# Carbon Cycle:
# What do we know?
# What else do we want to know?


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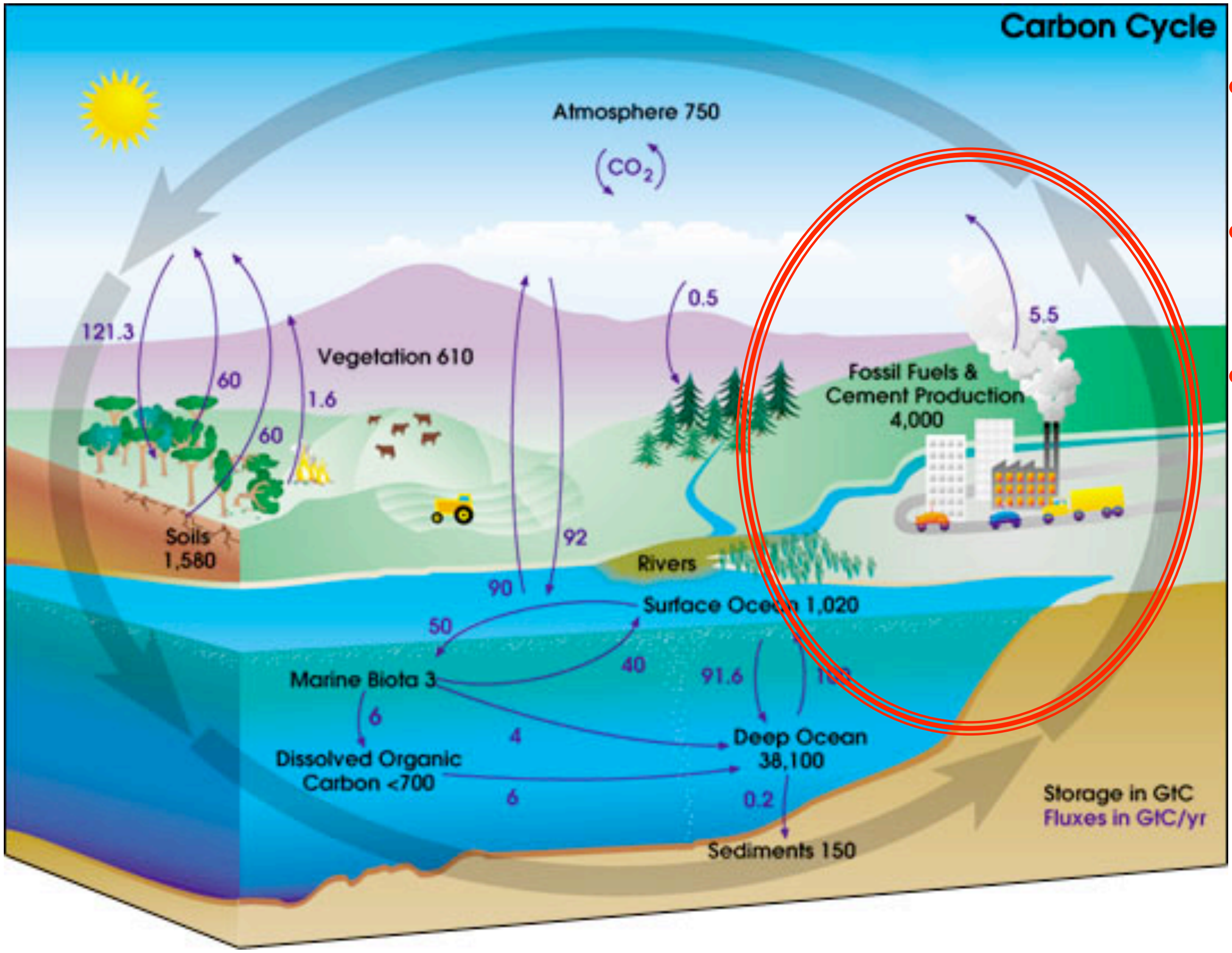
UC Berkeley

February 28 2010

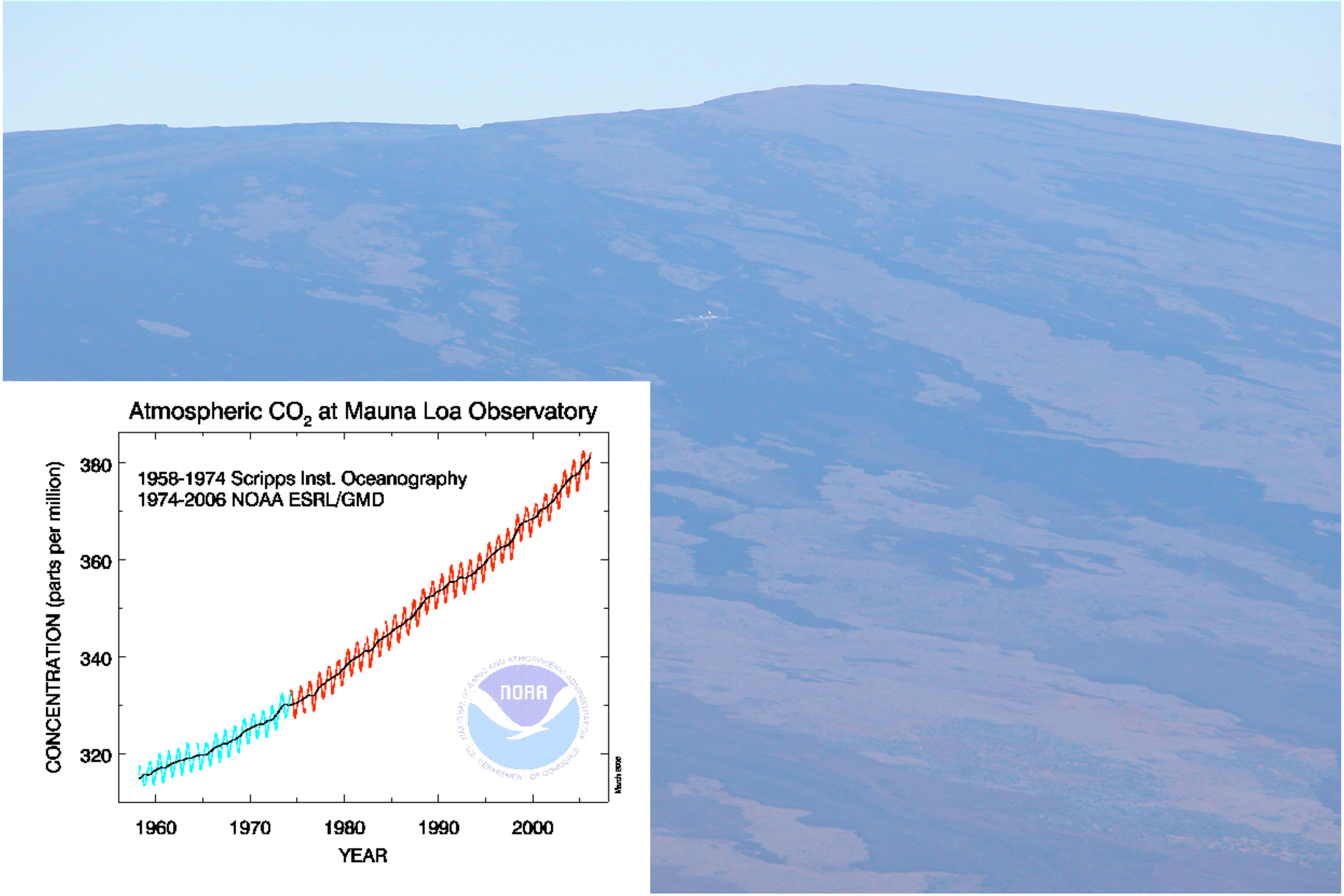
# Continuous Carbon Cycling




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

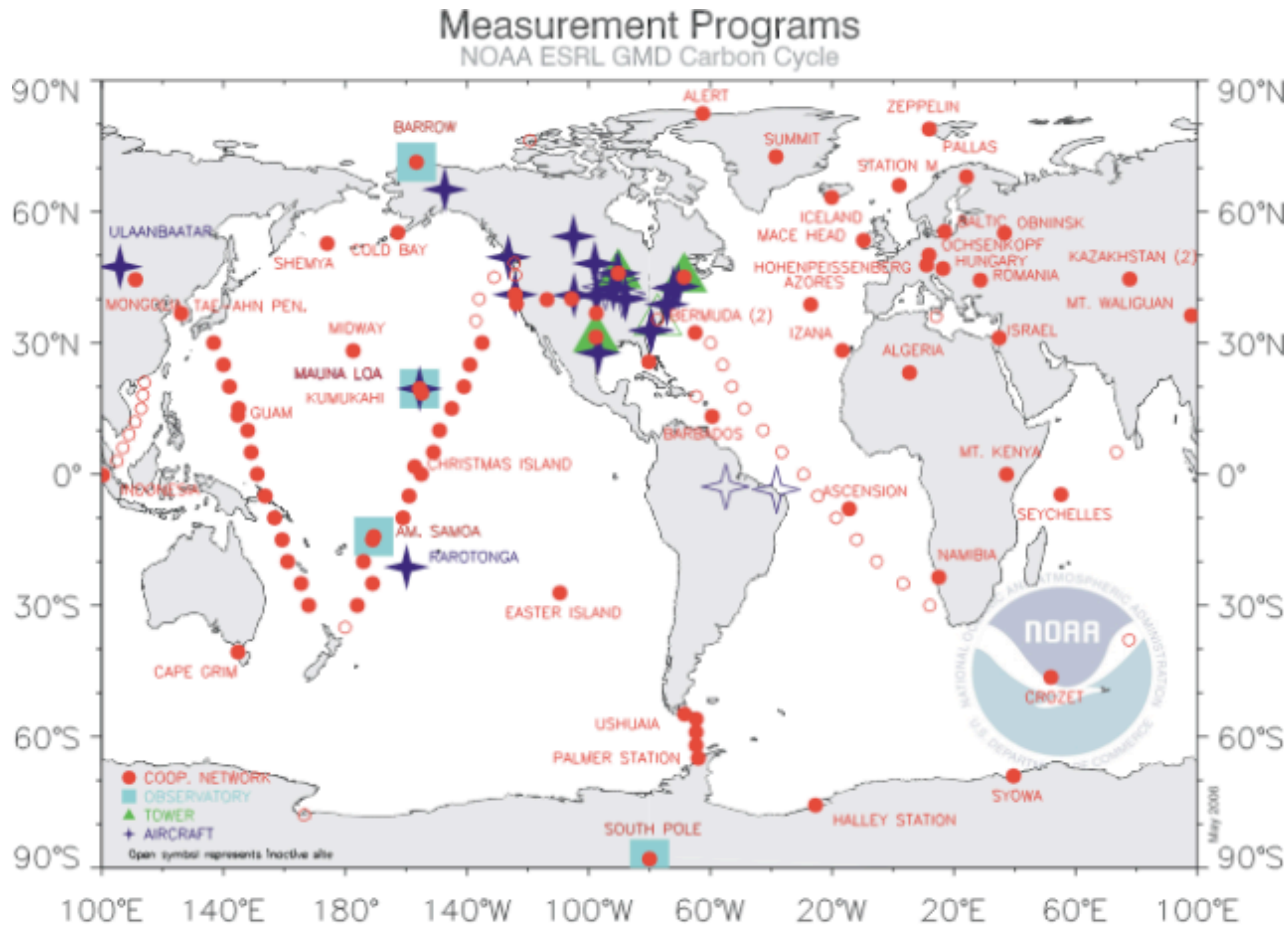
- Atm CO2 --> inventory
- Land: turnover time $10^1$-$10^2$ yrs. Ocean: turnover time $10^2$-$10^3$ yrs
- Difficult (time consuming and expensive) to measure changes in land and ocean inventories. Focus on fluxes

# Atm $CO_2$ measurements at Mauna Loa Obs



# What We've got: The data:  Atm CO2 (for now)

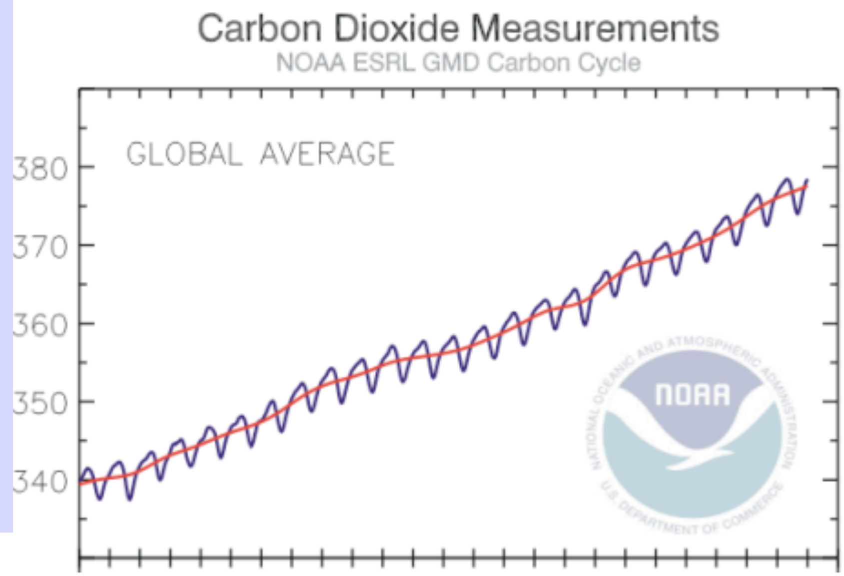
- Discrete surface flasks (~weekly)
- Continuous surface (hourly) observatories
- Tall towers continuous (hourly)
- Aircraft profiles (~weekly)




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).

# $CO_2$ mixing times in atm:

**~2 wks around lat circle**
**~3 mo within hemisphere**
**~1 yr bet' hemispheres**




- NOAA-ESRL
- ~ 100 sites at remote marine locations, bi-weekly flasks, 2m
- Long-term increase
- Seasonal cycle
- N-S gradient

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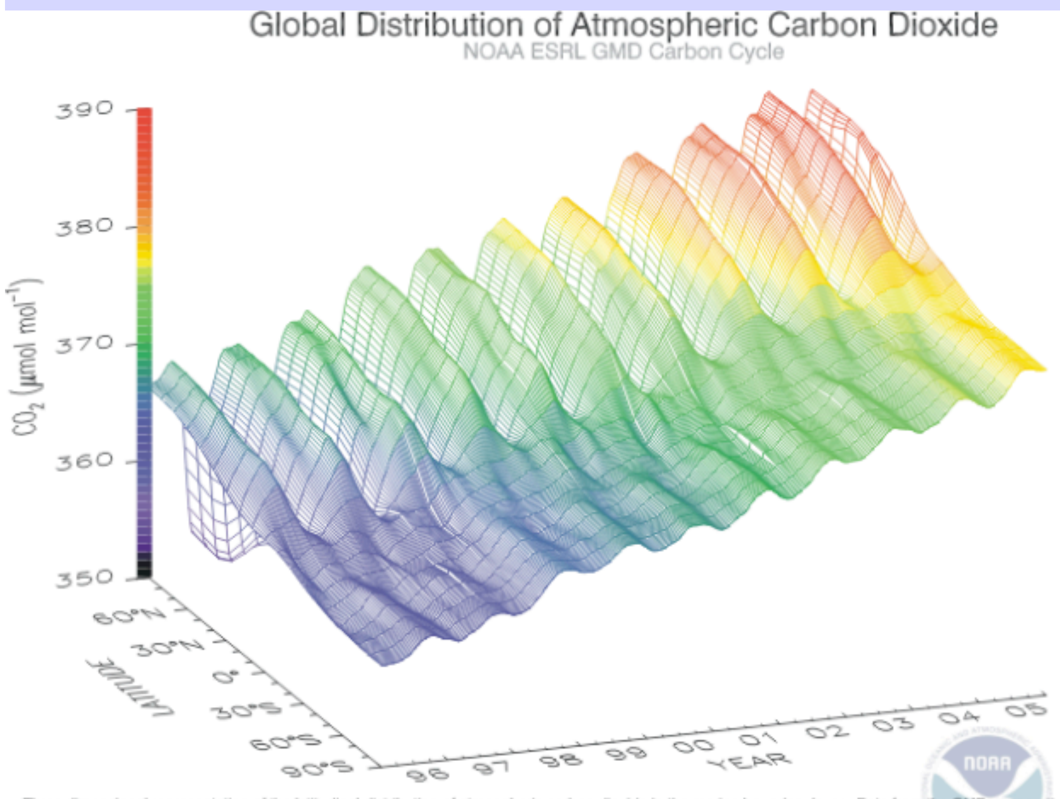
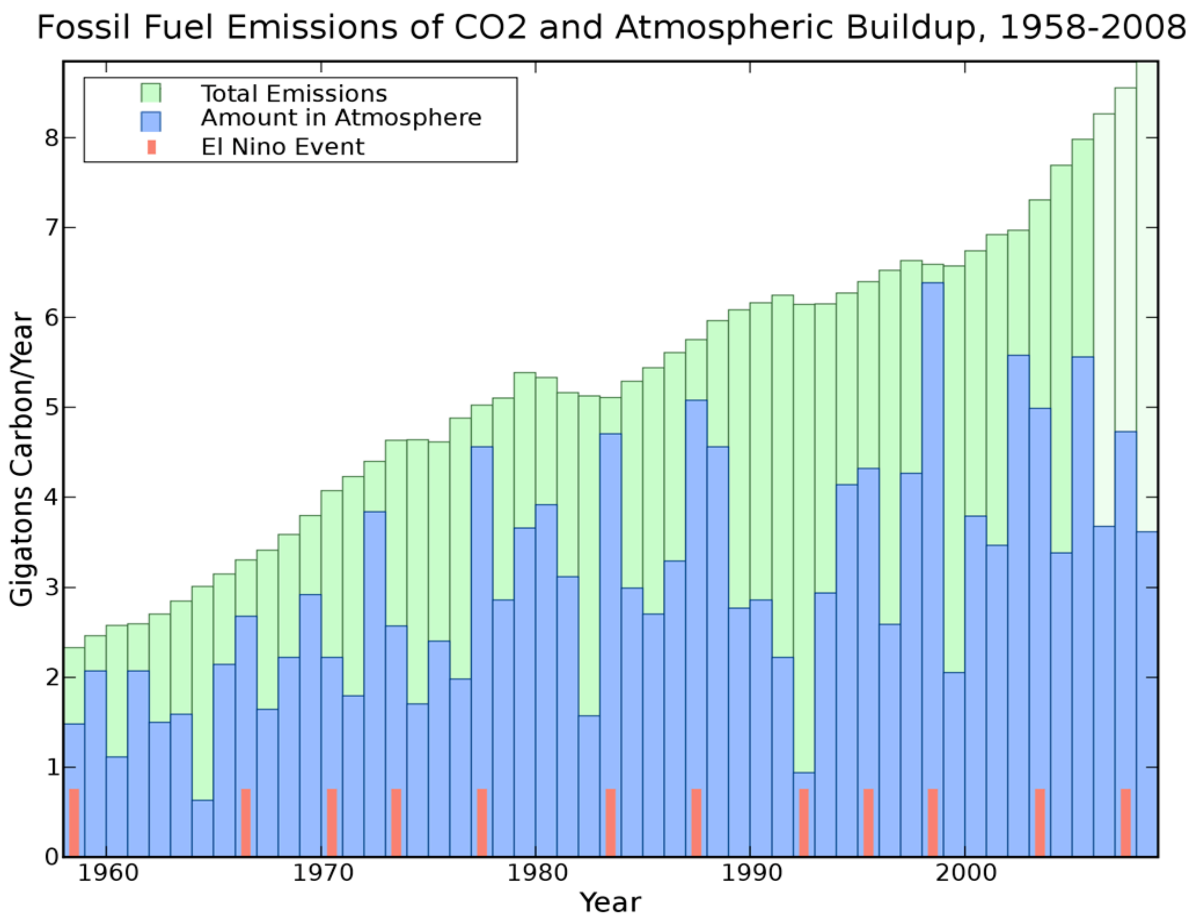
May 2006




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).

# PROBLEMS: Missing Sinks and Missing Sources

- Only half of the $CO_2$ produced by human activities is remaining in the atmosphere
- How well do we know the ***sources***?
- 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?



# Rule: Conservation of Carbon

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

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

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

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

**“Steady State”:** $$\Im(\overline{C}) = (\overline{F_{oa}} - \overline{F_{ao}}) + (\overline{F_{ba}} - \overline{F_{ab}})$$

# Units: 1 Pg = 1 Gt = $10^{15}$ gram

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

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

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

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

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

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

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

# “Known” and/or Observed

- Sources: fossil fuel emission
- Atmospheric $CO_2$
- Land carbon; incl deforestation
- Ocean carbon

# 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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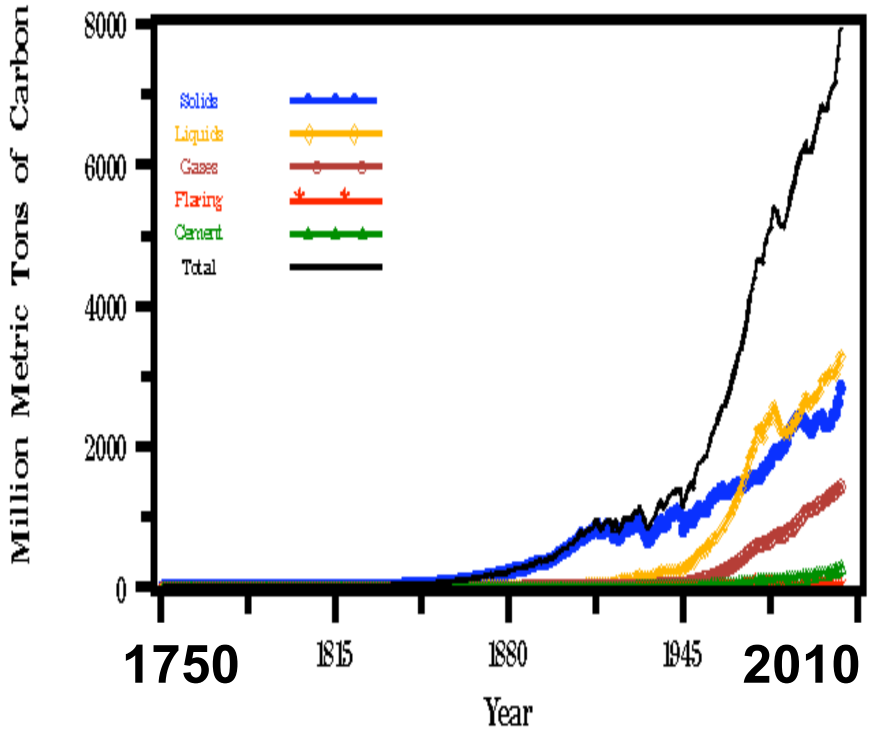
# CO2 Emission from Fossil Fuel Combustion & Industrial Processes

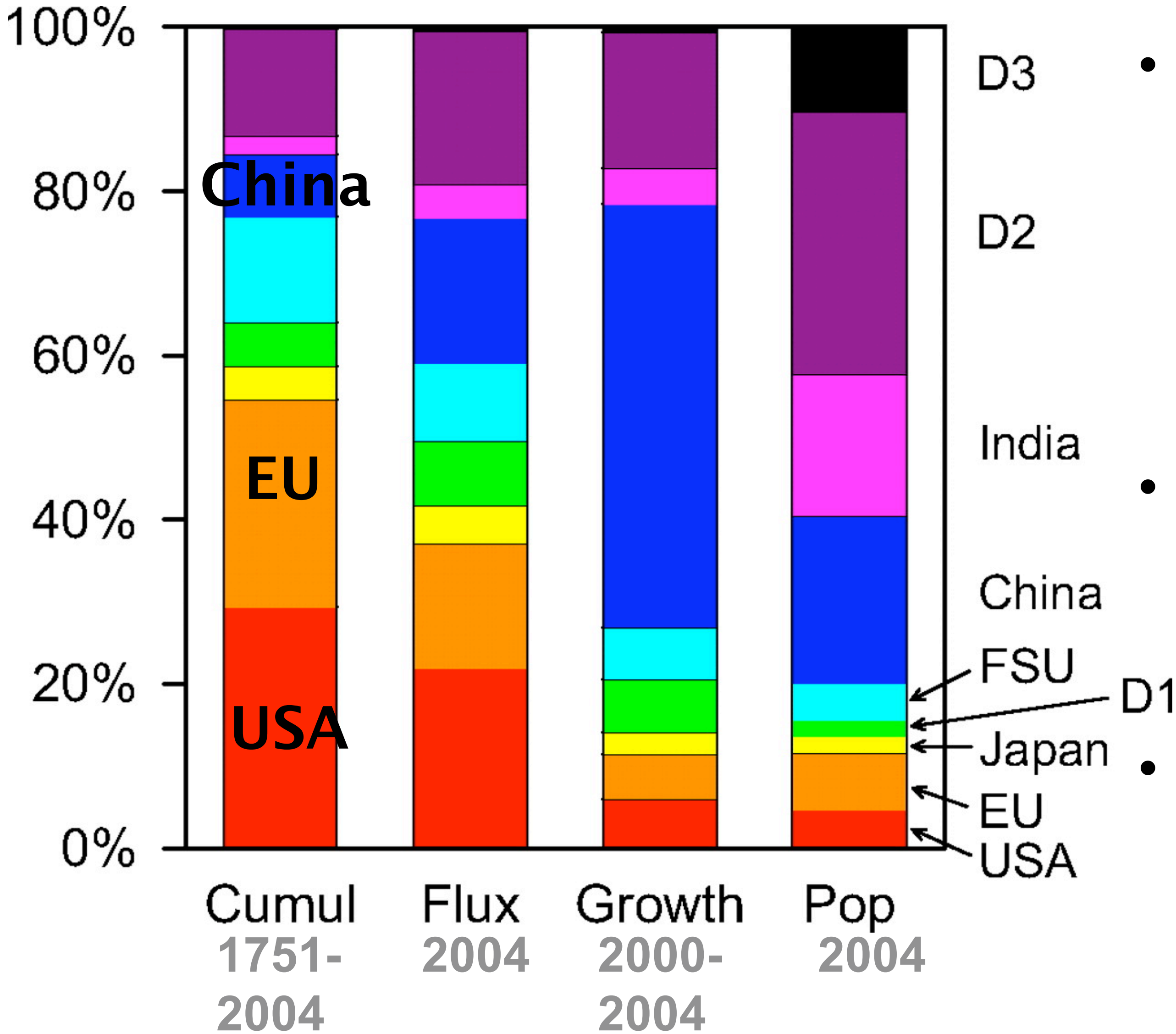



- Liquids (~36%)
- Solids (~35%)
- Gas (~20%)
- Cement production (~3%)
- Flaring at wells (<1%)
- Bunker fuels (~4%)
- Others (<1%)

$CO_2$ Emission Growth Rate:

- 1990-1999: 1.1% per year
- 2000-2004: >3% per year

# Shifting Emission Sources



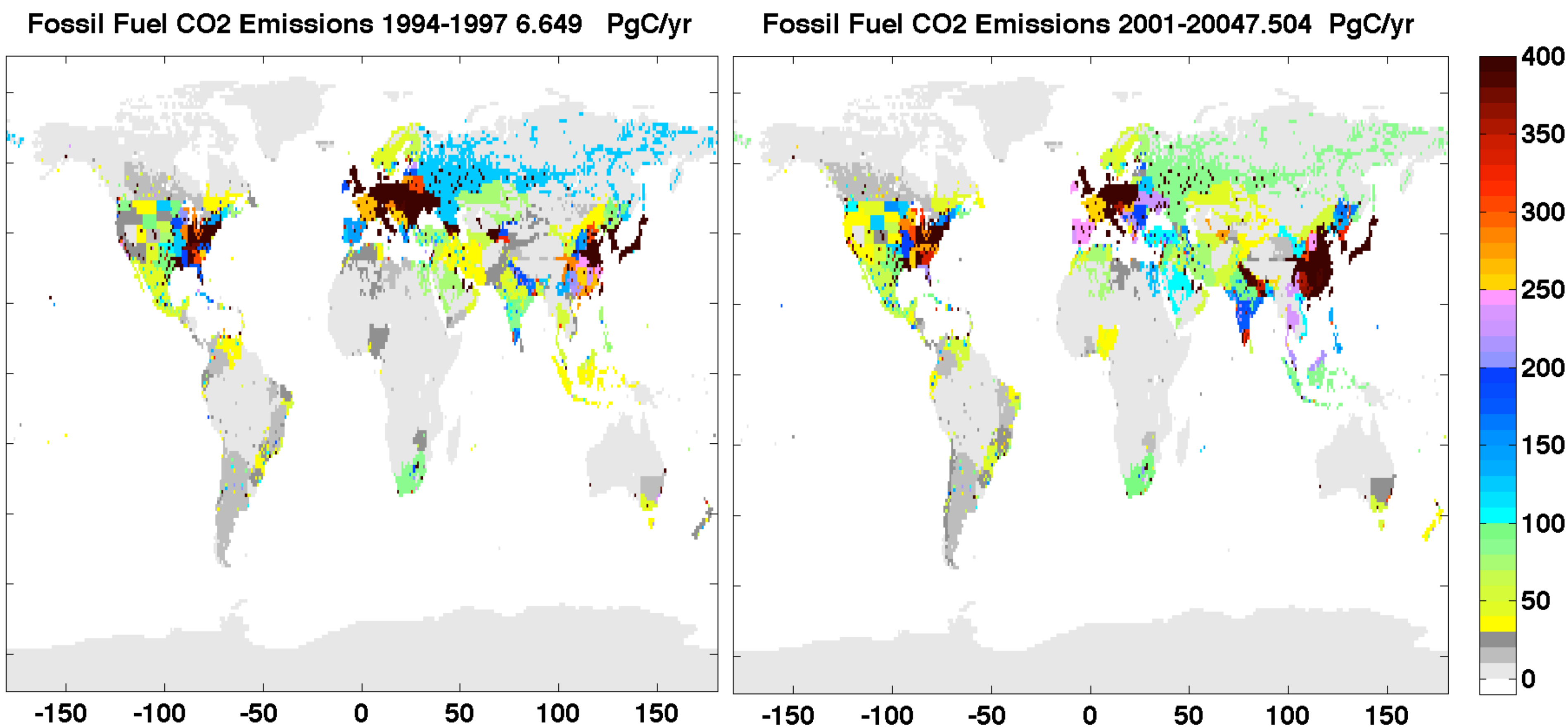

- **USA and EU contributed >50% of cumulative $CO_2$ emission since 1751**
- **China leads recent growth in emissions**
- **2004: China emissions close to US emissions**



**Raupach, Michael R. et al. (2007)** PNAS

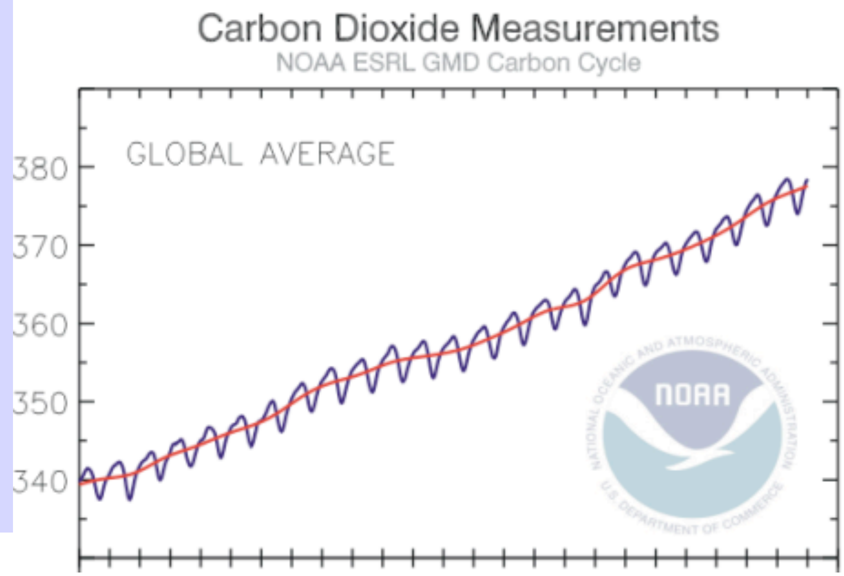
# Fossil Fuel CO2 Emissions

**1994-1997** **2001-2004**




**6.6 PgC/yr** **7.5 PgC/yr**

# $CO_2$ is a long-distance traveller in the atmosphere

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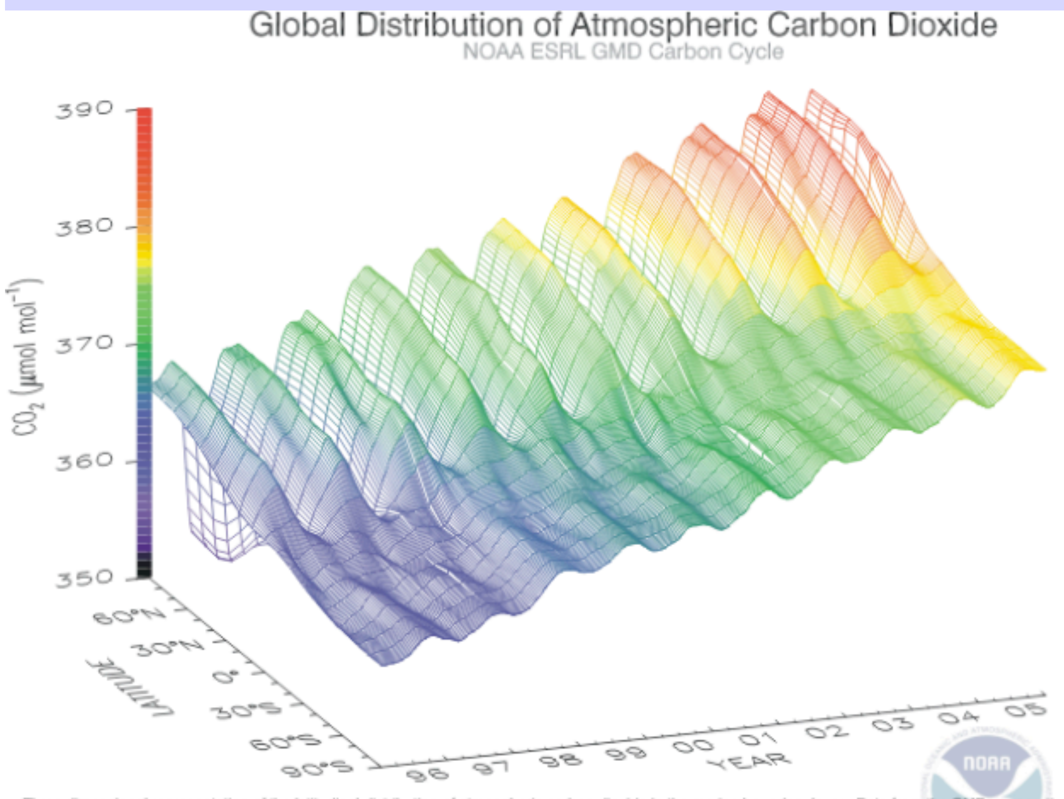


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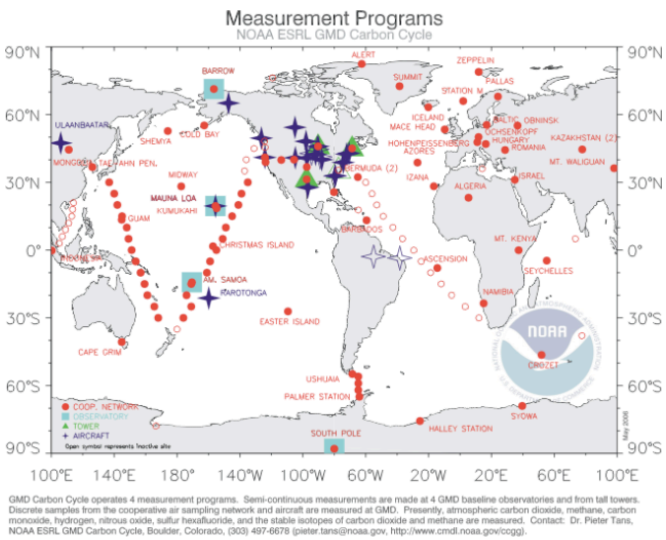
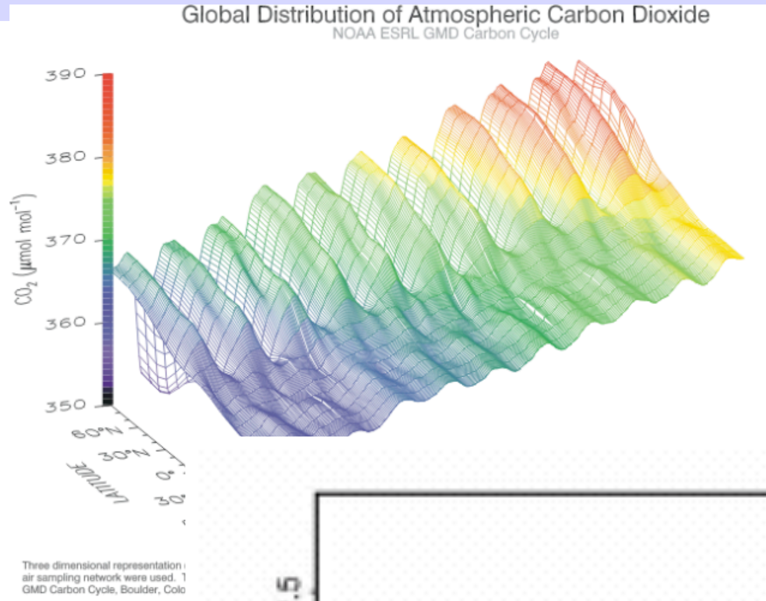
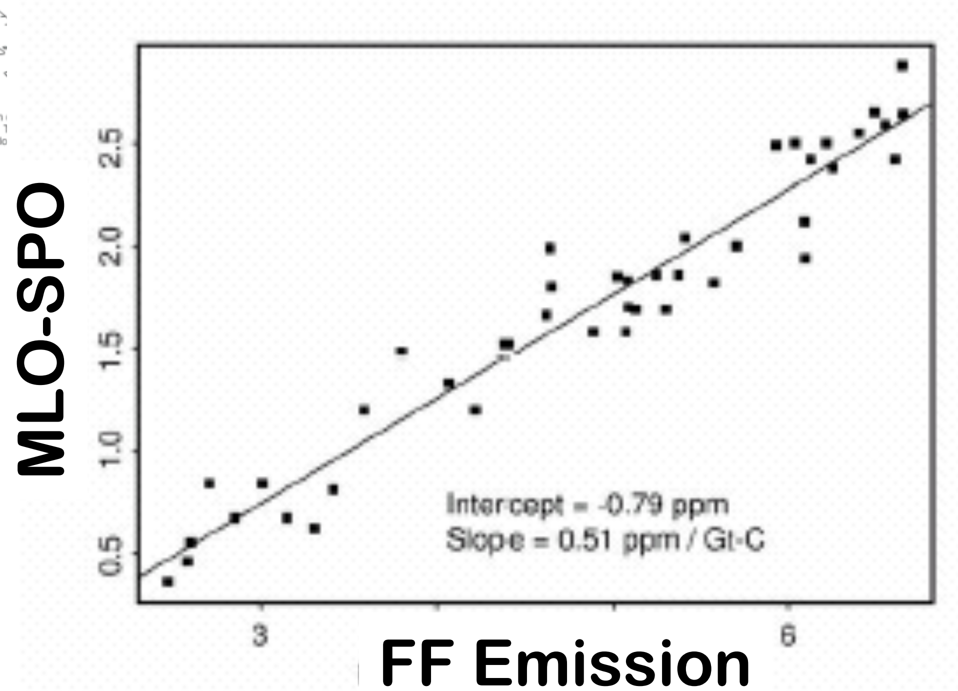
# Atm CO2 Obs:  (1)  Time series at stations



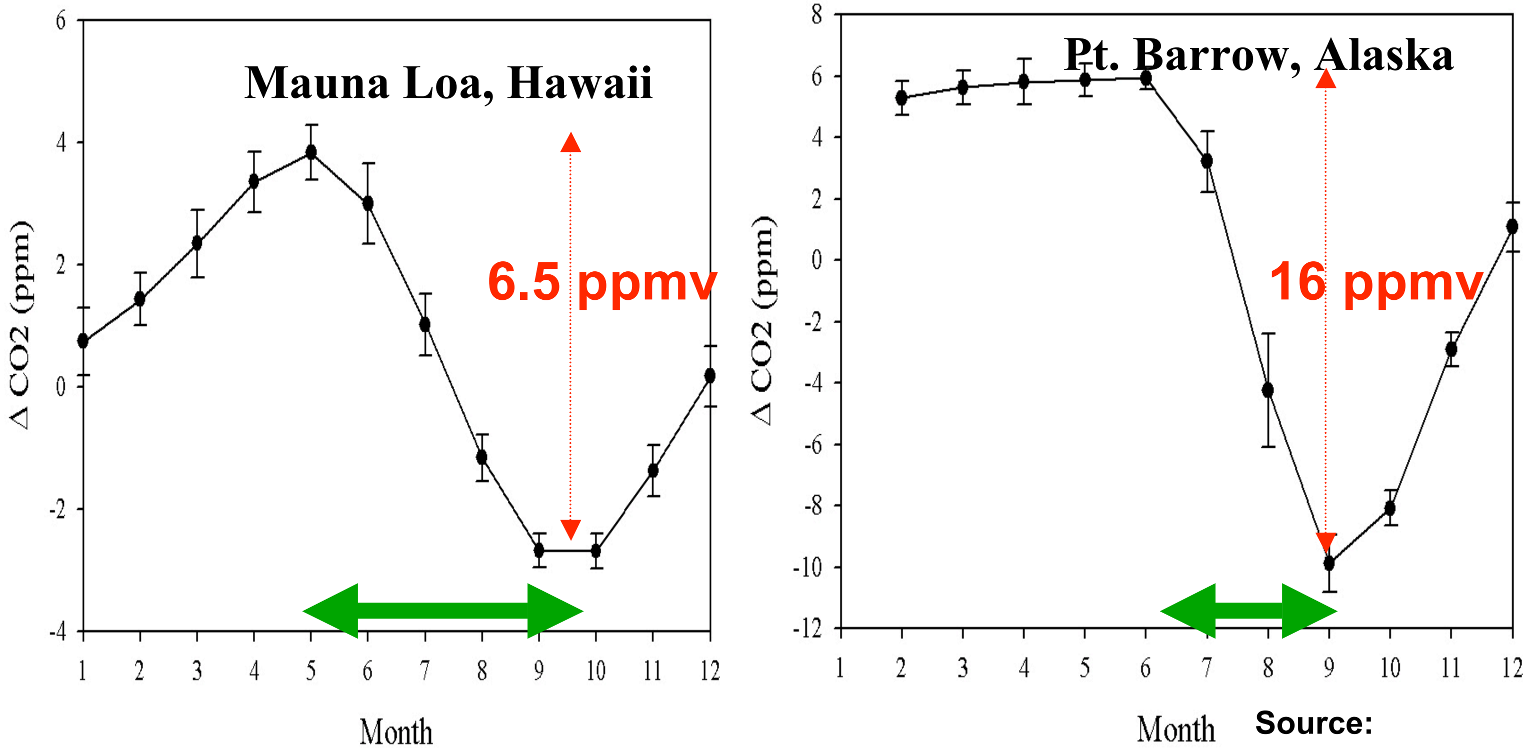




Mixing time between hemispheres ~ 1 year:

N-S gradient increases as FF emission (~NH source) increases



# Atmospheric $CO_2$ Signature of Ecosystem C Exchange: Seasonal Cycle

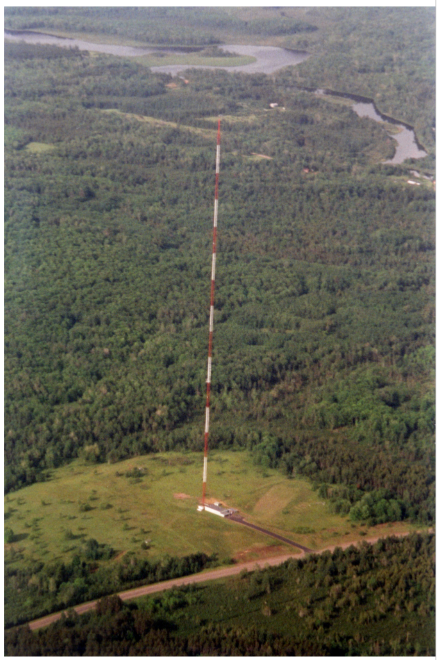


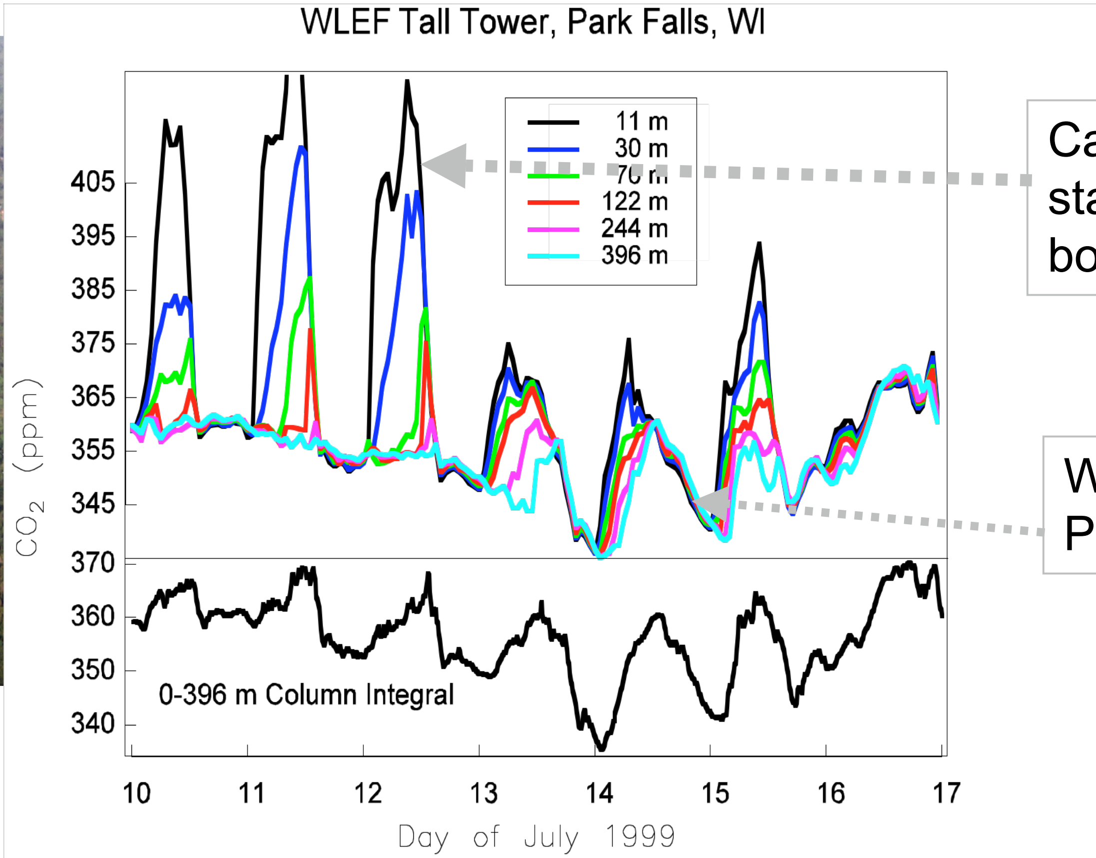

Source: NOAA/CMDL

•Mixing time within a hemisphere ~ 3 months
•MLO seasonal cycle integrates NH vegetation dynamics
•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

# (2) Tall Towers: Diurnal CO2 is highly variable in boundary layer (<500m)



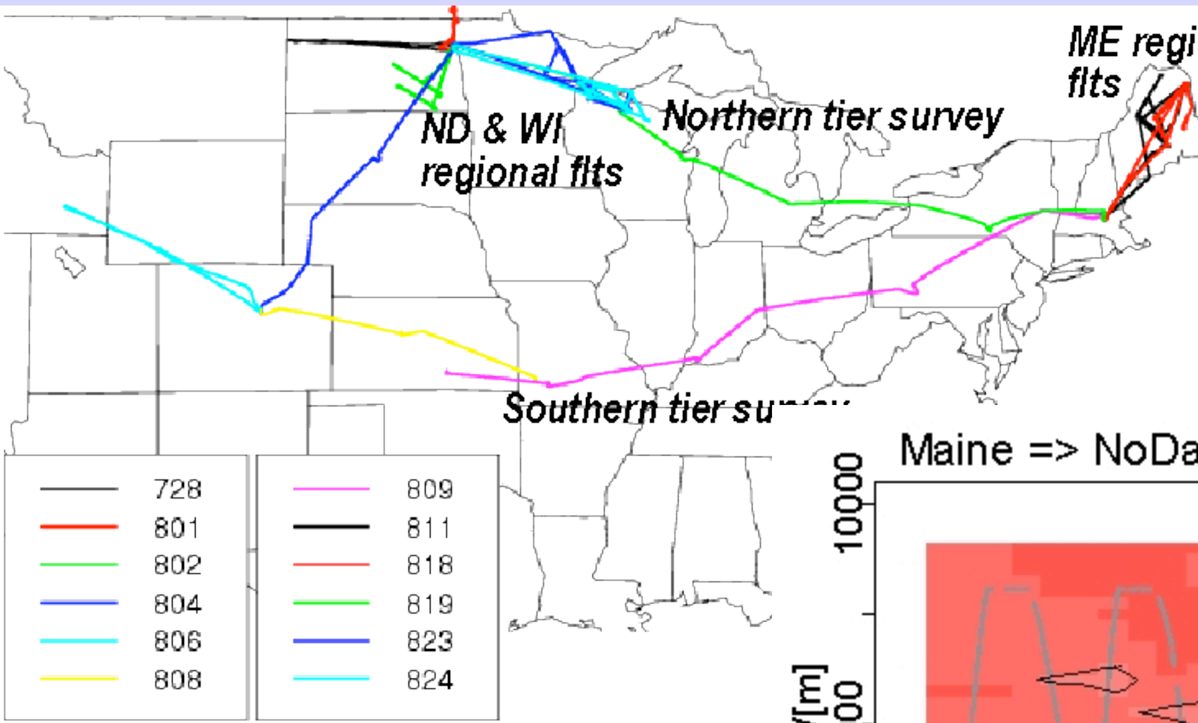


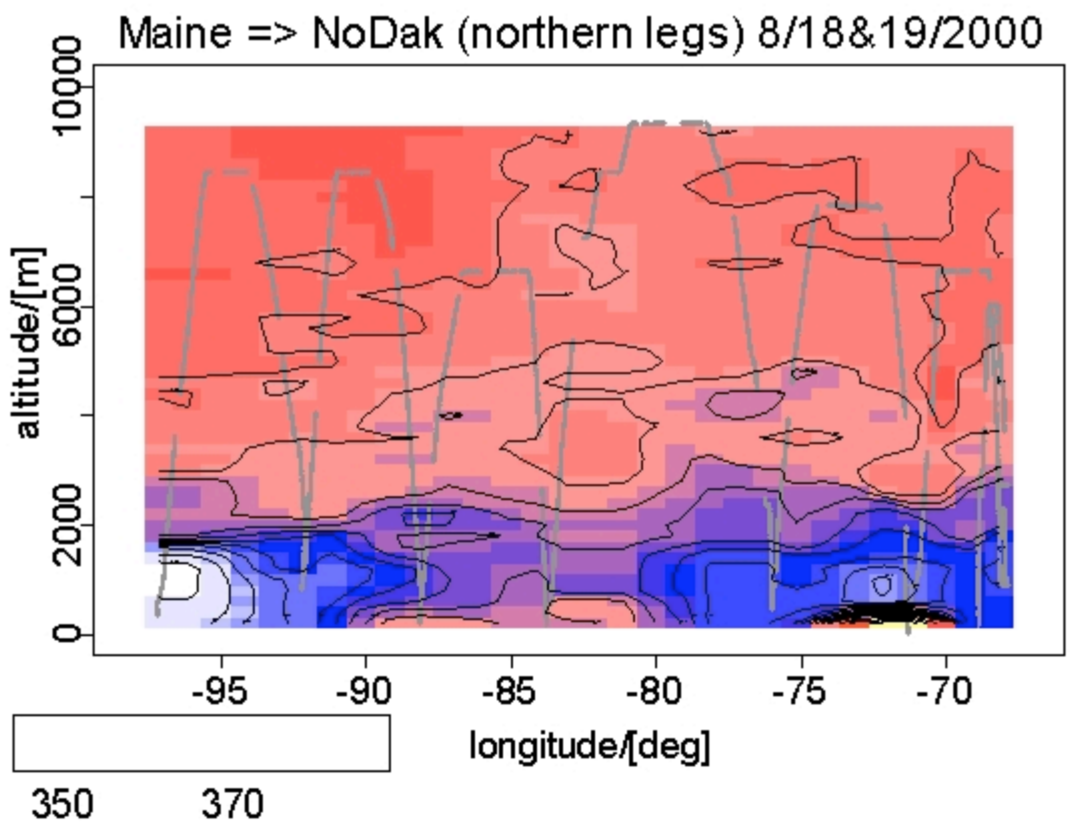

Calm night: stably stratified boundary layer

Well-mixed PBL

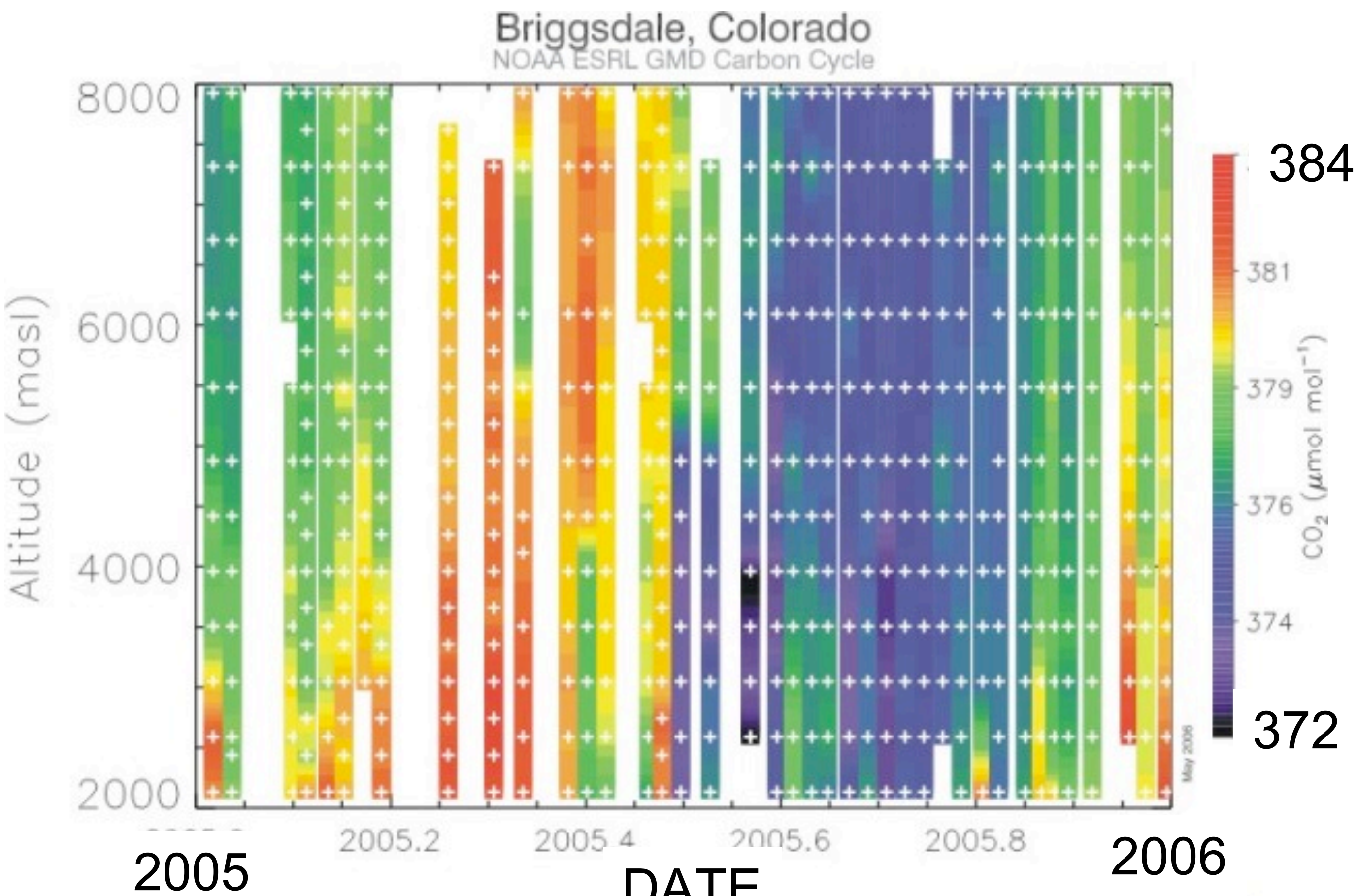
- **Local vertical mixing time- ~ minutes to hours**
- **Diurnal cycle of photosynthesis and respiration**
  - **→ > 60 ppmv (20%) diurnal cycle near surface**
- **Varying heights of the planetary boundary layer (varying mixing volumes)**

# (3a) Occasional Aircraft Campaigns



# (3b) “Regular” Aircraft Monitoring: 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).

# Conservation of Perturbation Carbon in Atm

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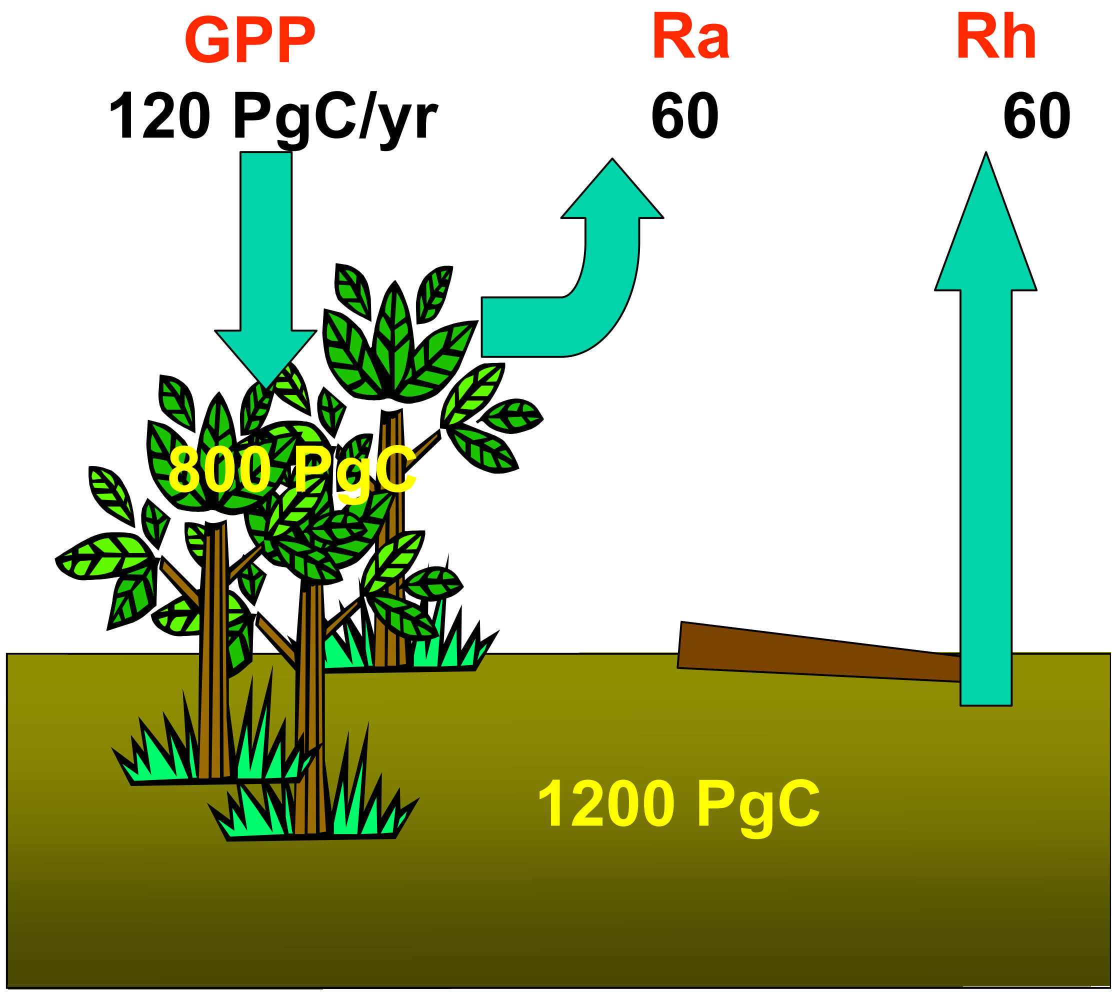
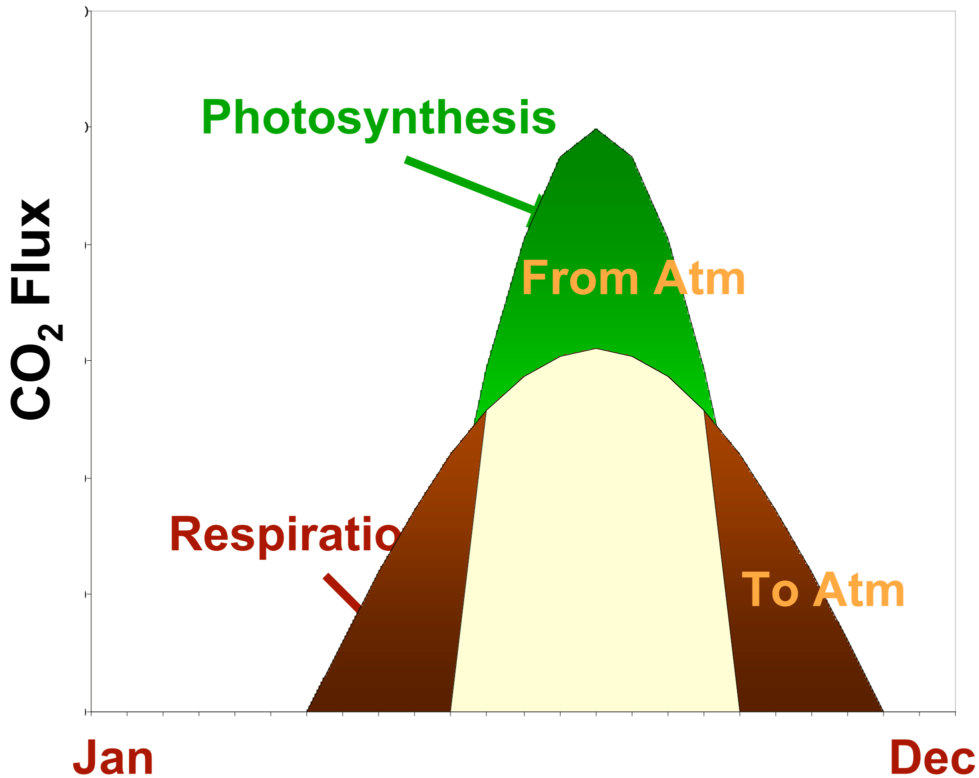
# Terrestrial Carbon Cycle

- 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



# Impact on Atmospheric $CO_2$

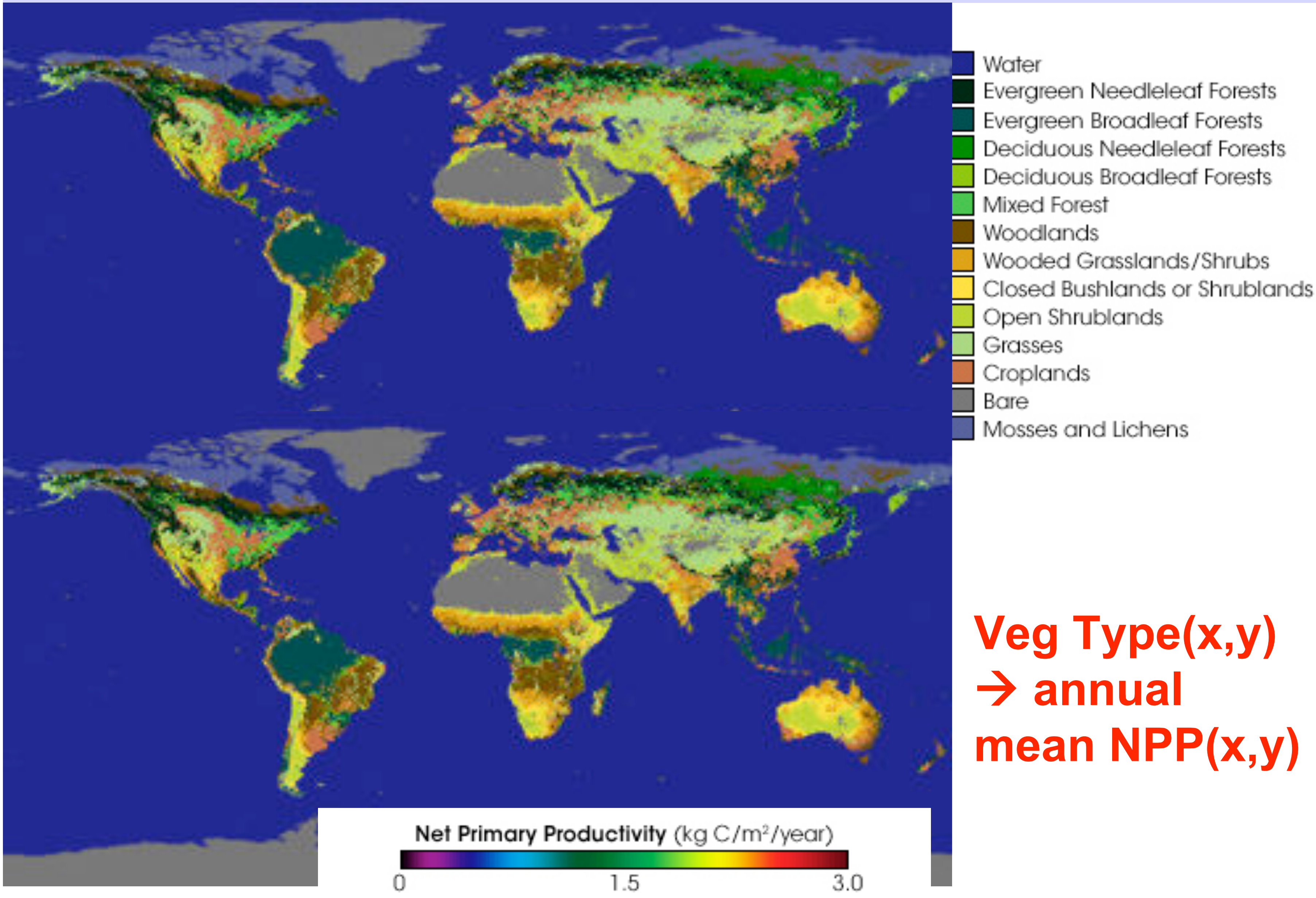



- **Seasonal asynchrony** between photosynthesis and decomposition

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

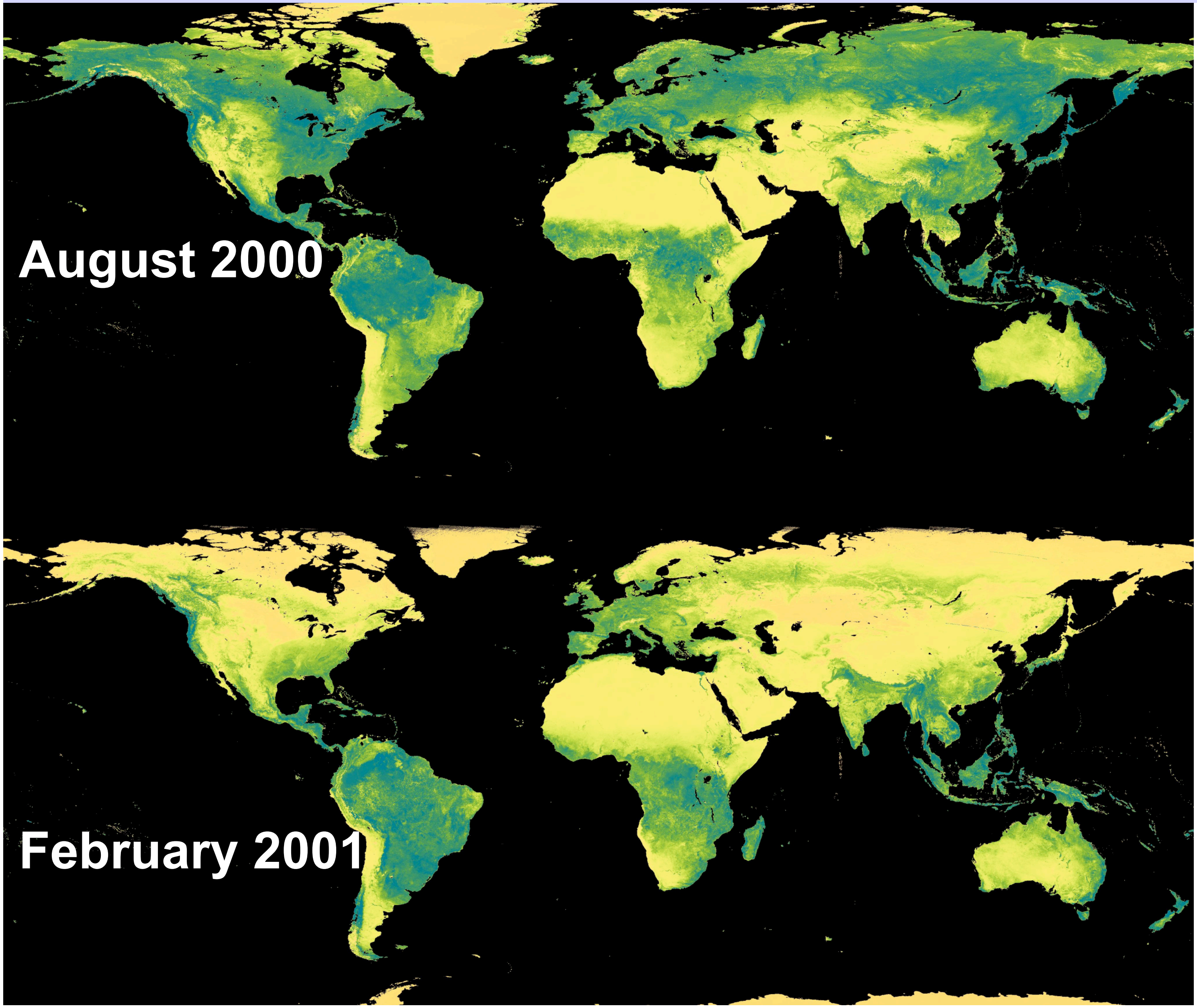
- **Annual imbalance** → carbon source/sink

# (1) History of Ecological Measurements




**Veg Type(x,y) → annual mean NPP(x,y)**

# (2) Satellite Greenness index: NDVI

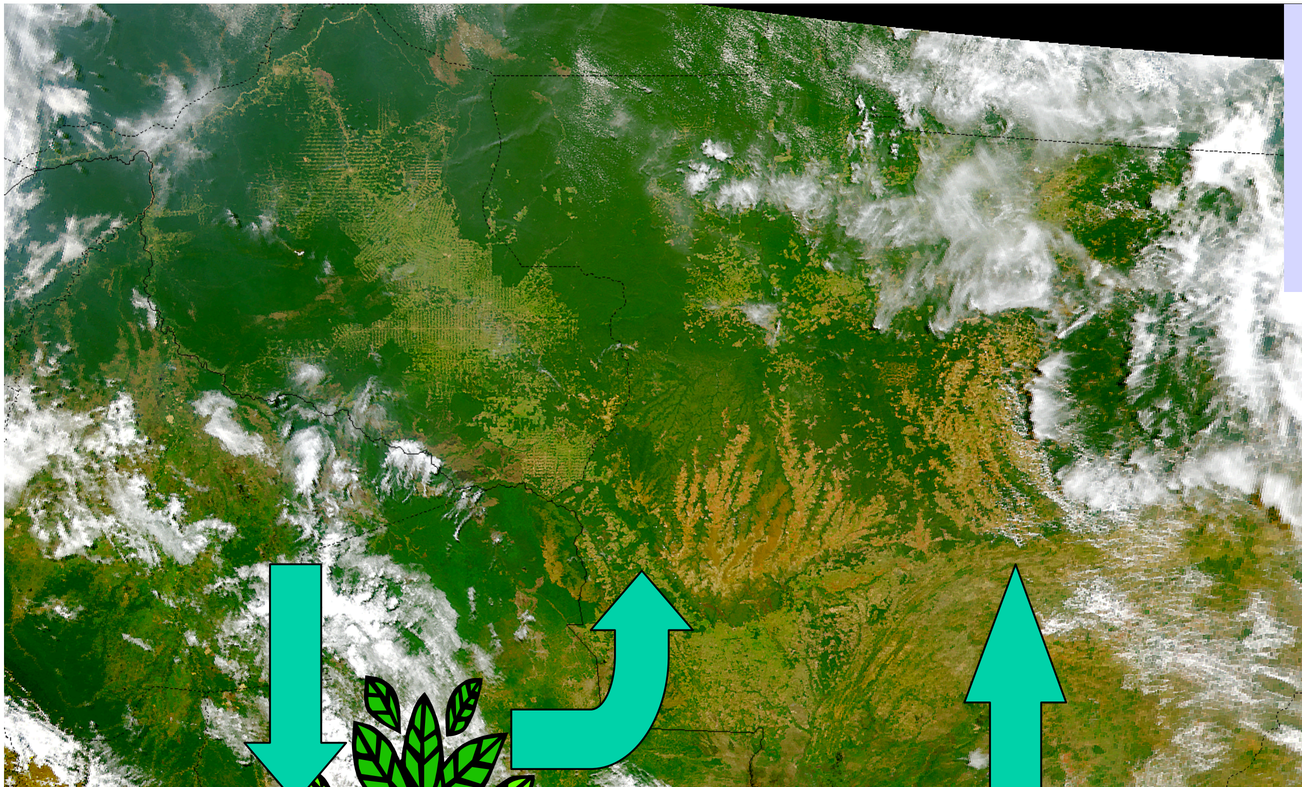


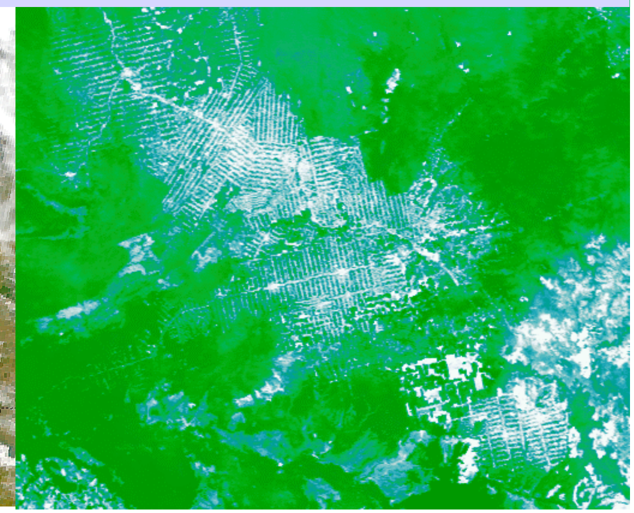

→ Seasonality of NPP

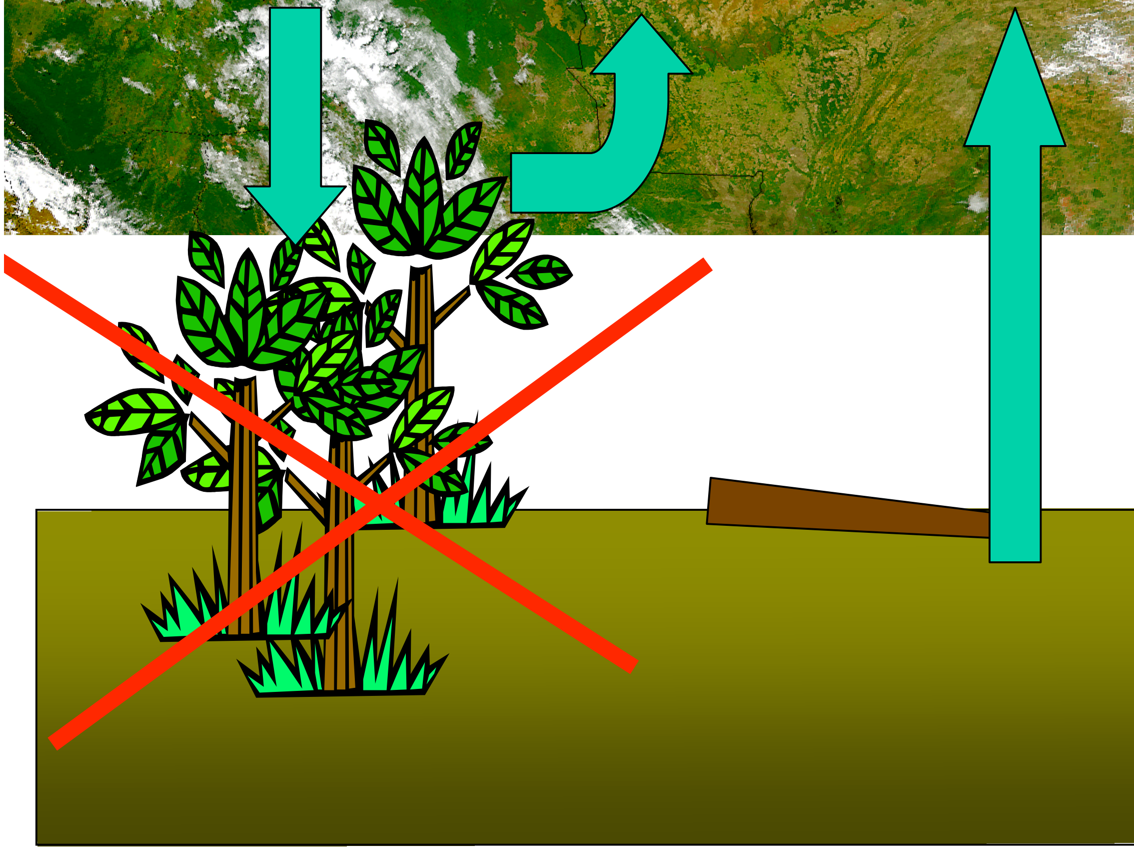
**Seasonality of Respiration not well-defined**

**Net flux not well-defined at every location**

# (3) Satellite Obs Deforestation



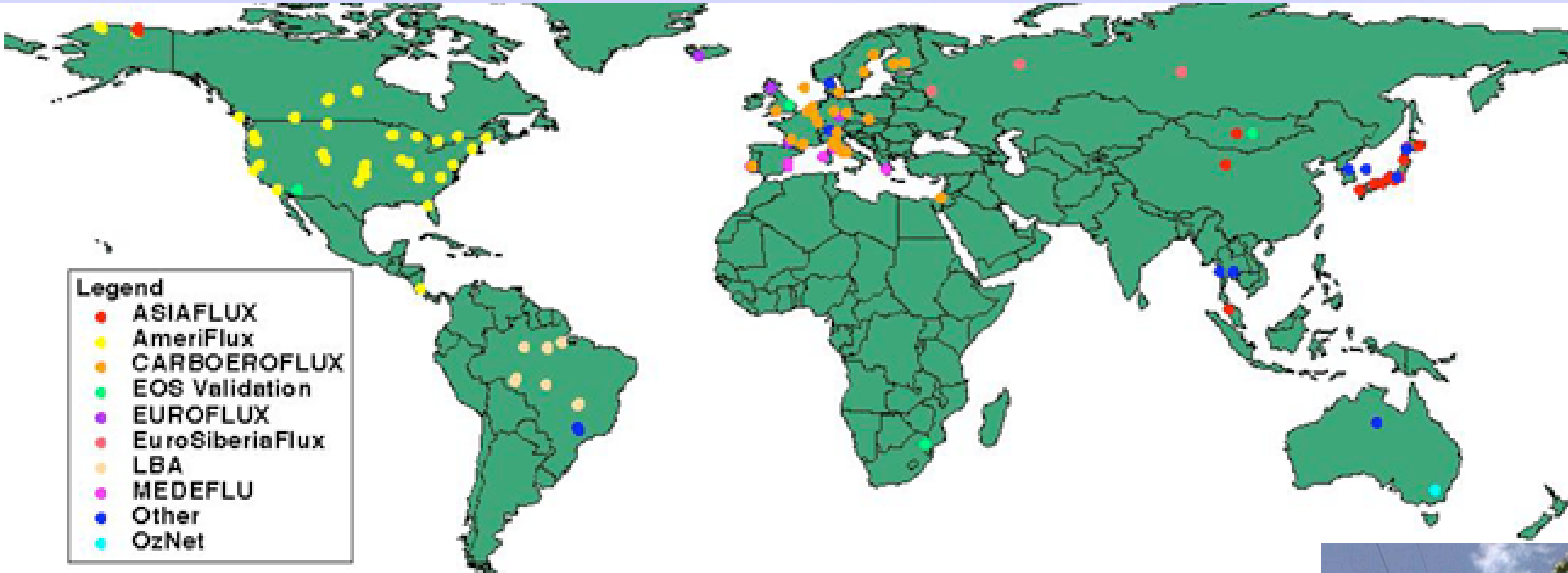




Tough to estimate
- deforested area
- Carbon inventory before deforestation
- Fate of removed carbon
- Fate of litter and soil carbon

Tough to discriminate atm CO2 signature

# (3) Network of (not very tall) CO2 Flux Towers




## At top of canopy

Vertical CO2 flux:  vertical velocity (w), CO2 (c )

$$wc = (\overline{w} + w')(\overline{c} + c')$$

$$= \overline{w}\,\overline{c} + w'\overline{c} + \overline{w}c' + w'c'$$

$$\overline{wc} = \overline{w}\,\overline{c} + \overline{w'c'}$$

# (4) Forest Inventory Analysis: Slow Process Observations

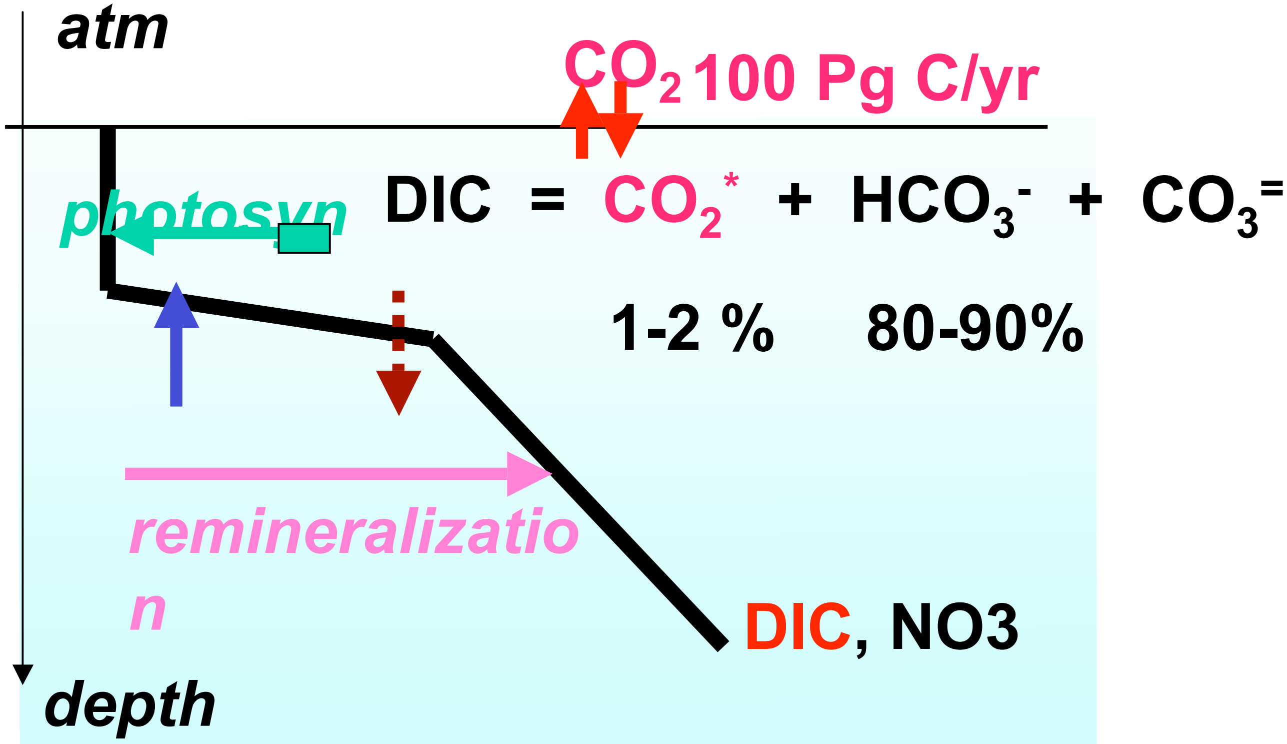
- **Plot-scale measurement of carbon storage, age structure, growth rates: 170,000 plots in US!**
- **Allows assessment of decadal trends in carbon storage**

# Conservation of Perturbation Carbon in Atm

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

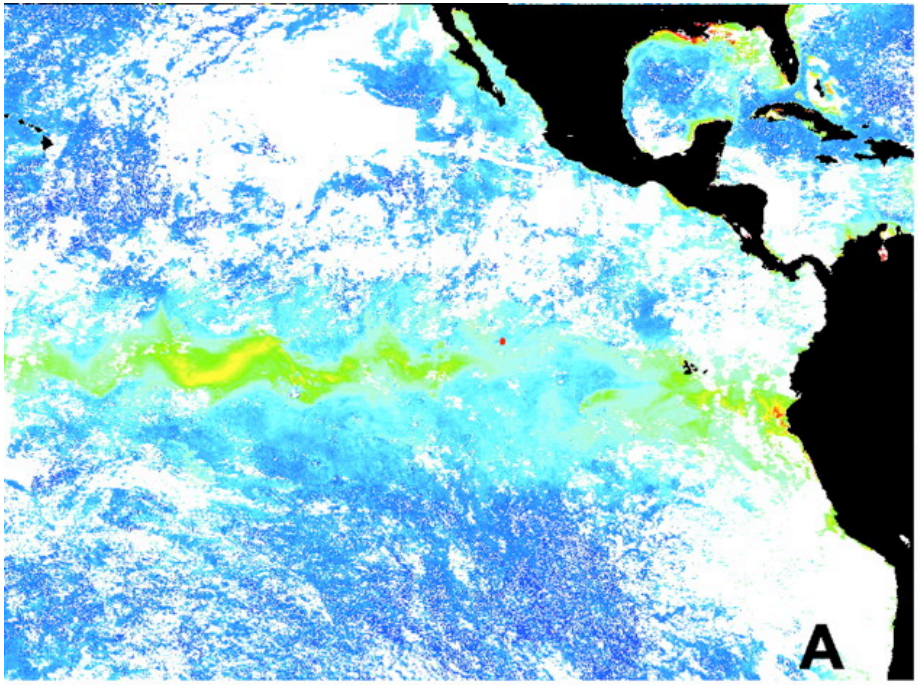
$$S = FF + LandUse + (F_{oa} - F_{ao}) + (F_{ba} - F_{ab})$$

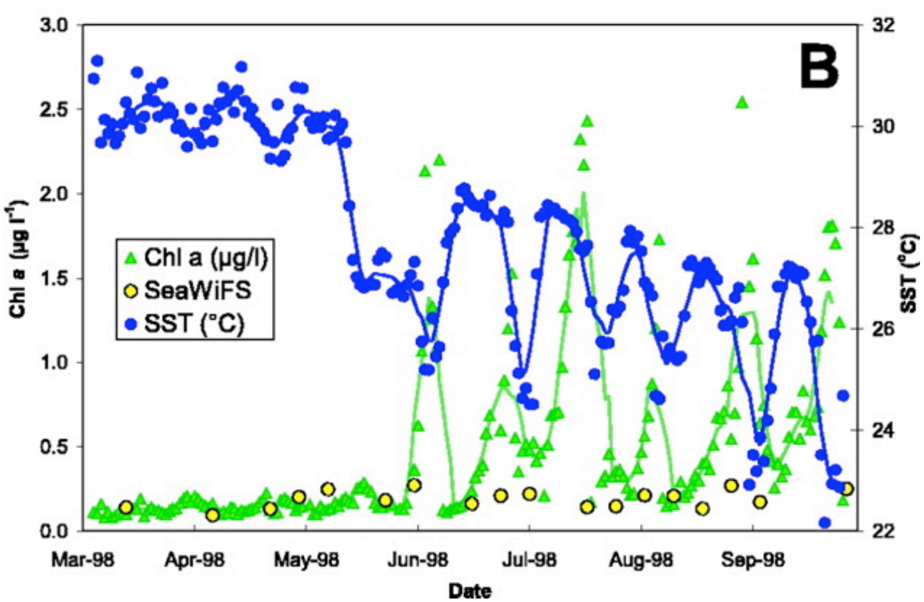
# Ocean C from the Atm's Perspective:




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

# Marine Productivity - redistributes DIC(z)



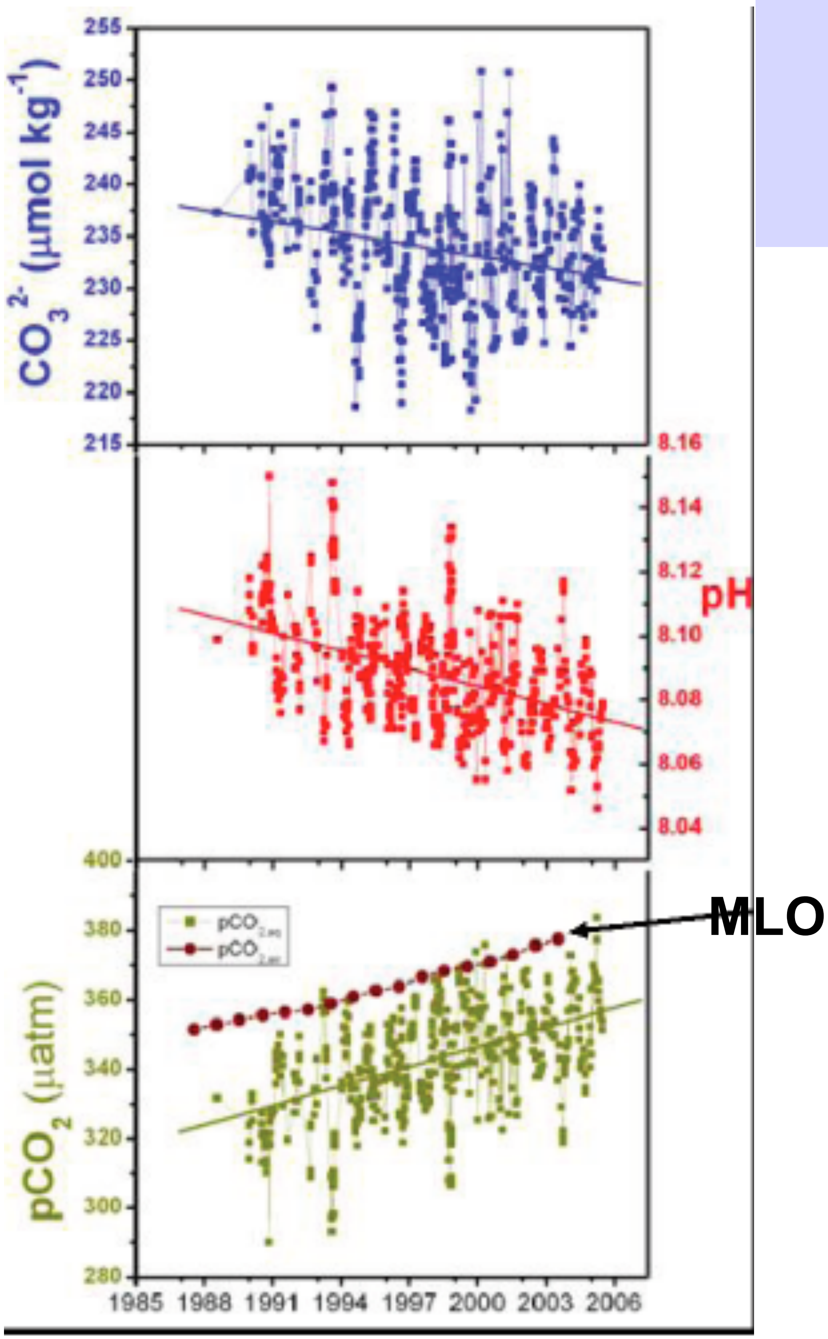




Productivity is possible when upwelling brings:

•Nutrients from below to euphotic zone
•Cold water

Small Flux, small inventory of organic C
But alters DIC(z)

# (1a) Time series: Hawaii (ALOHA) and Bermuda (BATS)

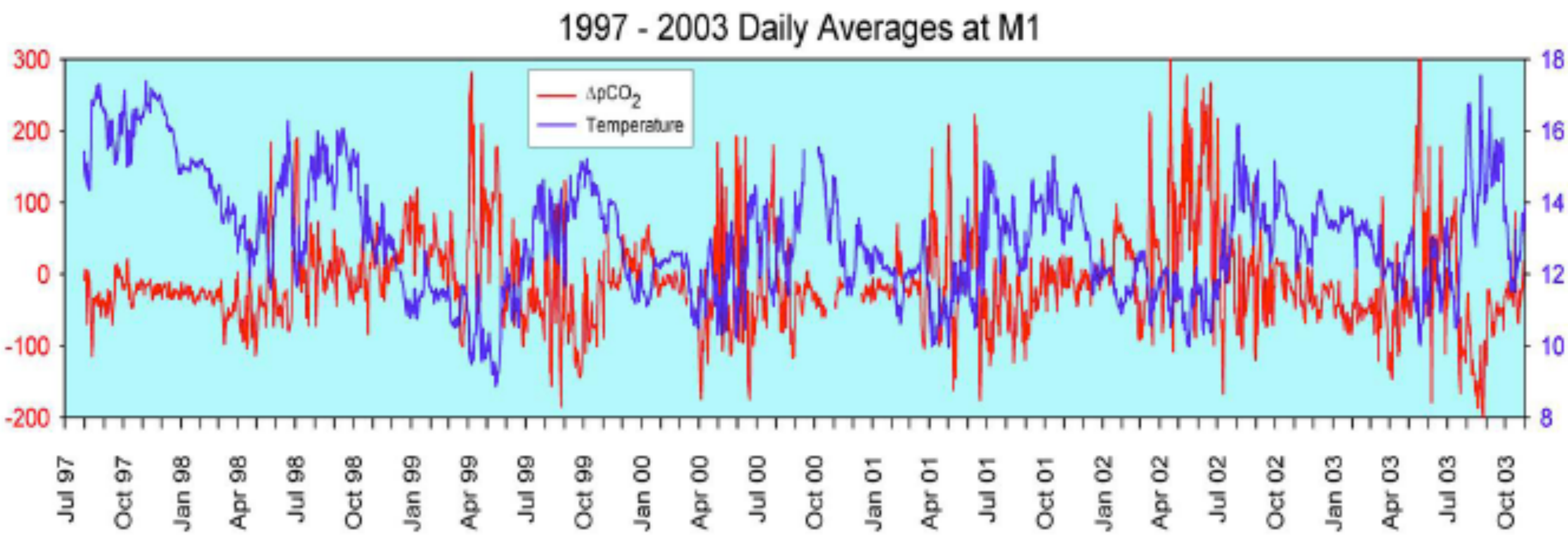



Carbonate ion decreasing: Tougher to precipitate

pH has decreased by 0.04 in 20 years - carbonate more soluble

Surface ocean $pCO_2$ increasing; follows the atmospheric record at Mauna Loa

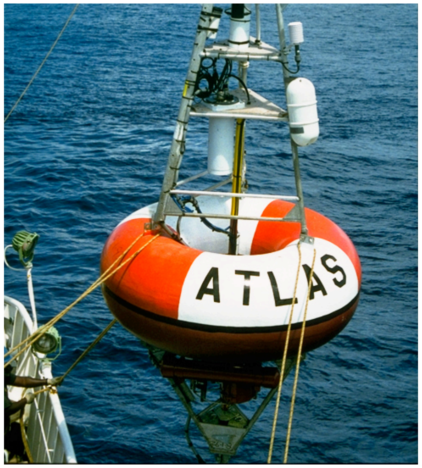
# (1b) Time Series: Buoys




**Air-sea difference in pCO2 is highly variable:**

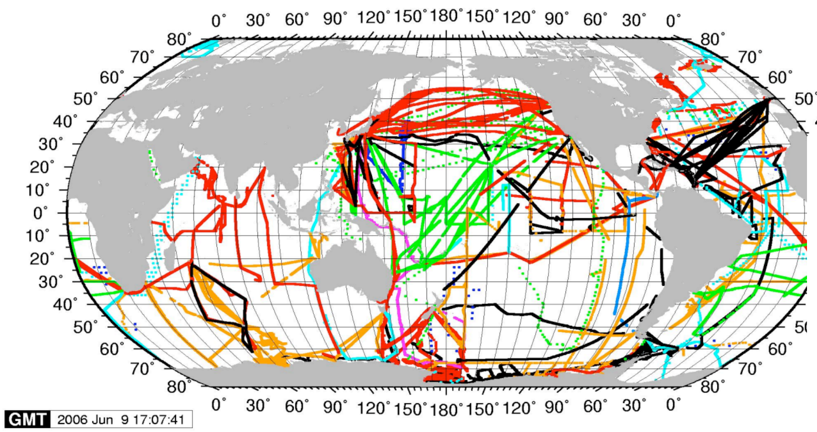
**>100 μatm**

Chavez et al.

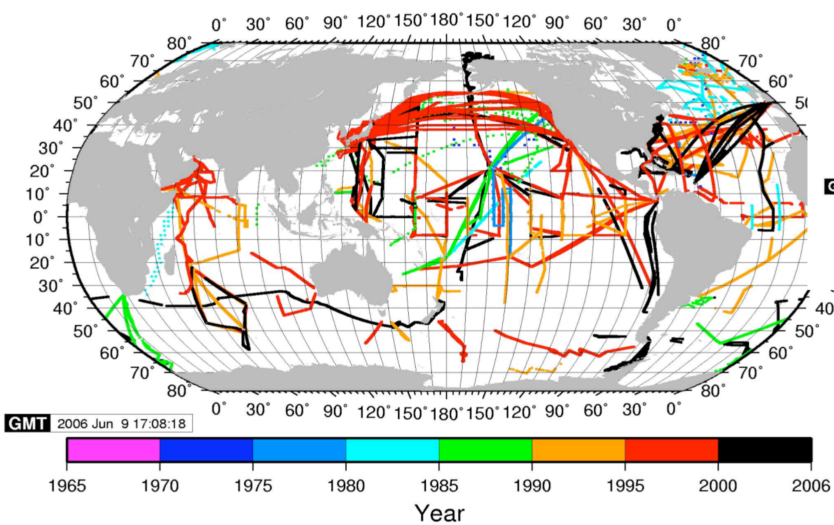


# (2) Research Cruises + Ships of Opportunity: Air sea difference in pCO2

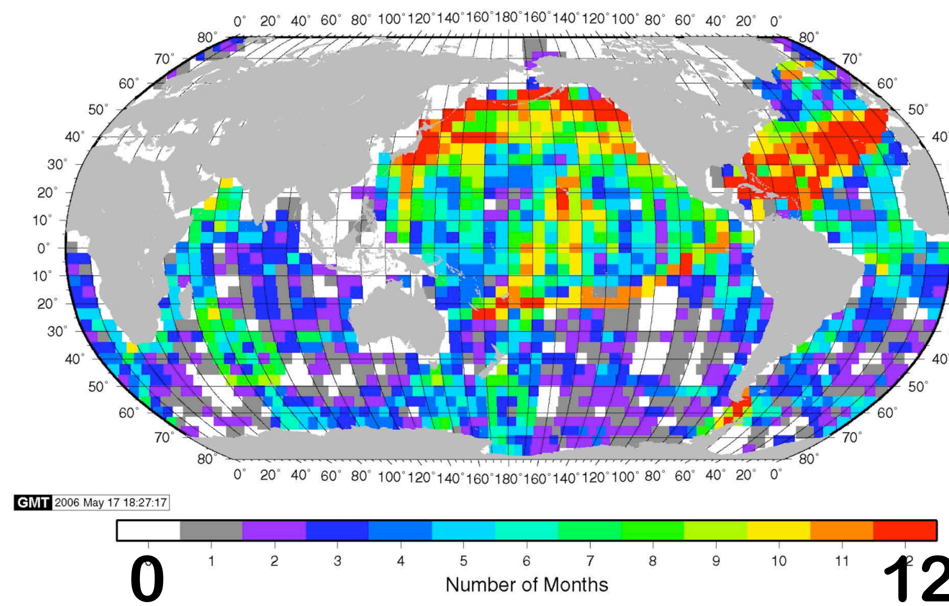
## Jan-Mar Obs



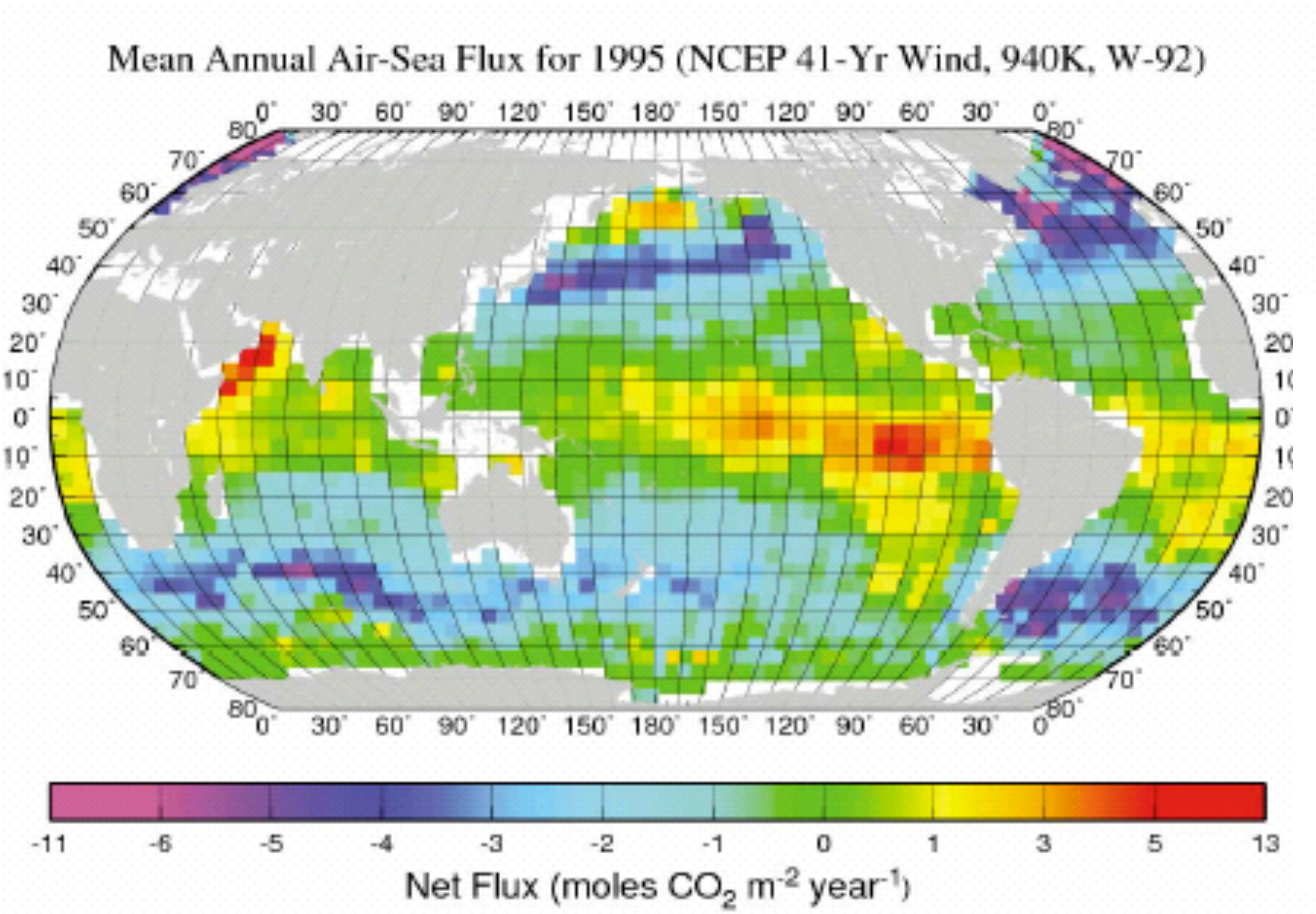

## Jul-Sept Obs

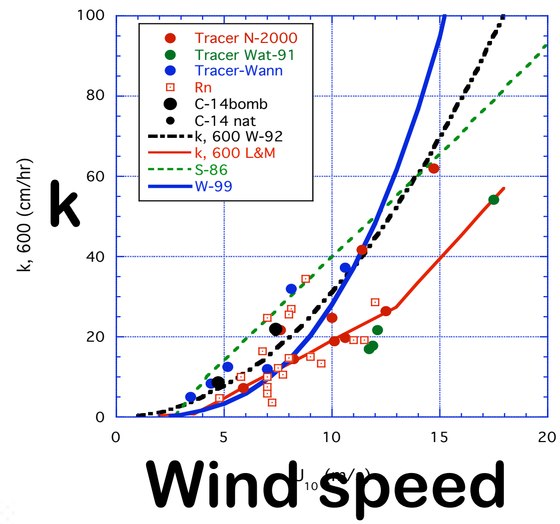



## No. Months with At least One Obs



# (2) Air-Sea Fluxes of CO2

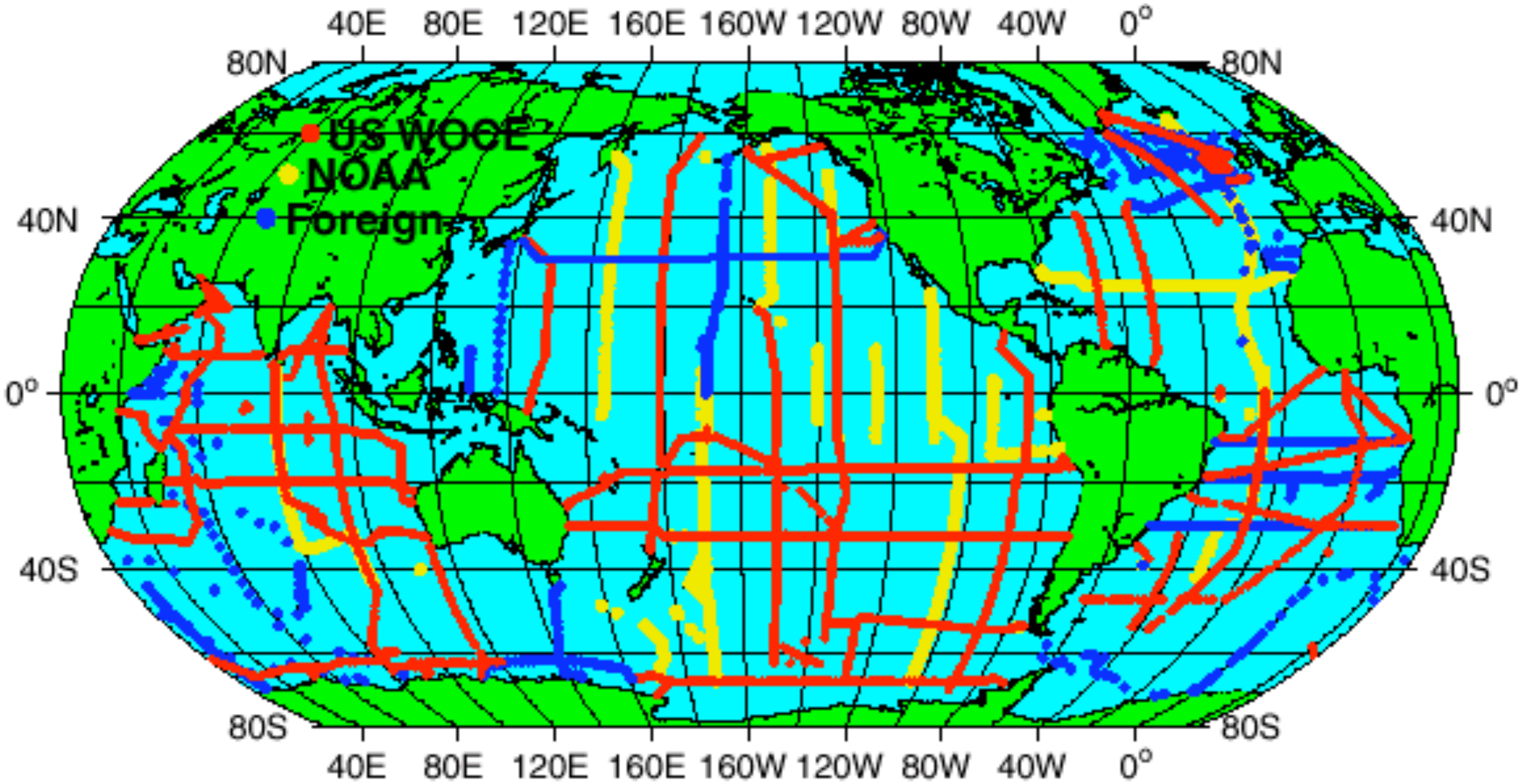



$$\Delta F_{ocn} = F_{oa} - F_{ao}$$

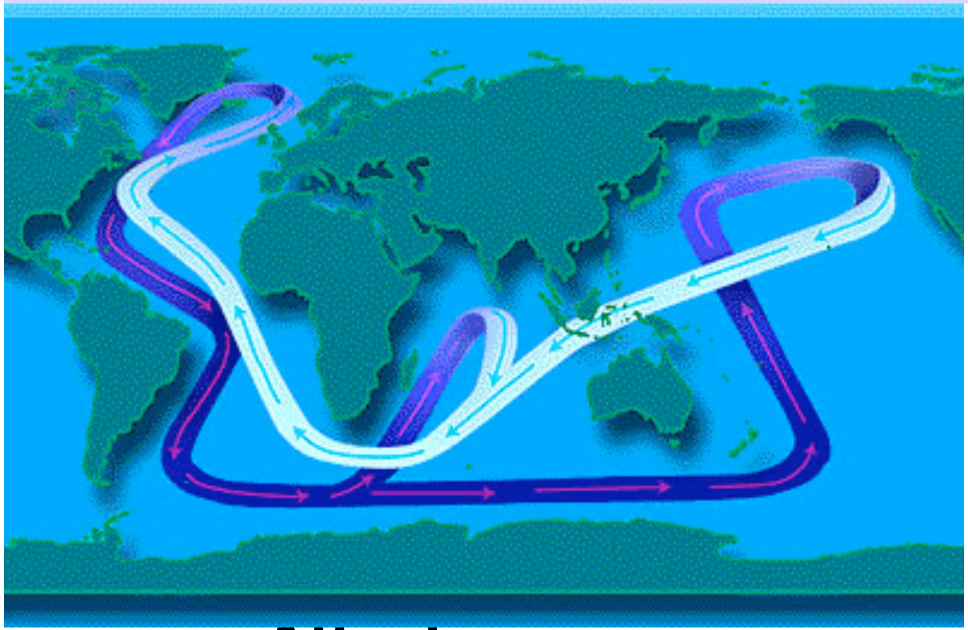
$$= \underbrace{k}_{GasExchRate(m/s)} \times (\underbrace{CO2^*_{sfc\_ocn}}_{moleC/m3} - \underbrace{\beta}_{solubility(T)} \times pCO2_{atm\_sfc})$$

# (3) International Research Campaigns:
## JGOFS/WOCE global survey (1980s and 1990s)




-Improved analytical techniques for inorganic carbon and alkalinity (±1-3 $\mu$mol/kg or 0.05 to 0.15%)
-Certified Reference Materials
-Data management, quality control, & public data access

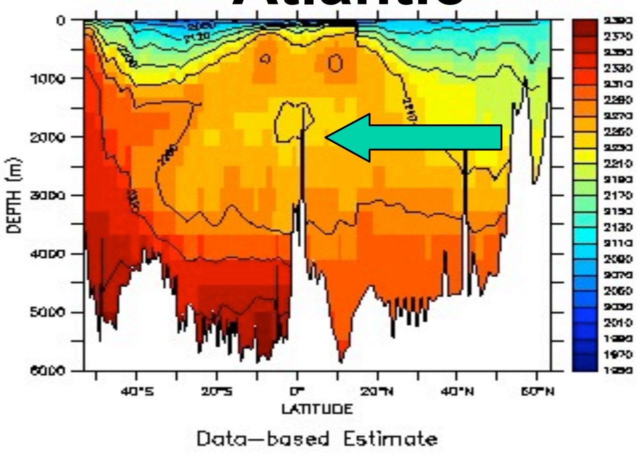
# (3) Campaigns:
# Total Dissolved Inorganic Carbon (DIC)



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

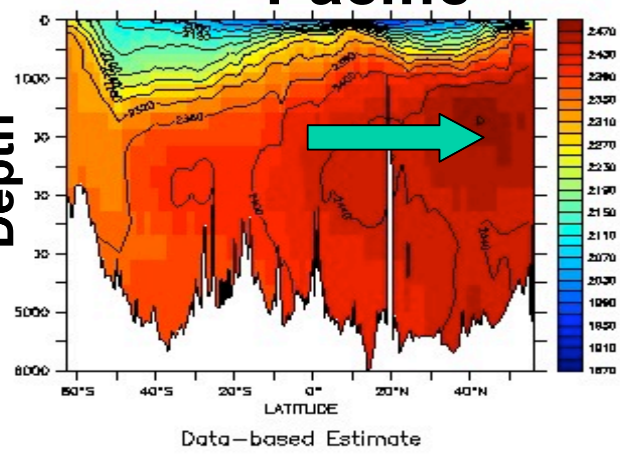
Ocn currents ~ cm/s
Time scale ~ $10^3$ yr

Atlantic




Pacific

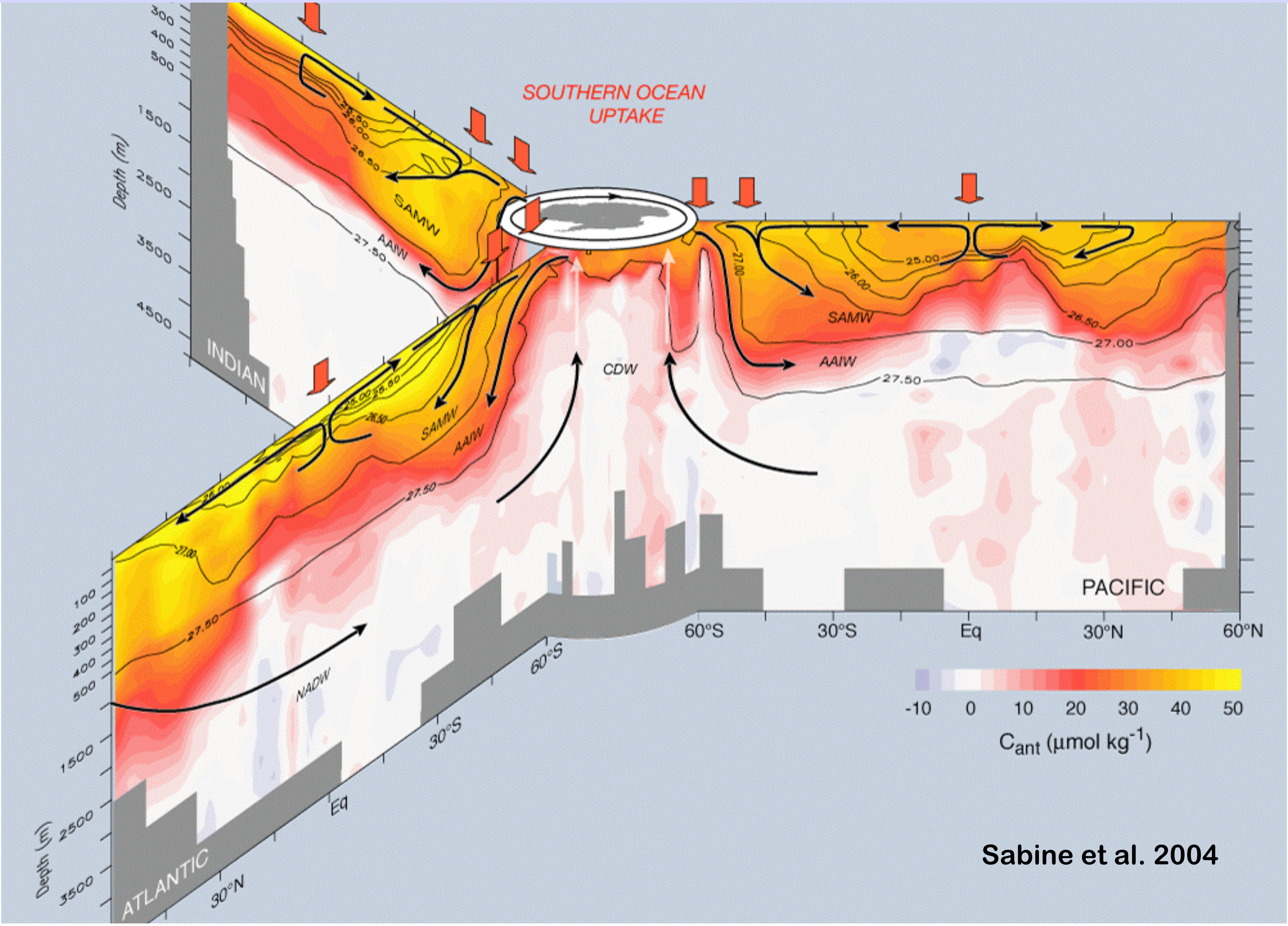
Depth




Latitude → N

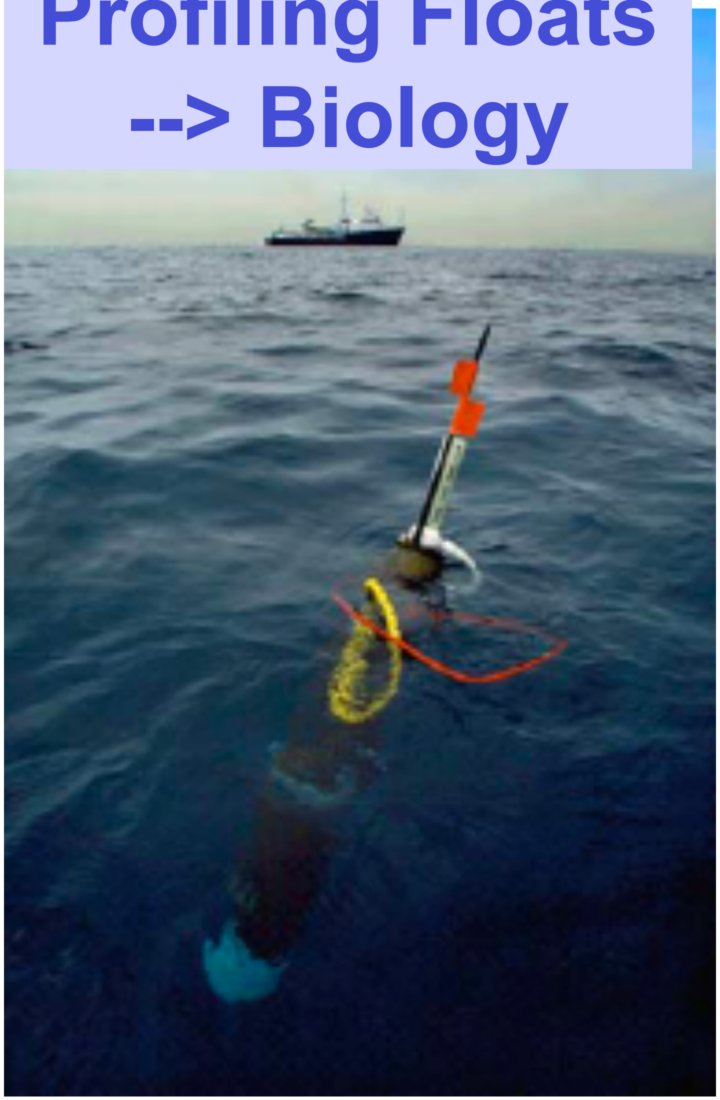
**Biology and DIC:**
- Depletion near sfc
- Enrichment at Depth

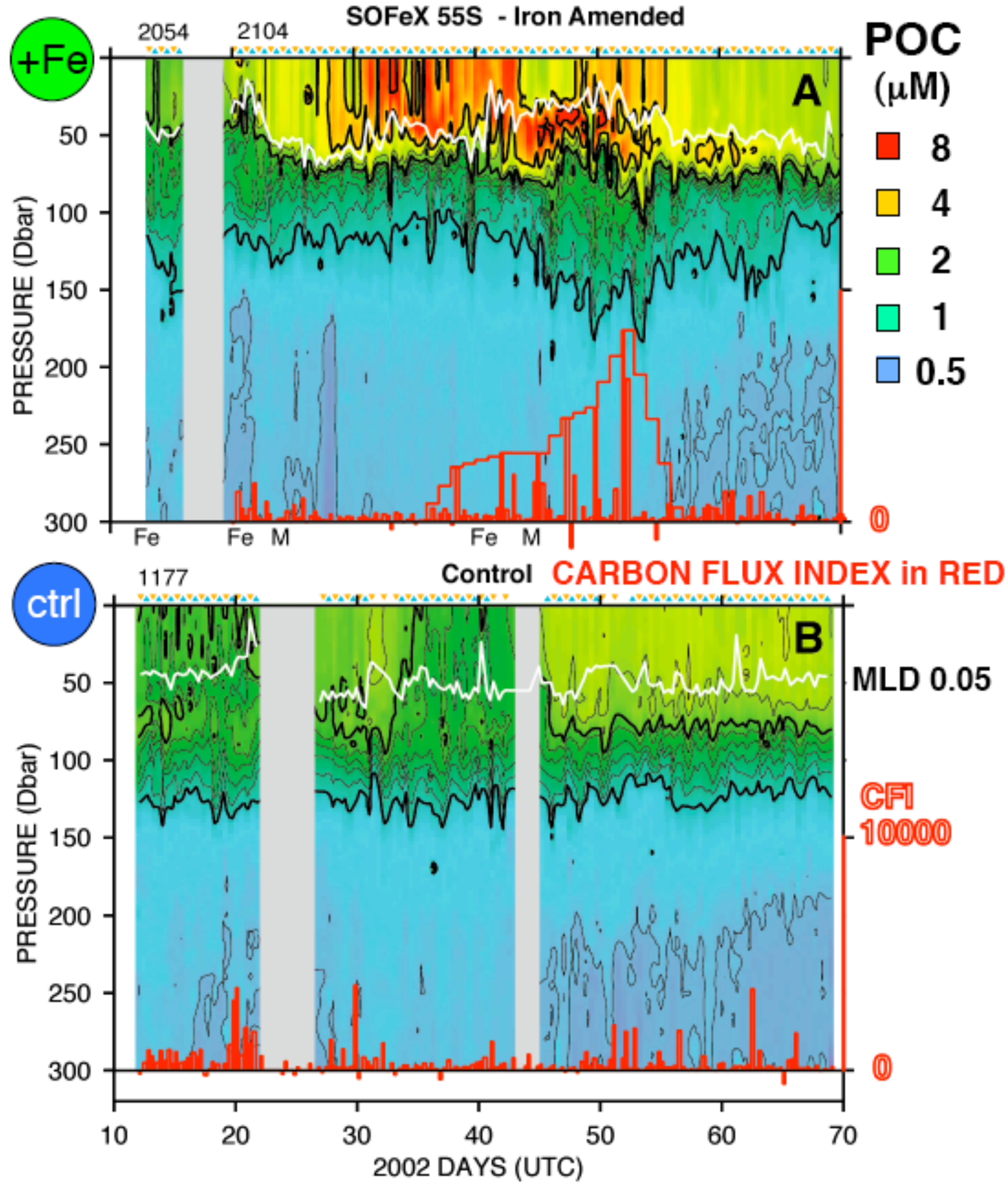
# (3) Campaigns: Penetration of Anthropogenic Carbon into Ocean Interior




Sabine et al. 2004

# (4) Autonomous Platforms: Profiling Floats --> Biology





# 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)

# How to harmonize the diverse data?

- Spatial scales
- Observing frequency
- Observing periods - varying meteorology and climate variability
- Incomplete suite - e.g. respiration

# Atm Carbon Models

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

## Other ways to write the same equation

$$\underbrace{x_b}_{forecast}(t_{i+1}) = \underbrace{M}_{model}(\underbrace{x_a}_{analysis}(t_i))$$

$X$=conc, fluxes, parameters

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

$X$ = conc

$u$ = fluxes

# An Atm Carbon Cycle Model

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

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

**What we've got:**

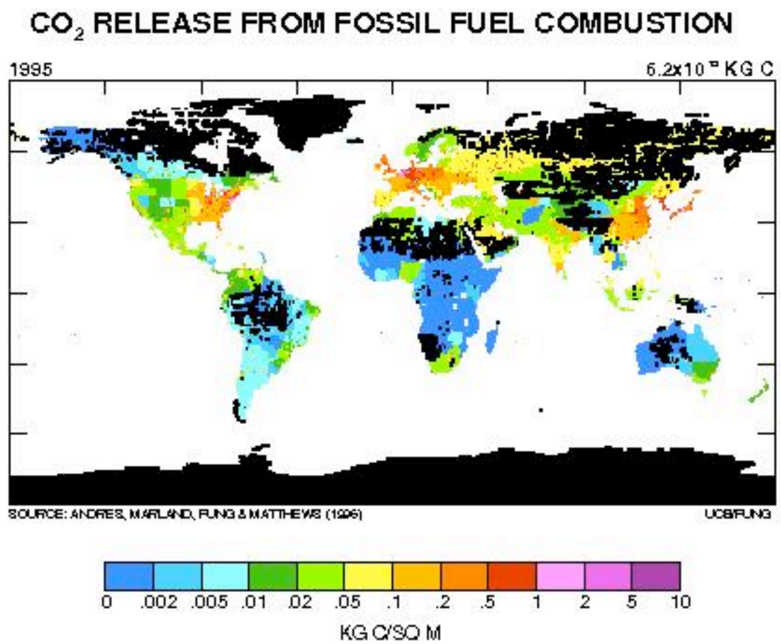
- **Sources/Sinks S known approximately or not well constrained**
- **$C_{obs}$ (actually mixing ratios $X_{obs}$) biweekly, at ~100 stations near the surface**
- **"Decent" transport model (winds, turbulent mixing)**

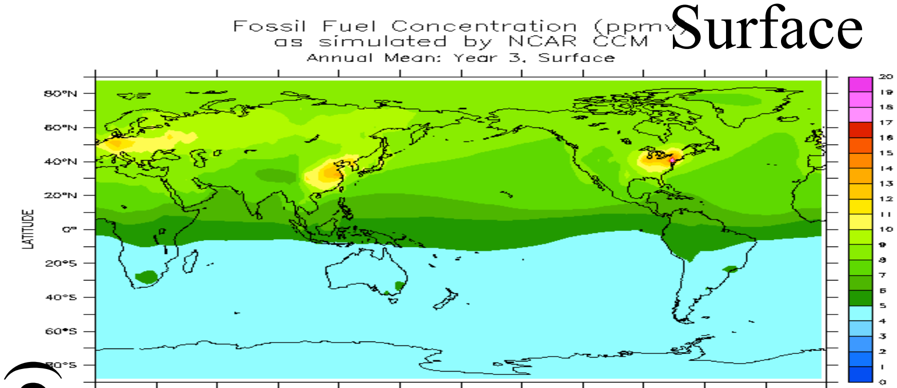
**What we want:**

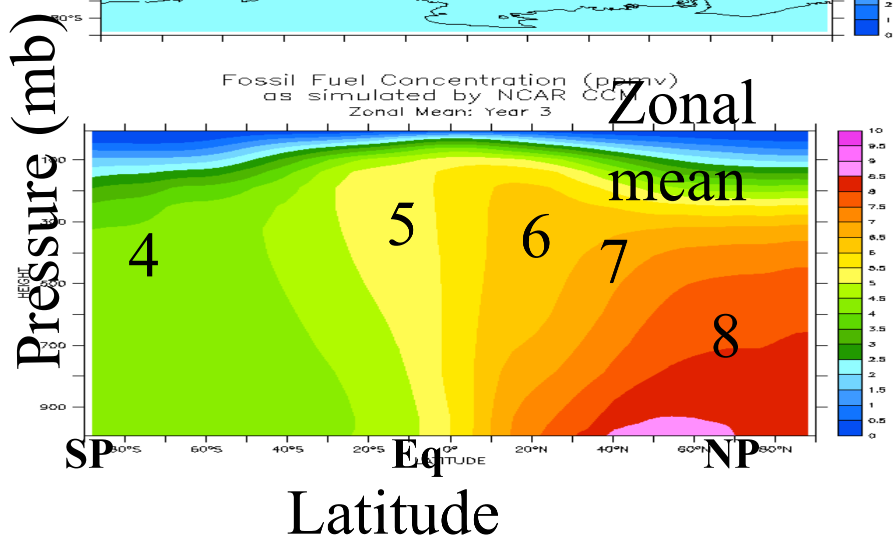
- **Where has the fossil fuel CO2 gone?** {Better estimates of the magnitude and distribution of S (e.g. land exchange)}
- **How did the fossil fuel CO2 get there? {improved understanding and representation of processes, e.g.**
    - **$F_{ab}$=LUE*AvailableLight; $F_{ba}$=exp($\alpha$T);**
- **Protocol verification: What are the strengths of local/regional emissions and sinks?**

# What we've got: (1) The Model:  NCAR climate model

**Source:  Fossil fuel combustion (6 PgC/y)** → ***C(x,y,z)*** **at steady state**

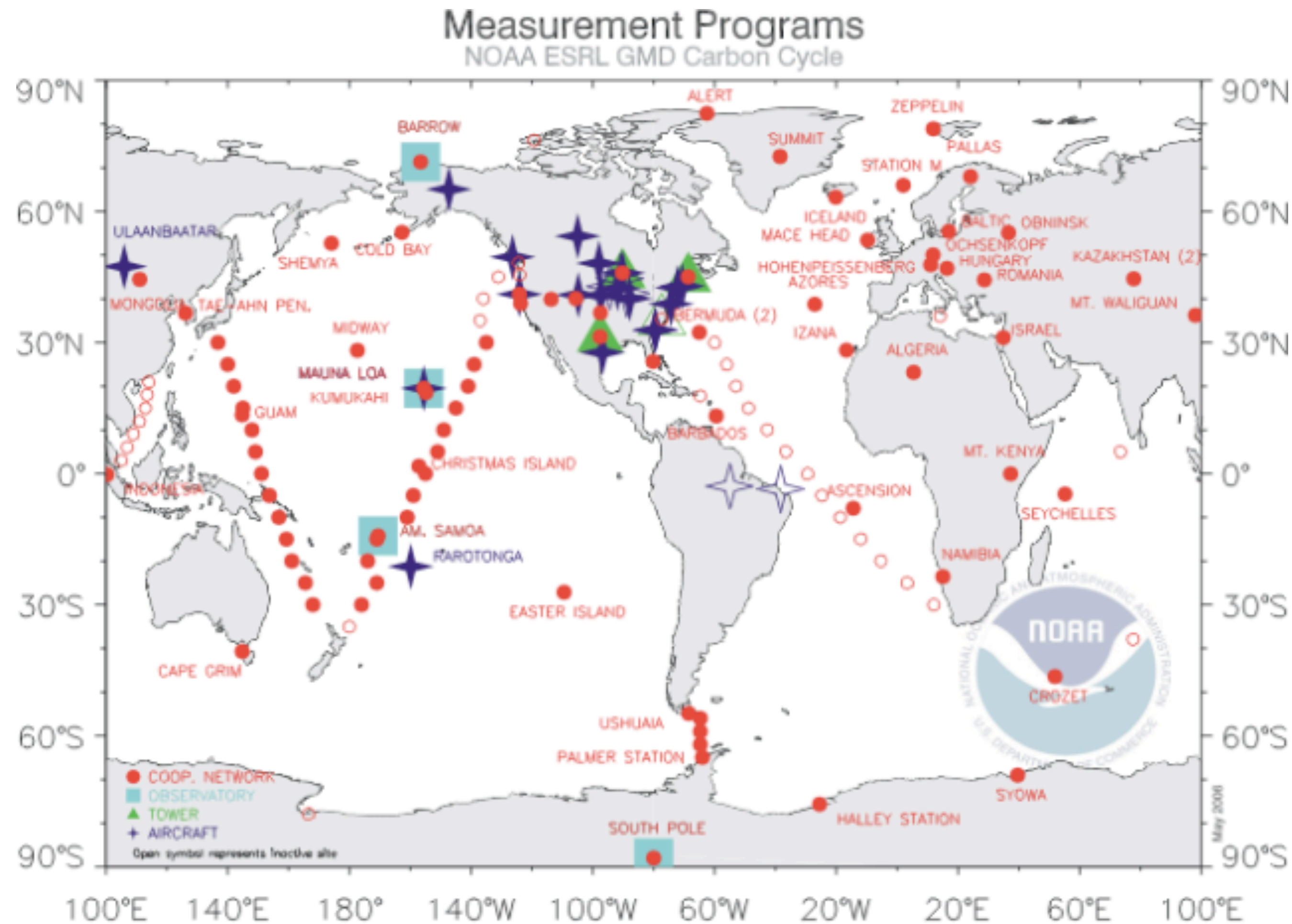


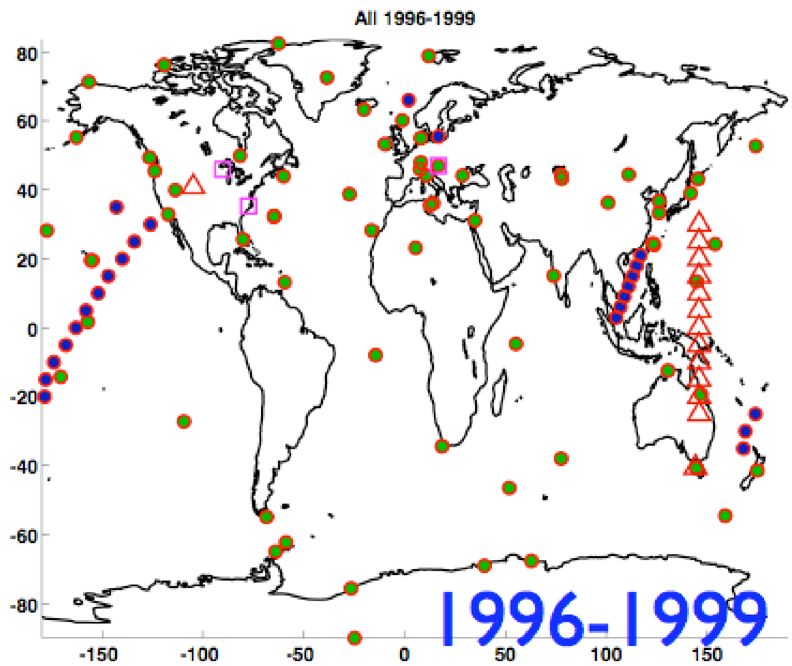
# What We've got (2): The data:  Atm CO2 (for now)

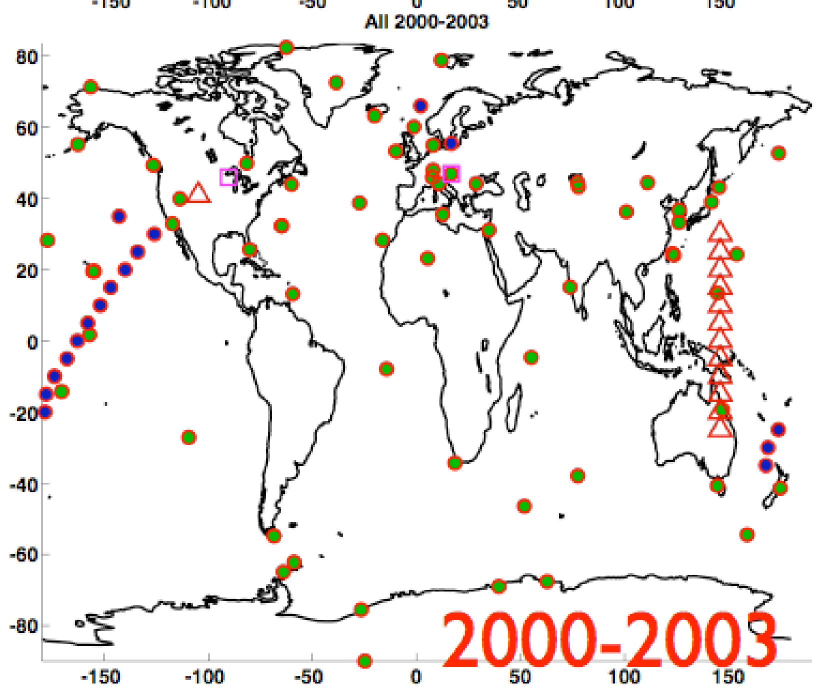
- Discrete surface flasks (~weekly)
- Continuous surface (hourly) observatories
- Tall towers continuous (hourly)
- Aircraft profiles (~weekly)

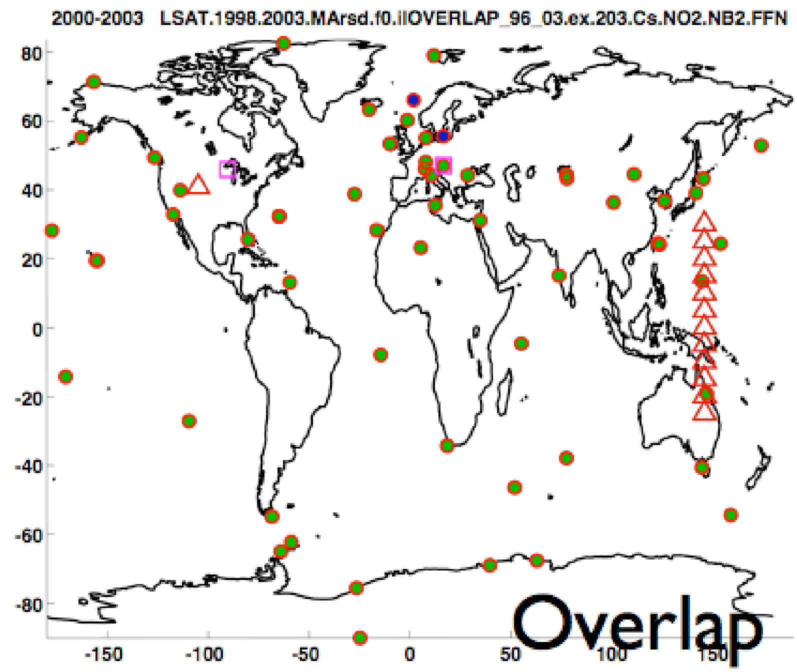



GMD Carbon Cycle operates 4 measurement programs. Semi-continuous measurements are made at 4 GMD baseline observatories and from tall towers. Discrete samples from the cooperative air sampling network and aircraft are measured at GMD. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, 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).

# Changing Monitoring Network



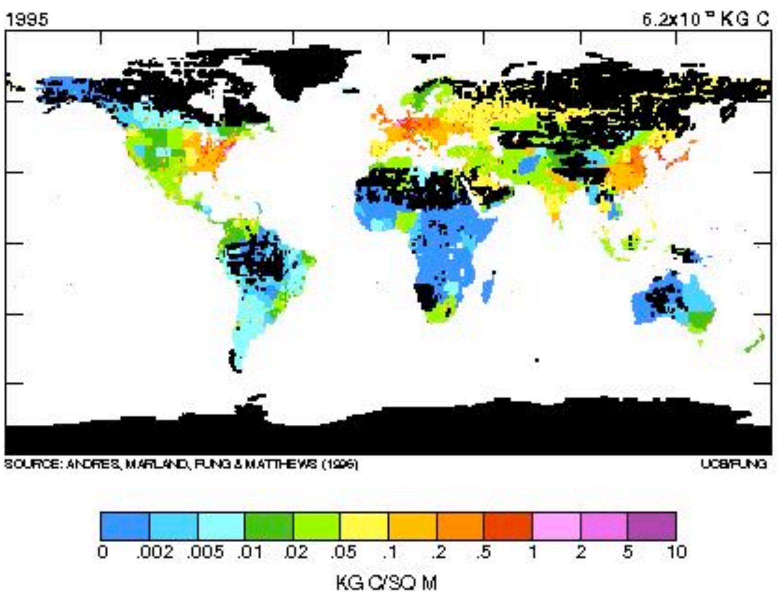

**Difficult to maintain an international monitoring network**

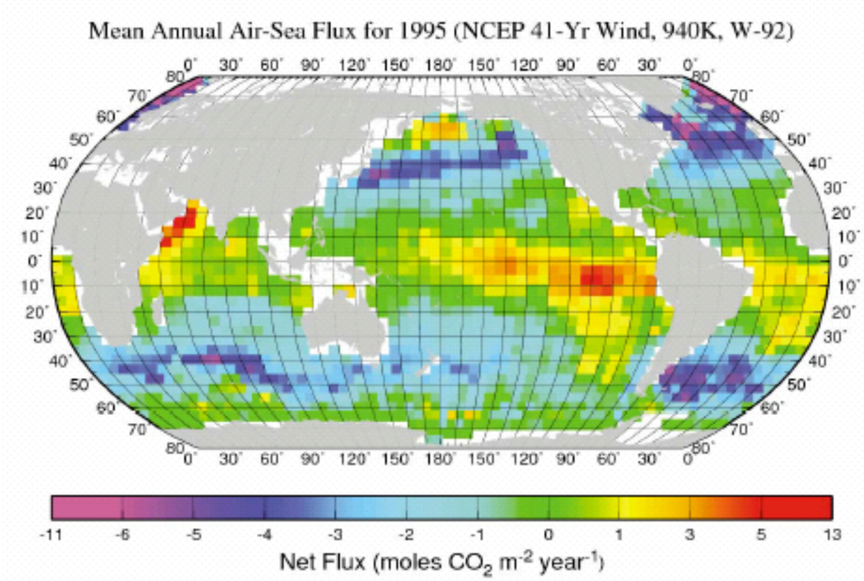
# What We've Got: (3) The Flux Priors

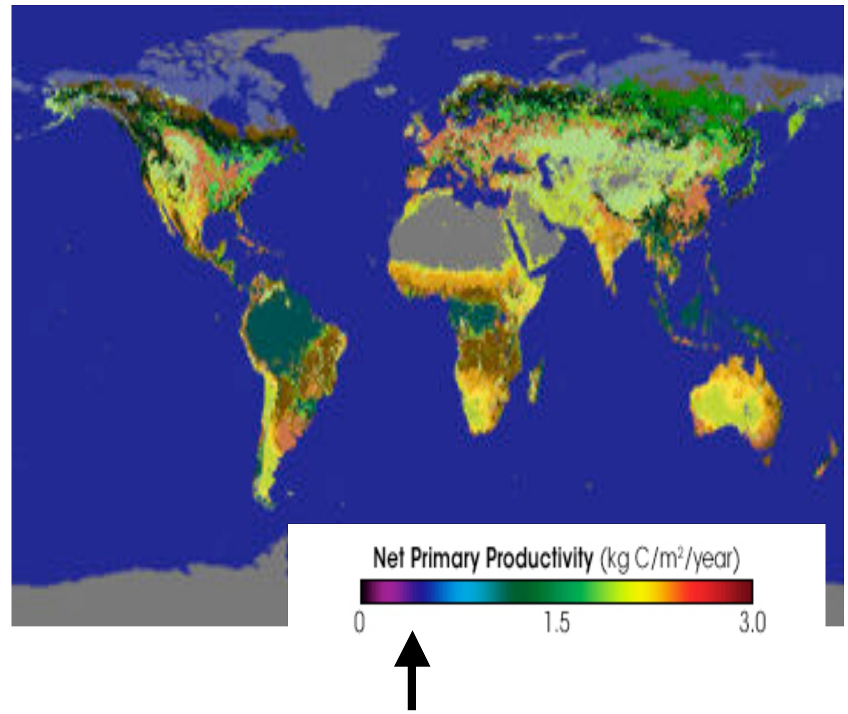
$$\frac{\partial C}{\partial t} + \underbrace{\Im(C)}_{Atm\_transport+mixing} = \underbrace{S|_{z=0}}_{SourcesSinks}$$

$$S = \underbrace{FF}_{"well-known"} + LandUse + \underbrace{(F_{oa} - F_{ao})}_{extrapolation\ of\ sparse\ obs} + (F_{ba} - F_{ab})$$

$CO_2$ RELEASE FROM FOSSIL FUEL COMBUSTION

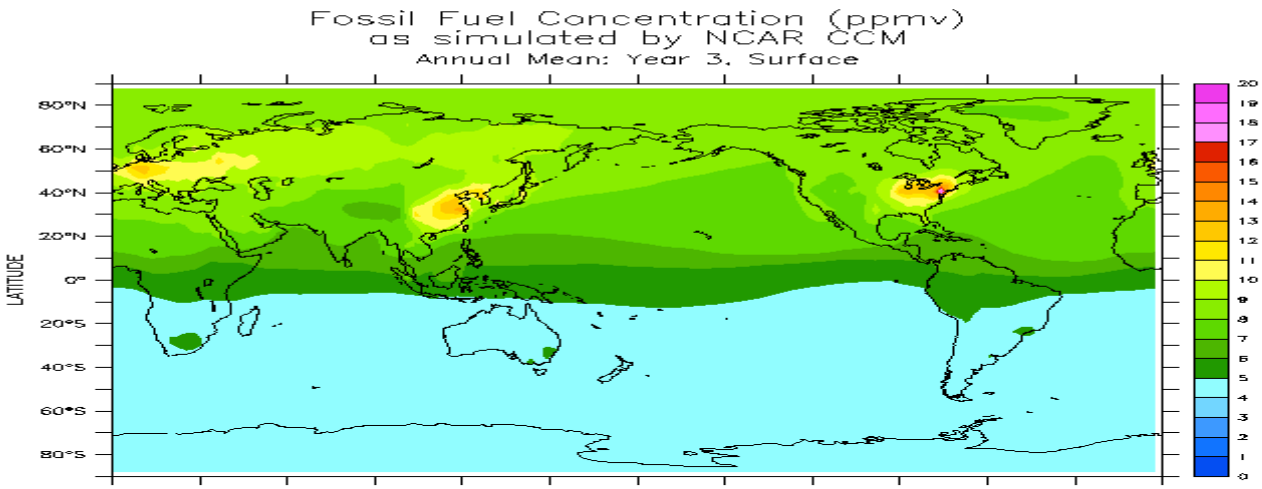


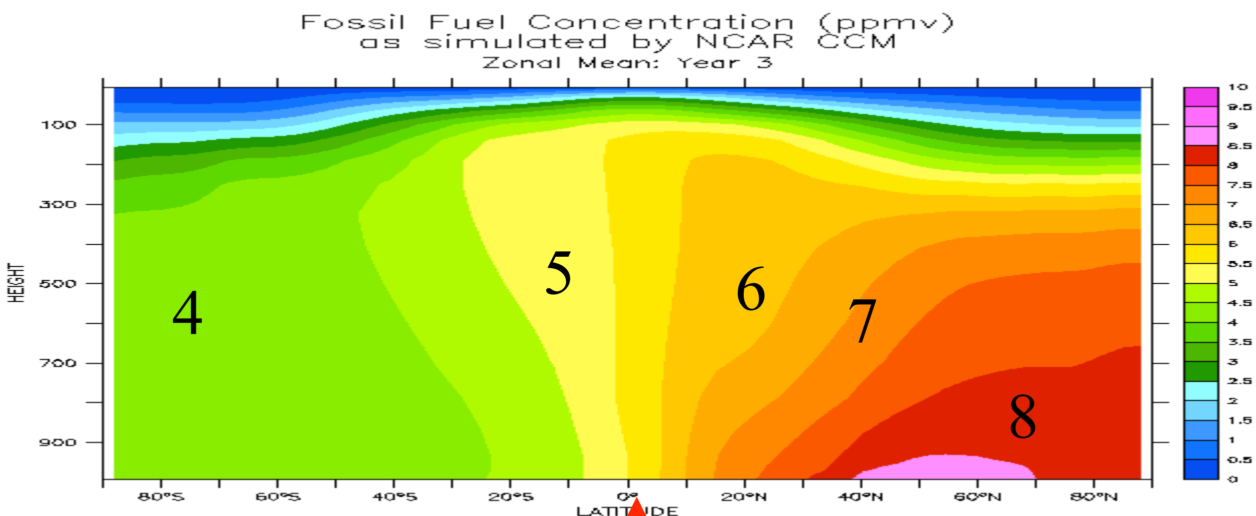

should net land flux ($F_{ba}$-$F_{ab}$) be prop to $F_{ab}$?

# Example I: A Simpler Model - reduce 3D atm to 2 hemisphere




Surface

Pressure (mb)




Zonal mean

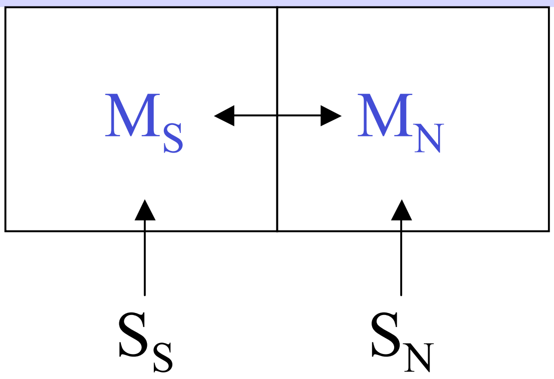
**SP** **Eq** **NP**

Latitude

# Example I: Interhemispheric Mixing: Two-Box Model, everything is perfect.

$$\frac{\partial M_N}{\partial t} = -\frac{M_N - M_S}{\tau} + S_N$$

$$\frac{\partial M_S}{\partial t} = +\frac{M_N - M_S}{\tau} + S_S$$



# Example 1: Interhemispheric Mixing: Two-Box Model, everything is perfect.

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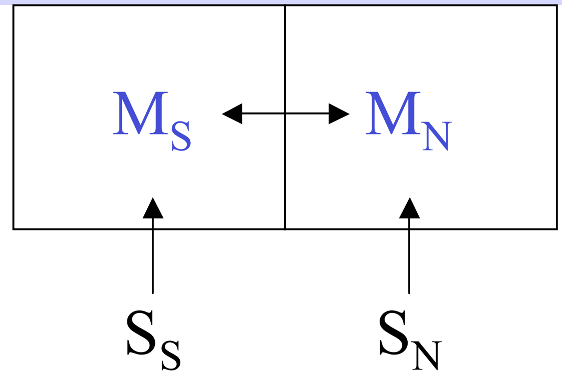


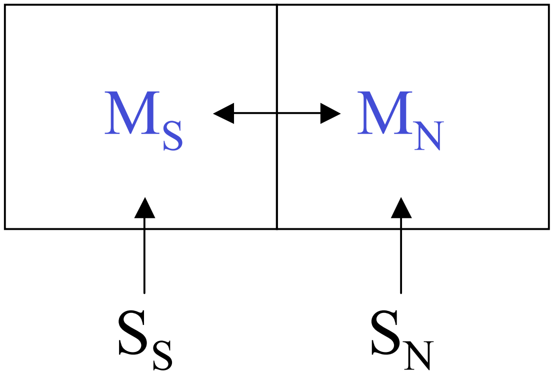

$$\frac{\partial (M_N - M_S)}{\partial t} = -2\frac{M_N - M_S}{\tau} + (S_N - S_S) = 0 \; @ \; SteadyState$$

$$\tau = 2\frac{M_N - M_S}{S_N - S_S}$$

Interhemispheric exchange time $\tau$ determined from inert tracers (e.g. CFC, with $S_s$=0): ~1-2 years

# Ex I: 2-Box Model Applied to the Carbon Cycle

$$M_N - M_S = \frac{\tau}{2}(S_N - S_S)$$




*Consider the case* $S_N = 6$ *PgC/yr;* $S_s = 0$

$\tau = 1$ *yr*

$\rightarrow M_N - M_S = 3$ *PgC*

*Recall* *1 PgC* $\rightarrow$ *0.5 ppmv* *if mixed in entire atm.*

*1 PgC* $\rightarrow$ *1 ppmv* *if mixed in a hemisphere.*

$\rightarrow X_N^{column} - X_S^{column} = 3$ *ppmv*

*Guess (3D model) surface gradient 1.5x column mean gradient*

$\rightarrow X_N^{sfc} - X_S^{sfc} = 4.5$ *ppmv*

Aircraft, Hippo: obs of vertical profile

# Ex I: 2-Box Model Applied to the Carbon Cycle

Forward problem: If 100% FF CO2 remained in atm

$$M_N - M_S = \frac{\tau}{2}(S_N - S_S)$$

$$S_N = 6\ PgC/yr;\ S_s = 0$$

$$\tau = 1\ yr$$

$$\rightarrow M_N - M_S = 3\ PgC$$

$$\rightarrow X_N^{sfc} - X_S^{sfc} = 4.5\ ppmv$$

$$But\ (X_N^{sfc} - X_S^{sfc})_{obs} = 2.5\ ppmv$$

Obs → only 50% of FF CO2 remains in atm

$$\frac{\partial(M_N + M_S)}{\partial t} = S_N + S_S = sources - sinks$$

$$\left.\frac{\partial(M_N + M_S)}{\partial t}\right|_{obs} = 3\ PgC/yr$$

$$sources = 6\ PgC/yr$$

$$\rightarrow Sinks_N + Sinks_S = 3\ PgC/yr$$

# Ex I: 2-Box Model Applied to the Carbon Cycle

**Inverse problem**

$$Model:\ M_N - M_S = \frac{\tau}{2}(S_N - S_S)$$

$$Given:\quad (X_N^{sfc} - X_S^{sfc})_{obs} = 2.5\ ppmv$$

$$\rightarrow (X_N^{column} - X_S^{column})_{obs} = 1.7\ ppmv$$

$$\rightarrow M_N - M_S = 1.7\ PgC$$

$$Invert\ model \rightarrow S_N - S_S = 2\frac{M_N - M_S}{\tau} = 3.4\ PgC/yr$$

$$(sources_N - sinks_N) - (sources_S - sinks_S) = 3.4\ PgC/yr$$

$$(6\ PgC/yr - sinks_N) - (0 - sinks_S) = 3.4\ PgC/yr$$

$$\rightarrow sinks_N - sinks_S = 2.6\ PgC/yr$$

Obs Carbon Budget

$$\boxed{Sinks_N + Sinks_S = 3\ PgC/yr}$$

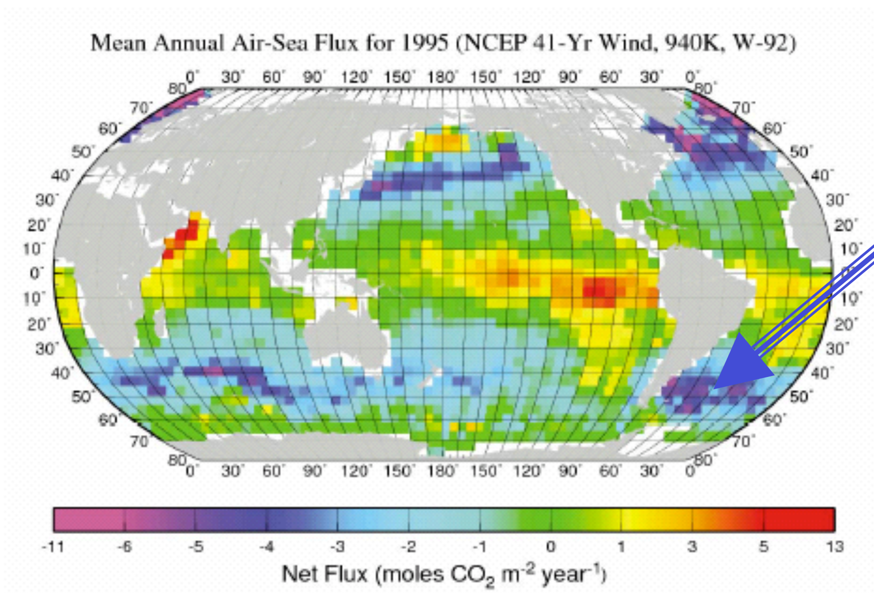
# Where are the Carbon Sinks?

***Budget*** $\quad sinks_N + sinks_S = +3\ PgC/yr$

***Gradient*** $\quad sinks_N - sinks_S = 2.6\ PgC/yr$

$\rightarrow sinks_N = 2.8\ PgC/yr; \quad sinks_S = 0.2\ PgC/yr$

Northern sinks > Southern Sinks !!!!!!!




"Data/Obs": Huge C sink in the large expanse of southern ocean; but large uncertainty in obs

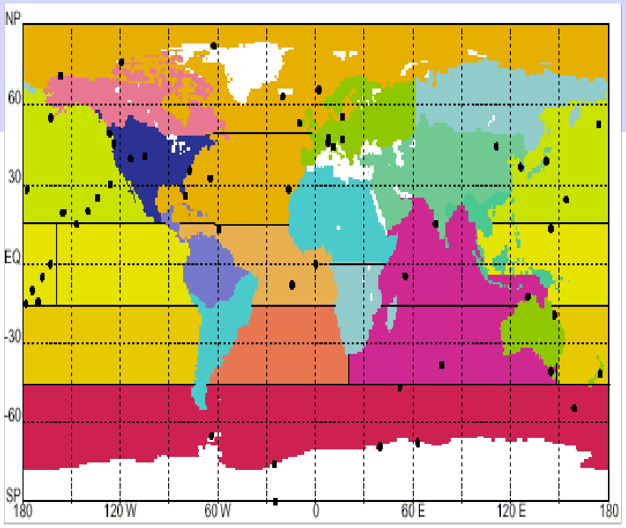
N ocn "better observed" → large Northern land sink!!!

# Example II: Perfect 3D atm circulation model. Steady state

## (1) Forward Step

- Premise: Atm $CO_2$ = linear combination of response to each source or sink

1.0 Divide surface into “basis regions”




1.1: Specify unitary source (e.g. 1 PgC/year) each year from each region

$$\widehat{s}_k(x,y)$$

1.2: Simulate atm $CO_2$ “basis” response with atm general circulation model

$$\widehat{s}_k(x,y) \xrightarrow{\text{transport model}} \widehat{c}_k(x,y,z,t)$$

1.3 Reconstruct fluxes and concentrations: unknown source strength $\mu_k$

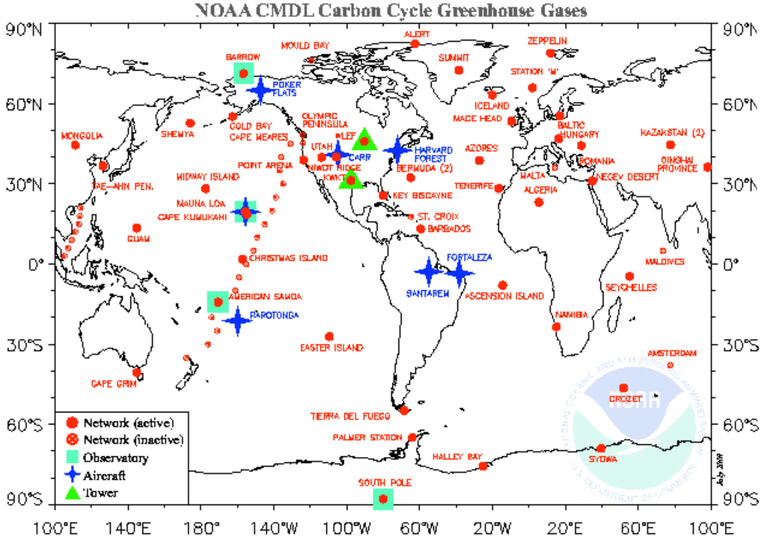
$$S = \sum_{k-regions} \underbrace{\mu_k}_{unknown} \times \widehat{s}_k(x,y)$$

$$c_{model}(x,y,z) = \sum_k \underbrace{\mu_k} \times \widehat{c}_k(x,y,z)$$

# Ex II: (Step 2) Bayesian Inversion: perfect circulation model

**Measurement Programs**

NOAA CMDL Carbon Cycle Greenhouse Gases




The NOAA CMDL Carbon Cycle Greenhouse Gases group operates 4 measurement programs. In situ measurements are made at the CMDL baseline observatories: Barrow, Alaska; Mauna Loa, Hawaii; Tutuila, American Samoa; and South Pole, Antarctica. The cooperative air sampling network includes samples from fixed sites and commercial ships. Measurements from tall towers and aircraft began in 1992. Presently, atmospheric carbon dioxide, methane, carbon monoxide, hydrogen, nitrous oxide, sulfur hexaflouride, and the stable isotopes of carbon dioxide and methane are measured. Dr. Pieter Tans, Carbon Cycle Greenhouse Gases, Boulder, Colorado, (303) 497-6678. ptans@cmdl.noaa.gov.

**Inversion: Seek the optimal source/sink combination $\{\mu_k\}$ to match atmospheric $CO_2$ data: *minimize***

$$J = \sum_{stn} \frac{[C_{obs}(stn) - \sum_{k-regions} \mu_k \times \hat{c}_k(stn)]^2}{\sigma_{stn}^{\;2}}$$

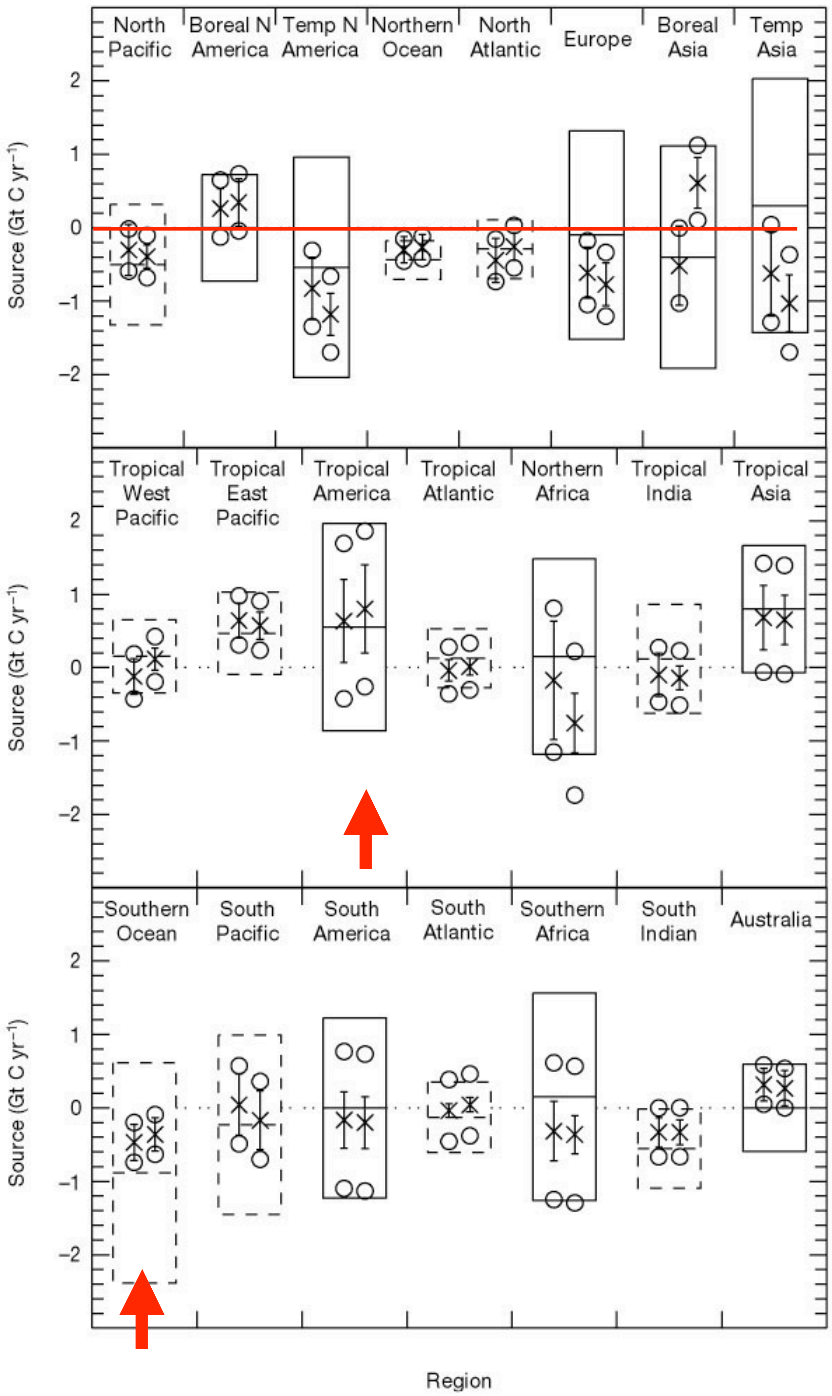
$$+ \sum_{k-regions} \frac{[\mu_k - \mu_k^{prior}]^2}{[\sigma_k^{prior}]^2}$$

- **Obs. Network –**
  - **mainly remote marine locations**

**Trying to infer information over land**

**Undetermined; non-unique solutions; prior estimates of source/sinks as additional constraints**

# Ex IIa: Posterior from many “perfect” circulation models




$\mu_k^{prior} \pm \sigma_k^{prior}$

Model m:

$\{\mu_{mk}^{posterior} \pm \sigma_{mk}^{posterior}\}$

Mean,std_dev ($\mu_{mk}^{posterior}$)

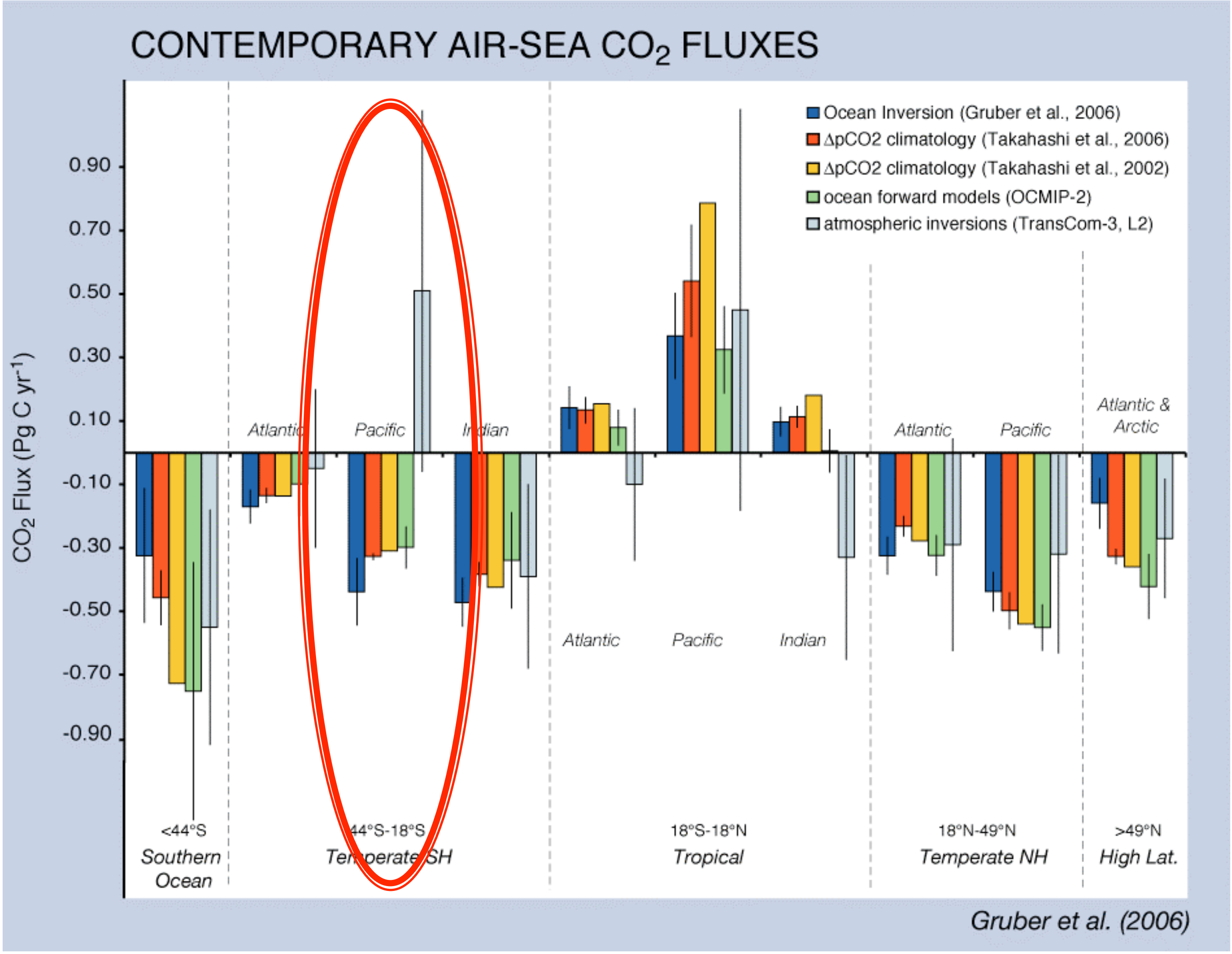
Mean ($\sigma_{mk}^{posterior}$ )

Little innovation in tropics, Africa

Great innovation in S. Ocean

Gurney et al. Nature 2005

# Separate atm and oceanic inferences of air-sea CO2 flux



# Variation 1: monthly and interannual

**Each region k: Pulse release into atm --> concentration for 24 months**

$$\hat{s}_k(x,y,\underbrace{t_0}_{1month}) \xrightarrow{transport} \hat{c}_k(x,y,z,t);\quad t = t_0, t_1, \ldots t_{24}$$

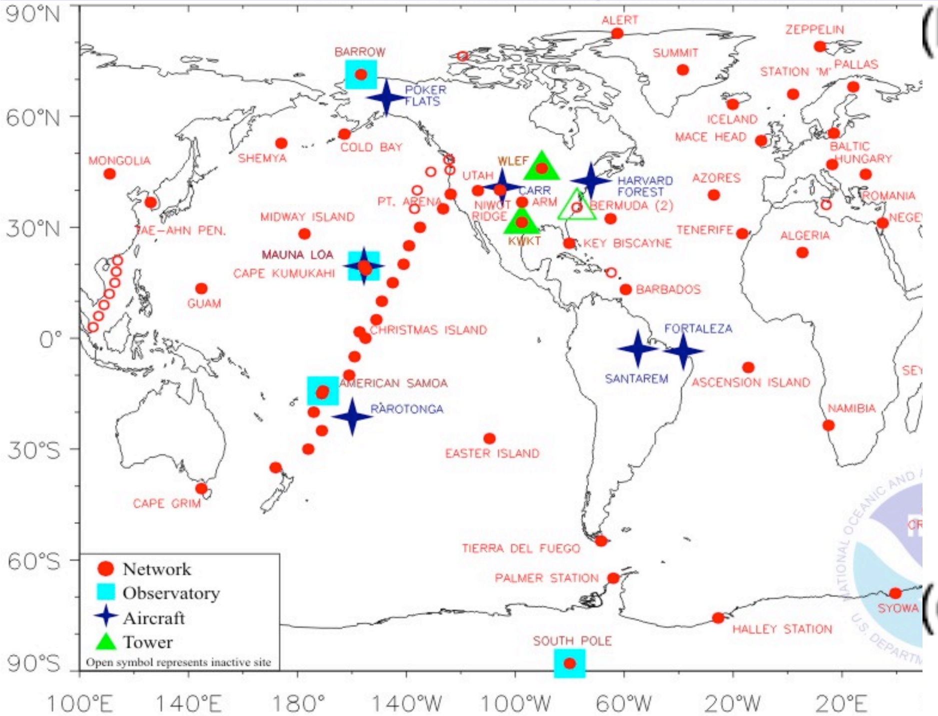
**Concentration at any time is the cumulative result of emission over the past 24 months**

$$C_{model}(x,y,z,t) = \sum_{k-regions} \int_{t-24}^{t} \mu_k(t') \cdot \hat{c}_k(x,y,t,t') \cdot dt'$$

**Find $\mu_k(t)$ that minimize J:**

$$J = \sum_t \{ \sum_{stn} \frac{[C_{obs}(stn,t) - C_{model}(stn,t)]^2}{\sigma_{stn}^{\;2}} + \sum_{k-regions} \frac{[\mu_k(t) - \mu_k^{prior}(t)]^2}{[\sigma_k^{prior}]^2} \}$$

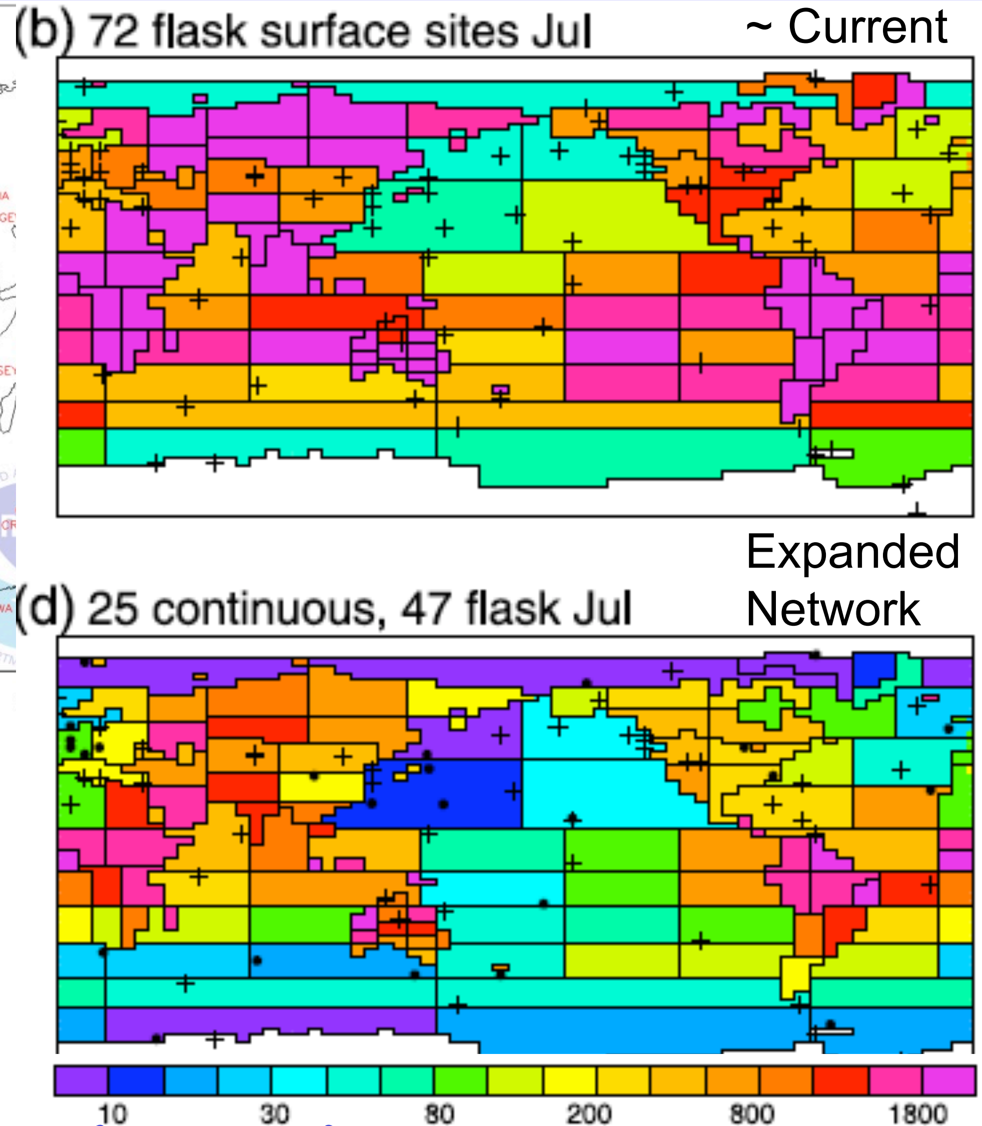
# Inferred Surface Fluxes




**Combine global surface network, transport models & linear inverse to resolve surface $CO_2$ fluxes at regional & monthly scales**

**Miller et al. J. Geophys. Res. 2007**

~ Current




Expanded Network

Flux Uncertainty g $C/m^2/y$

# Variations 2: don't like regions and/or prior flux pattern for each region

- Ignore flux strength priors in cost function --> non-unique mathematical solution may not be physically realistic (e.g. Fan et al.)

$$J = \sum_t \{ \sum_{stn} \frac{[C_{obs}(stn,t) - C_{model}(stn,t)]^2}{\sigma_{stn}^2} + \cancel{\sum_{k-regions} \frac{[\mu_k(t) - \mu_k^{prior}(t)]^2}{[\sigma_k^{prior}]^2}} \}$$

Still rely on some transport model to estimate C_model

- Solve for source strength for each grid box (Kaminiski et al.): unconstrained

- Geostatics: estimate flux correlation lengths (Rodenbeck, Michalak et al)

# Inversions using Satellite CO2: gaps in space and time

- Old-fashioned inversion (tracer model, min cost function J) for surface fluxes (source strengths for K regions) as before (Rayner and O'Brien):

  $c_{obs}(stn,t)$ --> $c_{sat}(x_{overpass},y_{overpass},t_{overpass})$

- 2-step: (1) Assimilate AIRS radiance at top of atm into weather prediction model --> full 4D CO2(x,y,z,t) (Engelen et al. 2009). (2) old fashioned inversion for surface fluxes (Chevallier et al. 2009)

- Estimation of C_model (transport model) and min(J) uncoupled

# CO2 Data Assimilation: 2 General Classes

- **Time-dependent inversion - {Kalman filter}**

  **At time $t_n$:**

  – **Find $CO2_{analysis}(t_n)$ by min(J): J includes flux parameters(regions), $CO2_{obs}(t_n)$, $CO2_{forecast}(t_n)$**

  – **update surface fluxes $\mu$ for regions**

  – **model: update $CO2_{forecast}(t_{n+1})$** (e.g. CarbonTracker)

- **Variational Approach - Find $\mu$ that minimizes J. Use adjoint model ($CO2(t_{n-1})$) to efficiently calculate $\partial J / \partial \mu$** (e.g. Baker)

# Challenge:  Transport Model

- Transport model needed to connect surface fluxes to CO2

- NCEP/ECMWF analysis --> “best approx” to real atm circulation every 3 or 6 hours.

- NCEP/ECMWF Reanalysis:  retrospective assimilation of all weather data using the same general circulation model (uniform model physics through time). Treated as “known”, with zero uncertainty.

- NCEP/ECMWF Reanalysis:  average of large ensemble of atm circulations; the average circulation is never realized.  Yields T and humidity profiles after mixing, and transport model needs to reconstruct convective mixing. Spread of circulation ensemble not utilized

# Assimilation of $CO_2$+meteorology

Following numerical prediction prediction:
Every 6 hours:

- Assimilate raw weather observations (u,v,T,q,Ps) + AIRS $CO_2$
- $CO_2(x,y,z,t)$
- Estimate surface flux from conservation equation (e.g. estimate evaporation from the full 4D water vapor field)