Continental-scale assimilation of satellite snow observations

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March 23, 2002
COAA Workshop

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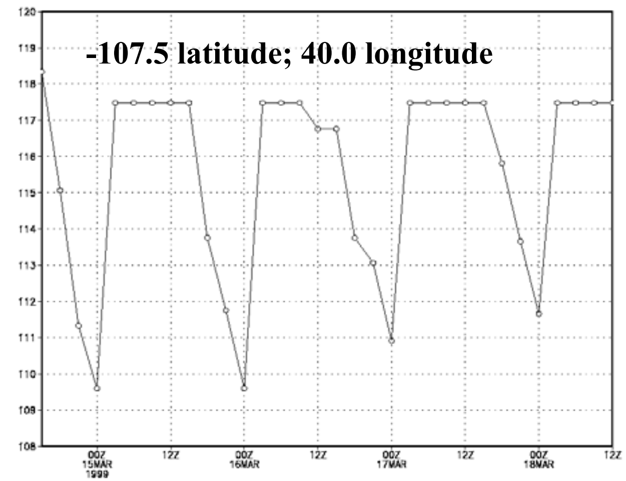
Importance of snow assimilation

- Snow has high albedo, low thermal conductivity and large spatial/temporal variability
- It impacts both the energy and water budgets, as well as the hydrological cycle (spring meltwater).
- Largest landscape feature in the northern hemisphere, the snow cover 7%-40%.
- NWP of air temperature sensitive to snow cover
- Snow adjacent to bare soil causes mesoscale wind circulations.
- Direct insertion does not account for model bias, may induce erroneous water flux



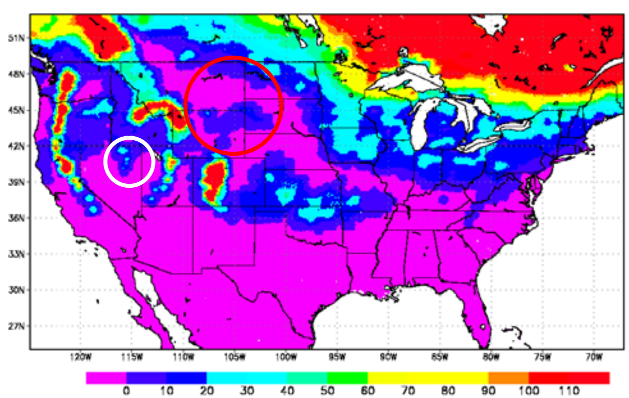
NCEP-Eta Snow Updating

Update Time

Melt

Update Time

3Z 3/15/99



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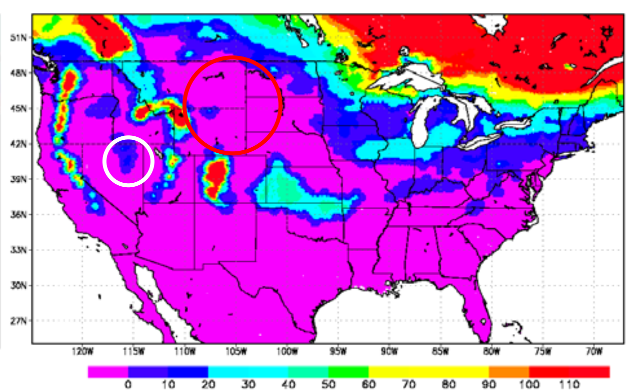

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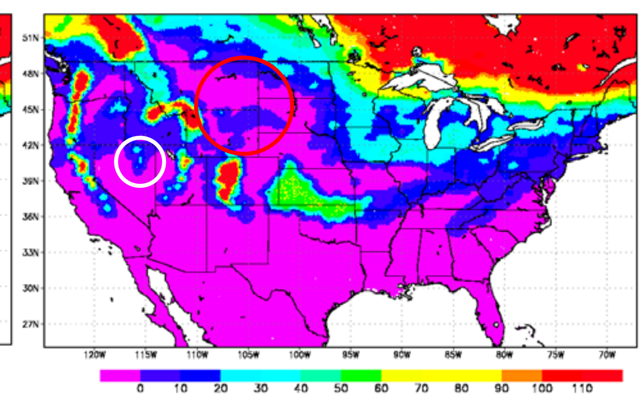


Snow Assimilation with the NSIPP Catchment-based Land Surface Model

- Land surface model: the NASA Seasonal-to-Interannual Prediction Project (NSIPP) catchment-based Land Surface Model (Koster *et al.* 2000) which includes a three-layer snow model component.

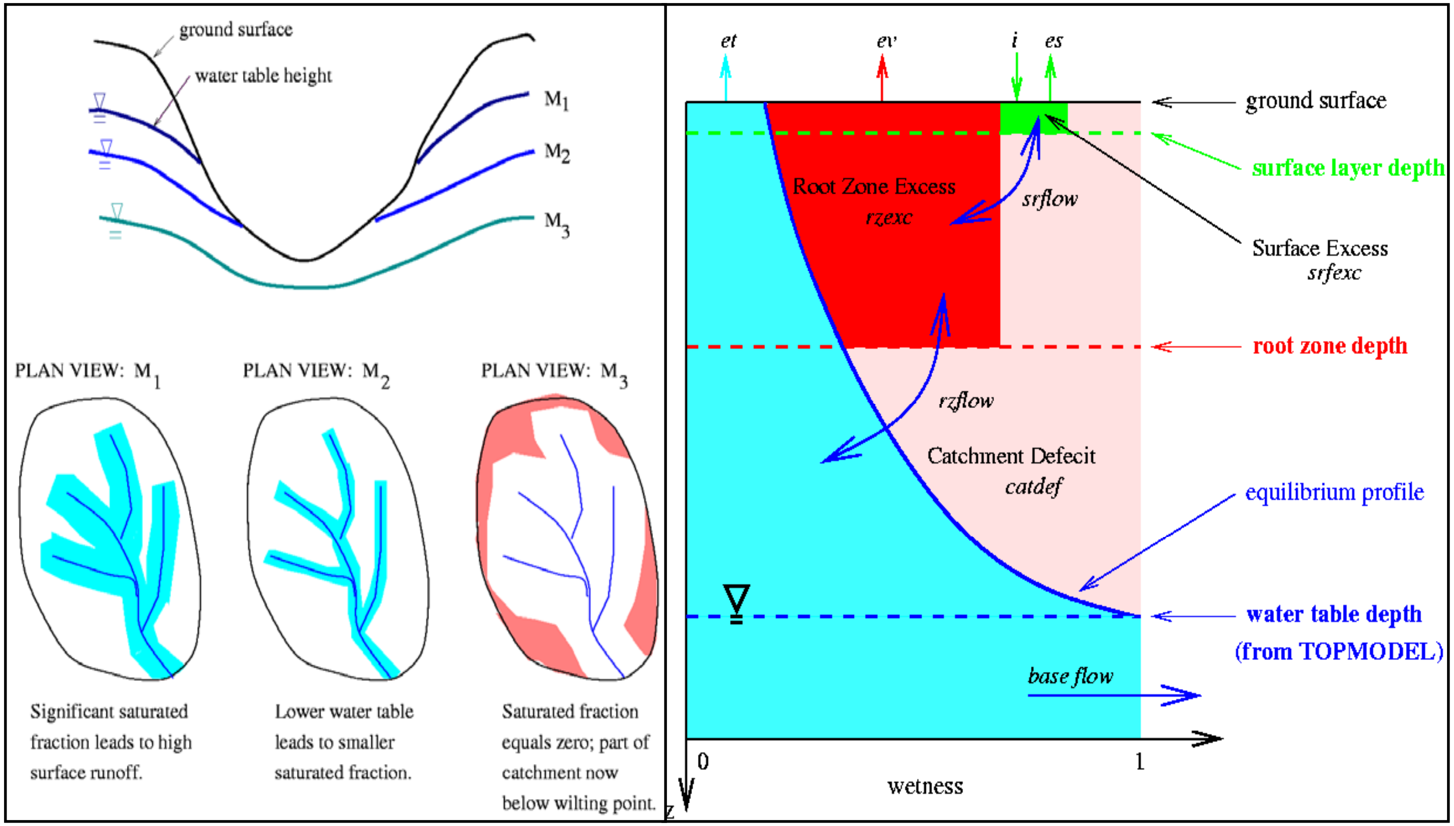
- Snow model: three-layer snow model (Fig. 1) that incorporates detailed physics including evaporation-sublimation-condensation, radiation, precipitation as rain or snow, mechanical compression, melt water flow through, etc (Lynch-Stieglitz, 1994; Stieglitz *et al*., 2001).

- 9 snow state variables in each catchment: snow water equivalent (SWE), snow depth and heat content (for each layer).

Note: To ensure a smooth transition from bare-soil to snow-cover conditions, a minimum snow water equivalent of 13 mm is assumed. When fresh snow falls on bare soil, the fractional coverage grows until the entire catchment is covered with snow. At this point, the model begins to grow the snow pack.

- Forcing: bias-corrected ECMWF forcing data for the past 20 years over North America (Berg *et al*., 2001).

The Catchment-based Land Surface Model (CLSM)



The LSM uses a non-traditional land surface modeling framework that includes an explicit treatment of sub-grid soil moisture variability and its effect on runoff and evaporation.

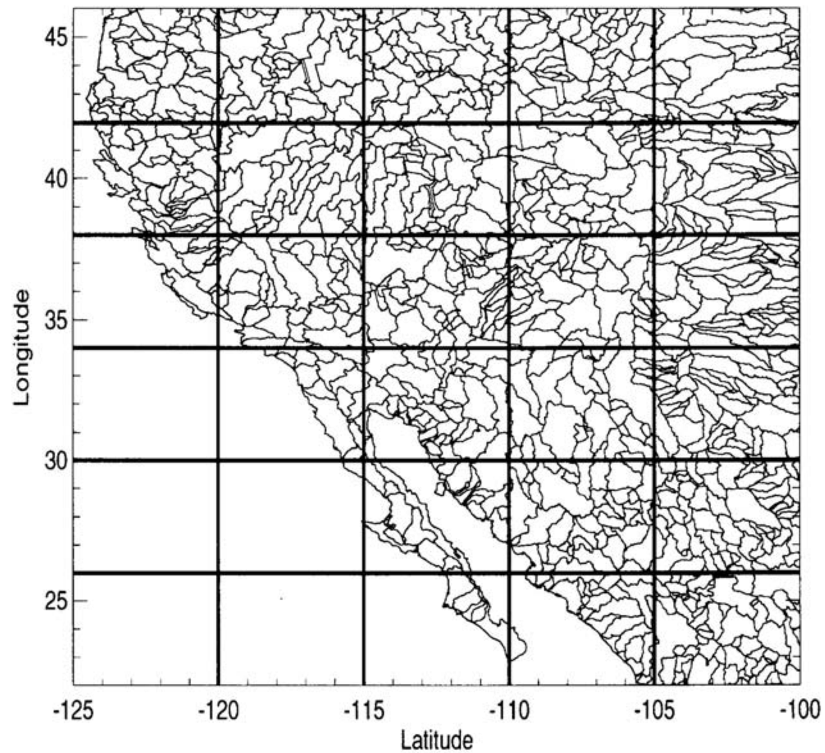
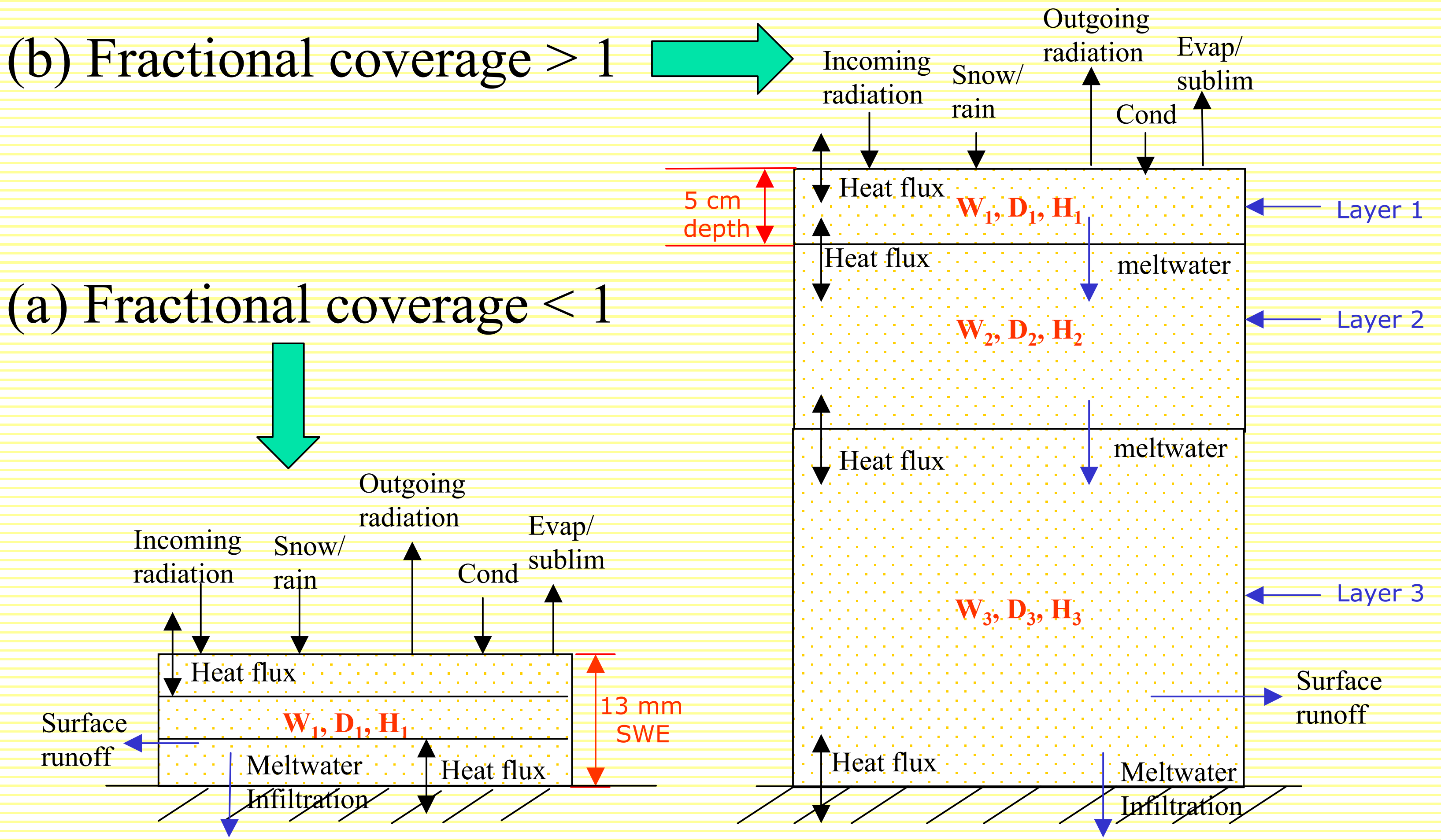


Figure 1. Illustration of catchment delineation in southwest North America. Overlain on the plot is a 4°×5° GCM grid.

Average catchment size in the North America: 3600 km^2
Total catchments in the N. America: 6000

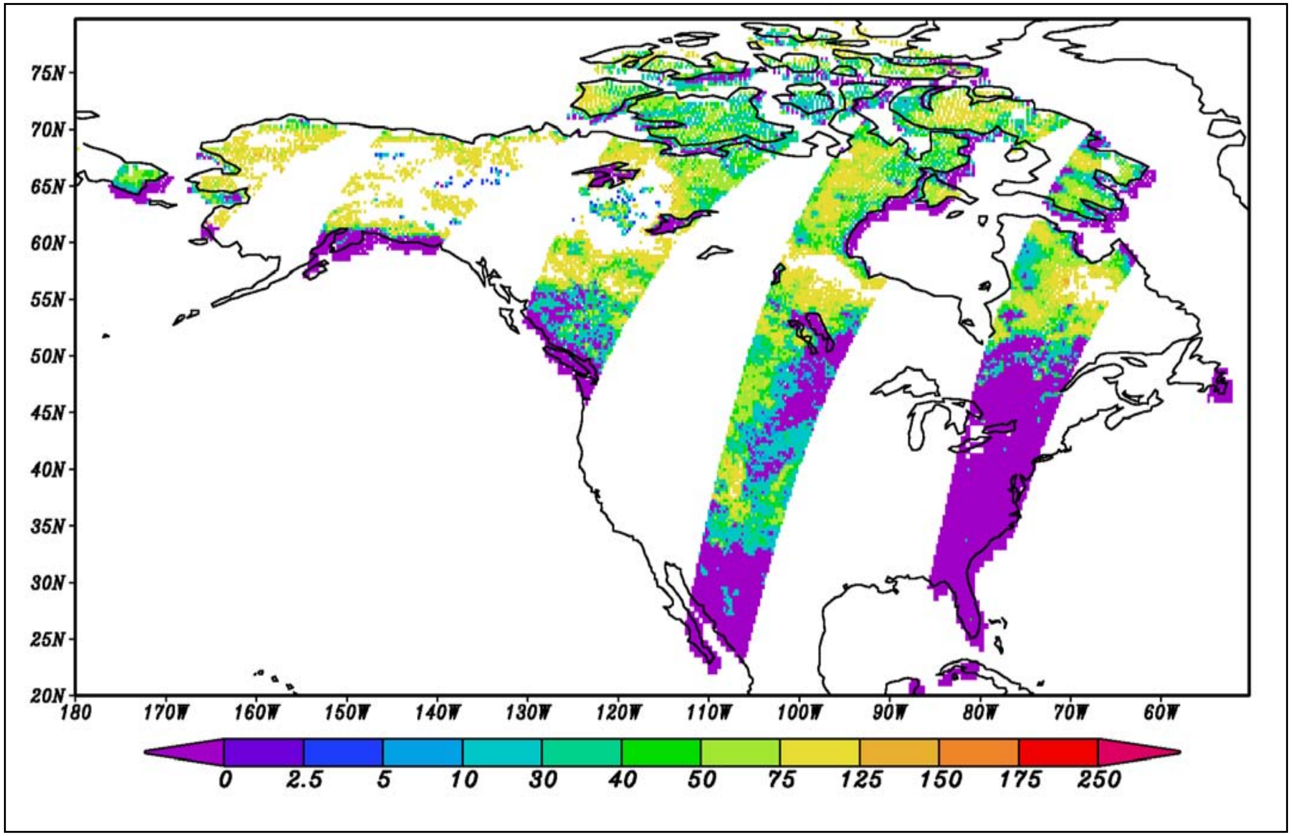


Schematic of the snow model: (a) when fractional snow coverage < 1, it is a single-layer model. (b) when fractional snow coverage >1, it is a three-layer model.

Remotely sensed snow observations

Retrieval of snow water equivalent (SWE) from passive microwave measurement: crystal size important

$$SWE = \beta\ (T_1 - T_2)$$



Example snow observation data for snow water equivalent (kg/m^2) from the SMMR instrument; 1 January 1983.

Points to ponder…

- Disappearing layers and states.
- Arbitrary redistribution of mass between layers.
- Lack of information in SWE on density and temperature.
- Lack of information in snow cover (e.g., NOAA visual snow maps, MODIS) on mass, density and temperature.
- Forcing error/bias causes unrealistic snowmelt or accumulation.

The extended Kalman filter (EKF)

(1) Forecasting step:

$$\mathbf{x}^{f} = M(\mathbf{x}^{a})$$

$$\mathbf{P}^{f} = \mathbf{M}\,\mathbf{P}^{a}\,\mathbf{M}^{T} + \mathbf{Q}$$

(2) Updating step:

$$\mathbf{K} = \mathbf{P}^{f}\,\mathbf{H}^{T}\,[\,\mathbf{H}\,\mathbf{P}^{f}\,\mathbf{H}^{T} + \mathbf{R}]^{-1}$$

$$\mathbf{x}^{a} = \mathbf{x}^{f} + \mathbf{K}\,(\,\mathbf{y} - \mathbf{H}\mathbf{x}^{f}\,)$$

$$\mathbf{P}^{a} = (\mathbf{I} - \mathbf{K}\mathbf{H})\,\mathbf{P}^{f}\,(\mathbf{I} - \mathbf{K}\mathbf{H})^{T} + \mathbf{K}\,\mathbf{R}\,\mathbf{K}^{T}$$

Assimilation of snow water equivalent (SWE) into the CLSM

1-D EKF, only **SWE** of each layer (or the bulk SWE of snowpack) is ***updated*** using the synthetic observation: **SWE** of the snowpack.

- Snow depth and heat contents are updated solely through the model physics and the updated SWE.
- The true states are generated from a model run, using initial condition from model spin-up forced with bias-corrected ECMWF data.
- The assimilation starts on 1/1/87 with a poor initial condition (no snow anywhere). The SWE is updated using observations extracted from the true states every six hours.
- For comparison, a control run is performed starting with the poor initial condition.

Assimilation procedure

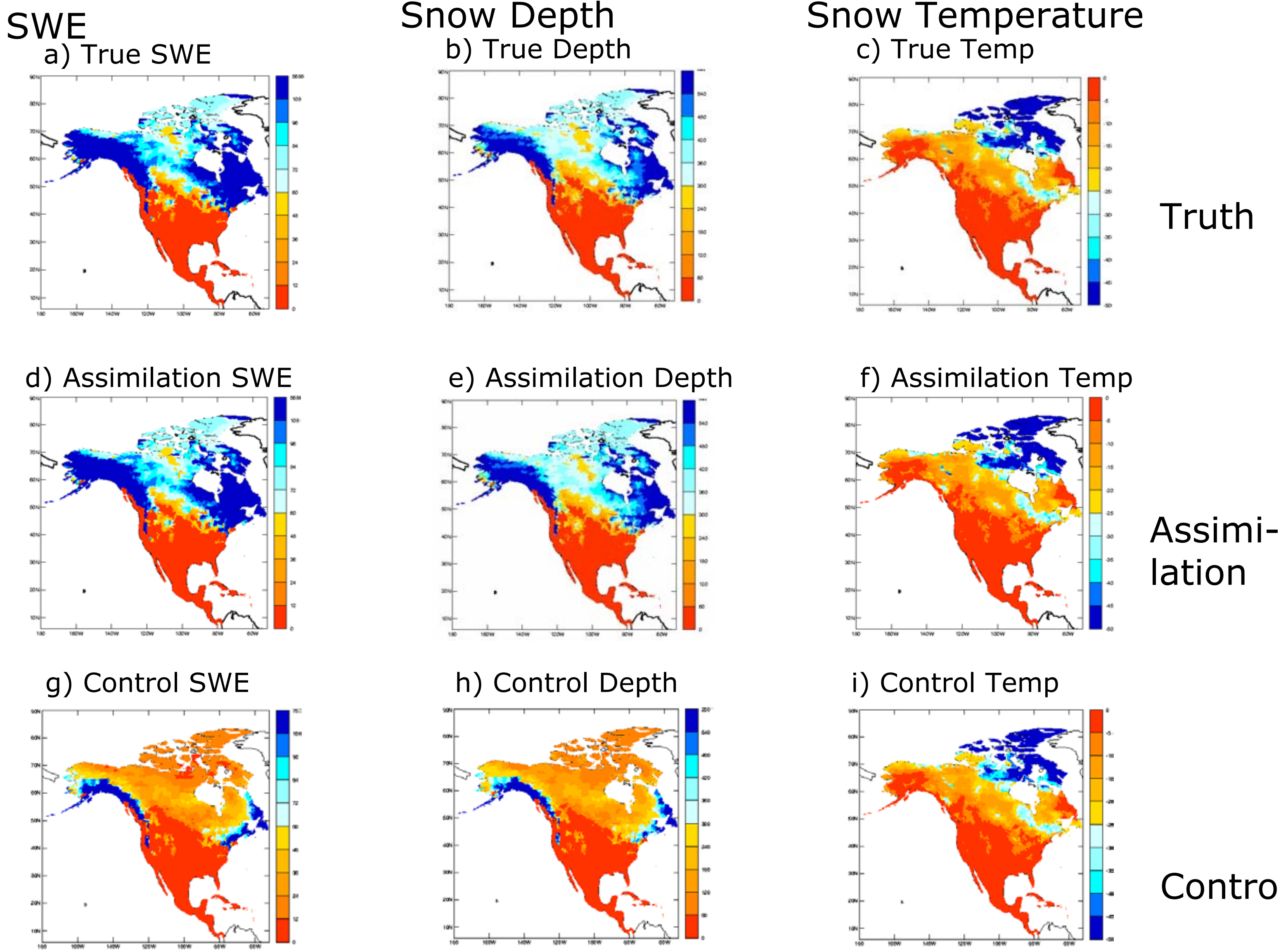
There are **three steps** to assimilate SWE observation at a given time step:

(1) Forecasting step*:* the SWE states evolve nonlinearly according to model dynamics; its forecast error covariances are propagated linearly with time.

(2) Updating step for SWE*:* the SWE of each layer is updated using the Kalman filter equations.

(3) Updating step for depth and heat content*:* Snow depth and heat content are calculated using updated SWE, model-predicted snow density and snow temperature.

Note: When the model predicts no snow and the updated SWE is non-zero, a value of 150 km/g^3 is assigned to the density and the air temperature at 2 m height to the snow temperature.



Snapshot of truth, assimilation and control (from poor initial condition) on 2/14/1987 for North America starting from 1/1/1987. Here, a), d), g) SWE (in mm); b), e) h) snow depth (in mm), c), f), i) T (in C)

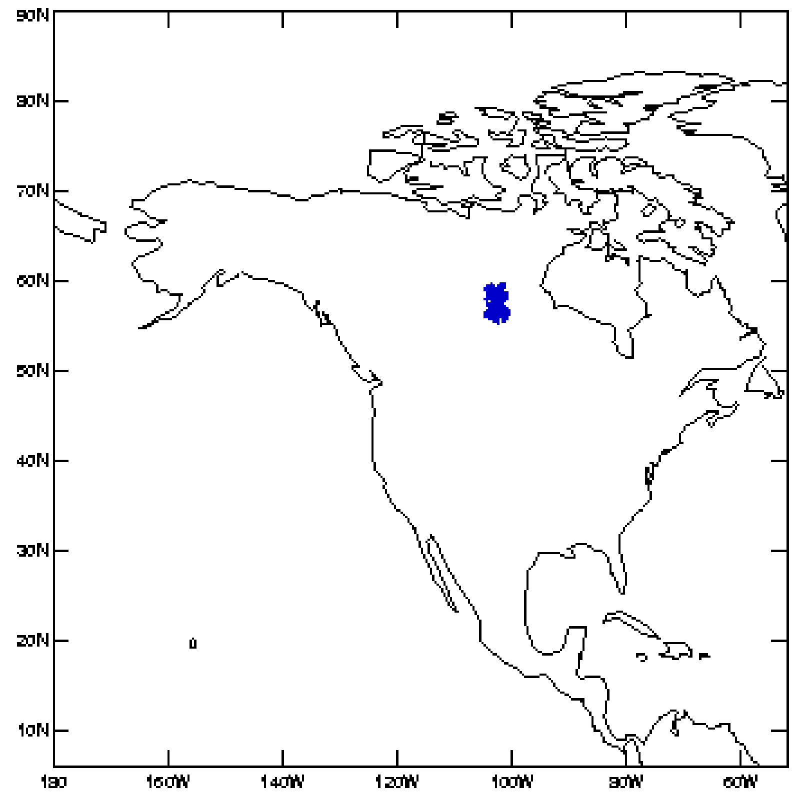
After 45 days

Detailed study

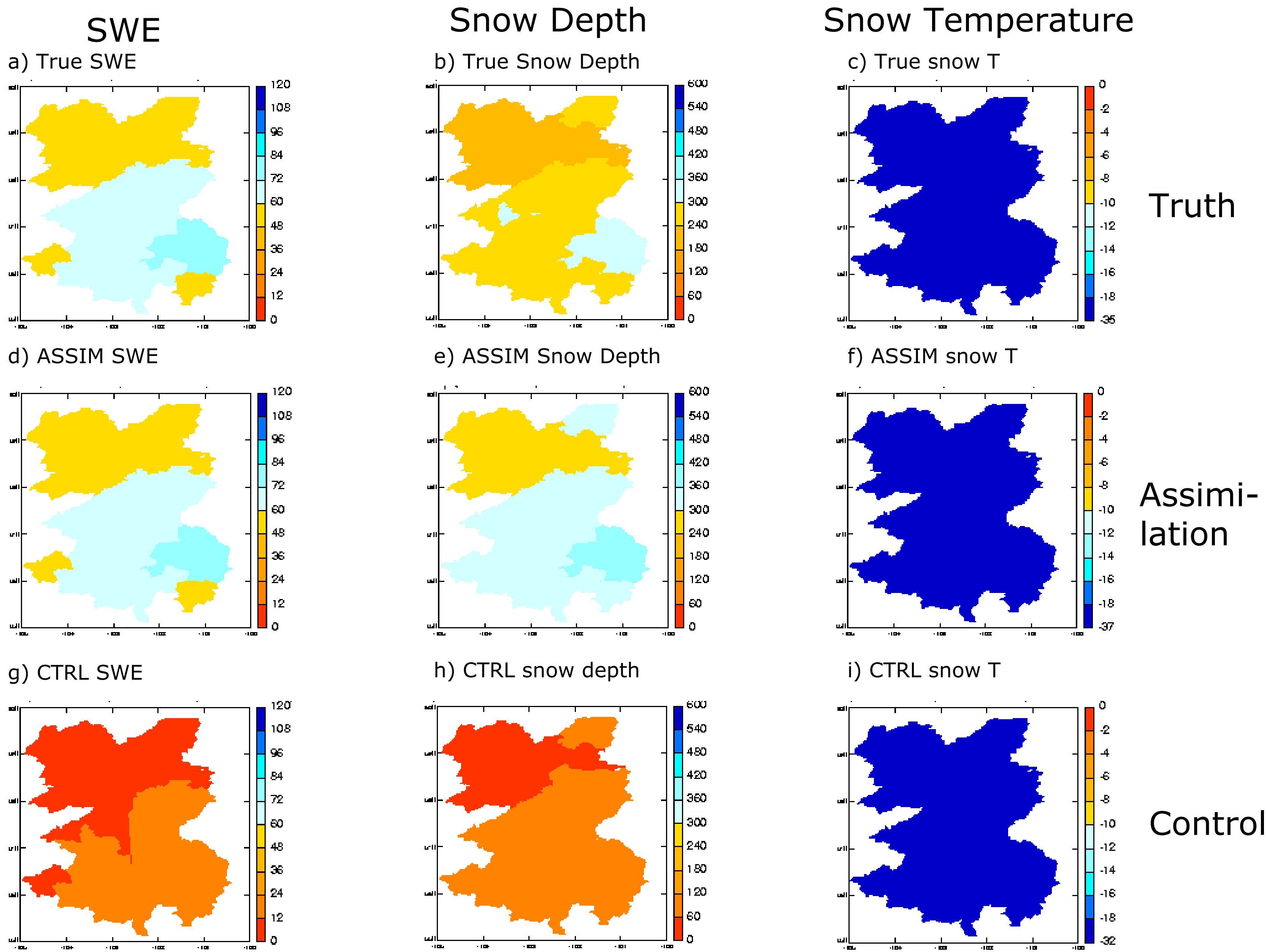
- Results are for 24 continuous catchments and 5002 catchments in N. America.

- Only snow water equivalent (SWE) in each layer is updated using the Kalman filter. Snow depth and heat content are then updated based on model-derived density and temperature, as well as the updated snow water equivalent.

- Forcing is from ECMWF reanalysis (bias corrected).

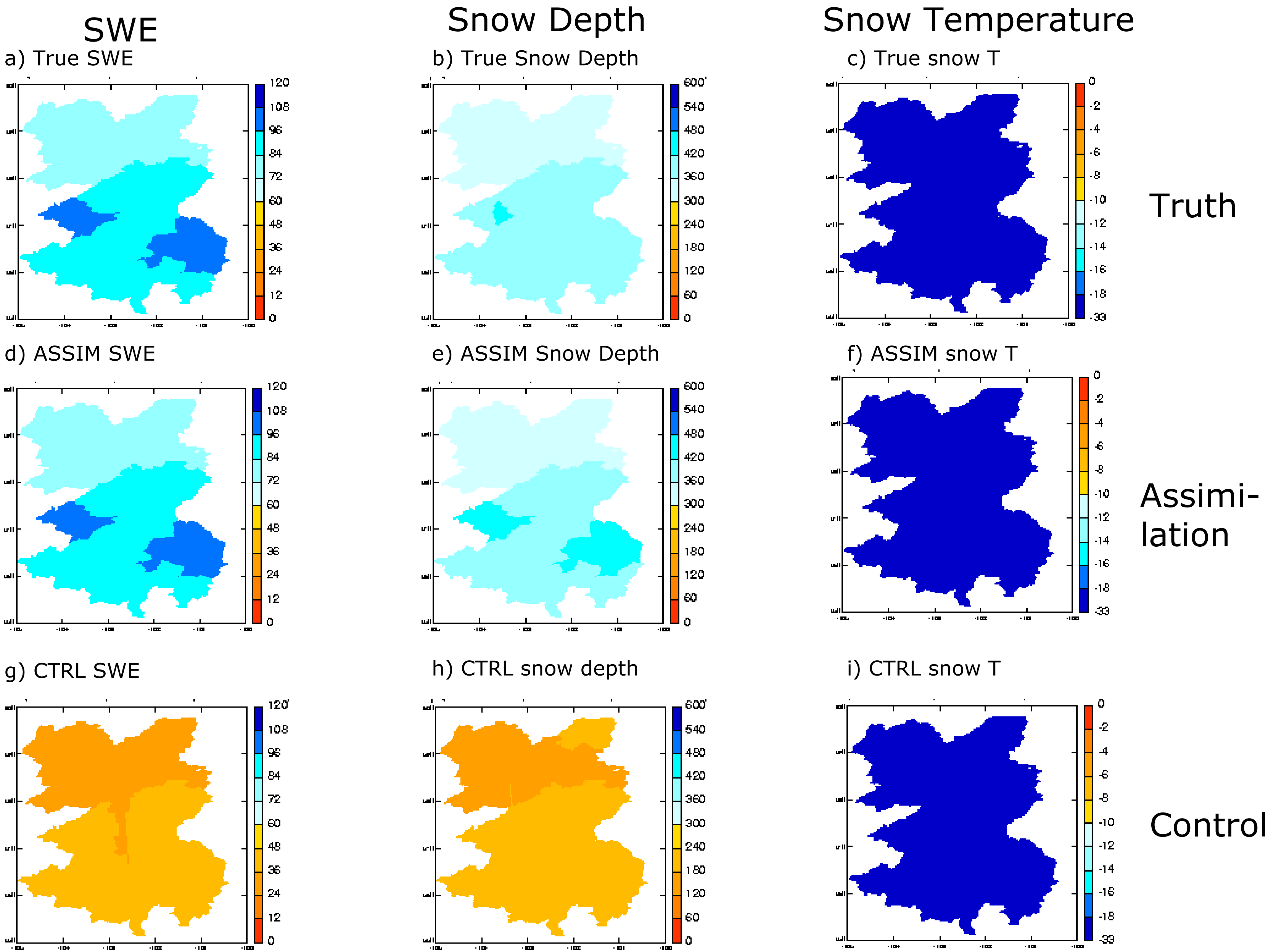


Location of 24 catchments in the detailed study.



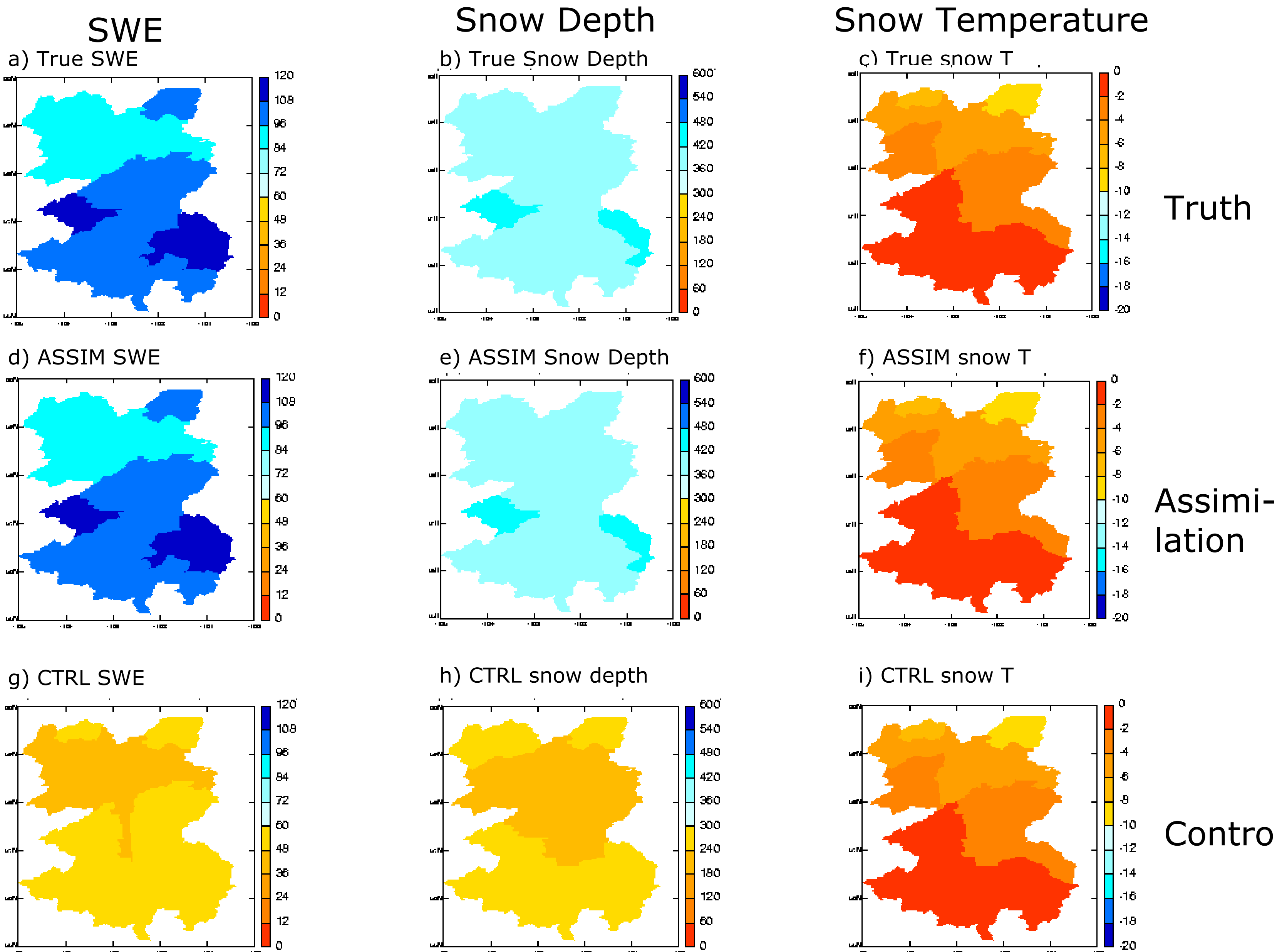
Snapshot of truth, assimilation and control (from poor initial condition) on 1/15/1987 starting from 1/1/1987. Here, a), d), g) SWE (in mm); b), e) h) snow depth (in mm), c), f), i) T (in C)

After 15 days



Snapshot of truth, assimilation and control (from poor initial condition) on 2/14/1987 starting from 1/1/1987.
Here, a), d), g) SWE (in mm); b), e) h) snow depth (in mm), c), f), i) T (in C)

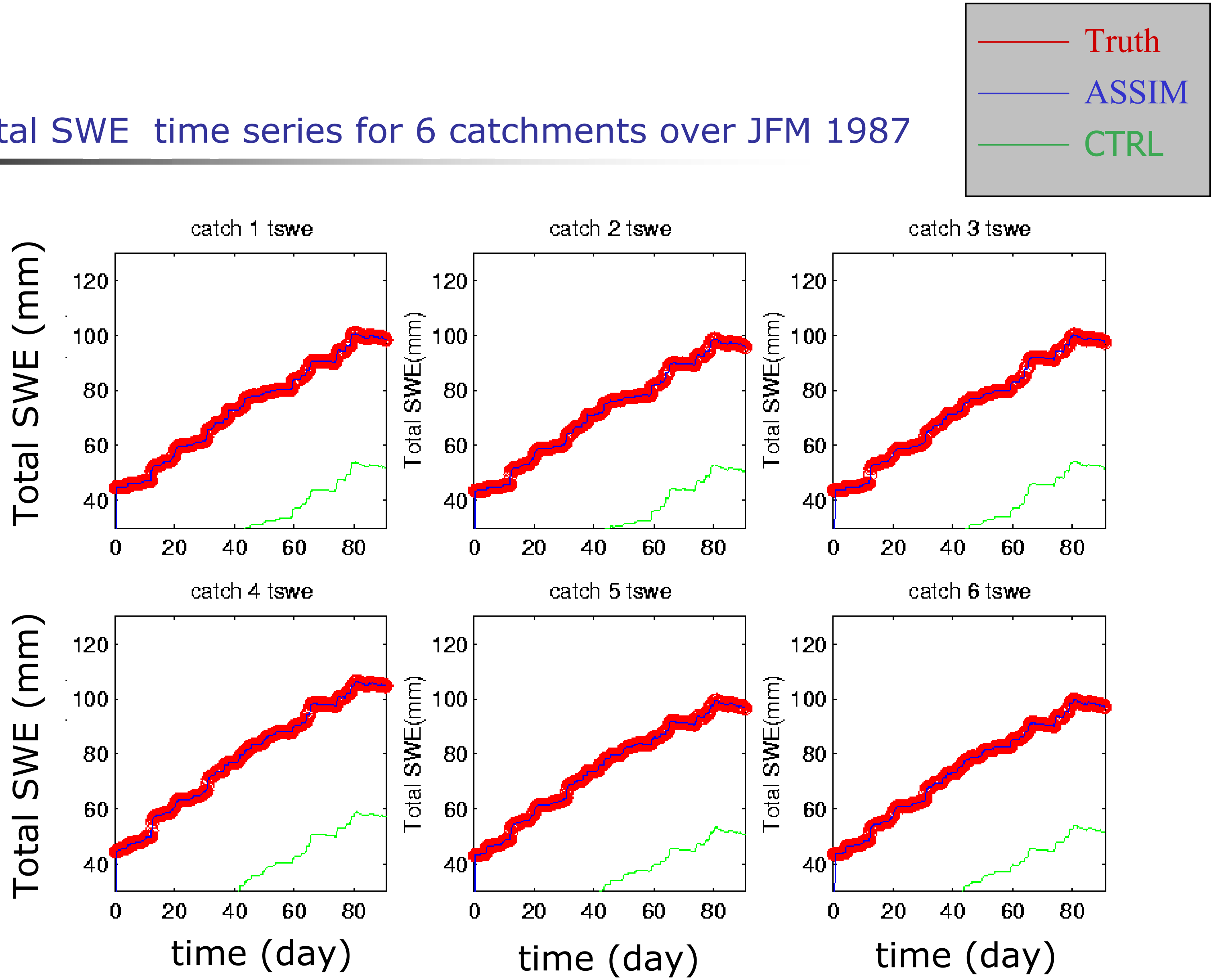
After 45 days



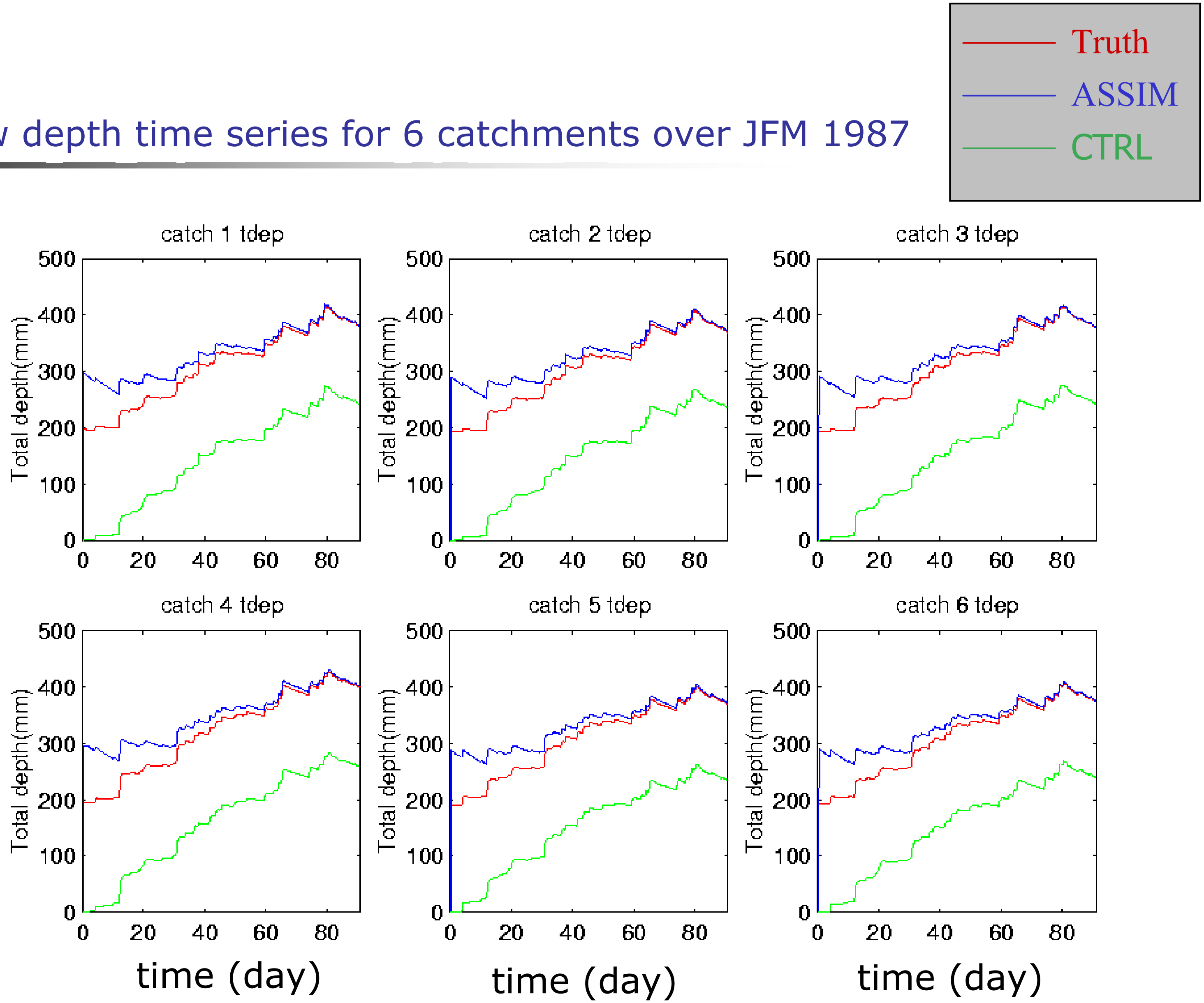
Snapshot of truth, assimilation and control (from poor initial condition) on 3/16/1987 starting from 1/1/1987.
Here, a), d), g) SWE (in mm); b), e) h) snow depth (in mm), c), f), i) T (in C)

After 75 days

Total SWE time series for 6 catchments over JFM 1987



Snow depth time series for 6 catchments over JFM 1987



Conclusions

- In the context of identical twin experiments, assimilation run starting from poor initial condition on 1/1/87, is able to converge to the truth effectively, by using the observation of bulk snow water equivalent (SWE).
- Assimilated snow water equivalent (SWE) is shown to rapidly converge toward the "truth". This is to be expected because the observation used is the total snow water equivalent.
- Snow depth is overestimated initially due to a poor estimate of the snow density by the model. It steadily converges towards the truth in about 2 months (by the end of February 1987).
- Snow temperature is well estimated in both the assimilation and forecast simulations .

Future directions…

- Study bias correction with respect to surface snow temperature and/or air temperature.
- Assimilate real data. Specifically, SWE measured by passive microwave measurement from satellites in the North America, specifically those measurements taken over the past 20 years from SSMR and SSM/I. This study may be expanded over the whole globe.
- Investigate the utility of assimilating novel snow observation products, such as snow melt signature and fractional snow cover.