Assimilation of multi-frequency, multi-polarization passive microwave brightness temperature observations in North America over snow-covered regions using support vector machines

Yuan Xue[1], Barton A. Forman[1], Rolf H. Reichle[2]

[1] University of Maryland College Park
[2] NASA Goddard Space Flight Center

10 January 2018

Snow matters and Snow risks

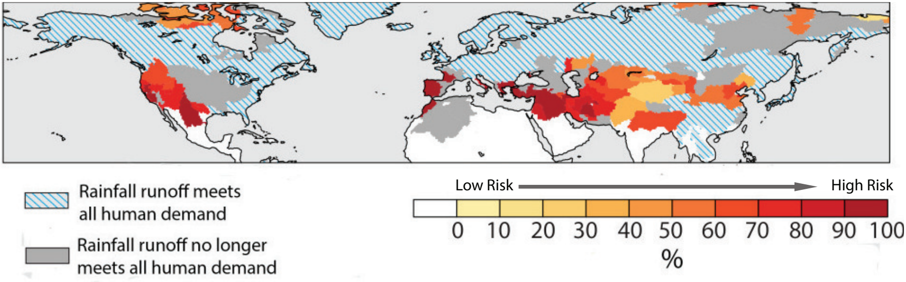
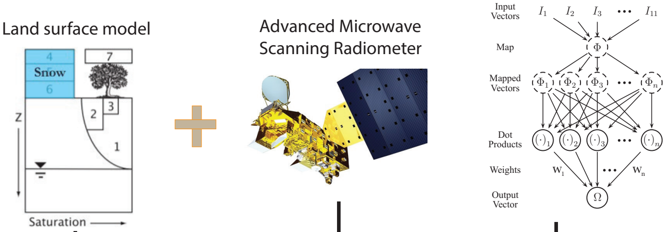


Figure: Projections of decreased potential for snowmelt water to supply human water demand by 2080. (Mankin et al., 2015 Environmental Research Letter)

Objective and Methodology

- Goal: Better characterize snow water equivalent (SWE) and snow depth across regional and continental scales.
- Study domain: North America
- Methodology: Data assimilation (DA) approach — Ensemble Kalman filter (EnKF) $\Longrightarrow$ 1D-EnKF
- Merge observations and model estimates

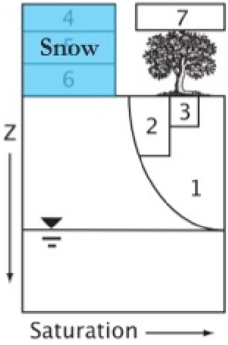
DA Formulation



$$\underbrace{x^{i+}}_{\text{Posterior SWE}} = \underbrace{x^{i-}}_{\text{Prior SWE}} + \underbrace{K}_{\text{Kalman Gain}} \left[\underbrace{(y + v^{i})}_{\text{obs. + obs. error}} - \underbrace{\Phi(x^{i-})}_{\text{Machine learning algorithm based predictions}} \right]$$

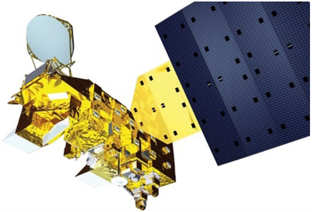
Figure: A conceptual representation of the update step in the EnKF, where the superscript i is the ith replicate in the ensemble.

Forward model



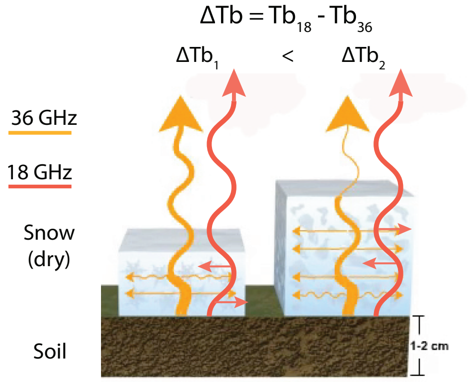
- NASA Catchment model, forced by Modern-Era Retrospective-Analysis for Research and Applications (MERRA)
- three-layer snow model
- 25-km Equal-Area Scalable Earth Grid (EASE-Grid)
- initialize when seasonal snow cover at minimum

Passive microwave observations



- Advanced Microwave Scanning Radiometer EOS (AMSR-E)
- measures passive microwave emissions (i.e., brightness temperatures (Tb))
- from 01 September 2002 to 01 July 2011
- multi-frequency (10 GHz, 18 GHz, and 36 GHz), multi-polarization (H pol., and V pol.) Tbs
- 25-km Equal-Area Scalable Earth Grid (EASE-Grid)

Relationship between SWE and ΔTb



- first-order approximation: ΔTb $\Uparrow$, SWE (or snow depth) $\Uparrow$
- similar approximation for $\Delta Tb = Tb_{10} - Tb_{36}$
- longer wavelength, deeper snow information

Observation operator

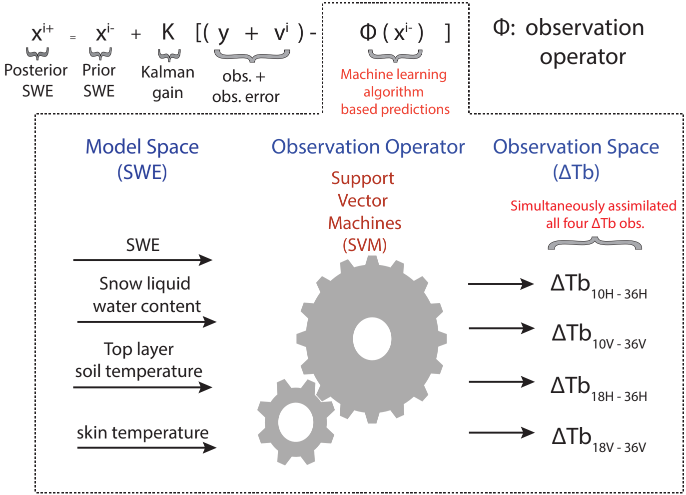


Figure: A conceptual representation of the machine learning algorithm based ΔTb prediction framework.

Others Terms in the EnKF Formulation

- Ensemble size: 40
- Perturb precipitation, shortwave radiation, and longwave radiation
- ΔTb observation error: $\sim \mathcal{N}(0, 3\text{K}) \Longrightarrow$ same for all four channels
- SWE is the only state variable in the EnKF update
- Other snow-related modeled states were adjusted accordingly

SVM-DA evaluation

- Model-derived results vs. ground-based stations
  - National Water and Climate Center Snow Telemetry (SNOTEL) SWE
  - SNOTEL snow depth
  - NOAA Global Summary of the Day (GSOD) snow depth
  - USGS daily and cumulative discharge
- Model-derived results vs. available snow products
  - Canadian Meteorological Centre (CMC) snow depth
  - AMSR-E SWE
  - European Space Agency (ESA) GlobSnow SWE

**Note: Model-derived results:

(1) open-loop derived (OL; without assimilation) ensemble mean

(2) data assimilation derived (DA; with assimilation) ensemble mean

Goodness-of-fit statistics

- e.g., bias, unbiased root-mean-squared error (ubRMSE)
- Normalized information contribution (NIC) (Kumar et al., 2009), including NIC_{RMSE}, and NIC_{NSE}
  - $\mathrm{NIC} > 0$: DA outperforms OL
  - $\mathrm{NIC} = 0$: DA is comparable to OL
  - $\mathrm{NIC} < 0$: DA degrades OL

*RMSE: root-mean-squared error
*NSE: Nash-Sutcliffe model efficiency coefficient

Comparison against snow products and ground-based stations

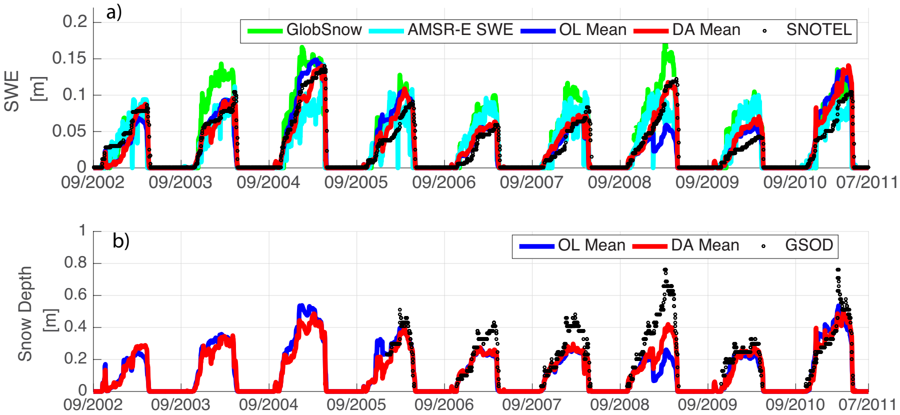
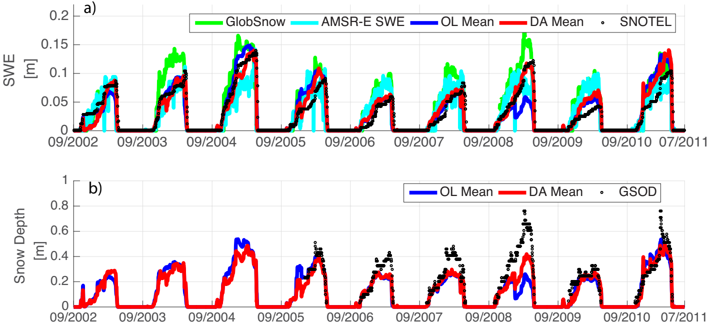


Figure: An example time series of SWE and snow depth for (64.78°N, 147.85°W) from 01 September 2002 to 01 July 2011. SNOTEL snow depth measurements are not available at this location.

Comparison against snow products and ground-based stations



- DA reduced the bias in snow depth estimates by 14% from OL (7.97cm) to DA (6.86cm)
- DA reduced the ubRMSE in snow depth estimates by 31% from OL (11.98cm) to DA (8.30cm)

Comparison against GSOD stations

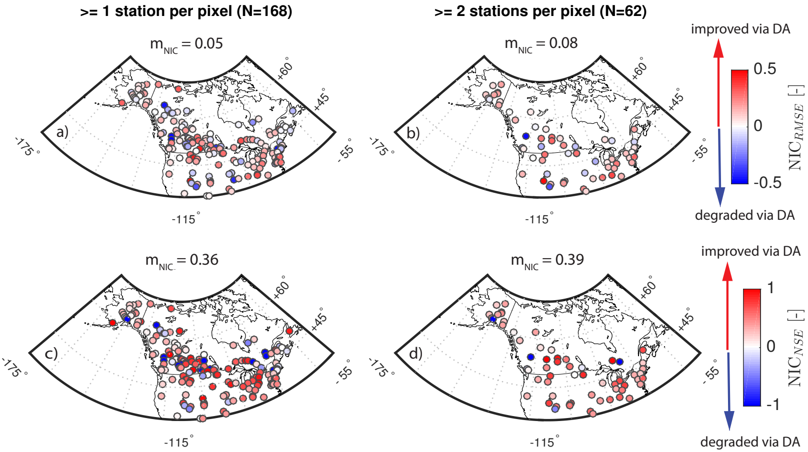
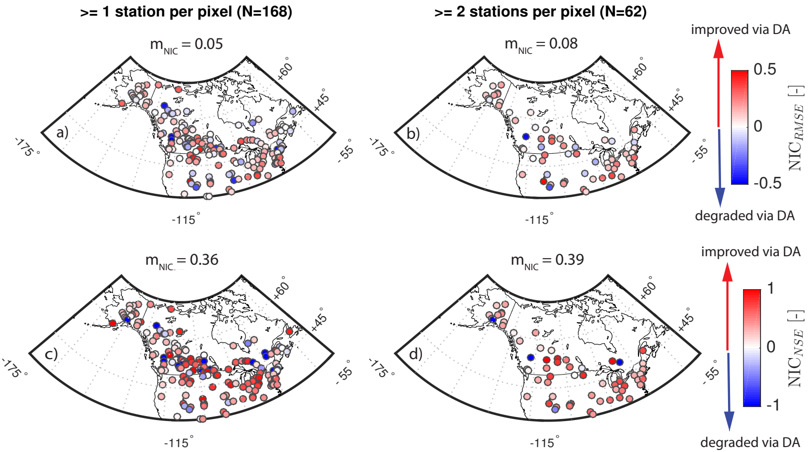


Figure: Spatial maps of NIC_{RMSE} (top row) and NIC_{NSE} (bottom row) during comparison against GSOD snow depth measurements from 2002 to 2011.

Comparison against GSOD stations



- DA agrees better with GSOD measurements than OL estimates in $\sim$82% (56 out of 62) pixels that are colocated with at least two ground-based stations.

Comparison against USGS discharge

- 13 major USGS gauged basins in Alaska (> 625 km^2, with at least two consecutive years of measurements record)

% of basins	**NICs > 0**	**NICs < 0**
vs. daily discharge	68.3%	31.7%
vs. cumulative discharge	84.7%	15.3%

- Relatively good snow estimates obtained from DA (relative to OL) also has the potential to translate into improved runoff estimates.

Filter sub-optimality assessment

- Normalized innovation (NI) sequence
- NI sequence approximates white noise $\Longrightarrow$ "optimal" assimilation
- Violation of assumptions: nonlinear observation model operator + nonlinear model dynamics + non-Gaussian model errors

Domain-averaged	10H-36H	10V-36V	18H-36H	18V-36V
$\overline{NI}$ [-]	0.00	0.03	-0.04	-0.02
σ_{NI} [-]	1.56	1.46	1.16	1.14

- higher σ_{NI}: might underestimate observation errors and/or forecast errors

Conclusions and ongoing research

- SVM can serve as an efficient and effective observation model operator within a radiance assimilation system (Xue et al., under review, WRR).
- Investigate the effects of removing non-SWE related signals from the observations prior to integrating into the DA (Xue and Forman, IGARSS, July 2017)
- Conduct feasibility test of a multi-sensor assimilation framework for global snow (e.g., GRACE + AMSR-E) (Wang et al., AGU, Dec 2017)

Conclusions and ongoing research

- SVM can serve as an efficient and effective observation model operator within a radiance assimilation system (Xue et al., under review, WRR).
- Investigate the effects of removing non-SWE related signals from the observations prior to integrating into the DA (Xue and Forman, IGARSS, July 2017)
- Conduct feasibility test of a multi-sensor assimilation framework for global snow (e.g., GRACE + AMSR-E) (Wang et al., AGU, Dec 2017)

Conclusions and ongoing research

- SVM can serve as an efficient and effective observation model operator within a radiance assimilation system (Xue et al., under review, WRR).
- Investigate the effects of removing non-SWE related signals from the observations prior to integrating into the DA (Xue and Forman, IGARSS, July 2017)
- Conduct feasibility test of a multi-sensor assimilation framework for global snow (e.g., GRACE + AMSR-E) (Wang et al., AGU, Dec 2017)

Thank you and Acknowledgment

Thank you!

- Financial support was provided by the NASA Earth and Space Science Fellowship Program (NNX14AN23H), and NASA New Investigator Program (NNX14AI49G).
- LIBSVM library provided by National Taiwan University
- University of Maryland supercomputing resources