Data Assimilation of Cosmic-ray Derived Soil Moisture

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COSmic-ray Soil Moisture Observing System

http://cosmos.hwr.arizona.edu

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Data Assimilation

\[ P(X | OBS) = \frac{P(OBS | X).P(X)}{\text{normalization factor}} \]

**EnKF**

- Integrate ensemble of states and compute sample covariance \( P \)
- Observation \( x^i \)
- Update ensemble members \( x^i \)

\( X = \text{state variable (e.g., soil moisture)} \)

Reichle et al. (2002)
Data Assimilation

\[ P(X \mid OBS) = \frac{P(OBS \mid X).P(X)}{\text{normalization factor}} \]

**EnKF**
- **Integrate** ensemble of states and compute sample covariance \( P \)
- **Observation**
- **Update** ensemble members \( x^i \)

\( x^i_{k-1} \)
\( x^i_k \)

\( t_{k-1} \)
\( t_k \)
\( t_{k+1} \)

\( X = \text{state variable (e.g., soil moisture)} \)

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Data Assimilation

\[ P(X | OBS) = \frac{P(OBS | X).P(X)}{\text{normalization factor}} \]

EnKF

- Integrate ensemble of states and compute sample covariance \( P \)
- Update ensemble members \( x^i \)
- Observation

\( X = \text{state variable (e.g., soil moisture)} \)

Reichle et al. (2002)
Data Assimilation

\[ P(X | OBS) = \frac{P(OBS | X) \cdot P(X)}{\text{normalization factor}} \]

**EnKF**
- Integrate ensemble of states and compute sample covariance \( P \)
- Update ensemble members \( x^i \)

\( x^i_{t+1} \)
\( x^i_{t-1} \)
\( x^i_t \)
\( x^i_{t+k} \)

\( t_{k-1} \)
\( t_k \)
\( t_{k+1} \)

\( X = \) state variable (e.g., soil moisture)

Reichle et al. (2002)
Soil Moisture and Measurement Depth

- “Effective” measurement depth depends on soil moisture
- Can reach several individual layers of a typical land surface model

Therefore, **direct assimilation of neutron intensity** is more desirable!!!
Can We Assimilate Neutron Counts?

**GOAL**

to update LSM soil moisture profiles by assimilating the cosmic-ray fast neutron count

Requires an accurate model to interpret modeled soil moisture profiles in terms of the above-ground fast neutron count

Monte Carlo Neutron Particle model (**MCNPx**)
does that but it is **too slow** for use in **data assimilation**
COSMIC is a simple analytic model which:

- captures the essential below-ground physics that MCNPX represents
- can be calibrated by optimization against MCNPX so that the nuclear collision physics is re-captured in parametric form

Exponential reduction in the number of high energy neutrons with depth

Isotropic creation of fast neutrons from high energy neutrons at level “z”

Exponential reduction in the number of the fast neutrons created at level “z” before their surface measurement
COsmic-ray Soil Moisture Interaction Code (COSMIC)

COSMIC is a simple analytic model which:
- captures the essential below-ground physics that MCNPX represents
- can be calibrated by optimization against MCNPX so that the nuclear collision physics is re-captured in parametric form

\[ N_{\text{COSMOS}} = \left( \frac{N_0}{\frac{m_s(z)}{L_1} + \frac{m_w(z)}{L_2}} \right) \cdot \left[ \rho_s(z) + \rho_w(z) \right] \cdot \left( \frac{2}{\pi} \right)^{\pi/2} \int_0^{\frac{\pi}{2}} \exp \left( -1 \cos(\theta) \frac{m_s(z)}{L_3} + \frac{m_w(z)}{L_4} \right) \, d\theta \, dz \]

- Exponential reduction in the number of high energy neutrons with depth
- Isotropic creation of fast neutrons from high energy neutrons at level “z”
- Exponential reduction in the number of the fast neutrons created at level “z” before their surface measurement
Calibrating COSMIC

Hypothetical soil water profiles

Fort Peck

Bondville

Chestnut Ridge

Santa Rita

Coastal Sage

Average Difference = 0.17%

Average Difference = -0.20%

Average Difference = -0.04%

Average Difference = -0.50%

Average Difference = 0.02%
Using COSMIC to estimate COSMOS counts from measured soil moisture profiles (TDT sensors)

The area-average soil moisture from the TDT sensors doesn’t sample the near-surface soil moisture (0-10 cm), so the COSMIC calculation based on it doesn’t recognize the faster rate of drying of surface soil moisture.
Data Assimilation Framework

COSMOS

Observations

another cycle?

initial state

state vector

diagnostics

model_to_dart

new model states

done.

COSMIC

Fortran namelist

Assimilate

state vector

restarts

No

Yes

OR

dart_to_model

initial model states

Unified Noah/OSU Land Surface Model

- Precipitation
- Condensation
- Transpiration
- Canopy Water Evaporation
- Turbulent Heat Fluxes/From Snowpack/Soil/Plant Canopy
- Direct Soil Evaporation
- Deposition/Withdrawal From Moisture Reservoir
- Runoff
- Interflow

- Soil Moisture Flux
- Interflow
- Soil Moisture Flux

- Surface Soil Moisture Flux
- Root Zone Soil Moisture Flux

- Gravitational Flux
- Interflow

http://www.ral.ucar.edu/research/land/technology/lsm.php

http://www.image.ucar.edu/DARes/DART/
NOAH-DART: Neutron Intensity Assimilation

\[ R^2 = 0.97, \text{ RMSE} = 40 \text{ cph, BIAS} = 26 \text{ cph} \]

\[ R^2 = 0.84, \text{ RMSE} = 50 \text{ cph, BIAS} = 832 \text{ cph} \]
NOAH-DART: Soil Moisture Profiles

NOAH Δz₁
NOAH Δz₂

Open Loop

07/03/11 07/10/11 07/17/11 07/24/11 07/31/11 08/07/11 08/14/11 08/21/11 08/28/11 09/04/11 09/11/11
0.05 0.1 0.15 0.2 0.25 0.3 0.35

Assim

07/03/11 07/10/11 07/17/11 07/24/11 07/31/11 08/07/11 08/14/11 08/21/11 08/28/11 09/04/11 09/11/11
0.05 0.1 0.15 0.2 0.25 0.3 0.35

TDT Network

07/03/11 07/10/11 07/17/11 07/24/11 07/31/11 08/07/11 08/14/11 08/21/11 08/28/11 09/04/11 09/11/11
0.05 0.1 0.15 0.2 0.25 0.3 0.35

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NOAH-DART: Integrated Soil Moisture

Daily Averages

\[ R^2 = 0.77, \text{RMSE} = 0.014 \, \text{m}^3 \, \text{m}^{-3}, \text{BIAS} = +0.120 \, \text{m}^3 \, \text{m}^{-3} \]

\[ R^2 = 0.89, \text{RMSE} = 0.008 \, \text{m}^3 \, \text{m}^{-3}, \text{BIAS} = +0.010 \, \text{m}^3 \, \text{m}^{-3} \]

\[ R^2 = 0.63 \]

\[ R^2 = 0.79 \]
Concluding Remarks

- **COSMIC** accurately **simulates** the equivalent **number of neutrons given** model-derived **soil moisture profile**

- **NOAH soil moisture** (surface + root zone) **improved** after assimilating COSMOS neutron counts

- Updated **soil moisture rate of change** could potentially be **used to constrain parameters** in **NOAH** (under investigation)

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H31G-1194. Measuring Total Surface Moisture with the COSMOS Rover by Bobby Chrisman
12.05.2012 (Wed), Poster, Moscone South

H52A-02. Estimates of near surface water flux at intermediate spatial scales using a cosmic-ray neutron probe by Trenton Franz
12.07.2012 (Fri) @ 10:35am, Moscone West 3014