Impact of Calibrated LSM Parameters on the Accuracy of Land-Atmosphere Coupling in WRF Simulations

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Objective: Examine the impact of ‘optimal’ land surface fluxes and improved model and initial conditions on coupled prediction.

Case Study: Extremes in the U.S. Southern Great Plains: Summer 2006 (dry), 2007 (wet), 2008 (avg)

Methodology:

a) Estimate parameters in Noah LSM to better fit observations of surface fluxes using LIS-OPT

b) Quantify the impact of improved surface fluxes on prediction of land and atmospheric variables (LIS-WRF) using recently developed diagnostics of Local Land-Atmosphere Coupling (‘LoCo’)

Motivation & LoCo
Motivation & LoCo

- **Land-atmosphere (L-A) interactions** play a critical role in supporting and modulating extreme dry and wet regimes, and must therefore be quantified and simulated correctly in coupled models.

- Recent efforts to quantify the strength of **Local L-A Coupling ('LoCo')** in prediction models have produced diagnostics that integrate across both the land and PBL components of the system.

- **LoCo diagnostics** provide simultaneous assessment of the land-PBL states, fluxes, and interactions, highlighting the accuracies and potential deficiencies in components of the modeling system.

\[
\begin{align*}
 DSM & \rightarrow DEF & \rightarrow DPBL & \rightarrow DENT & \rightarrow DEF & \rightarrow DPrecip/Clouds \\
(\text{a}) & & (\text{b}) & & (\text{c}) & & (\text{d}) \\
\text{SM: Soil Moisture} & & \text{PBL: Planetary Boundary Layer (Mixed-layer quantities)} & & \text{ENT: Entrainment fluxes} & & \text{EF: Evaporative Fraction} & & \text{P/Cloud: Moist processes}
\end{align*}
\]
Motivation & LoCo

- Soil moisture leads to significantly different signatures of heat and moisture.
- Provides a robust methodology to simultaneously evaluate the coupled L-A states and fluxes of the system versus observations.

NASA-Unified WRF (NU-WRF)

Overarching Goal:

*The NU-WRF project aims to develop, validate and provide the community with an observation-driven integrated modeling system that represents aerosol, cloud, precipitation and land processes at satellite-resolved scales.*

Integrates NASA-oriented capabilities into WRF-ARW:

- Land Information System (LIS)
- GOddard Chemistry Aerosols Radiation Transport (GOCART)
- Goddard Satellite Data Simulator Unit (SDSU)
- Goddard microphysics
- Goddard radiation (w/ explicit interaction between clouds and radiation)
- Land data assimilation system
- GOCART global transport
- Real-time forecasting system using GEOS and MERRA global analyses as init/bdy conditions
**LIS-WRF Coupling and Calibration**

**LIS - OPT/UE**
Optimization and Uncertainty Estimation (LM, GA, SCE-UA, RW-MCMC, DEMC)

**LIS - DA**
Data Assimilation (DI, EnKF)

**LIS - LSM**
Land Surface Models (Noah, CLM, Catchment, JULES, TESSEL, HySSiB, Sacramento, SNOW17)

**LIS - WRF**
Observations (Soil Moisture, Snow, Skin Temperature)

**WRF**
Water and Energy Fluxes, Soil Moisture and Temperature profiles, Land surface states

**Hydrologic Forecasts**

**LIS - OPT/UE**

**LIS - DA**

**LIS - LSM**

**Uncoupled or Analysis Mode**

**Coupled or Forecast Mode**

**Random search**

**Deterministic search**

LIS includes a multi-algorithm optimization subsystem (LIS-OPT/UE) that captures the spectrum of search strategies, ranging from techniques such as:

- Levenberg-Marquardt (LM)
- Shuffled Complex Evolution from the University of Arizona (SCE-UA)
- Genetic Algorithms (GA)
Experimental Design

- **2006-7 Dry/Wet Extremes**
  - Domain: U. S. Southern Great Plains (SGP; 500x500 @ 1km resolution)
  - LIS-Noah (v3.2) LSM + Yonsei University (YSU) PBL scheme

- **Optimization Runs**
  - Algorithm: GA
  - Parameter set: 32 soil, vegetation, and general (Noah) parameters
  - Observations: 20 EBBR (Energy Balance Bowen Ratio) and ECOR (Eddy CORrelation) flux tower sites
  - Objective Function: Cumulative RMSE of sensible (Qh), latent (Qle), and soil (Qg) heat flux

- **Parameter Classification**
  - The parameters are estimated individually at each station and then are grouped and averaged by vegetation type and soil type across the 20 sites
  - Parameters then assigned to full domain based on veg/soil classification.

- **4 Case Studies:**
  - 14 July 2006 (dry; LIS-WRF test case)
  - 18-19 July 2006 (dry; peak of dry-down)
  - 16-17 June 2007 (wet; little precip)
  - 19-20 June 2007 (wet; scattered precip)
Locations of the Atmospheric Radiation Measurement—Southern Great Plains (ARM-SGP) flux towers
Experimental Design

Methodology
1. Use **LIS-OPT** to calibrate LSM parameter sets in each year and use Land surface Verification Toolkit (LVT) to evaluate results.
2. Generate **new lookup tables** of soil, vegetation, and general parameters based on optimization results.
3. Run a suite of **offline LSM spinups** with both default and calibrated parameters.
4. Run **coupled LIS-WRF** initialized w/spinups for each case study and different parameter set.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Description</th>
<th>Spinup Parameters</th>
<th>Coupled Parameters</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>DEF</td>
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<tr>
<td></td>
<td>Default run w/lookup table params in LIS &amp; LIS-WRF</td>
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<tr>
<td>2</td>
<td>CPL</td>
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<tr>
<td></td>
<td>Impact of calibrating coupled LIS-WRF ONLY</td>
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<tr>
<td>3</td>
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<tr>
<td>4</td>
<td>SCP</td>
<td>Calibrated</td>
<td>Calibrated</td>
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<tr>
<td></td>
<td>Impact of full calibration (LIS and LIS-WRF)</td>
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</tbody>
</table>
Experimental Design

Research Questions:

1) Employ LIS-OPT to calibrate surface fluxes in an offline LSM using a mesoscale observing network and averaging across veg/soil characteristics.

2) Quantify impact of ‘optimal’ surface fluxes on coupled forecasts using an array of LoCo diagnostics.
Offline Calibration - 2006

Latent Heat Flux

Sensible Heat Flux

Soil Heat Flux

Qle

Qh

Qg
Offline Calibration - 2007

Latent Heat Flux

Sensible Heat Flux

Soil Heat Flux

Latent Heat Flux (W/m²)

Sensible Heat Flux (W/m²)

Ground Heat Flux (W/m²)

Qle

Qh

Qg

Latent Heat Flux

Sensible Heat Flux

Soil Heat Flux
• Sensible (Qh) and Latent (Qle) Heat Fluxes are improved at nearly all individual sites and over the full domain.

• Mean diurnal cycles of Qh and Qle are improved in both regimes.

• Largest improvement is seen in Qh for the dry and Qle for the wet regime.

• Little change in Qg during dry regime, and degrades during the wet regime with no improvement in phase.
LIS-OPT Coupled Experiments

Impact of Calibration

- **Default** (DEF) parameters lead to largest errors in T, q, fluxes and PBL.
- **Calibration** (SCP) improves all components of L-A coupling and reduces cumulative RMSE by 15-26% and T and Q biases by 8-30%.

### Table

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<tr>
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<td>6288.60</td>
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<td>-1.78</td>
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</table>

**Equations**

\[ b_{sfc} = \frac{Q_{h_{sfc}}}{Q_{le_{sfc}}} \]

\[ b_{ent} = \frac{Q_{h_{ent}}}{Q_{le_{sfc}}} \]

\[ A_{le} = \frac{Q_{le_{ent}}}{Q_{le_{sfc}}} \]

\[ A_{h} = \frac{Q_{h_{ent}}}{Q_{h_{sfc}}} \]
**Impact of Calibration**

- Calibration of both the offline and coupled parameters (SCP) produces the best coupling of the land surface forcing (Evaporative Fraction) and atmospheric response (PBL Height) in LIS-WRF.

**Offline vs. Coupled Calibration**

- Mismatch in offline vs. coupled parameter sets leads to surface net radiation and flux imbalance.
Impact on Ambient Weather Forecasts

14 July 2006

- Domain average stats
- Processed using Model Evaluation Toolkit (MET)
- 214 site observations at each analysis time (6h)

- Calibration (SCP) improves the 2m Temperature and Humidity forecasts across the full domain

- LIS Spinup (DEF) and Calibration (SCP) improves over default WRF

![Graphs showing impact on ambient weather forecasts](image_url)
14 July 2006
- Domain average stats
- Processed using LVT
- 19 ARM-SGP site observations at each analysis time (1h)

• Calibration (SCP) improves the Sensible, Latent, and Soil Heat Flux forecasts across the WRF domain
### 19-20 June 2007

#### NOAH – E4 – 19 June 2007

<table>
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#### NOAH – E4 – 20 June 2007

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<tr>
<td>N-S Efficiency</td>
<td>0.672</td>
<td>0.538</td>
<td>0.321</td>
<td>0.658</td>
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**2m Temperature (K)**

- 6.0
- 12.0
- 18.0
- 313.5
- 303.6
- 293.6

**2m Humidity (g/kg)**

- 6.0
- 12.0
- 18.0
- 313.5
- 303.6
- 293.6
Calibrated parameters improve fluxes (Sfc and PBL) and states (T2m and Q2m) during both regimes.

Near-perfect surface fluxes ($b_{sfc}$) often translate into better coupled components ($b_{ent}$, $A_h$, $A_{le}$), and are reflected in better Total RMSE/MAE, PBL Budgets and EF/PBLH.

Largest improvement and impact of the land model and parameters is seen during the dry regime.

Improvement due to calibrated parameters diminishes as regimes become more extreme (e.g. end of dry-down and during high-freq precipitation).
Implications for Improved Coupled Prediction

- Calibrated parameter sets are compensatory in terms of:
  A) Water and energy states (e.g. higher soil moisture)
  B) Water and energy fluxes (e.g. lower evaporation rate)

- As a result, the proper:
  a) land surface initial conditions AND
  b) evaporative physics

   are both required (SCP) to maximize calibration in coupled simulations.

- A calibrated LSM spinup (SPN) by itself can produce more accurate temperature and humidity forecasts, regardless of the parameter sets used in the coupled simulation.
Methodology
1. Use LIS-OPT to calibrate LSM parameter sets in 2008 and 2006-7-8 combined (May-Sept in each).
2. Evaluate the offline calibration in each year and the impact on coupled LIS-WRF forecasts from calibrating during different periods (dry, wet, normal, combined).

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<td>Impact of calibrating during 2007 only</td>
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<td>C08</td>
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<td>5</td>
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<td></td>
<td>Impact of calibrating to all three years combined</td>
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</table>
2006-7-8 Calibration

Latent Heat Flux

Sensible Heat Flux

Soil Heat Flux

Qle

Qh

Qg
Impact of Calibration Period:
- Default (DEF) and 2008-calibrated (C08) parameters lead to largest errors in T, q, fluxes and PBL evolution.
- Calibration in either the dry or wet year (C06, C07) improves all components of L-A coupling and produce very similar fluxes & states.
- Calibration using all available data (C678) improves prediction, but less than during extremes.

Impact of Calibration Period:

- Default (DEF) and 2008-calibrated (C08) parameters lead to largest errors in T, q, fluxes and PBL evolution.
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<td>Q2 BIAS</td>
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<td>T2 BIAS</td>
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<tr>
<td>N-S Efficiency</td>
<td>-1.782</td>
<td>-1.030</td>
<td>-2.303</td>
<td>-0.987</td>
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Impact of Calibration Period:

- Default (DEF) and 2008-calibrated (C08) parameters lead to largest errors in T, q, fluxes and PBL evolution.
- Calibration in either the dry or wet year (C06, C07) improves all components of L-A coupling and produce very similar fluxes & states.
- Calibration using all available data (C678) improves prediction, but less than during extremes.
Impact of Calibration Period:

- Calibration of the dry year during either of the extreme regimes (\textit{C06} and \textit{C07}) produces the best coupling of the land surface forcing (Evaporative Fraction) and atmospheric response (PBL Height) in LIS-WRF.

- Calibration during either extreme period acts to correct a dry bias in the Noah LSM.

- During a ‘normal’ regime (\textit{C08}), the calibration produces a slightly drier and less evaporative Noah.
**CZIL** Data

**CZIL**: Zilitinkevich coefficient relating surface fluxes to the roughness length for heat ($Z_{oh}$) and exchange coefficient ($C_h$)

- Higher values decrease $Z_{oh}$ and $C_h$
- Consistent with results from NCAR/NCEP

**FXEXP** Data

**FXEXP**: Exponent for bare soil evaporation calculation as fn(SM, Veg)

- Lower values increase $ET_{bare~soil}$
- Consistent with results of Santanello et al. (2007) and Peters-Lidard et al. (2008)
Impact of MCSIM:

- **Default** (DEF) based run
- **Fully Calibrated** (SCP)

- Five additional runs conducted using the parameter values sampled from a uniform prior distribution (MCSIM)

- The results indicate significant spread in hydrometeorological prediction resulting from land surface parameter uncertainty.

▶ A similar set of simulations are being conducted with DEMC where the parameter values are revised using ARM-SGP surface flux data
For improvements in coupled prediction using LSM calibration, the following must be considered:

**What to calibrate?**
- Fluxes most important for atmospheric/climate models
- Soil states are a by-product in this approach (hard to measure and validate)
- Near-future missions - focus on measuring soil states rather than fluxes
- Ultimately, both states and fluxes measured and used for calibration will inform on LSM performance and improvement in translating e.g. SM to Evap

**How to calibrate?**
- Averaging across soil and veg classes and categorizing soil-soil & veg-veg parameters appears to work overall (isolated sites where degrades)

**When to calibrate?**
- Seasonally to capture wings of the distribution (dry-downs and wet-ups) and model biases
- Not a one-size-fits-all approach: extremes (06/07) vs. normal conditions (08)
Summary

This experiment was designed as a prototype OSSE for future missions (e.g. SMAP).

Using LIS-OPT/UE, we can quantify the tradeoffs of data availability vs. accuracy in prediction:
- Space: Categorical estimation
- Time: Period of calibration
- Variables: Fluxes vs. States

In the future, simultaneous development of Earth Science technologies (e.g. microwave soil moisture sensors) and methodologies (e.g. thermal evapotranspiration retrievals) will warrant the LIS-OPT/UE approach.

With the NU-WRF and LIS-OPT/UE system, we can now jointly calibrate and assimilate land & atmosphere states and fluxes.