A Framework for Multi-Physics Representation of the Coupled Land-Atmosphere System for Predicting Extreme Weather Events

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http://www.geo.utexas.edu/climate
Climate change and its manifestation in terms of weather (climate extremes)

Global warming increases the frequency and intensity of extreme weather events.
How is the land surface and the atmosphere coupled?

One model but with multiple physics parameterizations! Both in the Atmosphere and at the Land Surface.
WRF: multi-physics options

1. Microphysics
2. Cumulus convection
3. Long- and shortwave radiation
4. Boundary layer turbulence
5. Subgrid-scale diffusion
6. Land surface parameterization

7. ... ...
Noah with multi-physics options

1. Leaf area index (prescribed; predicted)
2. Turbulent transfer (Noah; NCAR LSM)
3. Soil moisture stress factor for transp. (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: $\text{Gap} = F (3D \text{ structure}; \text{ solar zenith angle}; \ldots) \leq 1-\text{GVF}$
   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 snow- 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

$2 \times 2 \times 3 \times 2 \times 2 \times 2 \times 2 \times 3 \times 2 \times 4 = 4584$ combinations
We also remove known weaknesses in the default Noah LSM:

1. Failure to differentiate vegetation canopy temperature and ground temperature.
2. Free drainage at the bottom of the soil column.
3. Neglect of the effects of zero-displacement height ($d_0$) on CH → a smaller CH over forest regions.
4. Lumped snow and soil in computing the surface energy balance.
5. Too impervious frozen soil → too strong runoff peaks in cold regions.
Semi-tile method:

**Radiation: Modified two-stream**
(Yang and Friedl, 2001; Niu and Yang, 2004)

1. Evenly-distributed crowns
2. Between- and within-canopy gaps
3. Outputs: \( \alpha, S_{agr}, S_{av}, PAR_{shad}, PAR_{sun} \)

**Turbulent transfer: “Tile” scheme**
Two separated tiles: vegetation and bare

Vegetation tile:
- Canopy: \( S_{av} - F_{veg}(L_{av} + H_v + LE_v) = 0 \)
- Ground: \( F_{veg} S_{ag} - F_{veg}(L_{ag} + H_g + LE_g + G_v) = 0 \)

Bare-ground tile:
\( (1 - F_{veg}) S_{ag} - (1 - F_{veg})(L_{ab} + H_b + LE_b + G_b) = 0 \)
Snow submodel:

1. The 3-L snow model has 4 major prognostic variables: layer depth (or density), temperature, ice content, and liquid water content for each layer.

2. The 3-L snow temperatures and the 4-L soil temperatures are solved through one tri-diagonal matrix.

3. The skin temperature, $T_g$, is solved through iterative energy balance method.

4. Freezing/melting energy is assessed as the energy deficit or excess needed to change snow temperature to melting/freezing point (Yang and Niu, 2003):

$$H_{fm}(i) = C(i) \times dz(i) \times (T(i) - T_{frz}) / dt; \quad i\text{-th layer}$$

5. Snow cover fraction (Niu and Yang, 2007):

$$f_{sno} = \tanh \left( \frac{h_{sno}}{2.5 \times z_0 \times (\rho_{sno}/\rho_{new})^m} \right)$$

when melting factor, $m = 0.$, it turns to Yang et al. (1997)
Groundwater model:

Water storage:
\[
\frac{dW_a}{dt} = Q - R_{sb}
\]
\[
z_{\nabla} = \frac{W_a}{S_y}
\]

Recharge Rate:
\[
Q = -K_a \left( \frac{-z_{\nabla} - (\psi_{bot} - z_{bot})}{z_{\nabla} - z_{bot}} \right)
\]
\[
= K_a \left( 1 + \frac{\psi_{bot}}{z_{\nabla} - z_{bot}} \right)
\]

Problems when applied to CLM: too wet soil due to
- Too small recharge rate from soil to aquifer (too small $K_a$);
- Too strong upward flow (too large soil suction, $\psi_{bot}$);
- Too small groundwater discharge inducing overflow of groundwater to soil

Niu et al. (2007)
Capillary Fringe and Soil Pore-Size Distribution

Macropore effects:
1. Larger recharge rate (through macropores)
2. Smaller upward flow (through micropores)

See http://www.earthdrx.org/poresizegwflow.html
A Dynamic Leaf Model (Dickinson et al., 1998)

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↓, T, θ, e_air, CO₂, O₂, N ...)
2. Carbon allocation to carbon pools
3. Respiration of each carbon pool (T_vr, θ, T_root)

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

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

\[
\text{LAI} = M_{\text{leaf}} \times C_{\text{area}} \quad \text{where } C_{\text{area}} \text{ is area per leaf mass (m}^2/\text{g}).
\]
Snow Water Equivalent (in mm)

Snow Depth (in m)
Modeled $T_{skin}$ (July 12th, 21:00 UTC, 2004)

Niu et al. (2009)
Modeled Leaf Area Index (LAI) and Green Vegetation Fraction (GVF)

Niu et al. (2009)
Noah with multi-physics options

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36 Offline Ensemble Experiments:

Table 3. The first group of 12 experiments and their corresponding options of schemes.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Dynamic vegetation</th>
<th>$r_s$</th>
<th>$\beta$</th>
<th>Runoff schemes</th>
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<tbody>
<tr>
<td>EN1</td>
<td>Off</td>
<td></td>
<td>Noah</td>
<td>SIMGM</td>
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<tr>
<td>EN2</td>
<td></td>
<td></td>
<td></td>
<td>SIMTOP</td>
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<tr>
<td>EN3</td>
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<td></td>
<td>Schake96</td>
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<td></td>
<td>BATS</td>
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<tr>
<td>EN5</td>
<td>On</td>
<td>Ball-Berry</td>
<td>CLM</td>
<td>SIMGM</td>
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<td>BATS</td>
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</table>

Huge uncertainty to represent processes
Results from 36 Offline Runs

Graphs a, b, and c show the relationship between ET (mm/year) and Runoff (mm/year), and ET (mm/year) and Top 1m Soil Moisture (mm) for Global, Illinois, and Illinois, respectively. The data points are labeled with numbers for identification.
Study Case: An Extreme Precipitation Event in Texas July 2002

- San Antonio River Basin, Central Texas
- June 30 – July 10
- Stationary upper-level trough and strong southeasterly surface winds cause continuous low-level moisture flow across the Gulf of Mexico into Central Texas
- Heavy rainfall (>100mm/day) persists over the San Antonio area for 6 days

Zhang et al. (2006)
Model and Experiments

- WRF 3.0.1
- Initial/Boundary Conditions: NARR Reanalysis
- 30-km grid spacing
- July 1-3, 2002
- Experiments
  - WRF/Noah with three convection schemes (KF, BMJ, Grell)
  - WRF/Noah-MP (three runoff schemes: SIMGM, SIMTOP, Noah) and three convection schemes (KF, BMJ, Grell)
Comparison of July 1-3 Precipitation from observations and various runs
Comparison of July 1-3 Precipitation from observations and various runs.

Default Noah LSM / KF

Default Noah LSM / BMJ

Default Noah LSM / Grell

OBS
Hourly Precipitation (mm/hour) from July 1 to 3, 2002 for Various Convection & Runoff Runs
Hourly Precipitation (mm/hour) from July 1 to 3, 2002 for Various Convection & Runoff Runs.

Hourly Precipitation: Central Texas (30°N – 32°N, 100° – 97°N)
Summary

- We have developed a MP framework for the land surface. Together with the MP framework for the atmosphere, this MP framework is useful for probabilistic forecasts of the mesoscale extreme events. More research and experiments are warranted.

- Noah-MP improves over the default Noah LSM, both in offline and coupled simulations. In the coupled runs, runoff schemes have considerable effects on rainfall after day 1.

- Convection schemes dominate the simulations of extreme rainfall in the warm season!

- Special attention is required in initializing soil moisture and leaf biomass. A high-resolution land data assimilation system needs to be configured to provide required land data for initialization.
Thank you!

• Questions?