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**

- Panels c-h (-)

*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 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

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)

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

**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!!

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Girotto et al. (2014); HP

Cline et al. (1998), WRR

**Example FSCA depletion**
(Tokopah Watershed, California)

FSCA depletion

April

May

Jun

July

Use satellite observed FSCA to estimate SWE!!
Snow Reanalysis Concept

Example FSCA depletion
(Tokopah Watershed, California)

Reconstruction of SWE from:
- Depletion of fractional snow covered area [FSCA]
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- 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)

\[ [\Delta x]_t = K_t [M(x^t) - \text{obs}]_t \]
\[ K_t = C_{xM} [C_{MM} + R]_t^{-1} \]

\( t \): time when the \( \text{obs} \) is available!

\( \text{Obs} = fSCA; \Delta x = \Delta SWE; C_{xM} \) Relies on instant. \( fSCA \leftrightarrow SWE \)

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

\( \Delta x = \Delta SWE; C_{xM} \) obtained from a batch of \( fSCA \leftrightarrow SWE \)

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

Good for ephemeral SWE only;
weak correlation \( fSCA \leftrightarrow SWE \) for deep SWE

Andreadis and Lettenmaier (2006), AdWR

Obs. OL DA
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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
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Example: American River Watershed:
- \( f_{\text{veg}} = 52\% \),
- \( \text{elev} = 2400 \text{ m} \);
- co-located pillow/snow course data

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

3. Reduced SWE biased, & uncert.

(Margulis et al. 2016; JHM)
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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