Improving our understanding of carbon cycle, drought and fire dynamics during the 21st century (and beyond!)

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Stats 5
Pillars of climate science data analysis

• Three information streams:
  – Observations of changing climate and ecosystems from ground measurement systems and experiments
  – Satellite observations
  – Climate modeling

• Analysis:
  – Climate modeling relies on Fortran
  – Analysis of surface and satellite observations, and climate modeling often done using scripting languages:
  – Most important are Python, R, Matlab, IDL
  – Most data and simulation output exists in several commonly used formats
  – NetCDF, HDF5, ASCII text, much less frequently now, binary
Satellite data streams

**NASA’s Terra and Aqua:**
- Fire-emitted heat
- Surface reflectance & burned area
- Vegetation type and amount
- Surface temperature
- Atmospheric carbon monoxide
- Smoke aerosol levels

**NASA’s Landsat:**
- High spatial resolution fire scars
- Burn severity
- Deforestation

**NASA’s GPM:**
- Rainfall
- Fire forecasting

**CALIPSO:**
- Plume heights
- Smoke aerosols

**GRACE:**
- Soil moisture
- Snowpack
- Fire forecasting
Data Access

• NASA DAACs
  – Satellite data from several satellites, include Aqua and Terra
  – https://lpdaac.usgs.gov/

• Earth System Grid Federation
  – Climate model simulation output from 30 modeling centers
Two types of carbon feedback loops influence the temporal evolution of atmospheric CO$_2$. 

**Climate–carbon feedback**

- $\gamma$

**Concentration–carbon feedback**

- $\beta$
Science questions:

• How are ocean and land contributions to the climate-carbon feedback likely to evolve over time?
• How will climate change influence drought and fire dynamics?

The Community Earth System Model

Graphic credit: UCAR
What are important climate-carbon processes and feedbacks?

Processes in CESM1(BGC):

• Ocean:
  – Increasing stratification with warming
  – Dissolved inorganic carbon sensitivity to temperature
  – Biological pump responses to stratification

• Land:
  – Drought & temperature effects on primary production
  – Soil decomposition increases in response to temperature
  – Response of fires to changes in fuels and drought
  – Land use change

Not yet in most CMIP ESMs:

  – Species range shifts
  – Phosphorus limits on land carbon uptake (integration underway into ACME)
  – Permafrost dynamics (now in CLM4.5)
  – Peatlands
  – Fires
  – Insect-driven mortality
  – Drought effects on tree mortality
  – Climate effects on land use change
Experimental design: All three simulations have prescribed atm. CO₂ from RCP8.5.
## CESM1(BGC) experimental design

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Short name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully coupled</td>
<td>Full</td>
<td>CO$_2$ and other atmospheric anthropogenic drivers influence radiative transfer, biogeochemistry responds to CO$_2$ increases</td>
</tr>
<tr>
<td>No CO$_2$ radiative forcing</td>
<td>No CO$_2$ forcing</td>
<td>Non-CO$_2$ anthropogenic drivers influence radiative transfer, biogeochemistry responds to CO$_2$ increases</td>
</tr>
<tr>
<td>No anthropogenic radiative forcing from greenhouse gases or aerosols</td>
<td>No anthro. forcing</td>
<td>No atmospheric anthropogenic climate change, biogeochemistry responds to CO$_2$ increases</td>
</tr>
</tbody>
</table>

Validation:
Lindsay et al. (2014), Moore et al. (2013), Long et al. (2013), Keppel-Aleks et al. (2013)
Validation of carbon cycle processes in CESM with the International Land Model Benchmarking System

Mu et al., Lawrence et al. in prep.
Climate-carbon gain computed from compatible fossil fuel emissions (E) from fully coupled and no CO$_2$ forcing simulations

\[ g = \frac{E_{\text{no}CO_2} - E_{FC}}{E_{\text{no}CO_2}} \]
CESM1(BGC) temperature and salinity drivers of stratification at 2100

Randerson et al. (2015) GBC, Fu et al. (2015) BGD
Shutdown in Atlantic Meridional Overturning Reduces Carbon Uptake in CESM

(a) $T_A: 2100-1850$

(b) $T_A: 2300-1850$

(c) ocean carbon: 2100-1850

(d) ocean carbon: 2300-1850

Kg C per m$^2$
Forests in Central and South America exhibit a high degree of vulnerability to climate change-induced carbon loss.
Amazon broadleaf forest burned area from the fully coupled simulation
Toward the development of a global early warning system for fires

A conceptual model for fire predictability in the Amazon is based on a forest soils capacitor mechanism (Chen et al., 2013, JGR-B).
2015 Amazon fire season forecast
Using SSTs through March for a fire season that spans July-October

Conclusions

• Our understanding of Earth system dynamics, including processes that may contribute to ecosystem collapse, is woefully incomplete beyond 2100

• Ocean contribution to the climate-carbon feedback increases considerably over time for a “business as usual” scenario, and exceeds contributions from land after 2100
  – Land feedback likely reduced from land use change
  – Ocean feedback strength closely related to ocean heat content and AMOC shutdown

• Forcing from non-CO$_2$ agents for the RCP8.5 scenario is almost enough to surpass the 2 °C dangerous interference limit

• Tropical forests in Central and South America have a higher vulnerability to climate change than other tropical regions

• A better understanding and representation of fire processes in ESMs is essential for accurately predicting carbon cycle dynamics in drought-prone areas
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Fire Forecasting Model Performance

Chen et al. (2011) Science

Terra satellite number of fires

MODIS Predicted

Low fire years

High fire years

2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

# Mha⁻¹ yr⁻¹