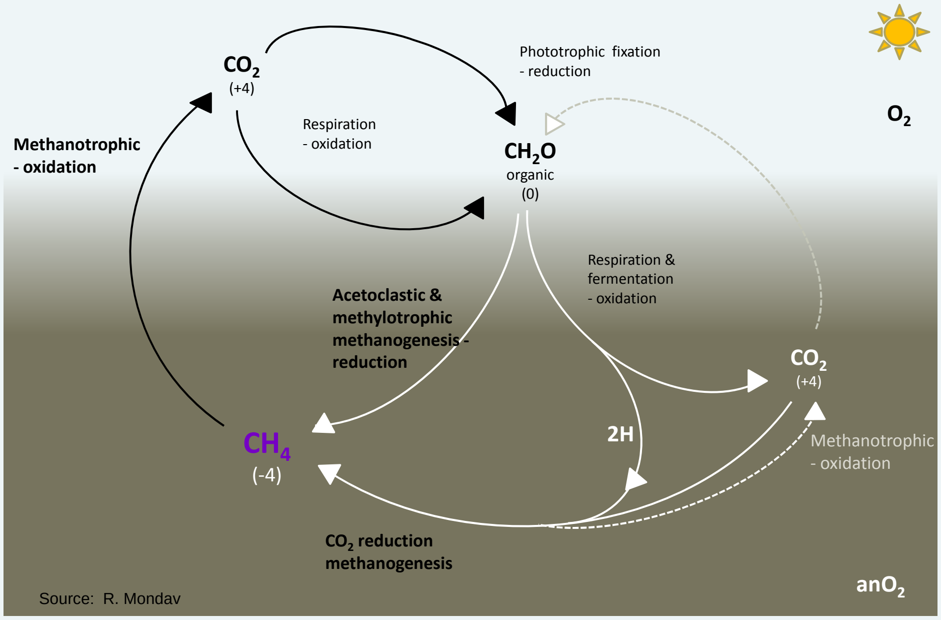
Carbon-cycle Biogeochemistry

SWES 410/510
March 7, 2014

I. Simplified C-cycle
II. Carbon dioxide
III. Methane

Simplified carbon cycle



CO_2
(+4)

Phototrophic fixation
- reduction

O_2

Respiration
- oxidation

Methanotrophic
- oxidation

CH_2O
organic
(0)

Respiration &
fermentation
- oxidation

Acetoclastic &
methylotrophic
methanogenesis -
reduction

CO_2
(+4)

2H

Methanotrophic
- oxidation

CH_4
(-4)

CO_2 reduction
methanogenesis

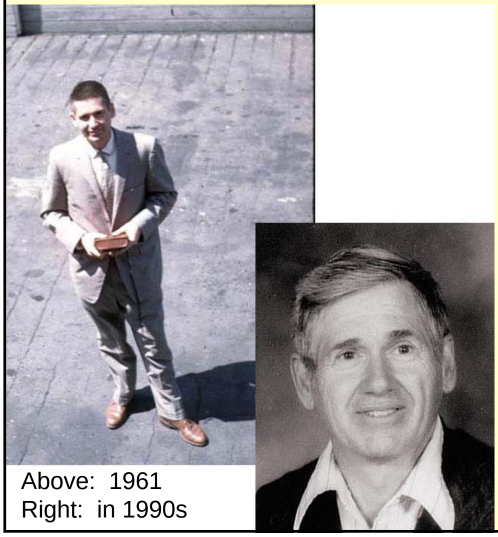
anO$_2$

Source: R. Mondav

A pressing question

What is the fate of all that fossil fuel CO_2?   Atmosphere? Ocean?

Charles David Keeling.



Above: 1961
Right: in 1990s

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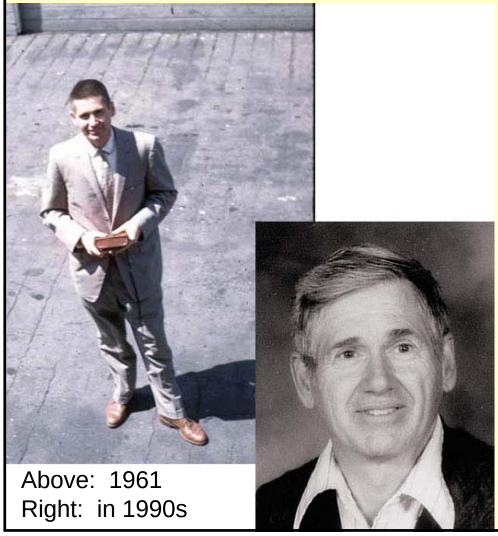

Above: 1961
Right: in 1990s

Made the first high-accuracy measurements of atmospheric CO_2 in a sufficiently remote place (the south pole) to be minimally influenced by transients or local biases.

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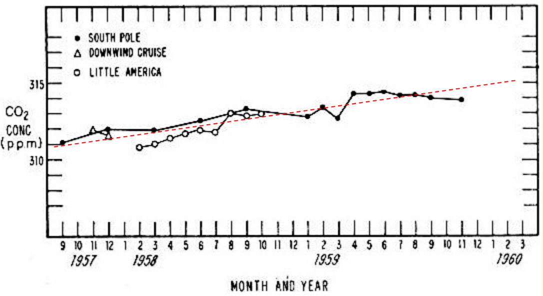

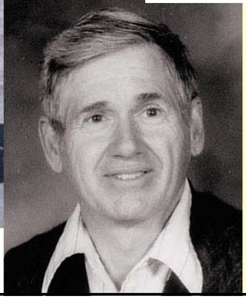

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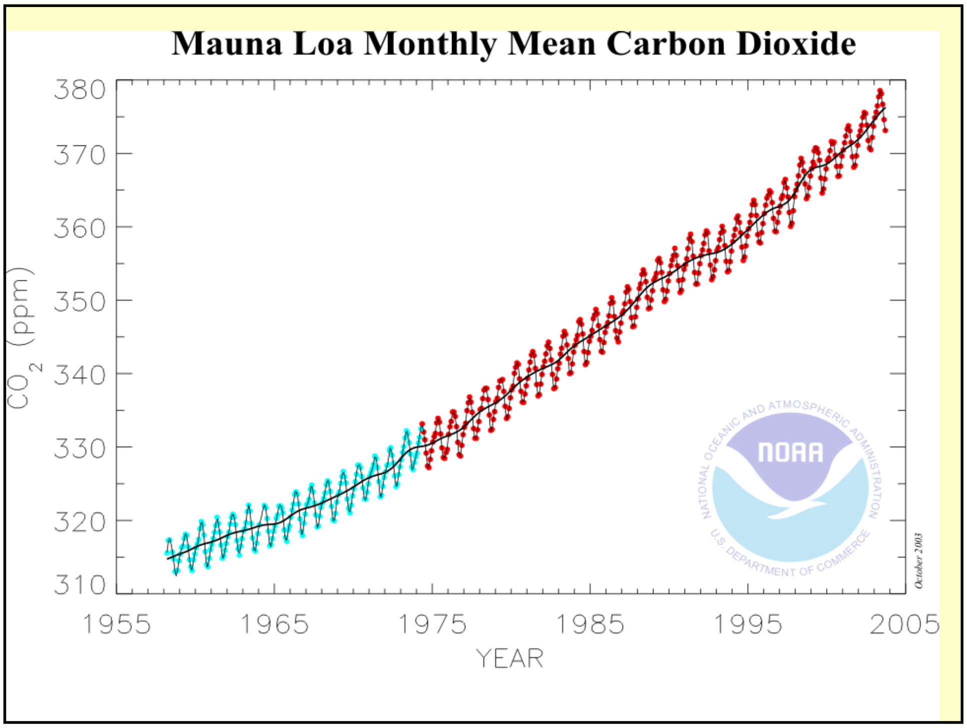
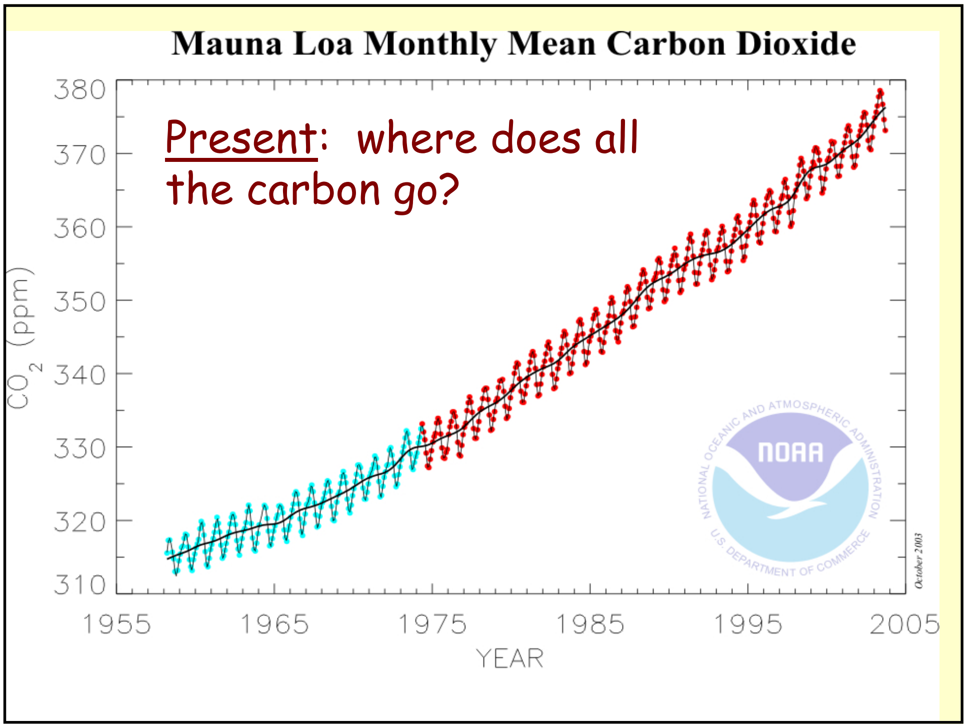
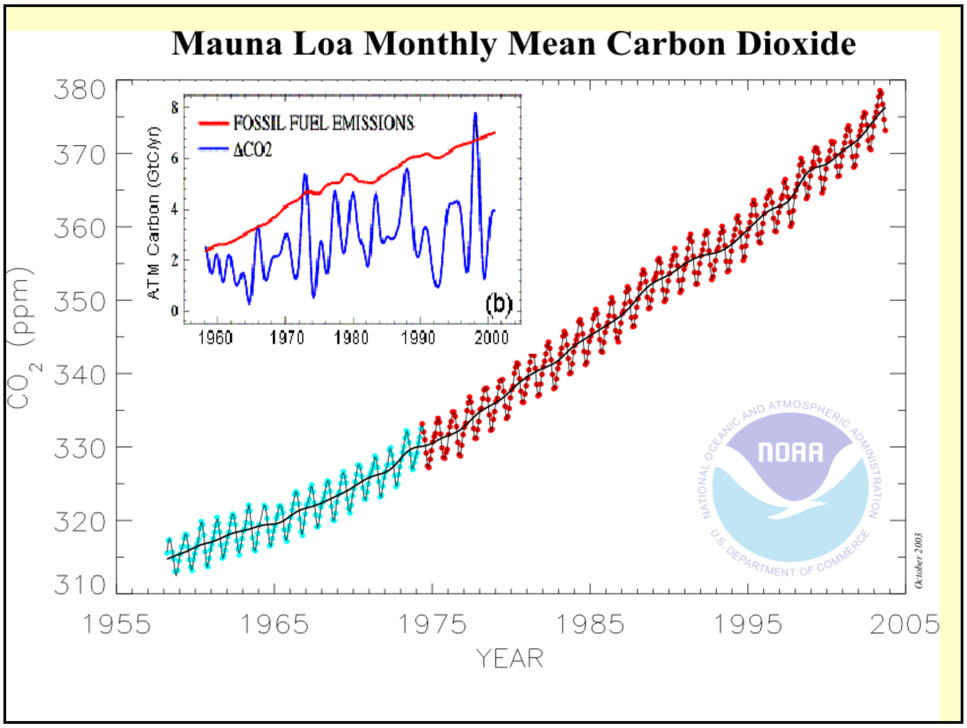
A rising level of CO_2 in the atmosphere was first demonstrated in 1960 in Antarctica, visible after only two years of measurements. (Keeling, 1960)

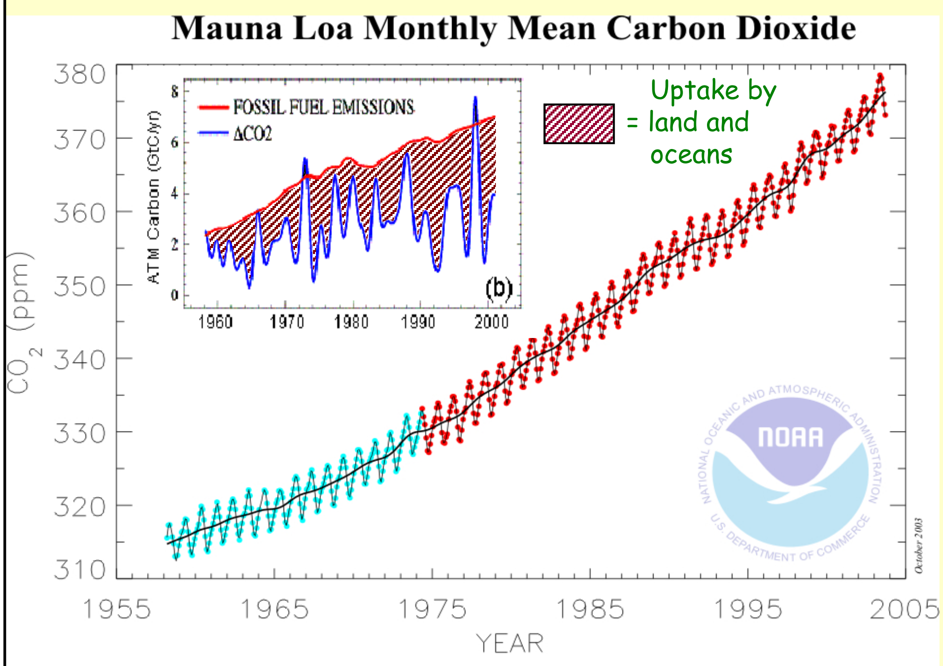


Mauna Loa Monthly Mean Carbon Dioxide



Present: where does all the carbon go?





▨ = Uptake by land and oceans

Questions about carbon uptake

<u>Part II.</u> Where does all the carbon go?

1. How do we tell how much is going into the land, and how much is going into the ocean?
2. What causes the high interannual variability in atm. CO2? (the wiggles?)

<u>Part III.</u> What about the future?

Reading: Latest update from IPCC (2013)

1. How much CO_2 is going into the land, and how much is going into the ocean?

Methods: Atmospheric “Inverse modeling”

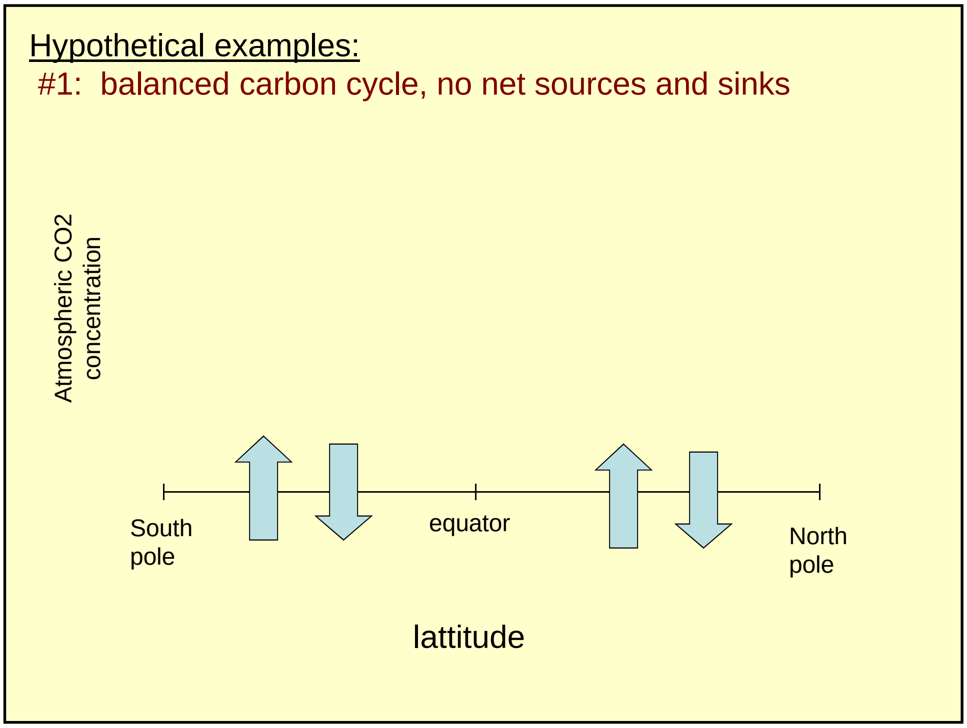
(a) combine global atmospheric CO2 data with global model of atmospheric transport
  - Identify where CO2 is added and removed to/from atmosphere
  - Gurney et al., 2002 - simple example

(b) Multi-tracer inversions

example: combine CO_2 and O_2
(Ralph Keeling et al)

What is “inverse modeling”?

- Imagine a model that, given a pattern of sources and sinks of CO2 on the earth’s surface, predicts a resultant pattern of concentrations in the atmosphere
- Run this model backward (i.e. “invert” the model) to get the pattern of sources and sinks from the atmospheric concentrations



Hypothetical examples:

#1: balanced carbon cycle, no net sources and sinks

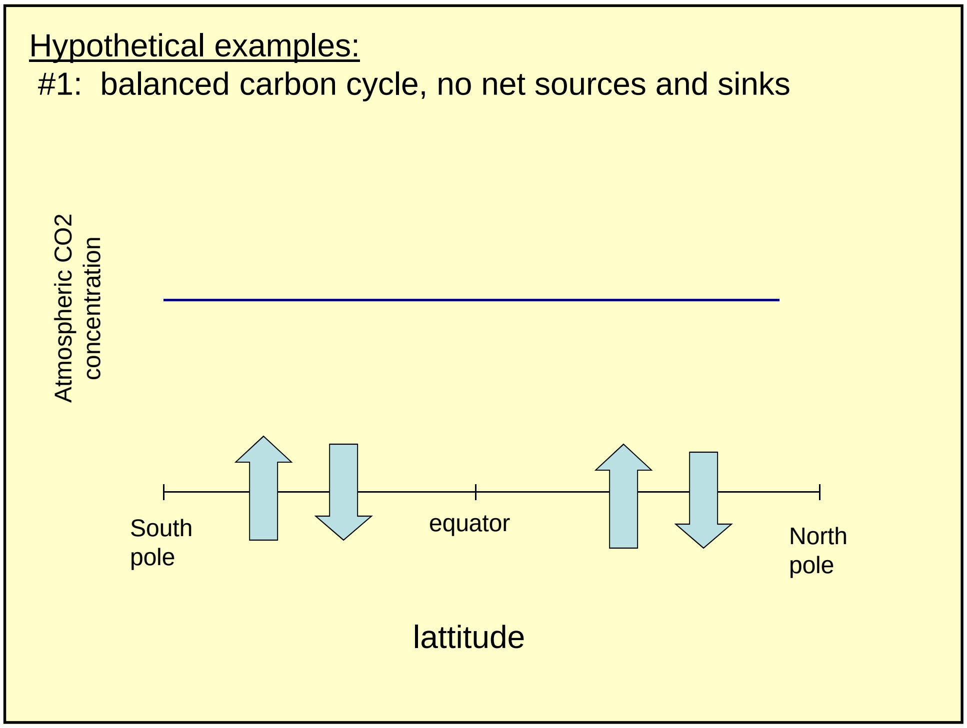
Atmospheric CO2 concentration

South pole

equator

North pole

lattitude



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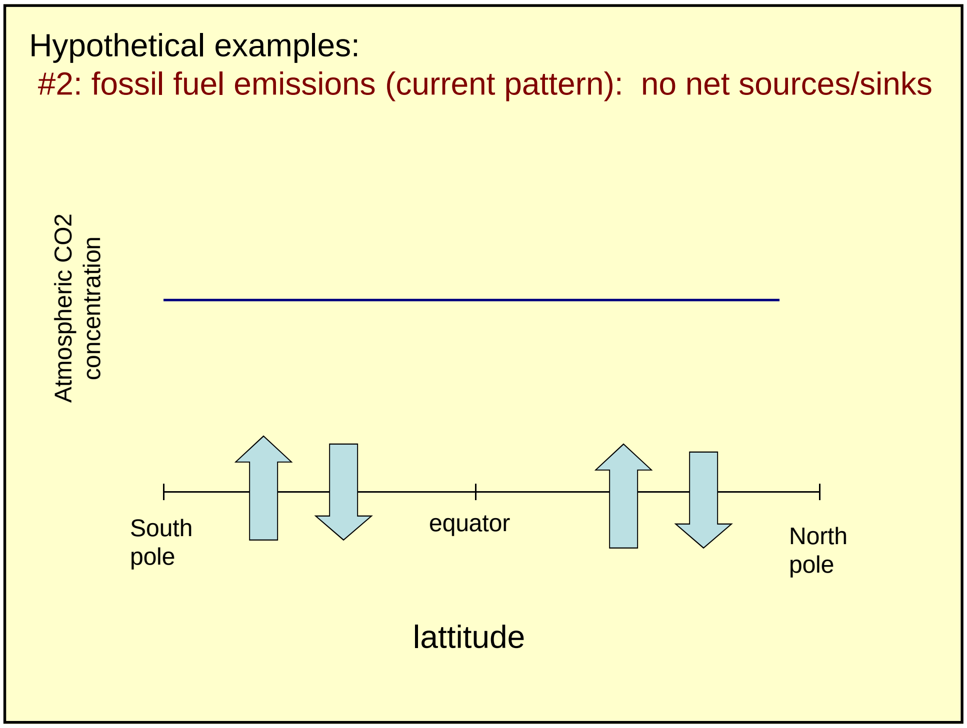
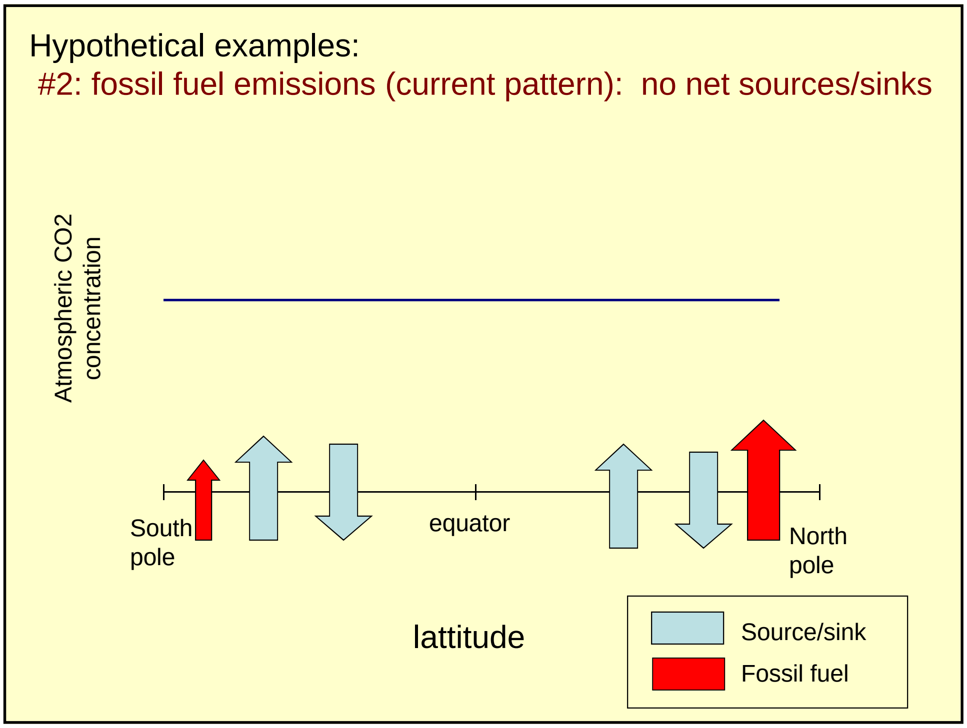


Hypothetical examples:

#2: fossil fuel emissions (current pattern): no net sources/sinks



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🟦 Source/sink
🟥 Fossil fuel

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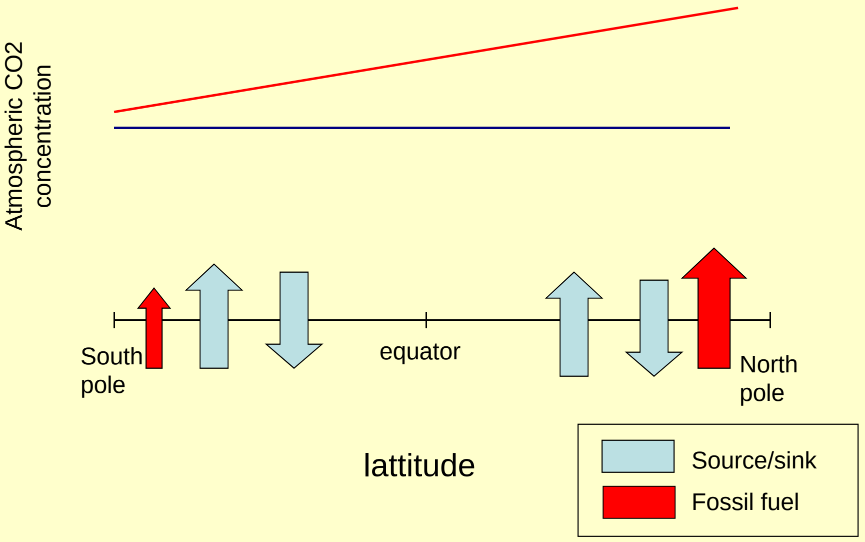
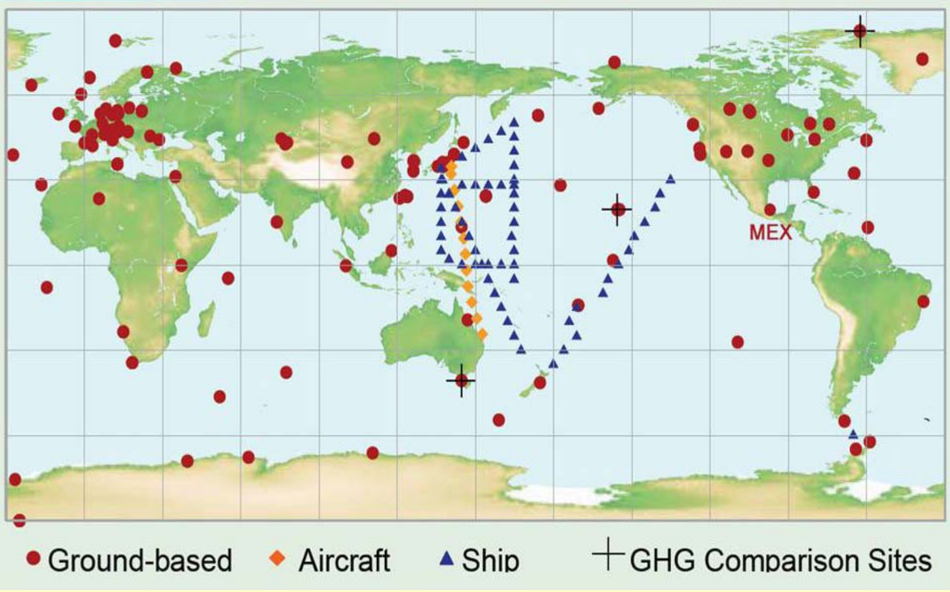
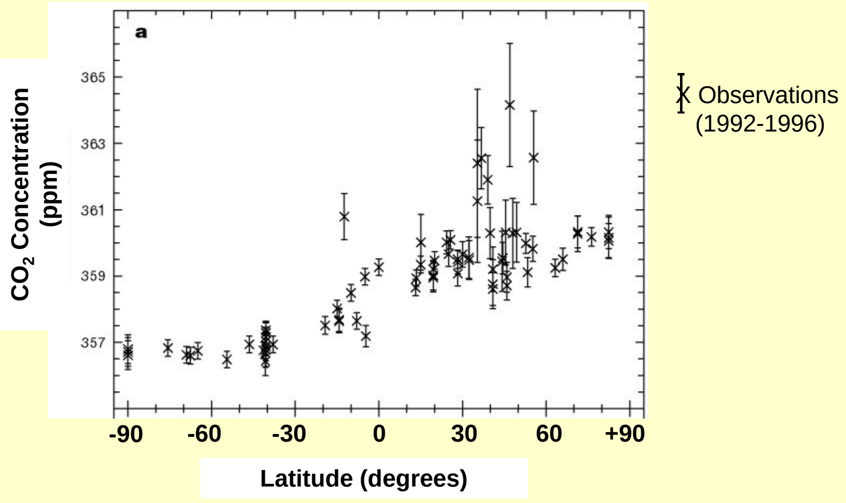


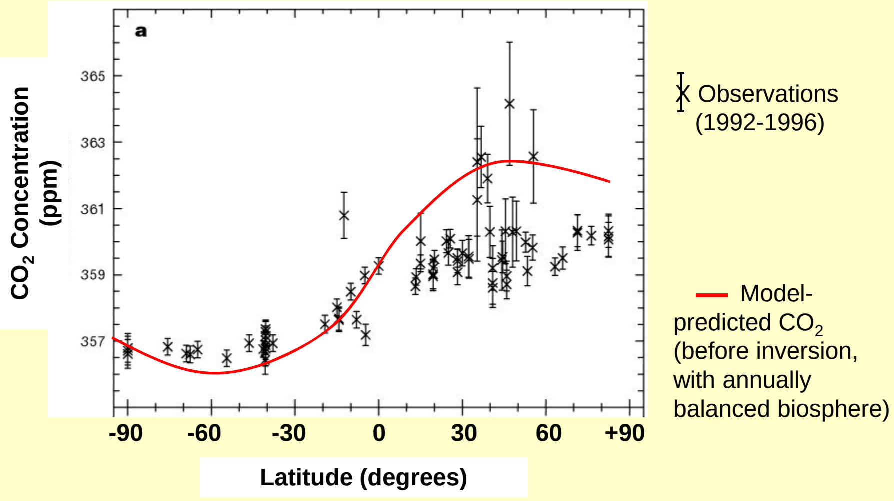
Global CO_2 observation network



NOAA Global Monitoring Division (GMD)



Gurney et al. (2002)



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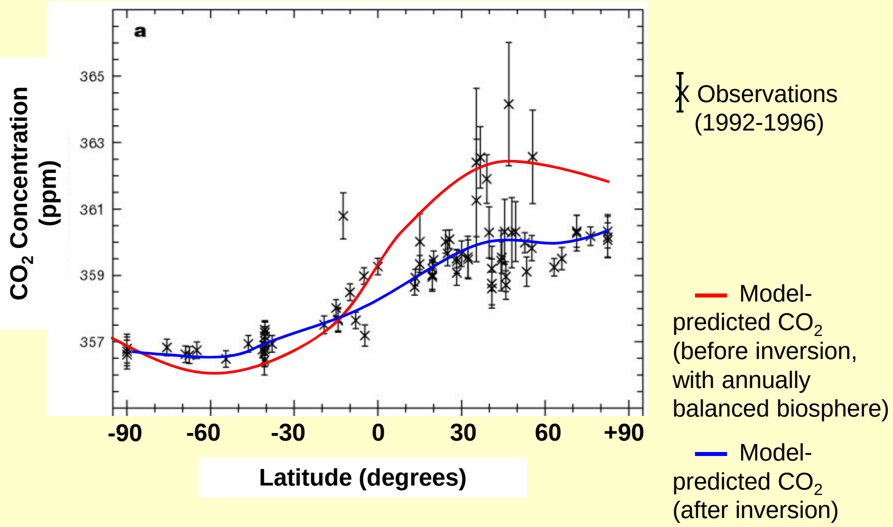

X Observations (1992-1996)

Model-predicted CO$_2$ (before inversion, with annually balanced biosphere)

Model-predicted CO$_2$ (after inversion)

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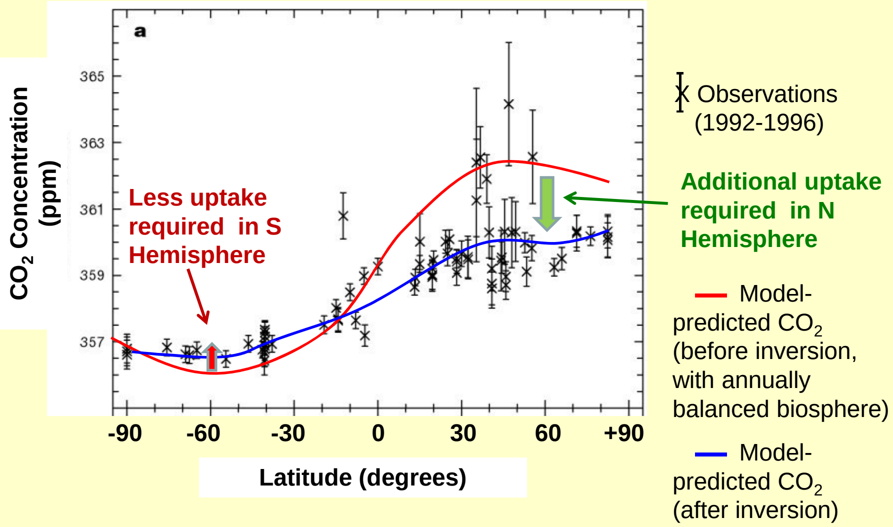

Less uptake required in S Hemisphere

Additional uptake required in N Hemisphere

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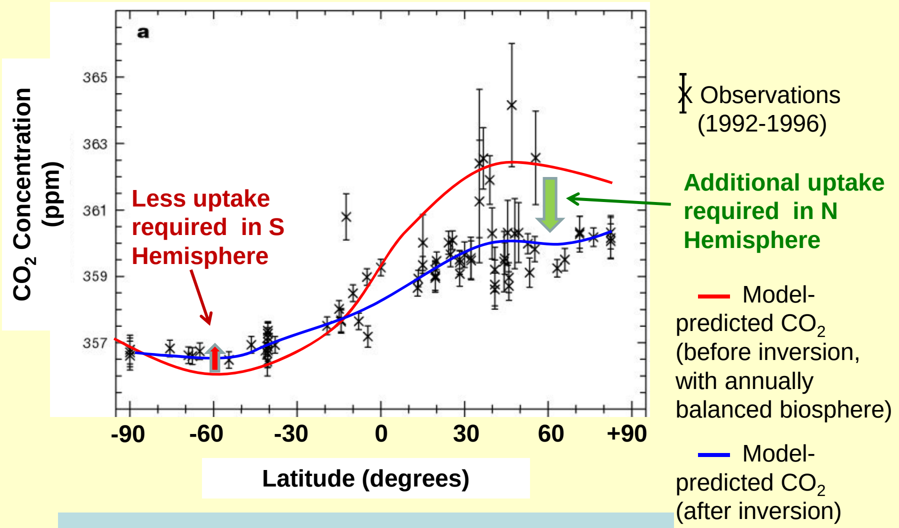

Conclusions:

- Given a NH source (fossil fuel), we require a NH sink to balance
- NH terrestrial biosphere a significant sink

Gurney et al. (2002)

Inverse model example (b): CO2 & O2

Partitioning terrestrial and oceanic carbon exchange:
a multiple tracer approach

A) Aerobic Biological CO_2 exchange is intimately coupled with O_2 exchange: photosynthesis produces O_2, respiration consumes it

Recall: Aerobic Carbon cycle:
Photosynthesis/Resp.: $H_2O + CO_2 \leftrightarrow CH_2O + O_2$

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B) Ocean-atmosphere CO_2 exchange is physical dissolution, so oceanic CO_2 uptake does not influence atmospheric O_2

C) Thus, the relationship between the CO_2 and O_2 content of the atmosphere provides *a fingerprint* of biological and oceanic CO_2 exchanges

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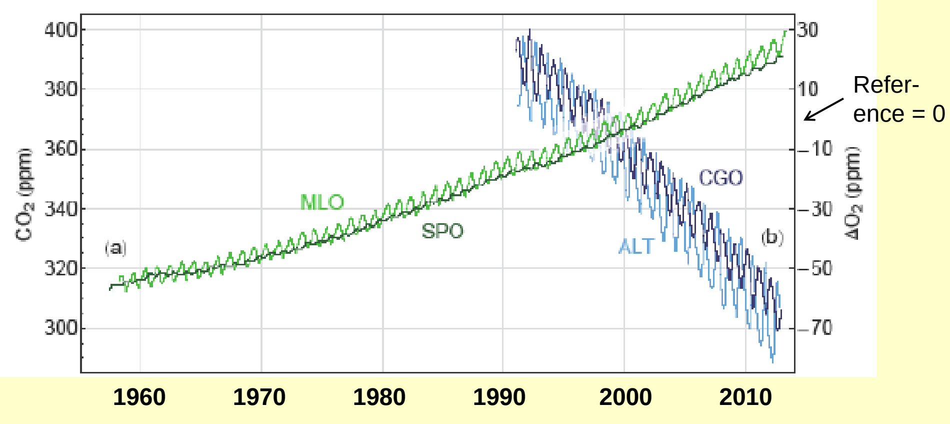
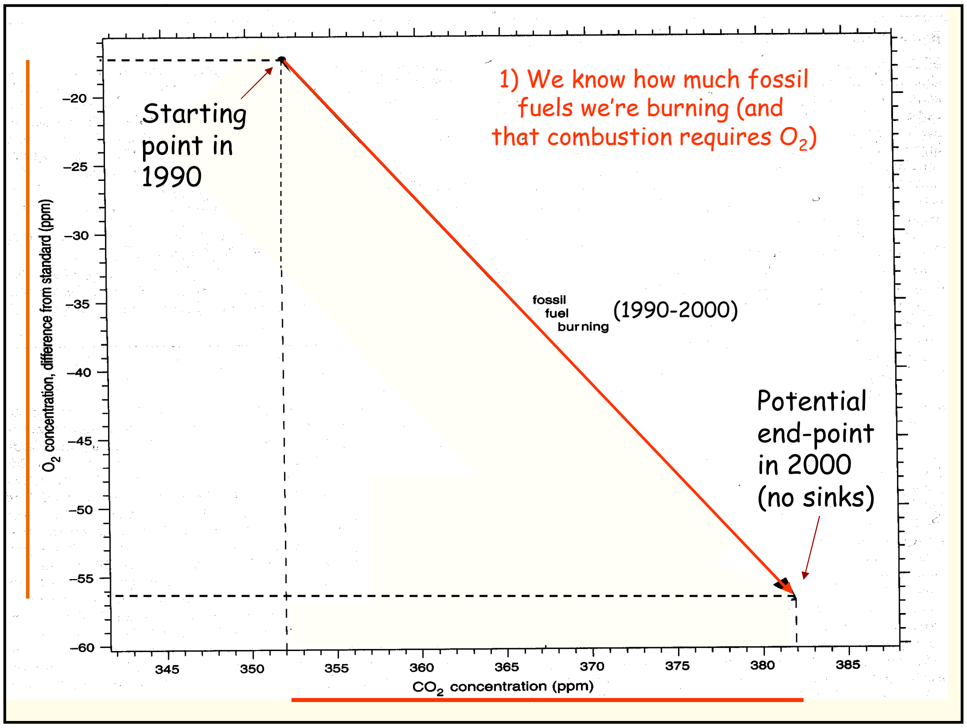


Green = CO_2 Keeling (David) et al. 2005 updated

Blue = O_2 Keeling (Ralph) et al. 1996 updated

IPCC ARG Draft (2013), Ch. 6)

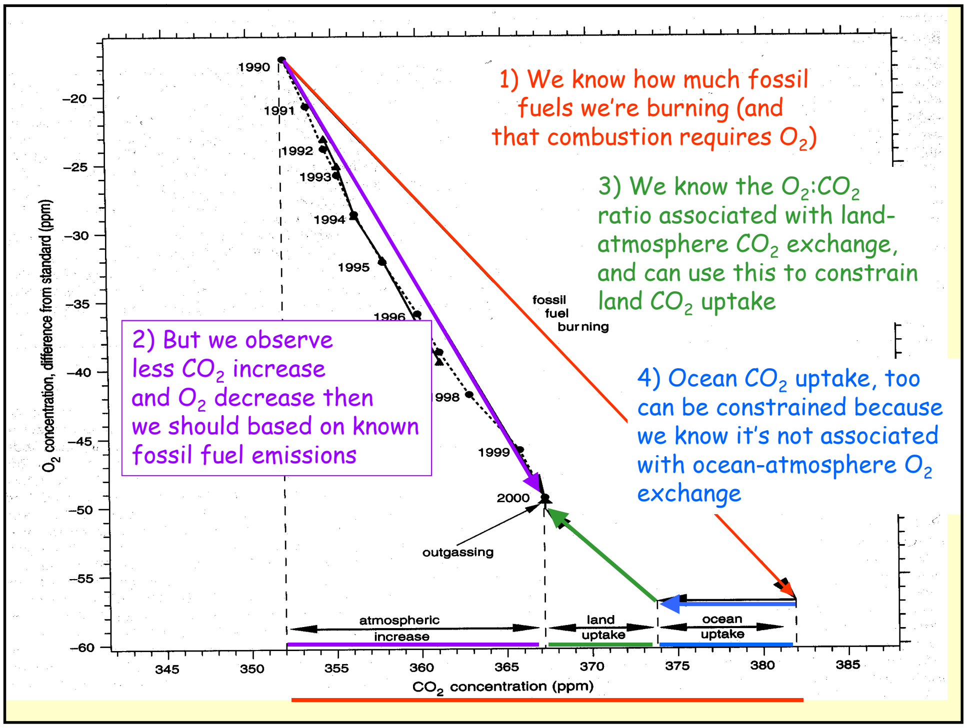


Starting point in 1990

1) We know how much fossil fuels we're burning (and that combustion requires O_2)

(1990-2000)

Potential end-point in 2000 (no sinks)

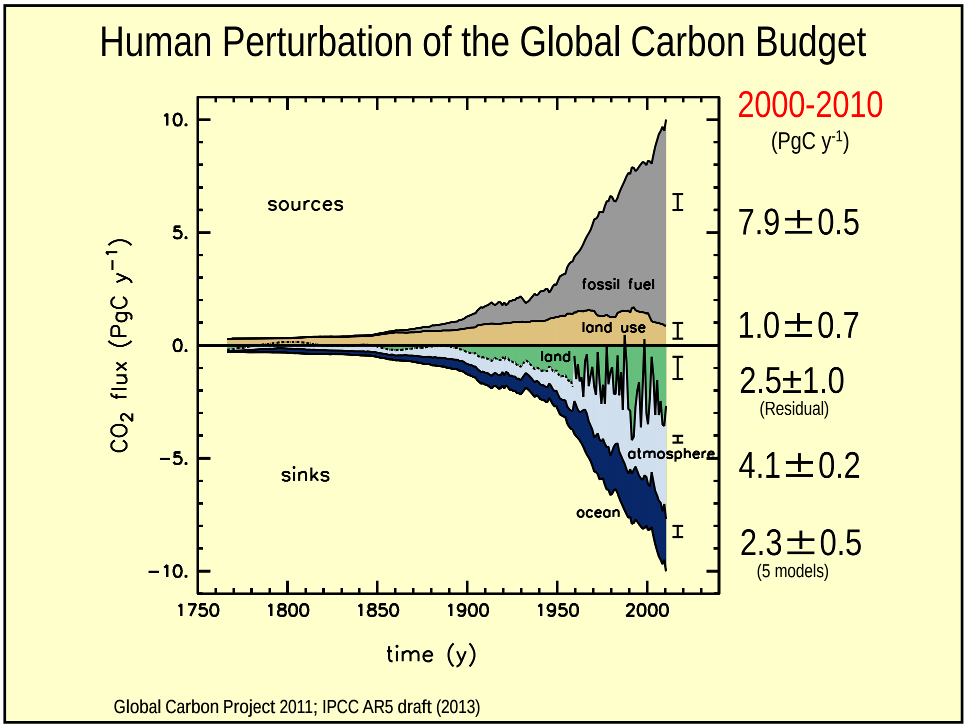


1) We know how much fossil fuels we're burning (and that combustion requires O_2)

2) But we observe less CO_2 increase and O_2 decrease then we should based on known fossil fuel emissions

3) We know the O_2:CO_2 ratio associated with land-atmosphere CO_2 exchange, and can use this to constrain land CO_2 uptake

4) Ocean CO_2 uptake, too can be constrained because we know it's not associated with ocean-atmosphere O_2 exchange



Human Perturbation of the Global Carbon Budget

2000-2010

(PgC y^{-1})

7.9±0.5

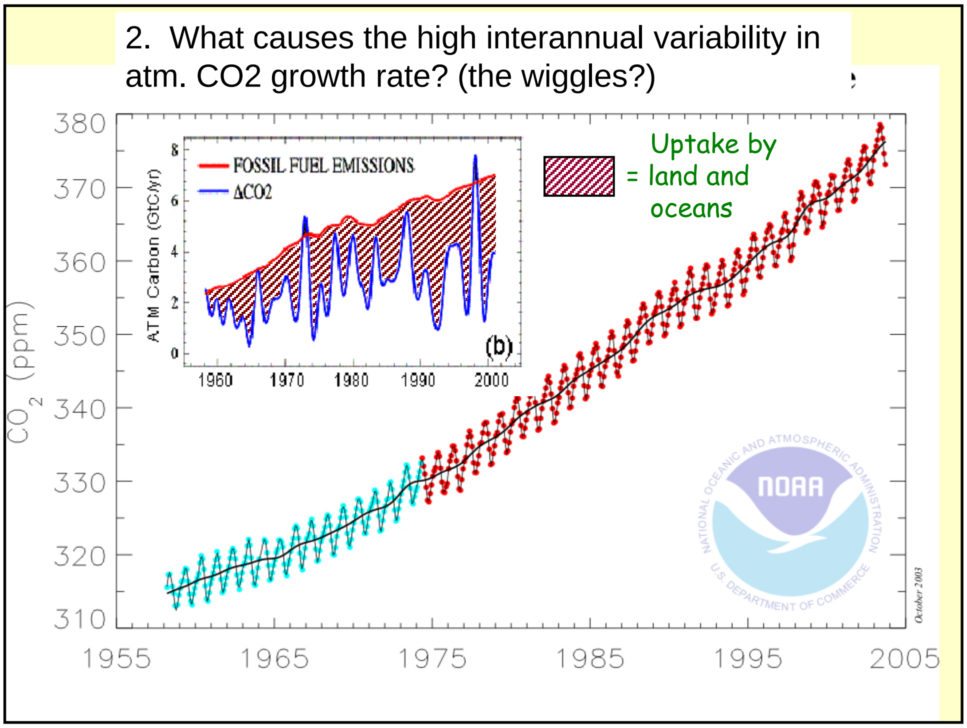
1.0±0.7

2.5±1.0
(Residual)

4.1±0.2

2.3±0.5
(5 models)

Global Carbon Project 2011; IPCC AR5 draft (2013)



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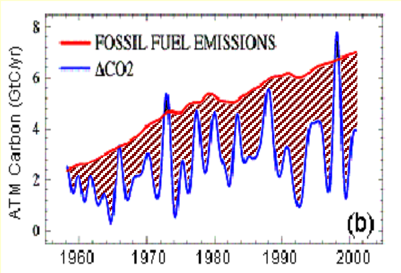

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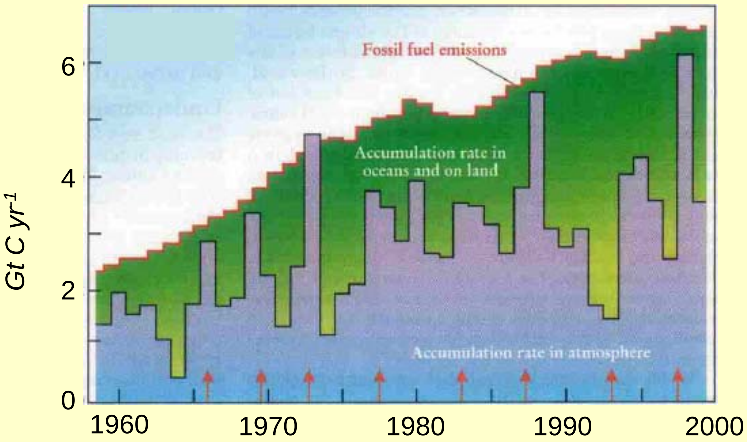

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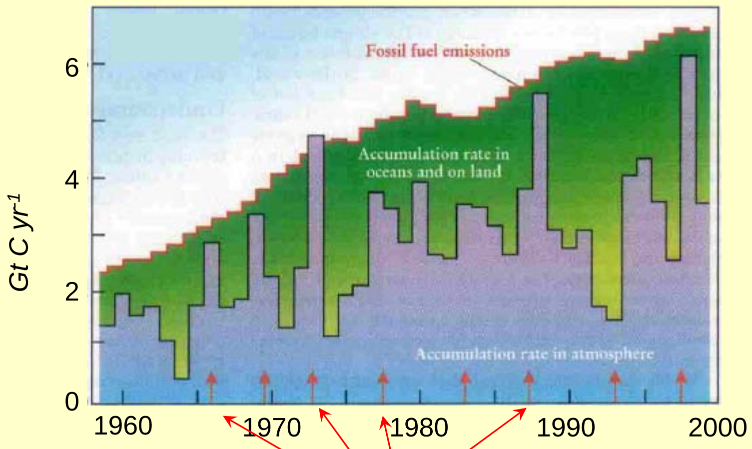

El Niño years

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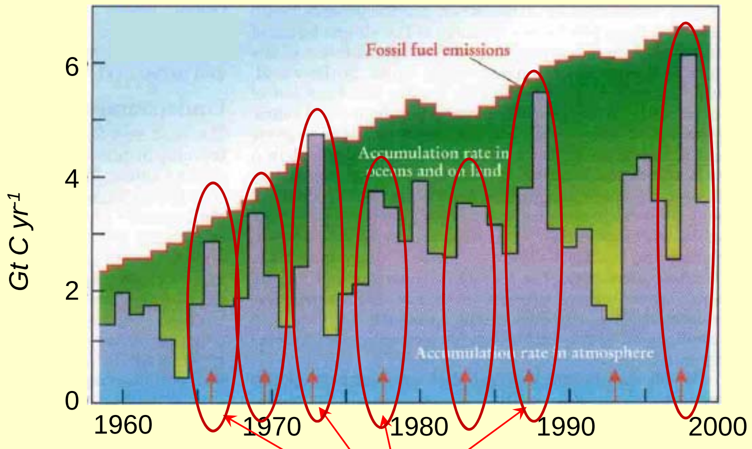

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Consistent spike in atm. growth rate during El Niño

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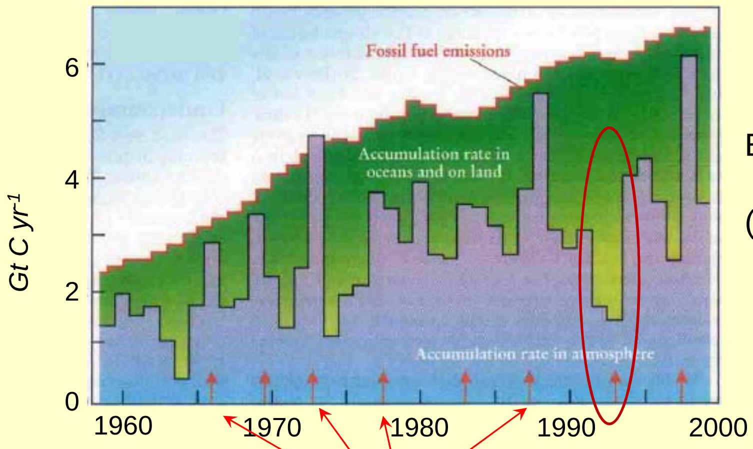

Except
early 90s!
(why?)

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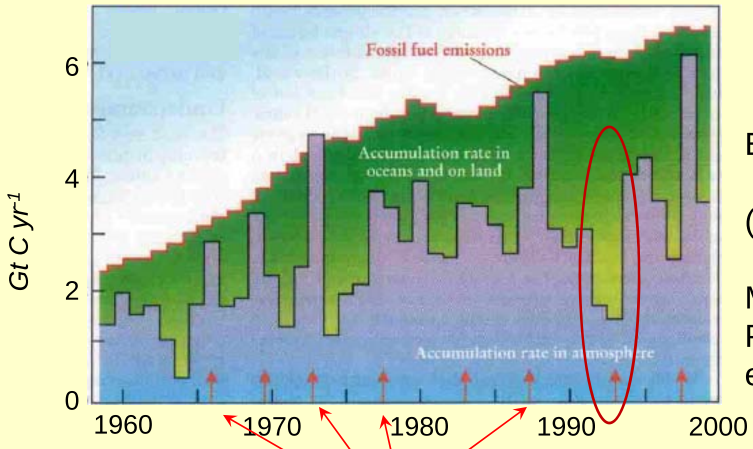

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Mt.
Pinatubo
eruption?

El Niño years

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Part III.
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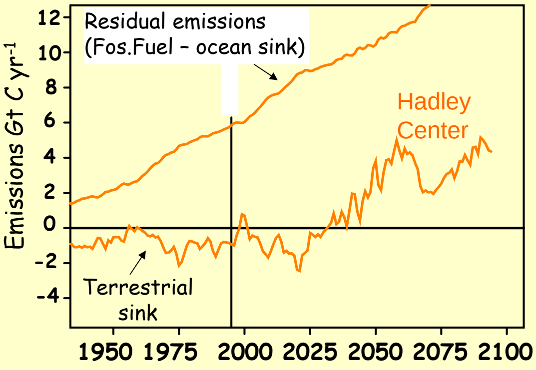
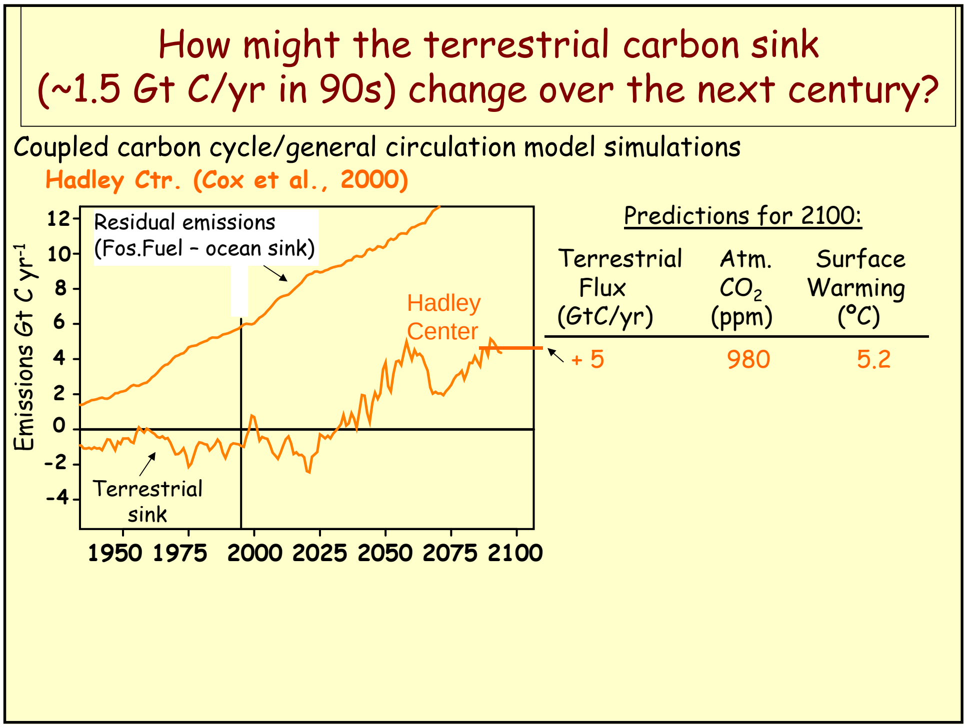
Coupled carbon cycle/general circulation model simulations

Hadley Ctr. (Cox et al., 2000)





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Terrestrial Flux (GtC/yr)	Atm. CO_2 (ppm)	Surface Warming (°C)
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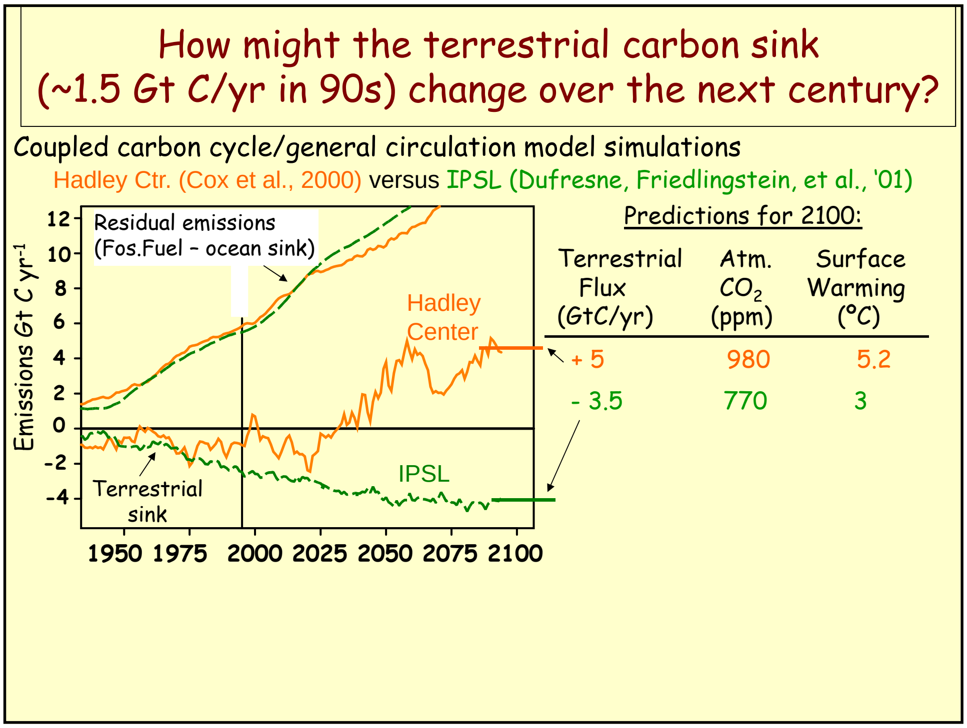

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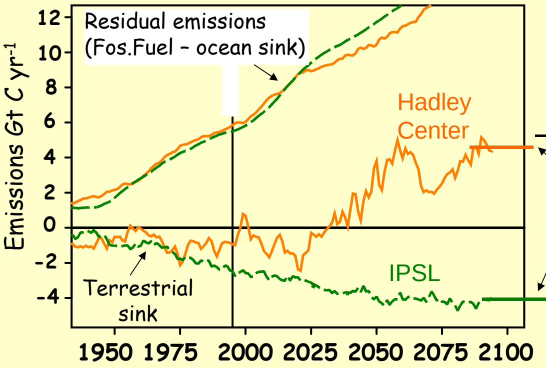

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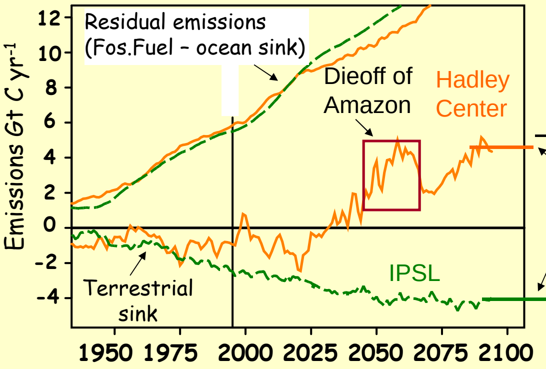

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Key factors driving model difference:
- High sensitivity of soil respiration (Q_{10} = 2) in Orange model
- Strong CO_2 fertilization effect in green model (IPSL)
- Drought-induced Dieoff of Amazon rainforest → savanna

How might the terrestrial carbon sink (~1.5 Gt C/yr in 90s) change over the next century?

Coupled carbon cycle/general circulation model simulations

Now we have full Suite of models that show even wider variation than the first two

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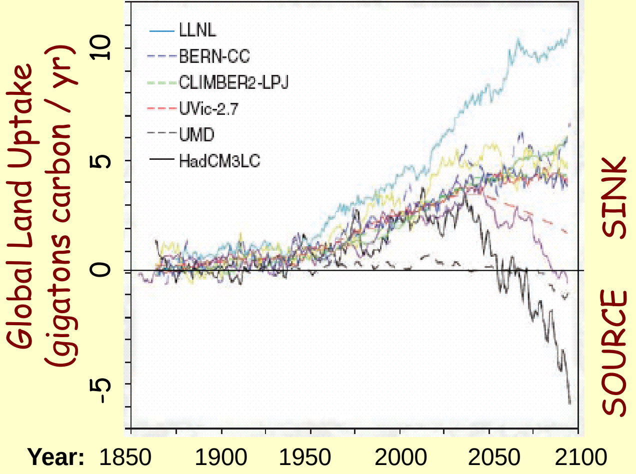
How might the terrestrial carbon sink (~2 Gt C/yr in 90s) change over the next century?

Dynamic Global Vegetation Models of terrestrial carbon sink show <u>very</u> wide variation



Friedlingstein et al., 2006 (as reported in Purves & Pacala, 2008)

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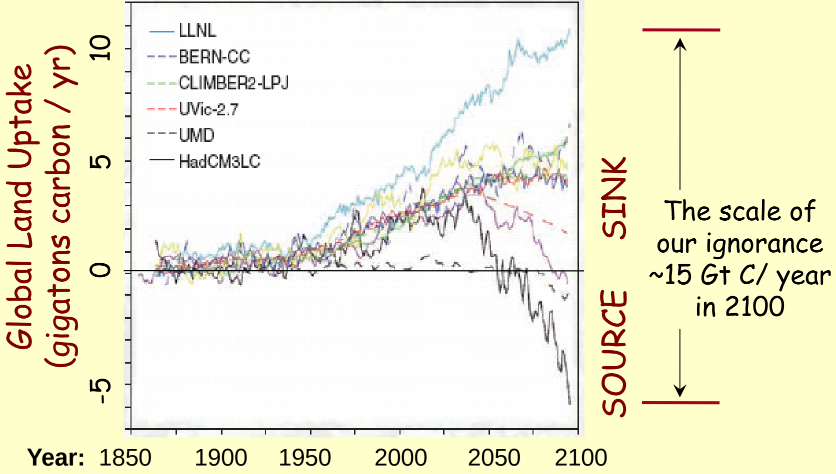

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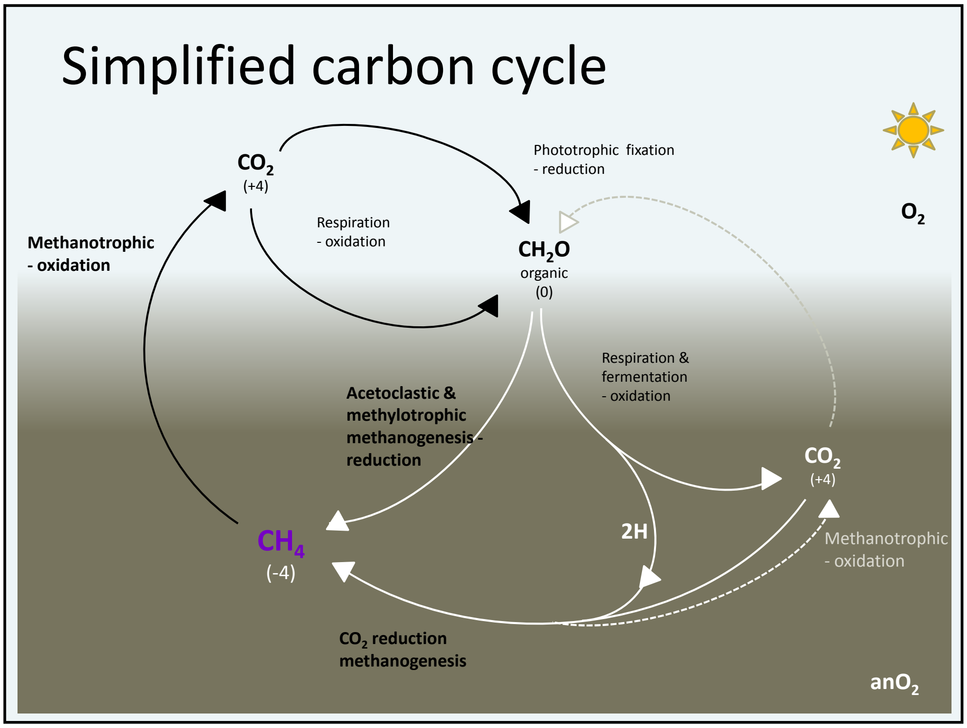
Methane:

1. CH_4 in the carbon cycle
2. The CH_4 “keeling curve” and the great methane slow-down puzzle
3. What is the future of CH_4 emissions



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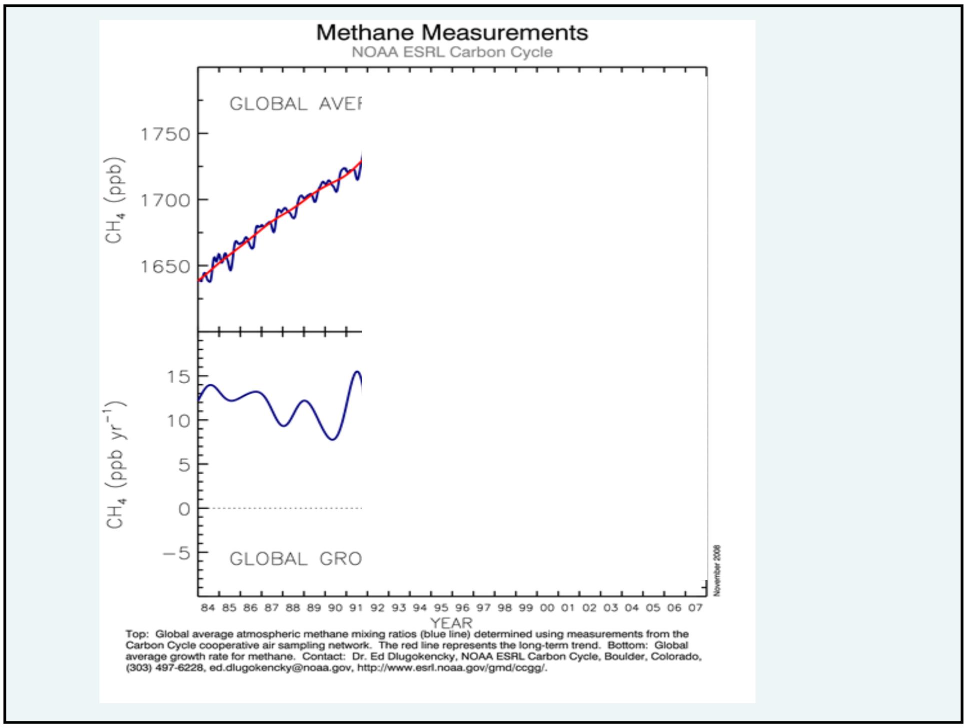
CO_2 reduction
methanogenesis

anO_2



Methane Measurements

NOAA ESRL Carbon Cycle

Top: Global average atmospheric methane mixing ratios (blue line) determined using measurements from the Carbon Cycle cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for methane. Contact: Dr. Ed Dlugokencky, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6228, ed.dlugokencky@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

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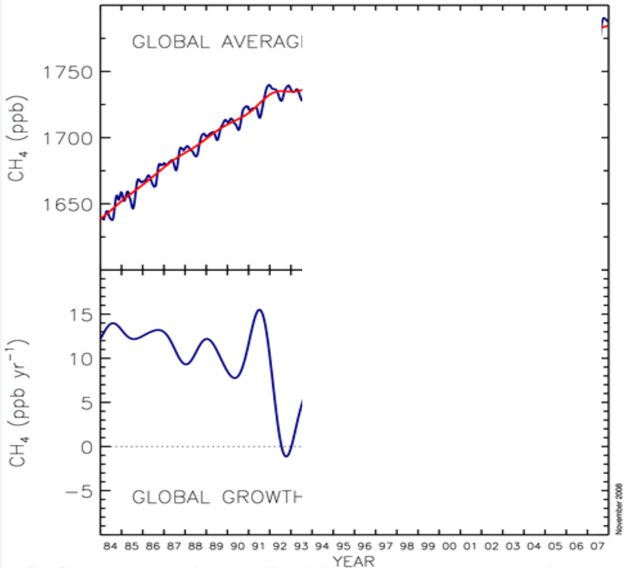

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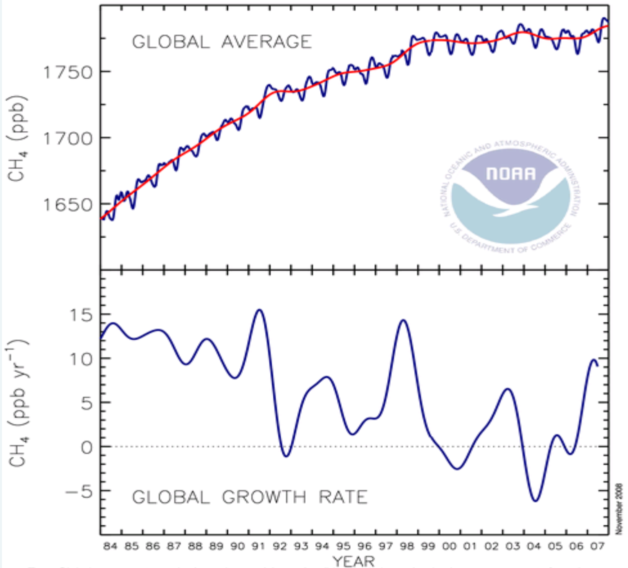

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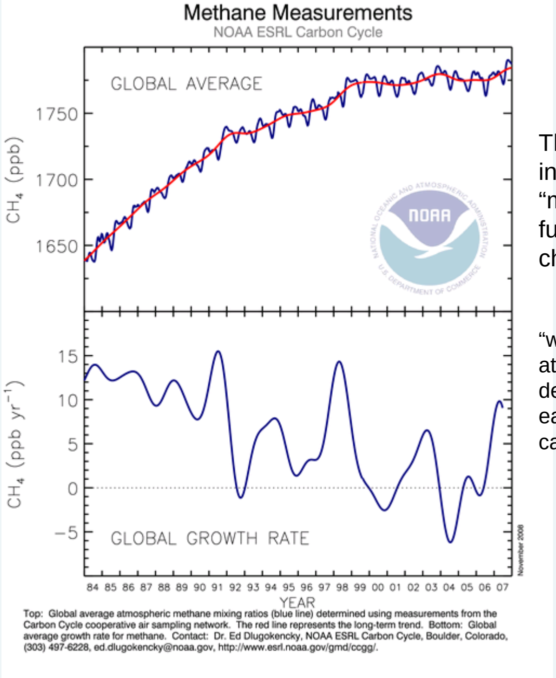

Top: Global average atmospheric methane mixing ratios (blue line) determined using measurements from the Carbon Cycle cooperative air sampling network. The red line represents the long-term trend. Bottom: Global average growth rate for methane. Contact: Dr. Ed Dlugokencky, NOAA ESRL Carbon Cycle, Boulder, Colorado, (303) 497-6228, ed.dlugokencky@noaa.gov, http://www.esrl.noaa.gov/gmd/ccgg/.

The recent slow-down in the increase in atmospheric methane "mak[es] it impossible to predict future concentrations based on past changes"

-- Khalil & Rasmussen 1993

"we have not been able to ascribe atmospheric CH_4 increases and decreases to specific processes. As of early 2000s, we have no predictive capability." -- Reeburgh, 2005

Timeline of Scientific Knowledge about Global Methane

	Atmospheric	**Biological**
1906		**isolation of methane-oxidizing bacteria (Sohngen 1906)**
1948	**atmospheric methane detected (Migeotte 1948)**	
1960s		**systematic research on taxonomy, physiology, biochemistry of methanotrophs (mostly aquatic systems)**
1978	**Begin systematic measurement of global CH_4**	
1981	**First report of upward trend in atmospheric CH_4 (Khalil & Rasmussen 1981)**	
1982		**Survey of 17 ecosystem types (includ. forest, savanna, & alpine meadow) concludes <u>all</u> are methane sources Ecosystem production estimated 910 Tg (!!), atm. lifetime 3.3 years (Sheppard et al. 1982) (faulty measuring method)** **First report of net CH_4 consumption in soil (swamp) (Harriss et al. 1982)**
Mid 80s	**Ice core data reveal longer-term atm. atmospheric trends**	**Keller et al. ('83) measure consistent consumption in forest soils, suggest soils may constitute ~ 1% of global sink** **Data on reaction kinetics for known isolated methanotrophs indicate that atm. concentrations insufficient to support growth (Conrad 1984)**
late 80s		**growing observation database of net methane consumption in soils**
early 90s	**Methane growth rate reported to be declining**	**Long-term methane emission measurements at Sallie's Fen (Crill & Frolking, 1995)**
1991	**Reaction rate for CH_4 + OH is 25% lower, lifetime is 25% higher (12 yr) (Vaghjiani & Ravishankara 1991)**	
1999-2006	**Atmospheric Methane growth rate is ~zero**	**Microbial genomics techniques (especially marine).** **Plants produce methane aerobically!? (Keppler et al. 2006)**

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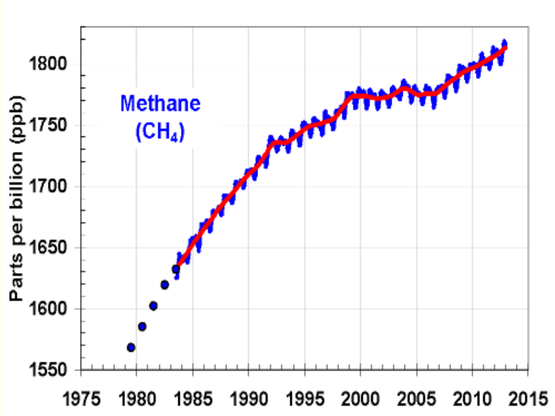
Understanding the global methane cycle: an outstanding challenge of biogeochemistry

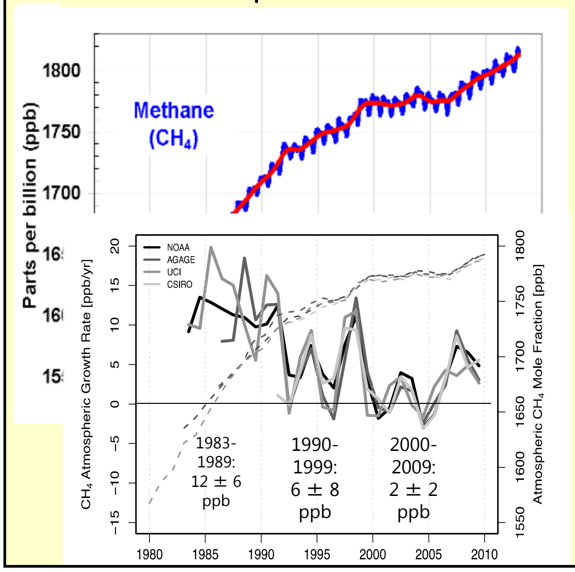
Atmospheric methane



NOAA, 2013

Understanding the global methane cycle: an outstanding challenge of biogeochemistry

Atmospheric methane



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- Slowdown of atmospheric growth rate before 2005
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Kirschke et al. 2013, Nature Geoscience; Data from NOAA, CSIRO, AGAGE, UCI atmospheric networks

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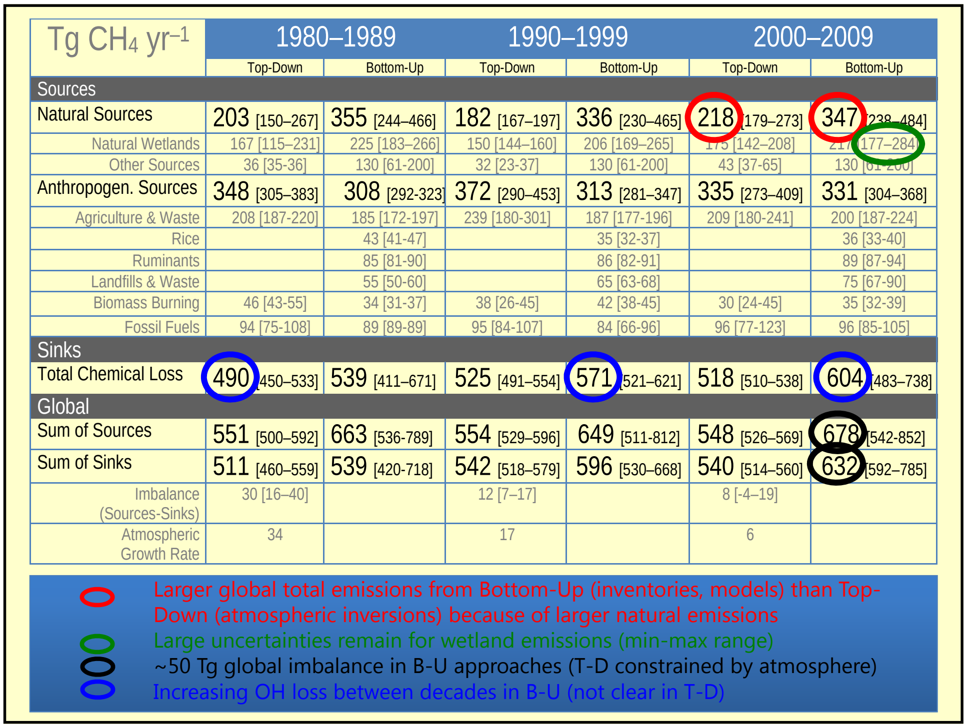
Tg CH$_4$ yr^{-1}	1980–1989		1990–1999		2000–2009	
	Top-Down	Bottom-Up	Top-Down	Bottom-Up	Top-Down	Bottom-Up
Sources						
Natural Sources	203 [150–267]	355 [244–466]	182 [167–197]	336 [230–465]	218 [179–273]	347 [238–484]
Natural Wetlands	167 [115–231]	225 [183–266]	150 [144–160]	206 [169–265]	175 [142–208]	217 [177–284]
Other Sources	36 [35-36]	130 [61-200]	32 [23-37]	130 [61-200]	43 [37-65]	130 [61-200]
Anthropogen. Sources	348 [305–383]	308 [292-323]	372 [290–453]	313 [281–347]	335 [273–409]	331 [304–368]
Agriculture & Waste	208 [187-220]	185 [172-197]	239 [180-301]	187 [177-196]	209 [180-241]	200 [187-224]
Rice		43 [41-47]		35 [32-37]		36 [33-40]
Ruminants		85 [81-90]		86 [82-91]		89 [87-94]
Landfills & Waste		55 [50-60]		65 [63-68]		75 [67-90]
Biomass Burning	46 [43-55]	34 [31-37]	38 [26-45]	42 [38-45]	30 [24-45]	35 [32-39]
Fossil Fuels	94 [75-108]	89 [89-89]	95 [84-107]	84 [66-96]	96 [77-123]	96 [85-105]
Sinks						
Total Chemical Loss	490 [450–533]	539 [411–671]	525 [491–554]	571 [521–621]	518 [510–538]	604 [483–738]
Global						
Sum of Sources	551 [500–592]	663 [536-789]	554 [529–596]	649 [511-812]	548 [526–569]	678 [542-852]
Sum of Sinks	511 [460–559]	539 [420-718]	542 [518–579]	596 [530–668]	540 [514–560]	632 [592–785]
Imbalance (Sources-Sinks)	30 [16–40]		12 [7–17]		8 [-4–19]	
Atmospheric Growth Rate	34		17		6	



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○ Larger global total emissions from Bottom-Up (inventories, models) than Top-Down (atmospheric inversions) because of larger natural emissions

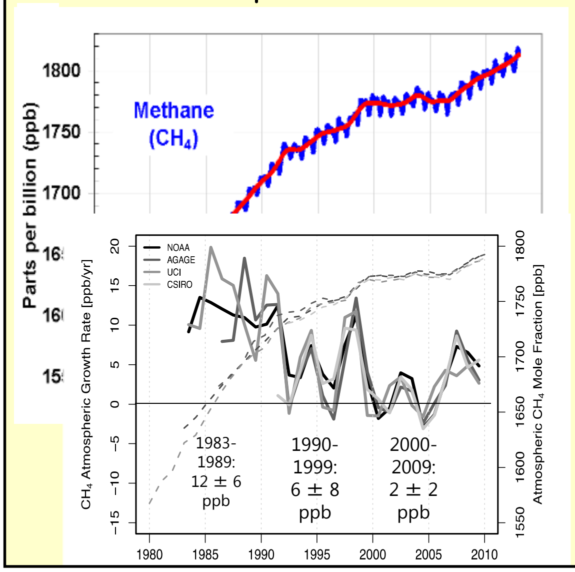
○ Large uncertainties remain for wetland emissions (min-max range)

○ ~50 Tg global imbalance in B-U approaches (T-D constrained by atmosphere)

○ Increasing OH loss between decades in B-U (not clear in T-D)

Understanding the global methane cycle: an outstanding challenge of biogeochemistry

Atmospheric methane



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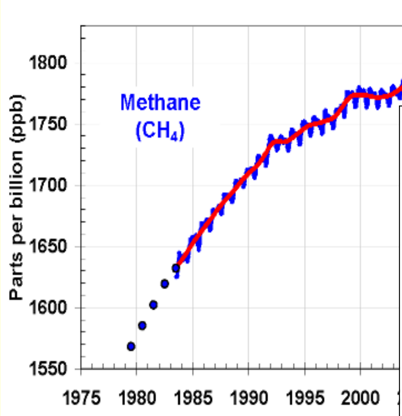
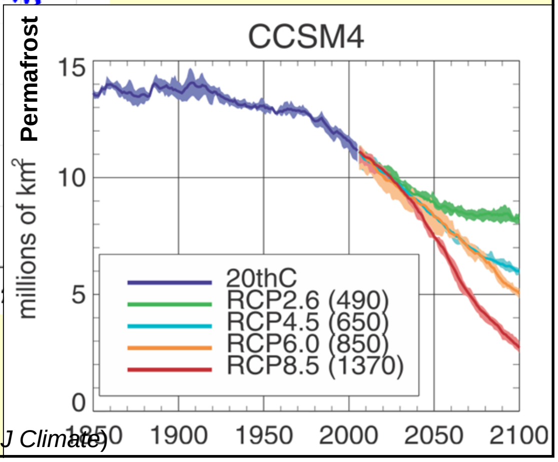
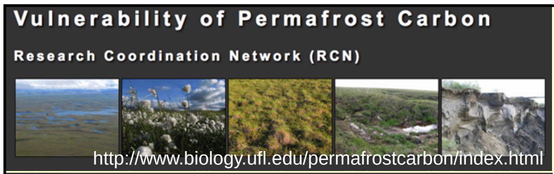


NOAA, 2013

An even bigger challenge for the future:



Lawrence et al. (2012, *J Climate*)



Vulnerability of Permafrost Carbon

Research Coordination Network (RCN)

http://www.biology.ufl.edu/permafrostcarbon/index.html

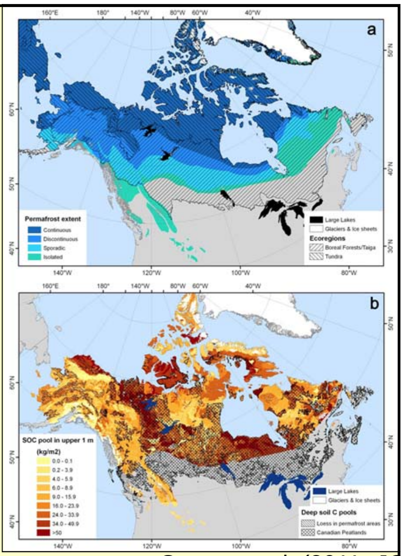
COMMENT

32 | NATURE | VOL 480 | 1 DECEMBER 2011

Abrupt thaw, as seen here in Alaska's Noatak National Preserve, causes the land to collapse, accelerating permafrost degradation and carbon release.

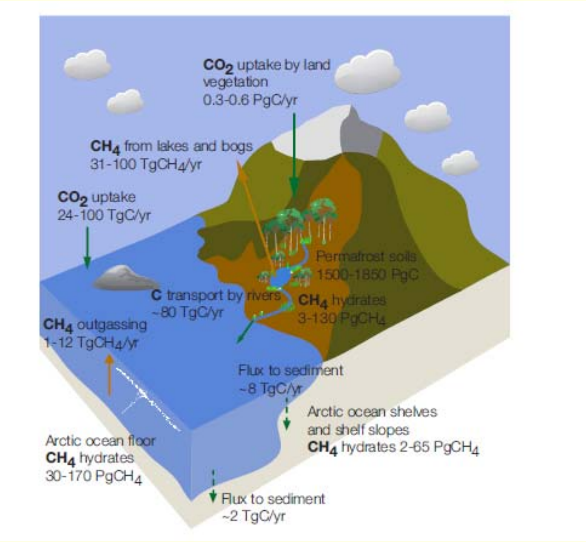
High risk of permafrost thaw

Northern soils will release huge amounts of carbon in a warmer world, say **Edward A. G. Schuur, Benjamin Abbott** and the Permafrost Carbon Network.



Grosse et al. (2011, *JG*

<u>'Known Knowns'</u>: • ~20M km^2 • ~1500 Pg C • decomposable
<u>'Known Unknowns'</u>: • thermokarst → landscape wetness →
CO_2:CH_4?



FAQ 6.2, Figure 1: A simplified graph of current major carbon pools and flows in the Arctic domain, Including permafrost on land, continental shelves and ocean (adapted from McGuire et al. (2009) and Tarnocai et al. (2009)). TgC = 10^{12} gC, and PgC = 10^{15} gC.

How big is the potential climate feedback from permafrost methane?

Perma-frost

Schuur and colleagues (2011): "We calculate that permafrost thaw will release the same order of magnitude of carbon as deforestation if current rates of deforestation continue. But because these emissions include significant quantities of methane, the overall effect on climate could be 2.5 times larger."

IPCC et al., 2013: "Until the year 2100, up to 250 PgC could be released as CO2, and up to 5 Pg as CH4. Given methane's stronger greenhouse warming potential, that corresponds to a further 100 PgC of equivalent CO2 released until the year 2100. These amounts are similar in magnitude to other biogeochemical feedbacks, for example, the additional CO2 released by the global warming of terrestrial soils. However, current models do not include the full complexity of Arctic processes that occur when permafrost thaws, such as the formation of lakes and ponds."

Hydrates

There is a large pool of hydrates: in the Arctic alone, the amount of CH4 stored as hydrates could be more than 10 times greater than the CH4 presently in the global atmosphere

NEW FIGS FROM IPCC AR5