Snow Data Assimilation via Kalman Filtering

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Hydro vs Atmo Snow Applications / Impacts

- **Hydrology**
  - Volume forecast
  - Flood forecasting
  - Reservoir operations
  - Water allocation

- **Meteorology / Climate**
  - Albedo
  - Energy sink
  - Soil moisture
  - Soil insulation
Snow Quantities to Assimilate

- **Volume**
  - Station SWE
  - Station Depth
  - Satellite SWE/Depth

- **Area**
  - Binary snow presence
  - Fractional unmixing

- **Gravity Anomaly**

*Photos: A. Slater.*
Uncertainty in Numerical Modeling

(1) Model Structure
- Parameterizations
- Piecing together components
- Numerical methods

(2) Model Forcing
- Spatial & Temporal structure

(3) Parameter Data
- Soils & Vegetation, type and distribution

(4) Initial Conditions
- Influences trajectory (forecasting = IVP)
Uncertainty in Numerical Modeling

1. Model Structure
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Snow Assimilation & Hydro Forecasting

- Snowpack has big impact
- Sub-optimal data cover

- **Aim**: best estimate of SWE initial conditions for streamflow prediction by combining models & observations

- **Research philosophy**
  - Calibration solves low frequency variability
  - Assimilation aids high frequency variability
Data Assimilation: Ensemble Kalman Filter

1. Project model state ($X$) forward as a function of last model state ($X_{t-1}$) and the forcing ($f_t$)

2. Compute a Kalman Gain ($K$) from covariances ($P$) of transformed ($H$) model data and observation variance ($R$) across ensemble

3. Update the model states using the gain and observations ($z$)
**Stochastic SNOW-17 Simulations**

- **SNOW-17**
  - Anderson (1973)
  - Conceptual model – needs only Temp. + Precip.
  - Runs *operationally* @ the NWS
  - Parameters: CBRFC operational code
  - Calibrated for streamflow, not SWE
  - Nine state variables used

- Model forced with ensemble of inputs
Uncertainties in model inputs (method)

Need estimate of Precip. and Temp. at each basin/box/point

PLUS

Error estimate

Occurrence:
\[ \beta_{\text{new}} = \beta_{\text{old}} + (X^TWX)^{-1} X^TW(Y - \pi) \]

Amounts:
\[ \beta = (X^TWX)^{-1} X^TWY \]
POP & PCP

- Location: Colorado
- Applied Logistic & OLS regression
- All estimates are locally-weighted
- SWE computed similarly
- Temp uses OLS
Obtaining Assimilation Data

- 1D EnKF needs data everywhere
- Convert $\text{SWE}_{\text{obs}}$ to Z-score
- Interpolate & cross validate
- Get $\text{SWE}_{\text{mod}}$ via model hindcast
- Model-space, unbiased value

$$Z = 0.292 \quad \sigma = 0.012 \quad Z + r\sigma = 0.302 \quad = 61.8\%$$

Assimilated SWE = 298
Obtaining “Truth”

- Model-space equivalent of observed SWE
- Match the non-zero SWE CDF’s
53 Upper C.R.B. SNOTEL Stations
Example: Lake Eldora (forcing)
Example: Kiln (forcing)
Rank Probability of Temperature (All Stations)
EnKF Sample Results

Interpolated SWE Mean & Std. Dev

Model

Truth
White without Red = B.L.U.E

- SWE contains red (time correlated) noise
- Only want to use “new” information
- Example – assimilate at same timestep
- Filter Divergence = potential problem
Final Assimilation Results
Requirement: new & better information
SWE Assimilation – Results Summary

• Analysis superior to Model or Observations
• Correlation structure removed
• Only one area of uncertainty covered so far
• Limited data sources, so far
• Model rebalanced for forecasting
• Improves short term forecasting
• Potential operational capabilities
Assimilation of Satellite SCA Information

- Experiments with a “toy” model
  - Temperature index snow model
  - Conceptual series of soil reservoirs
- Applied to the middle Boulder Creek at Nederland
Errors in Model Parameter Choice

- Monte Carlo Markov Chains
  - 100 chains (ensemble members) = 100 parameter sets
- Randomly couple each parameter set with each forcing ensemble
...uncertainty due to forcing plus parameters

[ensemble streamflow simulations at Middle Boulder Creek]
Application—subgrid SWE parameterization

- Model framework of Luce et al., 1999; Liston, 2004
- Variability in SWE determined by total accumulation and coefficient of variability parameter
- Melt assumed to be constant over the grid cell
Application—subgrid SWE parameterization

Accumulation Case

\[ \text{swe} = 100\text{mm} \]
\[ \text{swe} = 200\text{mm} \]

Melting Case

\[ \text{CV} = 0.3 \]
\[ \text{CV} = 0.7 \]
Identical twin experiments—SCA assimilation

- 1D EnKF—SCA used to update the sub-grid distribution of SWE as well as the basin water balance (augment state vector with CV parameter)
- One model ensemble member assumed to be “truth”
- The “truth” ensemble is used to update all other model ensembles

- “Observed SCA” is lower than the model ensemble
- Variability parameter increased; more SWE variability = more ground exposed
Identical twin experiments—SCA assimilation

Similar updates to other model state variables

...with subsequent effects on streamflow simulation
SCA Assimilation: Results Summary

- 1200 synthetic water years
- Small improvement near the end of the melt season
- Limitations on the use of SCA information:
  - A significant amount of melt may occur before any bare ground is exposed
  - The transition between 100% snow cover and 0% snow cover may occur rather quickly
- What is “significant” and what is “quick” will be basin dependent
MODIS Assessment & Field Validation

DEC 9 2007 Terra Modis data

DEC 9 2007 Aqua Modis data

Photo: A. Slater
MODIS SCA vs SNODAS SWE

Slater, Clark, et al (in prep)
SNODAS SWE & MODIS SCA: Sub-Basins

B7 = 300mm SWE

B10 = 1000mm SWE

Slater, Clark, et al (in prep)
**SNODAS SWE & MODIS SCA: Total-Basin**

American (North Fork) Basin Mean Snow Water Equivalent

![Graph showing the American (North Fork) Basin Mean Snow Water Equivalent](image)

American (North Fork) Basin Total Snow Covered Area

![Graph showing the American (North Fork) Basin Total Snow Covered Area](image)

Carson (East Fork) Basin Total Snow Covered Area

![Graph showing the Carson (East Fork) Basin Total Snow Covered Area](image)

Slater, Clark, et al (in prep)
**Snow Distribution**

- LiDAR depth data
- 1x1 km
- NASA CLP-X
- Colorado

McCreight et al, in prep
Passive Microwave SWE Estimation

CHASM SWE - APR 1980-2001 mean
NOAH SWE - APR 1980-2001 mean
CLM SWE - APR 1980-2001 mean
VIC SWE - APR 1980-2001 mean
ECMWF SWE - APR 1980-2001 mean
SMMR/SSMI SWE - APR 1980-2001 mean

Legend:
0 15 30 45 60 75 90 105 120 135 150 165 180 195 210 225 240 255 mm
AMSR-E Snow Products in Mountains

- Some information exists – can we exploit it?
- Global algorithm (Chang) is not ideal
- RT theory for Passive Microwave explains data
Albedo: WRF (physics set 1) vs. MODIS

WRF

MODIS: MOD43C

Albedo

07 APR 2006

0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Albedo