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
- CO2 drawdown for 5 months.
- Not symmetric, not exactly sinusoidal
- Seasonal amplitude (max-min) ~ 6 ppm
Increased activity of northern vegetation inferred from atmospheric CO₂ measurements

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

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 CO₂. a, At Mauna Loa Observatory, Hawaii. Annual values of
But CO2 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.

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

The dominance of Northern Hemisphere vegetation

- Vegetation takes up atmospheric CO₂ 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

Latitudinal distribution of $F_{TA}$ seasonal amplitude (SA)
The mean CO2 seasonal cycle III
Ocean and fossil fuel

- Atmosphere CO2 growth rate (CO2g=dCO2/dt) is determined by Fossil fuel emissions (FFE), ocean and land fluxes:

\[
\text{CO2g} = \text{F}_{\text{net}} = \text{F}_{\text{FE}} + \text{F}_{\text{OA}} + \text{F}_{\text{TA}}
\]

- 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 sites 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 $F_{\text{net}}$ corresponds to the fastest drawdown of CO2, but not the minimum of CO2 itself. Instead, the minimum of CO2 is reached when $F_{\text{net}}$ 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.

$$\frac{dCO2_{\text{global}}}{dt} = F_{\text{net}}$$
How to calculate seasonal amplitude (SA) and its change
Deconstructing a legendary time series

\[ \text{CO2}(t) = A(t) \cdot S(t^*) + B(t) \]

- \( \text{CO2}(t) \) — 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 (deseasonalized); low frequency as well as high frequency signal

1961-1970 min in Oct
2001-2010 min in Sep
What caused CSA increase?

CO2 fertilization+

• Estimated contribution (Kohlmeier et al., 1989) for the CSA increase
  – CO2 (25%, based on lab), N/P deposition another 10-20%
  – May be even smaller given the recent understanding of the strength of the CO2 fertilization effect

FACE Experiments
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

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

[Graph showing Fossil fuel emissions]}

Fossil fuel emissions seasonal amplitude has increased 3-4 times

Andres et al. (2011) Tellus
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

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%)
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...
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, CH4
Erosion, Riverine flux
C13/C14 isotop
The VEgetation-Global Atmosphere-Soil Model (VEGAS)

Gross Primary Productivity (GPP)

Autotrophic Respiration ($R_a$)

Heterotrophic Respiration ($R_h$)

$CO_2/CH_4$

Human Animals Insects Fungi Microbes

Decomposers

$C_{dcmp}$ (0.2y)

Direct Oxidation (Fire)

$C_{lmeta}$ (0.5y)

$C_{lstru}$ (3y)

$C_{sfast}$ (1.5y)

$C_{smed}$ (20y)

$C_{sslow}$ (750y)

Turnover

Erosion

$C_{vege} = C_{leaf} + C_{woods} + C_{woodh} + C_{rootf} + C_{rootc}$

$C_{soil} = C_{lmeta} + C_{lstru} + C_{dcmp} + C_{sfast} + C_{smed} + C_{sslow}$
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 1st-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:
  \[ MI = M_0 M_1 (1 + 0.2 \tanh\left( \frac{\text{year} - 2000}{70} \right) ) \]

- Irrigation enhances GPP by a ‘gentle’ enhancement of the soil moisture dependent function:
  \[ \beta = 1 - \frac{1 - w_1}{W_{irrg}} \]
Planting and harvesting
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.

\[ HI_{crop} = 0.45(1 + 0.6 \tanh\left(\frac{\text{year} - 2000}{70}\right)) \]

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\textsubscript{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
Seasonal characteristics change

GPP change at a US Midwest location
1900s – Natural vegetation
1960s - Agriculture
2000s – Agriculture intensified

Impact of agriculture on model simulation

Mean seasonal cycle has a larger drawdown during growing season (~20%)
Change in CSA 1961-2010

- A long-term increase in seasonal amplitude (SA) by about 15% (MLO CO2g and VEGAS $F_{TA}$)

- Large decadal (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 a 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*
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**

<table>
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<tr>
<th></th>
<th>CLIM</th>
<th>CO2</th>
<th>LU</th>
<th>SUM</th>
<th>ALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961-2010 trend (% per year)</td>
<td>0.094</td>
<td>0.076</td>
<td>0.128</td>
<td>0.298</td>
<td>0.319</td>
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<tr>
<td>Percentage contribution to SUM</td>
<td>31%</td>
<td>26%</td>
<td>43%</td>
<td>100%</td>
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- **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
NPP and Rh\(^*\) 2001-10 minus 1961-70
Land-atmo carbon flux (CFta): 2001-10 vs. 1961-70

Graph showing the comparison of land-atmosphere carbon flux (CFta) between January 1961 to December 1970 and January 2001 to December 2010, with a focus on the difference between these two periods.
Vegetation takes up atmospheric CO2 during the spring/summer growing season, while decomposition has a much weaker seasonal cycle.

FTA = Rh* - NPP

FTA is net land-atmosphere carbon flux, including heterotrophic respiration.
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 CO₂ has increased strongly in northern land ecosystems over the last 50 years

From Graven et al., Science, in press

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