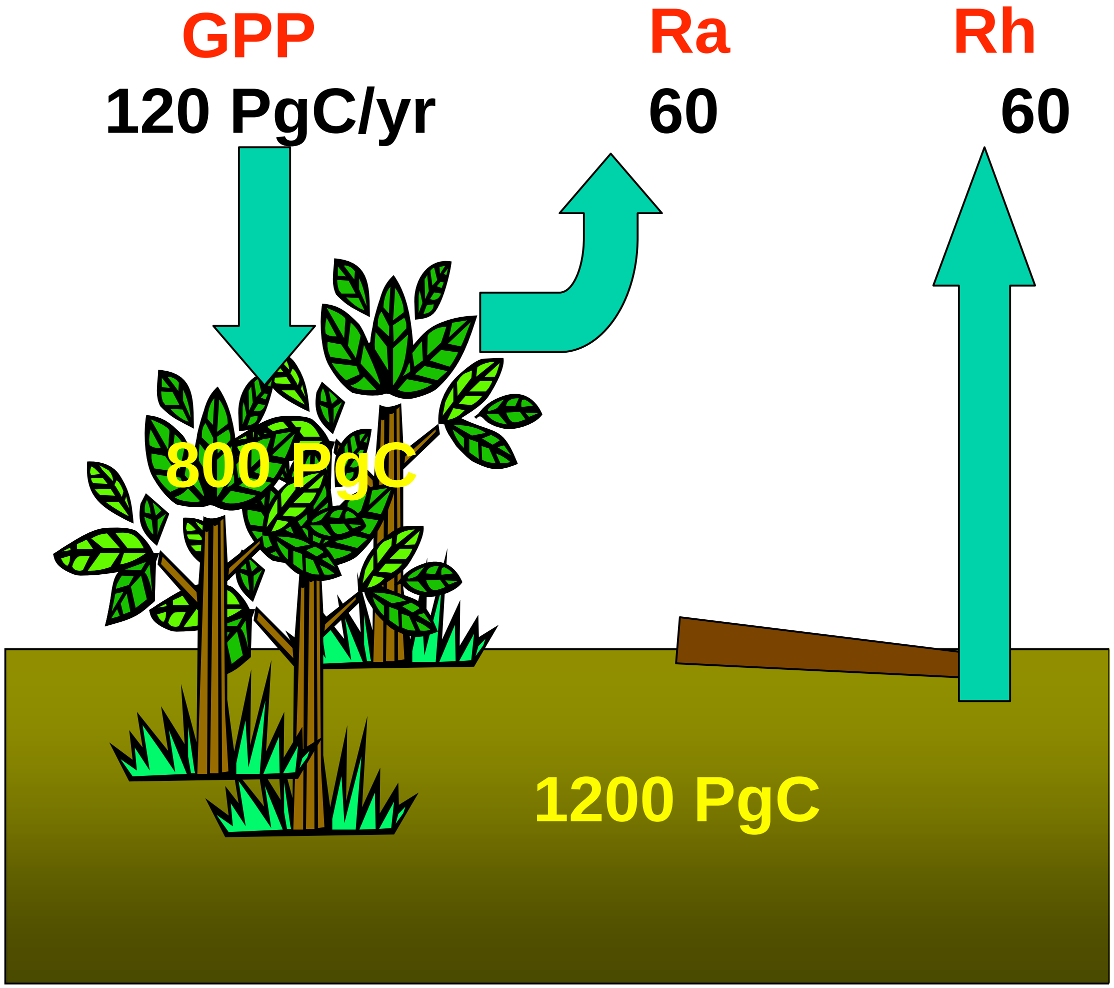
Conservation of Perturbation Carbon in Atm

$$\frac{\partial C}{\partial t} + \underbrace{\Im(C)}_{Atm\_transport+mixing} = \underbrace{S\big|_{z=0}}_{SourcesSinks} + \cancel{\underbrace{P}_{Chem\,Prod}}$$

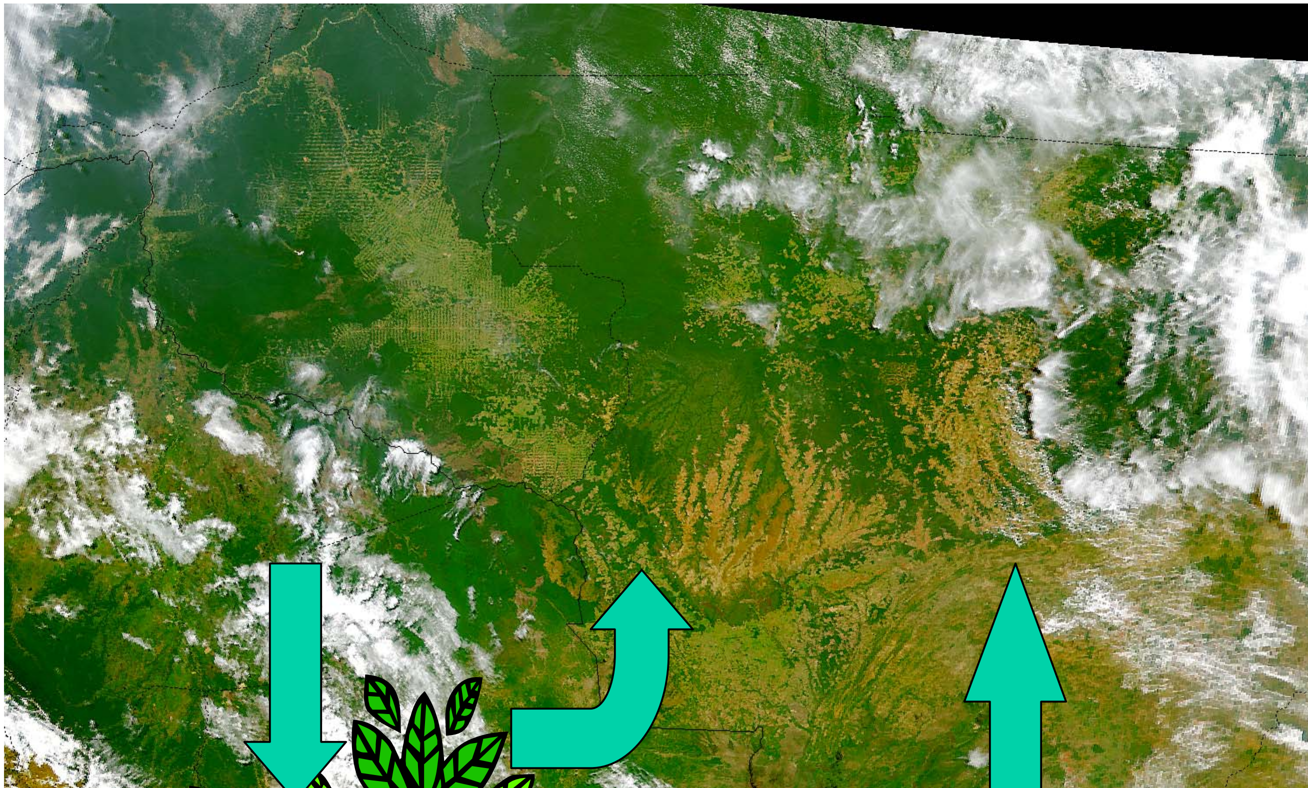
$$S = FF + LandUse + (F_{oa} - F_{ao}) + (F_{ba} - F_{ab})$$

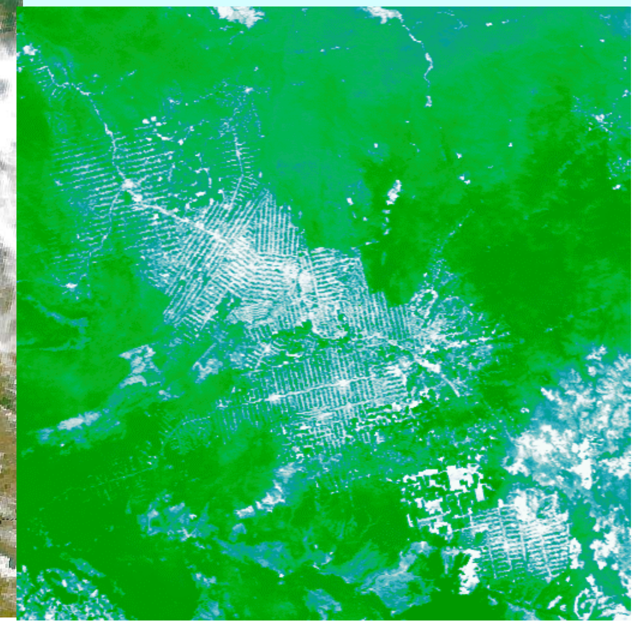
Terrestrial Carbon Cycle

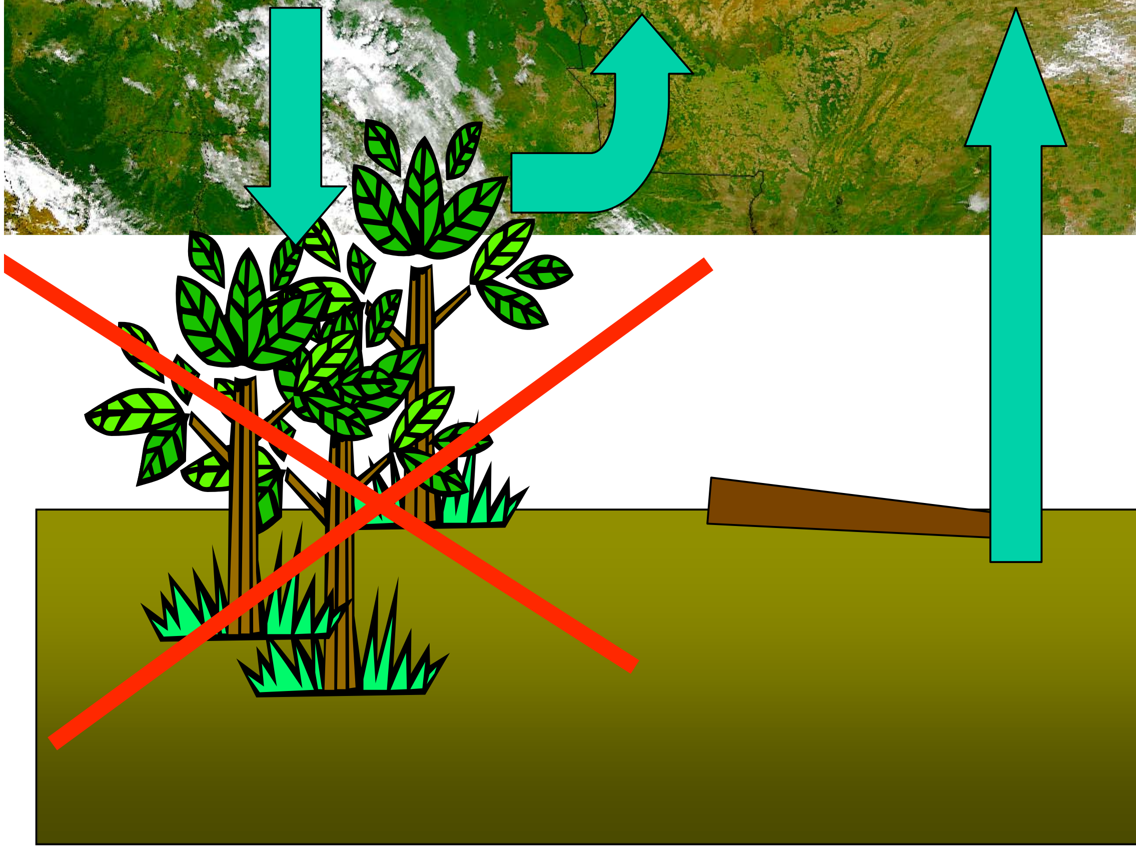
- Growth, mortality, decay
- GPP: Gross Primary Productivity (climate, CO_2, soil H_2O, resource limitation)
- Ra: Autotrophic respiration (T, live mass,…)
- Rh: Heterotrophic respiration: Decay (T, soil H_2O,..)
- NPP=GPP-Ra



Deforestation



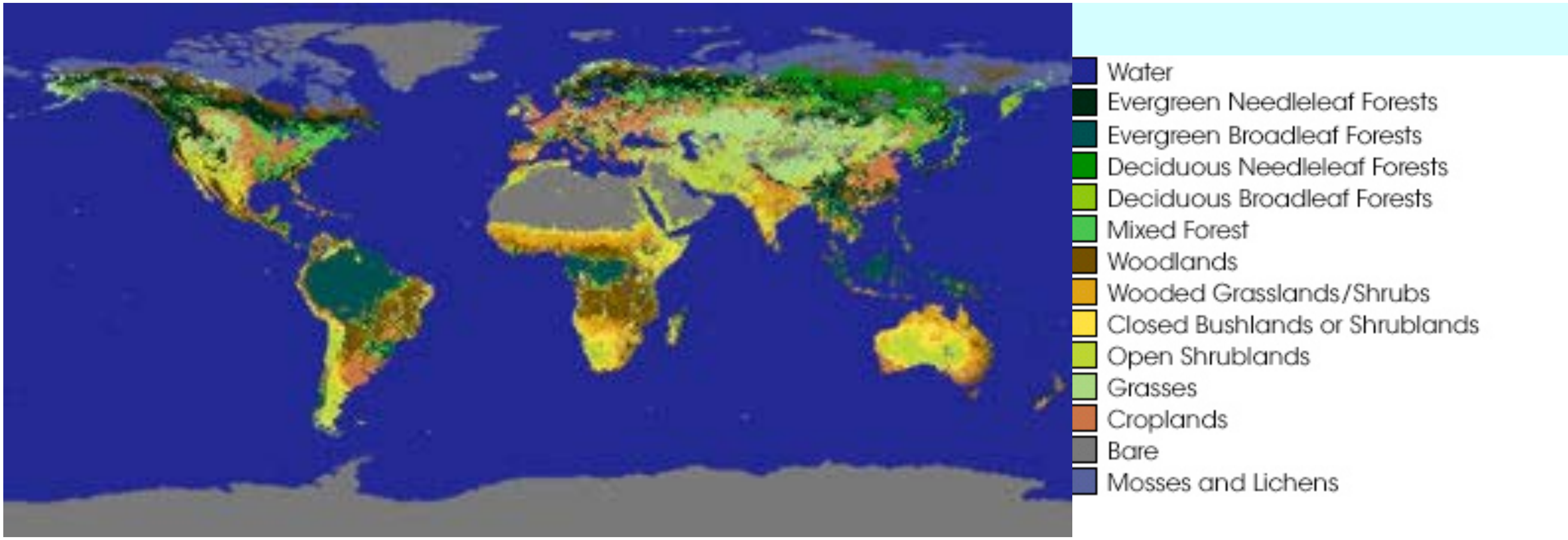


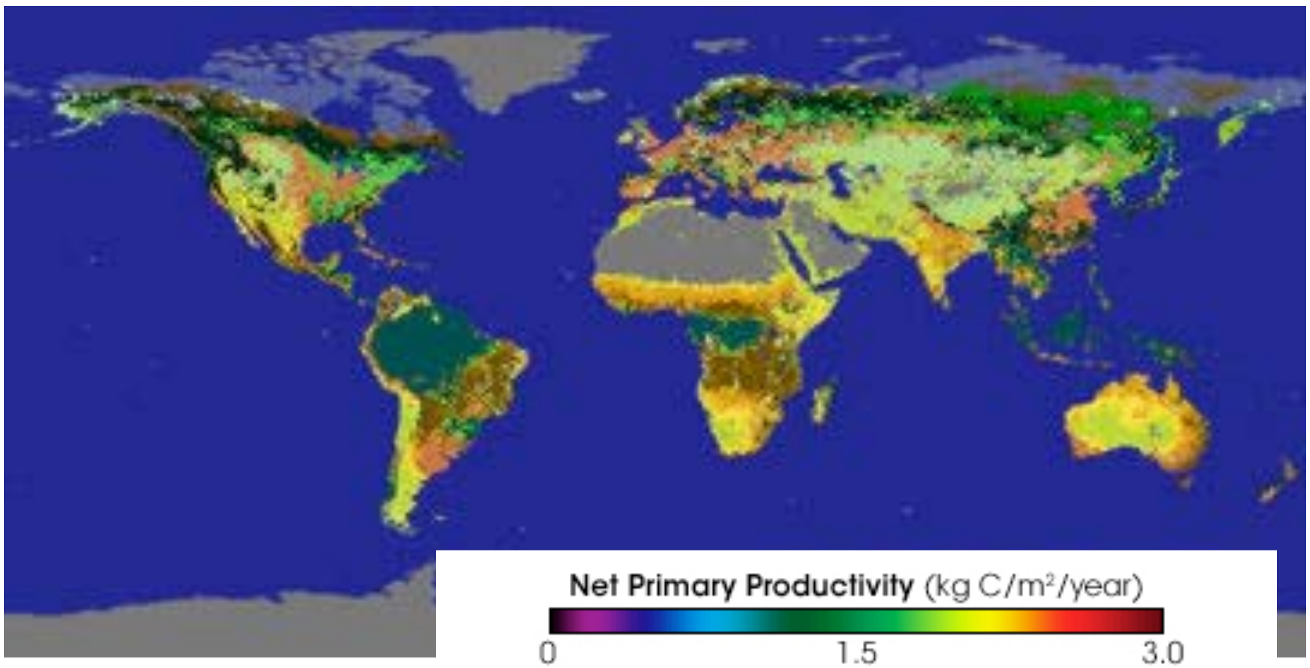


Tough to estimate

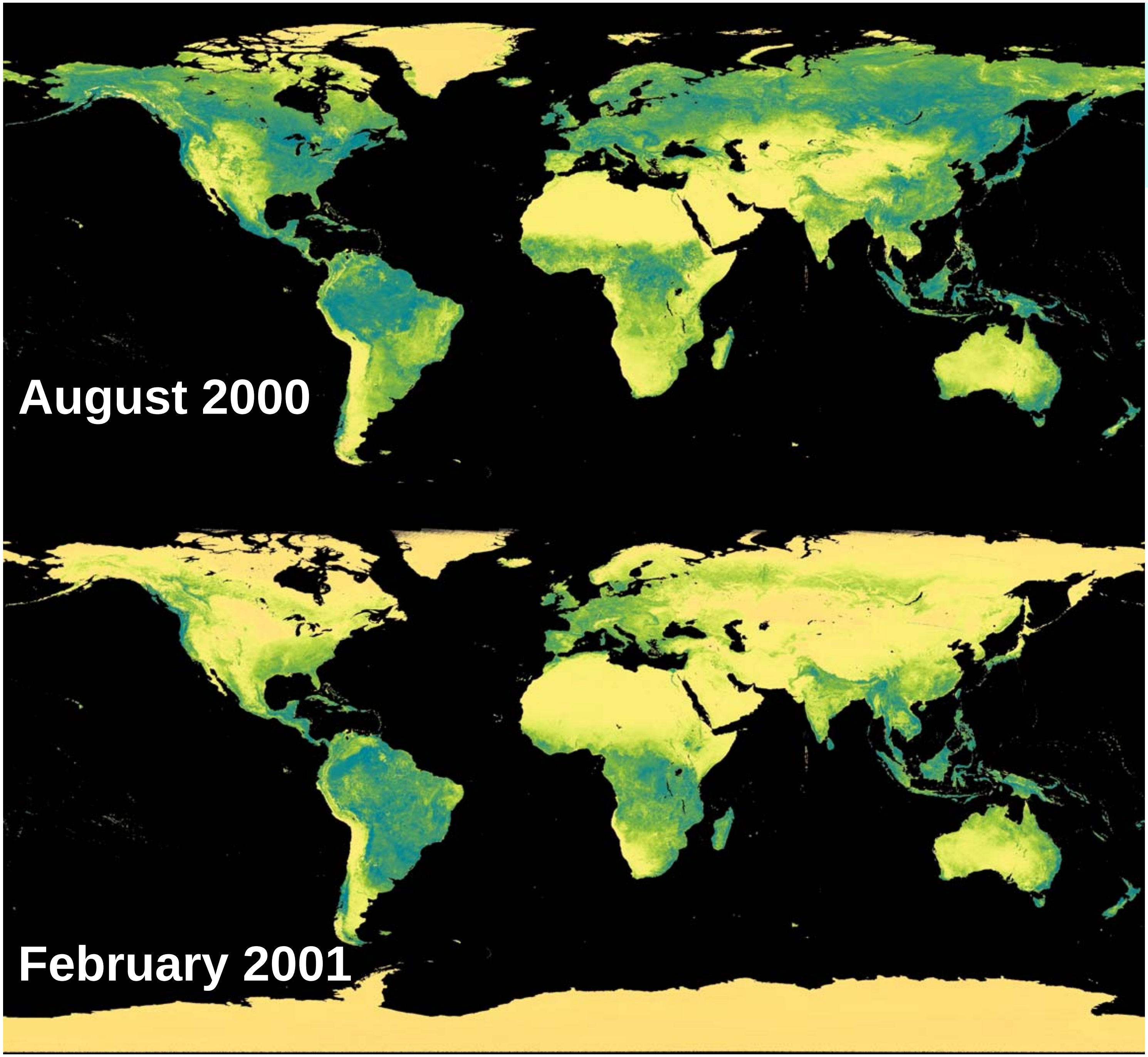
- **deforested area**
- **Carbon inventory before deforestation**
- **Fate of removed carbon**
- **Fate of litter and soil carbon**

Tough to discriminate atm CO_2 signature





Veg Type(x,y) → annual mean NPP(x,y)



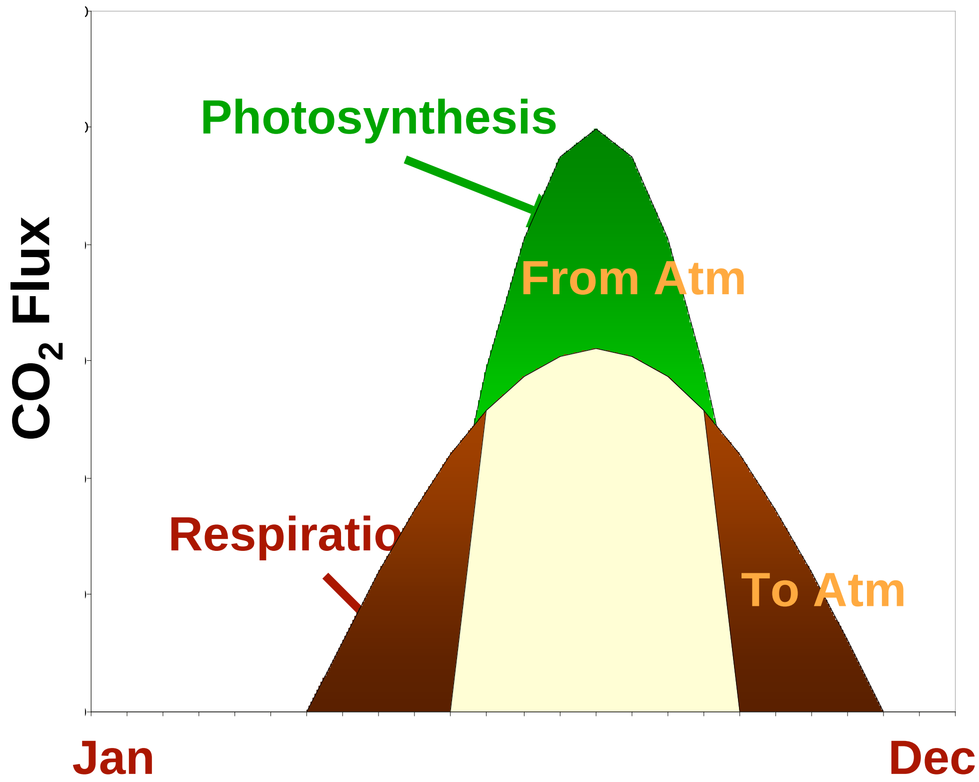
Satellite Greenness index: NDVI

→ Seasonality of NPP

Seasonality of Respiration not well-defined

Net flux not well-defined at every location

Impact on Atmospheric CO_2

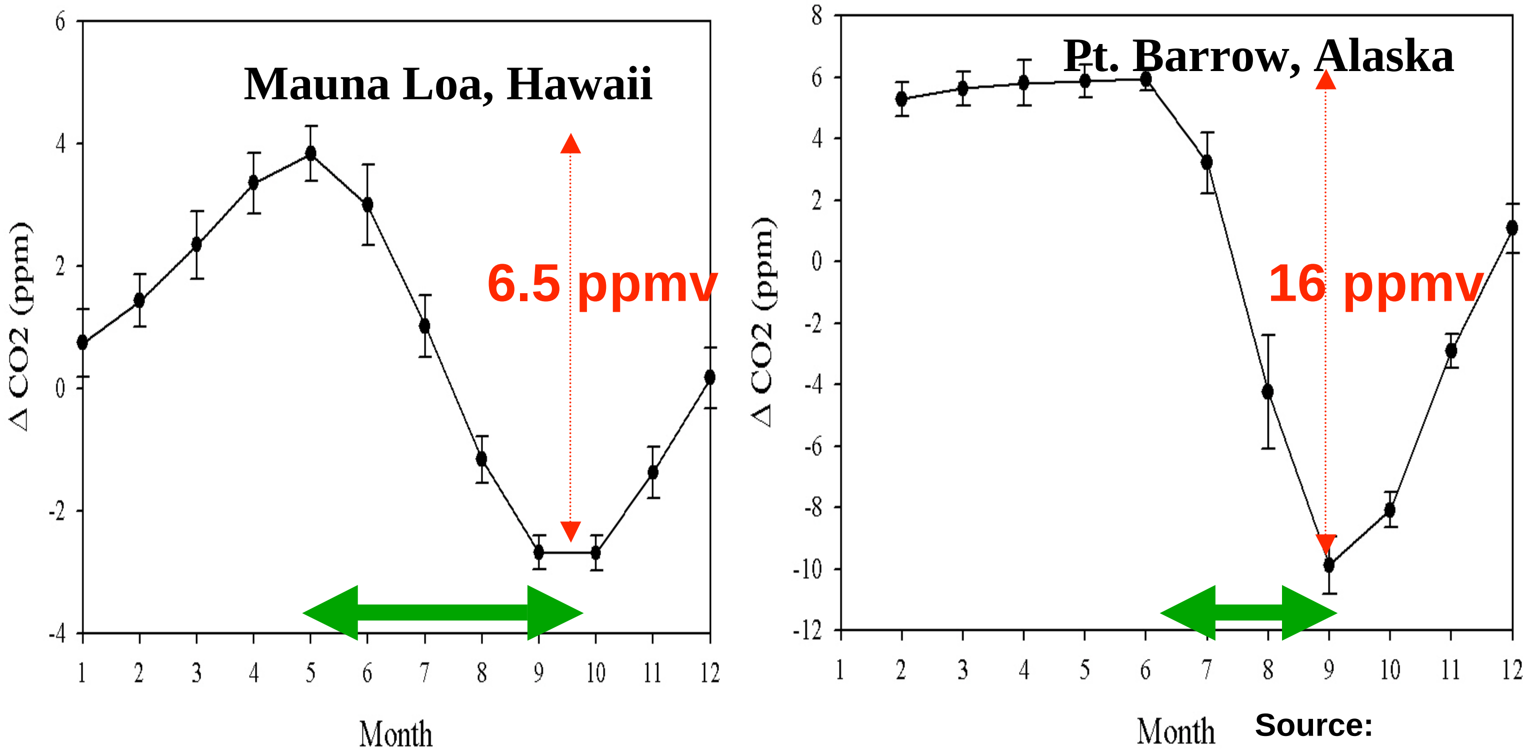


- **Seasonal asynchrony** between photosynthesis and decomposition

→ net fluxes of CO_2 to and from atm
→ seasonal cycle of CO_2 in atm

- **Annual imbalance → carbon source/sink**

Atmospheric CO_2 Signature of Ecosystem C Exchange: Seasonal Cycle



Source: NOAA/CMDL

- Amplitude of atmospheric CO_2 seasonal cycle increases poleward: telecoping of growing season and greater asynchroneity bet' fluxes

- Growing season net flux ~15-20% of annual NPP

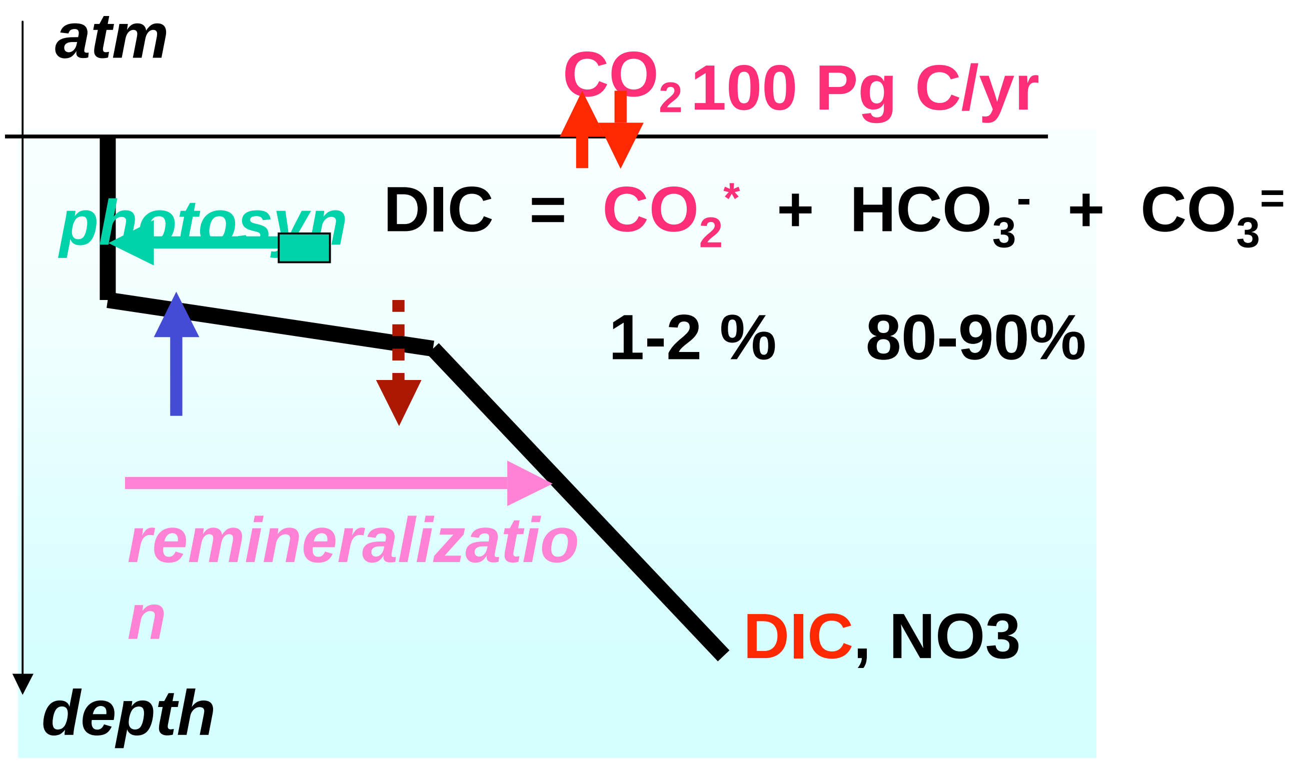
Conservation of Perturbation Carbon in Atm

$$\frac{\partial C}{\partial t} + \underbrace{\Im(C)}_{Atm\_transport+mixing} = \underbrace{S\Big|_{z=0}}_{SourcesSinks} + \cancel{\underbrace{P}_{Chem\,Prod}}$$

$$S = FF + LandUse + (F_{oa} - F_{ao}) + (F_{ba} - F_{ab})$$

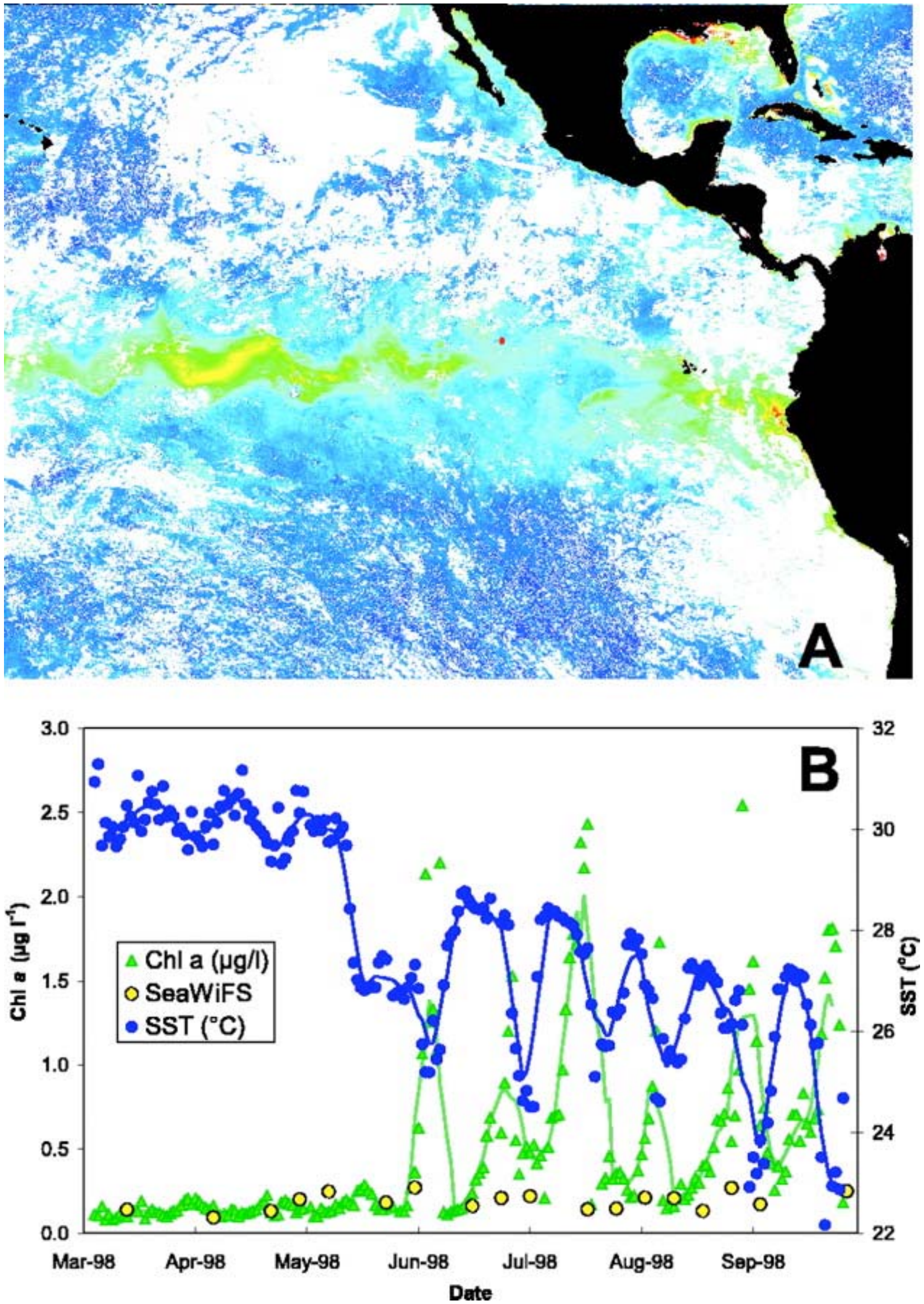
$$\Uparrow$$

Ocean C from the Atm's Perspective:



$$F_{oa} - F_{ao} = \underbrace{k}_{GasExchRate(m/s)} \times (\underbrace{CO2^*_{sfc\_ocn}}_{moleC/m3} - \underbrace{\beta}_{solubility(T)} \times pCO2_{atm\_sfc})$$

Marine Productivity



Is possible when upwelling brings:

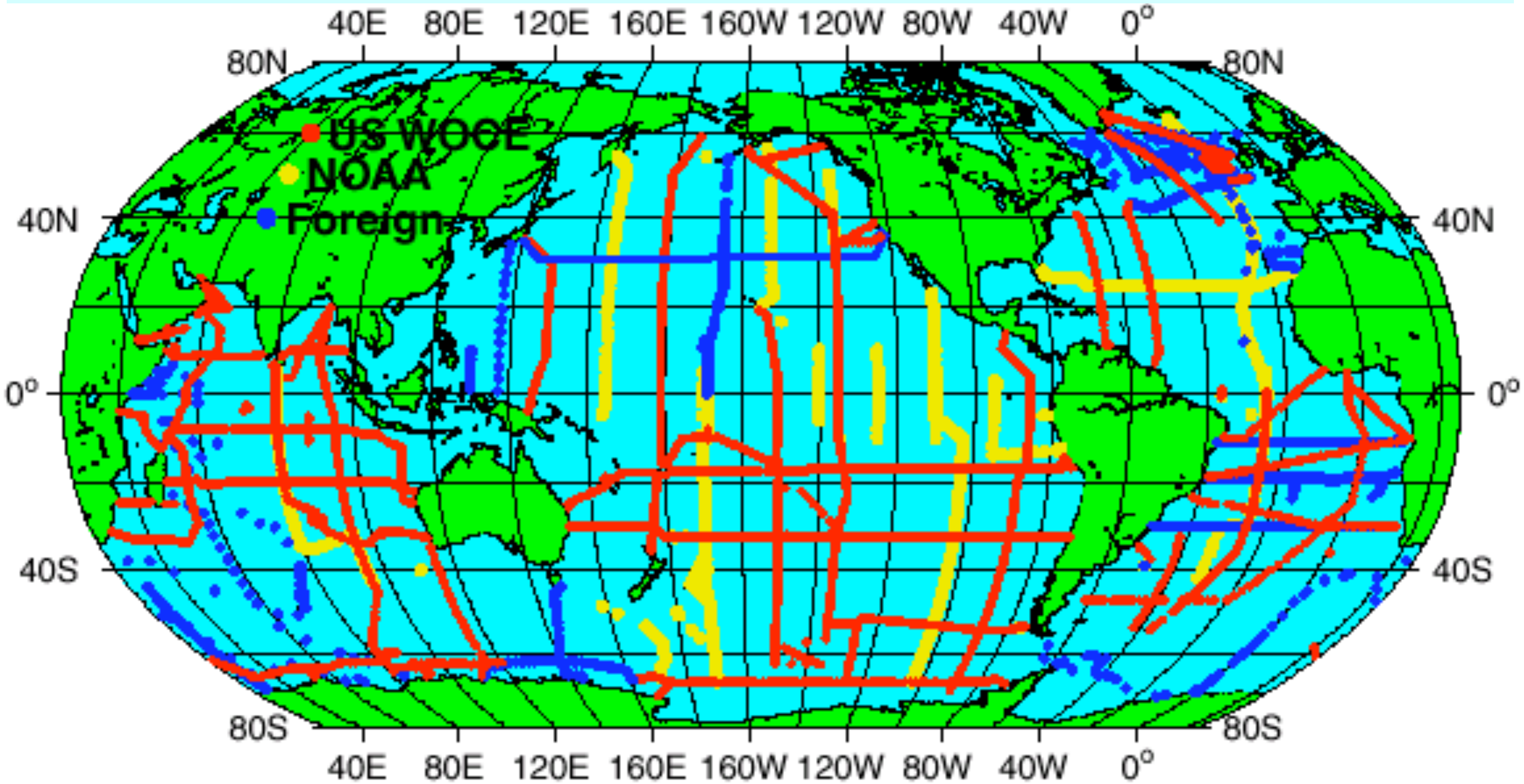
•Nutrients from below to euphotic zone

•Cold water

Small Flux, small inventory of organic C

But alters DIC(z)

JGOFS/WOCE global survey (1980s and 1990s)



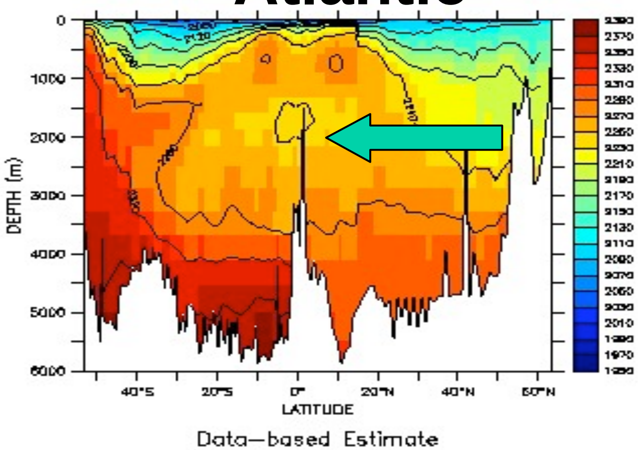
- -Global baseline (hydrography, transient tracers, nutrients, carbonate system)
- -Improved analytical techniques for inorganic carbon and alkalinity (±1-3 μmol/kg or 0.05 to 0.15%)
- -Certified Reference Materials
- -Data management, quality control, & public data access

OceanC : Mainly Dissolved Inorganic Carbon (DIC)

Conveyor Belt Transport of DIC:
- Southward in Atlantic
- Northward in Pacific

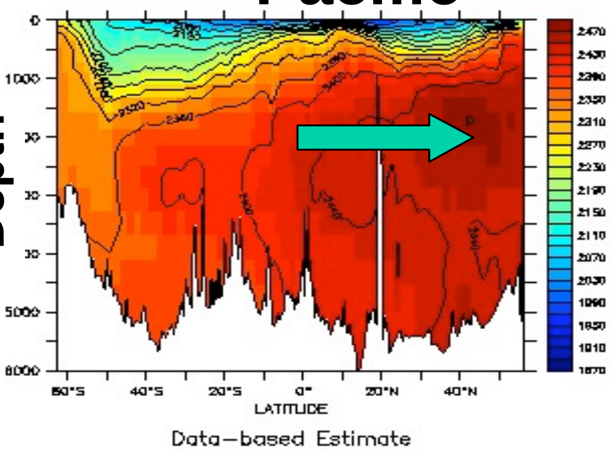
Ocn currents ~ cm/s
Time scale ~ 10^3 yr

Atlantic



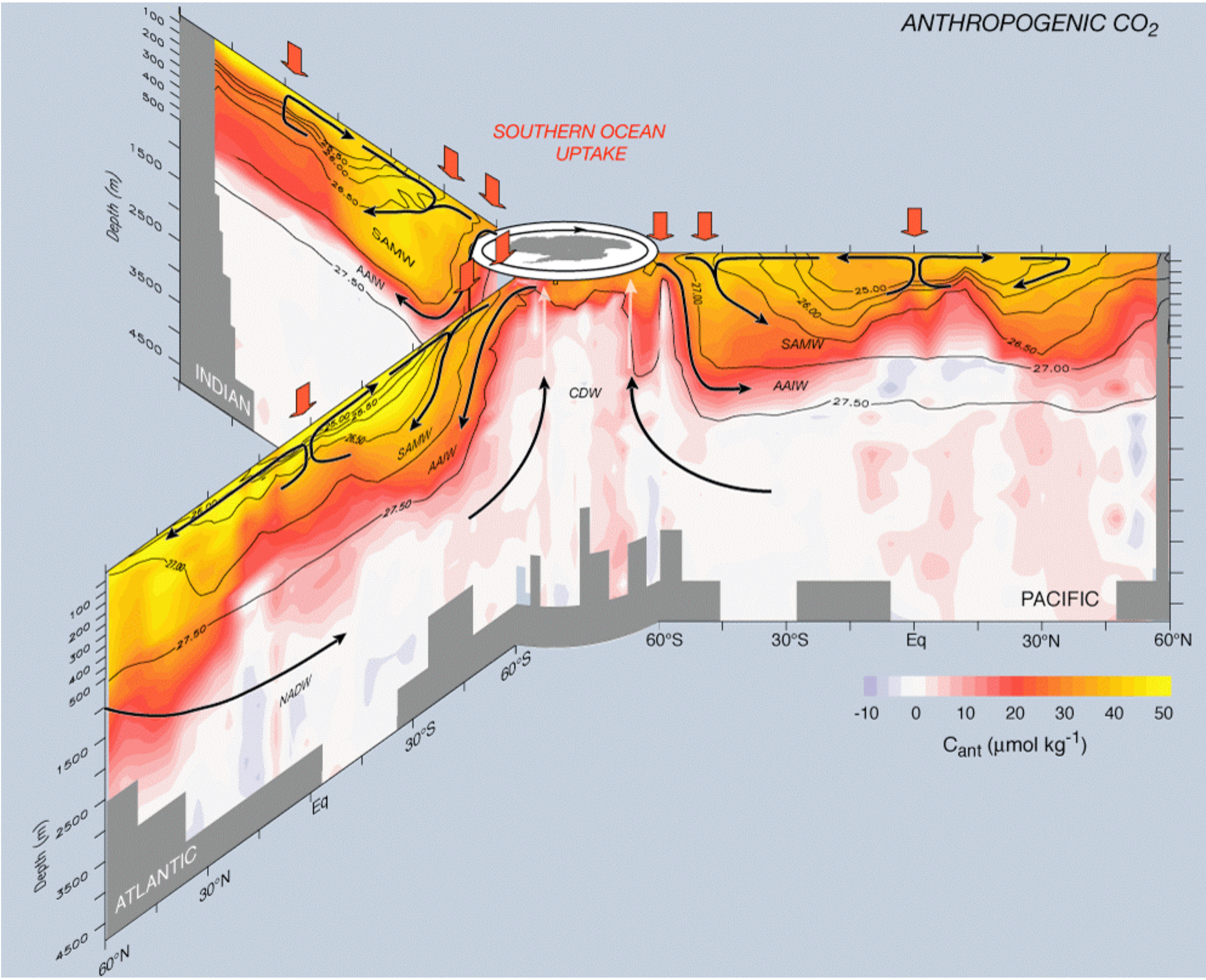
Pacific

Depth



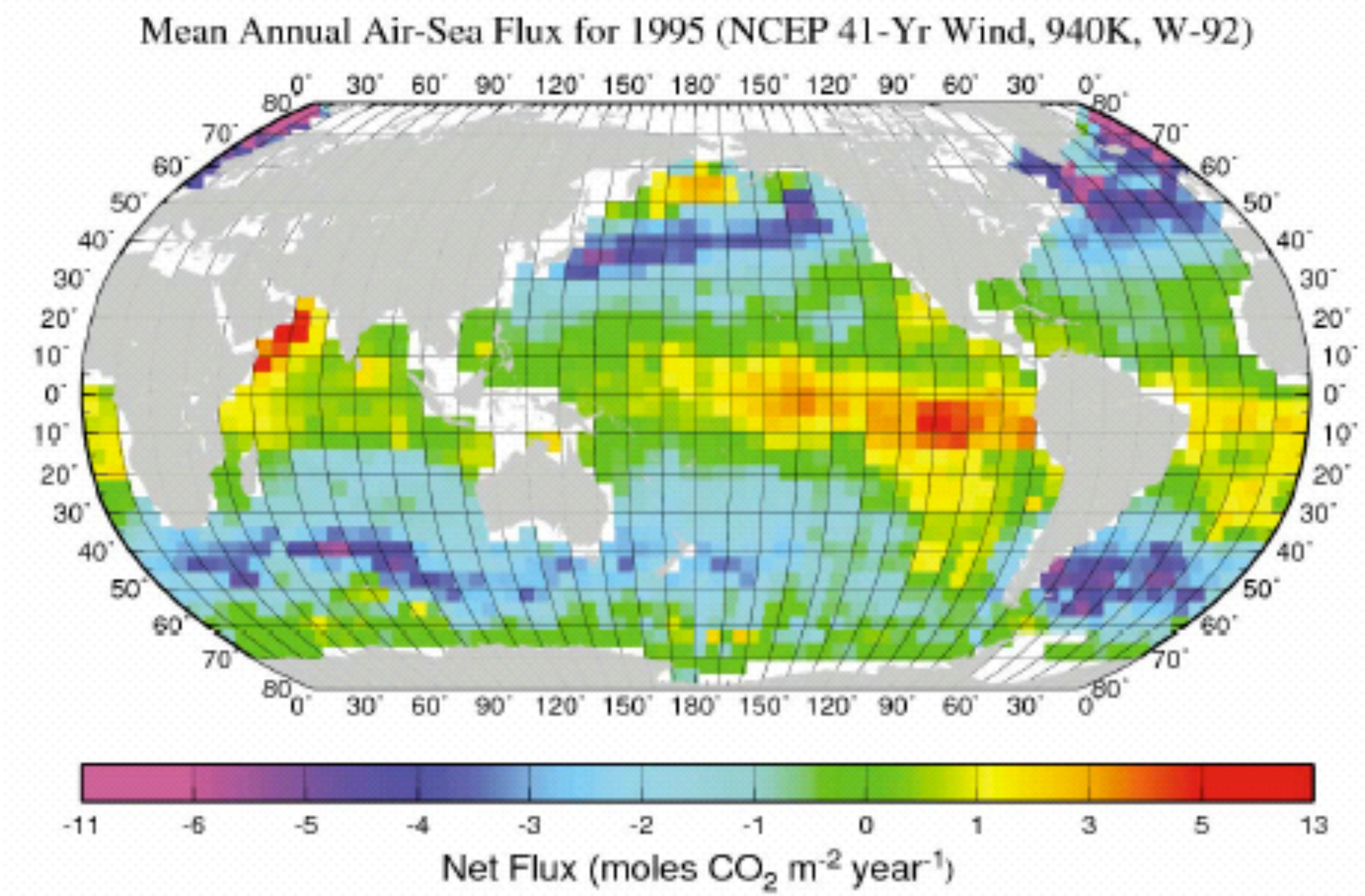
Latitude → N

Biology and DIC:
- Depletion near sfc
- Enrichment at Depth



ANTHROPOGENIC CO_2
SOUTHERN OCEAN UPTAKE
INDIAN
ATLANTIC
PACIFIC
Depth (m)
SAMW
AAIW
CDW
NADW
60°S
30°S
Eq
30°N
60°N
-10
0
10
20
30
40
50
C_{ant} (µmol kg^{-1})

Air-Sea Fluxes of CO2



$$\Delta F_{ocn} = F_{oa} - F_{ao}$$

$$= \underbrace{k}_{GasExchRate(m/s)} \times (\underbrace{CO2^*_{sfc\_ocn}}_{moleC/m3} - \underbrace{\beta}_{solubility(T)} \times pCO2_{atm\_sfc})$$

SUMMARY

$$\frac{\partial C}{\partial t} + \underbrace{\Im(C)}_{Atm\_transport+mixing} = \underbrace{S\big|_{z=0}}_{SourcesSinks}$$

$$S = FF + LandUse + (F_{oa} - F_{ao}) + (F_{ba} - F_{ab})$$

FF: mainly NH, relatively aseasonal

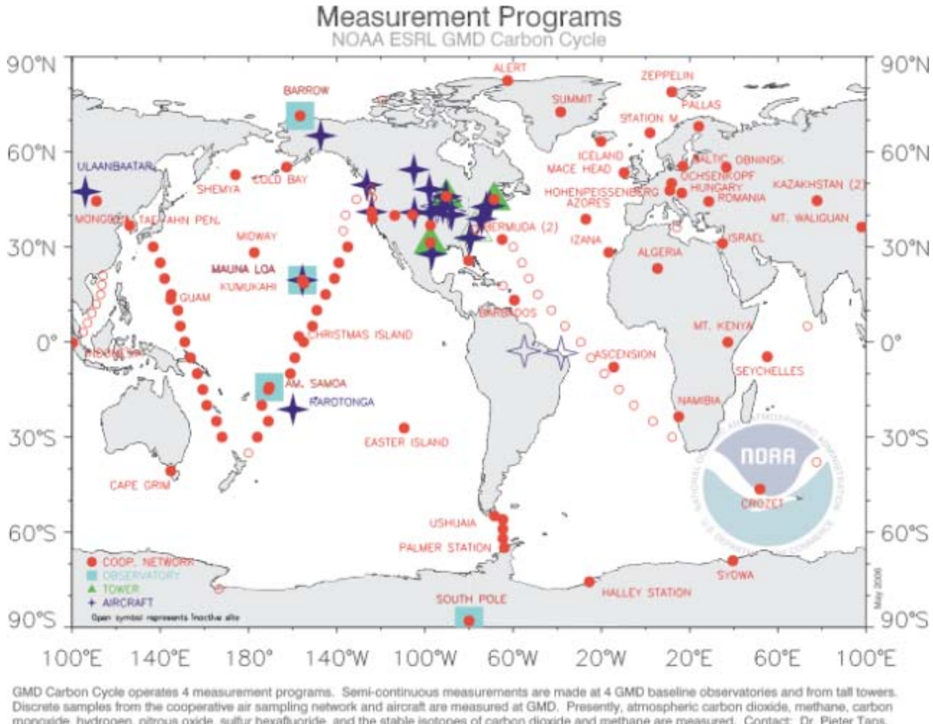
LandUse: mainly source tropics, sink in mid-latitudes

Ocean: outgassing in equatorial oceans, absorption at mid-hi latitudes (in summer. Not sure about winter)

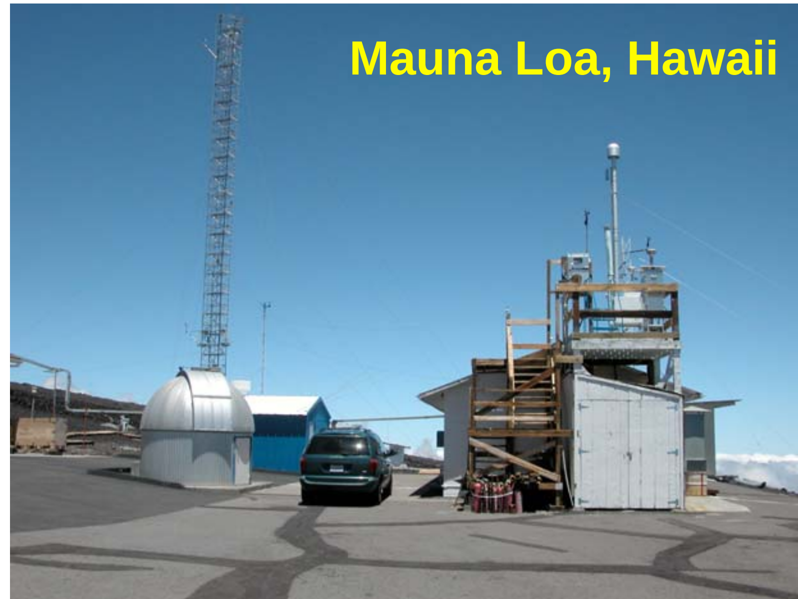
Vegetation and soils: annual mean fluxes~0 locally, fluxes have large diurnal (~100 ppmv) and seasonal ranges (~30 ppmv)

Atm CO2 data for assimilation

Atm CO2 Observations

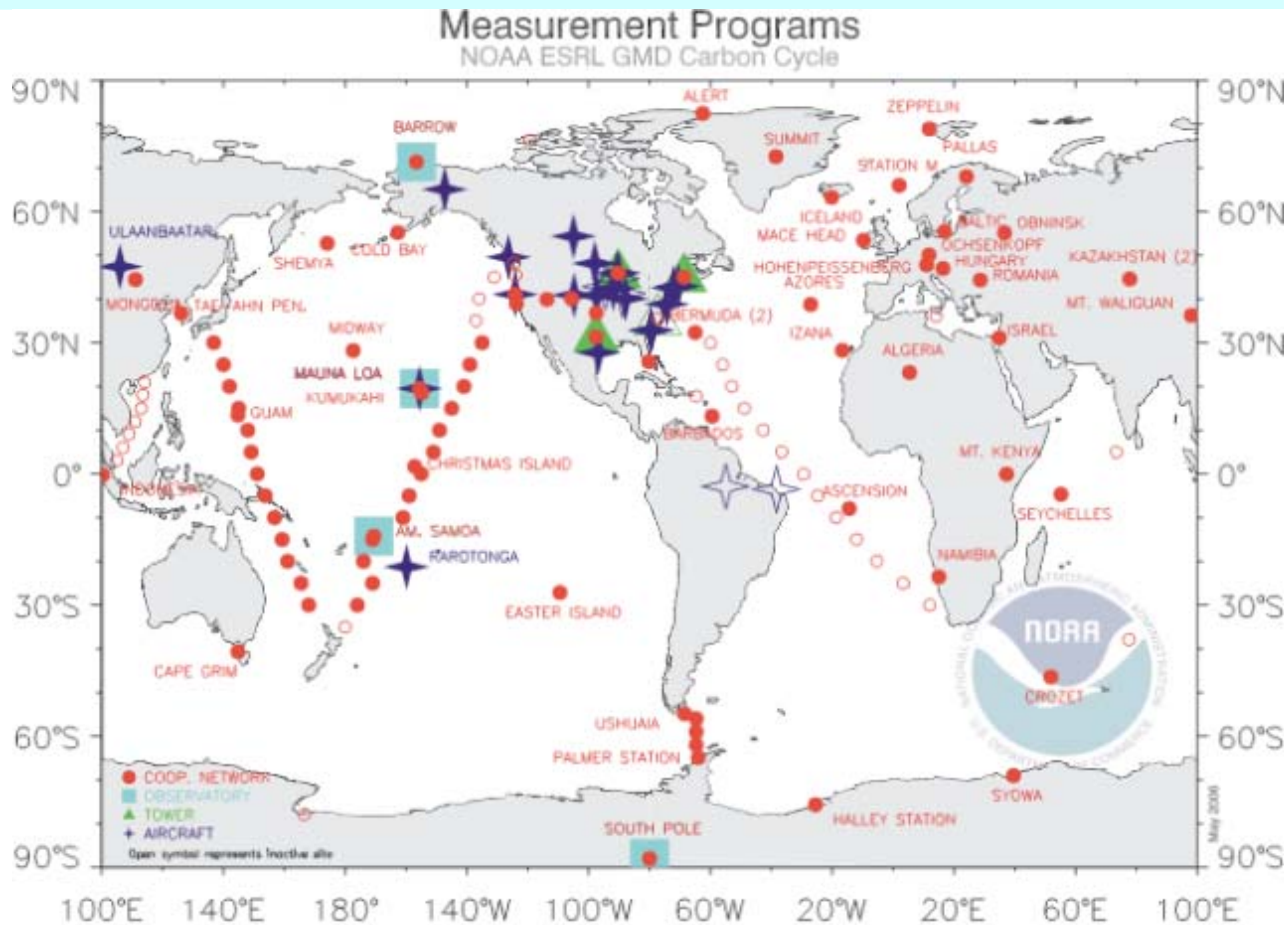


- **In situ**: tower, continuous
- **Flask**: 2m, twice weekly, ~10^2 locations
- **>400m Tall Tower**: 11, 30, 76, 122, 244 and 396 m; Continuous
- **Aircraft** data
- Very few obs over land (CO2 very variable)
- Upcoming: **satellite** data, column, (10^6 locations twice weekly)



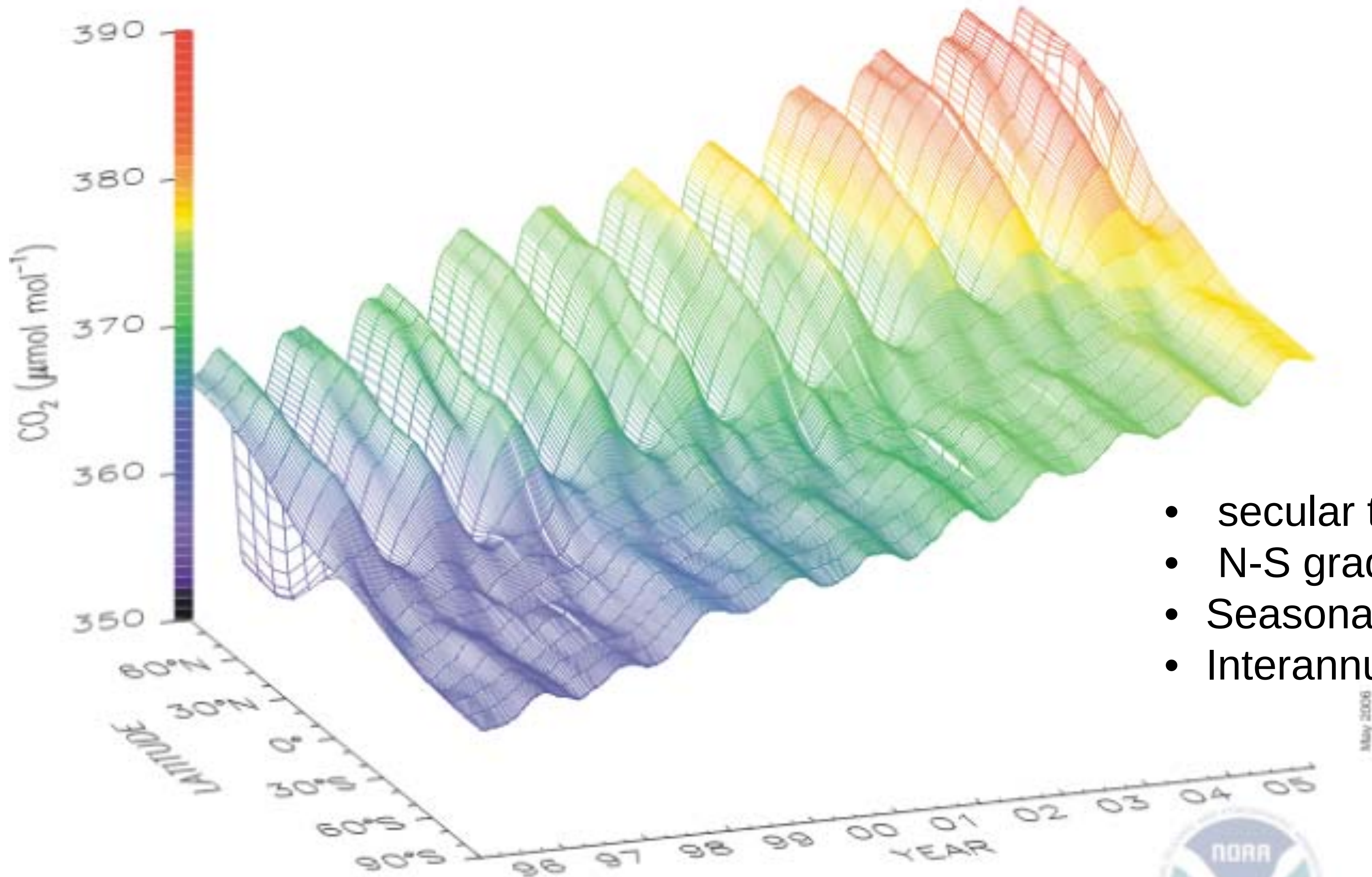
In-situ Atmospheric Observing Network

- Discrete surface flasks (~weekly)
- Continuous surface (hourly) observatories
- Tall towers continuous (hourly)
- Aircraft profiles (~weekly)



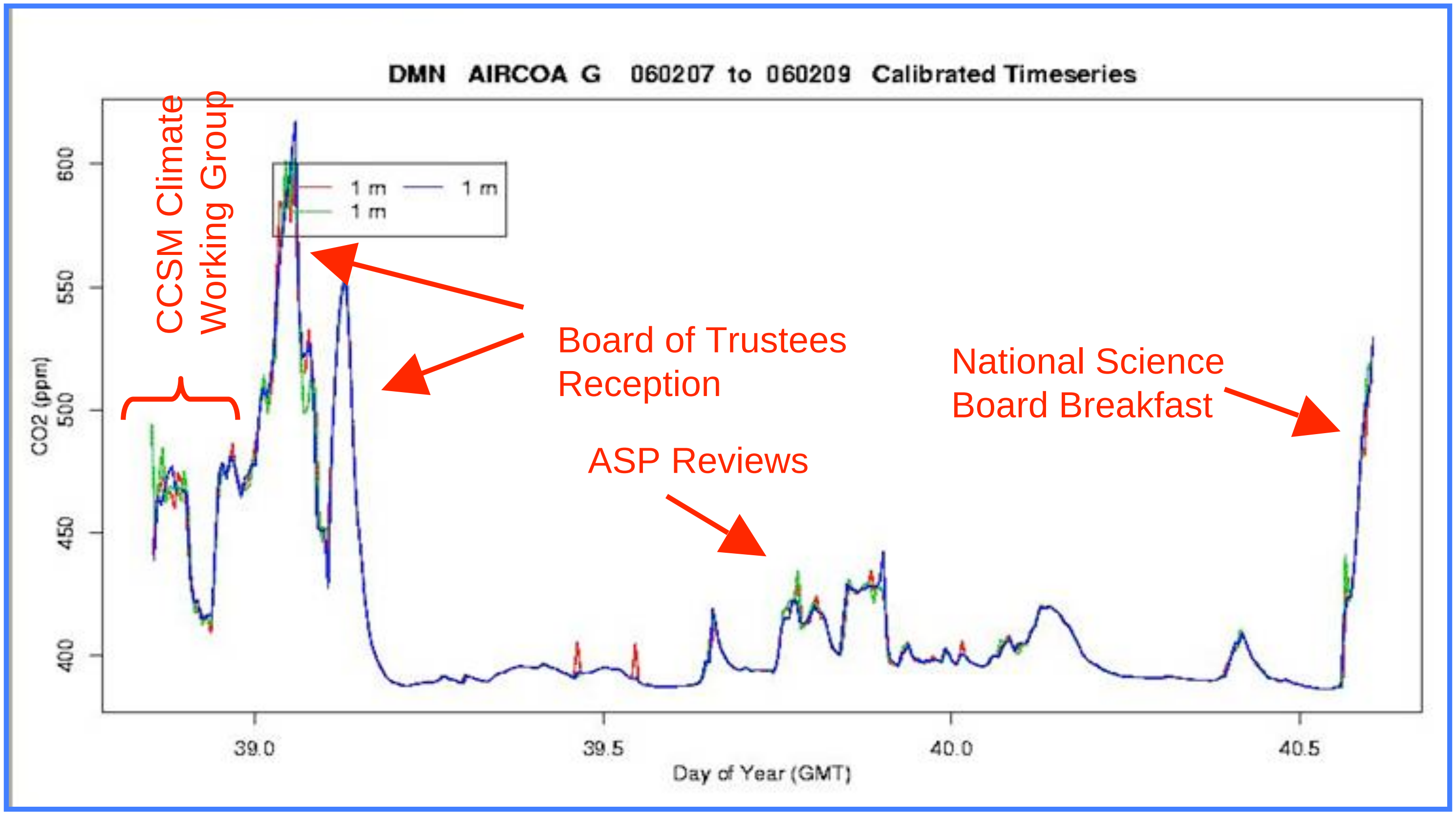
GMD Carbon Cycle operates 4 measurement programs. Semi-continuous measurements are made at 4 GMD baseline observatories and from tall towers. Discrete samples from the cooperative air sampling network and aircraft are measured at GMD. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexafluoride, and the stable isotopes of carbon dioxide and methane are measured. Contact: Dr. Pieter Tans, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

Global Distribution of CO2 in the lower troposphere



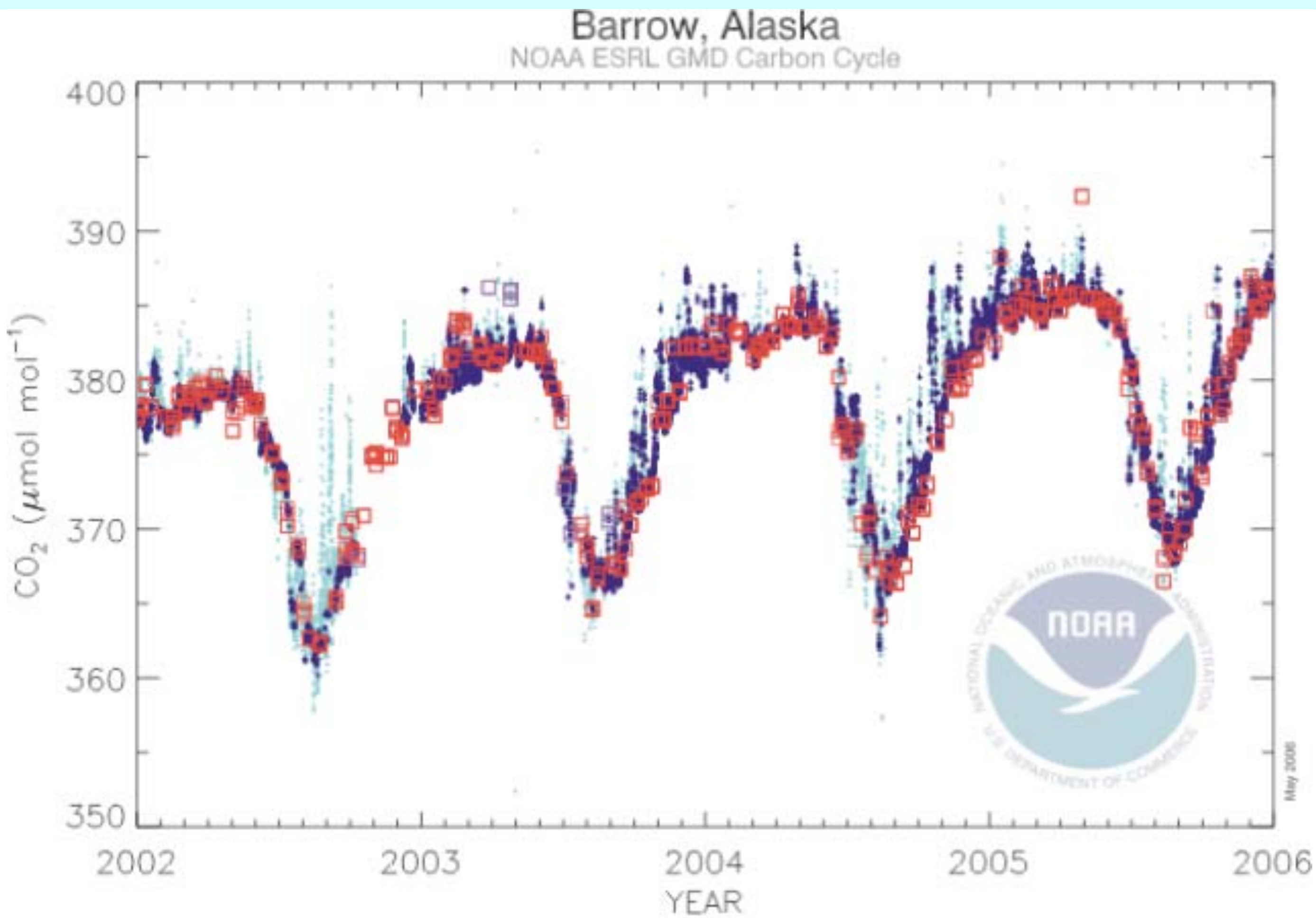
- secular trend
- N-S gradient
- Seasonal cycle
- Interannual variations

Three dimensional representation of the latitudinal distribution of atmospheric carbon dioxide in the marine boundary layer. Data from the GMD cooperative air sampling network were used. The surface represents data smoothed in time and latitude. Contact: Dr. Pieter Tans and Thomas Conway, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-6678 (pieter.tans@noaa.gov, http://www.cmdl.noaa.gov/ccgg).



CO_2 Concentration in the Outer Damon Room, NCAR Mesa Lab, 2/7 – 2/9/06

Surface Observatories

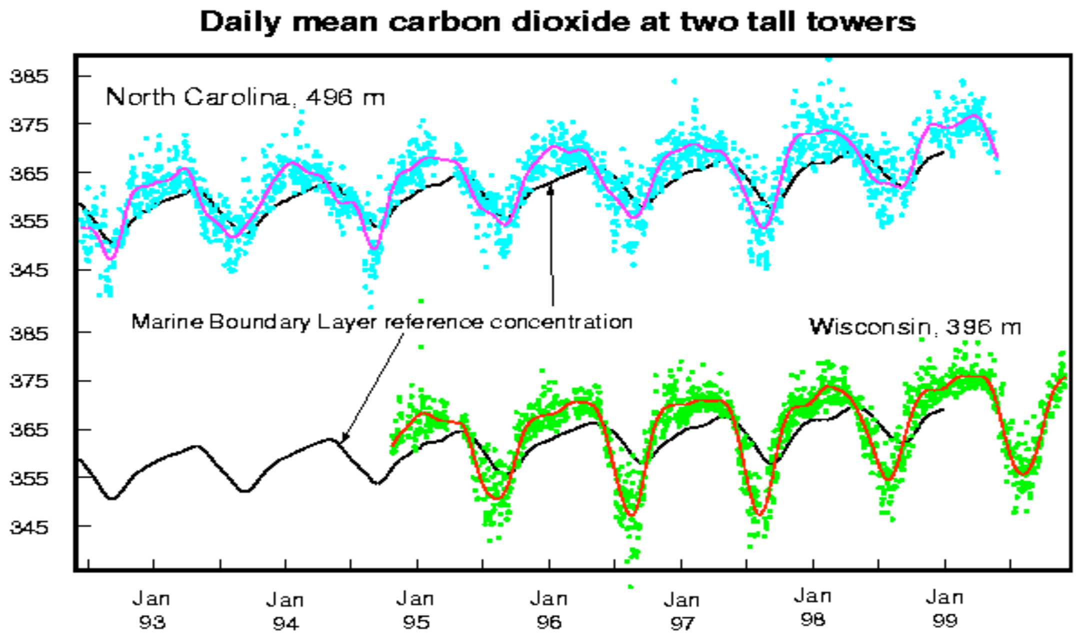


Time series showing measurements of atmospheric carbon dioxide using two independent methods. Hourly averaged values from the semi-continuous measurement system operating at the GMD baseline observatory are shown in blue (plus). Measurements thought to be representative of baseline conditions are identified in dark blue. Measurements thought to be locally influenced are shown in light blue. Retained measurements from weekly air samples collected at the observatory but analyzed at GMD in Boulder, Colorado are shown in red (square). Weekly samples thought to be affected by local influences are shown in purple (square). Contact: Dr. Pieter Tans, (303) 497-6678, (pieter.tans@noaa.gov; http://www.cmdl.noaa.gov/ccgg).

Where both insitu (hourly) and flask (biweekly) data are taken:

Diurnal and weather cycles on top of seasonal cycles

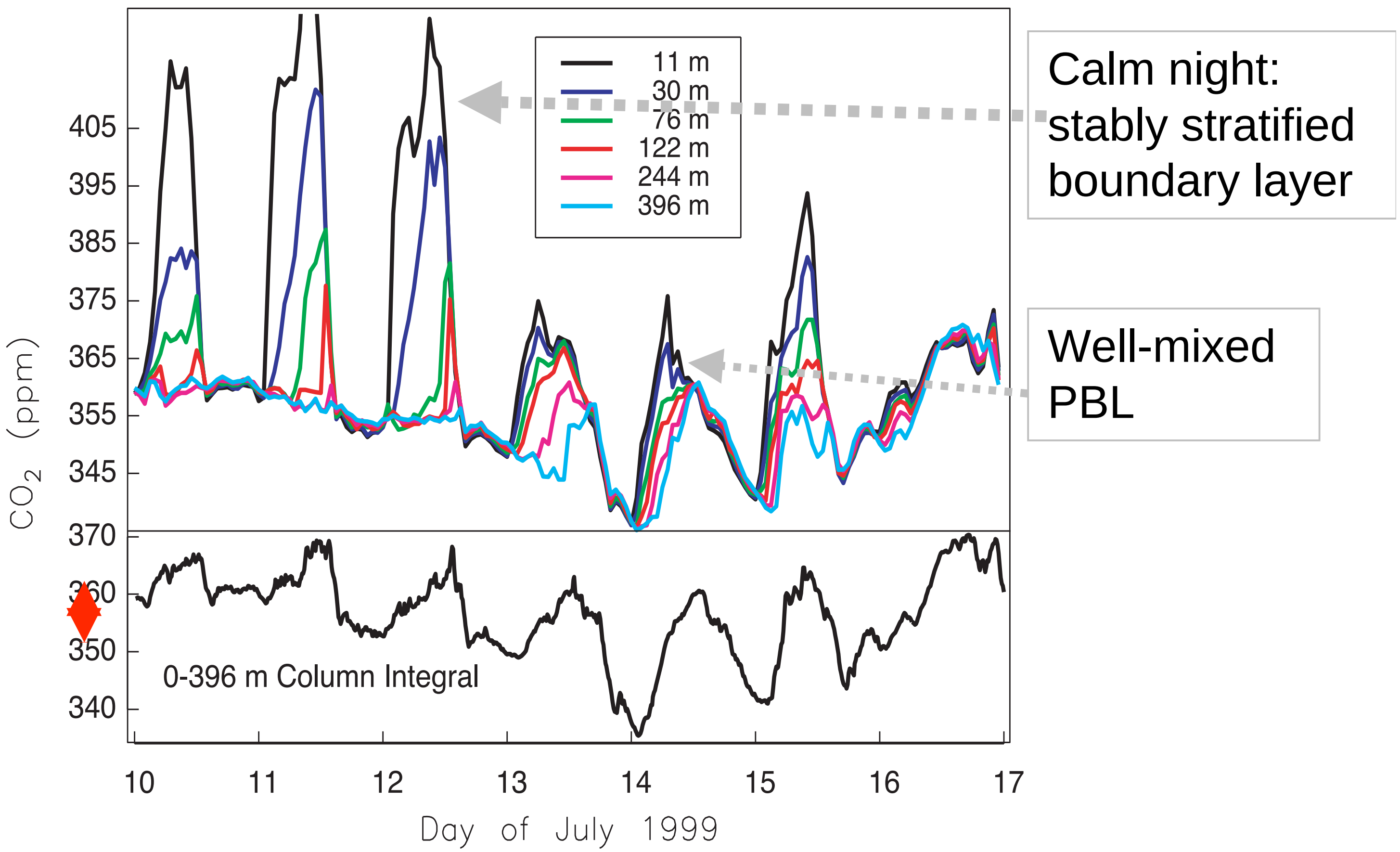
Seasonal CO_2: Continental vs Oceanic Sites



- CO_2 seasonal cycle attenuate, but still coherent, far away from source/sink region
- Peak-trough amplitude of seasonal cycle ~ 30 ppmv (~10%)

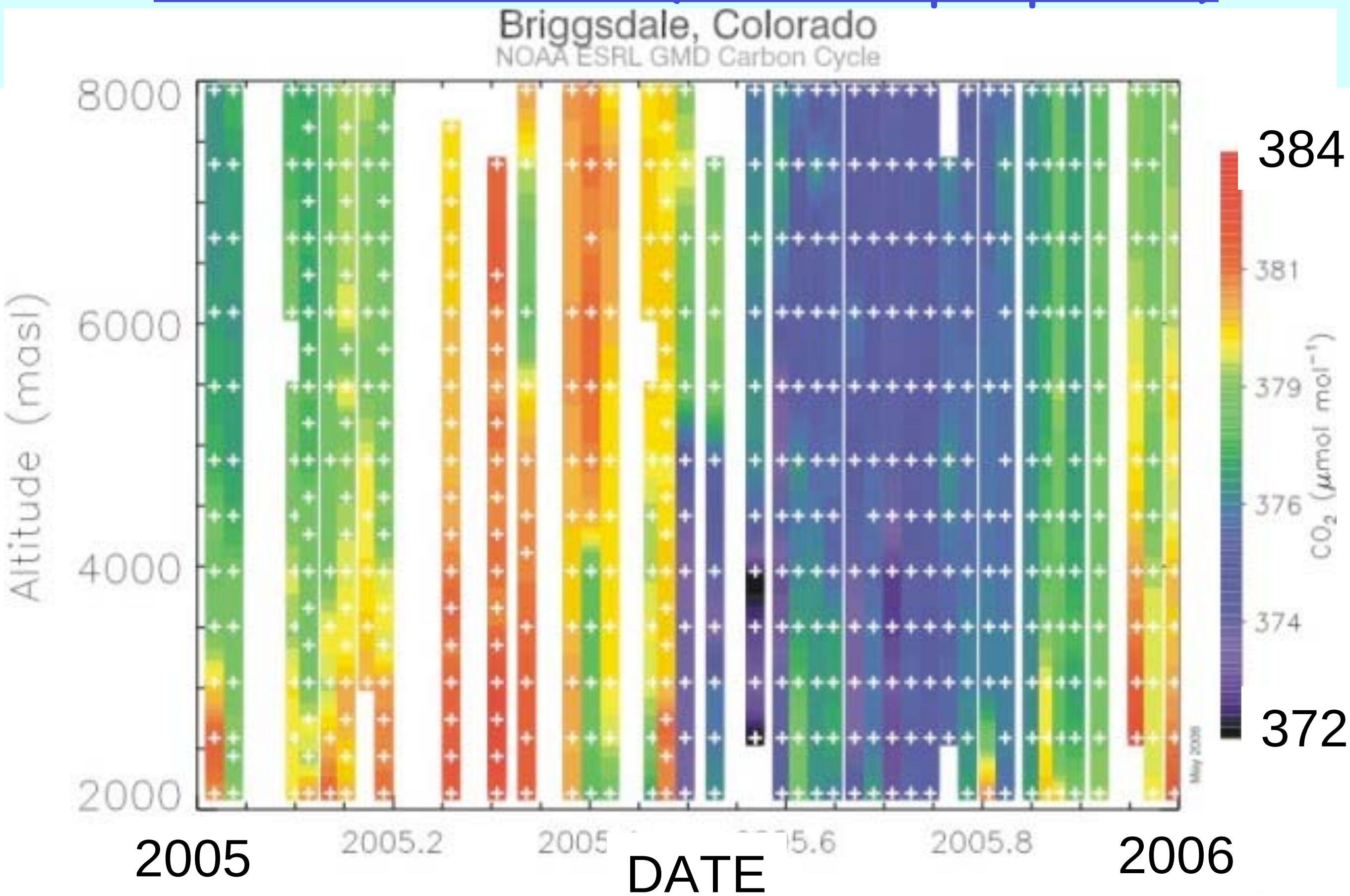
Diurnal CO_2: Highly variable in boundary layer

WLEF Tall Tower, Park Falls, WI



- Diurnal cycle of photosynthesis and respiration
  → > 60 ppmv (20%) diurnal cycle near surface
- Varying heights of the planetary boundary layer (varying mixing volumes)

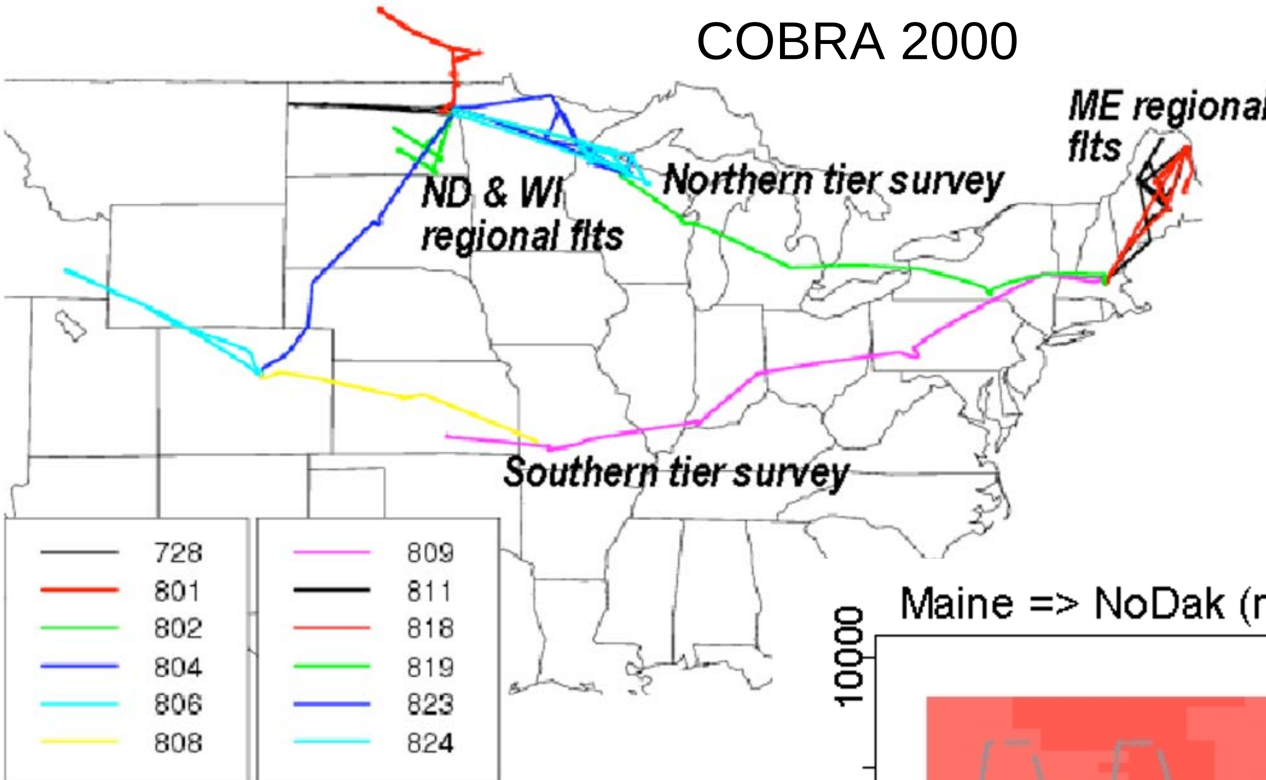
Vertical Profiles (free troposphere)

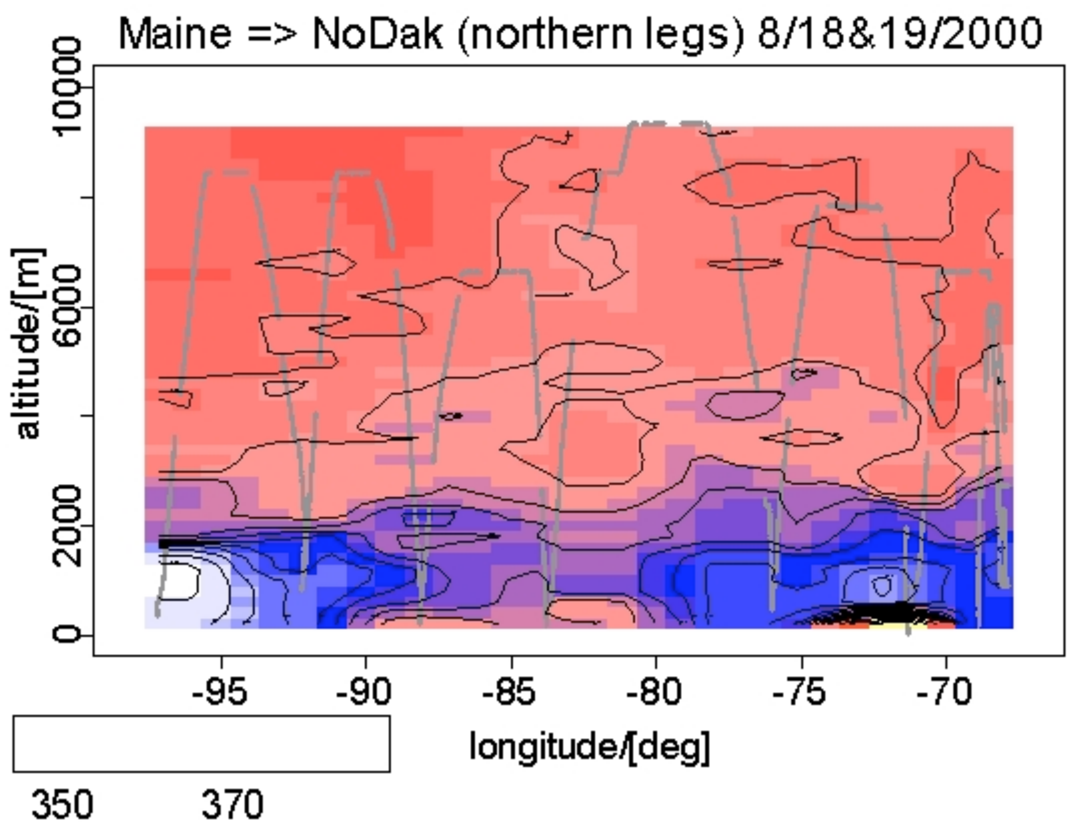


Vertical profiles of atmospheric carbon dioxide from samples collected during weekly flights over Briggsdale, Colorado (~1.7 km above sea level). A single year from the multi-year record is shown. White pluses identify altitudes at which actual samples were collected. Carbon dioxide mixing ratios (micromol CO_2 per mol dry air) are indicated by color. The general trend towards lower CO_2 mixing ratios in the spring and summer and higher CO_2 mixing ratios in the winter is driven primarily by ground based plant photosynthesis and respiration both locally and in surrounding regions. CO_2 production from fossil fuel burning and atmospheric mixing and transport also contribute to variability observed. Contact: Dr. Colm Sweeney, NOAA ESRL GMD Carbon Cycle, Boulder, Colorado, (303) 497-4771 (colm.sweeney@noaa.gov, http://www.cmdl.noaa.gov/ccgg).

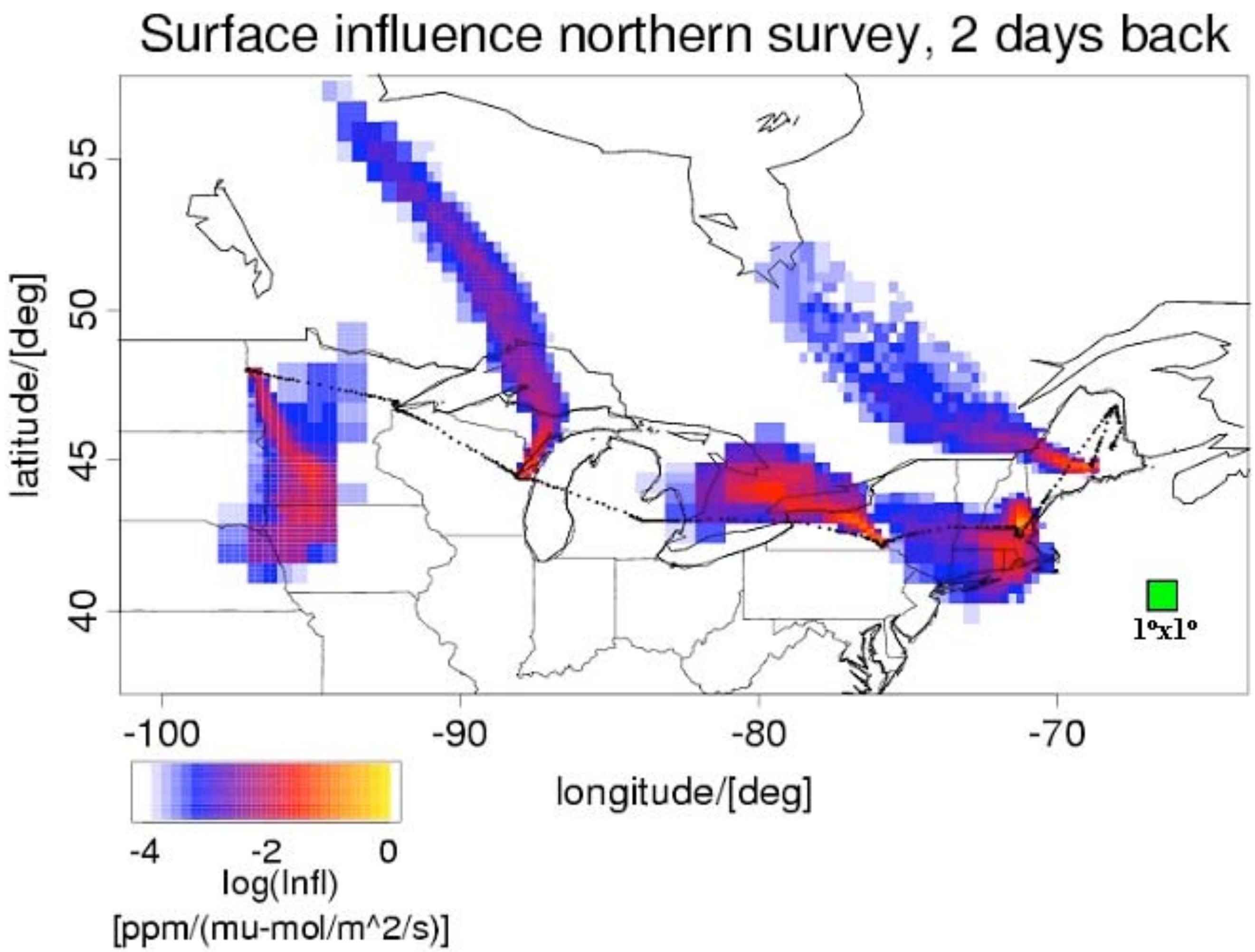
Aircraft Campaigns

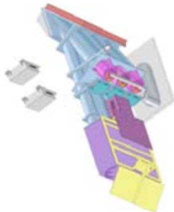
COBRA 2000



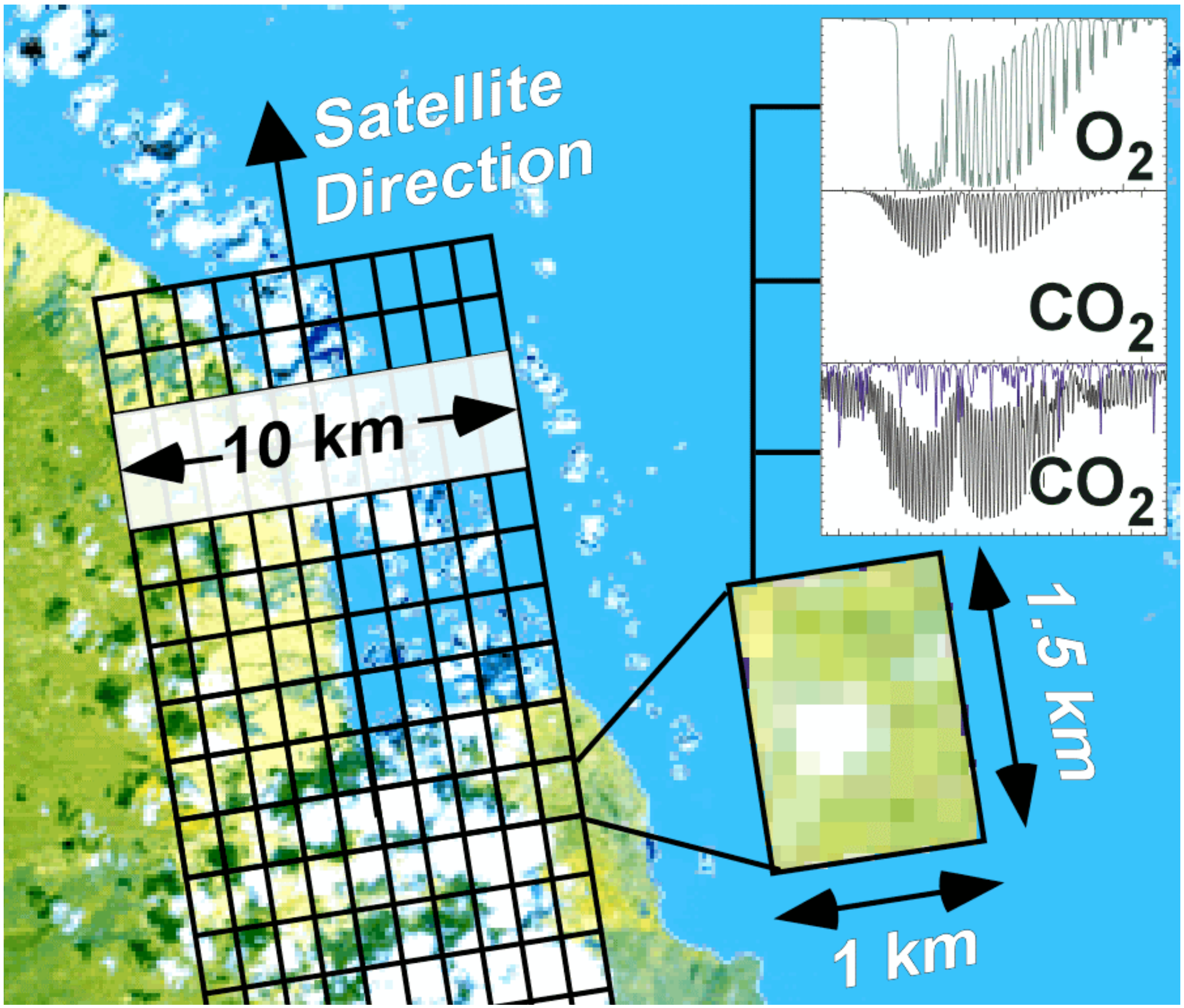


Surface Fluxes => Atmospheric CO2





Orbiting Carbon Observatory
(Planned Dec 2008 launch)



- Estimated accuracy for single column ~1.6 ppmv
- 1 x 1.5 km IFOV
- 10 pixel wide swath
- 105 minute polar orbit
- 26° spacing in longitude between swaths
- 16-day return time

Multiple Time/Space Scales