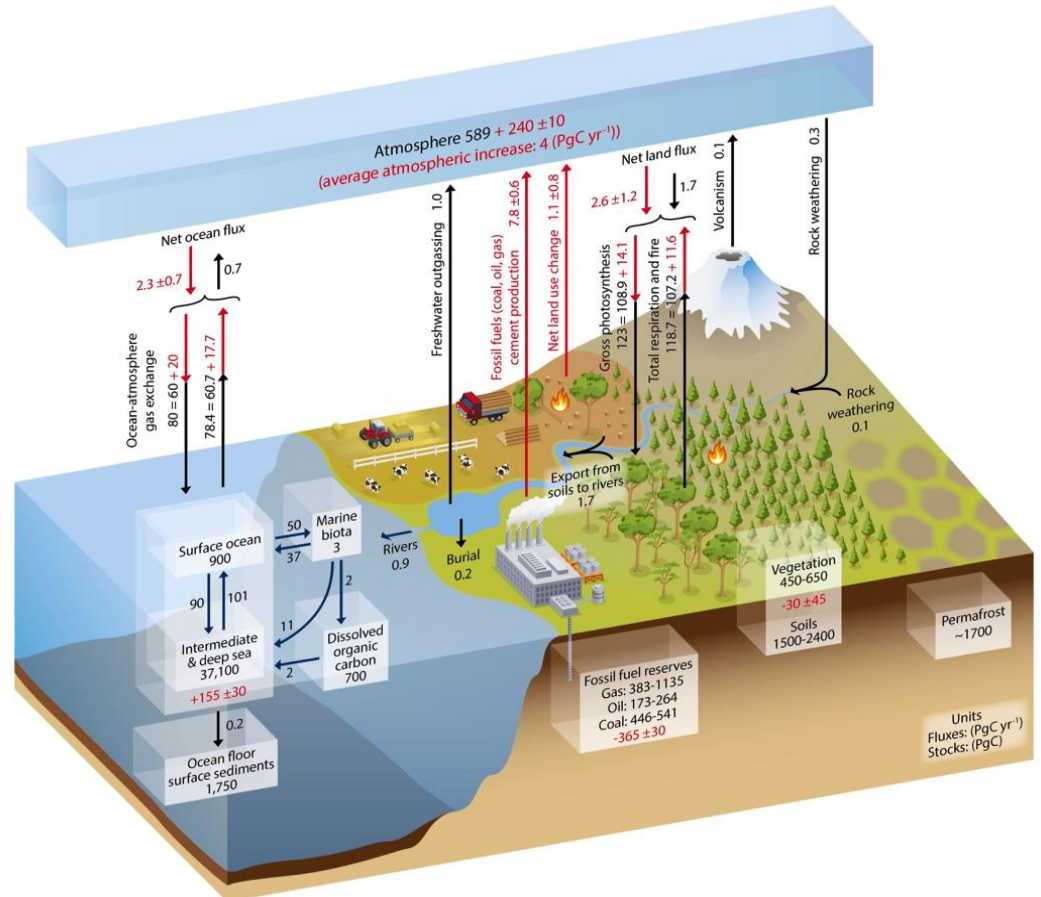


The role of the arctic and boreal region in the global carbon cycle

Debra Wunch
University of Toronto

The carbon cycle

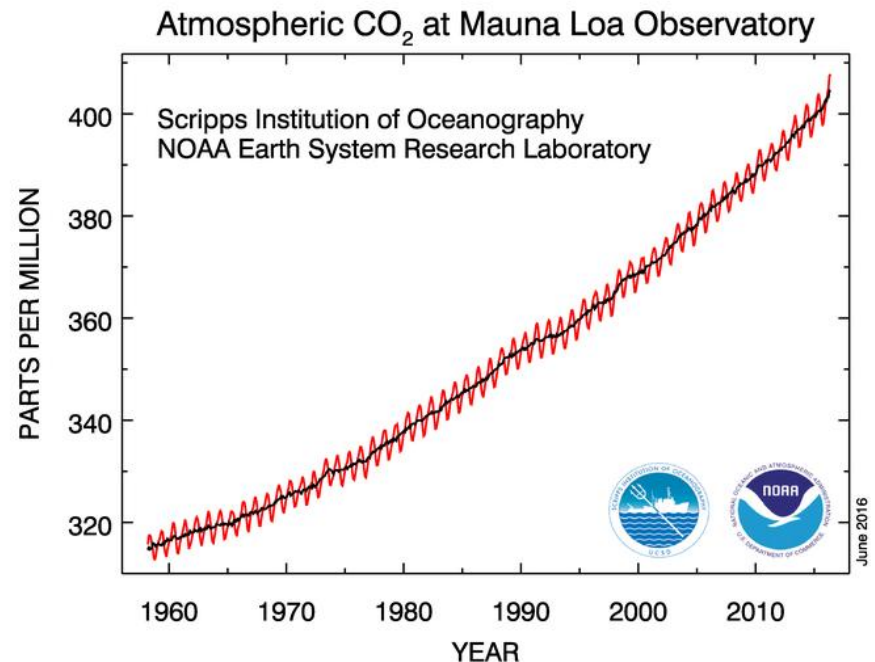
- Carbon dioxide is exchanged between the atmosphere and the surface and the ocean.
- Influenced by changes in sources and sinks.
 - Anthropogenic releases (fossil fuel burning)
 - Changes in land use
 - Respiration and photosynthesis of plants
 - Uptake and release by oceans



IPCC – Climate change 2013, The Physical Science Basis

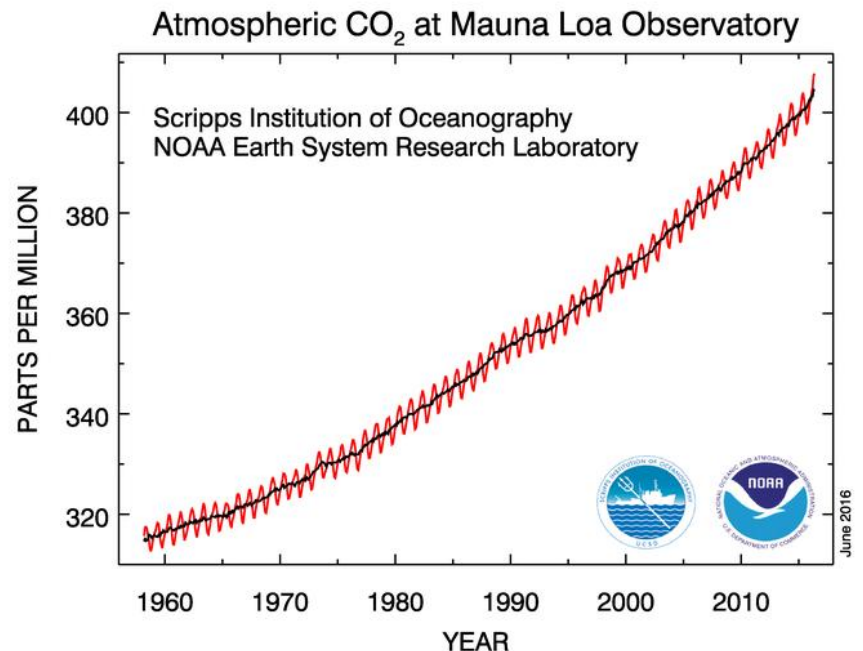
Atmospheric Carbon Dioxide (CO₂): The Keeling Curve

- Began in 1958 by Dave Keeling
- In situ measurements atop Mauna Loa, HI
- Fossil carbon accumulates in the atmosphere
 - The level of CO₂ in the atmosphere is rising in parallel with fossil fuel emissions and land use change
 - Radiocarbon measurements showed that the accumulation in the atmosphere was from (radiocarbon-depleted) fossil CO₂



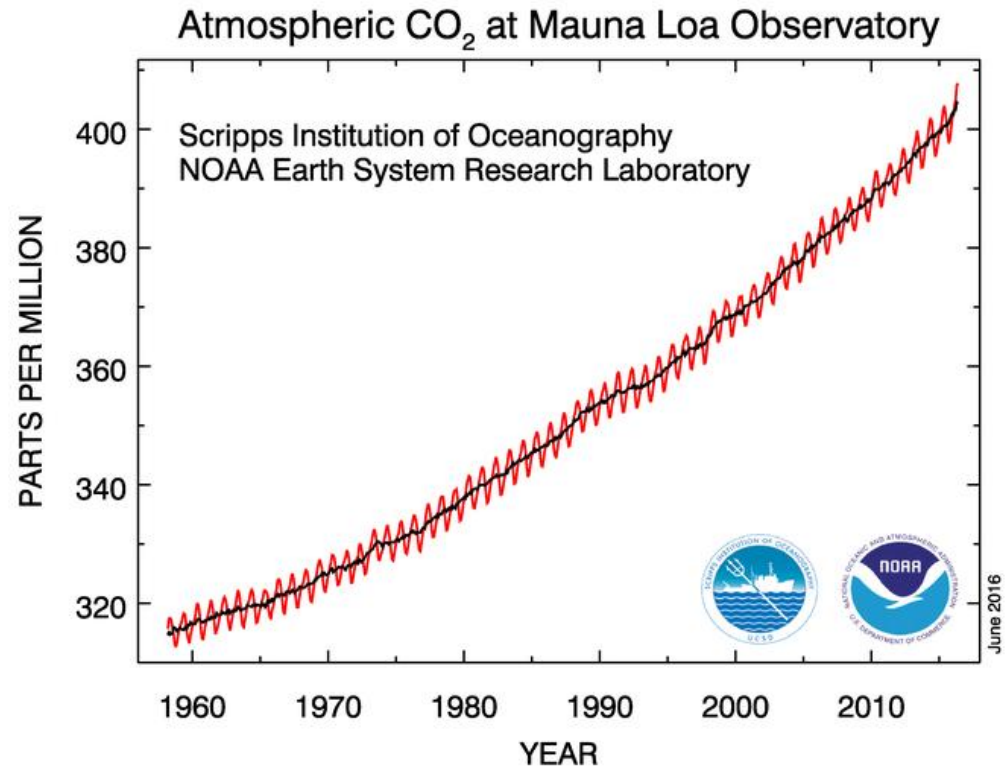
The Keeling Curve

- Not all fossil carbon accumulates in the atmosphere
 - Thus it must go somewhere else; either the oceans or the terrestrial biosphere
 - Since the impact of fossil fuel burning on climate depends on the atmospheric concentration via the greenhouse effect, these other “reservoirs” of carbon modulate the impacts
- If climate can impact the other reservoirs, we have a complex feedback system



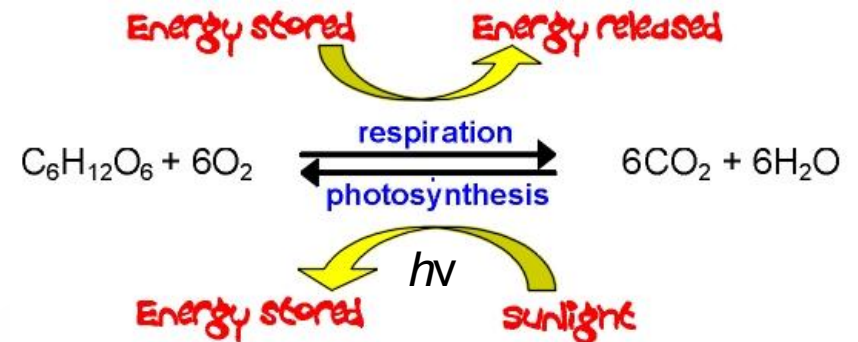
The Keeling Curve

- “Breathing of the Earth” is apparent in the strong seasonal cycle
 - Results from northern hemisphere summer photosynthesis (CO_2 is drawn down), and winter respiration (CO_2 is released into the atmosphere)



Plant Photosynthesis

- Plants “fix” carbon by creating sugars (chains of CH_2O) through the interactions of carbon dioxide and photons – called Gross Primary Productivity (GPP)
- Respiration (R) returns the sugars into CO_2
- Photosynthesis only occurs during the day; respiration occurs both day and night
- For a seasonal-scale drawdown in CO_2 to occur, more photosynthesis than respiration must occur (i.e., daytime must be significantly longer than night time)
- In the tropics, day and night are roughly the same length all year
- In the boreal and arctic regions, there is a strong asymmetry where summers have very long days and winters have very short days



<https://pmgbiology.com/tag/respiration/>

Global terrestrial carbon uptake

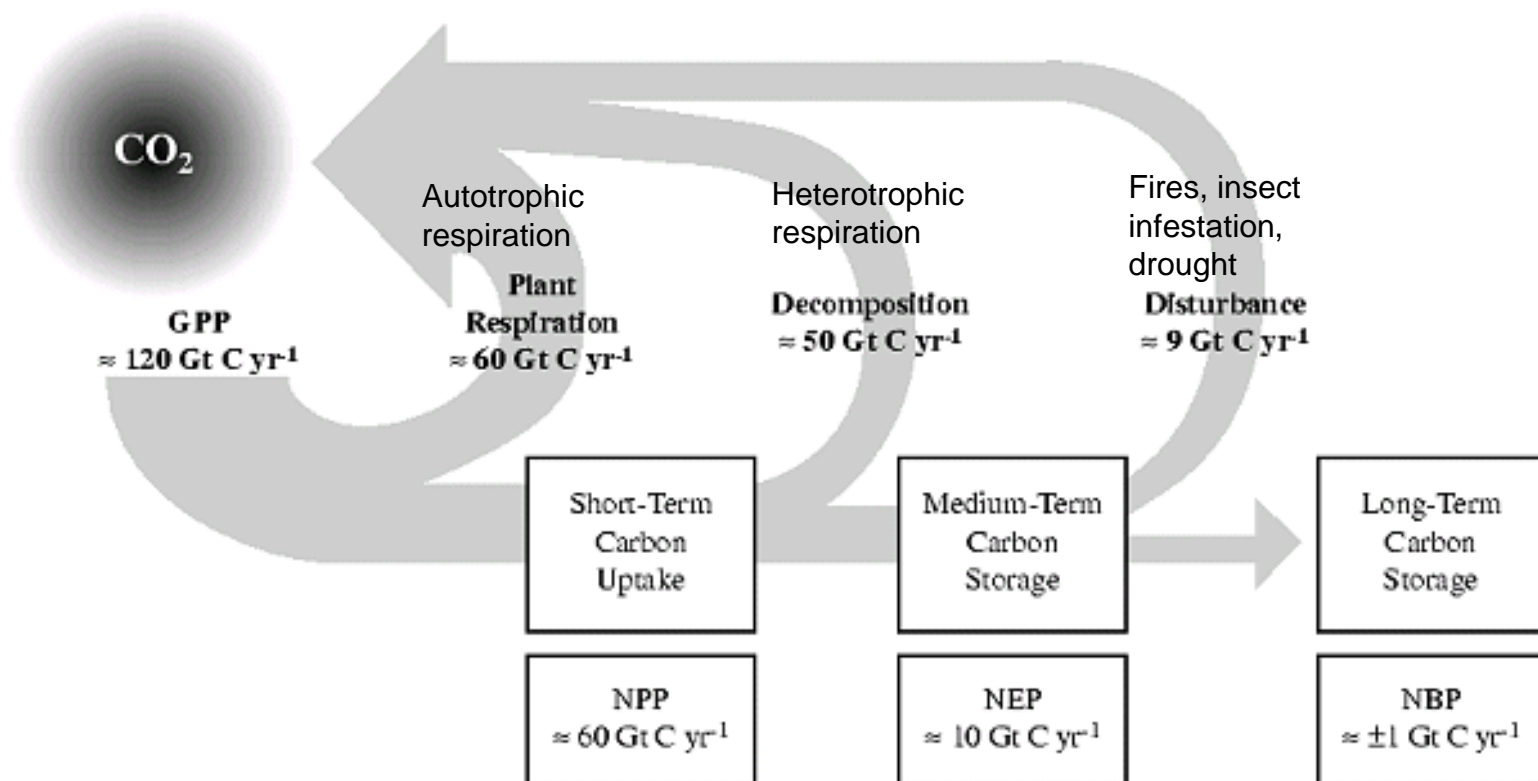
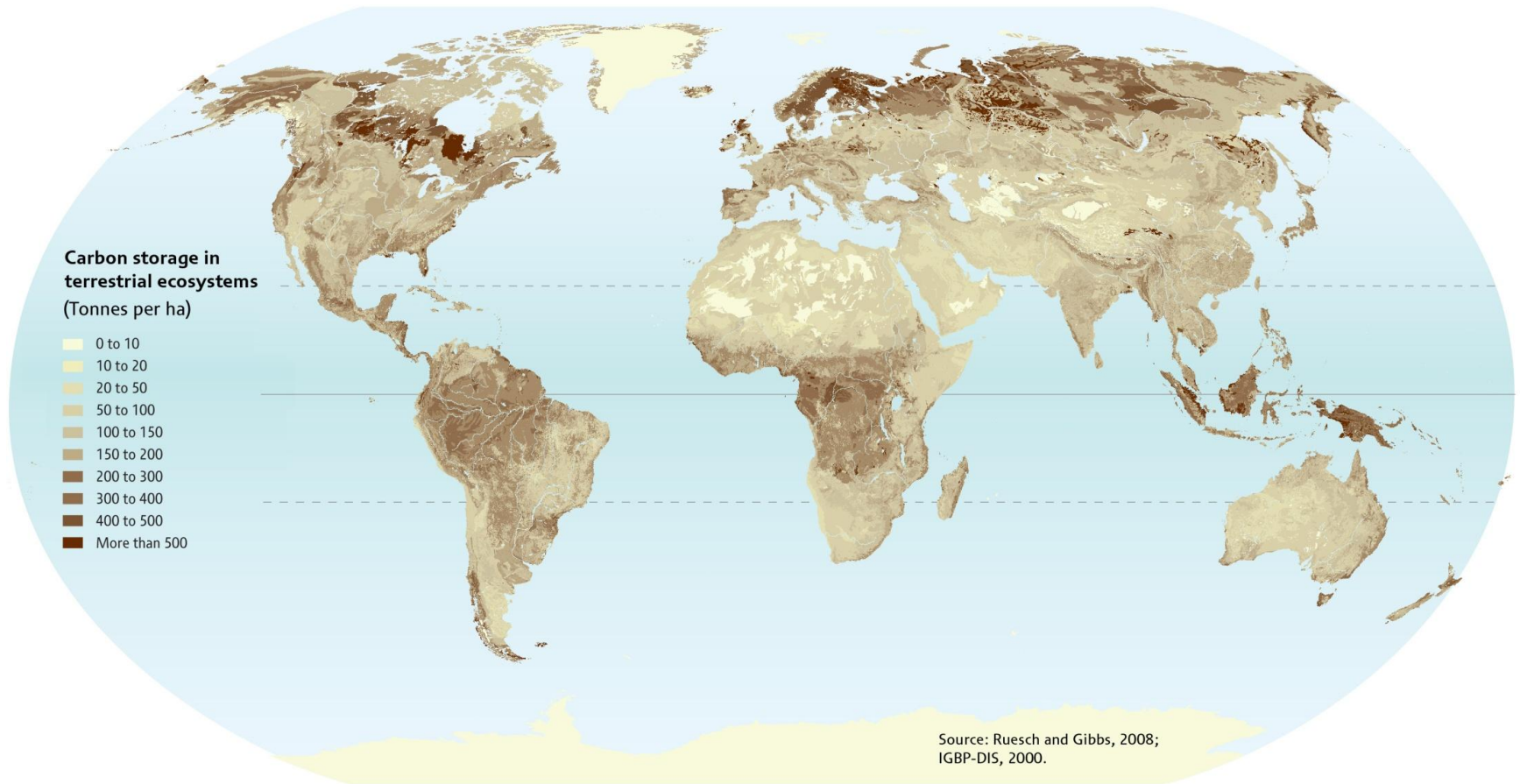


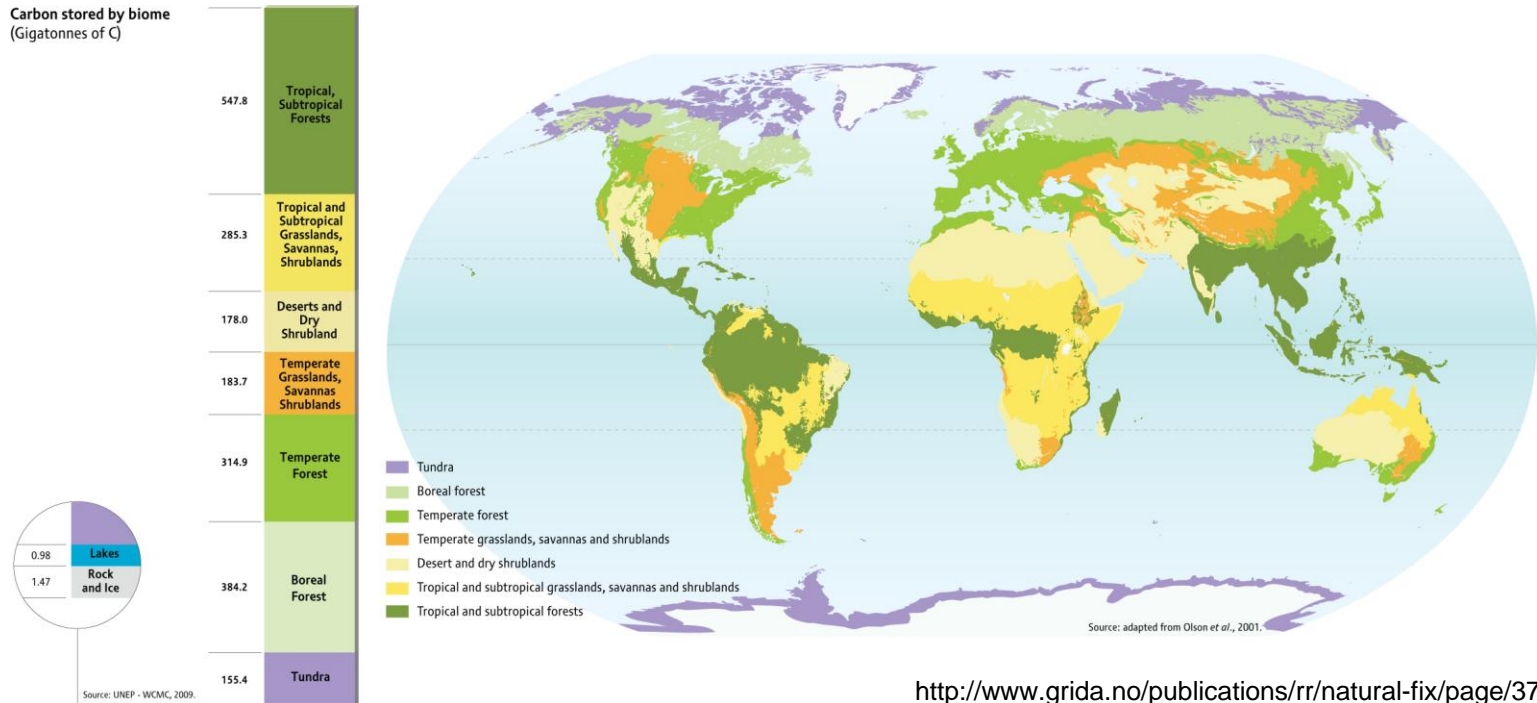
Figure 1-2: Global terrestrial carbon uptake. Plant (autotrophic) respiration releases CO₂ to the atmosphere, reducing GPP to NPP and resulting in short-term carbon uptake. Decomposition (heterotrophic respiration) of litter and soils in excess of that resulting from disturbance further releases CO₂ to the atmosphere, reducing NPP to NEP and resulting in medium-term carbon uptake. Disturbance from both natural and anthropogenic sources (e.g., harvest) leads to further release of CO₂ to the atmosphere by additional heterotrophic respiration and combustion-which, in turn, leads to long-term carbon storage (adapted from Steffen et al., 1998).

Global Carbon Stocks



Tundra and Boreal Carbon Stocks

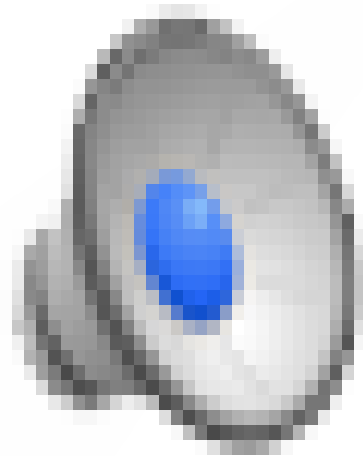
Carbon stored by biome
(Gigatonnes of C)



<http://www.grida.no/publications/rr/natural-fix/page/3724.aspx>

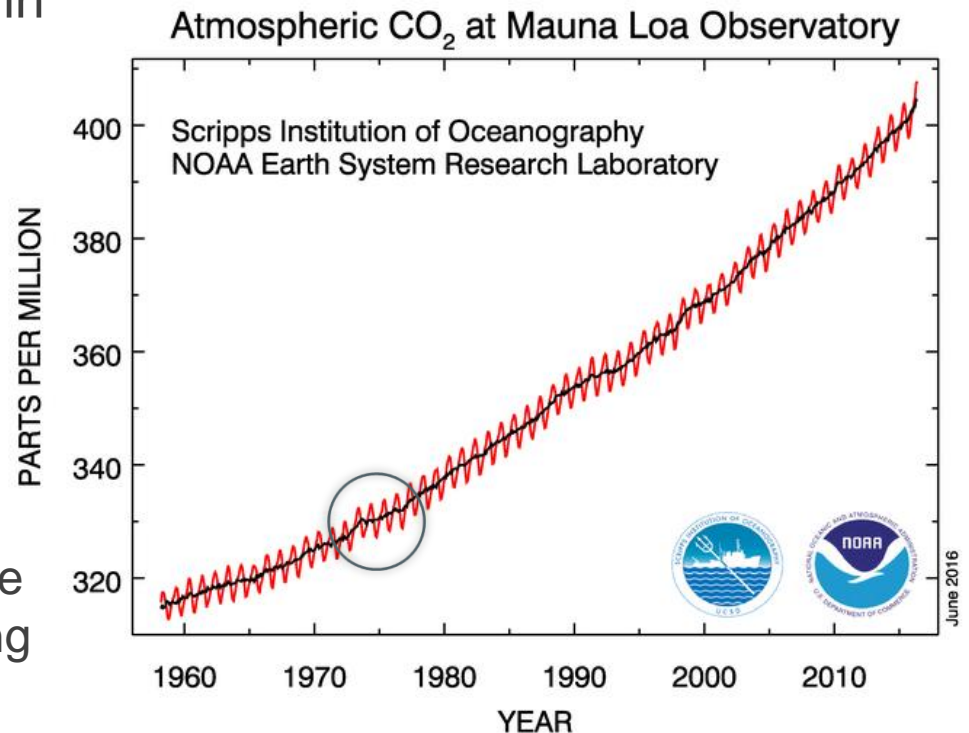
- Tundra carbon stocks locked in permafrost
 - Not much capacity to store more carbon, but much could be lost if permafrost melts
- The boreal forest biome holds the second largest stock of carbon; most of this is stored in the soil and litter.
 - The draining of boreal forest peatlands, inappropriate forestry practices and poor fire management may all cause significant losses of the carbon stored in this ecosystem.

Pump Handle: Boreal-Driven Seasonal Cycle



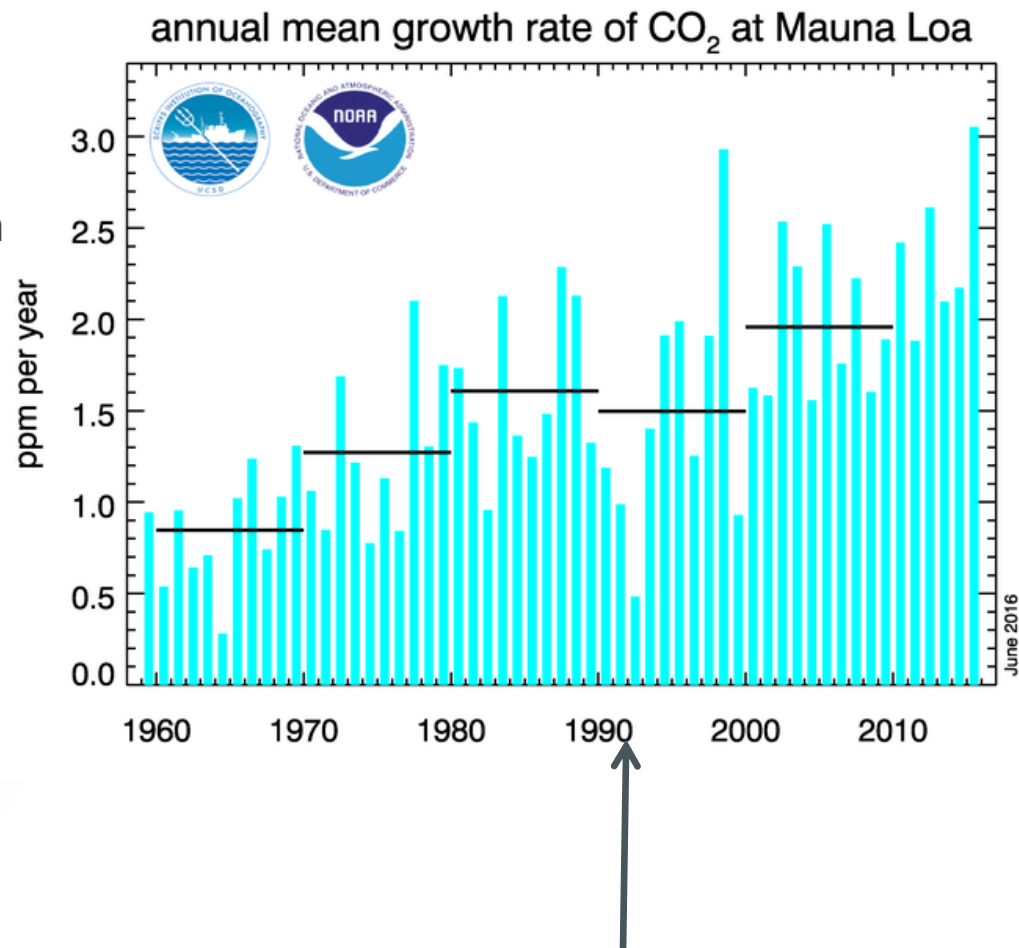
The Keeling Curve

- Variations in the growth rate in CO₂ describe Earth System events
- The Arab-Israeli war was followed in 1973 by an oil embargo: fuel prices spiked; worldwide consumption declined
 - Lower growth rates in CO₂ are seen in the few years following 1973



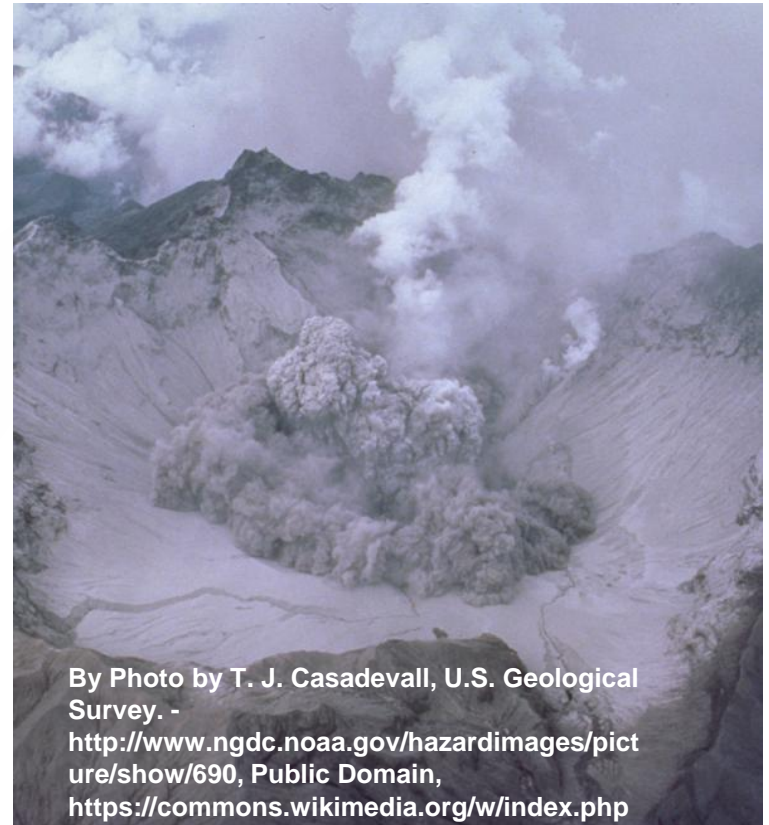
The Atmospheric Growth Rate: The Time Derivative of the Keeling Curve

- 1991: Mount Pinatubo
 - Increased terrestrial carbon storage
 - Cooling effect of aerosols, or increased diffuse radiation, stimulating plant growth?



Mount Pinatubo Eruption, 1991

The second-largest volcanic eruption of the 20th century, and by far the largest eruption to affect a densely populated area, occurred at Mount Pinatubo in the Philippines on June 15, 1991. The eruption produced high-speed avalanches of hot ash and gas, giant mudflows, and a cloud of volcanic ash hundreds of miles across. – Wikipedia

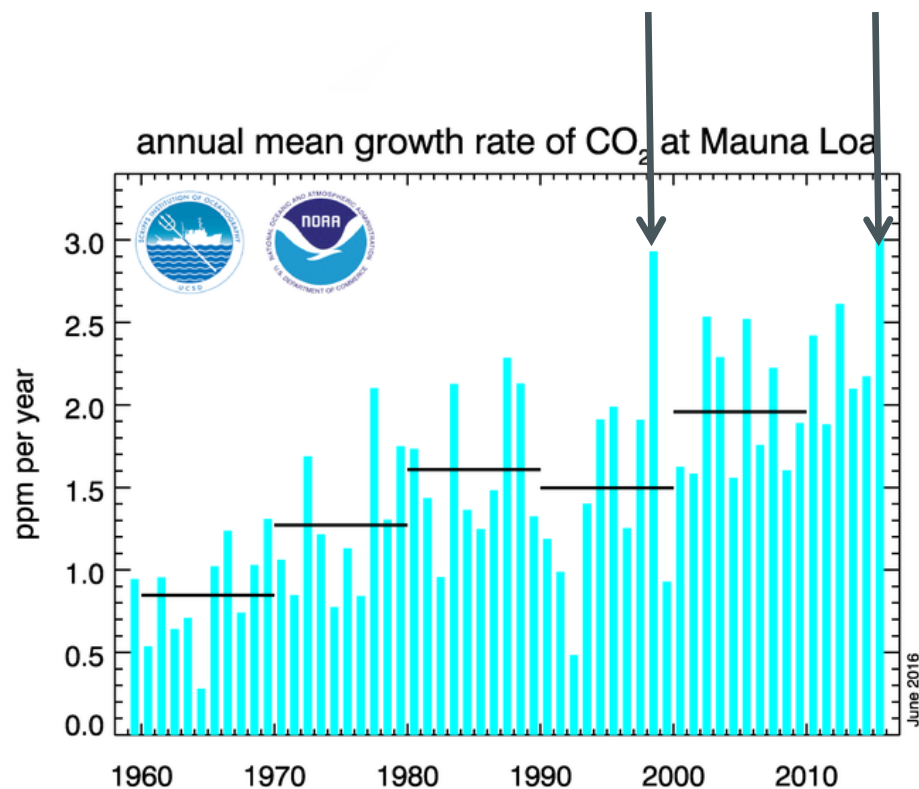


By Photo by T. J. Casadevall, U.S. Geological Survey. -
<http://www.ngdc.noaa.gov/hazardimages/picture/show/690>, Public Domain,
<https://commons.wikimedia.org/w/index.php>

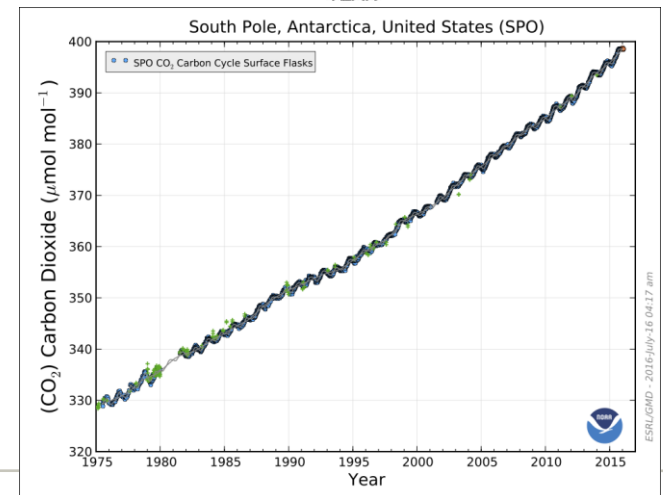
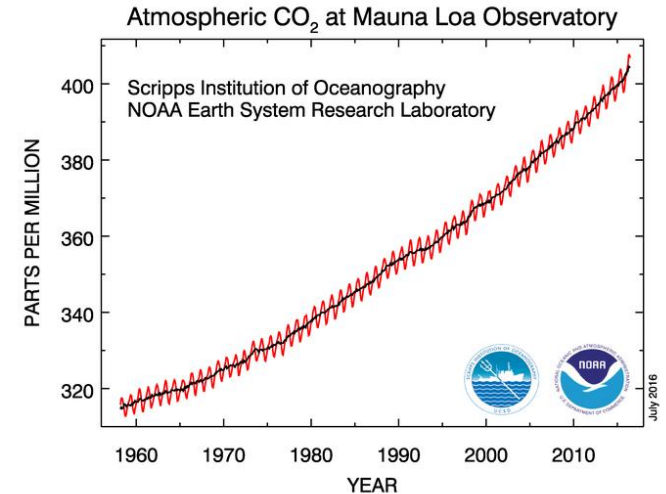
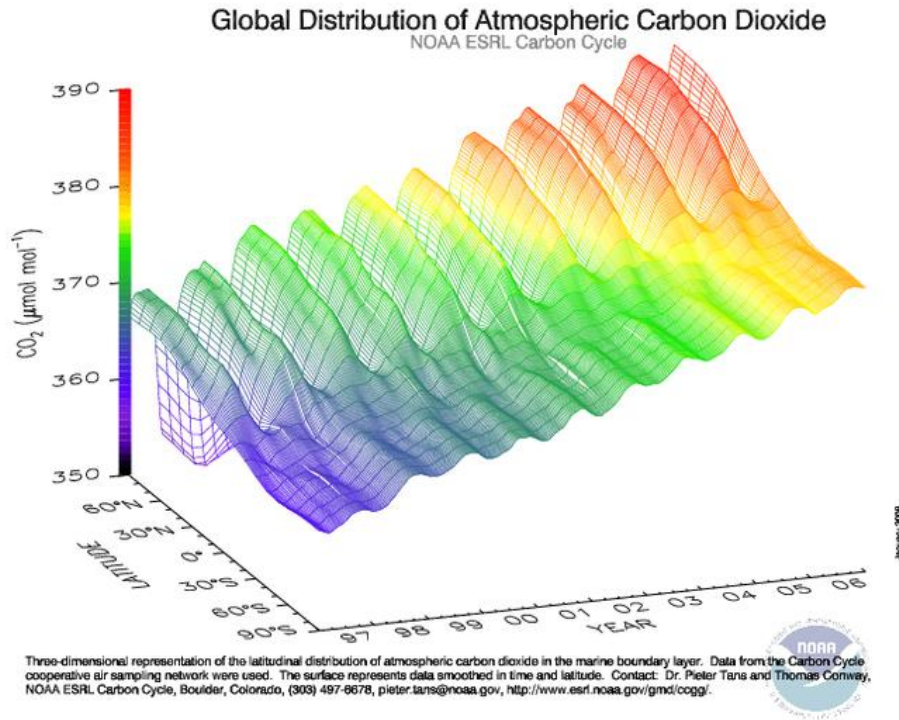
<http://pubs.usgs.gov/fs/1997/fs113-97/>

The Atmospheric Growth Rate: The Time Derivative of the Keeling Curve

- El Niño: 1997, 2016
- Change in oceanic circulation
 - Normally, the global ocean circulation of water transfers high- CO_2 (cold) water from high latitudes to low latitudes, and the water upwells in the tropics
 - During El Niño, tropical winds change direction, and warm water caps the upwelling regions, temporarily trapping the cold, high CO_2 water at depth, and prevents it from entering the atmosphere
- These circulation changes, though, cause widespread drought and often fires, resulting in the significant increase in atmospheric CO_2



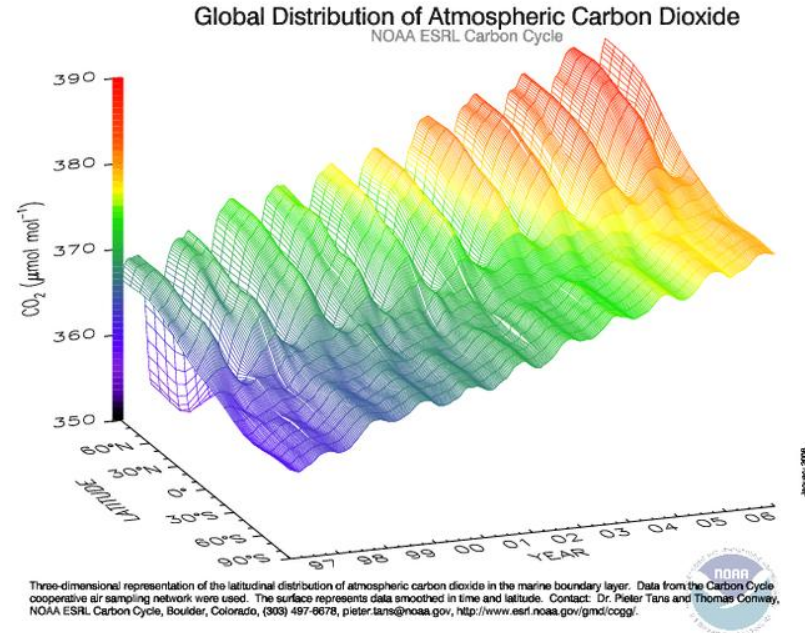
The Latitude Gradient in Atmospheric CO₂



- The northern hemisphere atmosphere CO₂ is higher than the southern hemisphere
 - Not surprising; the northern hemisphere is where most of the fossil fuels are burned

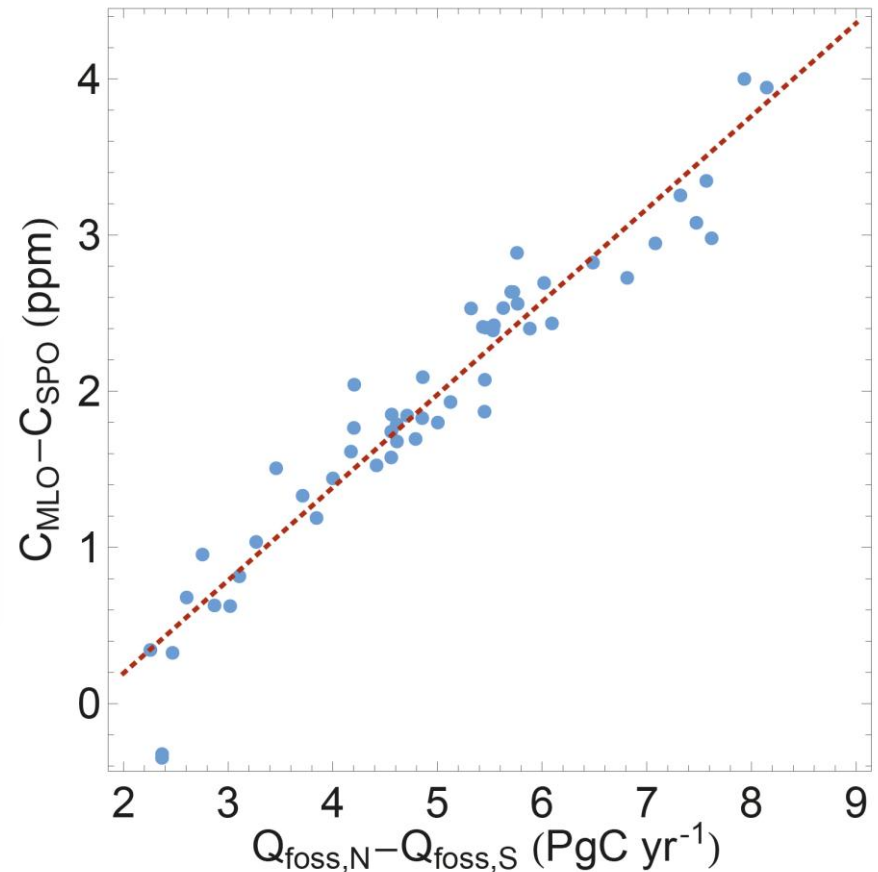
The Latitudinal Gradient in Atmospheric CO₂

- Tans, Fung, and Takahashi (1990) showed that models which did not include a significant terrestrial sink in the northern mid-latitudes could not reproduce the latitudinal gradient in CO₂
- The sink was larger in the northern hemisphere than the south and could not be explained by ocean uptake
- First definitive evidence of the terrestrial biosphere's control of atmospheric CO₂
 - And, importantly, the Boreal forest's role



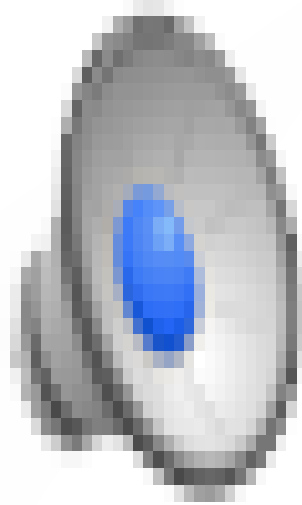
The Latitudinal Gradient in Atmospheric CO₂

- The latitudinal gradient in CO₂ gives a direct link to CO₂ emissions



The difference between CO₂ concentration in the NH and SH (y axis), computed as the difference between annual mean concentrations (ppm) at Mauna Loa and the South Pole (Keeling and Whorf, 2005, updated), compared with annual fossil fuel emissions (x axis; GtC; Marland, et al., 2006), with a line showing the best fit. The observations show that the north-south difference in CO₂ increases proportionally with fossil fuel use, verifying the global impact of human-caused emissions. (IPCC 2007)

Impact of Fossil Fuel Emissions



Global Carbon Cycle

- Oceans contain largest reservoir of active carbon (1000-year time scales)
- Land/rocks contain largest inactive reservoir (geological time scales)
- Plants and soil have significant active reservoir, but they are highly variable (sub-annual time scales)

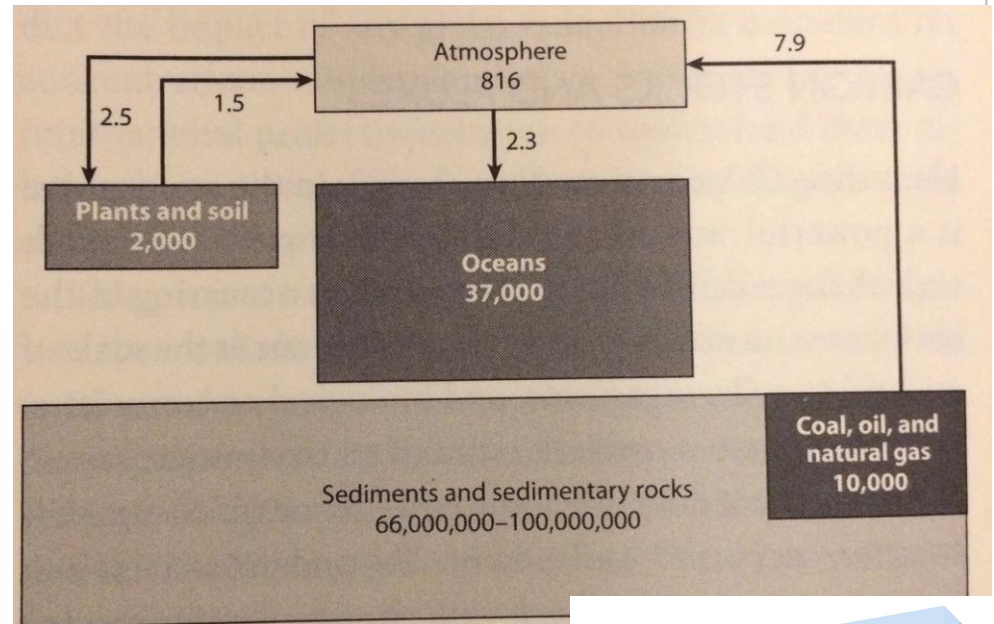
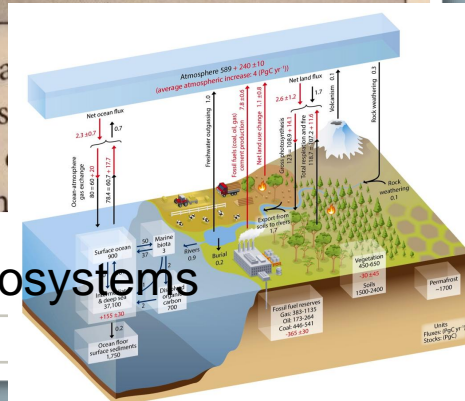


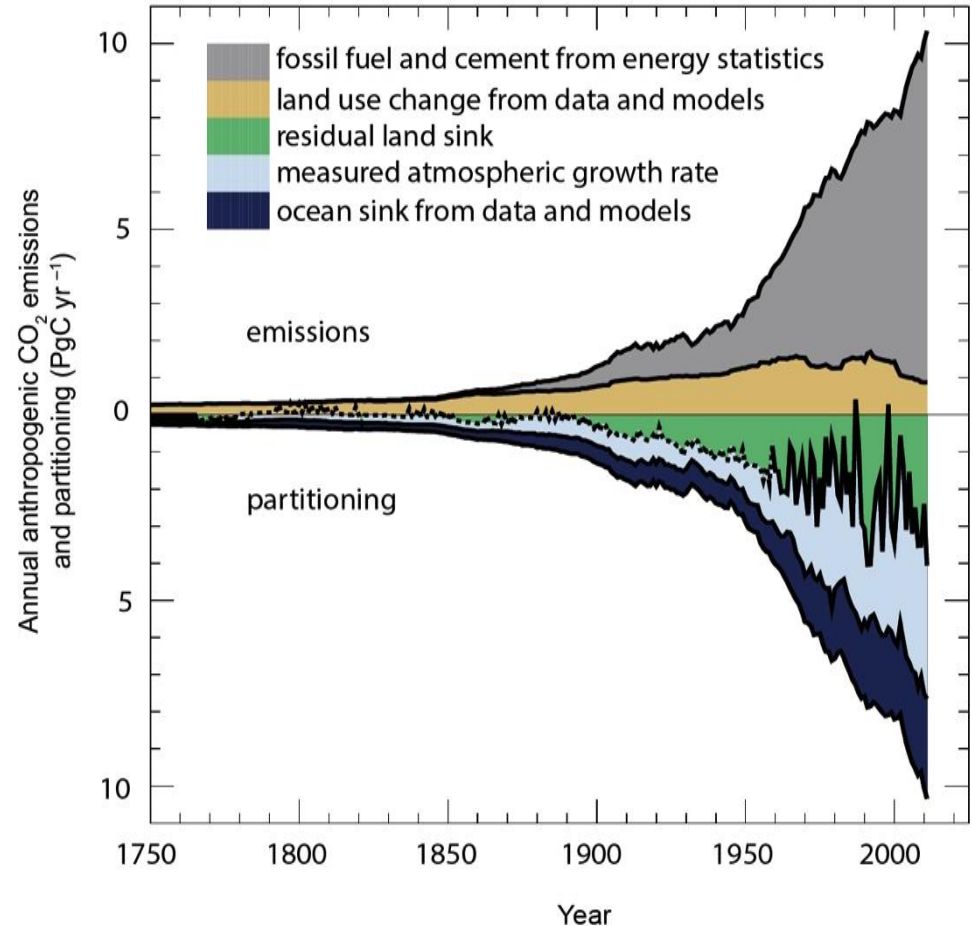
Figure 12. Global stocks and flows of carbon in Earth System reservoirs, and the fluxes of carbon from current emissions from fossil fuel and land use change, and from fossil fuel/deforestation CO₂ by the land

Schimel, Climate and Ecosystems



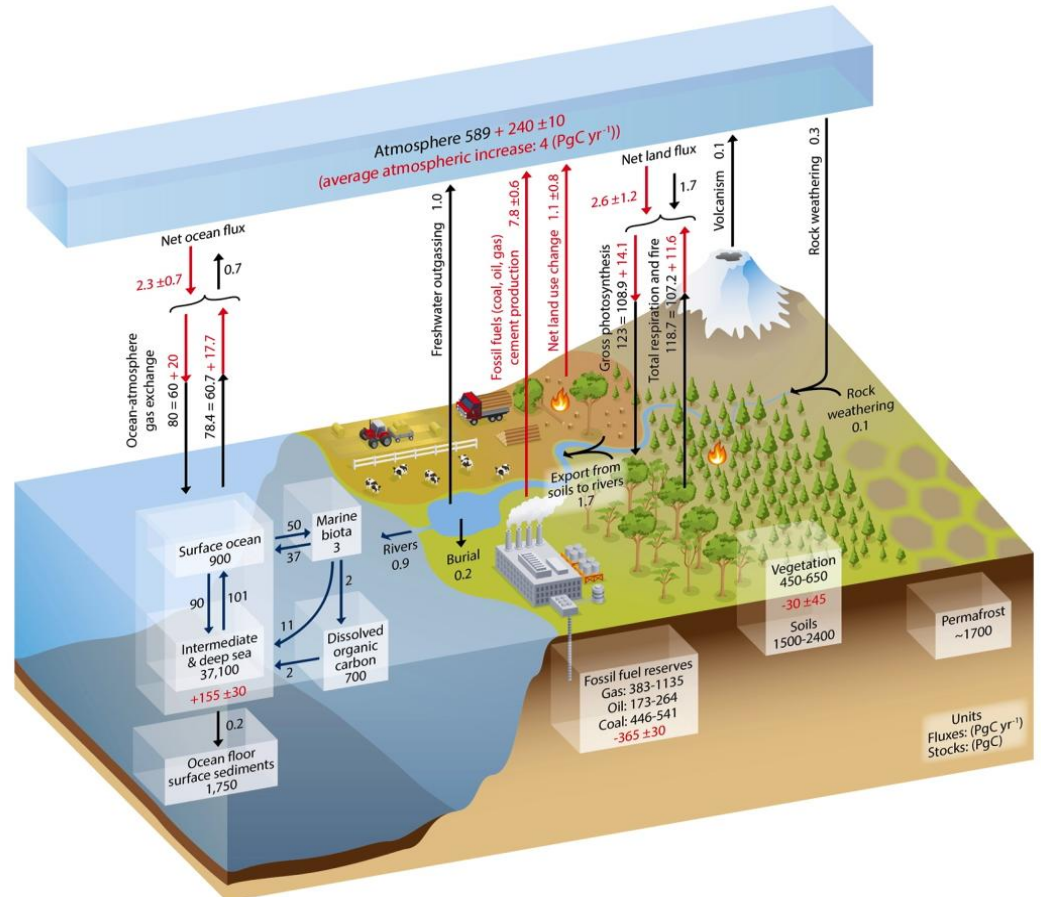
The airborne fraction of CO₂

- Atmospheric CO₂ is the difference between the emitted CO₂ from fossil fuel and land use change and the sinks of CO₂ (ocean and land)
- The land sink is by far the most variable from year to year
- From measurements of the atmosphere and ocean, and emissions data, we infer the “residual land sink”



The carbon cycle

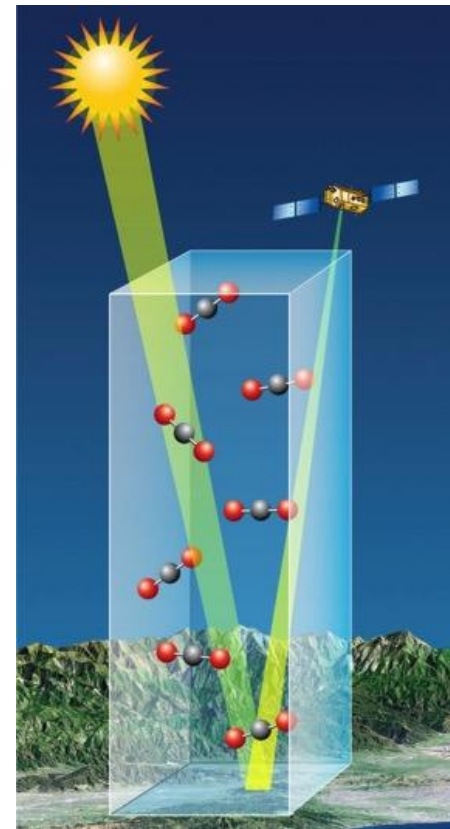
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IPCC – Climate change 2013, The Physical Science Basis

Measuring the atmospheric carbon cycle: beyond surface measurements

- To get global coverage requires space-borne measurements
- Must measure remotely and thus through the entire atmosphere: a column-averaged carbon dioxide measurement
- Must tie the space-borne measurements to the surface in situ network with a transfer standard
 - Ground-based column-averaged measurements that are precise and accurate compared with the surface in situ network

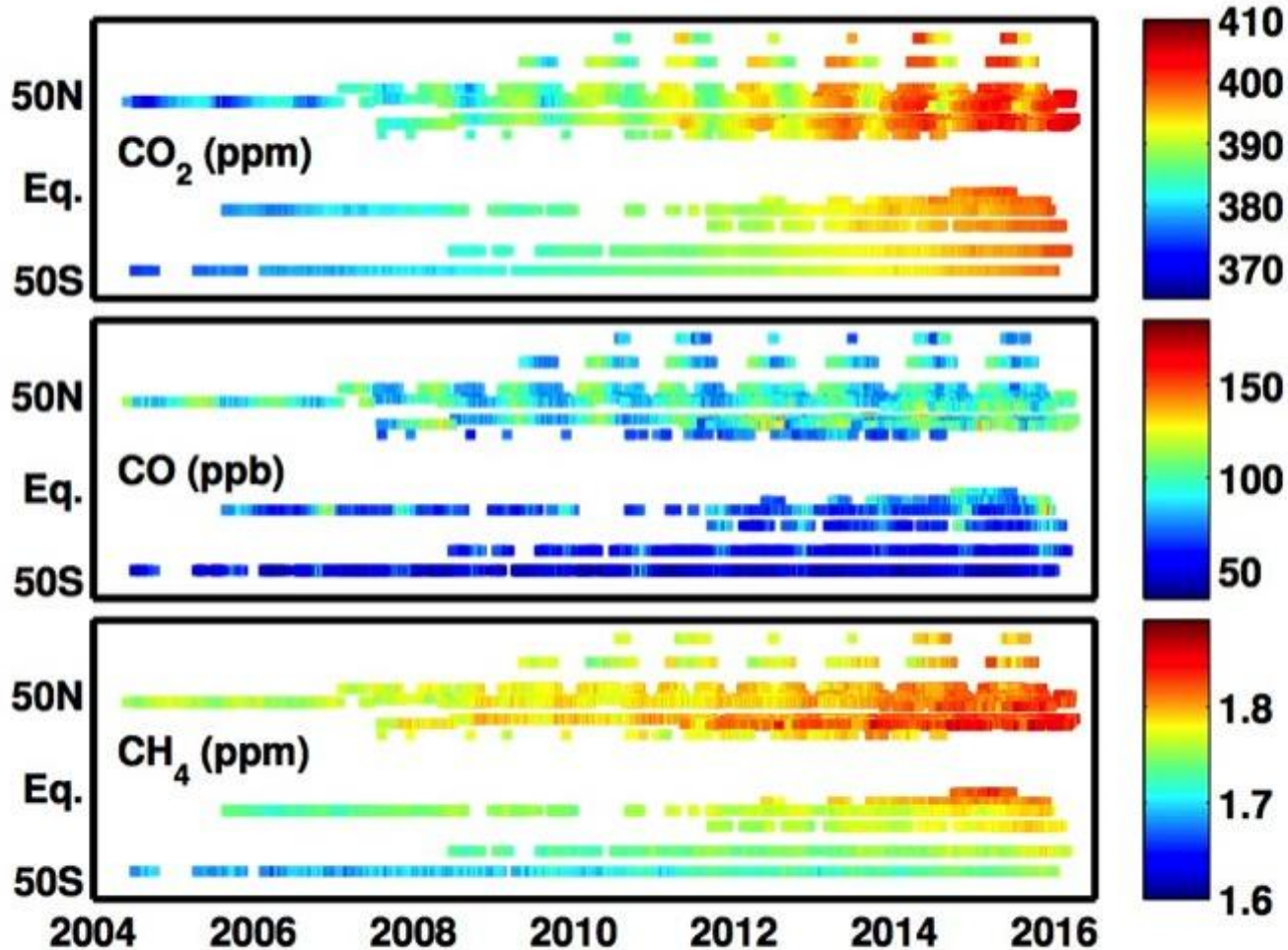


Total Carbon Column Observing Network (TCCON)

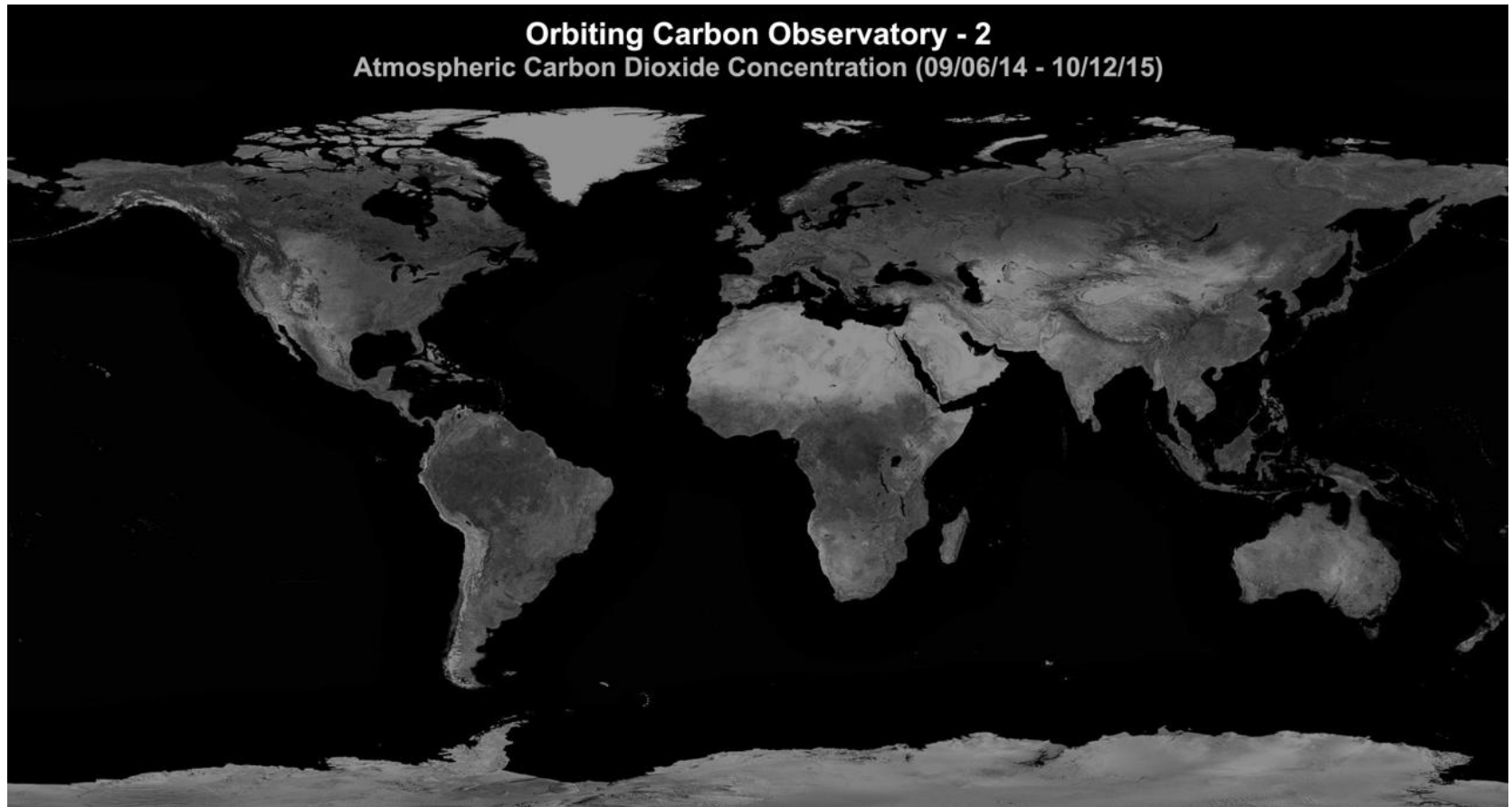


- Network of ground-based Fourier transform spectrometers
- Designed to measure globally-consistent, precise and accurate total column amounts of CO₂, CH₄, CO, N₂O, H₂O, HDO, HF

TCCON CO₂, CO and CH₄ time series

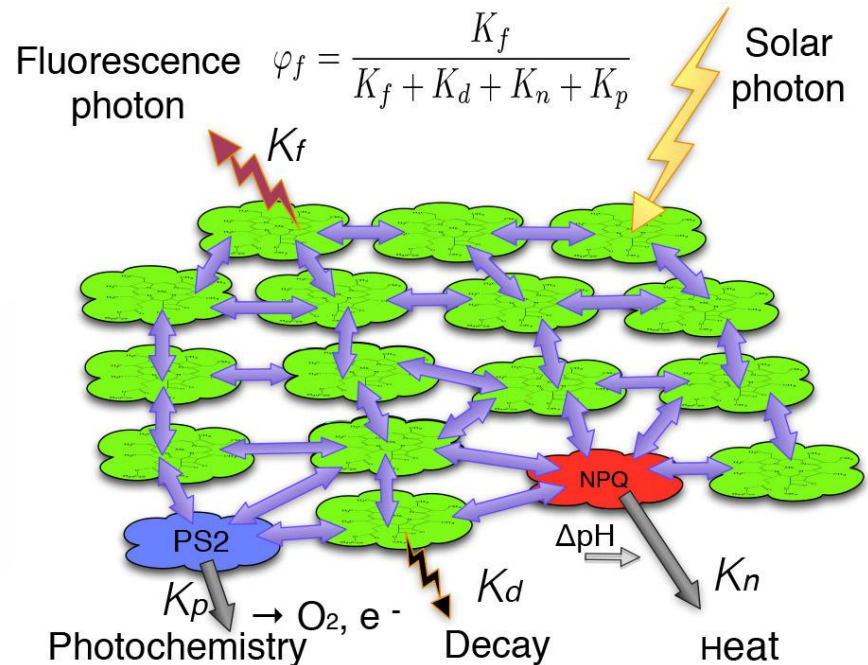
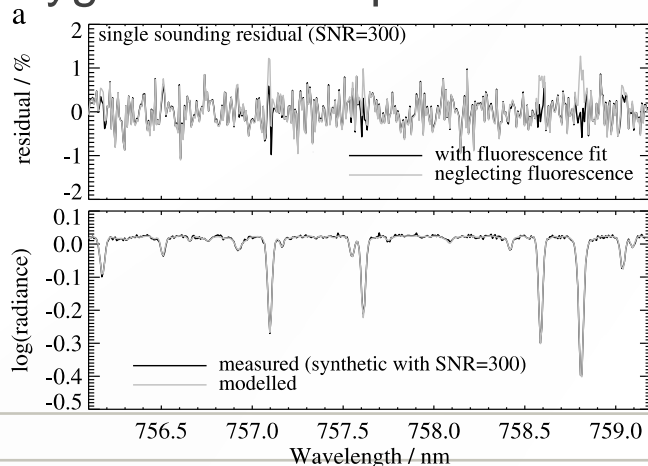


The future of carbon cycle science: measurements of carbon dioxide from space



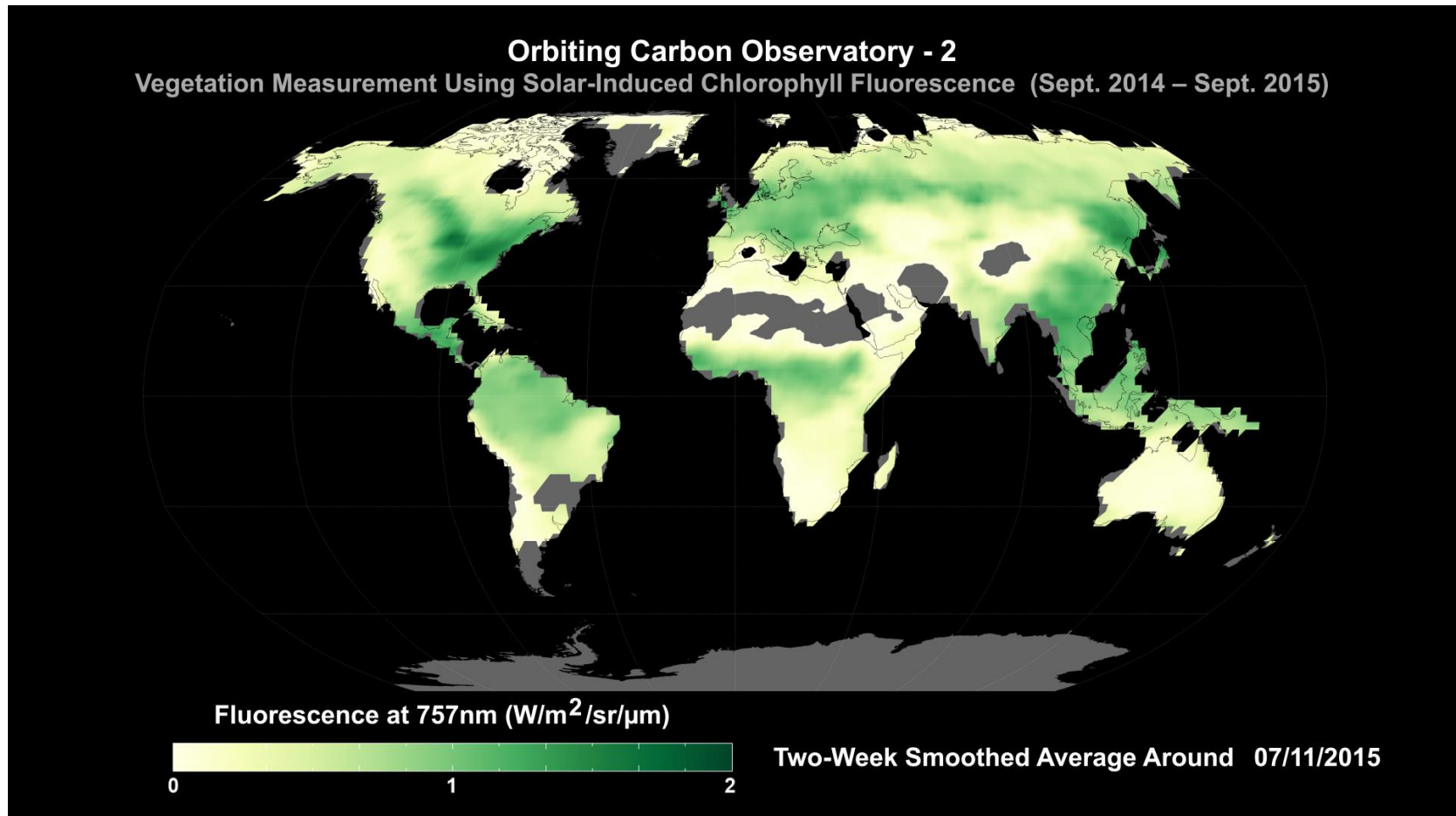
The future of carbon cycle science: measurements of fluorescence

- Fluorescence is emitted as a byproduct of photosynthesis
- Solar-induced fluorescence is a good proxy for Gross Primary Productivity
- It can be measured from space, by looking at the filled in Fraunhofer (solar) lines in the oxygen A-band spectrum

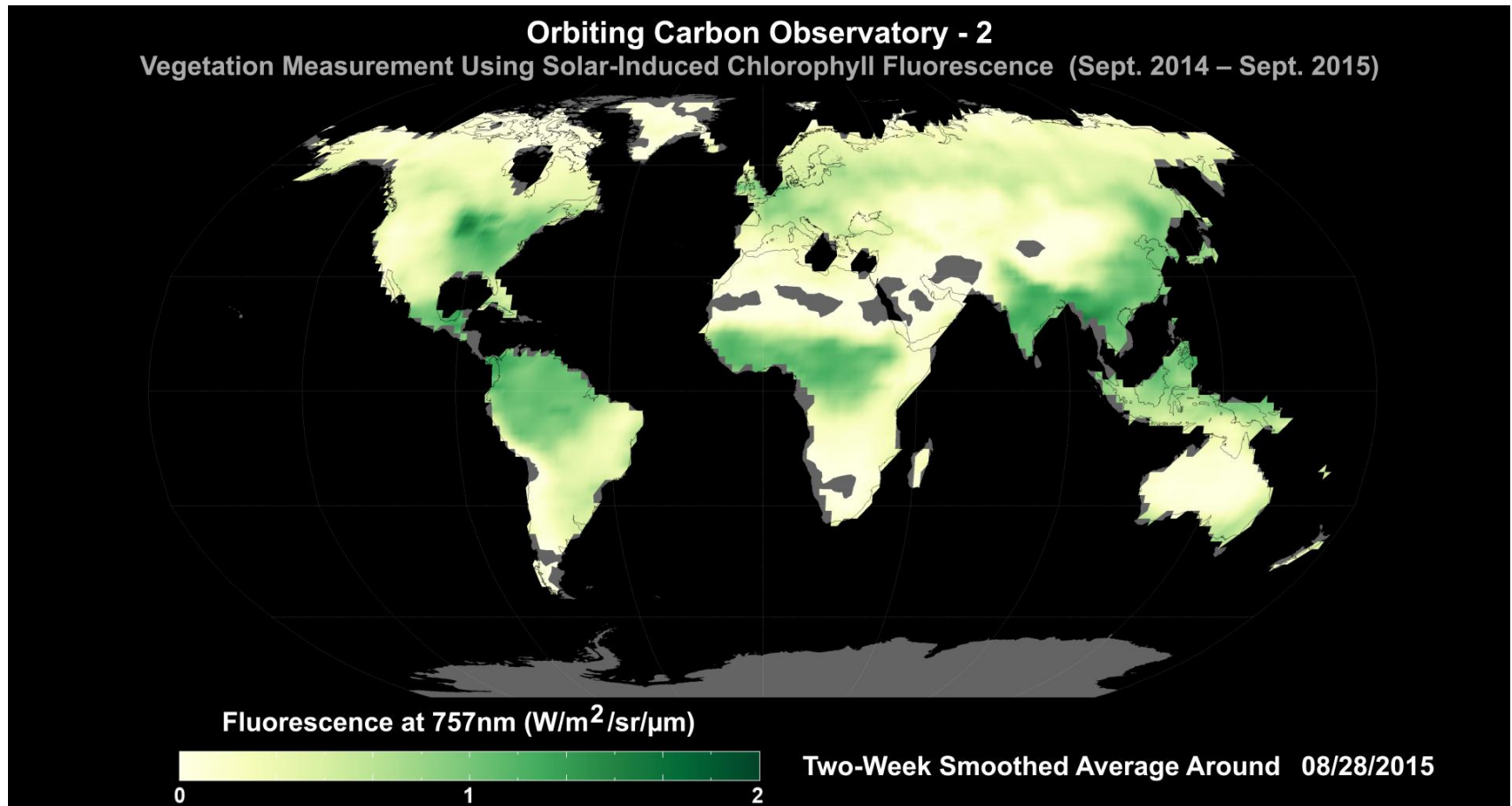


Arrays of chlorophyll molecules bound to protein absorb and process solar photons in plant leaves. A variable fraction (φ_f , typically $\sim 1\%$) of these leak back out as fluorescent photons. The absorbed photon can be lost as radiationless decay (K_d), re-emitted as a fluorescent photon (K_f), quenched by NPQs (K_n), or used for photochemistry (K_p). Photochemistry involves photosystem II (PS2), a photon-capturing enzyme. e^- : Electron. NPQs: Non-photochemical trapping centers. <http://spie.org/newsroom/4725-remote-sensing-of-terrestrial-chlorophyll-fluorescence-from-space>

The future of carbon cycle science: measurements of fluorescence

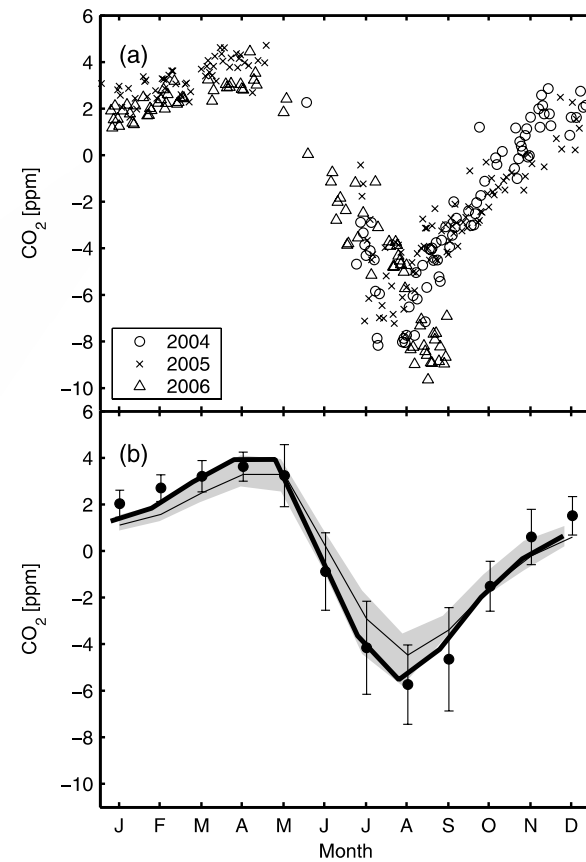


The future of carbon cycle science: measurements of fluorescence



Modeling the CO₂ Seasonal Cycle

- Models have had trouble capturing the seasonal cycle in the boreal region
- Seasonal cycle was not large enough
- Biases the entire global balance of the model

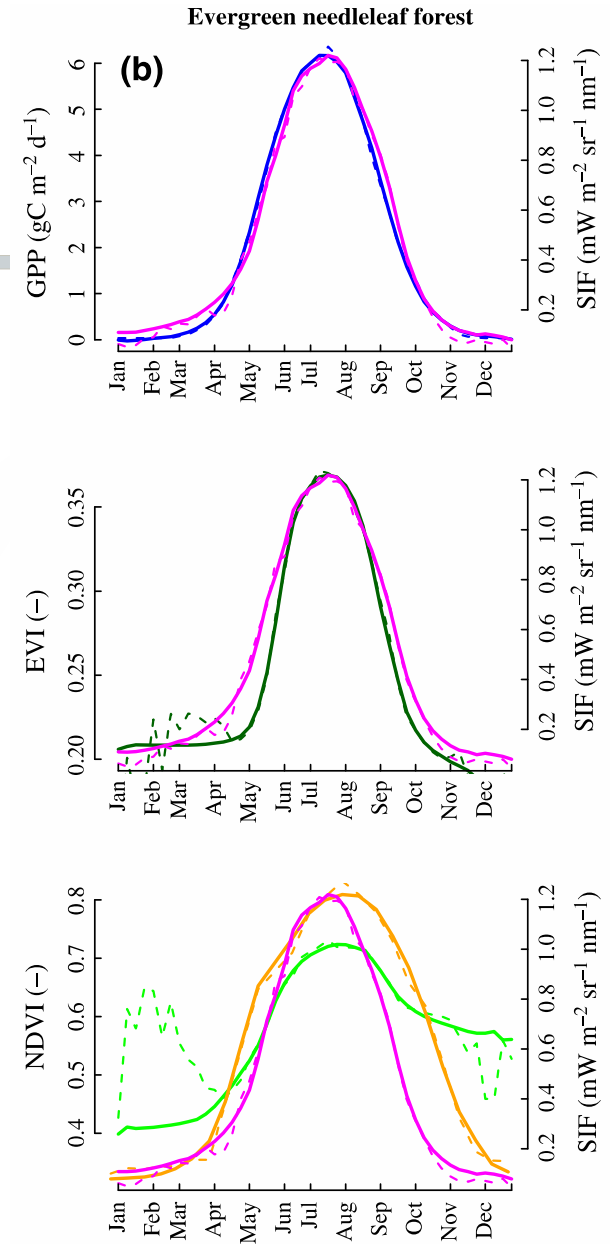


Yang, Z., et al. (2007), Geophys. Res. Lett., 34(12), L12807, doi:10.1029/2007GL029742.

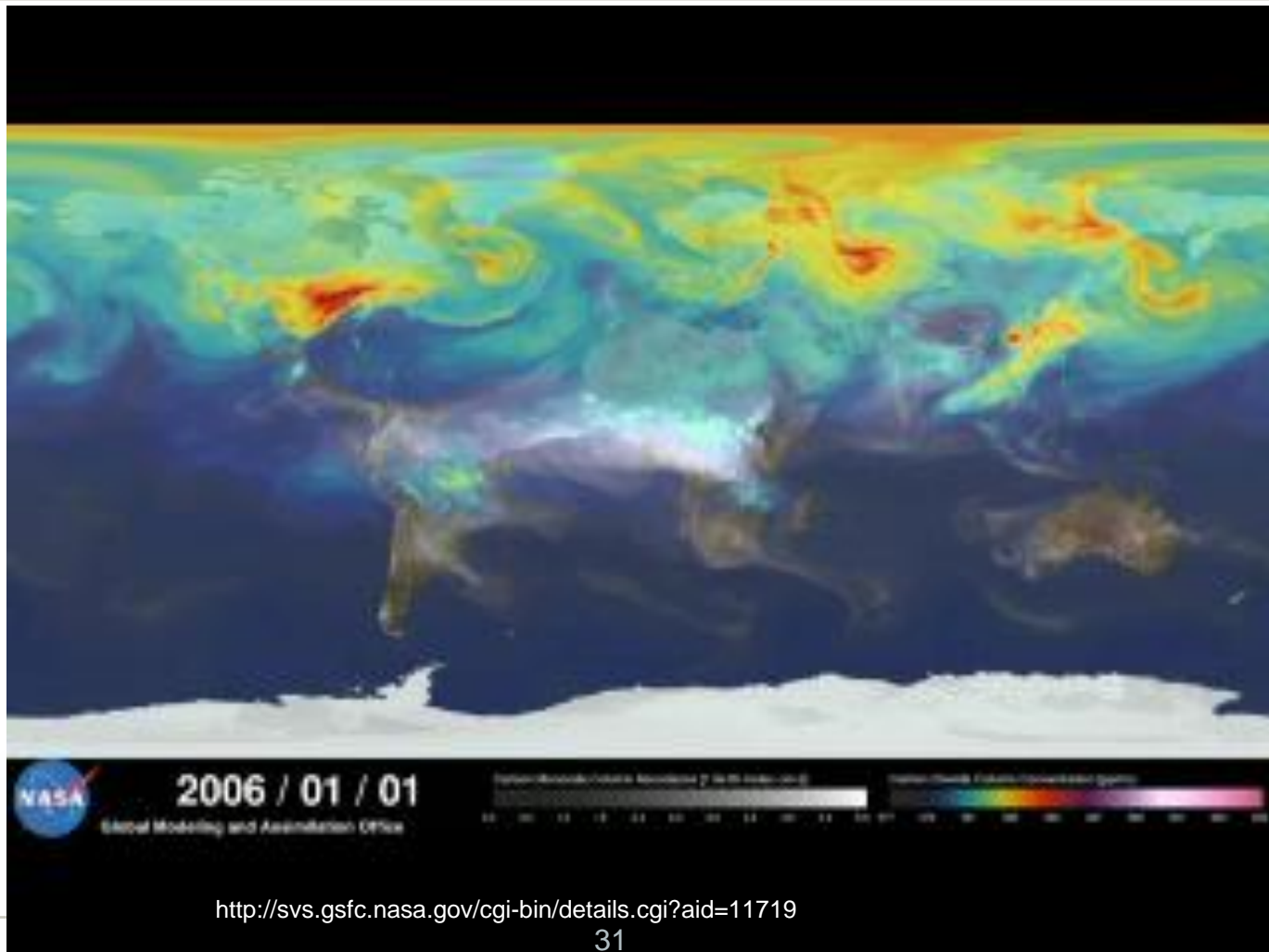
Recent results

- Shows that in Boreal biomes, data feeding models had poor seasonal cycle: late onset and incorrect timing in Fall
- Fluorescence measurements should better match reality (GPP) and could be readily assimilated into models
- Could vastly improve modeled boreal forest seasonal cycle

— EVI (—) — GPP (gC m⁻² d⁻¹) — NDVI3g (—)
— SIF (mW m⁻² sr⁻¹ nm⁻¹) — NDVI MODIS (—)



The future of carbon cycle science: modeling



Thank you!
