The Community Land Model - Biogeophysics

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Thanks to Dave Lawrence (LMWG co-chair), Gordon Bonan (TSS Head), and rest of TSS group for contributions

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Outline

• Role of a land surface model in an Earth System Model
• Main features of CLM

  – Structural aspects (surface/input datasets)
  – Parameterizations and submodels
    • Biogeophysics (SP)
    • Peter Lawrence - Biogeochemistry (BGC)

What distinguishes a land model within an Earth system model?

Land as the critical interface through which people affect, adapt to, and mitigate global environmental change

• Expanded capability to simulate ecological, hydrological, biogeochemical, and socioeconomic forcings and feedbacks in the Earth system
• Increased emphasis on impacts, adaptation, and mitigation
• Requires an integrated assessment modeling framework

  – Human systems (land use, urbanization, energy use)
  – Biogeochemical systems (C-N-P, trace gas emissions, isotopes)
  – Water systems (resource management, freshwater availability, water quality)
  – Ecosystems (disturbance, vulnerability, goods and services)
The role of the land model in an Earth System Model

– exchanges of momentum, energy, water vapor, CO$_2$, dust, and other trace gases/materials between land surface and the overlying atmosphere (and routing of runoff to the ocean)

– states of land surface (e.g., soil moisture, soil temperature, canopy temperature, snow water equivalent, C and N stocks in vegetation and soil)

– characteristics of land surface (e.g., soil texture, surface roughness, albedo, emissivity, vegetation type, cover extent, leaf area index, and seasonality)
Model design constraints and philosophy

Coupling with the atmosphere every model timestep is a fundamental constraint (< 30 minute timestep)
So is the need to represent the global land surface, including Antarctica, the Tibetan Plateau along with forests, grassland, croplands, tundra, desert scrub vegetation, and cities
Conservation of energy and mass is required
We strive to develop a process-level understanding across multiple ecosystems and at multiple timescales (instantaneous, seasonal, annual, decadal, centuries)

Top-down, empirical modeling

Thornthwaite: Monthly potential evapotranspiration driven by air temperature

\[ E_p = 16 \left( \frac{L}{12} \right) \left( \frac{N}{30} \right) \left( \frac{10T}{I} \right)^{a} \]

Priestley–Taylor equation: Daily potential evapotranspiration driven by radiation

\[ E_p = \alpha \frac{s}{s + \gamma} \frac{R_n}{\lambda} \]

Production efficiency model driven by radiation and empirical scalars

\[ GPP = \varepsilon S \downarrow f_1(T) f_2(\theta) f_3(VPD) \]

Annual NPP driven by temperature and precipitation

\[ NPP = \min \left\{ \frac{3000}{1 + \exp(1.315 - 0.119T)}, 3000 \left[1 - \exp(-0.000664P)\right] \right\} \]

Process modeling

Penman-Monteith equation
Farquhar photosynthesis model
Ball-Berry stomatal conductance model
Fick’s law of diffusion
Darcy’s law and Richards equation (soil water)
Fourier’s law (heat conduction)
# The role of CLM in CESM: Land to Atmosphere

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Latent heat flux</td>
<td>( \lambda_{vap} E_v + \lambda E_g )</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Sensible heat flux</td>
<td>( H_v + H_g )</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Water vapor flux</td>
<td>( E_v + E_g )</td>
<td>mm s(^{-1})</td>
</tr>
<tr>
<td>Zonal momentum flux</td>
<td>( \tau_x )</td>
<td>kg m(^{-1}) s(^{-2})</td>
</tr>
<tr>
<td>Meridional momentum flux</td>
<td>( \tau_y )</td>
<td>kg m(^{-1}) s(^{-2})</td>
</tr>
<tr>
<td>Emitted longwave radiation</td>
<td>( L \uparrow )</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Direct beam visible albedo</td>
<td>( I_{vis}^{\mu} )</td>
<td>-</td>
</tr>
<tr>
<td>Direct beam near-infrared albedo</td>
<td>( I_{nir}^{\mu} )</td>
<td>-</td>
</tr>
<tr>
<td>Diffuse visible albedo</td>
<td>( I_{vis} )</td>
<td>-</td>
</tr>
<tr>
<td>Diffuse near-infrared albedo</td>
<td>( I_{nir} )</td>
<td>-</td>
</tr>
<tr>
<td>Absorbed solar radiation</td>
<td>( \frac{\dot{S}}{} )</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>Radiative temperature</td>
<td>( T_{rad} )</td>
<td>K</td>
</tr>
<tr>
<td>Temperature at 2 meter height</td>
<td>( T_{2m} )</td>
<td>K</td>
</tr>
<tr>
<td>Specific humidity at 2 meter height</td>
<td>( q_{2m} )</td>
<td>kg kg(^{-1})</td>
</tr>
<tr>
<td>Snow water equivalent</td>
<td>( W_{sno} )</td>
<td>m</td>
</tr>
<tr>
<td>Aerodynamic resistance</td>
<td>( r_{am} )</td>
<td>s m(^{-1})</td>
</tr>
<tr>
<td>Friction velocity</td>
<td>( u_* )</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>2. Dust flux</td>
<td>( F_j )</td>
<td>kg m(^{-2}) s(^{-1})</td>
</tr>
<tr>
<td>Net ecosystem exchange</td>
<td>NEE</td>
<td>kgCO(_2) m(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>
## The role of CLM in CESM: Atmosphere to Land

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<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference height</td>
<td>$z'_{atm}$</td>
<td>m</td>
</tr>
<tr>
<td>Zonal wind at $z_{atm}$</td>
<td>$u_{atm}$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Meridional wind at $z_{atm}$</td>
<td>$v_{atm}$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Potential temperature</td>
<td>$\theta_{atm}$</td>
<td>K</td>
</tr>
<tr>
<td>Specific humidity at $z_{atm}$</td>
<td>$q_{atm}$</td>
<td>kg kg$^{-1}$</td>
</tr>
<tr>
<td>Pressure at $z_{atm}$</td>
<td>$P_{atm}$</td>
<td>Pa</td>
</tr>
<tr>
<td>Temperature at $z_{atm}$</td>
<td>$T_{atm}$</td>
<td>K</td>
</tr>
<tr>
<td>Incident longwave radiation</td>
<td>$L_{atm} \downarrow$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Liquid precipitation</td>
<td>$q_{rain}$</td>
<td>mm s$^{-1}$</td>
</tr>
<tr>
<td>Solid precipitation</td>
<td>$q_{sno}$</td>
<td>mm s$^{-1}$</td>
</tr>
<tr>
<td>Incident direct beam visible solar radiation</td>
<td>$S_{atm} \downarrow_{vis}$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Incident direct beam near-infrared solar radiation</td>
<td>$S_{atm} \downarrow_{nir}$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Incident diffuse visible solar radiation</td>
<td>$S_{atm} \downarrow_{vis}$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Incident diffuse near-infrared solar radiation</td>
<td>$S_{atm} \downarrow_{nir}$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>Carbon dioxide (CO$_2$) concentration</td>
<td>$c_a$</td>
<td>ppmv</td>
</tr>
<tr>
<td>Aerosol deposition rate</td>
<td>$D_{sp}$</td>
<td>kg m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>Nitrogen deposition rate</td>
<td>$NF_{ndep_smn}$</td>
<td>g (N) m$^{-2}$ yr$^{-1}$</td>
</tr>
<tr>
<td>Lightning frequency</td>
<td>$I_l$</td>
<td>flash km$^2$ hr$^{-1}$</td>
</tr>
</tbody>
</table>
At each time step the land model solves Surface Energy Balance

\[ \text{S}_\downarrow - \text{S}_\uparrow + \text{L}_\downarrow - \text{L}_\uparrow = \lambda E + H + G \]

- \( \text{S}_\downarrow, \text{S}_\uparrow \) are down(up)welling solar radiation,
- \( \text{L}_\downarrow, \text{L}_\uparrow \) are up(down)welling longwave rad,
- \( \lambda \) is latent heat of vaporization,
- \( E \) is evaporation,
- \( H \) is sensible heat flux
- \( G \) is ground heat flux
\[ P = E_S + E_T + E_C + R + \left( \Delta W_{soi} + \Delta W_{snw} + \Delta W_{sfcw} + \Delta W_{can} \right) / \Delta t \]

- \( P \) is rainfall/snowfall,
- \( E_S \) is soil evaporation,
- \( E_T \) is transpiration,
- \( E_C \) is canopy evaporation,
- \( R \) is runoff (surf + sub-surface),
- \( \Delta W_{soi} / \Delta t, \Delta W_{snw} / \Delta t, \Delta W_{sfcw} / \Delta t, \Delta W_{can} / \Delta t \)
  are the changes in soil moisture, surface water, snow, and canopy water over a timestep.
Carbon exchange

\[ \text{NEE} = \text{GPP} - \text{HR} - \text{AR} - \text{Fire} - \text{LUC} \]

- **NEE** is net ecosystem exchange
- **GPP** is gross primary productivity
- **HR** is heterotrophic respiration
- **AR** is autotrophic respiration
- **Fire** is carbon flux due to fire
- **LUC** is C flux due to land use change
Main Features of the Community Land Model

• Structural aspects (surface and input datasets)
  – Heterogeneity of landscape (vegetated, urban, lake, glacier, crop)
  – Plant Functional Types and associated parameters (optical, morphological, photosynthetic, fire)
  – Land cover/use change (changes in PFTs over time, wood harvest)
  – Soil texture (sand, silt, clay, organic matter) and color (albedo)
  – River directional map
  – Aerosol (snow albedo) and nitrogen deposition datasets
  – Max fractional saturated area, slope, elevation
  – Managed crop fraction (corn, soybean, cereals) and irrigation
  – \( \text{CO}_2 \)
  – Biogenic Volatile Organic Compounds emission factors
  – Population density, gross domestic productivity, peat area, agricultural waste burning
  – Urban characteristics

• Parameterizations and submodels
Heterogeneity of the Landscape (subgrid tiling structure)
Plant Functional Types:

0. Bare

Tree:
1. Needleleaf Evergreen, Temperate
2. Needleleaf Evergreen, Boreal
3. Needleleaf Deciduous, Boreal
4. Broadleaf Evergreen, Tropical
5. Broadleaf Evergreen, Temperate
6. Broadleaf Deciduous, Tropical
7. Broadleaf Deciduous, Temperate
8. Broadleaf Deciduous, Boreal

Herbaceous/Understory:
9. Broadleaf Evergreen Shrub, Temperate
10. Broadleaf Deciduous Shrub, Temperate
11. Broadleaf Deciduous Shrub, Boreal
12. C₃ Arctic Grass
13. C₃ non-Arctic Grass
14. C₄ Grass
15. C₃ Unmanaged Rainfed Crop
16. C₃ Unmanaged Irrigated Crop

Crop Types:
17. Rainfed Corn
18. Irrigated Corn
19. Rainfed Temperate Cereals
20. Irrigated Temperate Cereals
21. Rainfed Winter Cereals
22. Irrigated Winter Cereals
23. Rainfed Soybean
24. Irrigated Soybean
Plant Function Type distribution in CLM45 based on MODIS/Crop datasets

(a) Current Day (2000) Tree PFTs

(e) Current Day (2000) Grass PFTs

(c) Current Day (2000) Shrub PFTs

(g) Current Day (2000) Crop PFT

[Legend: 1 10 20 30 40 50 60 70 80 90 %]

Lawrence and Chase, 2007
Plant Functional Type Parameters

- **Optical properties (visible and near-infrared):**
  - Leaf angle
  - Leaf reflectance
  - Stem reflectance
  - Leaf transmittance
  - Stem transmittance

- **Fire:**
  - Combustion completeness
  - Fire mortality

- **Morphological properties:**
  - Leaf area index (annual cycle)
  - Stem area index (annual cycle)
  - Leaf dimension
  - Roughness length/displacement height
  - Canopy top and bottom height
  - Root distribution

- **Photosynthetic parameters:**
  - Specific leaf area
  - m (slope of conductance-photosynthesis relationship)
  - Vcmax (maximum rate of carboxylation)
  - Leaf carbon to nitrogen ratio
  - Fraction of leaf nitrogen in Rubisco
  - Soil water potential at stomatal open/closure

- **Land surface models are parameter heavy!!!**
Land use change (prescribed)

Wood harvest

Land Use Change

[Diagram showing land cover/land use change with categories: BET, C4 Grass, Crop]
Historical land use & land cover change, 1850-2005

Change in tree and crop cover (percent of grid cell)

(a) Historical (2005-1850) Tree PFTs

Cumulative percent of grid cell harvested

(b) Historical (2005-1850) Tree PFT Harvest

Historical LULCC in CLM4

- Loss of tree cover and increase in cropland
- Farm abandonment and reforestation in eastern U.S. and Europe
- Extensive wood harvest

P. Lawrence et al. (2012) J Climate 25:3071-3095
Soil Texture – thermal/hydrologic parameters

Soil parameters are derived from sand / clay percentage and soil organic matter content which is specified geographically and by soil level

- Soil moisture concentration at saturation
- Soil moisture concentration at wilting point
- Hydraulic conductivity at saturation
- Saturated soil suction
- Thermal conductivity
- Thermal capacity

Soil profile
10 soil levels (~3.8m)
5 bedrock levels (~42m)
River Directional Map

20-yr average river flow (m³ s⁻¹)

River discharge

- Raw GCM runoff
- Routed GCM runoff
- Observed riverflow
Parameterizations and Submodels

- Surface albedo and radiative fluxes (3,4)
- Momentum, sensible and latent heat fluxes (5)
- Soil and snow thermodynamics (6)
- Stomatal resistance and photosynthesis (8)
- Hydrology (7)
- Carbon / nitrogen pools, allocation, respiration (13)
- Vegetation phenology (14)
- Decomposition (15)
- External nitrogen cycle (16)
- Plant Mortality (17)
- Carbon isotopes (25)
- Lake model (9)
- Glacier model (10)
- River Transport model (11)
- Urban model (12)
- Fire model (18)
- Methane model (19)
- Crops and irrigation (20)
- DGV model (22)
- BVOC model (23)
- Dust emissions model (24)
Modeling surface albedo

Surface albedo a function of

- Vegetation cover and type
- Snow cover
- Snow age
- Soil moisture
- Soil color
- Solar zenith angle
- Amount of direct vs diffuse solar radiation
- Amount of visible vs IR solar radiation

Note: MODIS albedo biased low for snow at high zenith angle (Wang and Zender, 2010)
Two-stream radiative transfer

Radiative transfer uses the two-stream approximation (Dickinson, Sellers) to determine reflected and absorbed solar radiation.
Momentum flux

\[ u_a u_s = \frac{\tau}{\rho} \quad \text{and} \quad \tau = \rho (u_a - u_s) / r_A = \rho u / r_A \]

\[ r_A = \frac{1}{k^2 u} \left[ \ln \left( \frac{z-d}{z_{0A}} \right) - \psi_m (\xi) \right]^2 \]

Sensible heat flux

\[ \theta_a u_s = -H / (\rho c_p) \quad \text{and} \quad H = -\rho c_p (\theta_a - T_s) / r_A \]

\[ r_A = \frac{1}{k^2 u} \left[ \ln \left( \frac{z-d}{z_{0A}} \right) - \psi_m (\xi) \right] \left[ \ln \left( \frac{z-d}{z_{0A}} \right) - \psi_h (\xi) \right] \]

Evaporation

\[ q_a u_s = -E / \rho \quad \text{and} \quad E = -\rho (q_a - q_s) / r_A \]

\[ r_A = \frac{1}{k^2 u} \left[ \ln \left( \frac{z-d}{z_{0A}} \right) - \psi_m (\xi) \right] \left[ \ln \left( \frac{z-d}{z_{0A}} \right) - \psi_w (\xi) \right] \]
Plant canopies

Sensible Heat

Latent Heat
Snow Model

- Up to 5-layers of varying thickness
- Treats processes such as
  - Accumulation
  - Snow melt and refreezing
  - Snow aging
  - Water transfer across layers
  - Snow compaction
    - destructive metamorphosis due to wind
    - overburden
    - melt-freeze cycles
  - Sublimation
  - Aerosol deposition

State Variables

\[ N, w_{liq,i}, w_{ice,i}, \Delta z_i, T_i \]
Snow/Soil thermodynamics

Solve the heat diffusion equation for multi-layer snow and soil model

\[ C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K \frac{\partial T}{\partial z} \right) \]

where \( C_p \) (heat capacity) and \( K \) (thermal conductivity) are functions of:

- temperature
- total soil moisture
- soil texture
- ice/liquid content
Modeling Permafrost in CLM

Lawrence et al., J. Climate, 2011
Leaf photosynthesis, transpiration, and stomatal conductance

CO₂ + 2 H₂O → CH₂O + O₂ + H₂O

Slide courtesy G. Bonan
Leaf photosynthesis

(a) Net CO₂ assimilation vs. Photosynthetically active radiation (μmol m⁻² s⁻¹)
(b) Net CO₂ assimilation vs. Temperature (°C)
(c) Net CO₂ assimilation vs. Vapor pressure deficit (kPa) for 25°C and 35°C
(d) Net CO₂ assimilation vs. Foliage water potential (MPa)
(e) Net CO₂ assimilation vs. CO₂ concentration (μmol mol⁻¹)
(f) Net CO₂ assimilation vs. Foliage nitrogen (g m⁻²)

Slide courtesy G. Bonan
Leaf photosynthesis and stomatal conductance

Farquhar photosynthesis model

\[ A_n = \min(w_c, w_j, w_p) - R_d \]

- \( w_c \) is the rubisco-limited rate of photosynthesis, \( w_j \) is light-limited rate allowed by RuBP regeneration, \( w_p \) is product limited rate of carboxylation

rubisco-limited rate is

\[ w_c = \frac{V_{c\text{max}}(c_i - \Gamma^*)}{c_i + K_c(1+O_i/K_o)} \]

RuBP regeneration-limitation rate is

\[ w_j = \frac{J(c_i - \Gamma^*)}{4(c_i + 2\Gamma^*)} \]

product-limited rate is

\[ w_p = 3\Gamma_p \]

Ball-Berry stomatal conductance

\[ \frac{1}{r_s} = g_s = g_1 \frac{A_nh_s}{c_s/P_{\text{atm}}} + g_0\beta_i \]
Plant canopy as a “big leaf”

Most models use two-leaves (sunlit and shaded)

A Two-Big-Leaf Model for Canopy Temperature, Photosynthesis, and Stomatal Conductance

Yongzhu Dai
School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia, and Research Center for Remote Sensing and GIS, Beijing Normal University, Beijing, China

Robert E. Dickinson
School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia

Ying-Ping Wang
CSIRO Atmospheric Research, Aspendale, Victoria, Australia


Slide courtesy G. Bonan
Evaluating the model with tower flux data
Evaluating CLM4.5 with tower flux data

Howland Forest, Maine, July, 1996
Evaluation of radiation/photosynthesis models using global synthesis of tower flux data

Gross Primary Production

117 Pg C yr⁻¹

165 Pg C yr⁻¹

155 Pg C yr⁻¹

130 Pg C yr⁻¹

Radiative transfer for sunlit and shaded canopy

Radiative transfer and photosynthesis

CLM4 overestimates GPP. Model revisions improve GPP.

Fluxnet-MTE: Beer et al. 2010, Jung et al. 2010

Bonan et al. 2011, 2012
Evaluation of radiation/photosynthesis models using global synthesis of tower flux data

Model improvements reduce ET biases, especially in tropics, and improve monthly fluxes

Fluxnet-MTE: Beer et al. 2010, Jung et al. 2010

Bonan et al. 2011, 2012
Manhattan-Mannahatta: on right is a reconstruction of Manhattan Island circa 1609 (called “Mannahatta” by the Lenape native Americans), as compared to today, based on historical landscape ecology and map data.

Heterogeneity of the Landscape (subgrid tiling structure)
Spatial (and seasonal) variability controlled by urban properties (morphological, thermal, radiative), mix of density types (tall building district, high and medium density), rural landcover, and climate.

Model evaluated by comparing to observations at individual sites and remote sensing.

CESM1.2: CLM DOCUMENTATION

INTRODUCTION

The Community Land Model versions 4.0 and 4.5 in CESM1.2.0 are the latest in a series of land models developed through the CESM project. More information on the CLM project and access to previous CLM model versions and documentation can be found via the CLM Web Page.

DOCUMENTATION

- User's Guide for CLM4.5 and CLM4.0 in CESM1.2.0 [html] (Last update: Jul/20/2013)
- Technical Description for CLM4.5 (Last update: Aug/1/2013)
- Technical Description for CLM4.0, CLM4.0 Urban Model, CLM4.0 Crop and Irrigation Model
- Explanation of supported configurations in CLM4.5 and CLM4 in CESM1.2
- What's new in CLM in CESM1.2 (CLM4.5 release) Science, CESM1.2 (CLM4.5 release) Software, CESM1.1.1, CESM1.1.0, CESM1.0.5, CESM1.0.4, CESM1.0.3, CESM1.0.2, CESM1.0.1, CESM1.0, CCSM4.0 (CLM4.5 release).
- Known bugs in CLM in CESM1.2.0, CESM1.1.0, CESM1.0.4, CESM1.0.3, CESM1.0.2, CESM1.0.1, CESM1.0.
- Known limitations in CLM in CESM1.2.0, CESM1.1.0.

MODEL OUTPUT AND OFFLINE FORCING DATA AND DIAGNOSTIC PLOTS

- CLM4.0 and CLM4.5 offline control simulations: Diagnostic plots
- CLM4.0 and CLM4.5 offline control simulations (links need to be updated and data posted to ESG): Model output data
- CLM4.0 and CLM4.5 offline control simulations (links need to be updated and data posted to ESG): Model forcing data
- CLM4.0 and CLM4.5 offline historical and RCP simulations: CCSM4 coupler history forcing data

CLM POST-PROCESSING AND ANALYSIS UTILITIES

- CLM Diagnostic Package: Introduction, Code (via svn repository, registration required), and User's Guide
- Multivariate visual analytics tool: EDEN (Exploratory Data analysis ENvironment)
  Helps reveal associations among variables for guided analysis (beta version, comments to Chad Steed)

MODEL DESIGN AND DEVELOPMENT

- Request Form for Developer Access (active close collaborators only)
- CLM Developers' Guidelines
- CLM4/CESM1.2.0 Code Reference Guide

REFERENCES

- Bibliography of papers utilizing and/or developing CLM (Last update: Feb/12/2015)
Thank You

NCAR is sponsored by the National Science Foundation
CLM as a community modeling tool

AGU presentations with CLM in abstract or title

% of AGU presentations that included CLM

CLM3.5 [Oleson et al., 2008] (252 citations)
CLM4.0 [Lawrence et al., 2011] (240 citations)
CLM Development

http://www2.cesm.ucar.edu/working-groups/lmwg/developer-guidelines
Scientific goals driving CLM development and use

• Improve understanding of carbon and nitrogen cycle interactions and their impact on long term trajectory of terrestrial carbon sink

• Assess response and vulnerability of ecosystems to climate change and disturbances (human and natural)

• Evaluate utility of ecosystem management as mechanism to mitigate climate change

• Ascertain vulnerability of water resources under climate change; establish role of land in drought and flood

• Quantify land feedbacks to climate change: e.g. permafrost-carbon, snow- and vegetation-albedo, soil moisture-ET feedbacks
Scientific goals driving CLM development and use

- Assess urban-rural differences in climate change impacts
- Prognose anthropogenic and natural land cover/land use change and LULCC impact on climate and trace gas emissions
- Investigate role of surface heterogeneity in land-atmosphere interaction and carbon cycling, including scale issues
- Model – data fusion; Exploitation of experimental ecosystem data
- Uncertainty Quantification, parameter optimization
Model Development Process

1. **Model release (CESM1/CLM45)**
2. **Use model for scientific studies**
3. **Finalize and test within CESM**
4. **Build and test beta version of offline model**
5. **Present ideas/results at LMWG meetings**
6. **LMWG members develop parameterizations or add features**
7. **Evaluate competing parameterizations**
8. **Document; Control integrations**
9. **Plans for next (and next next) model version discussed at LMWG meetings**
10. **Detailed model assessment (identify strengths and weaknesses)**
11. **Publish papers**
Modeling evaporation and runoff

“The ability of a land-surface scheme to model evaporation correctly depends crucially on its ability to model runoff correctly. The two fluxes are intricately related.”

(Koster and Milly, 1997).

Runoff and evaporation vary non-linearly with soil moisture
A major control on soil moisture heterogeneity and thus runoff is topography. Lowland soils tend to be zones of high soil moisture content, while upland soils tend to be progressively drier.

Three main sources of runoff:
• Infiltration excess occurs over the unsaturated fraction
• Saturation excess occurs over the saturated fraction
• Baseflow (drainage)
SIMTOP: Simple TOPMODEL-based runoff model

Infiltration excess

\[ q_{\text{over}} = (1 - f_{\text{sat}}) \left( q_{\text{liq}, 0} - q_{\text{infl}, \text{max}} \right) \]

Niu et al. 2005
SIMTOP: Simple TOPMODEL-based runoff model

Infiltration excess

\[ q_{over} = \left(1 - f_{sat}\right) \left(q_{liq,0} - q_{infl,max}\right) \]

Saturation excess

\[ q_{over} = f_{sat} q_{liq,0} \]

\[ f_{sat} = \left(1 - f_{frz,1}\right) \times f_{max} \exp\left(-0.5 f_{over} z_{wt}\right) + f_{frz,1} \]

Niu et al. 2005
Groundwater controls runoff
(Yeh and Eltahir, 2005)

Groundwater affects soil moisture and ET (Gutowski et al, 2002; York et al., 2002)

Groundwater model (SIMGM) determines water table depth

Subsurface runoff is exponential function of water table depth

Niu et al. 2007
Abracos tower site (Amazon)

Latent Heat Flux

Model vs. OBS

CLM3

\[ r^2 = 0.91, \quad \text{slope} = 0.67, \quad \text{rmse} = 67.73, \quad \text{bias} = -28.89 \]

CLM3.5/4

\[ r^2 = 0.93, \quad \text{slope} = 1.05, \quad \text{rmse} = 48.60, \quad \text{bias} = 13.00 \]

Latent Heat Flux

Total soil water

OBS vs. CLM3.5/4, CLM3

Day from January 1, 1992
Snow cover fraction

How much of a grid cell is covered with snow for a given snow depth?

Niu and Yang 2007
Snow, Ice, and Aerosol Radiative Model (SNICAR)

- Snow darkening from deposited black carbon, mineral dust, and organic matter
- Vertically-resolved solar heating in the snowpack
- Snow aging (evolution of effective grain size) based on:
  - Snow temperature and temperature gradient
  - Snow density
  - Liquid water content and
  - Melt/freeze cycling

Flanner et al (2007), JGR
Flanner and Zender (2006), JGR
Flanner and Zender (2005), GRL
Soil (and snow) water storage (MAM – SON)

CCSM4

GRACE (obs)

CCSM3

GRACE satellite measures small changes in gravity which on seasonal timescales are due to variations in water storage.

CCSM3 and CCSM4 data from 1870 and 1850 control.