The Community Land Model, version 5

Building a community to build a community model

David Lawrence and many, many others

dlawren@ucar.edu

https://github.com/ESCOMP/ctsm
CCSM Distinguished Achievement Award to the Land Model Working Group
“for their cooperative work in producing CLM3.5 which is a considerable improvement over CLM3“

**CLM3.5**

- Updated surface data sets
- New parameterizations for canopy integration, canopy interception
- Frozen soil
- Soil evaporation
- TOPMODEL-based surface and subsurface runoff
- Simple groundwater model

**Partitioning of Evapotranspiration**

[Chart showing partitioning of evapotranspiration]
CLM3.5 (May 2007)

- Updated surface data sets
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- Simple groundwater model
CLM3.5

CLM4 (June 2010)

- Updated surface data sets
- New parameterizations for canopy integration, canopy interception
- Frozen soil
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- TOPMODEL-based surface and subsurface runoff
- Simple groundwater model

- Carbon and nitrogen model
- Prognostic vegetation state / phenology
- Transient land cover change
- Wood harvest
- ‘Permafrost-enabled’ – organic soil, deep ground
- Aerosol deposition onto snow
- Urban model

CLM4 widely used
> 1000 citations for paper
> 1300 citations for Tech Note
• Updated surface data sets
• New parameterizations for canopy integration, canopy interception
• Frozen soil
• Soil evaporation
• TOPMODEL-based surface and subsurface runoff
• Simple groundwater model

CLM3.5

• Carbon and nitrogen
• Prognostic vegetation phenology
• Transient land cover
• Wood harvest
• ‘Permafrost-enabled’ deep ground
• Aerosol deposition
• Urban model

CLM4

• Vertically-resolved soil C/N
• Co-limitation and acclimation of photosynthesis
• Variable river flow rates
• Natural CH₄ emissions
• Human triggering and suppression of fire
• Cold region hydrology
• Revised lake model
• Multiple urban density classes

CLM4.5 (June 2013)
<table>
<thead>
<tr>
<th>CLM3.5</th>
<th>CLM4</th>
<th>CLM4.5</th>
<th>CLM5 (Feb 2018)</th>
</tr>
</thead>
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More than 50 researchers from ~30 institutions involved in development and assessment of CLM5
CLM land-only forced with GSWP3

for full CLM results:
www.cesm.ucar.edu/experiments/cesm2.0/land/diagnostics/clm_diag_ILAMB.html

International Land Model Benchmarking (ILAMB) project

- Integrates analysis of ~30 variables against 70+ global, regional, and site-level observational datasets
- Graphics and scoring system for
  - RMSE
  - bias
  - seasonal cycle phase
  - spatial patterns
  - interannual variability
  - variable-to-variable relationships

Lawrence et al., 2019
<table>
<thead>
<tr>
<th>Variable to Variable Comparisons</th>
<th>CLM4</th>
<th>CLM4.5</th>
<th>CLM5</th>
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<tbody>
<tr>
<td>Burned Area vs Precipitation</td>
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<tr>
<td>Burned Area vs Surf Air Temp</td>
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<td>GPP vs ET</td>
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<td>GPP vs Surf Down SW Radiation</td>
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**Legend**
- **Red** indicates a worse value.
- **Green** indicates a better value.

**Graphs**
- **CLM4 (0.55)**
- **CLM5 (0.88)**
ILAMB assessment of CMIP6 models

Hoffman et al, in prep
CLM land-only forced with GSWP3

<table>
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<tr>
<th>Ecosystem and Carbon Cycle</th>
<th>CLM4</th>
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<tr>
<td>Biomass</td>
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<td>Burned Area</td>
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<td>Carbon Dioxide</td>
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<td>Gross Primary Productivity</td>
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<td>Leaf Area Index</td>
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<td>Global Net Ecosystem Carbon Balance</td>
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<td>Net Ecosystem Exchange</td>
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<td>Ecosystem Respiration</td>
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<td>Soil Carbon</td>
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<td>Terrestrial Water Storage Anomaly</td>
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1 PgC $\approx$ 0.5 ppm CO$_2$

- **Improved response to CO$_2$ and N-addition** (Wieder et al., 2019)
- **On longer timescales, uncertainty associated with historical climate uncertainty is high** (Bonan et al., 2019)
- **Strong parametric dependence** (Fisher et al., 2019)
Land carbon stock trends

CLM4

Ecosystem Carbon

CLM5

Zonal mean year-on-year changes in land ecosystem carbon

Blues are losses of carbon
Reds are gains of carbon
Soil hydrology (variable soil depth)

Grid cell in southwest US

CLM4.5

CLM5

ET

Soil moisture
Land management in CLM5

Exploring tradeoffs and co-benefits of various forms of land management

**Included in default CLM5/CESM2**
- Global crop model; planting, grain fill, harvest
- Crop irrigation
- Crop industrial fertilization
- Wood harvest
- Urban environments
- Anthropogenic fire ignition and suppression, degradation fires

* Corn
* Winter wheat
* Sugarcane
* Soy
* Cotton
* Rice

* Temperate and tropical varieties
Land-only land management experiments with CLM5 Embedded impacts model

Crop Yield

UN FAO
CLM5 all manage

Irrigation
Industrial fertilization
↑ crop area

Lombardozzi et al., 2020
Terrestrial Processes in CMIP6

Coordinated activities to assess land role and response to climate and climate change

• **Land-only** simulations forced with obs historical climate, land systematic biases

• **Land Use (LUMIP)**
  land use forcing on climate and carbon, impacts of land management, land management as mitigation

• **Water, Land-atmos (LS3MIP)**
  biogeophys feedbacks including soil moisture and snow feedbacks

• **Carbon (C4MIP)**
  land biogeochemical feedbacks on climate, permissible emissions
The CLM5 Development Process
Scientific priorities driving CLM development

Understanding and predicting …

• land processes in weather, climate variability, and climate change
• ecosystem vulnerability/resilience and impacts on carbon cycle and ecosystem services
• sources of predictability from land; ecological prediction
• land management for climate change and GHG mitigation; tradeoffs and co-benefits
• water and food security

For CLM5, parallel focus on mechanistic improvements and expansion of capabilities

• hydrology more consistent with state-of-art understanding
• more ecologically-relevant plant carbon, nutrient, and water dynamics
• expansion of representation of land management
The community that built CLM5

CLM

Hydrology
Ecology
Biogeo-Chemistry
Cryosphere

Land Management

CESM or CIME compatible model

Glacier
Lake
Runoff
River discharge
Urban
Wood harvest
Wetland
River Routing
Flooding
Competition
Disturbance
Vegetation Dynamics
Land Use Change
Growth
Crops
Irrigation
Wetland
Crops
Irrigation
Wetland
Crops
Irrigation

NCAR UCAR
The community that built CLM5
Contributions rolling in from 2012-2016

Hydrology
Land Management
Ecology
Cryosphere
Biogeochemistry
CLM
CESM or CIME compatible model

The community that built CLM5 with contributions rolling in from 2012-2016.
A big pile of things, will they work together?

- Flexible leaf stoichiometry
- Leaf N optimize for photosynthesis
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A big pile of things, will they work together?

Software integration

... and science integration
A big pile of things, will they work together?

Merging 3 branches of nitrogen-cycle development
Integration of contributions
Finally, a model configuration that runs with everything we wanted

software integration

... and science integration
Finally, a model configuration that runs with everything we wanted … but many new uncertain parameters and a growing realization that in some parts of the parameter space, plants do not survive through spinup

“The Dead Plant Problem”
Solving the Dead Plant Problem

Global parameter optimization
via machine learning!

many attempts, mostly dead

... meanwhile, the rest of the team focused on painstaking 'hand-tuning' of parameters

... while I ran interference with Jean-Francois
January 25, 2017 (a reenactment)

The scene: We were desperately trying to finalize CESM2 so that we could take advantage of the Cheyenne / Yellowstone overlap to run CMIP simulations. After multiple extensions, Jean-Francois gave us one last weekend to sort out our parameter problems or revert to CLM4.5. On Friday, Keith Oleson set off two CLM spinups, one with a new machine-learning calibrated parameter set and one with our best hand-tuned parameters.

6:45am Monday morning: Keith comes into my office and shows me the calibrated parameter results – mainly dead plants. Dave – “ok, that’s expected, check the other parameter set.”

10 minutes later: email from Keith – “Plants in backup parameter set are not surviving either. Uh-oh.”

20 minutes later: another email from Keith – “Scratch that. Bug in my code. Backup parameter set results looks great!”
Finally, most plants were living and many other metrics looked good.
Misadventures in parameterization and why the robots haven’t won (yet)

Ben Sanderson, Rosie Fisher, David Lawrence, Keith Oleson and Will Weider

(YET)
see intro to CLM5 Large Parameter Perturbation Experiments Community Project in Will Wieder’s LMWG presentation this afternoon
Timeseries of sea ice thickness in Labrador sea

Chimera-like parameter file
Solving the Dead Plant Problem

The giant crop problem
The irrigation problem
The glacier runoff problem
The C4 grass productivity problem
The hydraulic redistribution problem
The energy conservation problem
...

February 2018 CLM5 Release!
Perspectives on community driven model development

- Earth System model development is hard
- Research priorities can be used to guide decisions
- A robust and diverse development and user community is essential (and fun)
- Build and maintain that community
  - Be responsive to contributing collaborators
  - Encourage contributors to take ownership
  - Provide clear software development and decision-making guidance
  - Acknowledge and reward model development
Annual award, sponsored by Drew’s family, for the “best student or postdoc performance” at winter LMWG meeting
The Land Model Working Group

Andrew Slater Award

Is hereby granted to:

???

for best student or postdoc performance at LMWG Workshop
The Land Model Working Group

Andrew Slater Award

Marysa Laguë
U. Washington

Daniel Kennedy
Columbia University

Leah Birch
Woods Hole Inst

Megan Fowler
UC Irvine

Jesse Needham
LBNL

Katie Dagon
NCAR
• Earth System model development is hard
• Research priorities can be used to guide decisions
• A robust and diverse development and user community is essential (and fun)
• Build and maintain that community
• Clean, well-structured, and well-documented code is worth its weight in gold
• Full integration requires in-house experts
• Set realistic timelines and try hard to meet them

- Not: “I love deadlines. I like the whooshing sound they make as they fly by.” – Douglas Adams
Perspectives on community driven model development

- Earth System model development is hard
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- Build and maintain that community
- Clean, well-structured, and well-documented code is worth its weight in gold
- Full integration requires in-house experts
- Set realistic timelines and try hard to meet them
- Don’t panic!
- Keep it fun!
Keep it fun!
Some people think football (soccer) is a matter of life and death.

... I assure you, it's much more serious than that.
“Some people think climate / land modeling is a matter of life and death

... I assure you, it's much more serious than that”
Thanks again!
The “situation”

1. **Model proliferation**
Increasing number of land models, including 2 major models at NCAR

**CLM (CGD)**

**Noah-MP, WRF-Hydro (RAL)**

2. **“Shantytown” syndrome**
Ad-hoc approach to model development
The Community Terrestrial Systems Model
a model for research and prediction in climate, weather, water, and ecosystems

CLM (CGD)

SUMMA concepts

CTSM

Unify land modeling across NCAR

• More efficient use of NCAR and community resources
• Consistent with NCAR emphasis on unified modeling
• Extend NCAR leadership in community modeling
• Accelerate advances
• Increase flexibility and robustness of process representation, spatial disaggregation, and numerical solution (SUMMA concepts, modularization)
• Enable more hypothesis-driven science
• Integrate and expand land modeling research and development community
• Expand funding opportunities?
CLM continually evolving in response to research needs of next generation science questions

- Ecosystem vulnerability and impacts on carbon cycle and ecosystem services
- Sources of predictability from land processes; Ecological prediction
- Impacts of land use and land-use change on climate, carbon, water, and extremes
- Water and food security in context of climate change, climate variability, and extreme weather
The Scientific Paper Is Outdated

For the sake of research, their careers, and their mental health, scientists should spend more time developing software

By Ryan Abernathey | FEBRUARY 16, 2020

www.chronicle.com/article/The-Scientific-Paper-Is/248045
The interdisciplinary evolution of land models
The interdisciplinary evolution of land models

Land as a lower boundary to the atmosphere

Land as an integral component of the Earth System

Surface Energy Fluxes

Figure: Fisher, Lawrence, Bonan, Clark, unpublished