*SMAP Algorithms & Cal/Val Workshop, Oxnard, CA*

# *The SMAP Level 4 Surface and Root-Zone Soil Moisture (L4_SM) Product*

Jun 10, 2009


| | |
|---|---|
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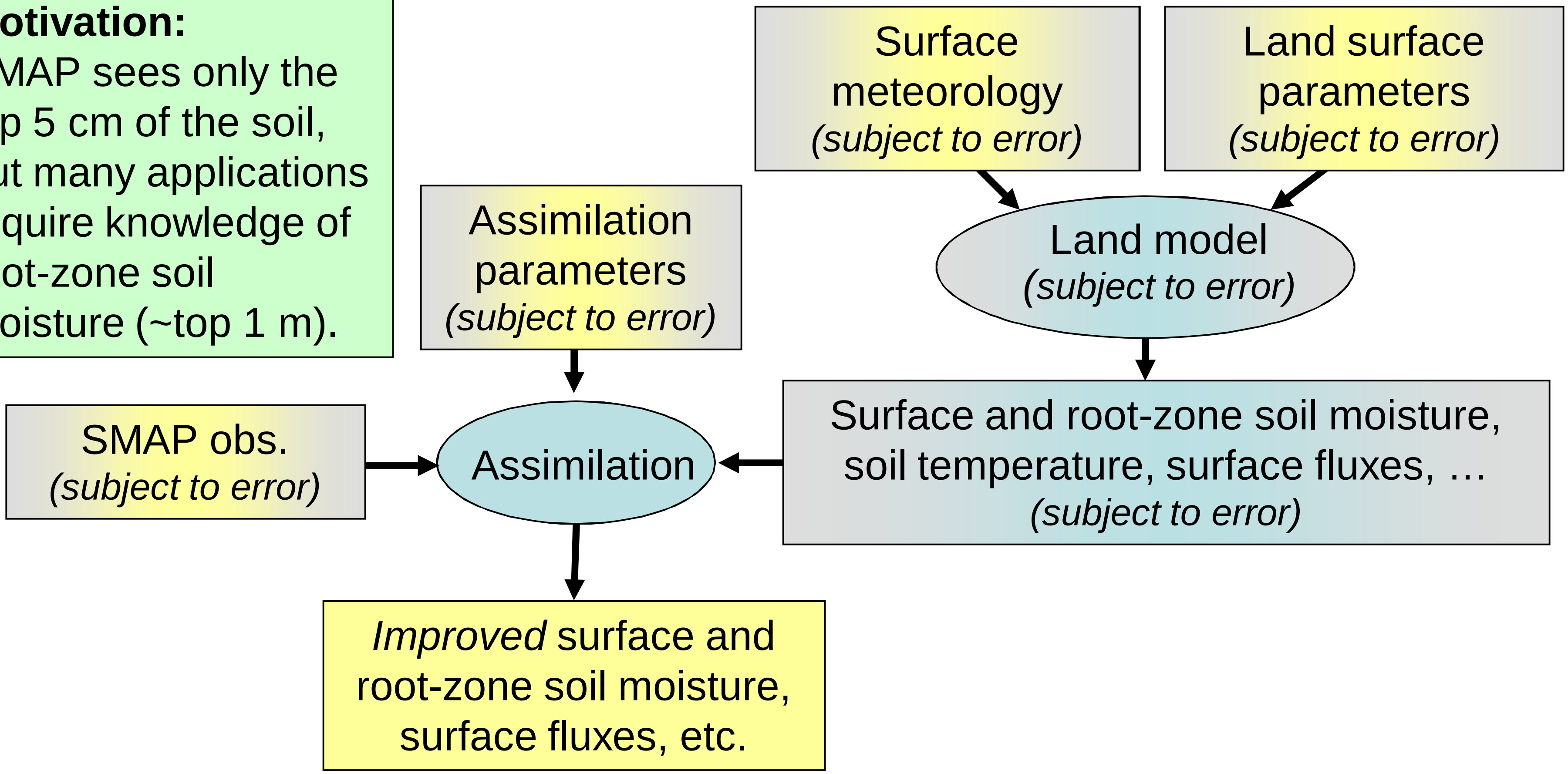
# *L4_SM motivation and overview*

**Motivation:**
SMAP sees only the top 5 cm of the soil, but many applications require knowledge of root-zone soil moisture (~top 1 m).



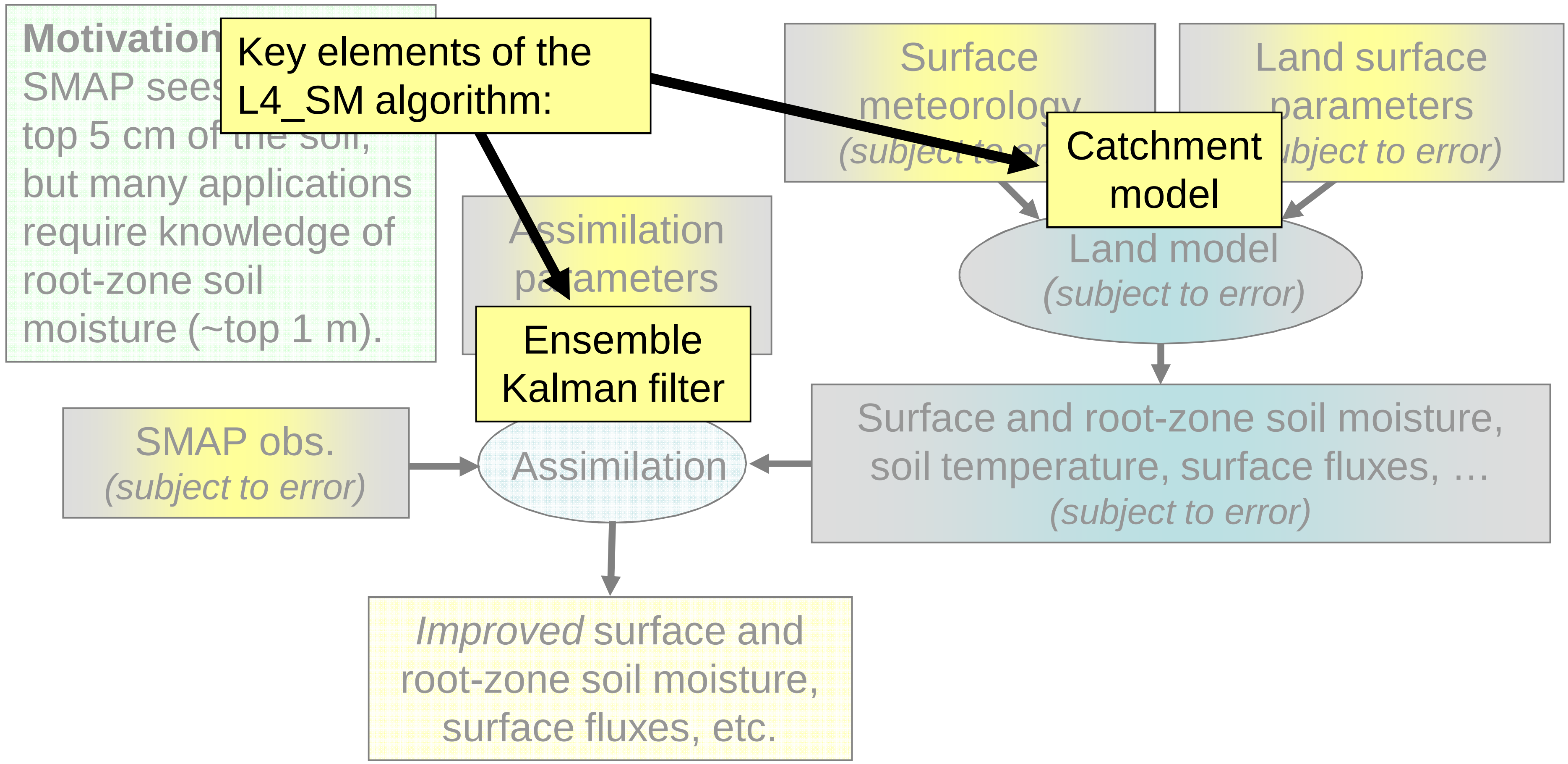

Assimilating **SMAP data** into a **land model** driven with **observation-based forcings (incl. precipitation)** yields:

(1) ***a root zone moisture product (reflecting SMAP data)***

(2) ***an improved surface product***

(3) ***a complete and consistent estimate of soil moisture & related fields***

# *L4_SM motivation and overview*




Assimilating **SMAP data** into a **land model** driven with **observation-based forcings (incl. precipitation)** yields:

(1) ***a root zone moisture product (reflecting SMAP data)***

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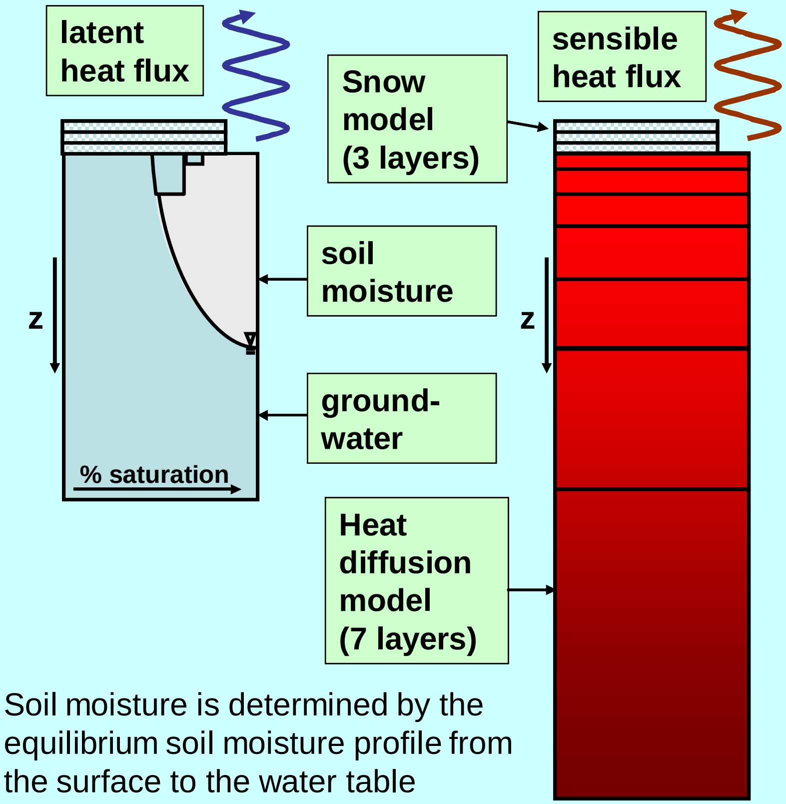
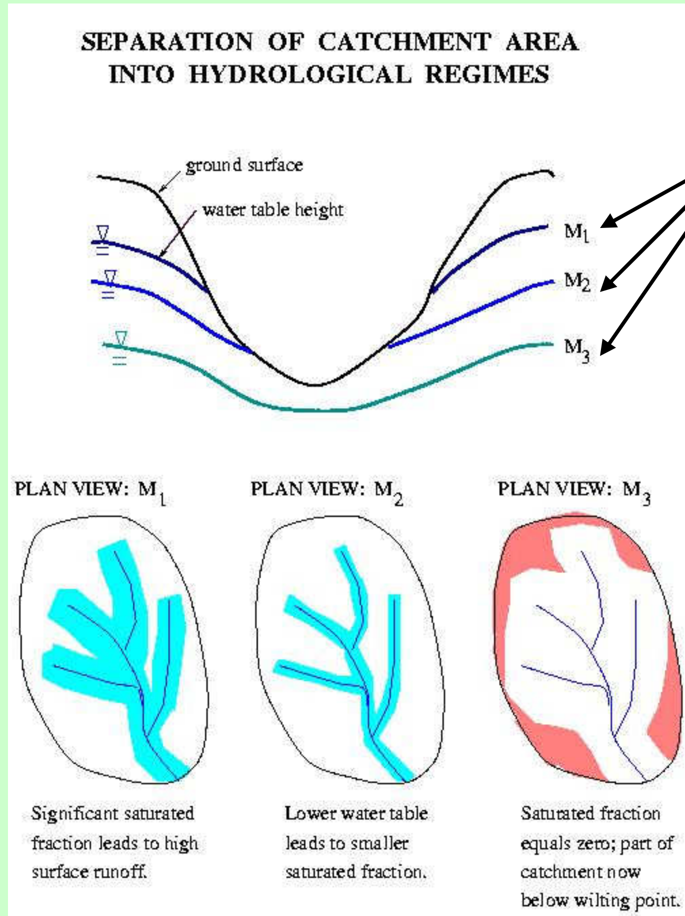
# NASA Catchment land surface model

## Vertical dimension




Soil moisture is determined by the equilibrium soil moisture profile from the surface to the water table (*"catchment deficit"*) and by two additional variables that describe deviations from the equilibrium profile: the average deviation in a 1 m root zone layer (*"root zone excess"*), and the average deviation in a 5 cm surface layer (*"surface excess"*). The model outputs surface (top 5 cm), root zone (top 1 m), and total profile soil moisture as diagnostics.

## Horizontal dimension




Different moisture levels (shown here as different water table depths)…

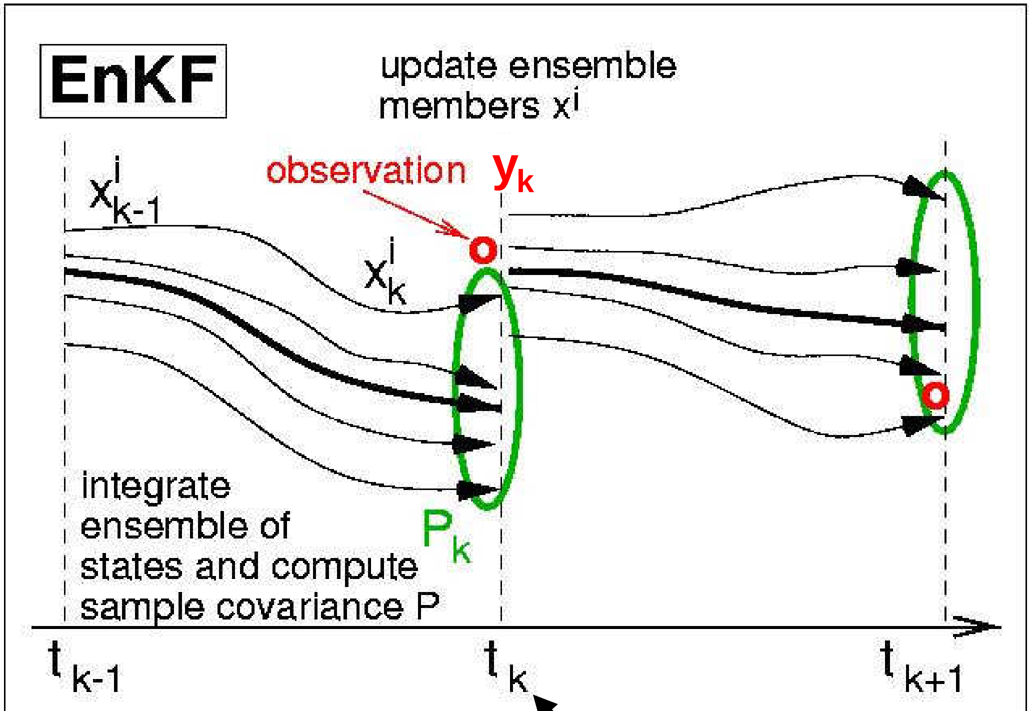
…lead to different areal partitionings of the catchment into saturated, unstressed, and wilting regimes.

The surface energy balance and surface runoff are computed separately for the saturated, transpiring, and wilting sub-areas of each catchment.

Implement for SMAP on a **9 km global grid** (same as L3_SM_A/P product)

Koster et al. 2000; Ducharne et al. 2000; Bowling et al. 2003; Guo and Dirmeyer 2006; Guo et al. 2006

# *Ensemble Kalman filter (EnKF)*




**Nonlinear** ensemble propagation approximates **model errors.**

Apply small **perturbations** to each ensemble member (model forcings and states) at every time step.

**Optional**: Adaptive estimation of error parameters

**Optional**: Dynamic bias estimation

Propagation $\mathbf{t_{k-1}}$ to $\mathbf{t_k}$:

$\mathbf{x_k^{i-} = f(x_{k-1}^{i+}) + e_k^i}$

**e** = model error

Update at $\mathbf{t_k}$:

$\mathbf{x_k^{i+} = x_k^{i-} + K_k(y_k^i - x_k^{i-})}$

for each ensemble member i=1…N

$\mathbf{K_k = P_k (P_k + R_k)^{-1}}$

with $\mathbf{P_k}$ computed from ensemble spread

$\mathbf{x_k^i}$ state vector (eg soil moisture)

$\mathbf{P_k}$ state error covariance

$\mathbf{R_k}$ observation error covariance

**Andreadis and Lettenmaier (2005); Durand and Margulis (2007); Kumar et al. (2008a, 2008b, 2009); Pan and Wood (2006); Reichle et al. (2002a, 2002b, 2007, 2008a, 2008b, 2009); Reichle and Koster (2003, 2004, 2005); De Lannoy et al. (2007); Crow and Reichle (2008); Zaitchik et al. (2008); Zhou et al. (2006)**

# L4_SM inputs and outputs

## SMAP inputs

*Baseline:*
**L3_SM_A/P** (9 km)
*Option:*
**L1C_S0_HiRes** (3 km)
+ **L1C_TB** (40 km)

**L3_F/T** (3 km)

## L4_SM algorithm

## Ancillary data inputs

**GMAO GEOS-x*:**
(~1/8º resolution by 2013)

Land model parameters⁺

Land cover, albedo, porosity, soil hydraulic and topographic parameters, LAI, greenness

Surface meteorology

Precipitation – corrected with observational product (e.g. pentad CMAP)

Downward longwave and shortwave radiation, air temperature and humidity, surface pressure and wind

Land assimilation parameters

Observation and model error standard deviations; temporal, spatial, and cross-correlation parameters

*GEOS-x = Land and atmospheric modeling and assimilation system at the NASA Global Modeling and Assimilation Office (GMAO)

⁺ adjusted for consistency with parameters used by other SMAP products

## L4_SM product

*Validated output (error<0.04 $m^3/m^3$)*
**- surface soil moisture (≡ top 5 cm)** (vol % & percentiles)
**- root zone soil moisture (≡ top 1 m)** (vol % & percentiles)

*Research output (not validated, exact list TBD)*
- surface temperature (**input to L4_C**)
- sensible, latent, and ground heat flux
- fraction of saturated, wilting, and unsaturated area
- snow water equivalent, snow depth, snow cover area
- runoff, baseflow, snowmelt
- surface meteorological forcings (air temperature, precipitation, …)
- Catchment model parameters
- **error estimates** (generated by assimilation system)

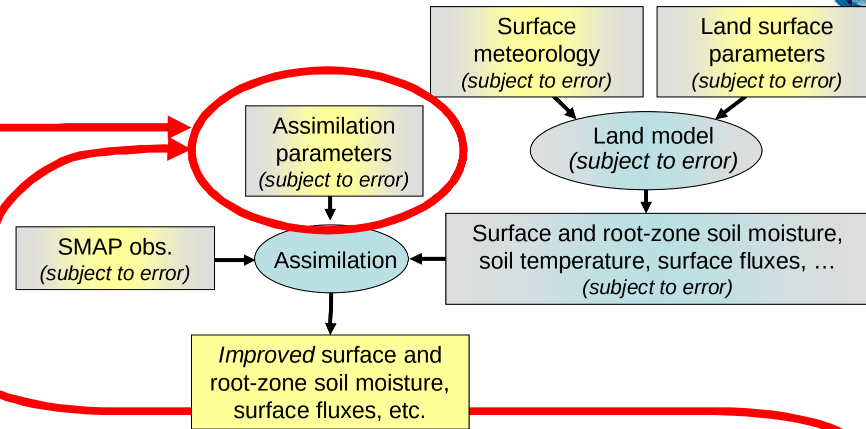
• **9 km global** grid with **5-day latency** (after 1-year cal/val phase)
• **3-hourly averages**
• **Snapshots** at/near SMAP overpass times (EnKF updates at 0z, 3z, …, 21z)

Data volume:
~4 MB/field
~45 GB/month
Output format:
netcdf4/hdf5

# *L4_SM assimilation parameters*

Observation error std from L3_SM_A/P (≤ 0.04 m³/m³)

Perturbations to model forcing and prognostic variables approximate "model errors".




| Perturbation | Additive (A) or Multiplicative (M)? | Standard deviation | AR(1) time series correlation scale | Spatial correlation scale | Cross-correlation with perturbations in | |
|---|---|---|---|---|---|---|
| | | | | | SW | LW |
| Precipitation | M | 0.5 | 1 day | 50 km | -0.8 | 0.5 |
| Downward shortwave (SW) | M | 0.3 | 1 day | 50 km | n/a | -0.5 |
| Downward longwave (LW) | A | 50 W m$^{-2}$ | 1 day | 50 km | n/a | |
| Catchment deficit | A | 0.05 mm | 3 h | 25 km | | |
| Surface excess | A | 0.02 mm | 3 h | 25 km | | |

Values are based on experience with AMSR-E assimilation (Reichle et al. 2007) and synthetic experiments (Reichle et al. 2002b; Reichle and Koster 2003).

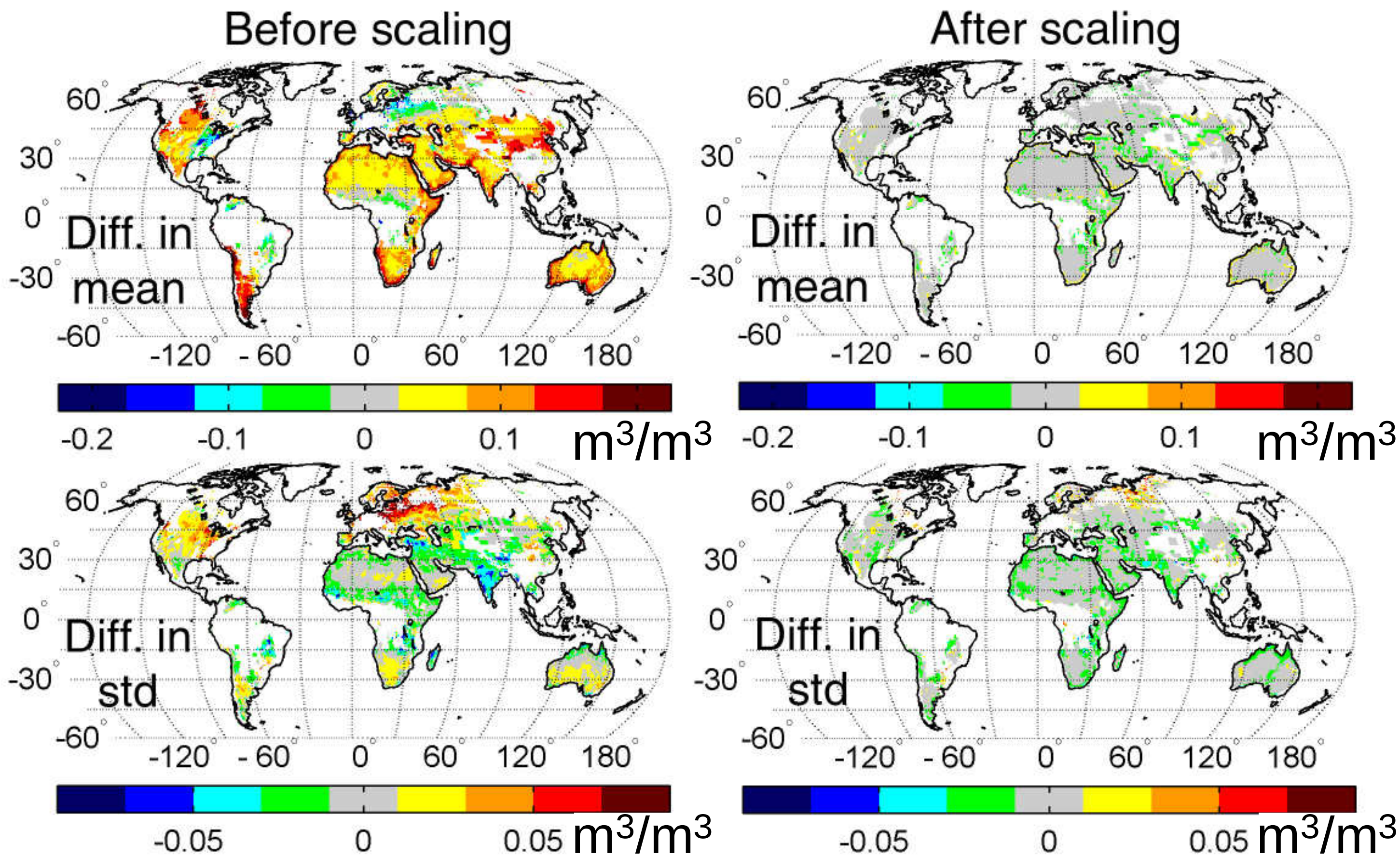
Will be tuned with SMOS observations.

Optional adaptive filtering module may help determine optimal values.

# *Bias and scaling*

Figure shows typical bias between satellite and model surface soil moisture that must be addressed in the assimilation system.

Scaling is based only on data from a single year.




**Baseline algorithm**: A priori scaling (cdf-matching) of L3_SM_A/P into Catchment model climatology (Reichle and Koster 2004, Drusch et al. 2005).

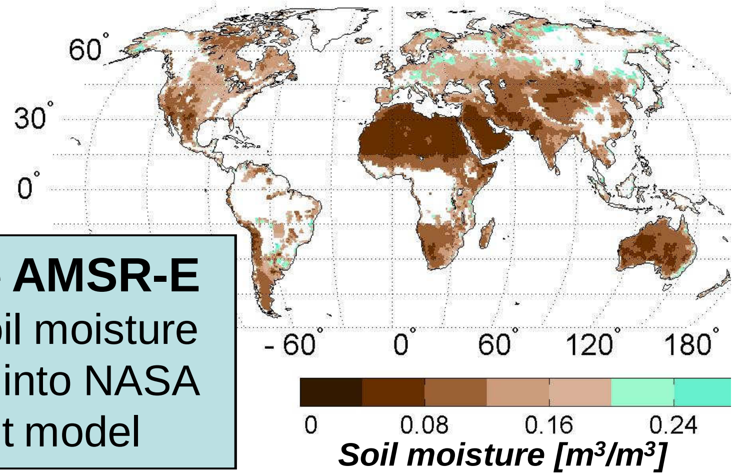
**Optional algorithm**: Dynamic bias estimation (De Lannoy et al. 2007).

Will be tuned with SMOS observations.

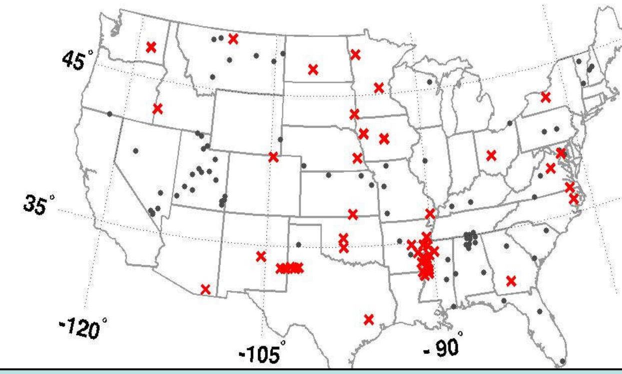
# *L4_SM cal/val*

| Pre-launch |
|---|
| – Use L4_SM system with SMOS obs & apply cal/val to the extent possible.<br>– Conduct OSSE's (calibration of assimilation parameters). |
| **Post-launch** |
| **Calibration within 1st year:**<br>Bias correction param's ("cdf matching"), assimilation param's (thru innovations).<br>**Validation with in situ observations:**<br>*Surface soil moisture*:<br>Apply L3_SM_A/P cal/val procedures.<br>*Root-zone soil moisture*:<br>In principle, cal/val is identical to surface soil moisture, but<br>- have fewer in situ obs. (e.g. from USDA/SCAN, NCDC/CRN)<br>- rarely/never have multiple in situ obs. within single grid cell |
| **Additional evaluation:**<br>– Examine "obs-minus-model" residuals for internal consistency of the L4_SM algorithm (Reichle et al. 2008; Crow and Reichle 2008).<br>– Evaluate with high-quality, independent precipitation obs (Crow 2007).<br>– Evaluate research product components (e.g. fluxes) to the extent possible. |
| ***Requirement***: Need as many **root-zone** soil moisture obs. as possible. |

# *Uncertainty estimates: Results from AMSR-E*




Assimilate **AMSR-E** surface soil moisture (2002-09) into NASA Catchment model




Validate with USDA SCAN stations (only 36 of 103 suitable for validation)

| ***Anomaly RMSE*** **v. in situ observations [m³/m³]** | | | | |
|---|---|---|---|---|
| | N | **AMSR-E** | **Model** | **Assim.** |
| Surface s.m. | 36 | 0.049 | 0.051 | 0.048 |
| Root zone s.m. | 32 | n/a | 0.039 | 0.036 |
| ***Anomaly R*** **time series correlation coeff. v. in situ observations, with 95% confidence interval** | | | | |
| | N | **AMSR-E** | **Model** | **Assim.** |
| Surface s.m. | 36 | .42±.01 | .38±.01 | .47±.01 |
| Root zone s.m. | 32 | n/a | .37±.01 | .45±.01 |

Anomalies ≡ Daily data with mean seasonal cycle removed

Higher quality of SMAP obs. will provide better improvements (see next slides).

**Results UPDATED from Reichle et al. (2007) *J Geophys Res*, doi:10.1029/2006JD008033.**

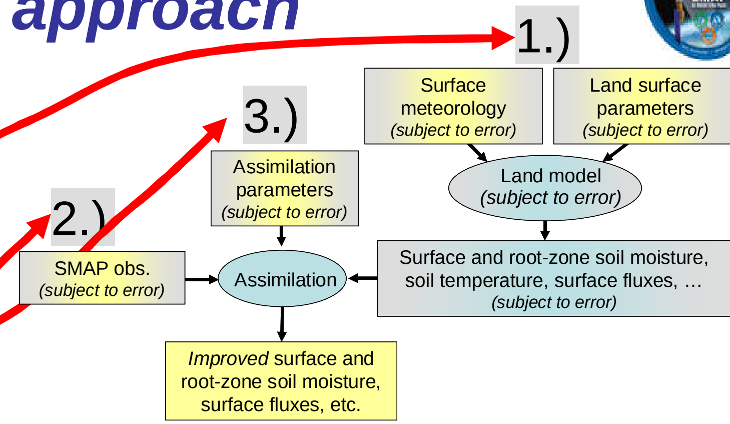
# *Uncertainty estimates: OSSE approach*

***Key error sources:***

1.) Errors in land model (***"model error"***), incl. errors in
   a) Surface meteorological forcing
   b) Land model parameterizations and parameters

2.) Errors in input SMAP products (***"obs error"***)

3.) Errors in assimilation parameters




***Soil moisture assimilation OSSE***
***(Observing System Simulation Experiment)***
Investigate *range* of obs and model errors by assimilating synthetic SMAP retrievals from a TOPLATS "truth" model integration into the Catchment model.

**Example: Skill of anomalies in terms of R** (=anom. time series correlation coeff. v. synthetic truth).

Each plus sign indicates result of one **19-year** assimilation integration over **Red-Arkansas domain**.

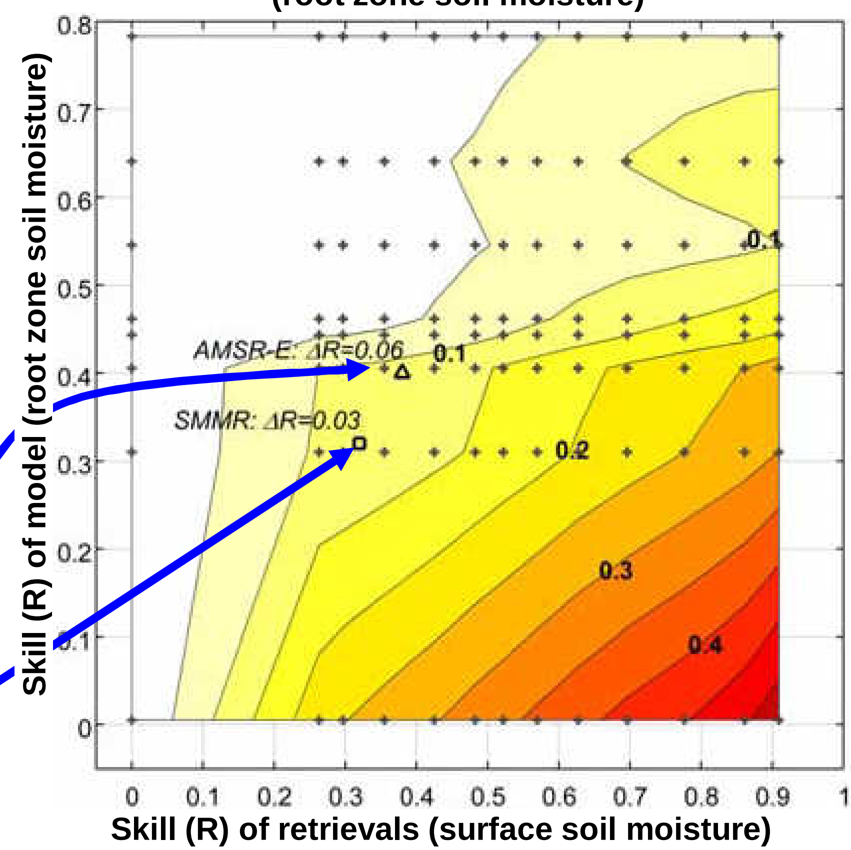
Contour surface shows skill *improvement* of assimilation estimates over model estimates.

Anomalies ≡ Daily data with mean seasonal cycle removed`

**OSSE is consistent with results from AMSR-E and SMMR assimilation.**

AMSR-E (Δ): *ΔR=0.06*
SMMR (□): *ΔR=0.03*

**Skill *improvement* of assimilation over model (ΔR)**
**(root zone soil moisture)**

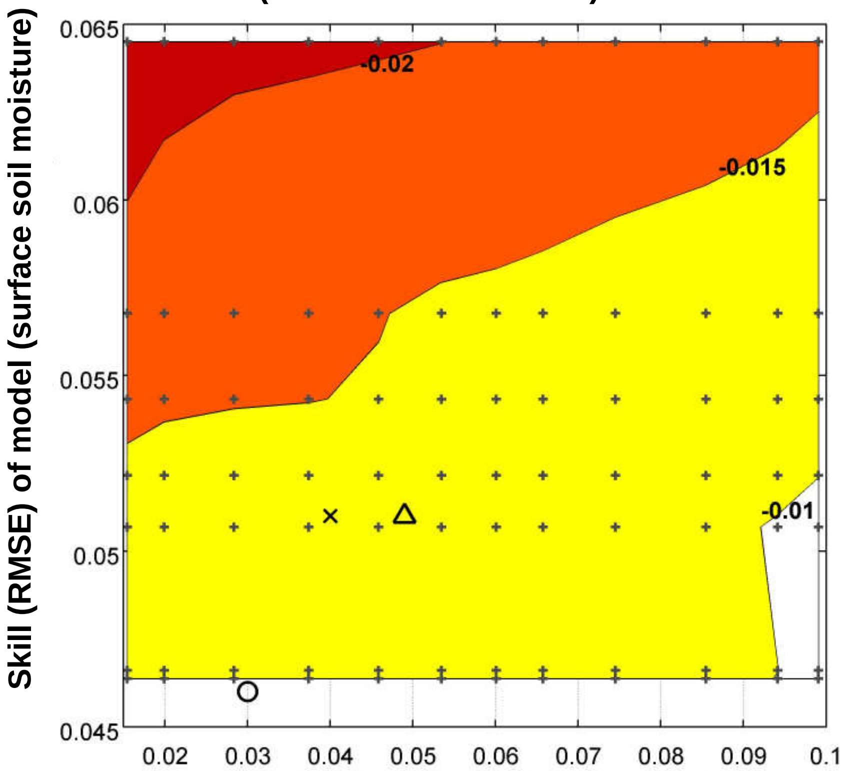



**Reichle et al. (2008) *Geophys Res Lett*, doi:10.1029/2007GL031986.**

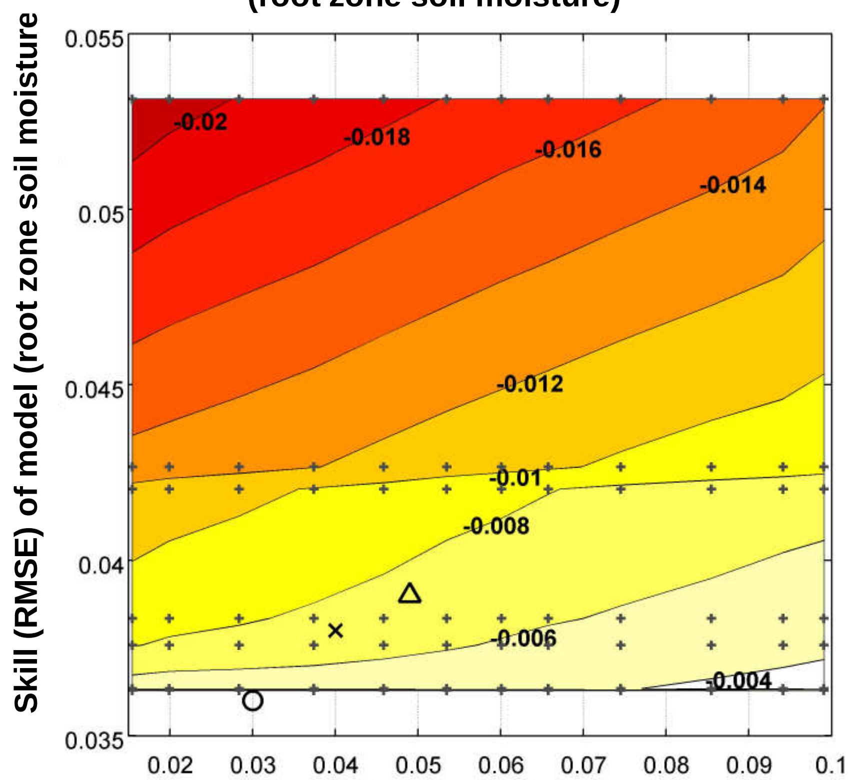
# *Uncertainty estimates: OSSE approach*

| *anomaly RMSE [m³/m³]* | |
|---|---|
| ***surface soil moisture*** | ***root zone soil moisture*** |

**Skill *improvement* of assimilation over model (ΔRMSE) (surface soil moisture)**




**Skill *improvement* of assimilation over model (ΔRMSE) (root zone soil moisture)**




```
o = L4_SM (high skill)
x = L4_SM (low skill)
Δ = AMSR-E
```

Symbols indicate (actual or estimated) skill for satellite observations and land modeling systems.

Anomalies ≡ Daily data with mean seasonal cycle removed

# L4_SM uncertainty estimates

***Interpreting the OSSE for SMAP yields:***

| | Skill scenario | L3_SM[1,3] (A/P) | Model[2,3] | L4_SM[3] | \|Δ\| |
|---|---|---|---|---|---|
| ***Expected anomaly RMSE [m³/m³]*** | | | | | |
| **Surface soil moisture** | High | 0.028 | 0.046 | 0.035* | 0.012 |
| | *Low* | *0.037* | *0.051* | *0.038** | *0.012* |
| **Root zone soil moisture** | High | n/a | 0.036 | 0.031 | 0.005 |
| | *Low* | *n/a* | *0.038* | *0.031* | *0.007* |
| ***Expected anomaly R*** | | | | | |
| **Surface soil moisture** | High | 0.78 | 0.63 | 0.71 | 0.08 |
| | *Low* | *0.70* | *0.41* | *0.54* | *0.13* |
| **Root zone soil moisture** | High | n/a | 0.55 | 0.63 | 0.08 |
| | *Low* | *n/a* | *0.46* | *0.59* | *0.13* |

[1]Source: SMAP measurement requirements.
[2]Source: USDA/SCAN results.
[3]Source: OSSE results.

|Δ| ≡ |Model – L4_SM| (skill contribution of SMAP over model)

anomalies ≡ daily data with mean seasonal cycle removed

*L4_SM skill appears worse than L3_SM skill because of OSSE legacy constraints.

Assimilation of SMAP obs will provide improvements (over model) of ~0.01 $m^3/m^3$ for surface and ~0.005 $m^3/m^3$ for root-zone soil moisture.

L4_SM is expected to meet the 0.04 $m^3/m^3$ error requirement.

# *Next steps and time line*

- **External review** *(in progress – more later)*
- **Finalize L4_SM ATBD** *(by Jan 2010)*
  - Error budget
  - Root-zone soil moisture cal/val
  - Refine specification of L4_SM product
- **L4_SM development and implementation**
  - **Catchment model customization for SMAP** *(start ASAP)*
    - 9 km global grid and 5 cm surface layer
  - **Assimilation system development**
    - L3_F/T assimilation development *(start ASAP)*
    - Decide between baseline and option algorithm *(start 2010)*
    - Operational implementation *(start Oct 2010)*
  - **Exercise L4_SM with SMOS obs. and apply cal/val**

# External review

Input on L4_SM algorithm requested from select *commentators.*

To date received 7 (of 8) responses – THANKS!!!

*[proposed] system […] is state-of-the-art*

*most important contribution […] is […] root-zone soil moisture*

*extremely beneficial;* *looks quite okay to me*

*great asset to the SMAP mission*

*very useful for a large range of applications*

*emphasis should […] be put on a flexible bias correction*

*assimilate Tbs and S0s [as opposed to L3 products]*

*Catchment land surface model is one of the best […]*

*Consider using an ensemble of models. I DO NOT believe the Catchment model is […] best*

*[for validation] need as a minimum […] 5 stations in a ‘grid’ cell*

**What do you think? Let us know!**

*From:* Rolf Reichle
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Stephane Belair, Environment Canada
Matthias Drusch, ESA
Robert Gurney, University of Reading, UK
Yann Kerr, CESBIO
Steven Margulis, UCLA
Patricia de Rosnay, ECMWF
Jeff Walker, University of Melbourne
Eric Wood, Princeton University

*Re:* Request for comments on the SMAP L4_SM algorithm and product

May 4, 2009

Dear Colleague:

As you are well aware, the NASA Soil Moisture Active Passive (SMAP; http://smap.jpl.nasa.gov) mission will measure *surface* soil moisture. The SMAP Level 4 Surface and Root-Zone Soil Moisture (L4_SM) product utilizes the SMAP *surface* soil moisture observations to provide estimates of *root zone* soil moisture as part of a spatially and temporally contiguous product that is based on data assimilation. For details please refer to the attached L4_SM Executive Summary and L4_SM Overview presentation.

As part of the mission preparations, the SMAP Science Definition Team (SDT) will solicit community input on SMAP algorithms at a workshop to which you are cordially invited (Oxnard, CA, 9-11 June 2009; http://smap.jpl.nasa.gov/events). In addition to the workshop, **the SDT is soliciting *written* input on the L4_SM product from select commentators, including you.** As you may know, NASA missions do not usually provide products that are based on data assimilation. We feel, however, that a root-zone soil moisture product is particularly important for SMAP to meet its science and applications objectives. Community input will help determine the degree to which such a product is feasible, appropriate, useful, and needed.

We highly value your experience in land data assimilation and kindly ask that you to provide written comments (in any format) on the L4_SM algorithm and product. In particular, please comment on

1.) the scientific merit of the proposed L4_SM algorithm,
2.) the impact of the L4_SM product over and above Level 3 SMAP products and estimates from ancillary data sources, and
3.) the utility of the proposed L4_SM product to the science and application communities.

Comments on other aspects of the L4_SM product are also welcome. If at all possible, **please return your written comments to me by June 1, 2009** so that they can be considered at the workshop, or let me know if you need more time. The attached documents provide a summary of the L4_SM algorithm and product. Upon request we can provide a draft of the L4_SM Algorithm Theoretical Basis Document which provides a more detailed description. Overview documents for other SMAP products are available at ftp://ftp.eecs.umich.edu/people/mmoghadd/SMAP_Alg_CalVal_Workshop_June2009.

Please do not hesitate to contact me with any questions that you may have. We greatly appreciate your help and look forward to a fruitful discussion. Many thanks and best regards,

Rolf Reichle

Rolf Reichle

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# *Discussion*

***Suggested topics (feedback from external review, project needs):***

- **Algorithm specifications**
  - baseline v. option algorithm (estimation of bias & assim. parameters)
  - choice of land model
  - smoother
  - F/T assimilation
- **Output product specifications**
  - fields
  - units
  - space-time resolution
- **Validation**
  - metric and bias
  - special case of root-zone soil moisture
- **Applications**
  - any specific requirements?

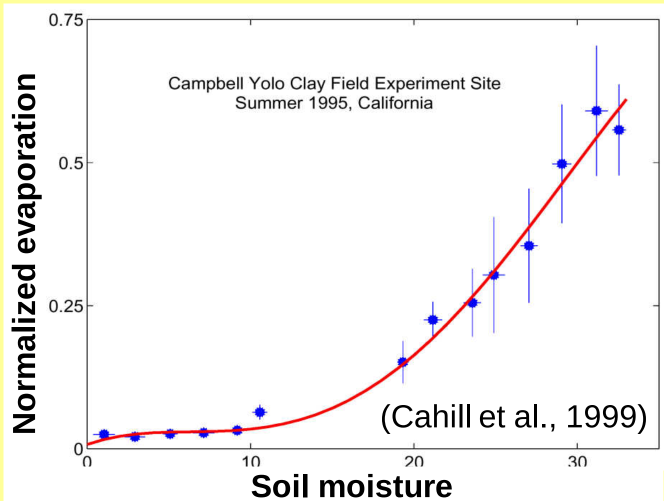
**THANK YOU FOR YOUR ATTENTION!**

## BACKUP SLIDES

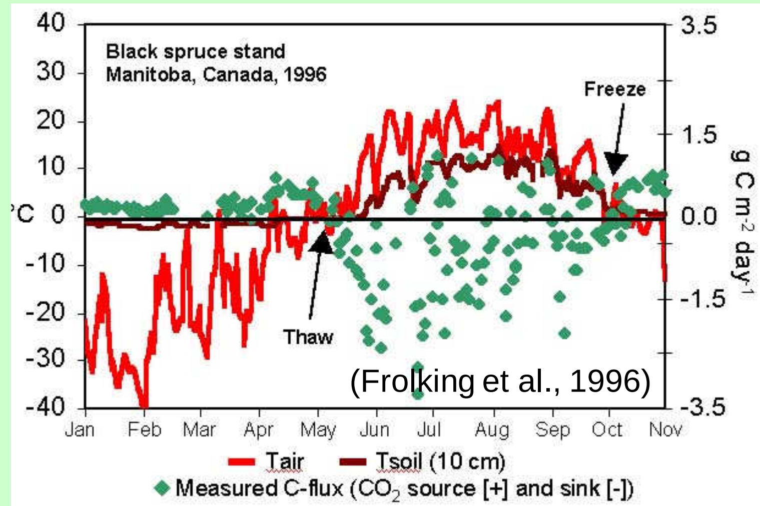
# NASA Soil-Moisture-Active-Passive (SMAP) mission

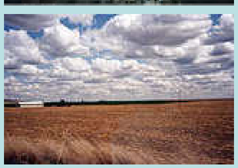
*First of NRC Earth Science Decadal Survey missions*

*Latent heat flux depends on soil moisture*




*Soil freeze-thaw drives boreal carbon balance*



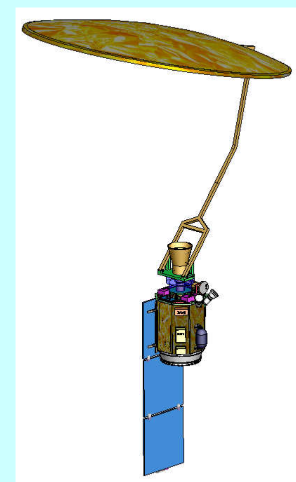
## Science objectives

- Global land surface water, energy, and carbon fluxes.
- Enhance weather and climate forecast skill.
- Improve flood prediction and drought monitoring.

## Platform and instruments

L-band (1.4 GHz) synthetic aperture radar (active) and radiometer (passive) with 6-m rotating antenna

| | |
|---|---|
| *Orbit:* | Sun-synchronous<br>~680km altitude<br>6am/pm overpass |
| *Swath width:* | 1000 km |
| *Resolution:* | 1-3 km (radar)<br>40 km (radiometer) |
| *Revisit:* | 2-3 days |
| *Duration:* | 2013-16 |
| ***Sensing depth:*** | **~5 cm** |



Only surface soil moisture!

# NASA Soil-Moisture-Active-Passive (SMAP) mission

**SMAP Baseline Science Data Products**

| Abbreviation | Description | Resolution | Latency |
|---|---|---|---|
| L1B_S0_LoRes | Low Resolution Radar Backscatter ($\sigma^o$) | ~ 30 km | 12 hours |
| L1C_S0_HiRes | High Resolution Radar Backscatter ($\sigma^o$) | ~ 1-3 km | 12 hours |
| L1B_TB | Radiometer Brightness Temperature ($T_B$) | ~ 40 km | 12 hours |
| L1C_TB | Radiometer Brightness Temperature ($T_B$) | ~ 40 km | 12 hours |
| L3_F/T_HiRes | Freeze/Thaw State | ~ 3 km | 24 hours |
| L3_SM_HiRes | Radar Soil Moisture (internal product) | n/a | n/a |
| L3_SM_40km | Radiometer Soil Moisture | ~ 40 km | 24 hours |
| L3_SM_A/P | Radar/Radiometer Soil Moisture | ~ 10 km | 24 hours |
| L4_SM | Surface & **Root-zone** Soil Moisture | ~ 10 km | 7 days |
| L4_C | Carbon Net Ecosystem Exchange | ~ 10 km | 14 days |

assimilate

# *L4_SM computational requirements*

The L4_SM algorithm will be
– based on the existing NASA GMAO land assimilation system,
– developed and implemented within the NASA GEOS modeling and assimilation framework,
– written primarily in Fortran90 and an object-oriented extension (ESMF), and
– executed on Linux-based cluster computing facilities at NASA.

**Estimated computational requirements:**

| | |
|---|---|
| Catchment model time step | 20 min |
| EnKF update time step | 3 h |
| Model/assimilation grid spacing | 10 km |
| Number of model grid cells | 1e6 |
| Number of ensemble members | ~24 |
| CPU requirement per simulated month | 18 h |
| Total memory requirement | 23 GB |
| Online (hard-drive) storage requirement (1 data month) | 90 GB |
| Long-term (tape) storage requirement (for entire 3-year mission) | 3 TB |

# *L4_SM applications*

A number of scientists in national and international agencies were identified who envision using the SMAP L4_SM product, primarily for reanalysis and/or research/validation w.r.t. their operations and products:

| ***Institution*** | ***POC*** |
|---|---|
| NOAA/NCEP, NOAA/NESDIS | Zhan |
| ECMWF | De Rosnay |
| Environment Canada | Belair |
| Air Force Weather Agency | Eylander |
| NOAA Climate Prediction Center | Mo, Xie |
| US Army | Davis |
| US Army | McWilliams |
| USGS Famine Early Warning System | Verdin |

We anticipate that the SMAP L4_SM product will be widely used in academic and government research
– because it includes root-zone soil moisture and related land surface fields,
– because of its complete coverage, and
– because of the availability of consistent and comprehensive estimates of land surface hydrologic conditions.

# *Baseline v. option algorithm*

Baseline: Assimilate L3_SM_A/P + L3_F/T

Option: Assimilate L1C_S0_HiRes + L1C_TB + L3_F/T

***Advantages of option algorithm:***

Consistent handling of surface soil temperature.

L4_SM processing independent of L3 algorithms.

***Disadvantages of option algorithm:***

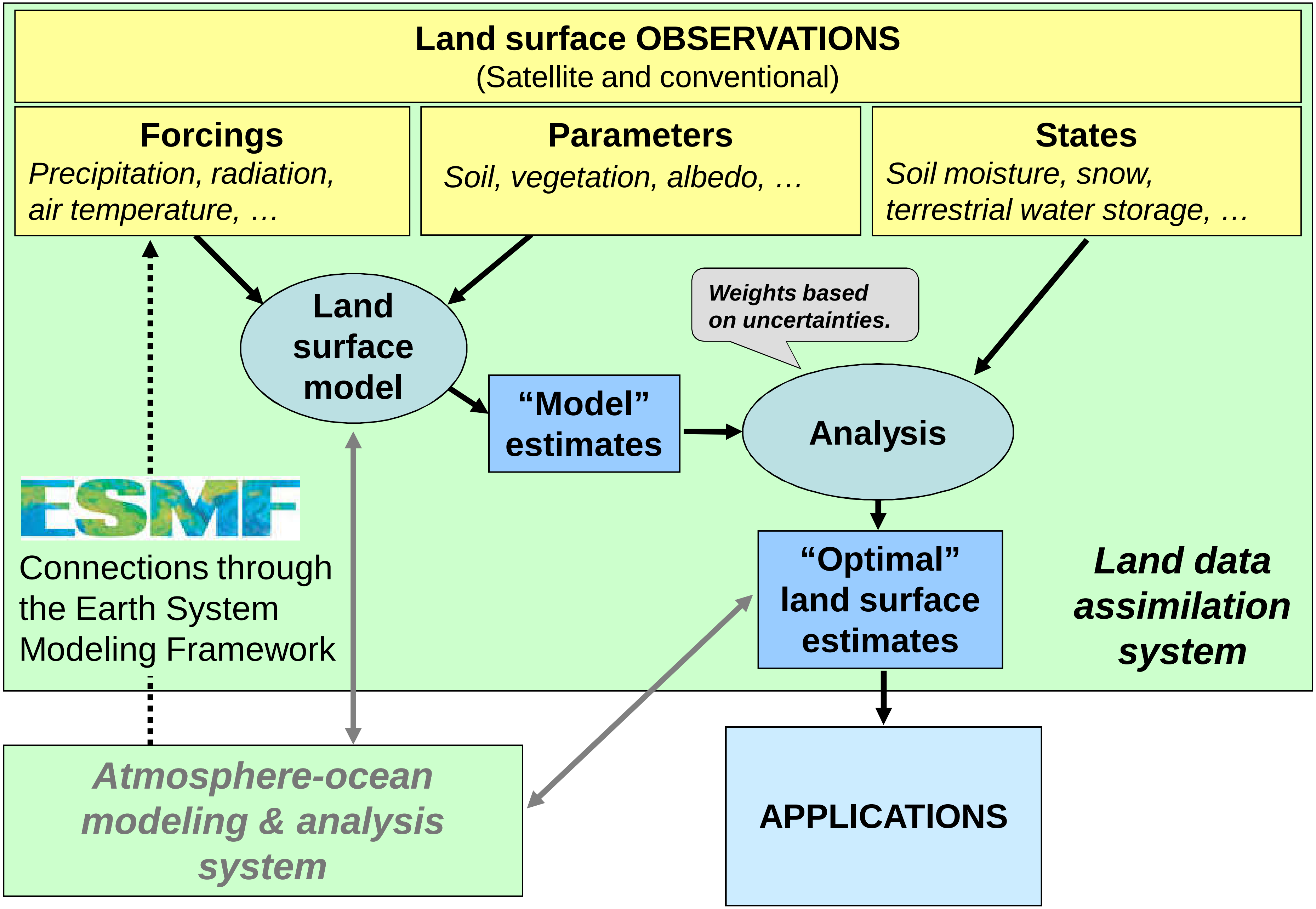
Option algorithm requires implementation of forward radiative and backscatter transfer model within L4_SM processing system.

May not be as sophisticated as the corresponding inverse algorithms.

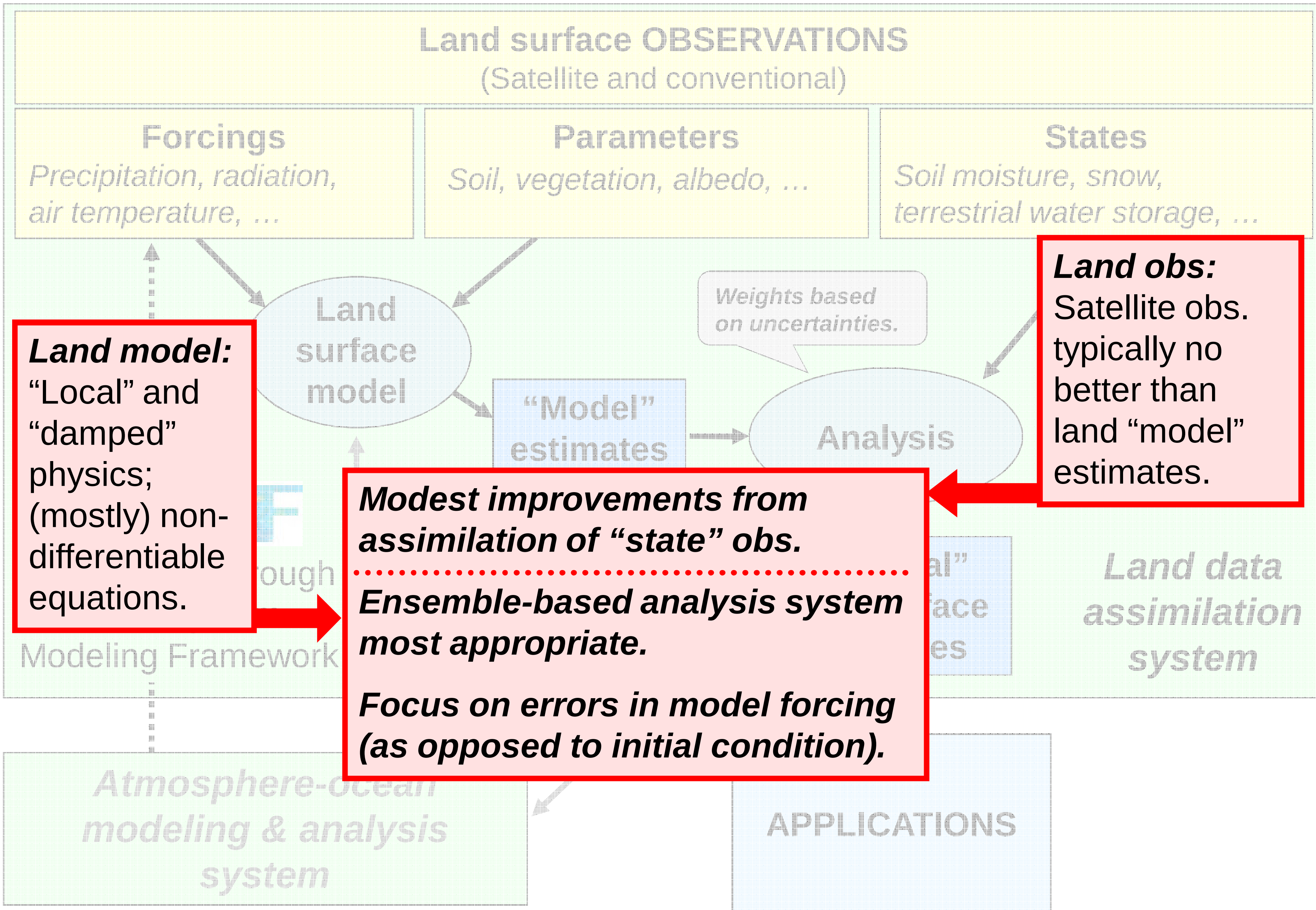
**For now, focus on baseline algorithm.**

**Test option algorithm when permitted by L3 algorithm development, L4 implementation, and availability of SMOS data.**

# *A generic land data assimilation system*



# *What is special about land assimilation?*




***Land model:*** "Local" and "damped" physics; (mostly) non-differentiable equations.

***Land obs:*** Satellite obs. typically no better than land "model" estimates.

***Modest improvements from assimilation of "state" obs.***

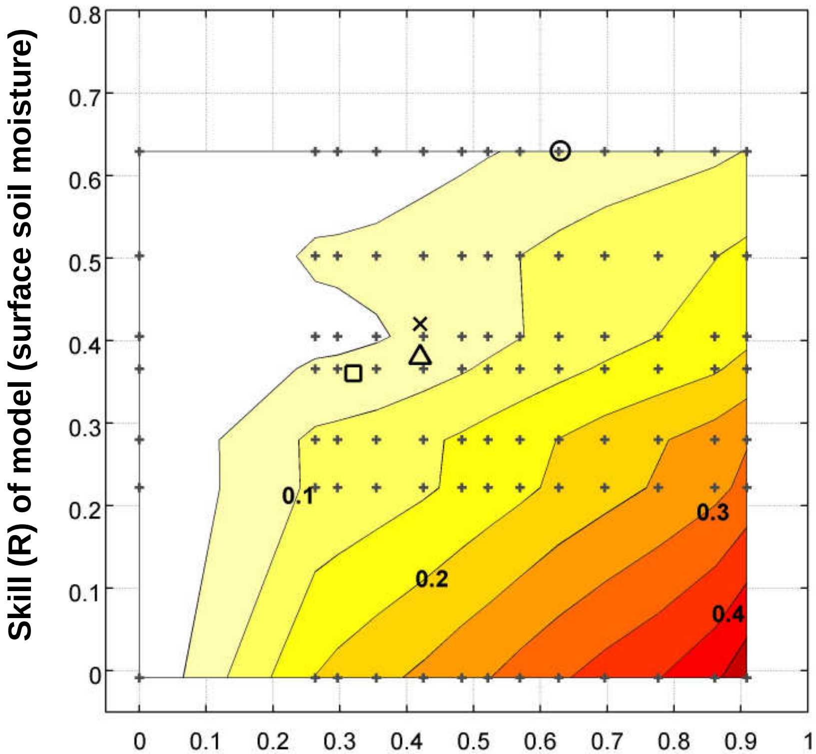
***Ensemble-based analysis system most appropriate.***

***Focus on errors in model forcing (as opposed to initial condition).***

# *Uncertainty estimates: OSSE approach*

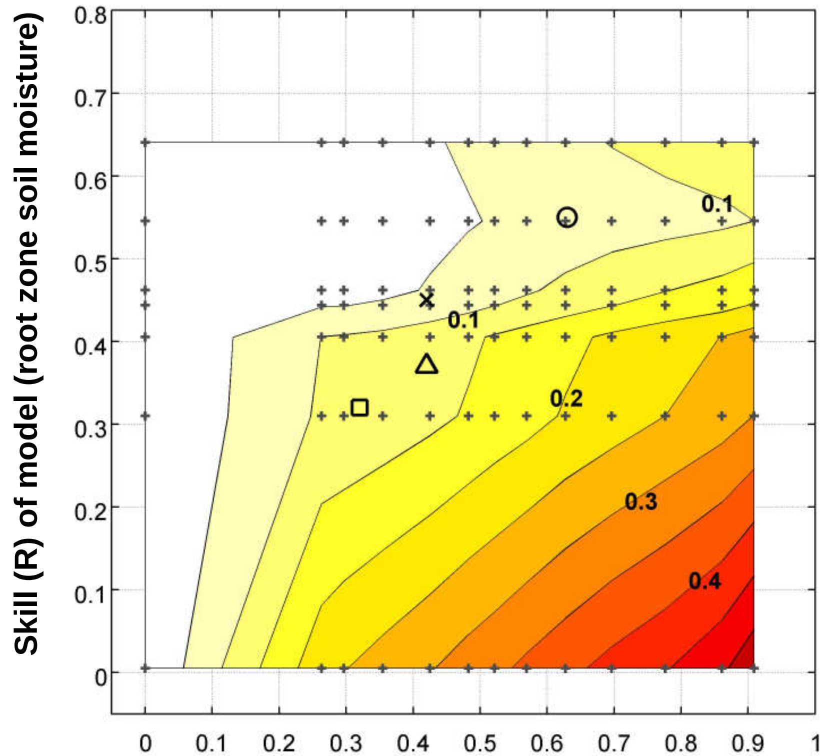
| *anomaly R* | |
|---|---|
| ***surface soil moisture*** | ***root zone soil moisture*** |

**Skill *improvement* of assimilation over model (ΔR)**
**(surface soil moisture)**




**Skill (R) of retrievals (surface soil moisture)**

**Skill *improvement* of assimilation over model (ΔR)**
**(root zone soil moisture)**




**Skill (R) of retrievals (surface soil moisture)**

```
o = L4_SM (high skill)
x = L4_SM (low skill)
Δ = AMSR-E
□ = SMMR
```

Symbols indicate (actual or estimated) skill for satellite observations and land modeling systems.

Anomalies ≡ Daily data with mean seasonal cycle removed

# *Multi-model soil moisture assimilation*

Goddard Space Flight Center
Land Information System

How does land model formulation impact assimilation estimates of root zone soil moisture?

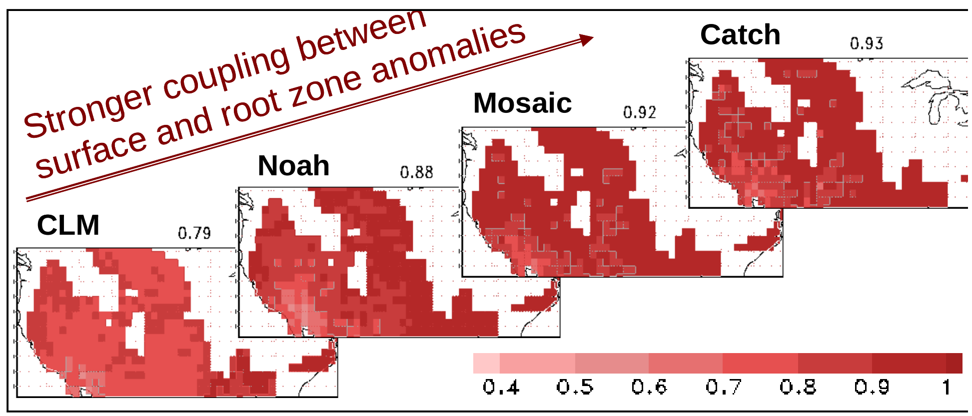
***Normalized ROOT ZONE soil moisture improvement from assimilation of surface soil moisture***

| | | Synthetic observations from | | | | Avg |
|---|---|---|---|---|---|---|
| | | Catch | Mos | Noa | CLM | |
| Model | Catch | 0.71 | 0.54 | 0.36 | 0.38 | **0.50** |
| | Mos | 0.55 | 0.69 | 0.31 | 0.33 | **0.47** |
| | Noa | 0.43 | 0.43 | 0.36 | 0.26 | **0.37** |
| | CLM | 0.11 | 0.21 | 0.10 | 0.45 | **0.22** |
| Avg | | **0.45** | **0.47** | **0.28** | **0.36** | **0.39** |

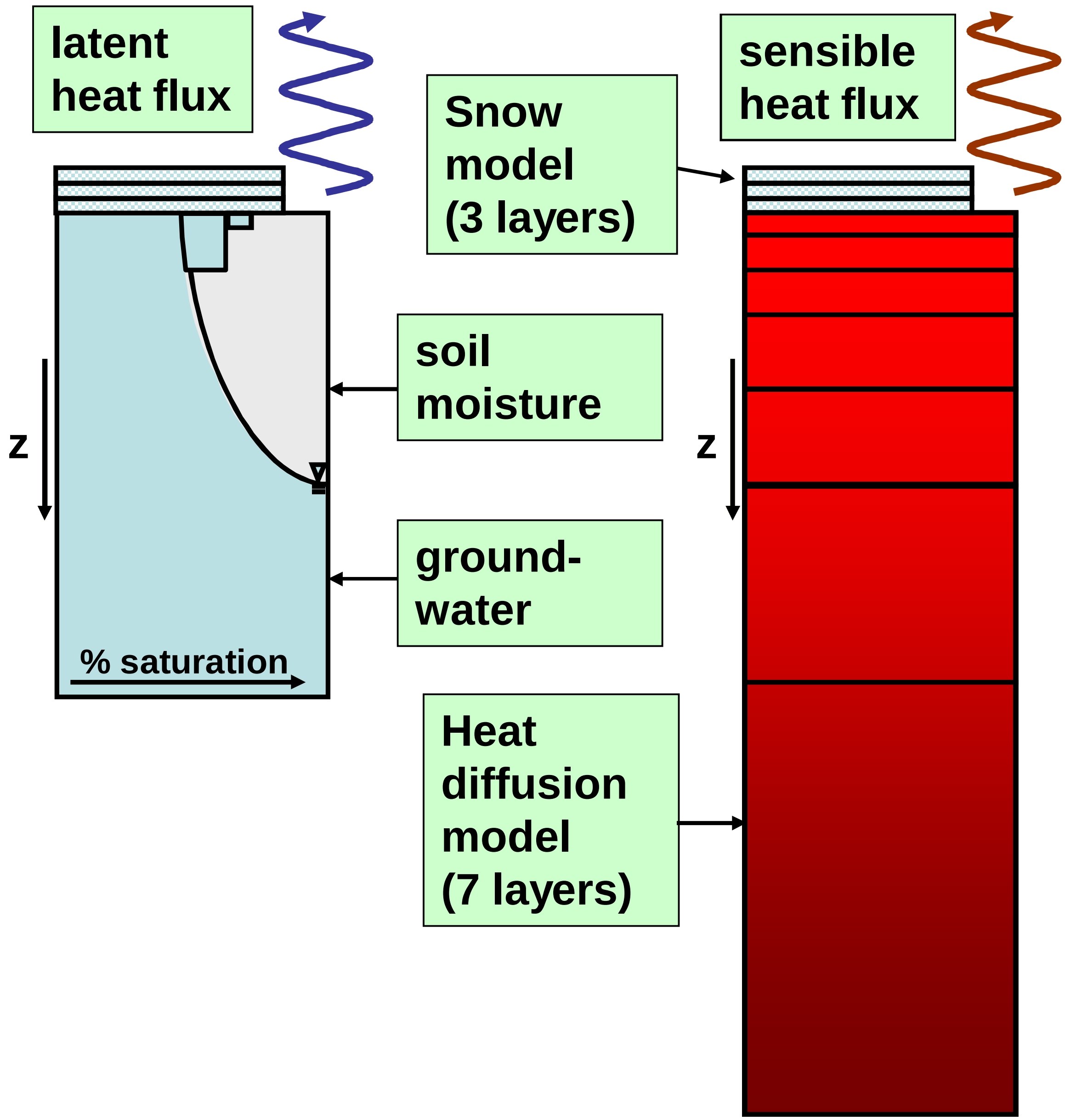
Catchment and Mosaic work better for assimilation than Noah or CLM.

Catchment or MOSAIC "truth" easier to estimate than Noah or CLM "truth".

*Stronger coupling between surface and root zone provides more "efficient" assimilation of surface observations.*




Kumar et al. (2008) *Water Resour. Res.*, in press.


latent heat flux
sensible heat flux
Snow model (3 layers)
soil moisture
ground-water
z
z
% saturation
Heat diffusion model (7 layers)