A Method for Snow Reanalysis: The Sierra Nevada (USA) Example

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Presentation outline

- Motivations
- A Method for Snow Reanalysis
- Proof of Concept: Sierra Nevada Case
- Conclusions
Importance of Snow

Water Balance Prospective:

- Water Reservoir
- Snow Water Equivalent (SWE, i.e. the amount of water stored as snow)

Energy Balance Prospective:

- High Snow Albedo
  (Strong influence on land-atmosphere interaction, weather and climate feedbacks)

We need accurate estimates of SWE → Accurate water, weather, climate forecasts.

Barnett et al., (2005), Nature
Snow Bias in Global Reanalysis Datasets

**OBSERVATIONS**

- a) UA Maximum SWE (mm)
- b) SNODAS Maximum SWE (mm)
- c) ratio(CFSR to UA)
- d) ratio(ERA-I to UA)
- e) ratio(ERA-I/Land to UA)
- f) ratio(MERRA to UA)
- g) ratio(MERRA-Land to UA)
- h) ratio(MERRA2 to UA)

**REANALYSES**

Broxton et al., (2016), JHM

- SWE is underestimated
- Larger biases in deep snowpack
- Biases marginally explain by spatial resolution and snowfall biases

Need to provide unbiased reanalysis estimates of SWE
Snow Observations

- **In-Situ Observations**
  - Direct Observations
  - Sparse in Space/Time
  - Insufficient (global) Network

- **Satellite Observations**
  1) Passive Microwave (e.g., SSM/I; AMSRE-E)
    - All weather
    - Daily, 25 km
    - 1987 – present
    - Sensitive to Snow Depth
    - But only shallow SWE
  2) Visible/Near-infrared (e.g., Landsat, MODIS)
    - Daily-Weekly, sub-km scales
    - 1984 – present
    - Clear-sky only
    - No direct estimate of SWE
    - Only Fractional Snow Cover Area (FSCA)

Snow Modeling

Snow processes are known to be a **weakness** of land surface modeling:
- Insufficient winter precipitation forcings
- Complexity of Mountainous Environments

But, models are **good** because providing continuous (space/time) estimates of SWE and FSCA

None of these streams can (alone) provide accurate estimates of SWE
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Snow Reanalysis Concept

Example FSCA depletion
(Tokopah Watershed, California)

Reconstruction of SWE from:
- Depletion of fractional snow covered area [FSCA]
- Space/Time continuous energy fluxes
- SWE as a sum of melt ($m_i$) events

Use satellite observed FSCA to estimate SWE!!

Girotto et al. (2014); HP

Cline et al. (1998), WRR
Snow Reanalysis Concept

Example FSCA depletion
(Tokopah Watershed, California)

Reconstruction of SWE from:
• Depletion of fractional snow covered area \([FSCA]\)
• Space/Time continuous energy fluxes
• SWE as a sum of melt \(m_i\) events

Probabilistic Approach
(Ensemble Kalman Smoother)

Girotto et al. (2014); HP
Sequential vs. Smoothing Schemes

Sequential schemes (e.g., EnKF)

\[
[\Delta x]_t = K_t [M(x_t) - \text{obs}]_t
\]

\[
K_t = C_{xM} [C_{MM} + R]^{-1}
\]

- \( t \): time when the obs is available!
- \( \text{Obs} = fSCA \);
- \( \Delta x = \Delta \text{SWE} \);
- \( C_{xM} \) Relies on instant. \( fSCA \leftrightarrow \text{SWE} \\

Smoother schemes (e.g., EnKS, or PS)

\[
[\Delta x] = K [M(x_t) - \text{obs}]
\]

\[
K = C_{xM} [C_{MM} + R]^{-1}
\]

- \( \text{Obs} = fSCA \) for the entire ablation season
- \( \Delta x = \Delta \text{SWE} \); \( C_{xM} \) obtained from a batch of \( fSCA \leftrightarrow \text{SWE} \\

- Deeper snowpacks
- No real-time applications
- Useful in for reanalysis

Good for ephemeral SWE only;
weak correlation \( fSCA \leftrightarrow \text{SWE} \) for deep SWE
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The Sierra Nevada Example

- Landsat observations (Landsat 5-8 record)
- Forcings: NLDAS
- Temporal Extent: 31 years
- Spatial resolution: 90 m
- Temporal resolution: daily
- Analysis: Particle Smoother
- Maritime snowpack (max. SWE ~1-2m)

- Validation:
  - 108 snow-pillow
  - 202 snow-courses
The Sierra Nevada Example

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Water Year (WY): Oct. 1st - Sept. 30th

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Example: American River Watershed:
- fveg = 52%,
- elev = 2400 m;
- co-located pillow/snow course data

The Sierra Nevada Example

2. Prior vs. Obs mismatch (post fits the obs. by design)

3. Reduced SWE biased, & uncert.
The Sierra Nevada Example

SWE estimates validated against >9000 station-years (snow pillow & snow course data)

SWE statistics show encouraging results:

• ME ~ -2 cm
• RMSE ~ 12 cm
• Corr. ~ 0.96

(Margulis et al. 2016; JHM)
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Conclusions & Future Directions

- This SWE reanalysis provides **unbiased** estimates of SWE even for **large snowpacks** (at least for the Sierra Nevada Mountains).
- SWE reanalysis provides an **unique** dataset in terms of large spatial/temporal extent, high spatial/temporal resolution, accuracy.
- Batch (or **smoothing**) approaches need to be used (as opposed to sequential techniques) to assimilate the entire FSCA depletion.
- The next step is to test the validity of the methods for **global reanalysis**.
Thanks!!!

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