Assimilating Snow Cover Fraction Observations into CLM

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Introduction

- The role of snow in forecasts …
- *Hydrological Prediction* ~ Improving snow water equivalent (SWE) estimates may improve *snowmelt runoff and streamflow prediction*
- *Weather and Climate Prediction* ~ Improving snow cover and albedo estimates can contribute to better estimates and forecasts of *energy and moisture budgets and fluxes*

Snow Cover Assimilation

- Visible satellite-based snow cover fraction (SCF) data offer snapshots of high resolution estimates of snow presence and extent.
- Since snow cover plays a crucial role in albedo and energy budget estimates, assimilating these observations with LSM snow states could lead to improved forecasts.
- **One Data Assimilation Challenge**:
  SCF only provides a partial source of information needed to estimate the snowpack states, since snow cover is typically not treated as a model state!

Research Objectives

- To assimilate NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) SCF products within the Community Land Model (CLM) to obtain more accurate SWE and snow depth analyses
- Test two data assimilation (DA) approaches: *Direct insertion (DI) and 1-D Ensemble Kalman Filter (EnKF)*
- Though the filters were checked to meet basic assumptions, no additional optimization (e.g., bias correction) was applied → Purpose: To demonstrate a more direct use of the SCF observations

Objectives (con’t.)

- Since this and most LSMs do not treat SCF as a state, relationships between SCF and SWE (or snow depth) are used to update the LSM snow states
- Thus, different SCF-SWE or SCF-snow depth relationships were applied and tested in both DA methods to see their impact on the SWE and snow depth analyses

Model and Observations Background

The Community Land Model, v2

- The Community Land Model, version 2 (**CLM2**; *Oleson et al, 2004*) physics and parameterizations are derived from of a variety of LSMs (*e.g., Bonan, 1998; Dai and Zeng, 1997; and Dickinson, 1993*).
- **5-layer snow scheme**: Liquid and frozen water represented in each layer and allows for gravitational water flow
- Total snow mass is conserved while the layers can be divided or combined when snowfall, snowmelt, etc. occur.
- Snow albedo scheme is a function of snow cover and age, snowfall freshening, grain size, and solar-zenith angle

CLM2 and Meteorological Forcing Set up

NASA's ***Land Information System*** (*LIS; Kumar et al., 2006, 2008*) is used as the main integration system software that –

- Includes different DA methods, like ***DI, 1D-EnKF*** (*Reichle et al., 2002*), and recently 3D-EnKF (*De Lannoy et al., 2010; in LIS version 5).*
- Drives CLM2 with the 0.125 degree ***North American Land Data Assimilation System*** (*NLDAS*) meteorological forcing dataset (*Cosgrove et al. 2003*),
- Downscales NLDAS to ***0.01° (~1 km) resolution*** and applies ~1 km elevation adjustments to forcing fields (*2m air temp., specific humidity, downward longwave and surface pressure*)

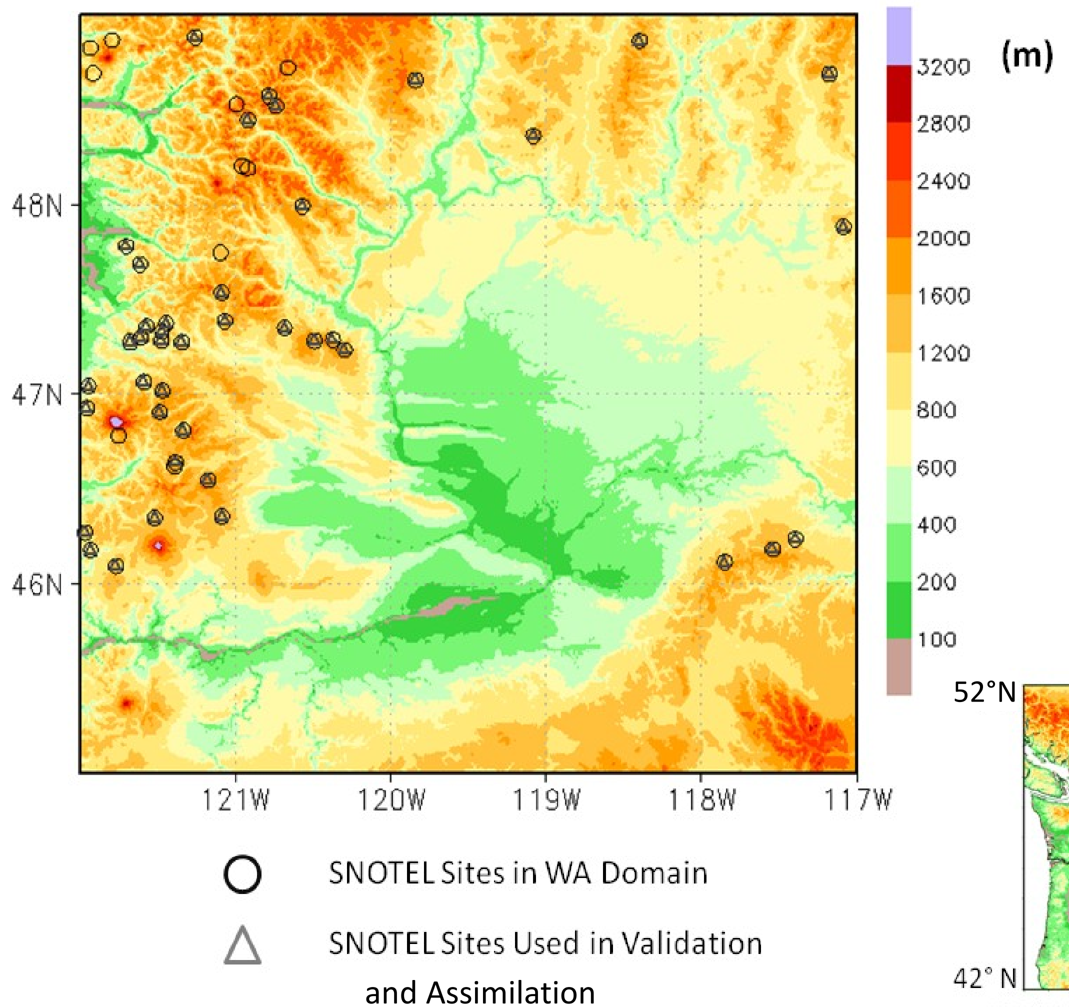
Washington (WA) Domain

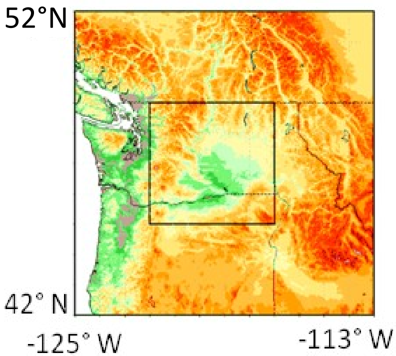
30 m National Elevation dataset aggregated to 0.01° LIS grid and used as main elevation parameter file.

SNOTEL Sites:

52 stations total in the WA domain;

42 used for the assimilation and validation

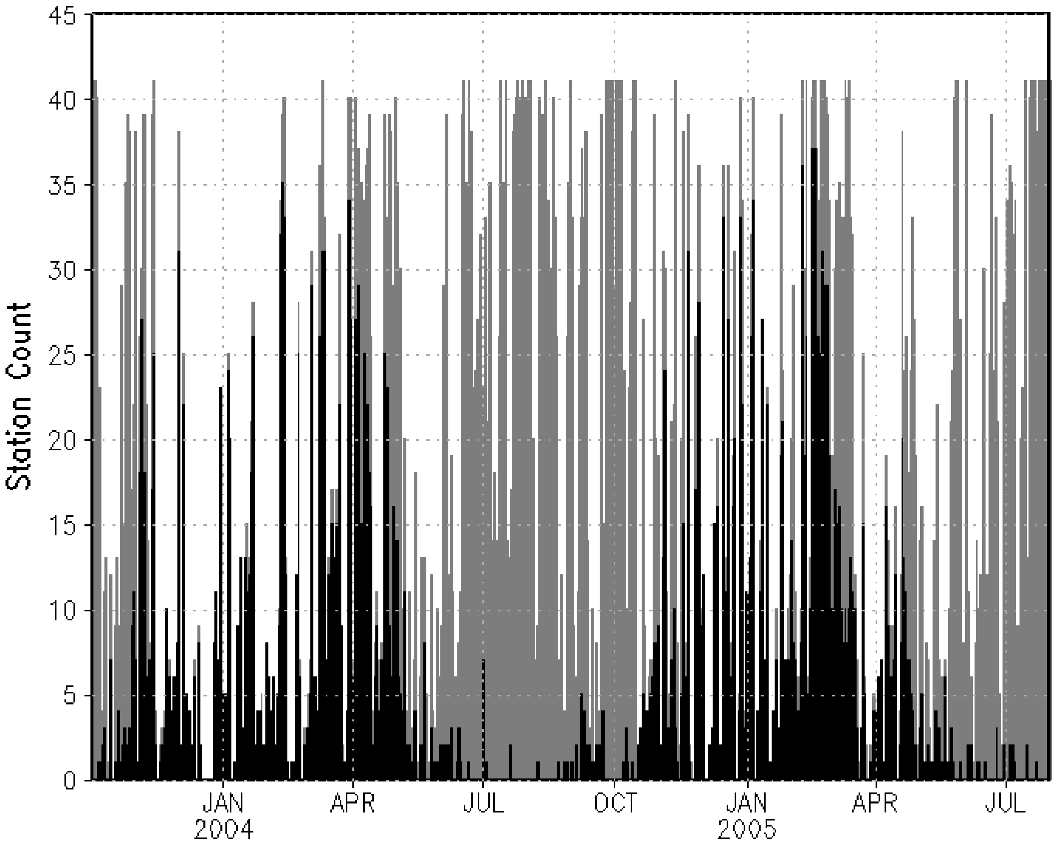




MODIS Snow Cover Fraction (SCF)

Daily MODIS SCF Data Count at 42 SNOTEL Station Points:

- Low pixel counts in winter
- Higher counts in spring for *SCF >= 1%,* due to less cloud coverage
- Summer months show high snow-free pixel counts



Black – SCF: 1-100%

Grey – SCF: 0% or Snow Free

Setting Up LIS-CLM2 Runs

- **Description of Model Runs:**
  - Model spin-up: Sept. 2000 to Sept. 2003; *1-hour* timestep
  - Main DA experiments are run for two water years (WY)*:
    - ***WY2004*** – Normal snow year for WA domain
    - ***WY2005*** – Anomalously low snow year for this domain
- Daily 500-m MODIS SCF data pixels resampled to the LIS 0.01° grid, using a nearest neighbor approach

** Note: A Water Year is from October to September (e.g., Oct. 1, 2003 to Sept. 30, 2004)*

Data Assimilation Methods

Data Assimilation Methods

- The two methods used are:

1) *Direct insertion (DI)*, which uses a rule-based approach or directly ingests information into the model

2) *1-D Ensemble Kalman Filter (EnKF)*, which requires perturbing the meteorological forcings and model states and also knowledge about the SCF observation errors.

- To account for the *SCF-SWE conversion*, we utilize different SCF-SWE (or SCF-snow depth) relationships, also known as *observation operators*.

Mapping of MODIS SCF to LSM Snow States

Compare observations to state forecasts… [Obs-Forecast]

➔ Bring state (swe or snowdepth) to observation (*scf*) space:

$scf^{-} = \mathbf{h}(\text{state})$ Observation operator

1. CLM-based operator:

$$y^{-} = scf^{-} = \mathbf{h}(\text{snow depth}^{-}) = \frac{\text{snow depth}^{-}}{(0.1 + \text{snow depth}^{-})}$$

2. Observation-based operators:

$$y^{-} = scf^{-} = \mathbf{h}(\text{swe}^{-}) = a(\text{swe}^{-})^3 + b(\text{swe}^{-})^2 - c(\text{swe}^{-}) + d$$

➔ Innovation = [y-**h**(x)]

Observation Operators:
SWE vs. SCF Relationships

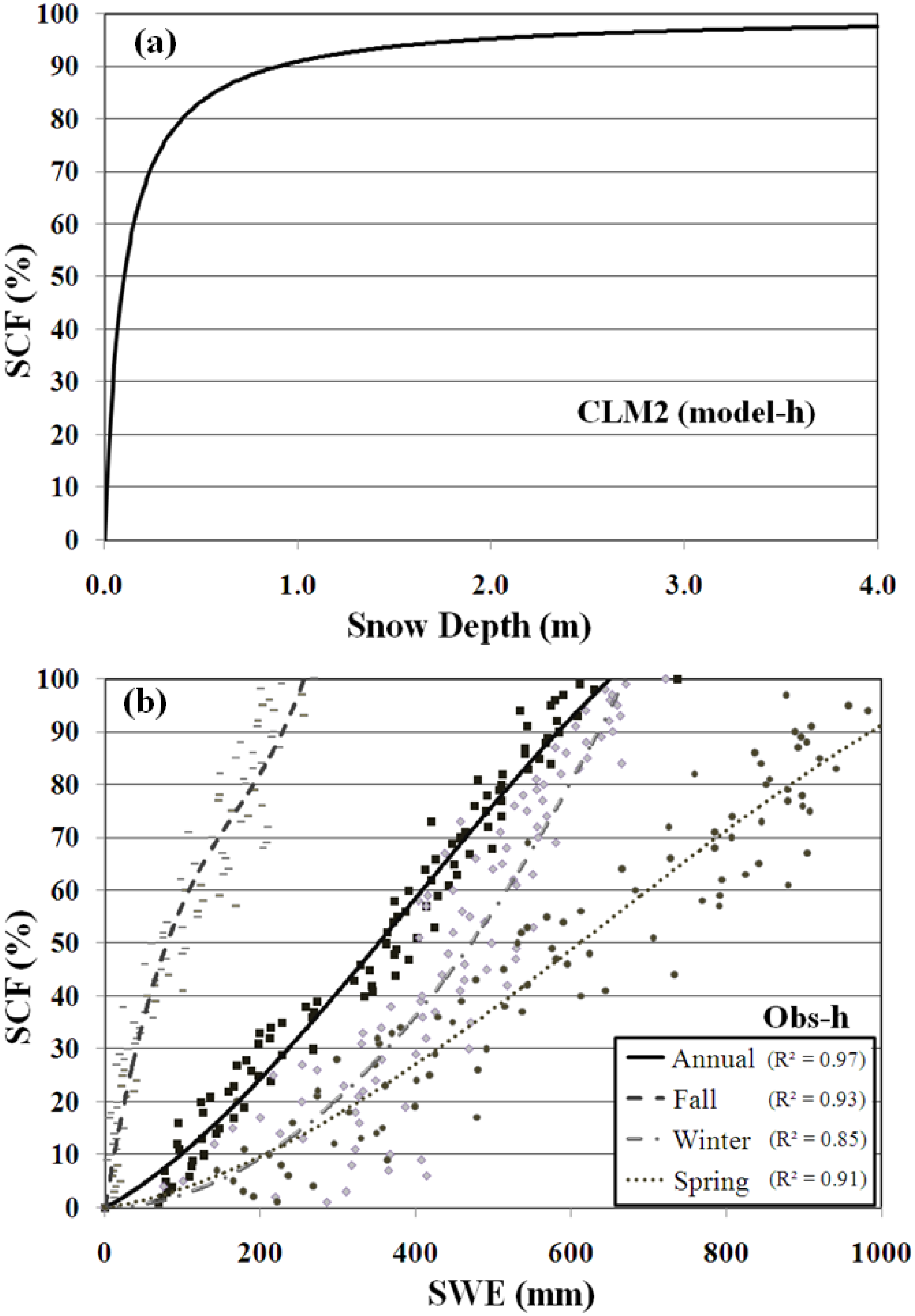
- **CLM2 Curve (model-h):**

  Snow depth vs. SCF

- **Observation-based (obs-h):**
  Related SNOTEL SWE (52 sites) **with 500-m MODIS SCF pixels** (WYs 2001-03, 2006-07)

- **Fitting multi-degree polynomials, we obtain R^2 values of 0.85 and higher.**

- **Annually and seasonally derived curves (annual and seasonal obs-h, respectively)**



DI Approach

<u>Two DI Approaches Applied</u>:

1) Rodell and Houser (2004) rule-based DI approach

2) Application of the observation operator functions –

   - Use the observation operators and an iterative method (e.g., Newton method) to update SWE and snow depth states for a given MODIS SCF observation

- At the time of Terra's overhead pass (~10:00 am local time), MODIS SCF values are used to determine if snow is "detected" and then compared against whether CLM2 predicted snowpack conditions for that same pixel.

EnKF Approach

1) State vector **x** = [swe, snowdepth]^T.

Model state predictions are uncertain:

➔ generate an *ensemble* of state predictions – perturbing 4 forcings and 2 state variables (also known as *open-loop* runs, *OL*)

➔ obtain $\mathbf{P}^-$, the state error covariance matrix

2) MODIS SCF Observation: y = [scf]

Observations are uncertain:

➔ perturb the observations

➔ set **R**, the observation error (co)variance matrix

3) **P/R** determines the weight or Kalman gain, **K**

CLM2 Forecast and Observation Error Background

- 12-Member ensemble mean (no DA)
- EnKF experiments with observation standard errors, for each observation operator type:

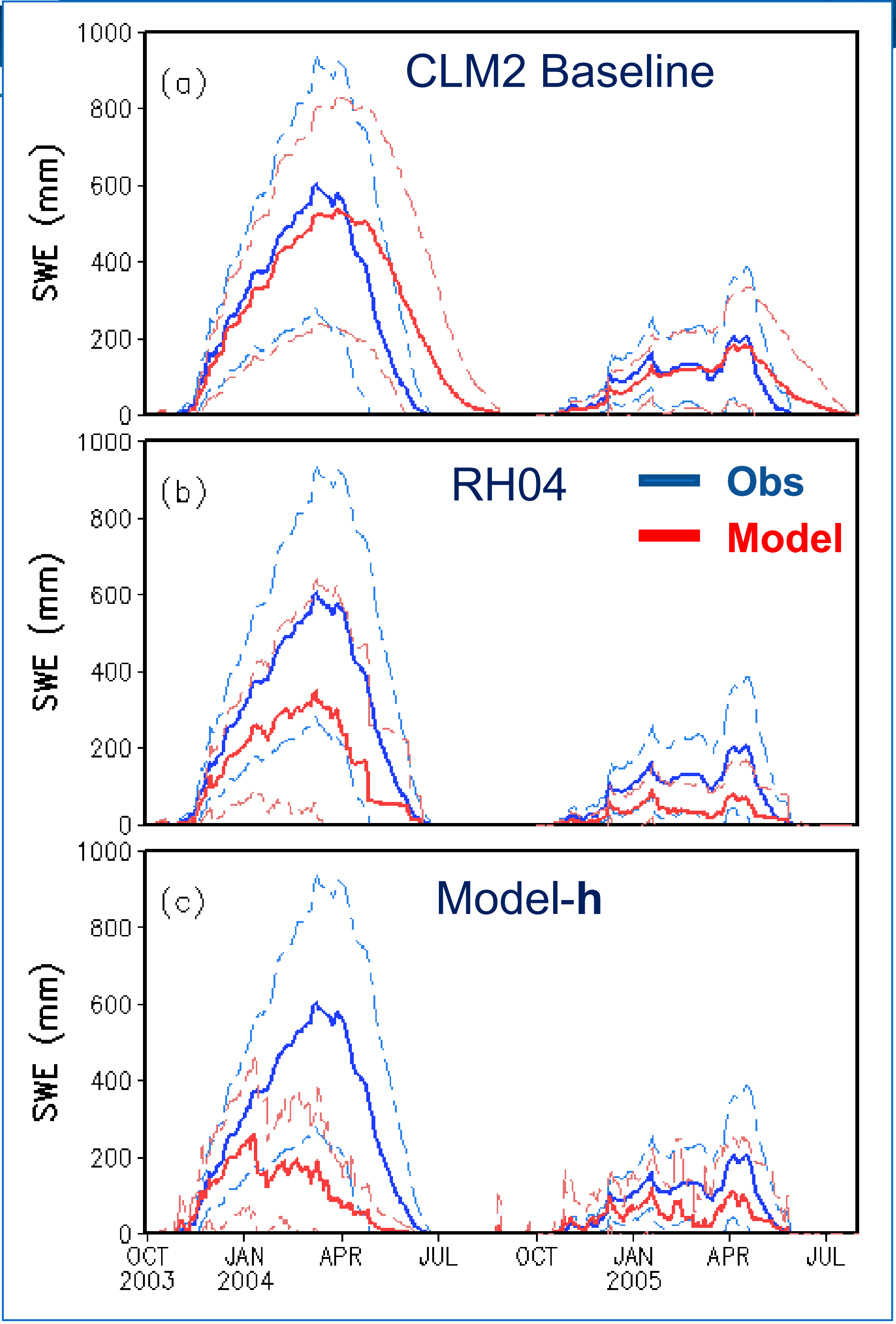
Model-h	➔ σ_{obs}	= 34.8%
Annual Obs-h	➔ σ_{obs}	= 35.4%
Seasonal Obs-h	➔ σ_{obs}	= 31.3%

Results

CLM2 Baseline (Control) and DI Runs

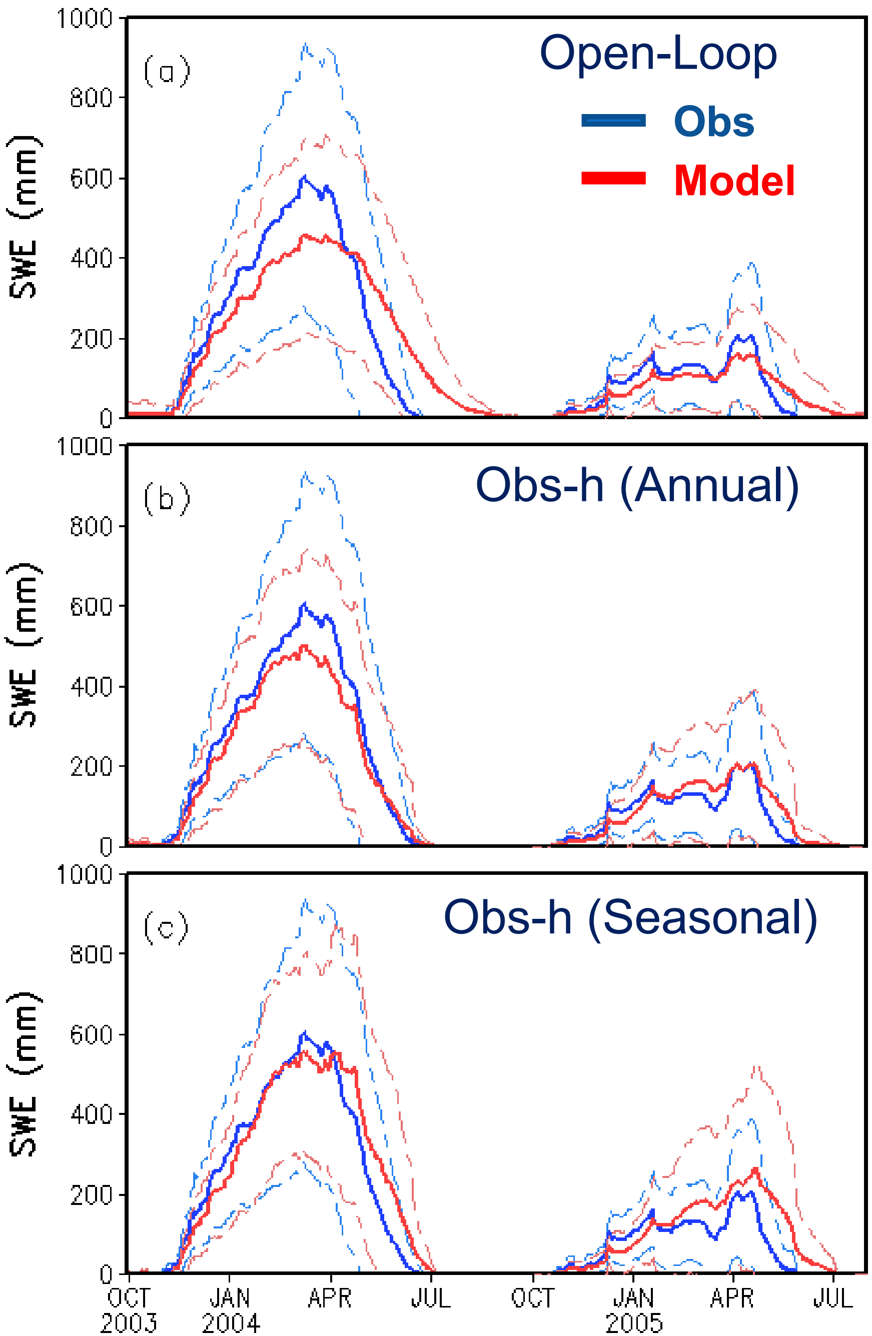
- **CLM2 baseline (default) run:**
  - Similar SWE amplitudes to SNOTEL observations
  - However, positive SWE bias in spring-summer months
- **RH04 DI Run:**
  - Less SWE amplitude
  - Springtime melt bias removed
- **Model-h DI Run**:
  - SWE analyses greatly underestimated when compared to observations
  - This relates to deficiencies in the model's SCF-snow depth curve and DI approach

Note: On the right, dashed lines indicate 1-standard deviation spread over sites.



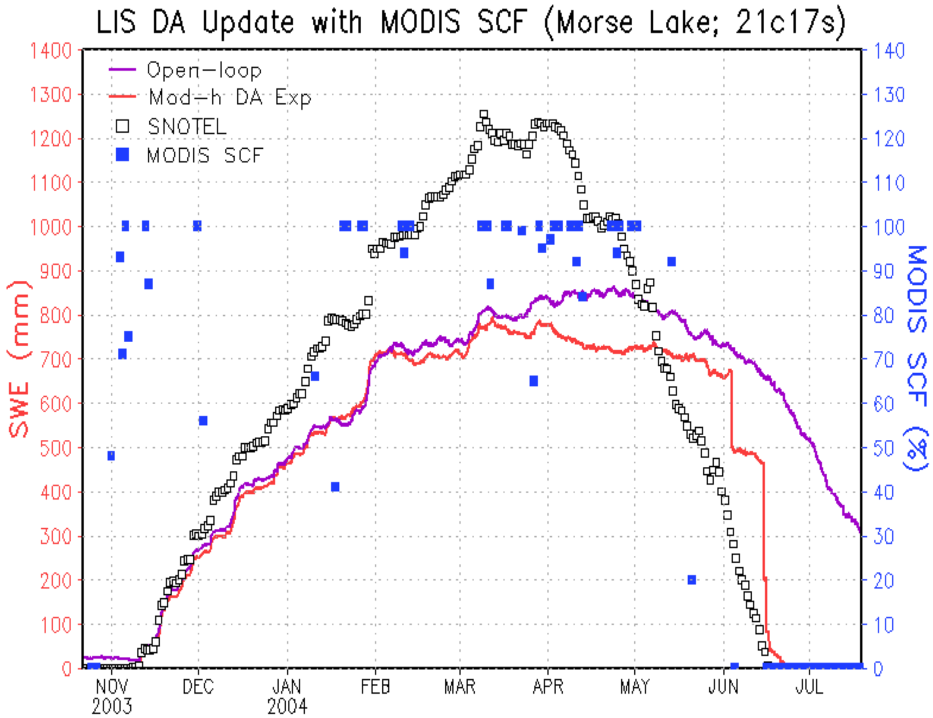
Open-Loop and EnKF Runs

- **Open-loop (Ensemble) run:**
  - Similar SWE amplitudes as SNOTEL SWE
  - Also has positive SWE bias in spring-summer months
- **Annual Obs-*h* EnKF experiment:**
  - SWE amplitude improved over OL run, especially in wintertime
  - Springtime snowmelt bias removed
- **Seasonal Obs-*h* EnKF experiment:**
  - Similar SWE amplitude to above EnKF experiment
  - Positive spring-time SWE bias reduced -- still later than *annual* obs-*h* experiment

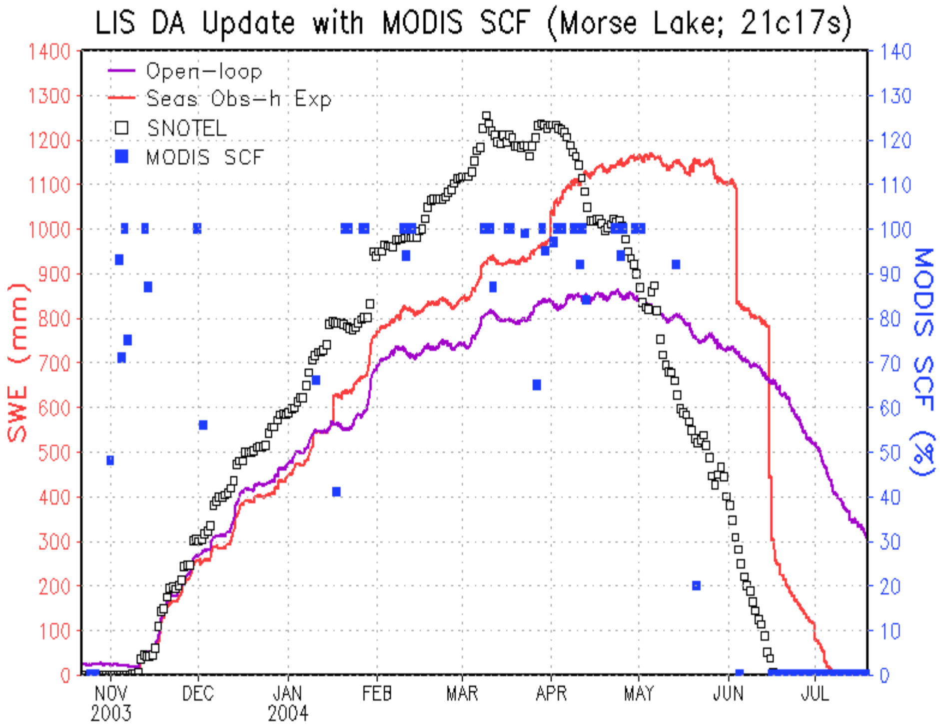


SCF DA Analysis for Individual Station

Model-*h* vs. Seasonal Obs-*h* Curves – 1D EnKF Experiments for WY2004



Model-h



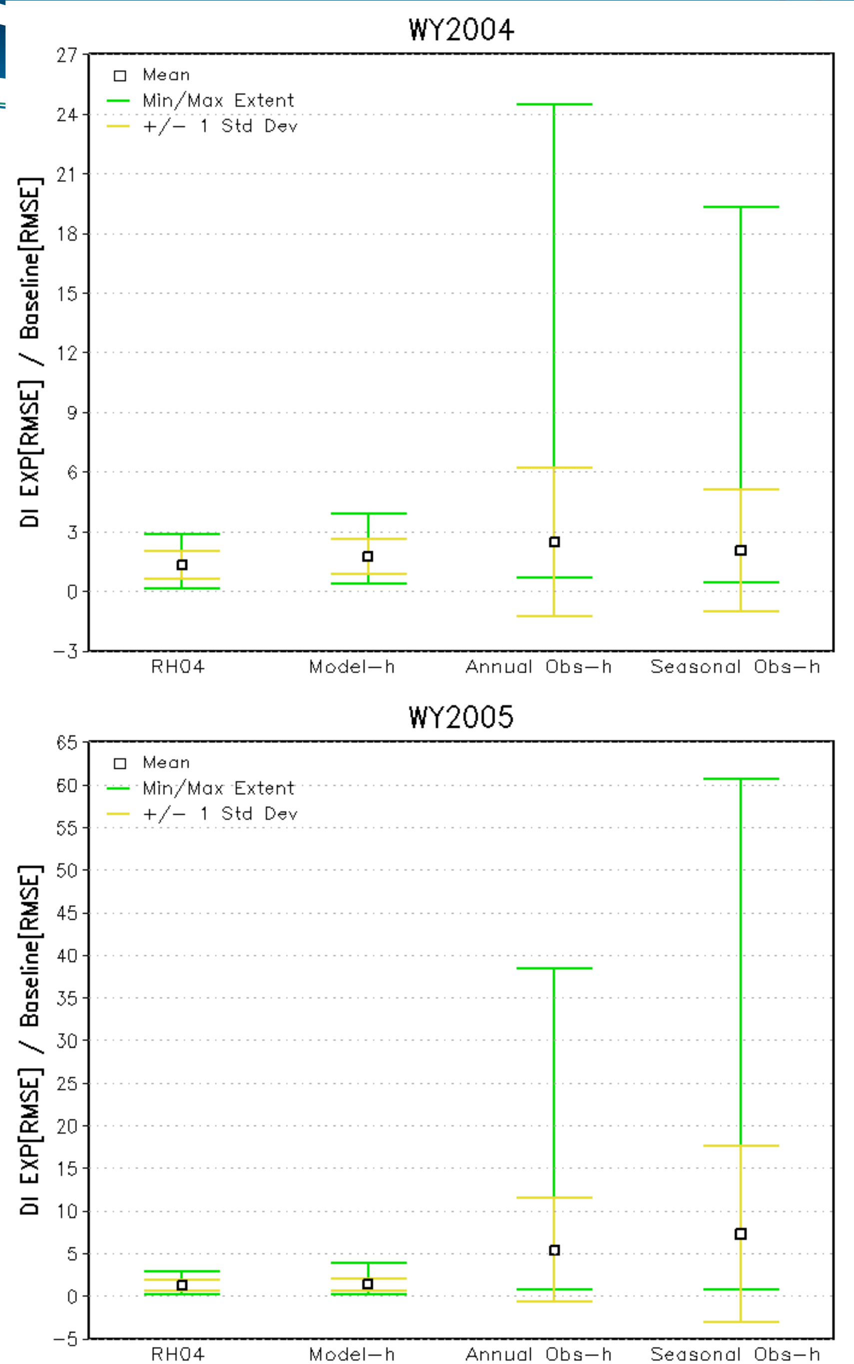
Seasonal Obs-h

Morse Lake SNOTEL Site in Washington:

Long: -121.48°; Lat: 46.91°; Elev: 1645.9 m; Located: In a valley

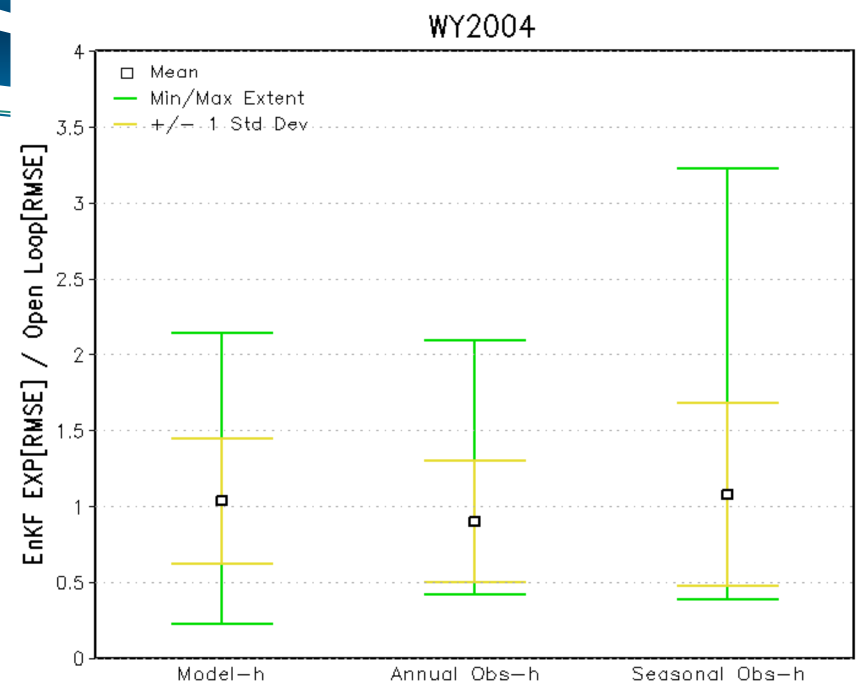
RMSE of DI Experiments Normalized with CLM2 Baseline RMSE

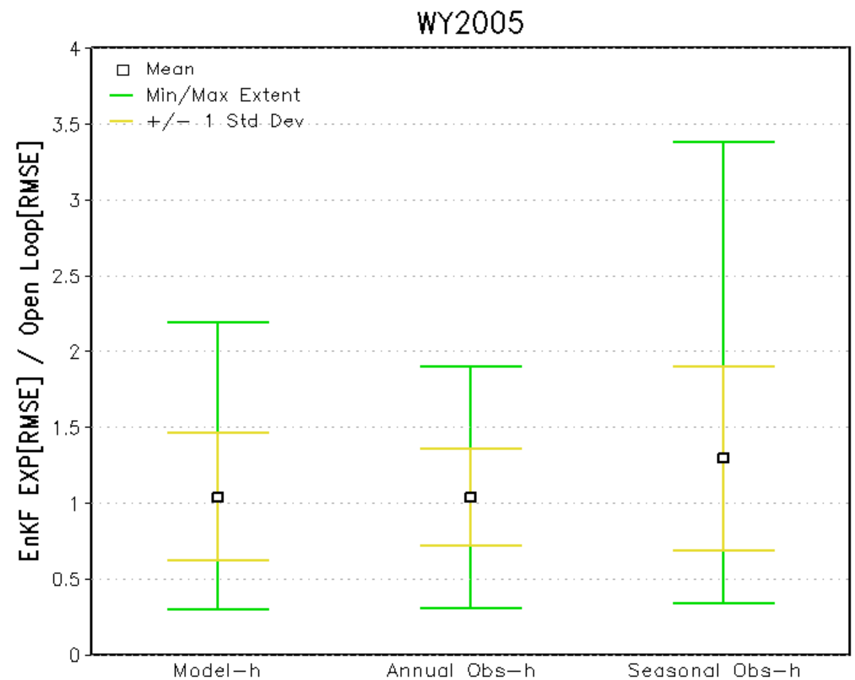
- **Normalized RMSE Results:**
  - DI experiments and baseline RMSE are calculated for months: Oct-June
  - Then DI experiment RMSE is normalized by the baseline RMSE
  - Figures on right show mean, error bars, min and max. over all 42 analysis points
  - Any value <u>**≤**</u> **1** shows DI experiment improved over the baseline case.
  - ***RH04*** had lowest mean and spread of DI experiments but did <u>not</u> show improvement over the baseline run



RMSE of EnKF Experiments Normalized with Open-Loop RMSEs

- **Normalized RMSE Results:**
  - EnKF experiments and open-loop (OL) RMSE calculated for months: Oct-Jun
  - Each EnKF experiment RMSE is normalized by the OL RMSE
  - Figures on right similar to DI comparison, again with values **≤ 1** indicating DA experiment improved over the OL case.
  - Annual obs-*h* had lowest mean and spread and **≤ 1** for at least WY2004
  - Model-h and annual obs-*h* lowest overall, with seasonal obs-h with higher means and spreads





Discussion

- Data assimilation is designed to improve the state analyses over both open-loop and observations (MODIS SCF) to obtain a more true snow state estimate (e.g., SNOTEL SWE as reference)
- However, only slight improvements for both DI and EnKF experiments are made due to assumptions ….
  - For DI: Observations are treated as "perfect"…
  - For EnKF: Forecasts biased due to large observation uncertainty and conversion between model snow states and SCF
- Despite these shortcomings, 1-D EnKF is better at overcoming some of the biases and measurement (SCF) uncertainties

Discussion (con't)

- Sources of biases and errors:
  - Forecasts biased by model error (including forcing)
  - Conversion between SWE and SCF – uncertainty in observations
  - Scaling discrepancy and errors between observation types
- Ongoing Work:
  - Apply to different regions and time periods
  - Optimize observation operators (e.g., more temporally varying) or account for characteristics (e.g., elevation)

Summary and Conclusions

- Assimilated daily, remotely sensed MODIS SCF into CLM2 to obtain more accurate SWE analyses through DI and EnKF DA approaches.
- One challenge in using SCF observations is that they only provide a partial source of information needed to estimate model snow states (SWE and snow depth).
- Different observation operators (including annual- and seasonal-based) were derived and applied.

Summary and Conclusions

- Both DA approaches were able to remove the excessive CLM2 snow in spring and summer seasons,
- 1-D EnKF was able to remove the largest SWE errors of the DA methods overall; DI-RH04 procedure performed best of the DI approaches,
- The best results were found with the annual-based observation operator (obs-*h*), which captured a more general SCF-SWE relationship for the two assimilated snow years.

Thank you!

Questions??