Next 3 weeks

Tu 2/24: Terrestrial CO_2 uptake (LJ)

Th 2/26: Paper discussion (Solomon et al., “Irreversible climate change due to CO_2 emissions, 2009, PNAS)

Tu 3/3: Geoengineering (JS+LJ)

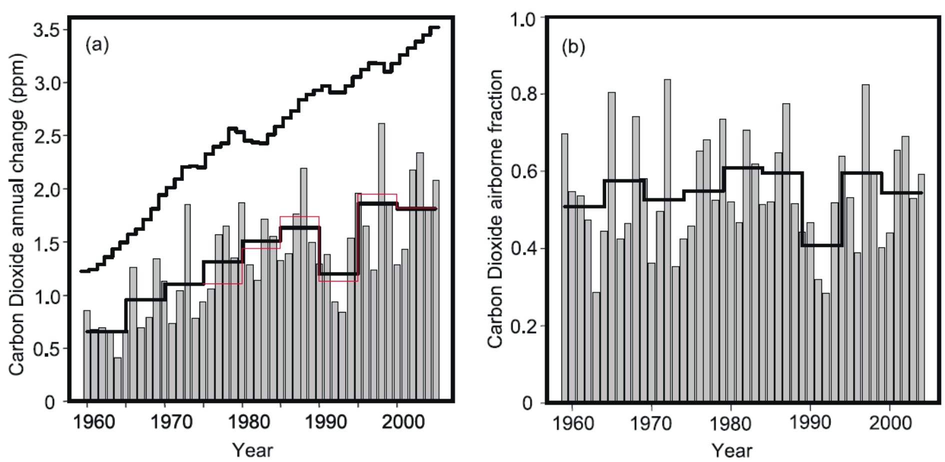
Th 3/5: Geoengineering (JS)

Last week of class (03/10+03/12): Student presentations.

Papers due on Monday March 9.

References:
- IPCC (2007), Section 7.3 “The carbon cycle and the climate system”

- 55% of FF emissions remain in the atmosphere (“airborne fraction”)
- Large interannual variability
- Remarkably constant airborne fraction despite 40% increase in emissions over last 20 years



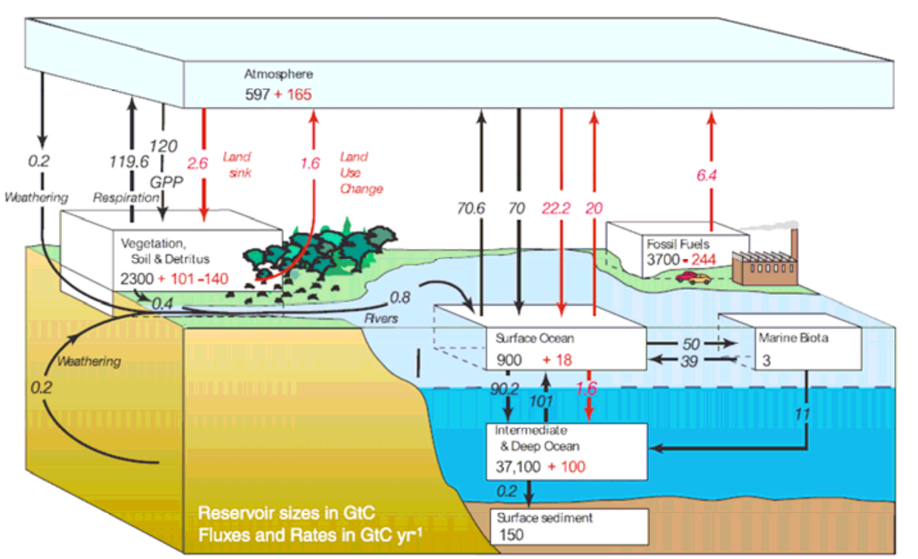
IPCC (2007), Fig 7.4

Where did the anthropogenic CO_2 go?

	1980s	1990s
Atmospheric Increase	3.3±0.1	3.2 ±0.1
Emissions (fossil fuel, cement)	5.4 ±0.3	6.4 ±0.4
Ocean-Atmosphere flux	-1.8 ±0.8	-2.2 ±0.4
Net land-atmosphere flux	-0.3 ±0.9	-1.0 ±0.6
Land use change flux	1.4	1.6
Residual terrestrial sink	-1.7	-2.6

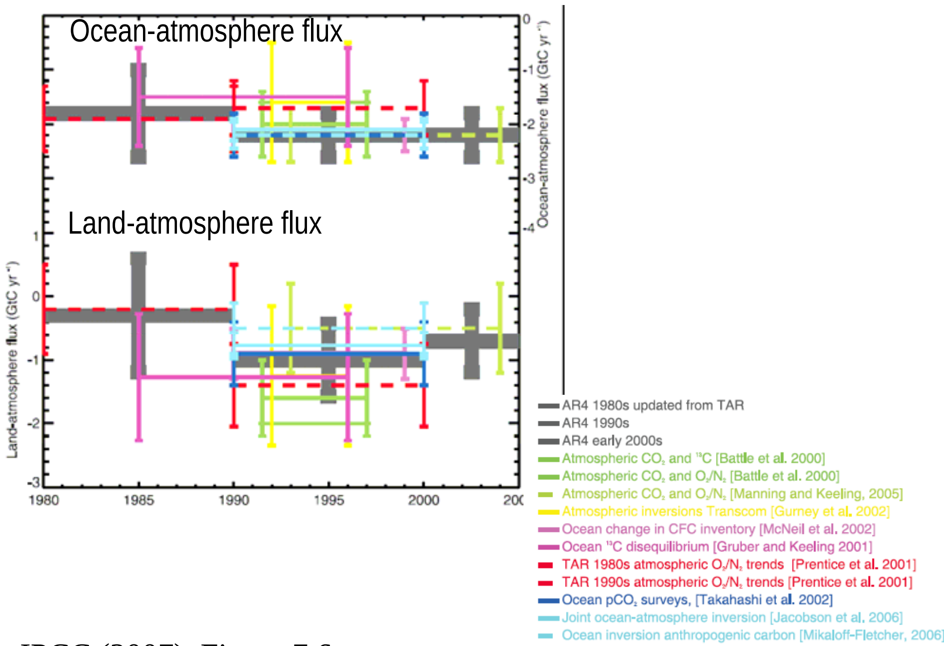
Units: GtC/yr (1 Gigaton = 1 Pg = 10^{15} g)

IPCC, 2007, Table 7.1



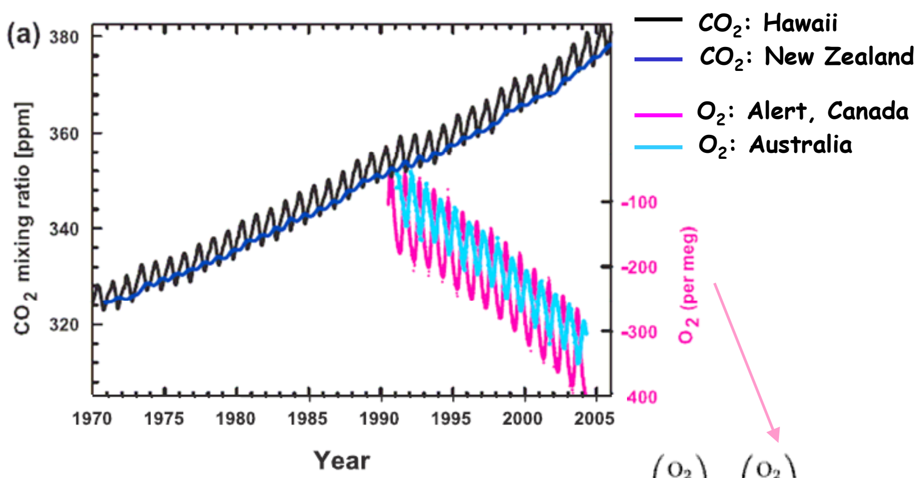
The global carbon cycle for the 1990s

IPCC (2007), Fig 7.3



IPCC (2007), Figure 7.6

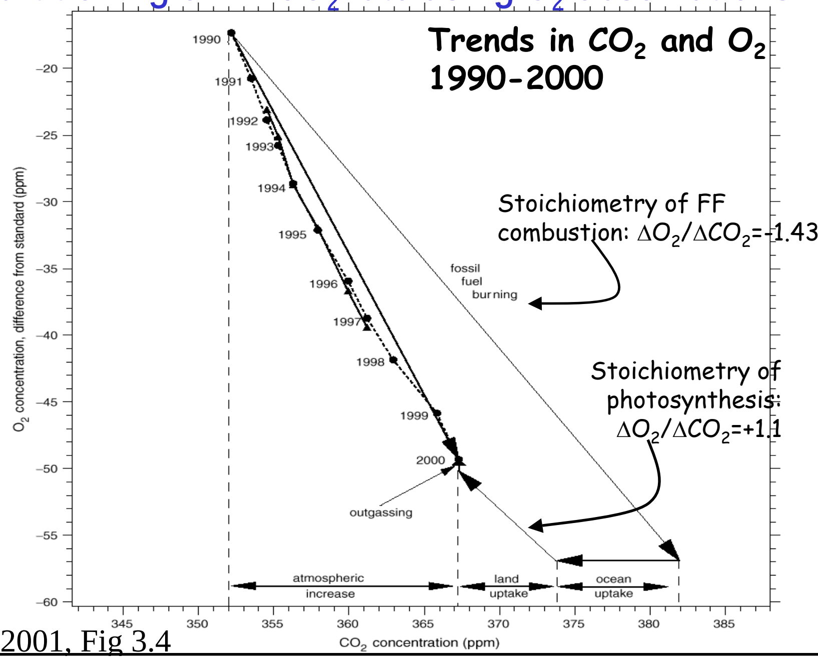
Observed O_2/CO_2 trends and seasonal cycles



$$\delta\left(\frac{O_2}{N_2}\right) = \frac{\left(\frac{O_2}{N_2}\right) - \left(\frac{O_2}{N_2}\right)_{ref}}{\left(\frac{O_2}{N_2}\right)_{ref}} \times 10^6,$$

IPCC, 2001

Partitioning of FF CO_2 fate using O_2 observations



IPCC, 2001, Fig 3.4

Terrestrial carbon: Processes

Carbon uptake (sinks)
- forest regrowth
- fire management
- woody encroachment
- CO_2 fertilization
- nitrogen fertilization
- climate change (temperate+arctic): warmer, longer growing season

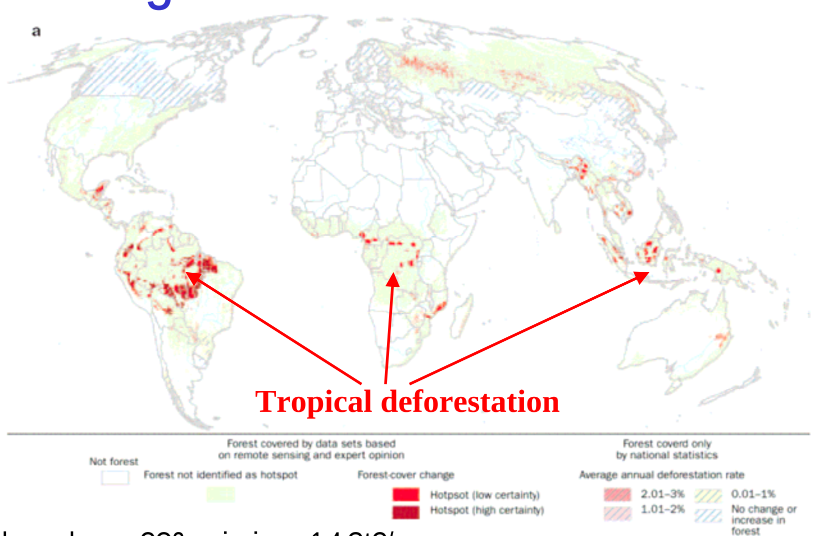
-5 to -0.9 GtC/yr

Carbon release (sources)
- deforestation
- land cultivation
- biomass burning
- insect outbreaks
- respiration (increasing as T rises?)
- climate change (tropics): warmer, drier
- pollution (ozone, SO_2)

0.3 to 2.8 GtC/yr

Uptake is slow (decades-centuries), release is fast (days-years)

Changes in forest area 1980-2000



Land use change CO2 emissions: 1.4 GtC/yr

Tropical Americas: 0.6 GtC/yr

Tropical Asia: 0.6 GtC/yr

Tropical Africa: 0.2 GtC/yr

Lepers et al., Bioscience (2005)

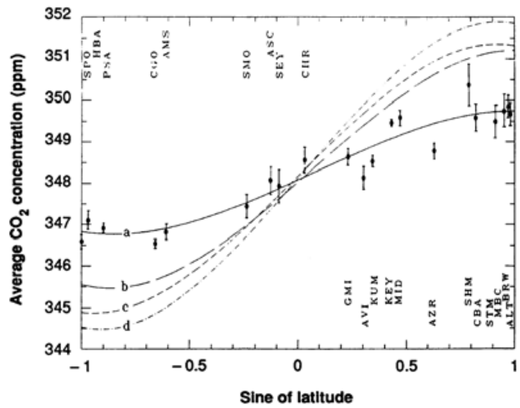
Where is the residual (‘missing’) CO_2 land sink?

- Location inferred from inverse models (top-down): mostly in Northern Hemisphere land
- Causes: Forest regrowth (legacy of prior land use change), land management practices, CO_2 fertilization, nitrogen fertilization, response to warming?

Observational Constraints on the Global Atmospheric CO_2 Budget

PIETER P. TANS, INEZ Y. FUNG, TARO TAKAHASHI

***Science*, 1990.**



Model: 6-7 ppmv

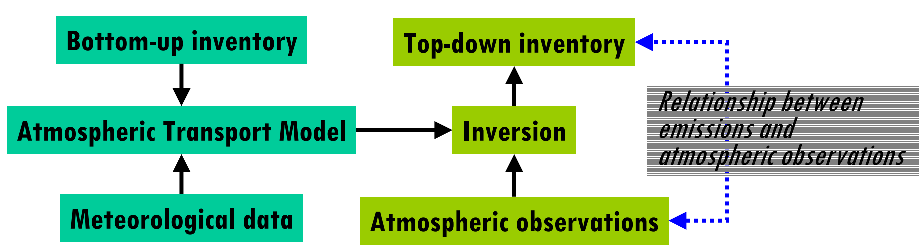
Observations: 3 ppmv

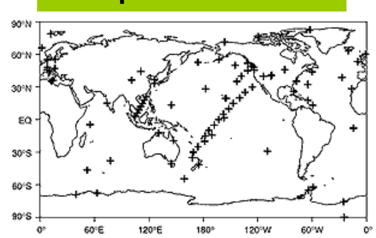
Mismatch in north-south atmospheric CO2 gradient between model and observations

This suggests a terrestrial sink of CO_2 in the northern hemisphere which is not represented in the model

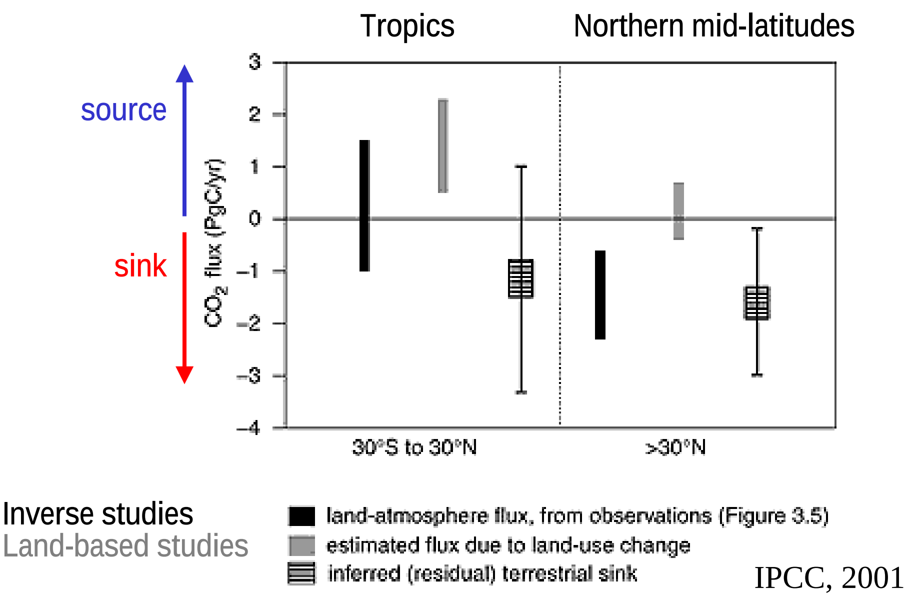
Where is this sink? → inverse modeling

Inverse modeling of atmospheric CO_2



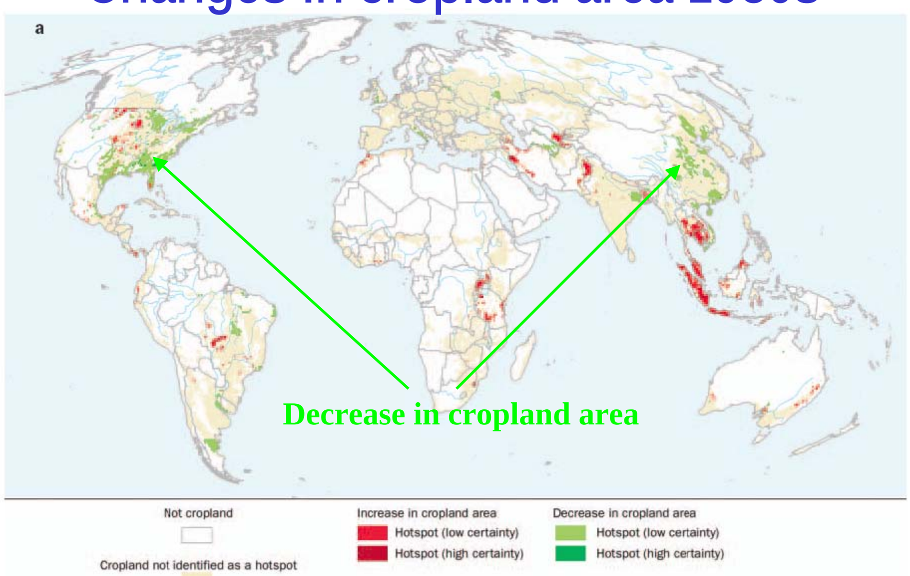


Partitioning in the 1980s land-atmosphere flux



IPCC, 2001

Changes in cropland area 1980s



More food is grown in less land! Mechanisation of agriculture, increased fertilizer use, high-yield crops

Lepers et al., Bioscience (2005)

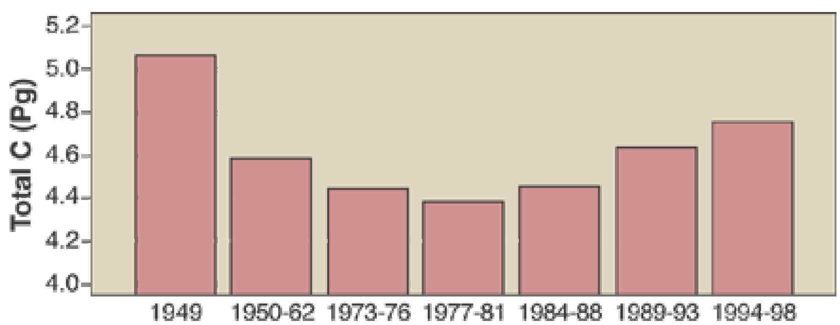
Uptake of atmospheric CO_2 by vegetation and soils in the U.S.

Only ~25%

Pacala *et al.*, *Science* **292**, 2316 (2001).

Total uptake of carbon in the continental United States: 0.3 and 0.6 Pg C per year, (equivalent to 20-40 % of U.S. fossil fuel emissions !!!)

Changes in sequestered carbon in Chinese forests



National policies in China since the late 1970s: boost reforestation and plantation of new forests
← flood and erosion control, protection of water supplies, and production of wood for fuel.

J. Fang *et al.*, *Science* **292**, 2320 (2001)

CO_2 fertilization

• Short term studies of agricultural plant species: 20-40% higher photosynthesis and growth under $2xCO_2$ conditions

→ above and below-ground carbon stock increases

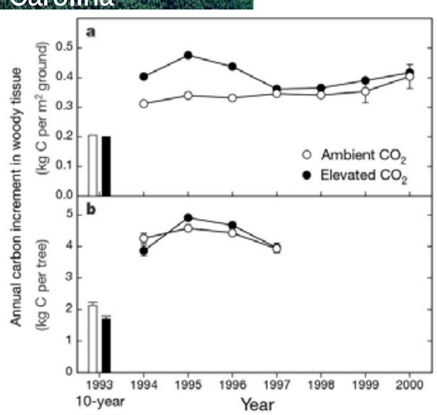
• Response depends on photosynthesis pathway

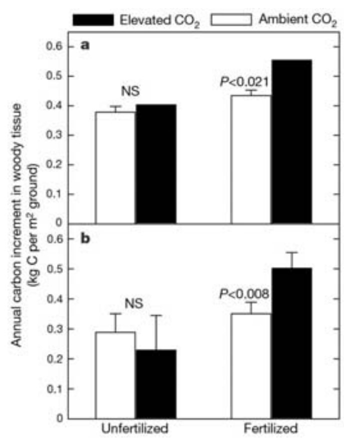
→C_3 plants (all trees, ~all plants in cold climate, many crops): increased rate of photosynthesis with higher CO_2

→C_4 plants (tropical and temperate grasses; shrubs; maize): no or less of a response to higher CO_2

• More recent FACE (Free Air CO_2 Experiments): For a 50% increase in atmospheric CO_2, there is a ~12% increase in NPP but saturation is reached after a few years due to nutrient limitations

Nutrient limitation to CO_2 fertilization



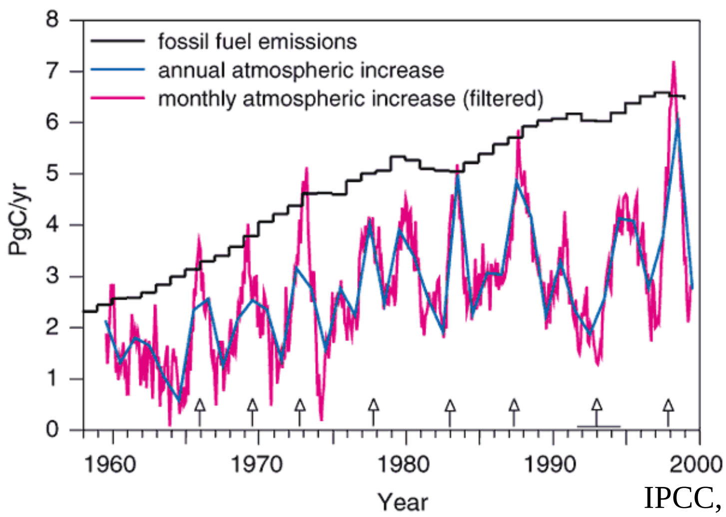


Oren et al., *Nature* **411**, 469 - 472 (2001)

Effects of anthropogenic nitrogen deposition

- Nitrogen availability is a limiting nutrient: increased nitrogen deposition leads to plant growth
- Plant growth only increases up to a point (saturation reached in polluted regions of Europe)
- Enhanced ozone and SO_2 in pollution: decrease growth (leaf injury), soil acidification → limit C uptake

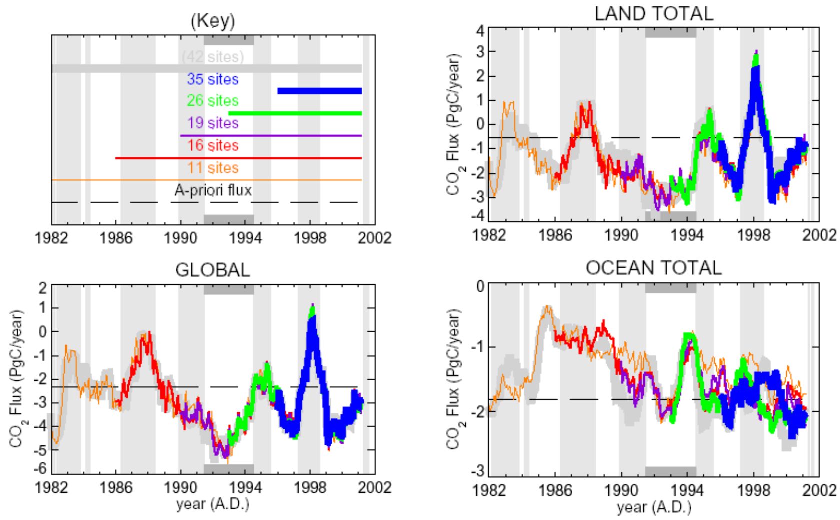
What drives the interannual variations in atmospheric CO_2?



IPCC, 2001

Time-dependent CO_2 inversion: 1982-2001

→Time Series of Global CO_2 Surface Fluxes



Rodenbeck et al., Atmos. Chem. Phys., 3, 1919-1964, 2003

Space-based observations of CO_2

Measure CO_2 absorption in the infrared

thermal infrared (Terrestrial IR radiation)

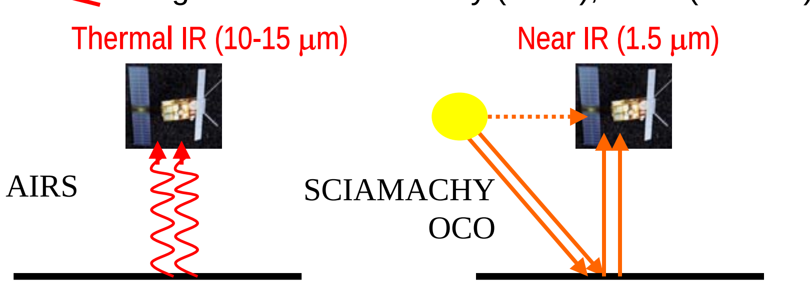
near infrared (solar IR radiation)

Currently 2 instruments:

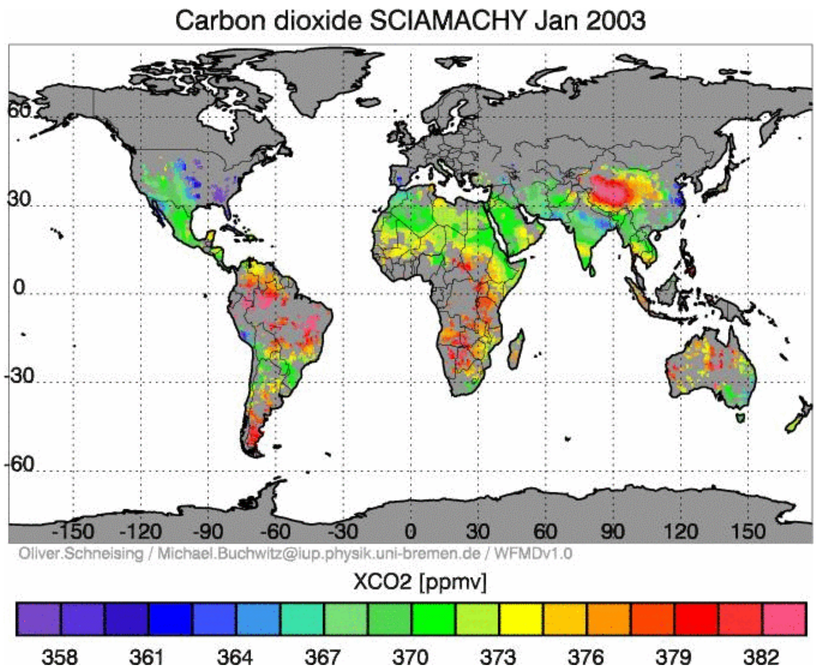
SCIAMACHY on European ENVISAT satellite (near IR)

AIRS on NASA's AQUA satellite (thermal IR)

~~**Planned:**~~ Orbiting Carbon Observatory (OCO), 2009 (near IR)



→ Requirement: better than 1% precision!



Terrestrial carbon cycle models

1. Terrestrial biogeochemical models (coupled fluxes of carbon, water and nitrogen within ecosystems)

2. Dynamic global vegetation models: TBM + coupling to ecosystem structure and composition

Validation

Local scale: comparison to field observations (CO_2 fluxes; soil carbon; …)

Global scale:

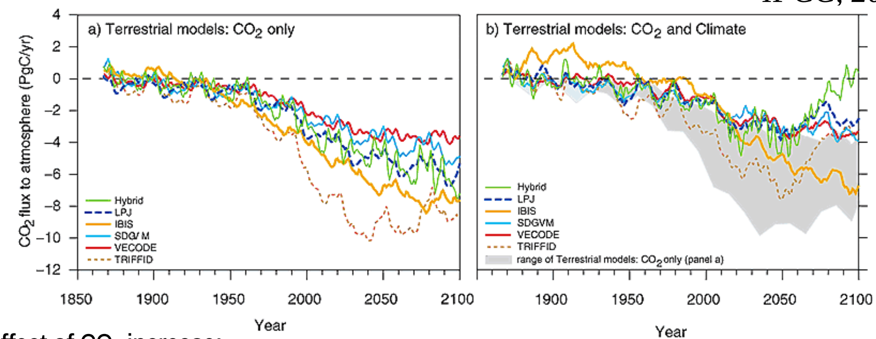
Satellite observations

atmospheric CO_2 seasonal cycle

+ interannual variability (couple to chemical transport models)

Projections of terrestrial CO_2 uptake

IPCC, 2001



Effect of CO_2 increase:
- CO_2 increase alone leads to continued uptake by land (CO_2 fertilization)
- But efficiency will decrease in the future (saturation of land C sink)

CO_2 increase + climate feedbacks:
- Tropical drying: Large losses of CO_2 from tropical forests (reduced plant growth, enhanced respiration, more wildfires)
- Northern Mid-latitudes: increased productivity and enhanced C uptake
- Net: positive feedback, but large uncertainty in magnitude of feedback