Catchment-CN: Using CLM Carbon Dynamics in the NASA GMAO Land Model

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Overview

1. Introduction to Catchment-CN
2. Science Applications
   i. Impact of atmospheric carbon variability on terrestrial carbon fluxes
   ii. Impact of land initial conditions on sub-seasonal to seasonal (S2S) carbon forecasts
   iii. Evaluation of fire carbon emissions
   iv. Vegetation parameter optimization
3. Transition to Catchment-CN 5.0
**Catchment-CN model**

- Experimental land component in NASA GEOS Earth System Model
- Merger of Catchment LSM & CLM CN dynamics

**The Catchment LSM:**
- Calculates all the water and energy balances
- Provides the CN model:
  - Soil moisture and temperature
  - Canopy temperature
  - Snow depth and coverage

**The CN model:**
- Calculates all the carbon and nitrogen fluxes and reservoirs, and
- Provides the Catchment LSM LAI and canopy conductance.

⇒ We do not use CLM soil layer structure, hydrology, energy balance calculations, etc..
⇒ We use only CLM photosynthesis, stomatal conductance, and C and N flux and reservoir calculations.
i. Impact of atmospheric CO2 variability on terrestrial biosphere

**Objective:** Quantify the sensitivity of terrestrial carbon fluxes (GPP) on the spatiotemporal variability of atmospheric CO2

**Figure:** Overview of experiments changing nature of atmospheric CO2 variability

- **3hCO2 (CTRL)**: 3-hourly (365x14x8 fields)
- **dCO2**: Daily (365x14 fields)
- **mCO2**: Monthly (12x14 fields)
- **maCO2**: Mean annual (spatially varying)
- **magCO2**: Mean annual global
- **magtCO2**: Mean annual global trend (interpolated)
- **cCO2**: Constant (392.34 ppm)

Lee et al., 2018
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i. Impact of atmospheric CO2 variability on terrestrial biosphere

(a) No diurnal variation

(b) ΔGPP (dCO2 – Control) [%]

Figure: Impact of removing CO2 diurnal variability on GPP

Lee et al., 2018
i. Impact of atmospheric CO2 variability on terrestrial biosphere

Conclusion: Accounting for atmospheric CO2 temporal variability reduces terrestrial carbon fluxes overall

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Lee et al., 2018
i. Impact of atmospheric CO2 variability on terrestrial biosphere

**Conclusion:** Accounting for atmospheric CO2 temporal variability reduces terrestrial carbon fluxes overall.

**Figure:** Impact of removing CO2 diurnal variability on GPP

**Figure:** Impact of removing CO2 spatial variability on GPP
i. Impact of atmospheric CO2 variability on terrestrial biosphere

**Conclusion:** Accounting for atmospheric CO2 temporal variability reduces terrestrial carbon fluxes overall.

**Figure:** Impact of removing CO2 diurnal variability on GPP

**Conclusion:** Accounting for atmospheric CO2 spatial variability increases terrestrial carbon fluxes on average, but with regional variations

**Figure:** Impact of removing CO2 spatial variability on GPP  
Lee et al., 2018
i. Impact of atmospheric CO2 variability on terrestrial biosphere

**Conclusion:** Accounting for atmospheric CO2 temporal variability reduces terrestrial carbon fluxes overall.

**Conclusion:** Magnitude of sensitivities is small relative to magnitude of GPP.

**Conclusion:** Accounting for atmospheric CO2 spatial variability increases terrestrial carbon fluxes on average, but with regional variations.
ii. Role of Land in S2S carbon forecasts

Objective: Investigate the impact of land initial conditions (IC) on subseasonal-to-seasonal (S2S) forecasts of GPP

Lee et al., in prep
ii. Role of Land in S2S carbon forecasts

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*Figure: Experiment set-up*
ii. Role of Land in S2S carbon forecasts

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**CTRL:** Regular forecast, meteorology and land ICs vary temporally

**EXP2016_met:** Fixed (2016) meteorology; soil moisture and carbon states vary temporally → impact of land ICs

**EXP2016_met_sm:** Fixed (2016) meteorology and soil moisture ICs; carbon states vary temporally → impact of carbon ICs

*Figure:* Experiment set-up

Lee et al., in prep
ii. Role of Land in S2S carbon forecasts

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**CTRL:** Regular forecast, meteorology and land ICs vary temporally

**EXP2016_met:** Fixed (2016) meteorology; soil moisture and carbon states vary temporally -> impact of land ICs

**EXP2016_met_sm:** Fixed (2016) meteorology and soil moisture ICs; carbon states vary temporally -> impact of carbon ICs

**Conclusion:** Land ICs significantly contribute to carbon forecast skill at spatial and temporal scales

**Conclusion:** Impact of soil moisture ICs dominates impact of carbon ICs at early lead months

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Lee et al., in prep
Objective: Evaluate Catchment-CN4.5 fire carbon emissions and burnt area against Global Fire Emissions Database
iii. Evaluation of Wildfire simulations

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**Fire burned area (1997 – 2016)**

GFED v4.1s

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**Conclusion:** Catchment-CN4.5 captures observed wildfire impact better than Catchment-CN4.0

Follette-Cook et al., in prep
iii. Evaluation of Wildfire simulations

Objective: Evaluate Catchment-CN4.5 fire carbon emissions and burnt area against Global Fire Emissions Database

Fire carbon emissions (1997 – 2016)

Catchment-CN4.0
~500 Tg C yr\(^{-1}\)

Catchment-CN4.5
~1700 Tg C yr\(^{-1}\)

GFED v4.1s
~2100 Tg C yr\(^{-1}\)

van der Werf et al., 2017

Follette-Cook et al., in prep
iii. Evaluation of Wildfire simulations

**Objective:** Evaluate Catchment-CN4.5 fire carbon emissions and burnt area against Global Fire Emissions Database

Fire carbon emissions (1997 – 2016)

- Catchment-CN4.5
  - $\sim 1700$ Tg C yr$^{-1}$

- GFED v4.1s
  - $\sim 2100$ Tg C yr$^{-1}$

Improved fire carbon emissions in Catchment-CN4.5. However, these are accompanied by a reduced skill in modelling terrestrial carbon fluxes

van der Werf et al., 2017

Follette-Cook et al., in prep
iv. Vegetation Parameter Optimization

Objective: Use MODIS FPAR observations to optimize Catchment-CN vegetation parameters.

- Calibration parameters:
  - Timing of phenological cycle (seasonal variability)
  - Photosynthetic efficiency (bias)
  - Carbon storage/allocation (interannual variability)

Kolassa et al., 2020
iv. Vegetation Parameter Optimization

Change in RMSE vs MODIS FPAR

$\Delta \text{RMSE} = \text{RMSE}_{\text{cal}} - \text{RMSE}_{\text{local}}$; $\Delta \text{RMSE} = -0.025$

Kolassa et al., 2020
iv. Vegetation Parameter Optimization

- Dominance of bias in model error skews calibration towards efficiency parameters

Kolassa et al., 2020
iv. Vegetation Parameter Optimization

Dominance of bias in model error skews calibration towards efficiency parameters

Conclusion: Two-stage calibration to address first the bias and then the timing would be more effective

Kolassa et al., 2020

Change in RMSE vs MODIS FPAR

$\Delta{\text{RMSE}}_{\text{cal}} - \Delta{\text{RMSE}}_{\text{nocal}}; \Delta \text{RMSE}: -0.025$

$\Delta{\text{abs(bias)}}_{\text{cal}} - \Delta{\text{abs(bias)}}_{\text{nocal}}; \Delta \text{abs(bias)}: -0.035$

$\Delta R_{\text{cal}} - \Delta R_{\text{nocal}}; \Delta R: -0.0075$
iv. Vegetation Parameter Optimization

- Calibration is effective, but skill changes are small relative to total error

**Conclusion:** Parameter estimation can only reduce a part of the total model error, model structure changes are needed to address remaining error

Kolassa et al., 2020
Looking ahead: Work with CatchmentCN5.0

Catchment-CN5.0: Catchment + CLM5.0

Applications:

(Relatively) Immediate:
-- Analyses of fire in the climate system, including all feedbacks between land and atmosphere (trace gas emissions from fire)
-- Incorporation of CatchmentCN5.0 (in some form) into the next version of the operational S2S forecast system – allow initialization and evolution of vegetation phenology to influence forecasts
-- More studies of the linkages between the water, energy, and carbon cycles in the coupled land/atmosphere system (improvements from plant hydraulics)

Longer-term goals:
-- Incorporation of CatchmentCN5.0 into the full suite of GMAO operational systems, including reanalysis generation
-- Studies of the carbon cycle with fully coupled ocean/land/atmosphere system
References


Catchment-CN model

Each basic Catchment land surface element is separated into:

- Three dynamic hydrological zones that vary with time depending on water availability
- Three static carbon zones (10%, 45%, 45%) with independent carbon states traced in each.

Our treatment of subgrid-scale hydrology can thus capture topographical effects on vegetation distributions.

Koster et al., 2014
Performance of Catchment-CN4.5 – GPP

(42.54N, 72.17W)
Deciduous Broadleaf Forest

(44.45N, 121.56W)
Evergreen Needleleaf Forest

Follette-Cook et al., in prep
Main issue with Catchment-CN4.5 GPP

**NCAR**

- CLM4 C,N
- CLM4 Energy, Water
- GPP=165 Pg C yr⁻¹
  - (Bonan et al. 2011)

**GMAO**

- CLM4 C,N
- Catchment Energy, Water
- MERRA-2 Forcing data
- GPP=127 Pg C yr⁻¹
  - (Lee et al. 2018)

- CLM4.5 C,N
- CLM4 Energy, Water
- Qian et al. (2006) Forcing data
- GPP=130 Pg C yr⁻¹
  - (Bonan et al. 2011, 2012)

- CLM4.5 C,N
- Catchment Energy, Water
- MERRA-2 Forcing data
- GPP= ...

- TOO HIGH!
- About right
- TOO LOW!
Main issue with Catchment-CN4.5 GPP

**NCAR**
- CLM4 C,N
- CLM4 Energy, Water
- Qian et al. (2006) Forcing data

⇒ GPP = 165 Pg C yr\(^{-1}\)

**GMAO**
- CLM4 C,N
- Catchment Energy, Water
- MERRA-2 Forcing data

⇒ GPP = 127 Pg C yr\(^{-1}\)

This (and other problems) have prompted us to move towards the implementation of Catchment-CN5.0 (Catchment merged with CLM5.0)

Update to CLM4.5

**NCAR**
- CLM4.5 C,N
- CLM4 Energy, Water
- Qian et al. (2006) Forcing data

⇒ GPP = 130 Pg C yr\(^{-1}\)

(Bonan et al. 2011, 2012)

**GMAO**
- CLM4.5 C,N
- Catchment Energy, Water
- MERRA-2 Forcing data

⇒ GPP = ...

TOO LOW!

About right
**Science changes to be implemented in Catchment-CN5.0**

**Vegetation:**
- Introduction of plant hydraulics and hydraulic redistribution
- Stomatal conductance formulation choice: Medlyn (default) or Ball-Berry; based on N-limited photosynthesis
- *FATES* ecosystem demography
- Ozone damage to plants

**Nitrogen:**
- More mechanistic representation of nitrogen cycle through Fixation and Uptake of Nitrogen (FUN) model
- Introduction of separate soil nitrogen pools
- Nitrogen uptake has ‘carbon cost’ for plants
  - Variable C:N ratio in leaves
  - Leaf nitrogen, photosynthesis and stomatal conductance vary according to nitrogen cost
  - Inclusion of Leaf Use of Nitrogen for Assimilation (LUNA) model: Vcmax dependent on leaf N and environmental drivers -> prognostic

**Carbon:**
- Fixed carbon allocation
- Weaker decrease of soil carbon decomposition rate with depth
- Stronger soil moisture control on decomposition

**Fire:**
- Fire occurrence and spread depends on fuel wetness for non-peat fires
- *Simulation of trace gas emissions*

**Crop:**
- A multitude of crop functional types (CFTs) that are treated independently from PFTs
- Coupled to an irrigation model