The Changing CO_2 Seasonal Cycle

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With Fang Zhao, Jim Collatz, Eugenia Kalnay, Ross Salawitch and Tris West

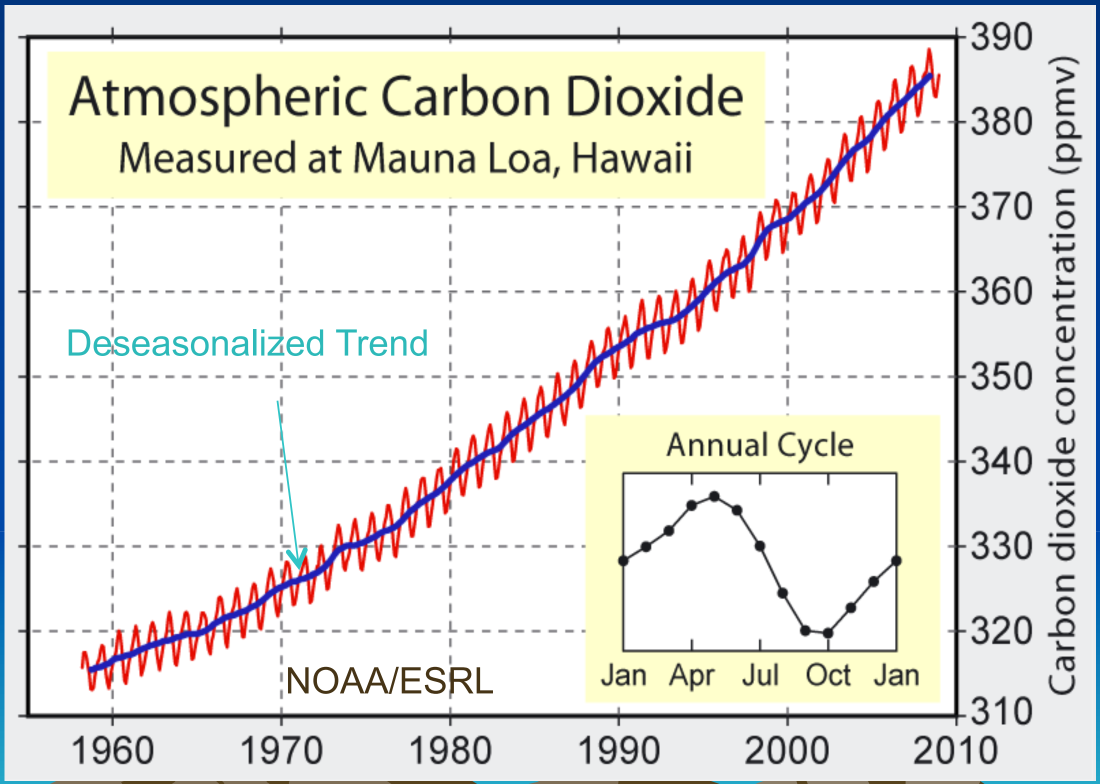
Outline of the talk

- The mean climatological seasonal cycle
- Increasing CO2 seasonal amplitude (CSA)
- Causes of the increase in CSA
  - CO2 fertilization
  - High latitude warming
  - Agricultural Green Revolution
  - Ocean and fossil fuel emissions

The Keeling Curve

Major signals:

Trends (long-term change)
Seasonal cycle
Interannual-decadal variabilities, to a lesser degree



Mean seasonal cycle:

Max in May, min in October
CO_2 drawdown for 5 months.
Not symmetric, not exactly sinusoidal
Seasonal amplitude (max-min) ~ 6 ppm

Increased activity of northern vegetation inferred from atmospheric CO_2 measurements

C. D. Keeling*, J. F. S. Chin† & T. P. Whorf*

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The amplitude of CO2 seasonal cycle increased by 20% at MLO, 40% at Barrow from 1960-1995

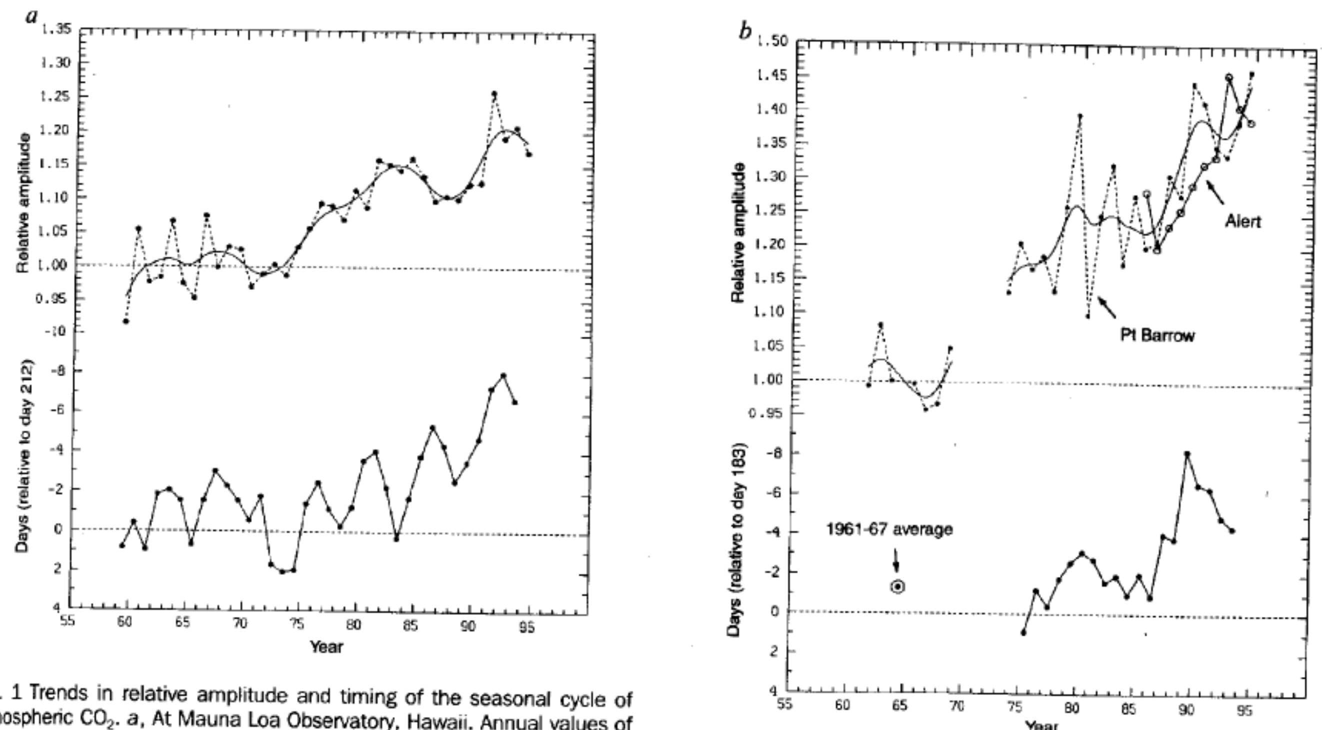

FIG. 1 Trends in relative amplitude and timing of the seasonal cycle of atmospheric CO_2. *a*, At Mauna Loa Observatory, Hawaii. Annual values of

Also:
Pearman and Hyson, 1981
Cleveland, 1983
Bacastow et al., 1985

The changing carbon cycle at Mauna Loa Observatory

Wolfgang Buermann*†, Benjamin R. Lintner‡§, Charles D. Koven*, Alon Angert*¶, Jorge E. Pinzon‖, Compton J. Tucker‖, and Inez Y. Fung*,**

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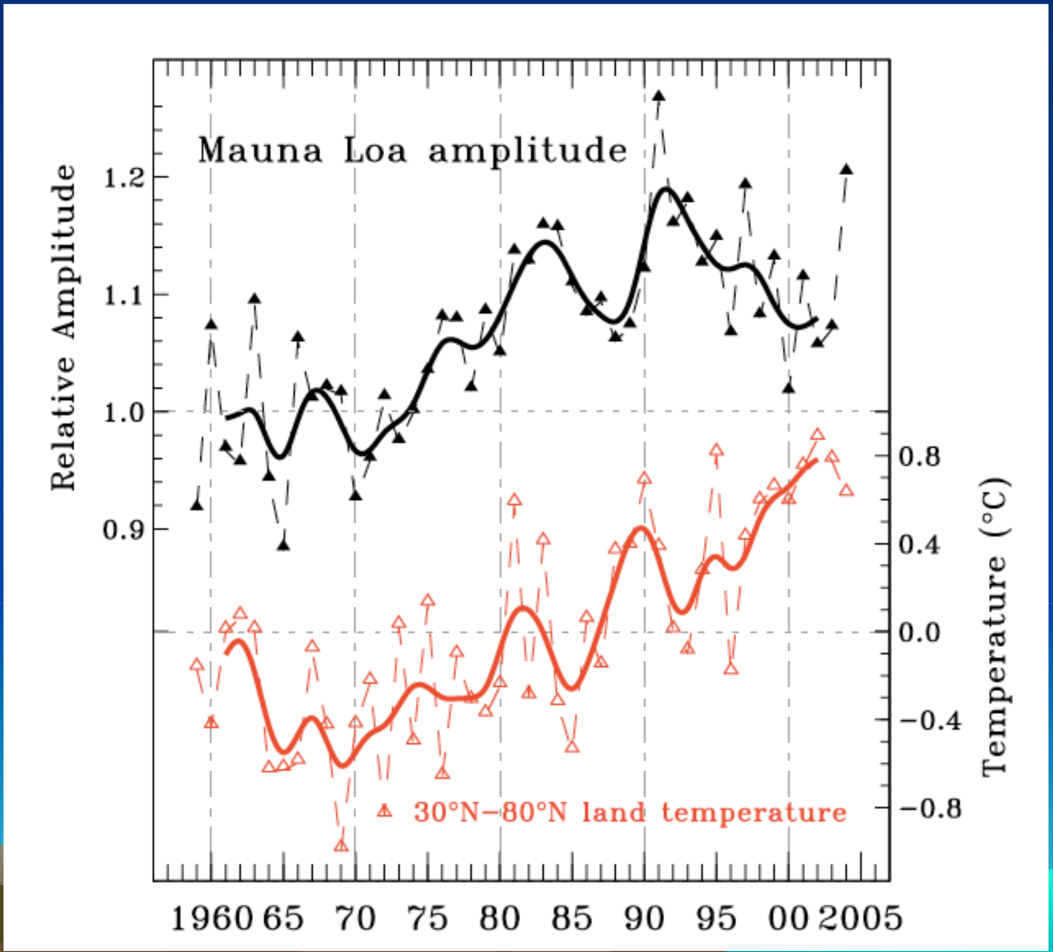
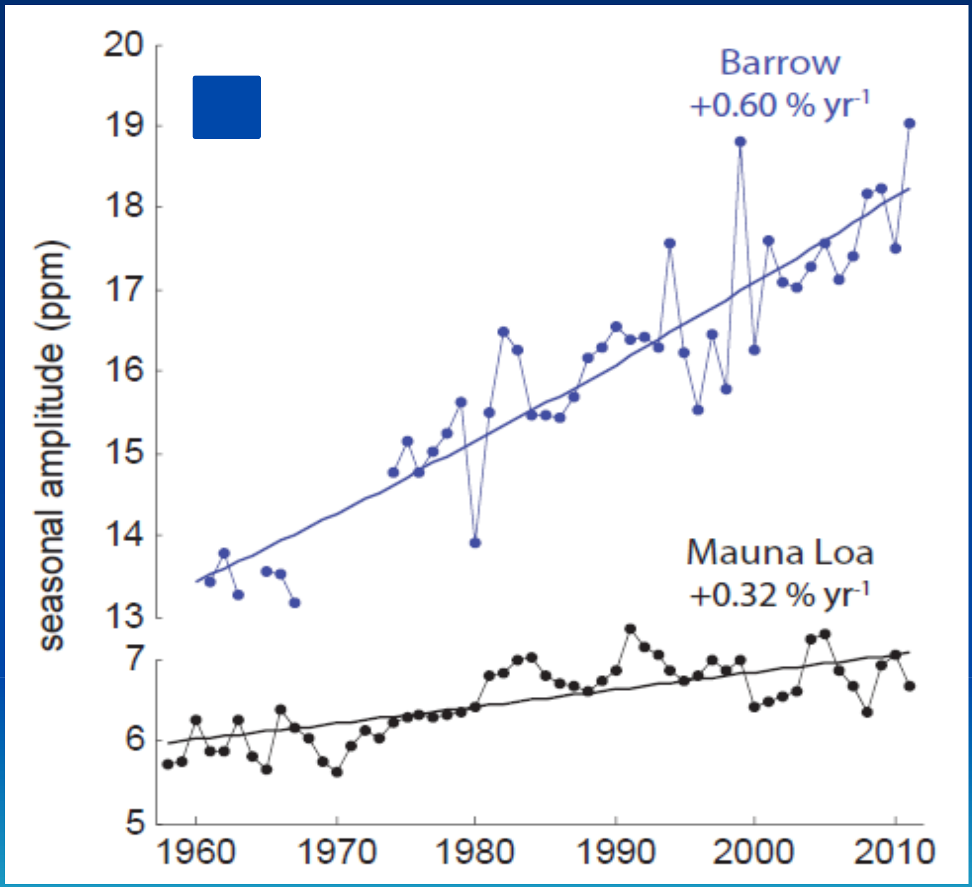
But
CO_2 seasonal amplitude decreased in the 1990s

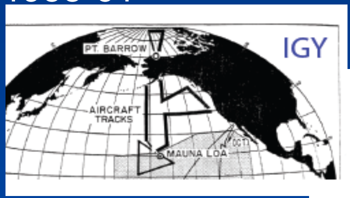


The seasonal amplitude of CO_2 has increased by 35% at Barrow but only 15% at Mauna Loa since 1960

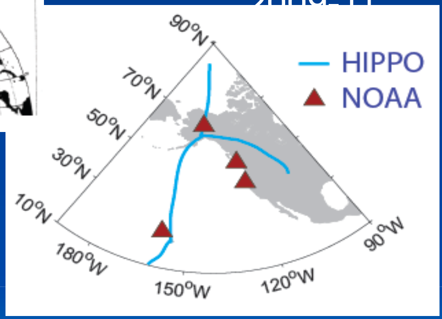


Comparison of aircraft data can now assess whether these trends are representative of the large-scale pattern

1958-61



2009-11



From Graven et al., Science, in press

See also H. Graven's poster here at the colloquium

Keeling et al. 1996; Keeling et al. 1968; Wofsy et al. 2011; C. Sweeney unpub. data

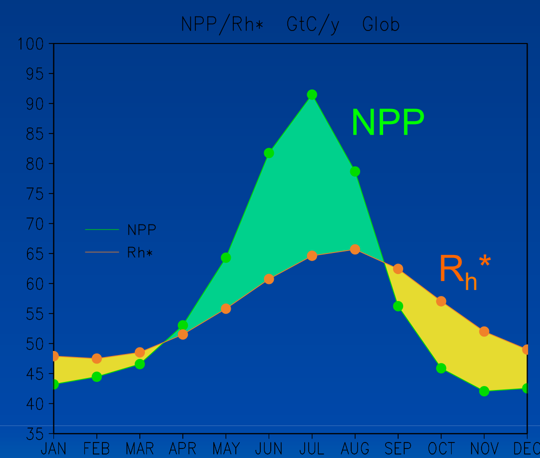
Data/model products

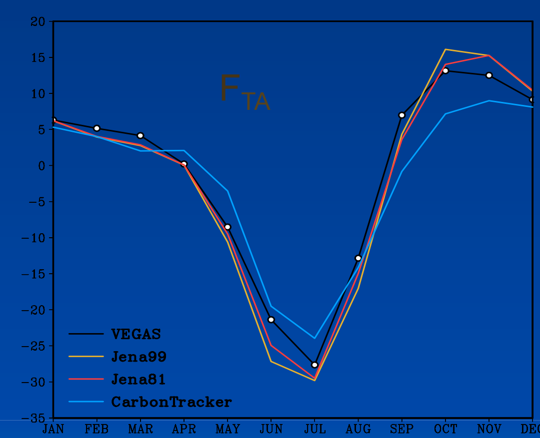
- MLO CO2
- Global CO2 index based on 20+ marine stations (NOAA/ESRL)
- Atmospheric inversions v3.4 (MPI/Jena)
- CarbonTracker 2011 (NOAA/ESRL)
- Terrestrial carbon models: VEGAS (UMD) + LPJ + ORCHIDEE
- Statistics (population, land use, crop production etc.)
- FLUXNET

The mean CO2 seasonal cycle I
The dominance of Northern Hemisphere vegetation

- Vegetation takes up atmospheric CO_2 during spring/summer growing season, while respiration and decomposition has a much weaker seasonal cycle

- $F_{TA} = R_h^* - NPP$



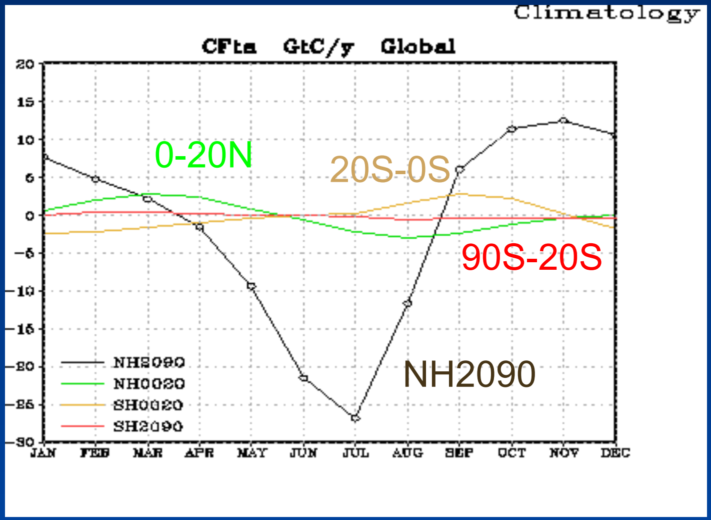


F_{TA} -- Net land-atmosphere carbon flux

R_h^*-- Respiration extended (including heterotrophic respiration, fire and other losses).

The mean CO2 seasonal cycle II
The Tropics and the Southern Hemisphere

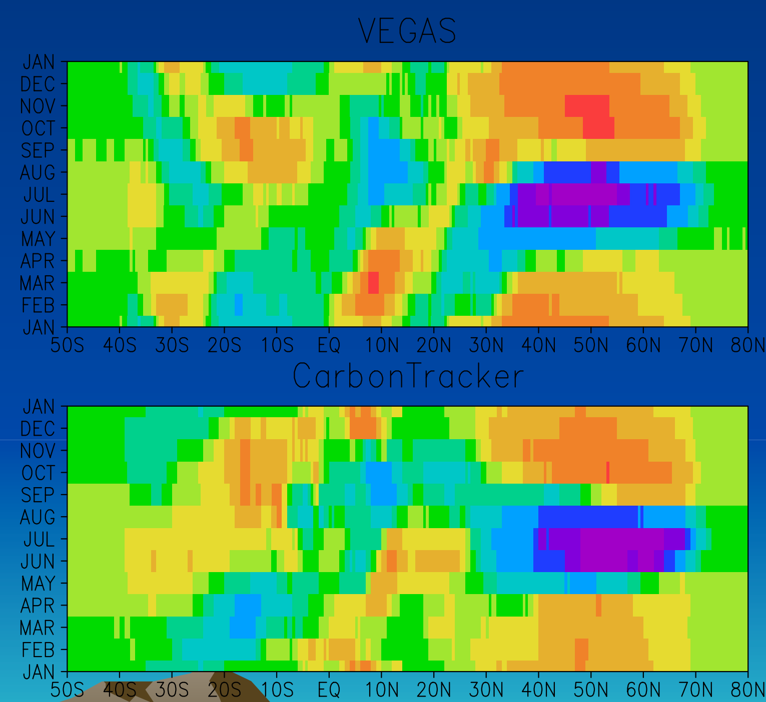
- The Southern Hemisphere land mid-high latitude region has a seasonal cycle opposite of the Northern Hemisphere, but the total amount of biospheric production is much smaller than NH due to the smaller land area in the SH
- The tropical vegetation has small seasonal cycle because growth is largely year round
- Subtropical land off the equatorial zone, wet and dry seasons caused by the movement of the ITCZ and monsoons leads to modest seasonal changes but the regions north and south of the equator are out of phase so they largely cancel each other out



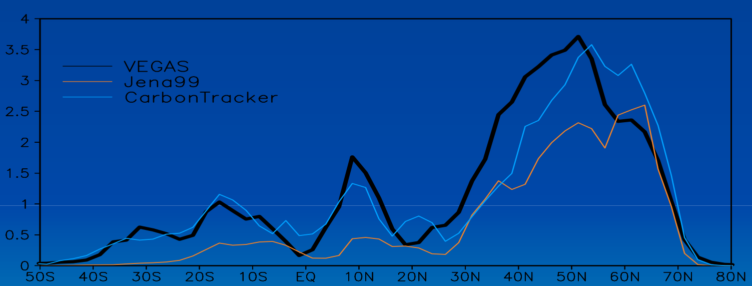
The mean CO2 seasonal cycle II

Comparison of mechanistic model with atmospheric inversions

Latitude-time evolution of F_{TA}

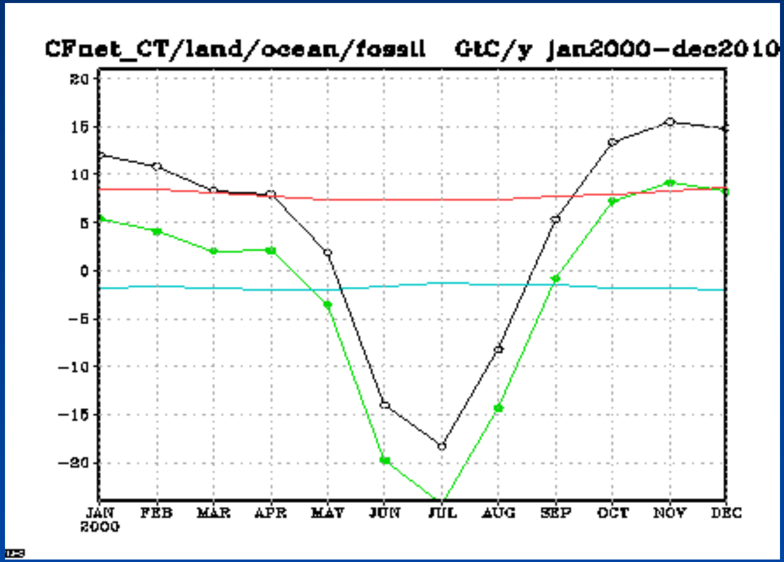


Latitudinal distribution of F_{TA} seasonal amplitude (SA)



The mean CO2 seasonal cycle III
Ocean and fossil fuel

- Atmosphere CO2 growth rate (CO2g=dCO_2/dt) is determined by Fossil fuel emissions (FFE), ocean and land fluxes:

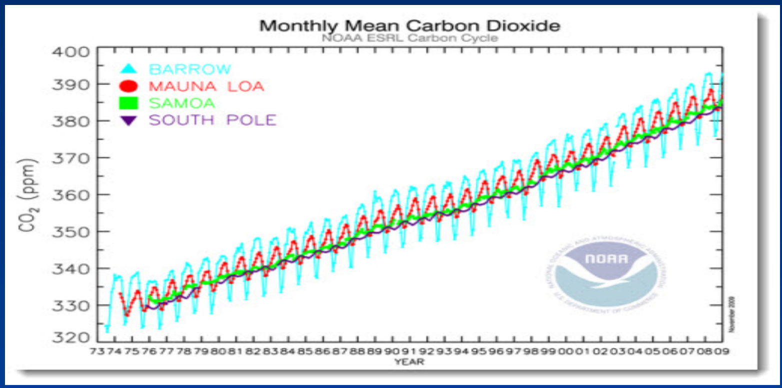


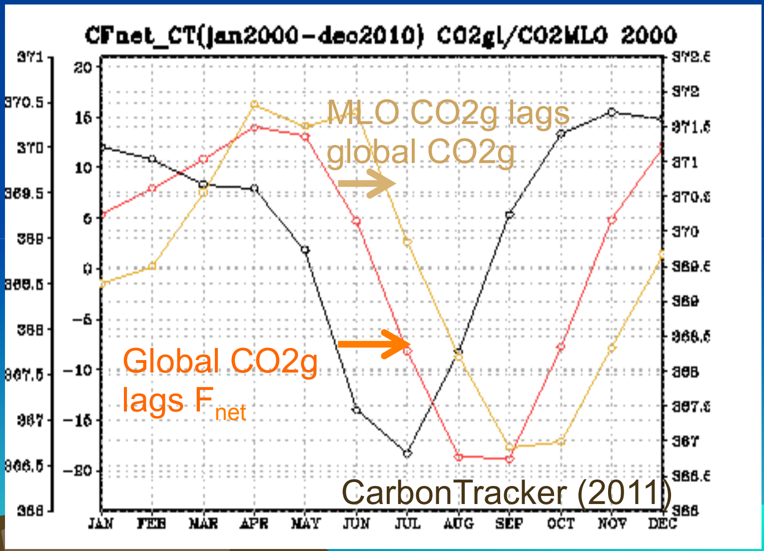
$$CO2g = F_{net} = F_{FE} + F_{OA} + F_{TA}$$

- Fossil fuel emissions has a small seasonal cycle, broadly in phase with terrestrial flux. Similar to vegetation, NH dominates over SH also for FFE because of the larger population in the NH.
- Oceanic CO2 flux has a small seasonal cycle that is probably opposite of terrestrial.

The mean CO2 seasonal cycle IV
Atmospheric transport

- The CO2 seasonal cycle at different site can be drastically different. This reflects the source distribution, but also importantly, the atmospheric transport: fast in the zonal direction (several days), but relatively slow in the meridional direction. In particular, cross-equator mixing is on the order of 1 year
- Phase lag between surface-atmosphere flux and CO2 concentration. The July max in F_{net} corresponds to the fastest drawdown of CO2, but not the minimum of CO2 itself. Instead, the minimum of CO2 is reached when F_{net} is zero in October. Because NH vegetation growing season is concentrated in the summer, the seasonal cycle is not symmetric: CO2 decreases only from May-September, with major decreases in only 3 months June-August.



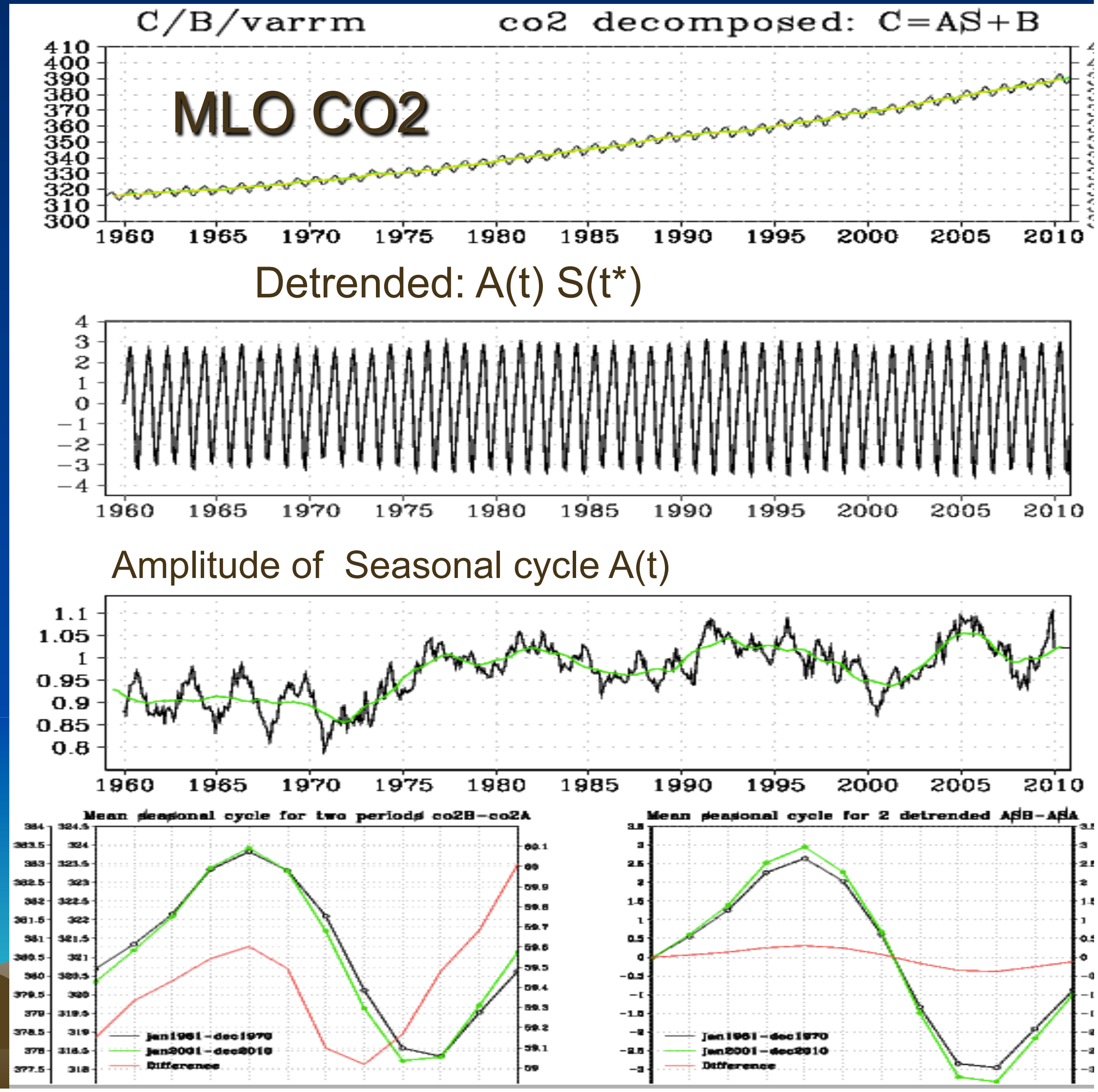


$$dCO2_{global}/dt = F_{net}$$

How to calculate seasonal amplitude (SA) and its change
Deconstructing a legendary time series

$$CO2(t) = A(t)\, S(t^*) + B(t)$$

CO2(t) – Original CO2
S(t*) – An 'average' seasonal cycle (fixed: varying seasonally, but does not change from year to year)
A(t) – Amplitude of the seasonal cycle that may vary with time
B(t) – Trend (diseasonalized); low frequency as well as high frequency signal



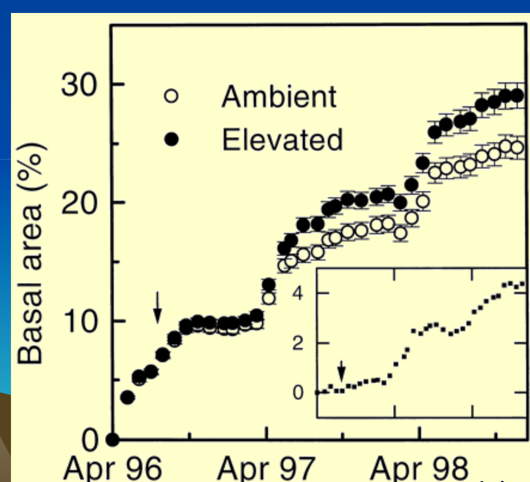
1961-1970 min in Oct
2001-2010 min in Sep

What caused CSA increase?
CO_2 fertilization+

- Estimated contribution (Kohlmeier et al., 1989) for the CSA increase
  - CO_2 (25%, based on lab), N/P deposition another 10-20%
  - May be even smaller given the recent understanding of the strength of the CO_2 fertilization effect

DeLucia et al., Science, 1999

FACE Experiments

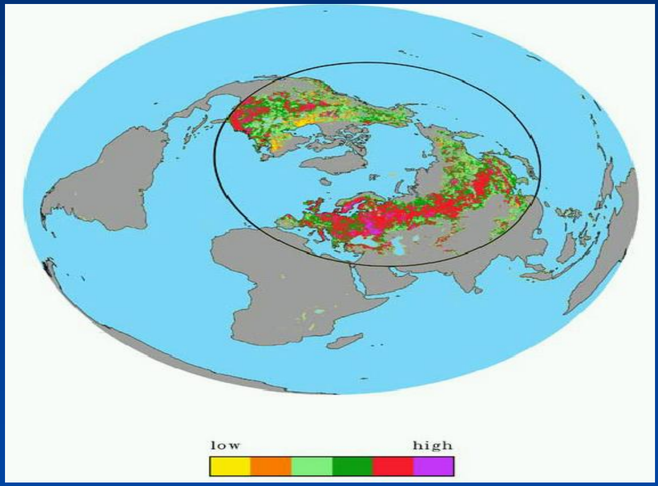


Schlesinger et al. Nature, 2001

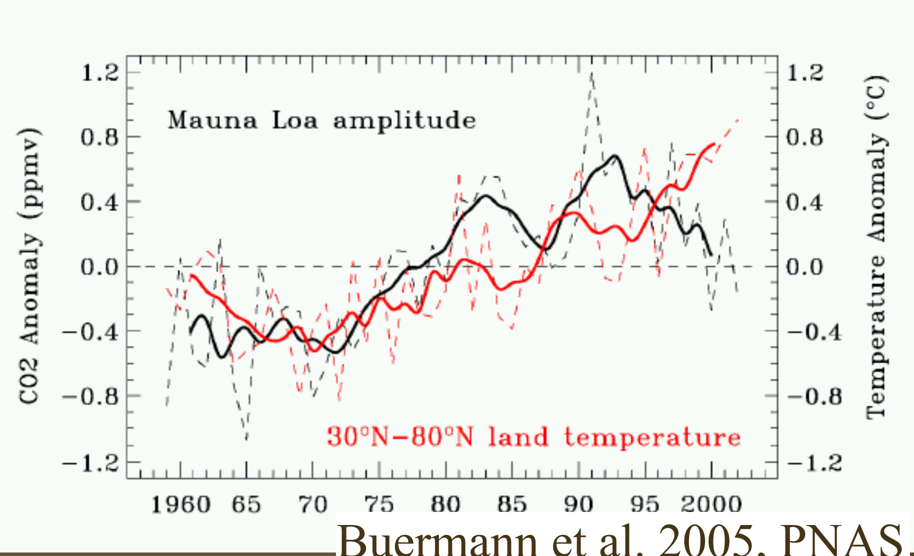
What caused CSA increase?
High-latitude warming

Estimated contribution (Keeling et al., 1996) for the CSA increase

- 10-25%, based on NPP dependence on temperature



Greening of the high latitude due to warming that leads to higher NPP, higher CO2 drawdown during growing season



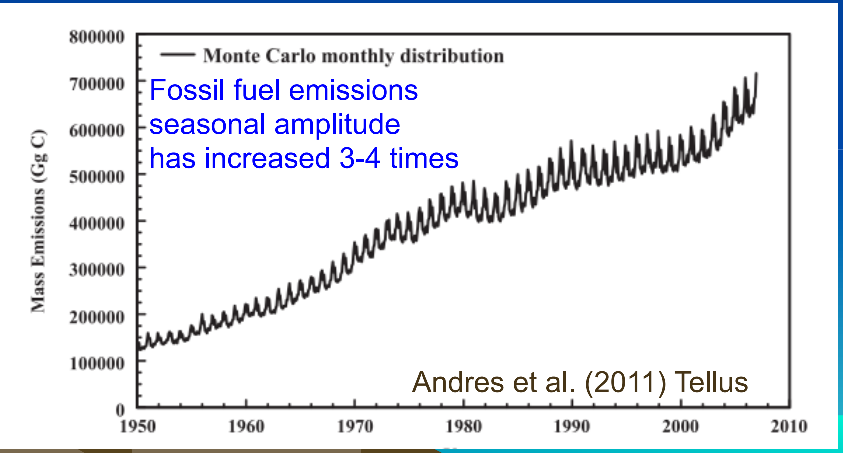
Buermann et al. 2005, PNAS

1970-80s: Increase: warming?
1990s on: Level-off/decrease: drought?

Proposed causes of CSA increase
Other factors

- FFE and ocean 5% (Kohlmeier et al., 1989)

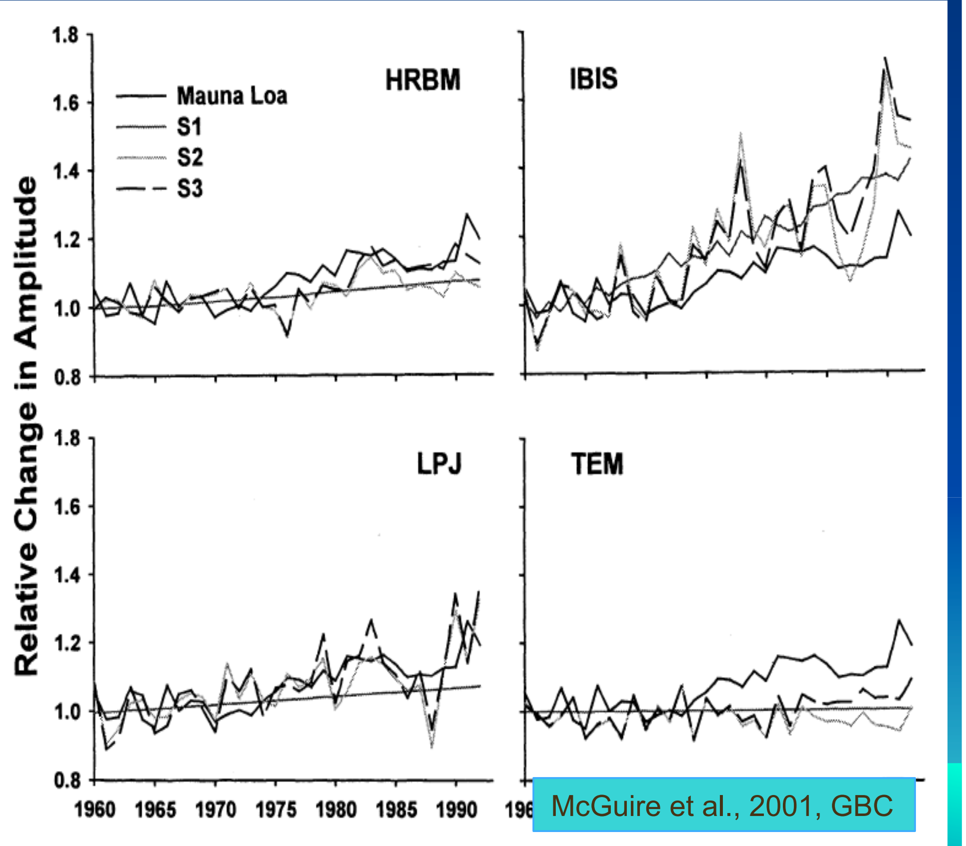
All together (land+ocean+FFE), about 60% can be explained with the combination of the above mechanisms



Testing these hypotheses with mechanistic models (CCMLP)

- Terrestrial carbon models driven by
  - CO2 (S1)
  - CO2+Climate (S2)
  - CO2+Climate+Land use (S3)

- Results
  - 3 of the 4 models simulated larger than observed CSA increase, one almost none
  - Dominated by CO2 fertilization
  - Climate effect is uncertain
  - Land use contributed slightly to CSA increase in 3 models



McGuire et al., 2001, GBC

How does this compared to the 60% estimate above?

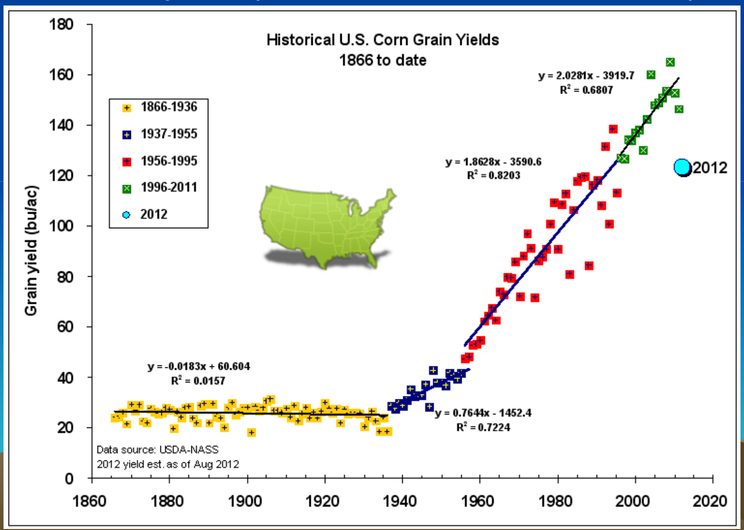
CCMLP: the "Grand Slam" Project, McGuire et al., 2001

A closer look at land use

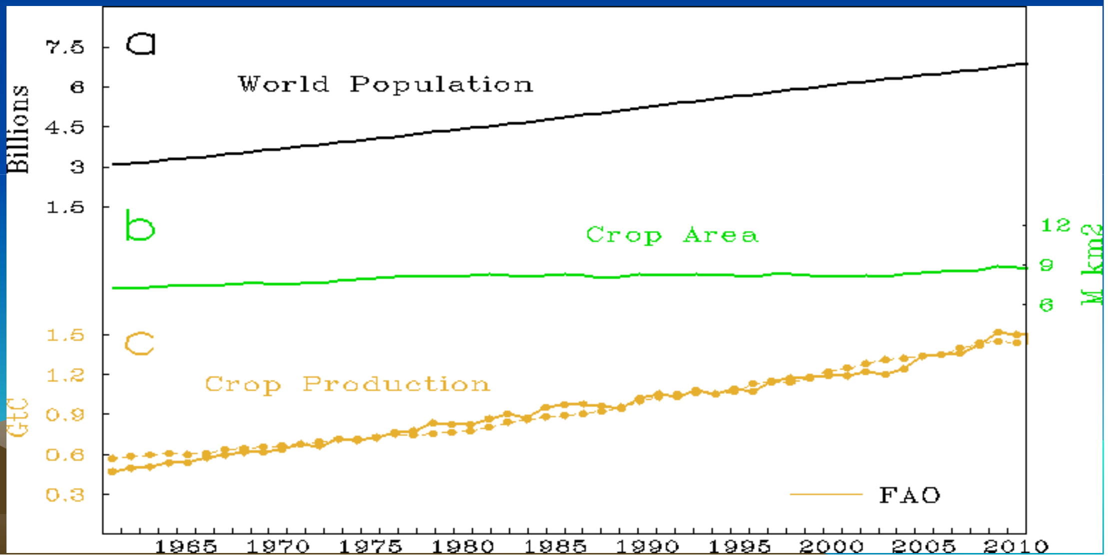
Not just land cover change, but also management intensity

- Over the last 5 decades (1961-2010)
  - World population increased from 3 to 7 billion (130%)
  - Crop production increased from 0.5 to 1.5 PgC/y (200%)
  - Crop area 7.2 to 8.7 Mkm2 (20%)

US corn yield (200% increase 1960-2010)



World population, crop area and crop production (FAO, 2012)



Can intensification of agriculture contribute to CSA increase?

- Global NPP is 60 PgC/y, of which about 6-8 PgC/y is human appropriated NPP (HANPP)
- Now assume HANPP doubled as the result of the agricultural Green Revolution since 1960, so that ΔNPP=3 PgC/y
- Further assume that seasonal characteristics (shape/phase) of NPP and Rh do not change (e.g., Randerson et al., 1999)

This leads to a NPP change of 3/60=5% change, 1/3 of observed CSA increase at MLO

Test this hypothesis in a mechanistic model…

The VEgetation-Global Atmosphere-Soil Model (VEGAS)

5 Plant Functional Types:
- Broadleaf tree
- Needleleaf tree
- C3 Grass (cold)
- C4 Grass (warm)
- Crop/grazing

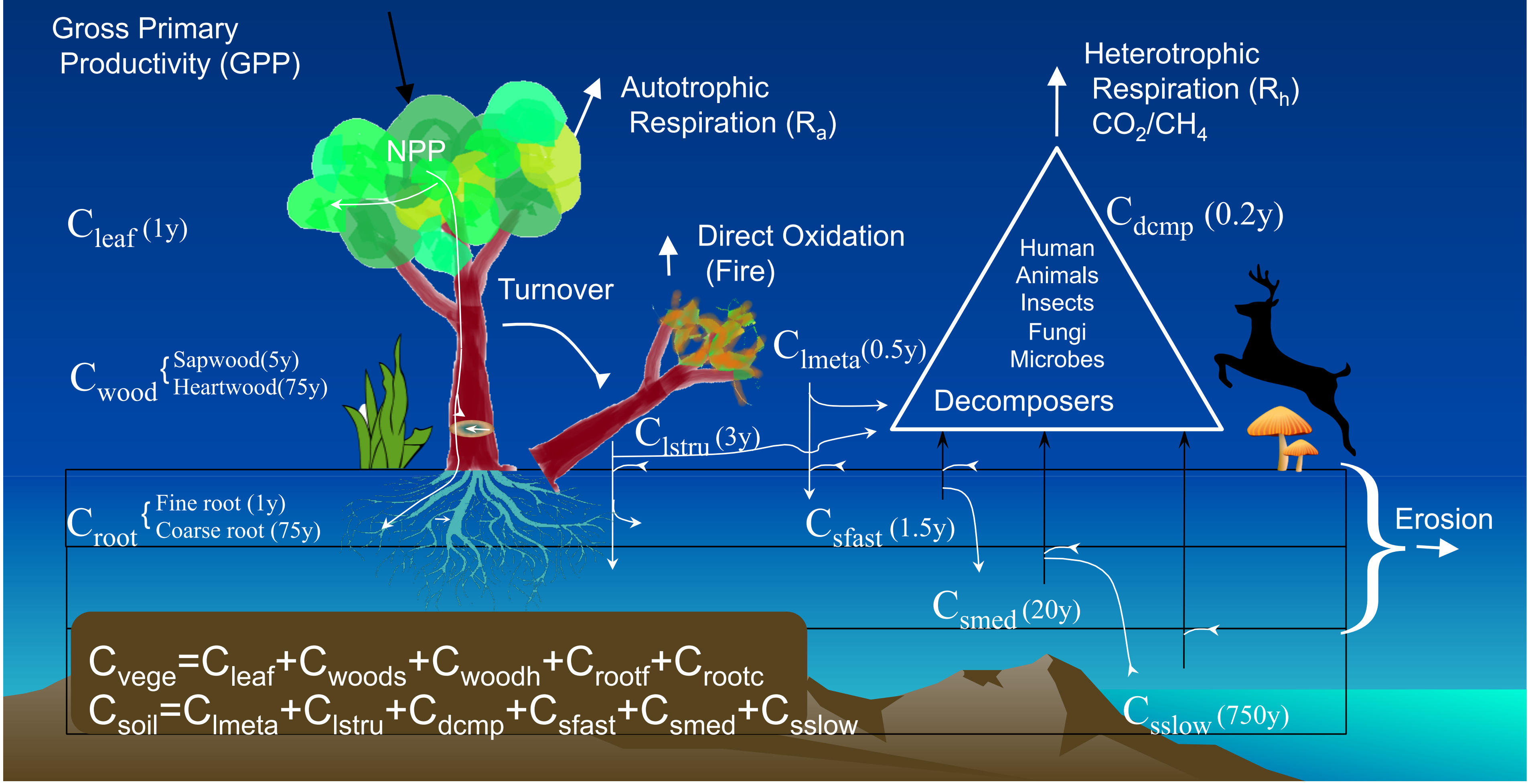
Deciduous or evergreen is dynamically determined

5 Vegetation carbon pools:
- Leaf
- Root (fine, coarse)
- Wood (sapwood, heartwood)

6 Soil carbon pools:
- Decomposer
- Litterfall: metabolic, structural
- Fast, Intermediate, Slow

Fire determined by soil moisture, temperature, fuel load
Wetland, CH_4
Erosion, Riverine flux
C13/C14 isotop

The VEgetation-Global Atmosphere-Soil Model (VEGAS)



Modeling agriculture in VEGAS

- One generic crop functional type that represents an average of the 3 dominant crops: maize, wheat, and rice; avoiding large amount of input data/parameters in a typical crop model; our target is to capture the 1^{st}-order effects on global carbon cycle
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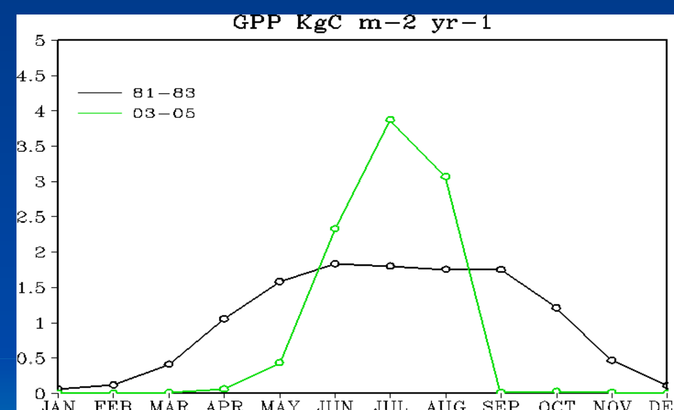
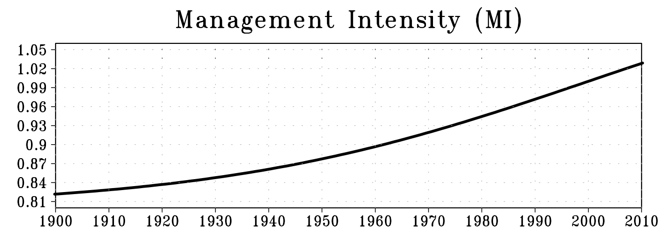


- carbon assimilation rate A_g by the human-selected cultivar, application of fertilizers and pesticides, and irrigation.

Cropland management change over time
---Modeling the Agricultural Green Revolution

- Three major factors changed over time and are thought to have contributed equally to increase in agricultural productivity in the later half of the 20th century (Sinclair, 1998)
  - High-yield cultivars
  - Fertilizer/pesticide
  - Irrigation



- Due to lack of data, simple rules are used. A management intensity factor (MI) due to cultivar and fertilizer enhanced productivity is a function of space (M_1, regional difference) and time:

$$MI = M_0 M_1 (1 + 0.2 \tanh(\frac{year - 2000}{70}))$$

- Irrigation enhances GPP by a 'gentle' enhancement of the soil moisture dependent function:

$$\beta = 1 - \frac{1 - w_1}{W_{irrg}}$$

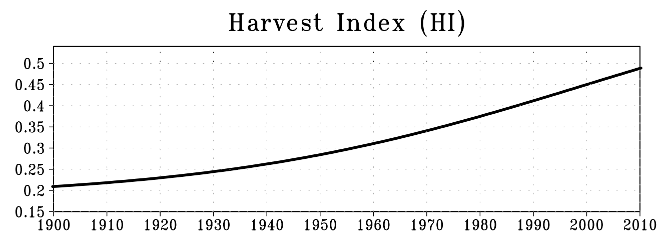
Planting and havesting

Harvest Index (HI) change over time

- Planting is allowed whenever climate condition is suitable, .e.g. due to spring warming in cold/temperate climate
  - Captures much of temperate agriculture
  - Doesn't get winter wheat which grows earlier
- Harvest occurs when leaf area index (LAI) growth rate slows to a threshold
  - May lead to double crop in some tropical regions
- After harvest, grain goes into a harvest pool while the remainder goes to the two litter pools. The harvest grain is laterally transported according to population density and trade
- Harvest Index (HI) is the ratio of grain and total above ground biomass.

$$HI_{crop} = 0.45(1 + 0.6\tanh(\frac{year - 2000}{70}))$$

HI is 0.45 in 2000, and 0.31 in 1960: result of high yield cultivar

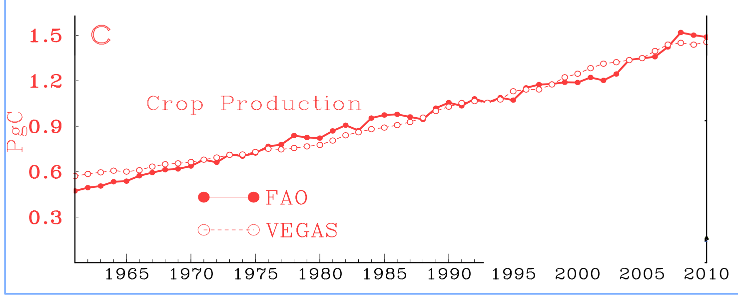


Deforestation, crop abandonment and regrowth

- A sub-grid mesh to represent age-structure without change of model structure: an idea explored and developed over last 10 years.
- A 0.5x0.5 resolution simulation is represented by a mosaic at 0.125x0.125 resolution, so that each grid contains 16 sub-grids, representing 16 cohorts of different age.
- Final results are aggregated back to 0.5x0.5 degree resolution.
- Results can also be provided on finer resolution, and in fact the finer resolution is closer to reality (such as from high resolution remote sensing product) than the cropland fractional coverage information provided in a typical land use dataset that based on statistics.

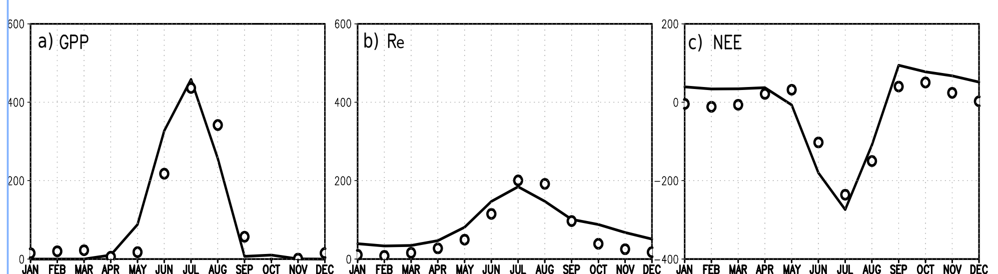
Validation of crop simulation in VEGAS

1. Crop production increased by 0.8, compared to FAO by 1 PgC/y

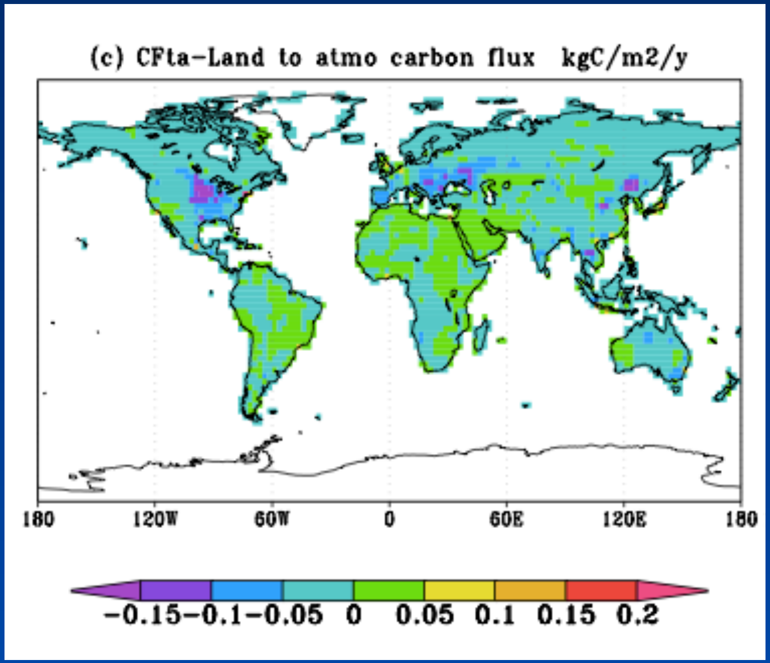


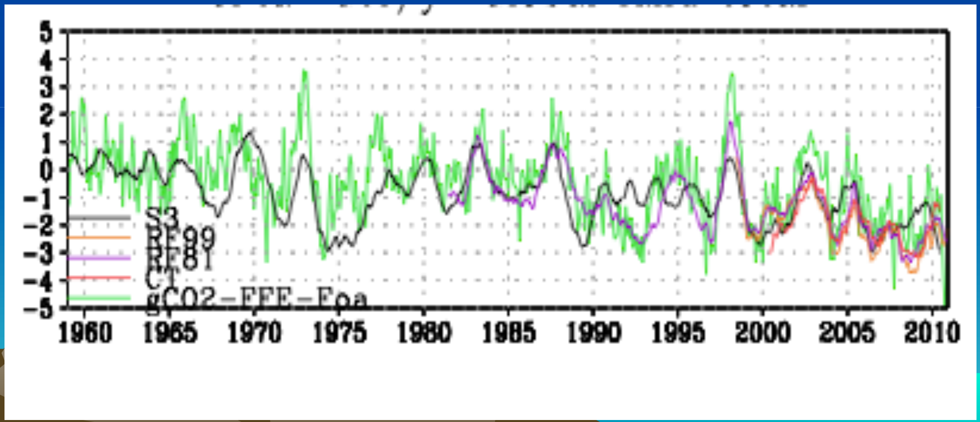
2. Simulated crop NPP_{crop} is 6.2 PgC/y, compared to HANPP 6-8 PgC/y (Vitousek et al., 1986; Haberl et al., 2006)

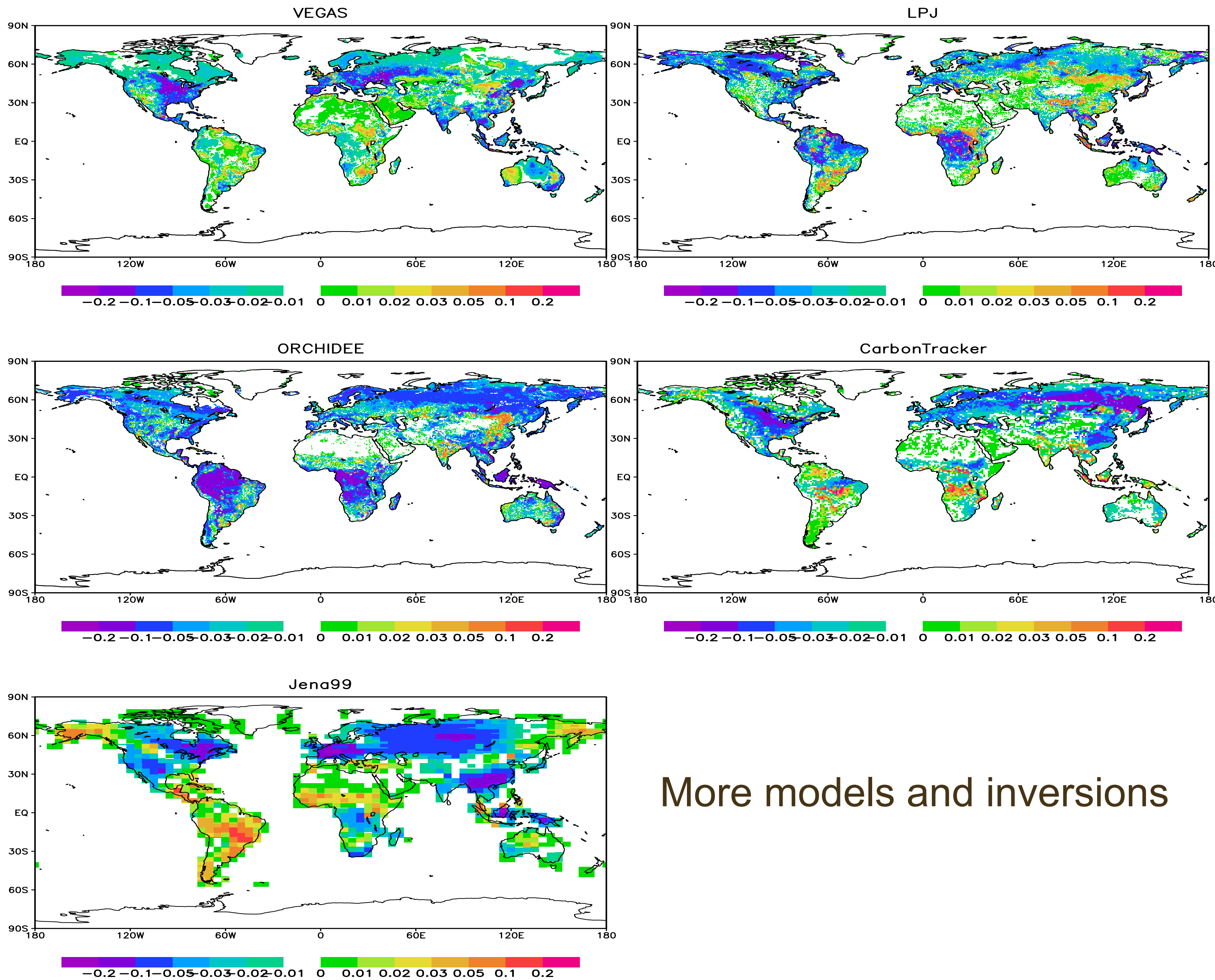
3. Comparison of VEGAS with FLUXNET measurement at Bondville, Illinois



More model simulation results



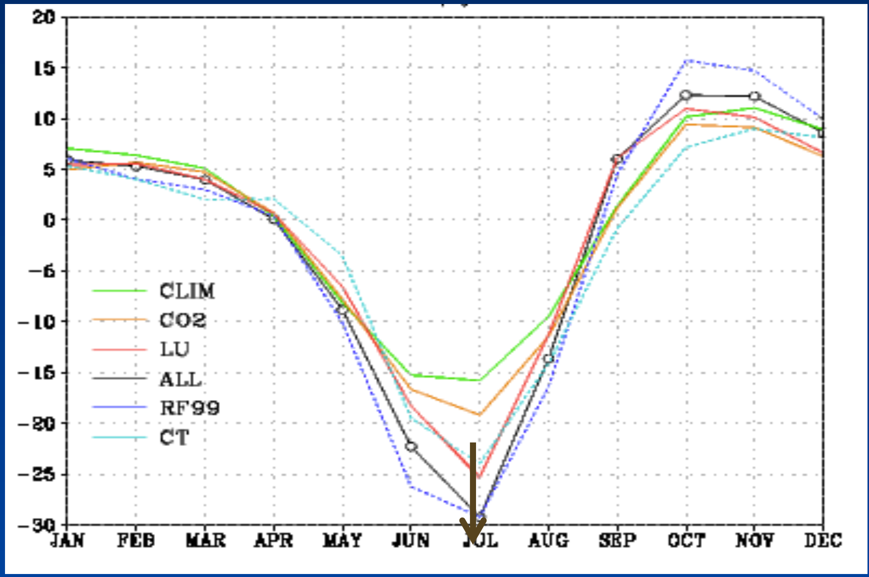




More models and inversions

Impact of agriculture on model simulation

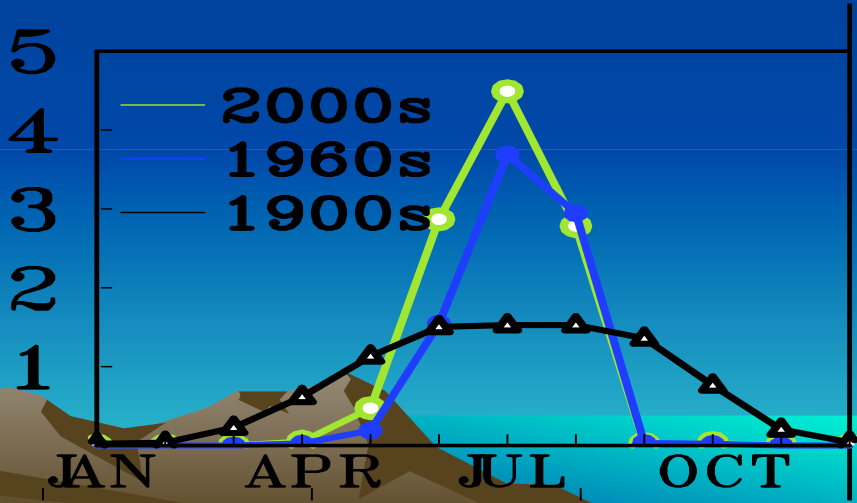
Mean seasonal cycle has a larger drawdown during growing season (~20%)



Seasonal characteristics change

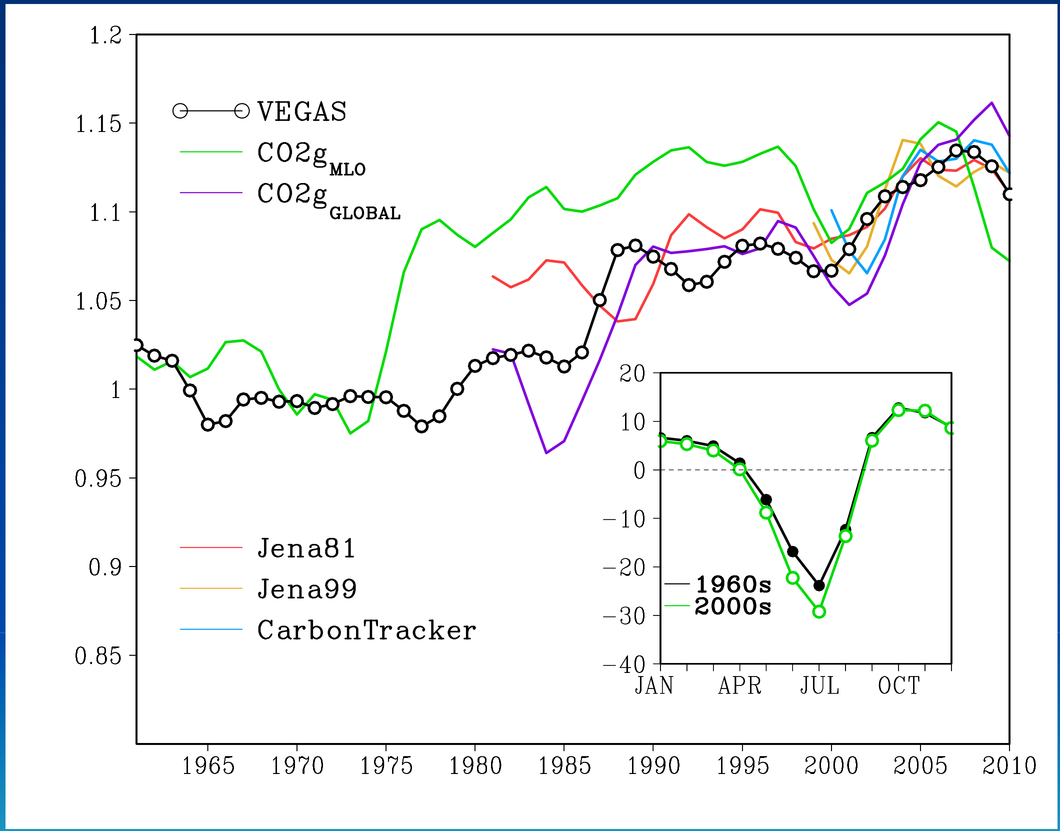
GPP change at a US Midwest location

- 1900s – Natural vegetation
- 1960s - Agriculture
- 2000s – Agriculture intensified

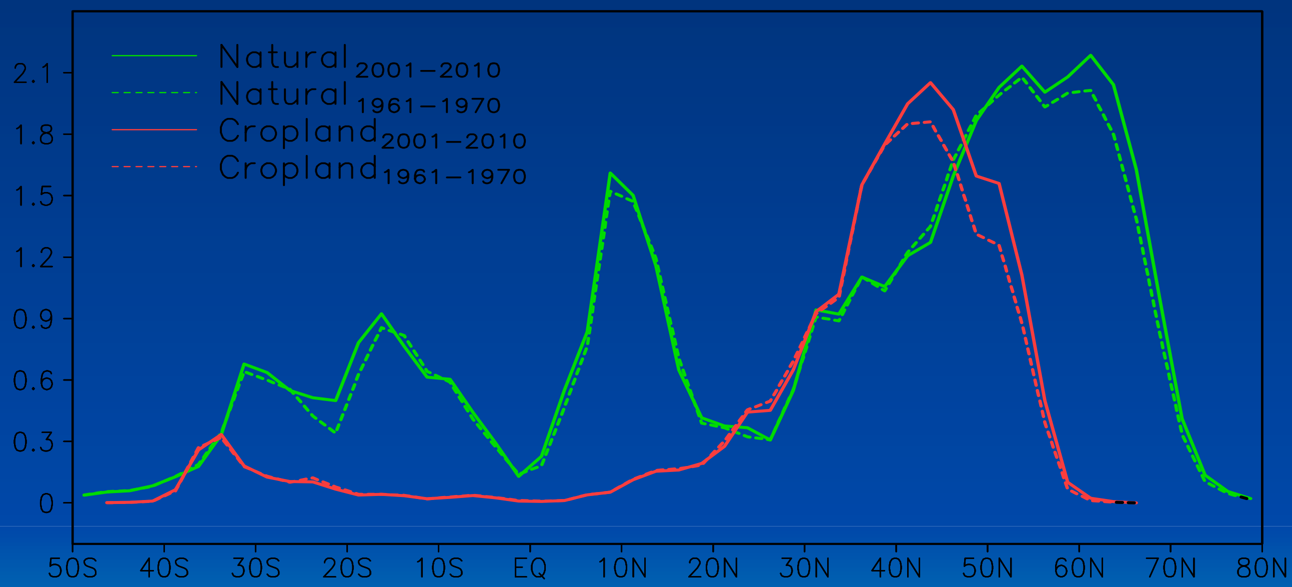


Change in CSA 1961-2010

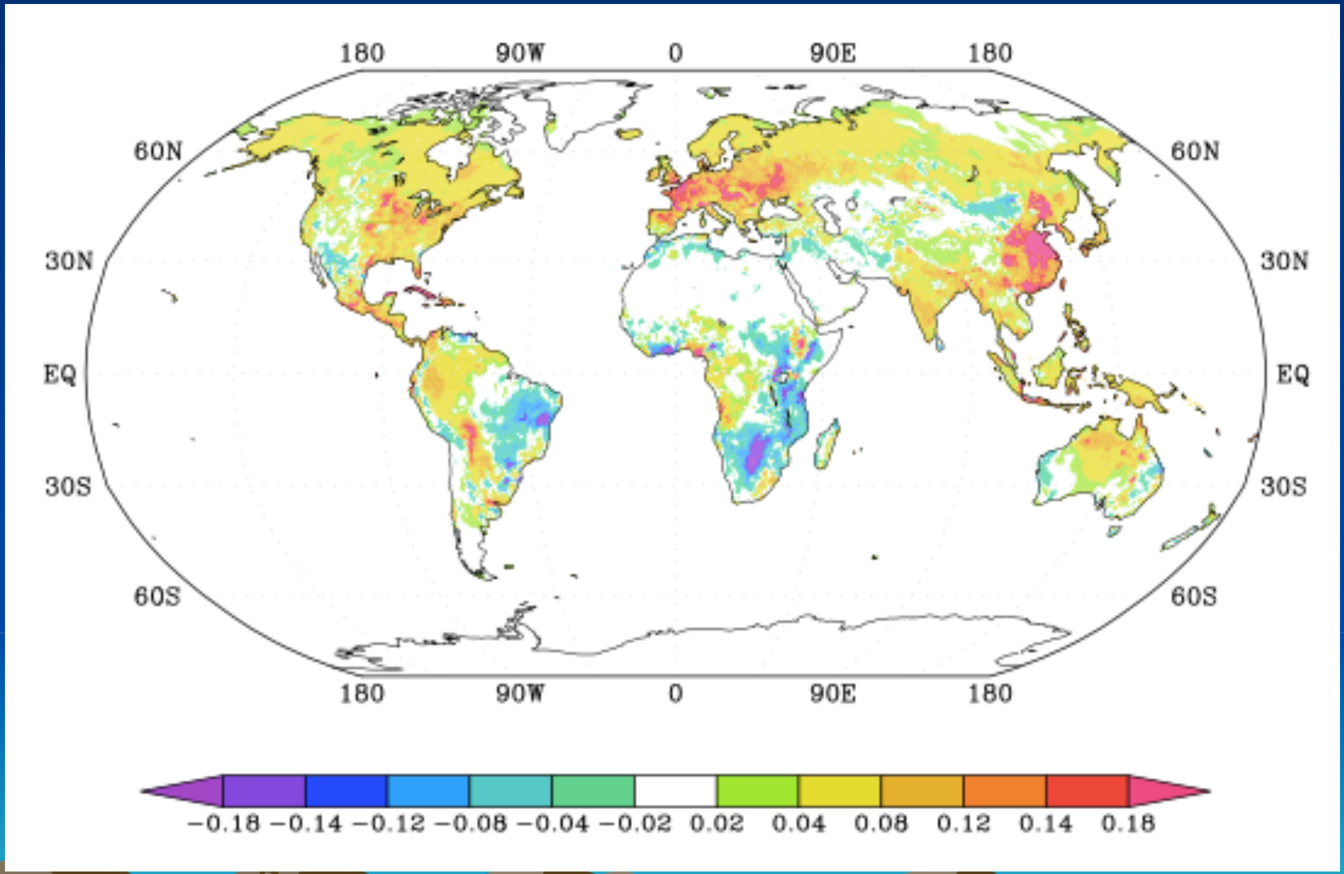
- A long-term increase in seasonal amplitude (SA) by about 15% (MLO CO2g and VEGAS F_{TA})
- Large dacadal (interannual filtered out) variability
- Good agreement on both trend and decadal variability among model, CO2g (MLO and GlOBAL), inversions (MPI/Jena and CarbonTracker)
- Compared to the 1960s, 2000s has a larger drawdown in NH spring/summer; early by about 10 days
- Corresponding to an stronger mean carbon sink by 1.6 PgC/y



Separating cropland and natural vegetation

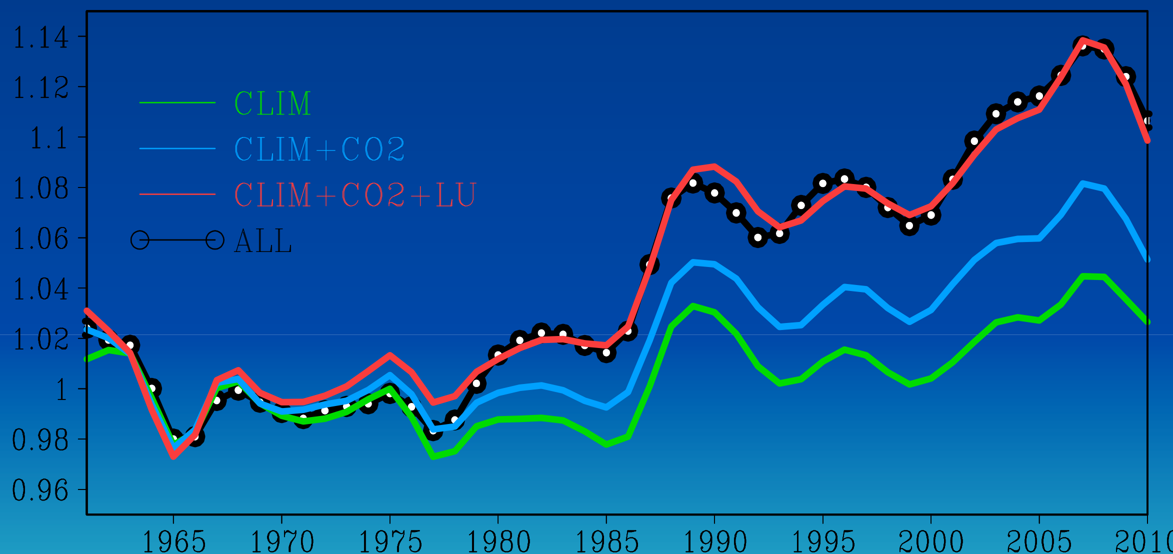


1961-2010 trend in NPP

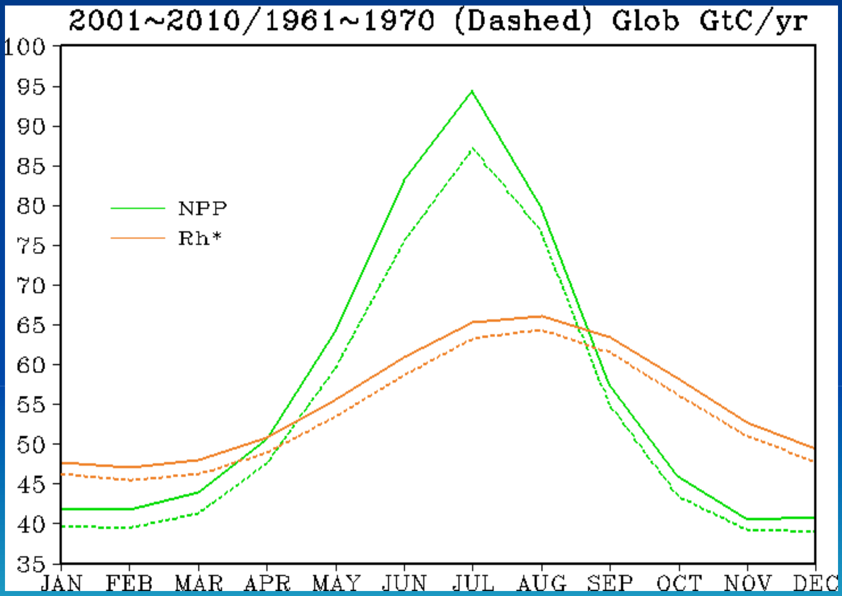


Sensitivity experiments

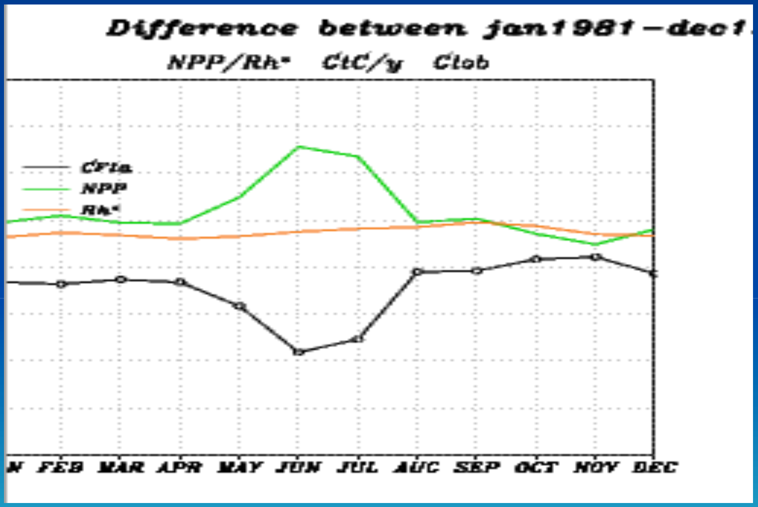
CLIM: Climate only
CO2: CO2 fertilization only
LU: Land use and management



NPP vs. Rh*



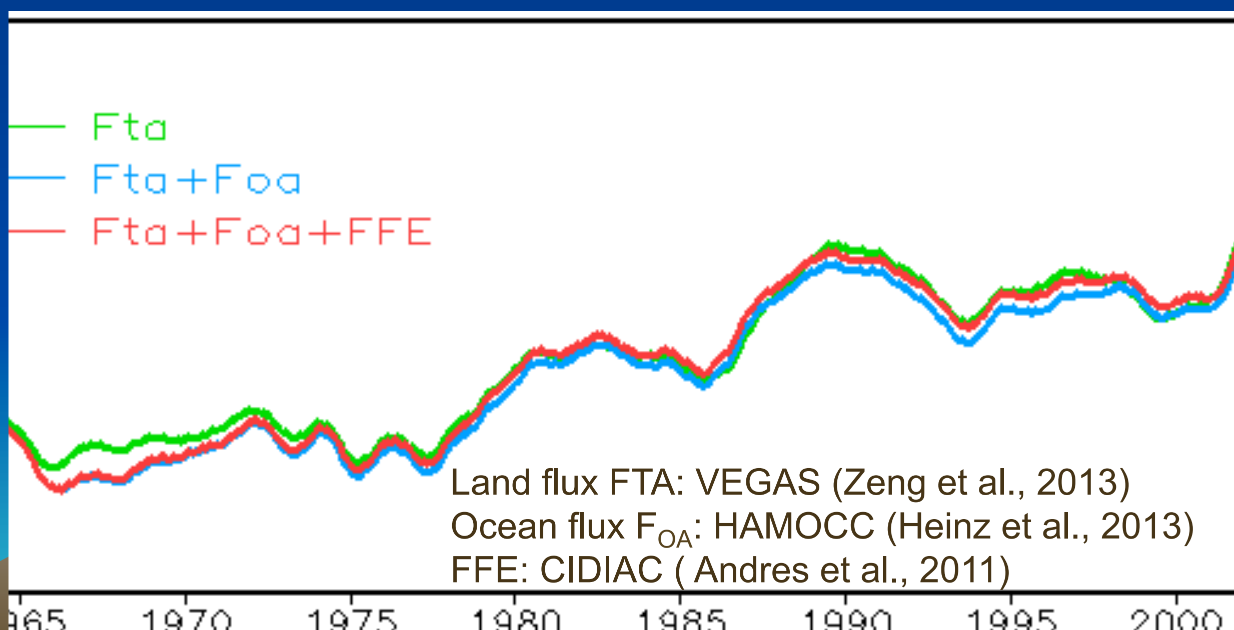
2001~2010/1961~1970 (Dashed) Glob GtC/yr
100
95
90
85
80
75
70
65
60
55
50
45
40
35
NPP
Rh*
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC



Difference between jan1981–dec1
NPP/Rh* GtC/y Glob
CFla
NPP
Rh*
FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

Ocean and fossil fuel

- Ocean SA increased, and since it has opposite phase, it cancels out the effect of land slightly
- FFE SA increased
- The net effect of ocean+FFE is very small



Summary

- Land

1

	CLIM	CO2	LU	SUM	ALL
1961-2010 trend (% per year)	0.094	0.076	0.128	0.298	0.319
Percentage contribution to SUM	31%	26%	43%	100%	

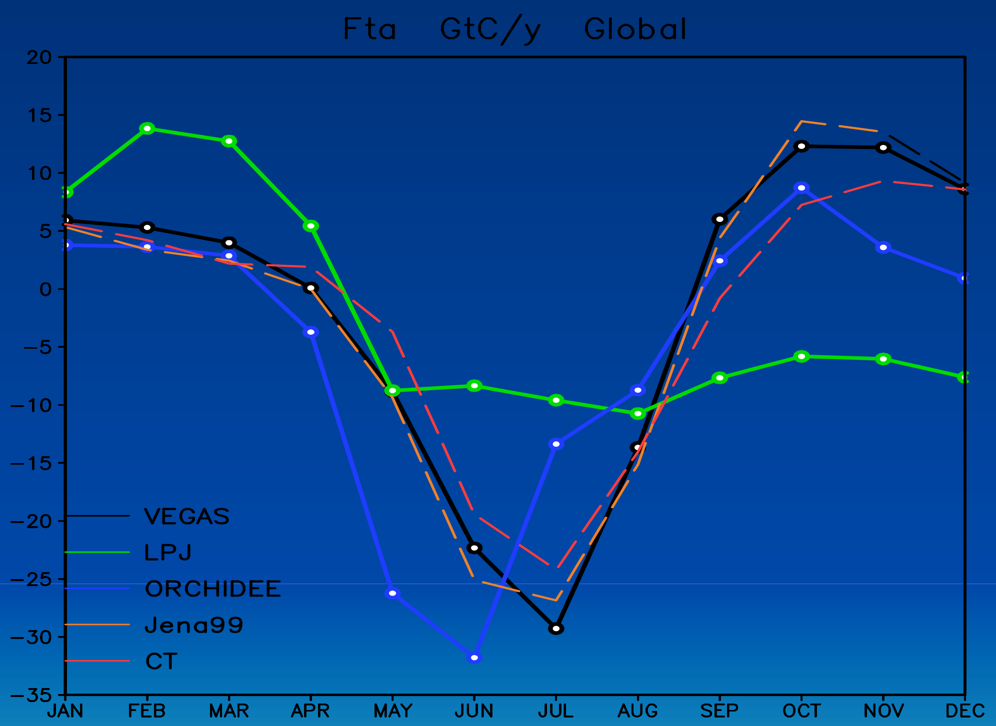
- Ocean/FFE: some influence

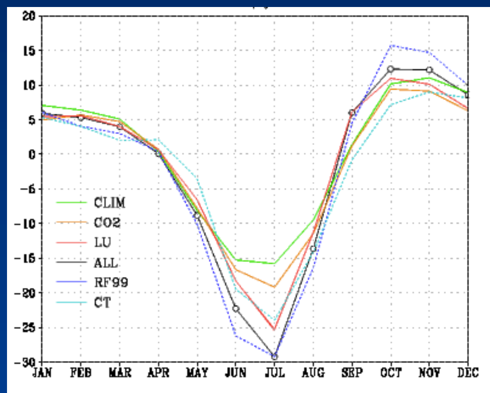
Conclusion

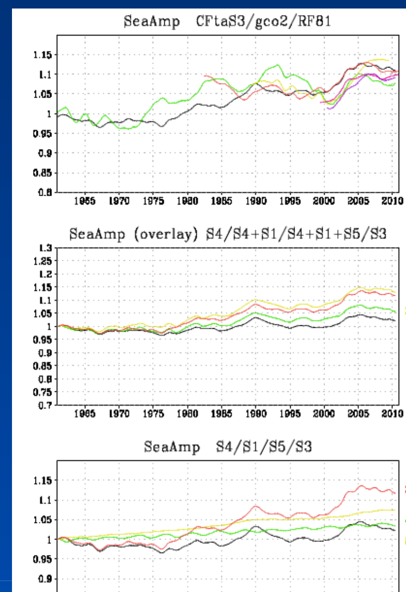
- The basic rhythm of the biosphere: seasonal 'breathing' has been changing: 15% increase in CSA with large decadal-interannual variations
- CO2 fertilization, high latitude warming contributed
- We suggest a missing link: the agricultural Green Revolution

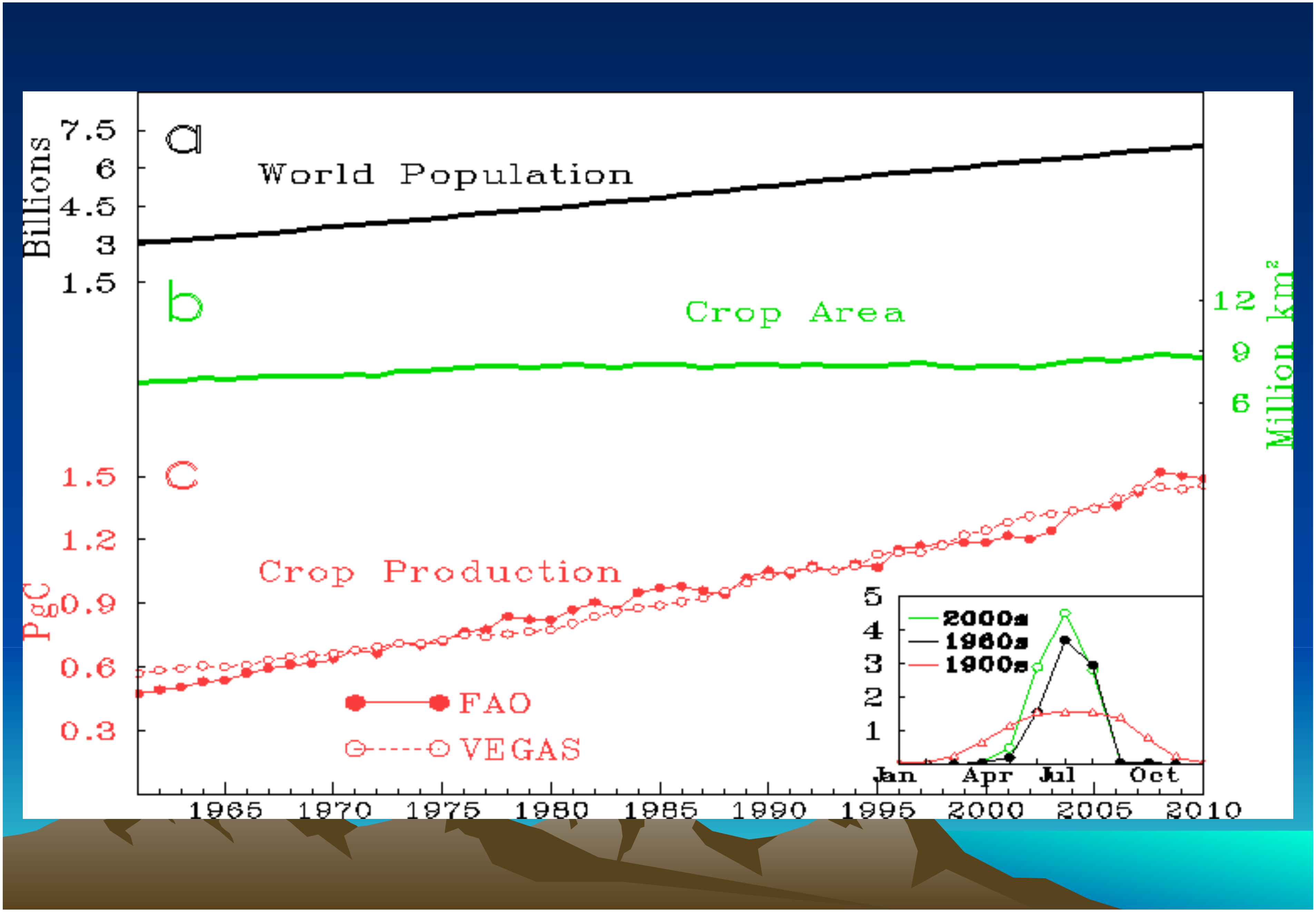
Question: How is this 'enhanced' activity related to the land carbon sink?


Thank you!
All data available upon request to zeng@umd.edu

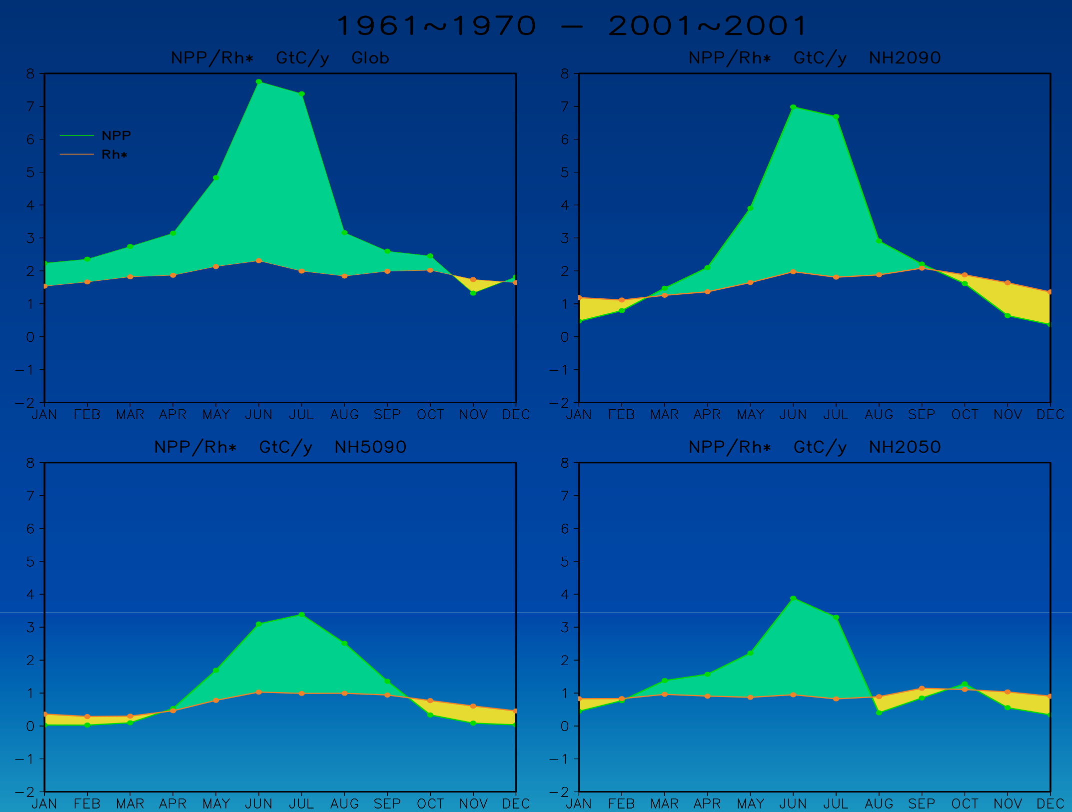

Fta GtC/y Global
20
15
10
5
0
−5
−10
−15
−20
−25
−30
−35
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
VEGAS
LPJ
ORCHIDEE
Jena99
CT

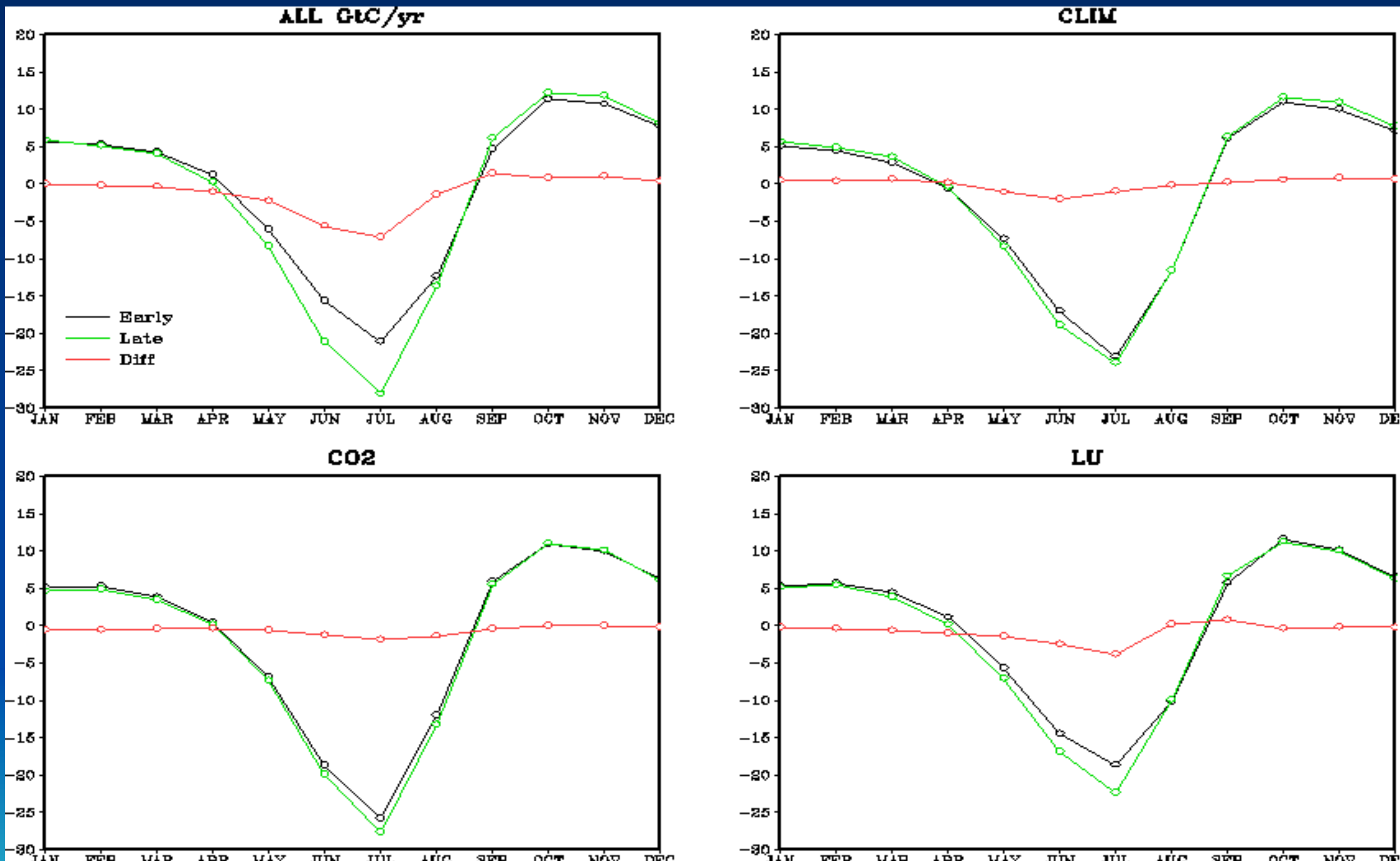

CLIM
CO2
LU
ALL
RF99
CT
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC


SeaAmp CFtaS3/gco2/RF81
SeaAmp (overlay) S4/S4+S1/S4+S1+S5/S3
SeaAmp S4/S1/S5/S3

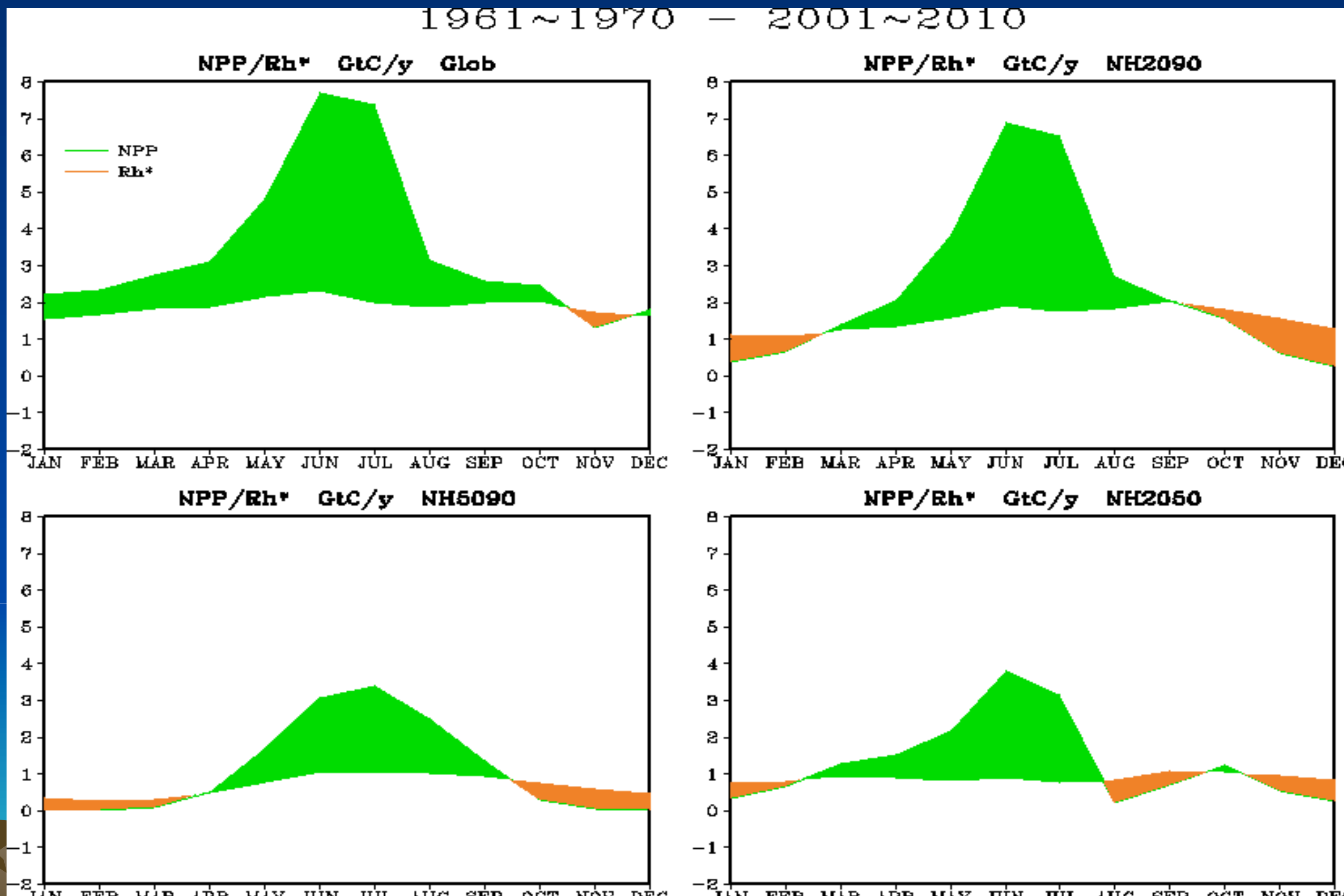


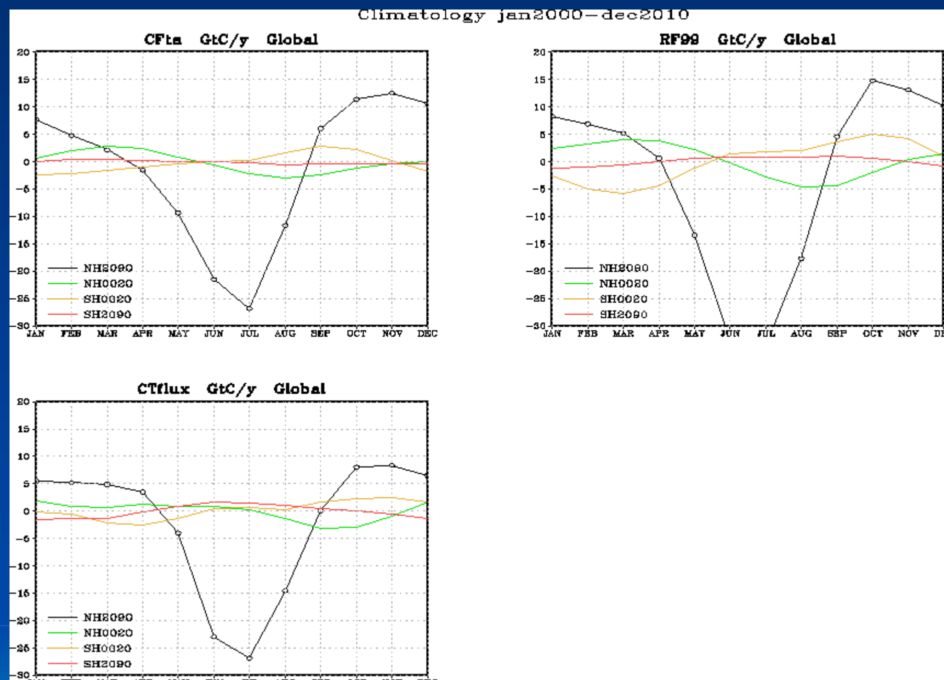
Billions
7.5
6
4.5
3
1.5
a
World Population
b
Crop Area
12
9
6
Million km2
c
1.5
1.2
0.9
0.6
0.3
PgC
Crop Production
FAO
VEGAS
5
4
3
2
1
2000s
1960s
1900s
Jan
Apr
Jul
Oct
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

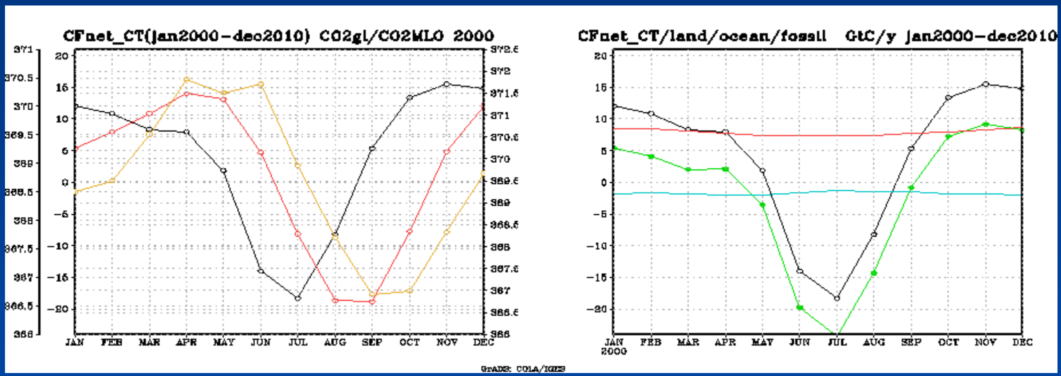

1961~1970 — 2001~2001
NPP/Rh* GtC/y Glob
NPP/Rh* GtC/y NH2090
NPP/Rh* GtC/y NH5090
NPP/Rh* GtC/y NH2050
NPP
Rh*
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
8 7 6 5 4 3 2 1 0 −1 −2


ALL GtC/yr
CLIM
CO2
LU
Early
Late
Diff
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
20 15 10 5 0 −5 −10 −15 −20 −25 −30

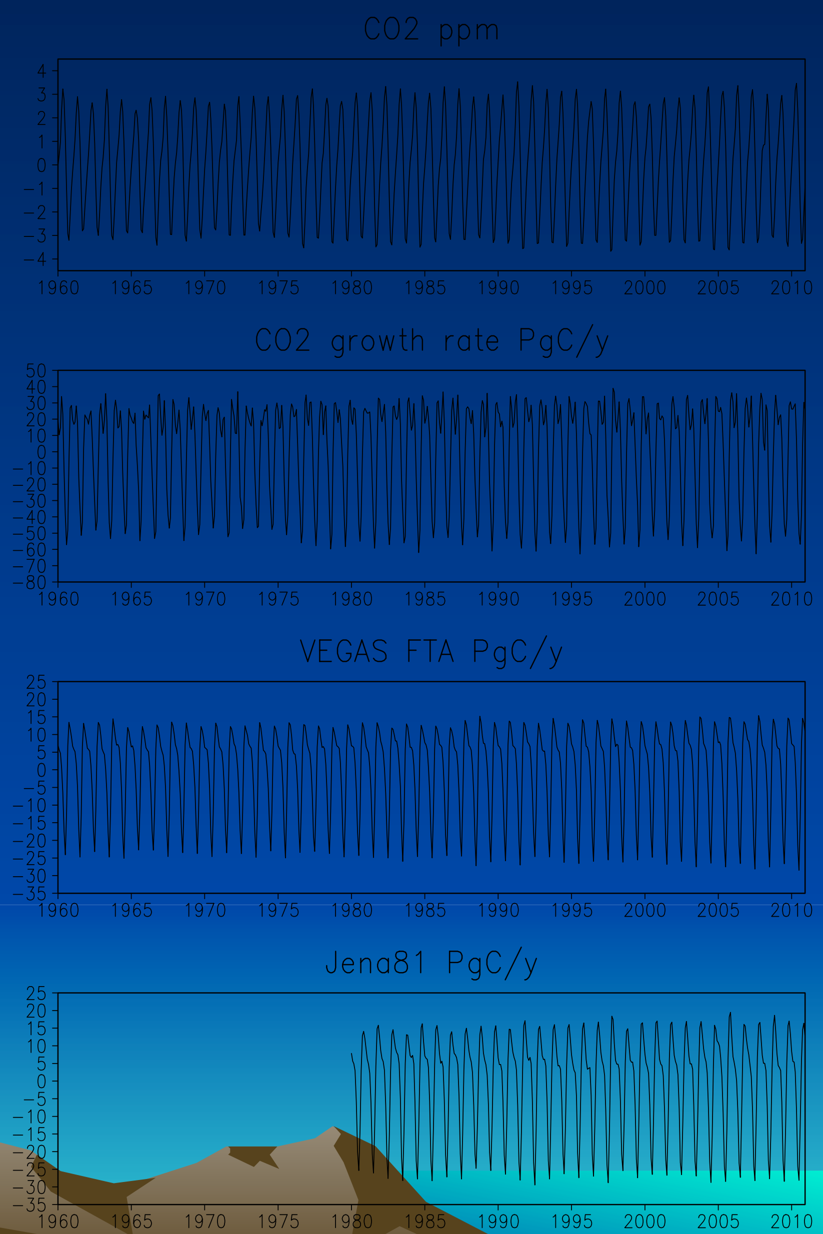
NPP and Rh* 2001-10 minus 1961-70



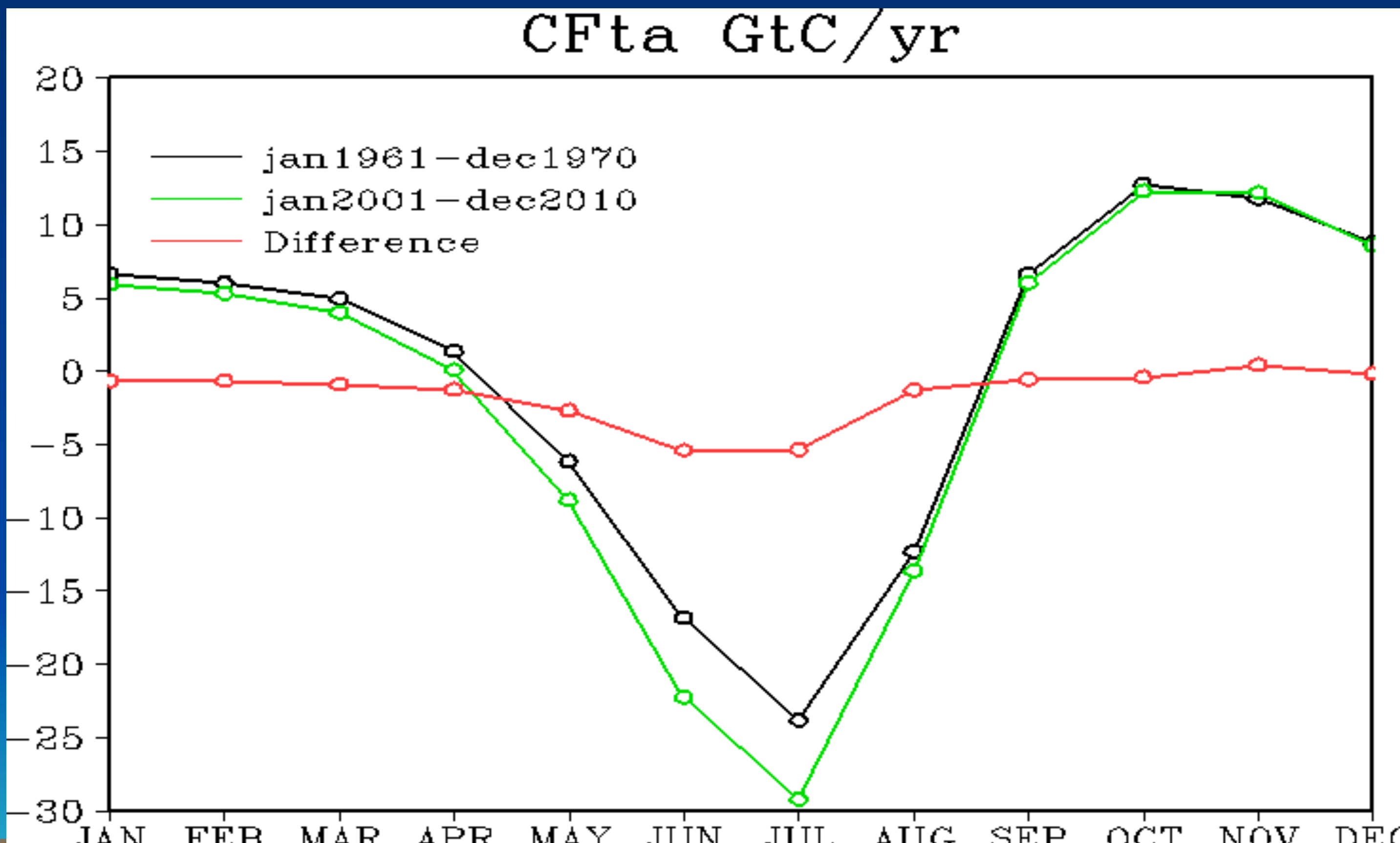

Climatology jan2000–dec2010
CFta GtC/y Global
RF99 GtC/y Global
CTflux GtC/y Global
NH2090
NH0020
SH0020
SH2090
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
20 15 10 5 0 -5 -10 -15 -20 -25 -30



CFnet_CT(jan2000-dec2010) CO2gl/CO2MLO 2000
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
CFnet_CT/land/ocean/fossil GtC/y jan2000-dec2010
JAN 2000 FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
GrADS: COLA/IGES


CO2 ppm
4
3
2
1
0
−1
−2
−3
−4
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
CO2 growth rate PgC/y
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
VEGAS FTA PgC/y
25
20
15
10
5
0
−5
−10
−15
−20
−25
−30
−35
Jena81 PgC/y

Land-atmo carbon flux (CFta): 2001-10 vs. 1961-70

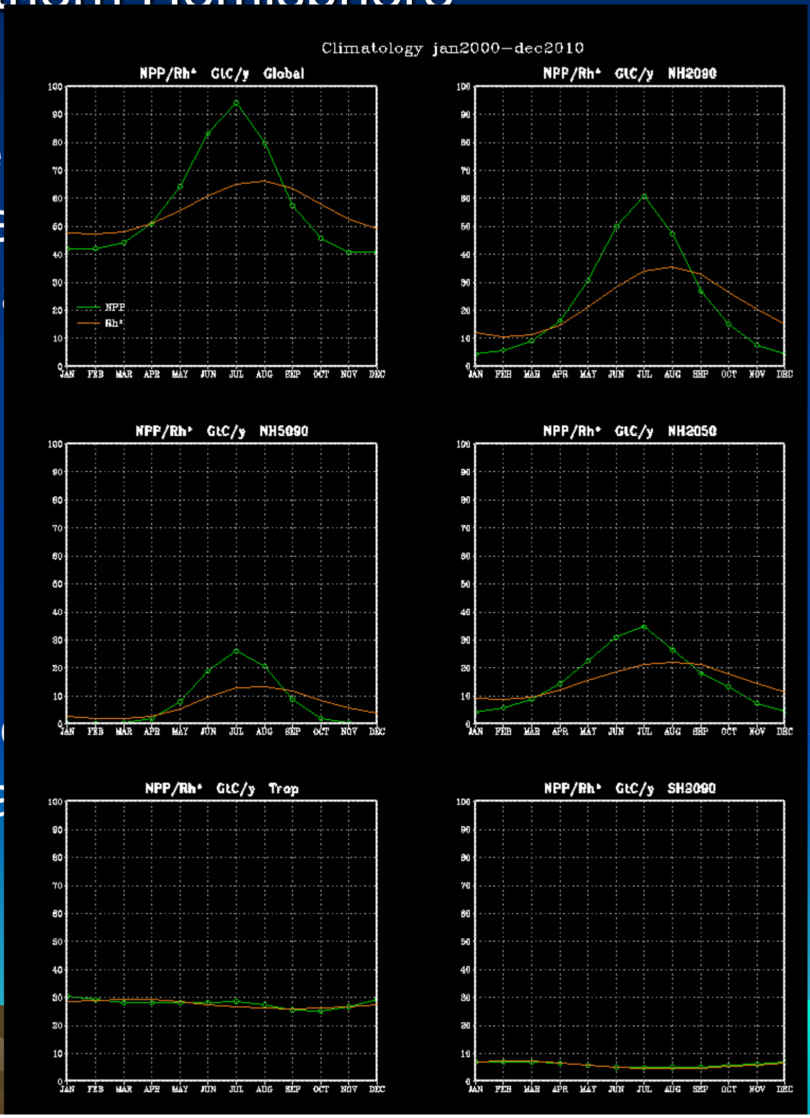


Fundamentals of CO2 seasonal cycle II
The Tropics and the Southern Hemisphere

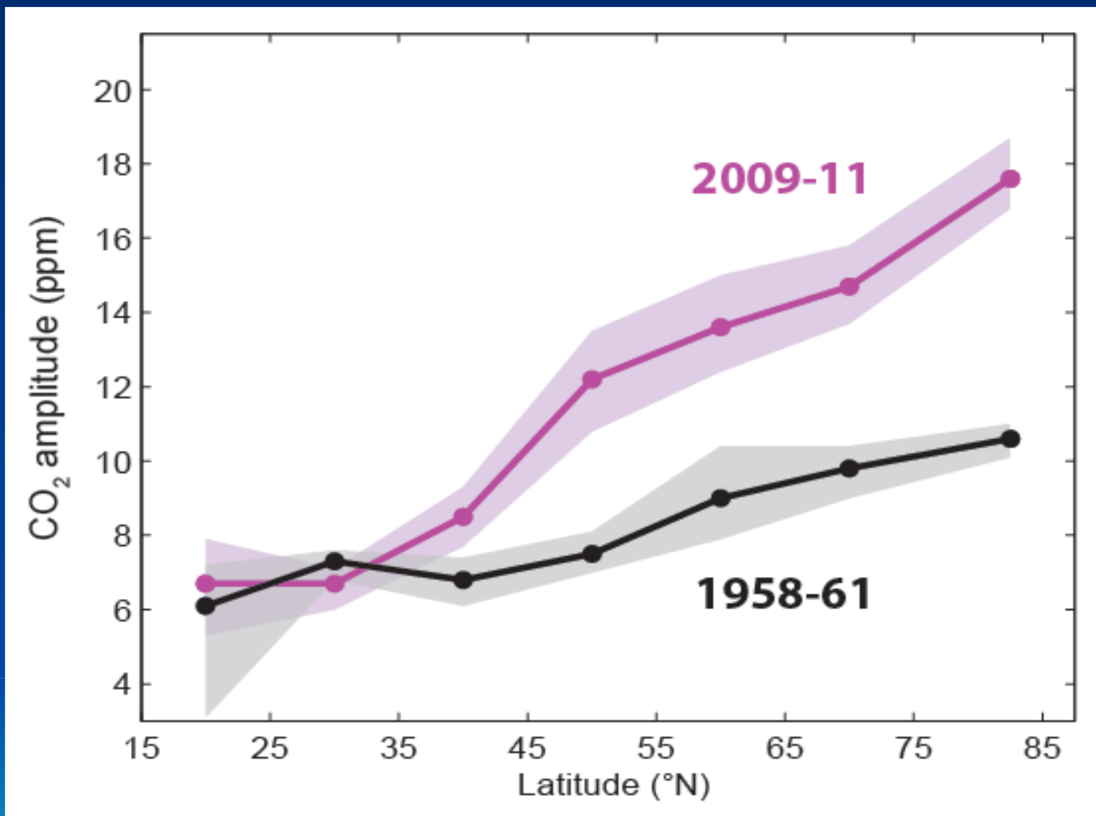
- Vegetation takes up atmosphe summer growing season, while decomposition has a much we

- FTA=Rh*-NPP

- where Fta is net land-atmosph (including heterotrophic respira



Aircraft data at 500 mb show large-scale increases in amplitude of 50-60% north of 45°N



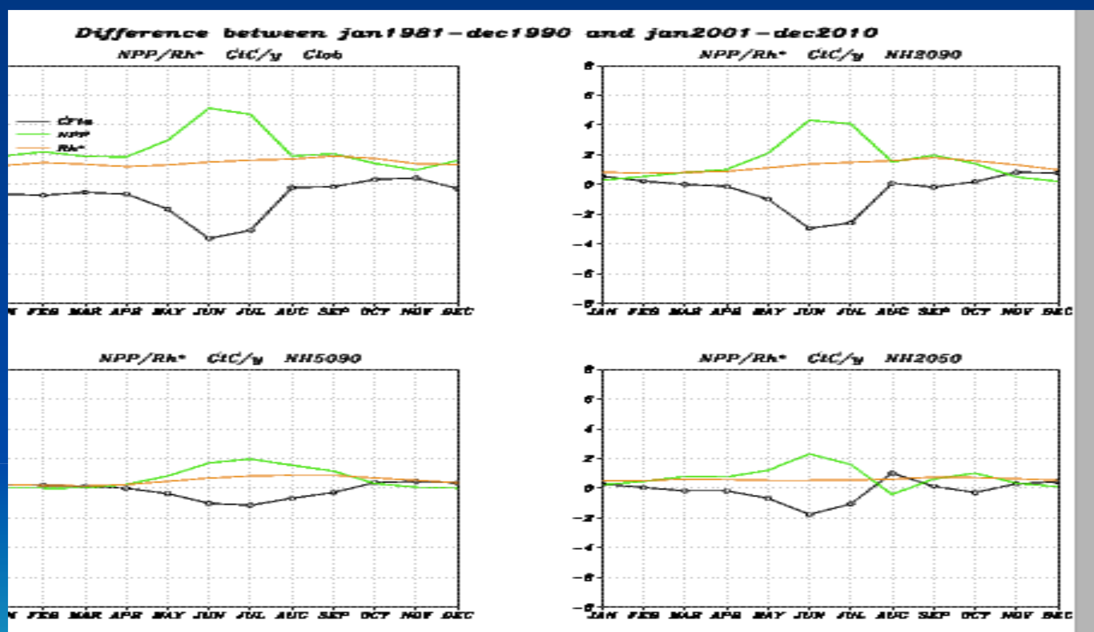
Lower latitudes changed by less than 25%

Similar pattern as Mauna Loa and Barrow

Seasonal exchange of CO_2 has increased strongly in northern land ecosystems over the last 50 years

rom Graven et al., Science, in press

See also H. Graven's poster here at the colloquium


Difference between jan1981–dec1990 and jan2001–dec2010
NPP/Rh* GtC/y Glob
NPP
Rh*
NPP/Rh* GtC/y NH2090
NPP/Rh* GtC/y NH5090
NPP/Rh* GtC/y NH2050
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC