Improving Hydrological Representation in the Community Noah Land Surface Model for Intra-seasonal to Interannual Prediction Studies

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http://www.geo.utexas.edu/climate
Objectives

To investigate how Noah LSM’s augmentation with additional land memory processes (e.g., snow, groundwater and dynamic vegetation) influences its soil moisture memory.

To develop high-resolution datasets of land surface state variables (e.g., soil moisture) in conjunction with NCAR’s HRLDAS.

To perform ensembles of WRF simulations illustrating the role of soil moisture, groundwater, vegetation, frozen soil, and snow in predicting precipitation at intra-seasonal to interannual timescales.
Why Augment Noah LSM?

1. Modeled snow water equivalent or snow depth is too shallow.
Why Augment Noah LSM?

2. Modeled soil moisture is too low, especially in deep soil layers and in the summertime.
3. The present model lacks leaf area–rainfall interaction. Feedbacks between rainfall and rain-green vegetation are hypothesized to play a role in intra-seasonal to interannual climate predictions; see observations below.

Matsui et al. (2005) JCL
4. The present model does not distinguish vegetation canopy temperature and ground temperature, which makes it difficult to incorporate other physically-based processes.

5. Seamless predictions and ensemble forecasts demand more from the current Noah LSM. A model with multi-physics options would be highly pertinent.
What Have We Done?


2. Chen visited UT in October 2006.


4. UT, NCEP/EMC, NCEP/OHD, NCAR, and NASA had a 4-hour telecon meeting where Yang’s group presented.


6. Chen hosted the Noah development workshop at NCAR in July 2007; Mitchell, Yang, Peters-Lidard, and others attended.

7. Regular telecon meetings among UT, NCEP, NCAR, and others in the past year.
Progress to date

Posters at this meeting
1. Niu et al., The Community Noah LSM with multi-physics options: A new framework conducive for ensemble weather and climate predictions
2. Jiang et al., How do groundwater dynamics and vegetation growth affect precipitation on intra-seasonal to seasonal time scales?
3. Su et al., Mapping North American snow water equivalent using MODIS, GRACE, EnKF, EnKS and land surface modeling
4. Rosero et al., A new, metrics-based framework for evaluating and developing land surface models

Peer-reviewed papers
2) Jiang et al., 2008: JGR (in review)
3) Niu et al., 2008: BAMS (in preparation)
4) Rosero et al., 2008a,b: J Hydromet. (in revision)
5) Su et al., 2008a: JGR; Su et al., 2008b: JGR (in preparation)
Noah-UT with new features

1. Major components:
   1-layer canopy; **3-layer snow**; 4-layer soil

2. Subgrid scheme: semi-tiled vegetation and bare soil (Niu et al., 2008).

3. Iterative energy balance method to predict the canopy and snow/soil surface (skin) temperatures.

4. Modified two-stream radiation transfer scheme to consider the 3-D structure of the canopy (Niu and Yang, 2004).


6. TOPMODEL-based runoff scheme (Niu et al., 2005).

7. Unconfined aquifer interacting with overlying soil (Niu et al., 2007).


10. Dynamic (or interactive) leaf area (Dickinson et al., 1998).
Noah-UT with multi-physics options

1. Leaf area index (*prescribed; predicted*)
2. Turbulent transfer (*Noah; NCAR LSM*)
3. Soil moisture stress factor for transpiration (*Noah; BATS; CLM*)
4. Canopy stomatal resistance (*Jarvis; Ball-Berry*)
5. Snow surface albedo (*BATS; CLASS*)
6. Frozen soil permeability (*Noah; Niu and Yang, 2006*)
7. Supercooled liquid water (*Noah; Niu and Yang, 2006*)
8. Radiation transfer:
   *Modified two-stream*: \( \text{Gap} = F (3D \text{ structure}; \text{solar zenith angle}; ...) \leq 1-\text{GVF} \)
   *Two-stream applied to the entire grid cell*: \( \text{Gap} = 0 \)
   *Two-stream applied to fractional vegetated area*: \( \text{Gap} = 1-\text{GVF} \)
9. Partitioning of precipitation to snowfall and rainfall (*CLM; Noah*)
10. Runoff and groundwater:
    *TOPMODEL with groundwater*
    *TOPMODEL with an equilibrium water table (Chen & Kumar, 2001)*
    *Original Noah scheme*
    *BATS surface runoff and free drainage*

More to be added

Niu et al. (2008)
Maximum # of Combinations

1. Leaf area index (prescribed; predicted) 2
2. Turbulent transfer (Noah; NCAR LSM) 2
3. Soil moisture stress factor for transp. (Noah; BATS; CLM) 3
4. Canopy stomatal resistance (Jarvis; Ball-Berry) 2
5. Snow surface albedo (BATS; CLASS) 2
6. Frozen soil permeability (Noah; Niu and Yang, 2006) 2
7. Supercooled liquid water (Noah; Niu and Yang, 2006) 2
8. Radiation transfer: 3
   Modified two-stream: Gap = F (3D structure; solar zenith angle; ...
   \leq 1-GVF
   Two-stream applied to the entire grid cell: Gap = 0
   Two-stream applied to fractional vegetated area: Gap = 1-GVF
9. Partitioning of precipitation to snow- and rainfall (CLM; Noah) 2
10. Runoff and groundwater: 4
    TOPMODEL with groundwater
    TOPMODEL with an equilibrium water table (Chen&Kumar, 2001)
    Original Noah scheme
    BATS surface runoff and free drainage

\[2x2x3x2x2x2x3x2x4 = 4584 \text{ combinations}\] (Go multiply! That’s why we like about Noah – one Noah produces thousands of variations of Noah.)
Recommended # of Combinations

1. Leaf area index (prescribed; predicted) 1
2. Turbulent transfer (Noah; NCAR LSM) 1
3. Soil moisture stress factor for transp. (Noah; BATS; CLM) 3
4. Canopy stomatal resistance (Jarvis; Ball-Berry) 2
5. Snow surface albedo (BATS; CLASS) 1
6. Frozen soil permeability (Noah; Niu and Yang, 2006) 1
7. Supercooled liquid water (Noah; Niu and Yang, 2006) 1
8. Radiation transfer:
   - Modified two-stream: Gap = F (3D structure; solar zenith angle; ... ≤ 1-GVF
   - Two-stream applied to the entire grid cell: Gap = 0
   - Two-stream applied to fractional vegetated area: Gap = 1-GVF
9. Partitioning of precipitation to snow- and rainfall (CLM; Noah) 1
10. Runoff and groundwater:
    - TOPMODEL with groundwater
    - TOPMODEL with an equilibrium water table (Chen&Kumar, 2001)
    - Original Noah scheme
    - BATS surface runoff and free drainage

1x1x3x2x1x1x1x1x1x4 = 24 combinations

Niu et al. (2008)
The structure of vertical soil layers remains the same as in the previous Noah version except for the 3-L snow above it and an unconfined aquifer below it.

<table>
<thead>
<tr>
<th>Δz(-2): 0.025 - 0.05m</th>
<th>( T_{-2} ) ices(-2), liq(-2), ps(-2)</th>
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</thead>
<tbody>
<tr>
<td>Δz(-1): 0.05 - 0.10m</td>
<td>( T_{-1} ) ices(-1), liq(-1), ps(-1)</td>
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<tr>
<td>Δz(0): 0.10 ~ (snowh-( \Delta z(-1) )-( \Delta z(-2) ))</td>
<td>( T_{-0} ) ices(0), liq(0), ps(0)</td>
</tr>
</tbody>
</table>

- **Tg**
- **Snow**
- **Soil**
- **Aquifer**
### One Matrix Solving All Temperatures

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<tr>
<th>B(-2)</th>
<th>C(-2)</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>0</th>
<th>T(-2)</th>
<th>R(-2)</th>
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</thead>
<tbody>
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<td>C(-1)</td>
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<tr>
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<td>B(2)</td>
<td>C(2)</td>
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<td>R(2)</td>
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<td>B(3)</td>
<td>C(3)</td>
<td>T(3)</td>
<td>R(3)</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>A(4)</td>
<td>C(4)</td>
<td>T(4)</td>
<td>R(4)</td>
</tr>
</tbody>
</table>

A(i), B(i), C(i), R(i) are a function of:
- $\lambda(i)$ - thermal conductivity
- $C(i)$ - heat capacity
- $z(i)$ - layer-bottom depth from the snow/soil surface (neg.)

R(-nsn+1) is a function of $G$:

$$G = \lambda(1) \left( T12 - T(-\text{nsn+1}) \right) / \left( 0.5 \times dz(-\text{nsn+1}) \right)$$

T12: skin temperature
Given GVF (green vegetation fraction) for a land grid, how to represent radiative and turbulent processes?

Radiative transfer needs to consider the shadow effects or the zenith angle dependence.
Subgrid Vegetation Scheme

**Radiation:** Modified Two-stream (Yang and Friedl, 2001)

1. Evenly-distributed crowns
2. Between-canopy and within canopy gaps
3. Computes over the whole grid-cell:
   - $SAG$ – ground absorbed solar $R$
   - $SAV$ – vegetation absorbed $R$

**Turbulent transfer**
Two tiles: dominant vegetation and bare ground

**Energy balance:**

- vegetation-tile:
  - Canopy: $SAV - GVF \times (IRC + SHC + EVC + TR) = 0$.
  - Ground: $SAG - (IRG + SHG + EVG + GHV) = 0$.
  - Bare ground:
    - $SAG - (IRB + SHB + EVB + GHB) = 0$.

- The grid cell $SH$ and $EV$:
  - $SH = (SHG + SHC) \times GVF + SHB \times (1 - GVF)$
  - $EV = (EVG + TR + EVC) \times GVF + EVB \times (1 - GVF)$

Niu et al. (2008)
- The 3-L snow model has 4 major prognostic variables: layer depth (or density), temperature, ice content, and liquid water content for each layer.
- The 3-L snow temperatures and the 4-L soil temperatures are solved through one tri-diagonal matrix.
- The skin temperature, $T_g$, is solved through an iterative energy balance method.
- Freezing/melting energy is assessed as the energy deficit or excess needed to change snow temperature to the melting/freezing point (Yang and Niu, 2003):
  \[ H_{fm}(i) = C(i) \times dz(i) \times (T(i) - T_{frz}) / dt \]
  i-th layer
- Snow cover fraction (Niu and Yang, 2007):
  \[ f_{sno} = \tanh \left( \frac{h_{sno}}{2.5z_0} \frac{\rho_{sno}}{\rho_{new}} \right) \]
  when melting factor, $m = 0$, it turns to Yang et al. (1997)
Snow Cover Fraction Over 9 River Basins

Niu et al. (2008)
Snow Water Equivalent Over 9 River Basins

Niu et al. (2008)
Snow Depth Over 9 River Basins

Niu et al. (2008)
A Simple Groundwater Model (SIMGM)

Water storage in an unconfined aquifer:

\[
\frac{dW_a}{dt} = Q - R_{sb}
\]

\[
Z_{\nabla} = \frac{W_a}{S_y}
\]

Recharge Rate:

\[
Q = -K_a \left( -\frac{Z_{\nabla}}{Z_{\nabla} - Z_{bot}} \left( \psi_{bot} - Z_{bot} \right) \right)
\]

\[
= K_a (1 + \frac{\psi_{bot}}{Z_{\nabla} - Z_{bot}})
\]

Modified to consider macropore effects:

\[C_{mic} \ast \psi_{bot}\]

\[C_{mic} \rightarrow \text{fraction of micropore content}\]

\[0.0 - 1.0 (0.0 \sim \text{free drainage})\]

Niu et al. (2007)
A Simple Groundwater Model (SIMGM)

Micropore fraction: $C_{mic} = 0.5$

Niu et al. (2008)
Dynamic Vegetation Canopy

DLM includes a set of carbon mass (g C/m²) balance equations for:
1. Leaf mass
2. Stem mass
3. Wood mass
4. Root mass
5. Soil carbon pool (fast)
6. Soil carbon pool (slow)

Processes include:
1. Photosynthesis ($S_\downarrow, T, \theta, e_{air}, CO_2, O_2, N…$)
2. Carbon allocation to carbon pools
3. Respiration of each carbon pool ($T_v, \theta, T_{root}$)

\[
\frac{\partial M_{leaf}}{\partial t} = R_{gain} - R_{loss}
\]

Carbon gain rate: photosynthesis * fraction of carbon partition to leaf
Carbon loss rate: leaf turnover (proportional to leaf mass)
respiration: maintenance & growth (proportional to leaf mass)
death: temperature & soil moisture

\[
LAI = M_{leaf} * C_{area}
\]

where $C_{area}$ is area per leaf mass (m²/g).

Dickinson et al. (1998)
Comparison of Modeled and MODIS Estimated LAI

Model winter

MODIS winter

Model DJF; Mean = 0.80

MODIS DJF; Mean = 0.80

Model Summer

MODIS summer

Model JJA; Mean = 1.41

MODIS JJA; Mean = 1.35

Niu et al. (2008)
Improving Seasonal Precipitation Prediction Through A Coupled Groundwater-Vegetation-Atmosphere System

Jiang, X.Y., G.Y. Niu, and Z.-L. Yang, 2008: JGR
WRF/Noah Model

- The version 2.1.2 of the Weather Research and Forecasting model (WRF) with time-varying sea surface temperatures.

- WRF Physics options:
  - Lin et al. microphysics scheme;
  - Kain-Fritsch cumulus parameterization scheme;
  - Yonsei University Planetary boundary layer;
  - A simple cloud interactive radiation scheme;
  - Rapid Radiative Transfer Model longwave radiation scheme

- Default Noah LSM augmented by:
  - dynamic vegetation canopy (DV) of Dickinson et al. (1998)
  - a simple groundwater model (GW) of Niu et al. (2007)

- NCEP-NCAR reanalysis data

The model domain covers the whole continental U.S. and the resolution is 32 km
<table>
<thead>
<tr>
<th>Cases</th>
<th>Start from different dates to 8/31/2002</th>
<th>Experiment description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEFAULT</td>
<td></td>
<td>Use prescribed greenness fraction in the WRF model</td>
</tr>
<tr>
<td>DV</td>
<td>05/31 00:00 05/31 06:00 05/31 12:00 05/31 18:00 06/01 00:00</td>
<td>Use dynamic Vegetation in the WRF model</td>
</tr>
<tr>
<td>DVGW</td>
<td></td>
<td>Include dynamic vegetation and groundwater in the WRF model</td>
</tr>
</tbody>
</table>
WRF Simulated & Observed Monthly and Seasonal Mean Precipitation in Central Great Plains

Monthly precipitation (mm/day)

JJA June July August

Obs Default DV DVGW

Jiang et al. (2008)
Summary

1. We, working closely between UT, NCAR and NCEP investigators and scientists, have significantly restructured the Unified Noah LSM by including the latest developments in groundwater, dynamics vegetation, snow, and frozen soil.

2. The most important feature is multi-physics options, a new framework conducive for ensemble weather and climate predictions.

3. Regional and global offline tests show promising results.

4. Coupled WRF/Noah simulations show groundwater dynamics and vegetation growth improve intra-seasonal to seasonal precipitation predictions, especially in transitional regions (i.e. the central U.S.). More tests using the Noah-UT are required.