# Comparison and error analysis of reconstructed SWE to Airborne Snow Observatory measurements in the Upper Tuolumne Basin, CA

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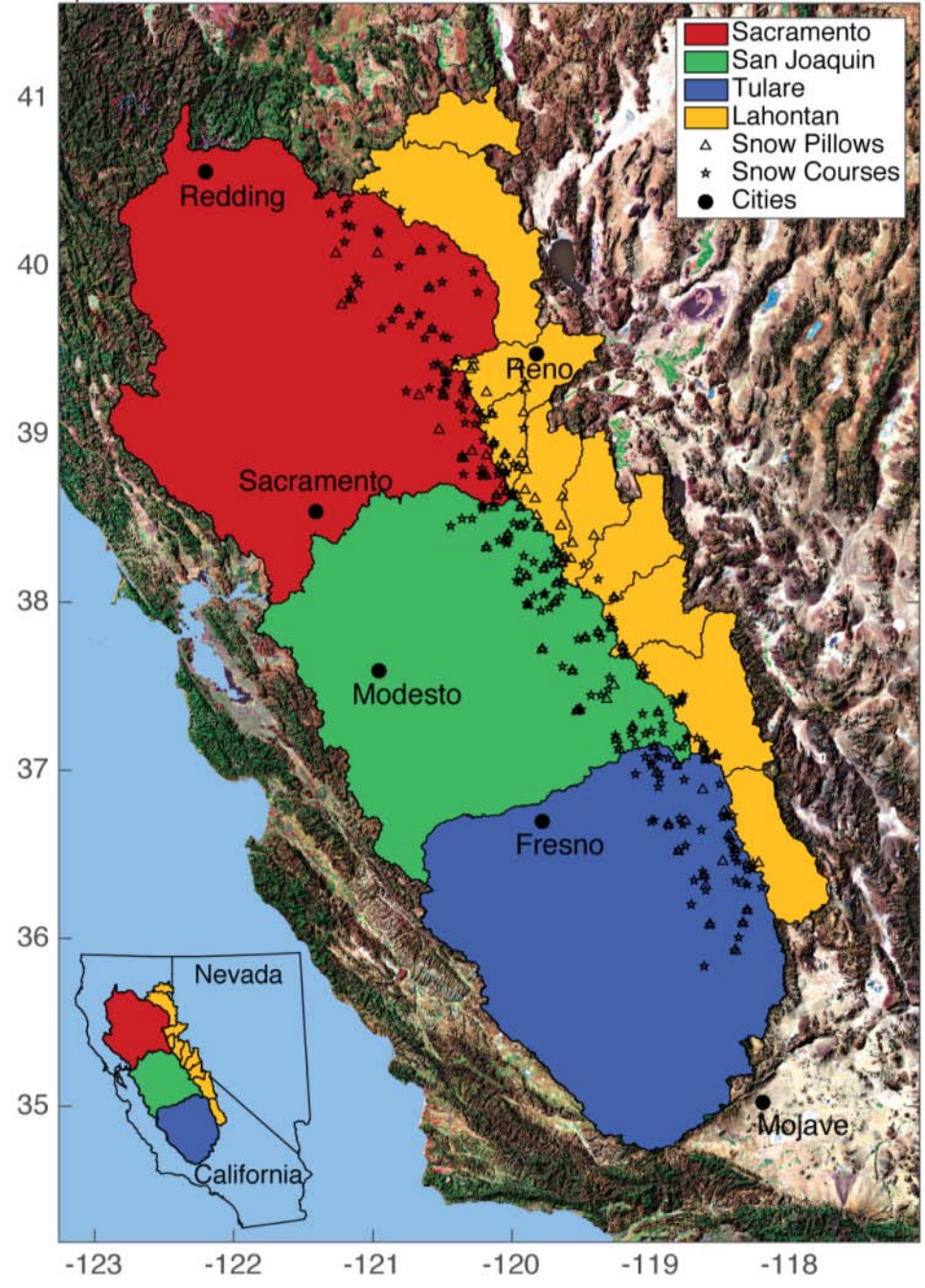
Photo Courtesy of McKenzie Skiles

# Airborne Snow Observatory (ASO)

- Measurements from a plane with a LiDAR and a spectrometer combined with some in situ measurements
- 2014 and 2015 Upper Tuolumne SWE measurements at 50 m, available at aso.jpl.nasa.gov

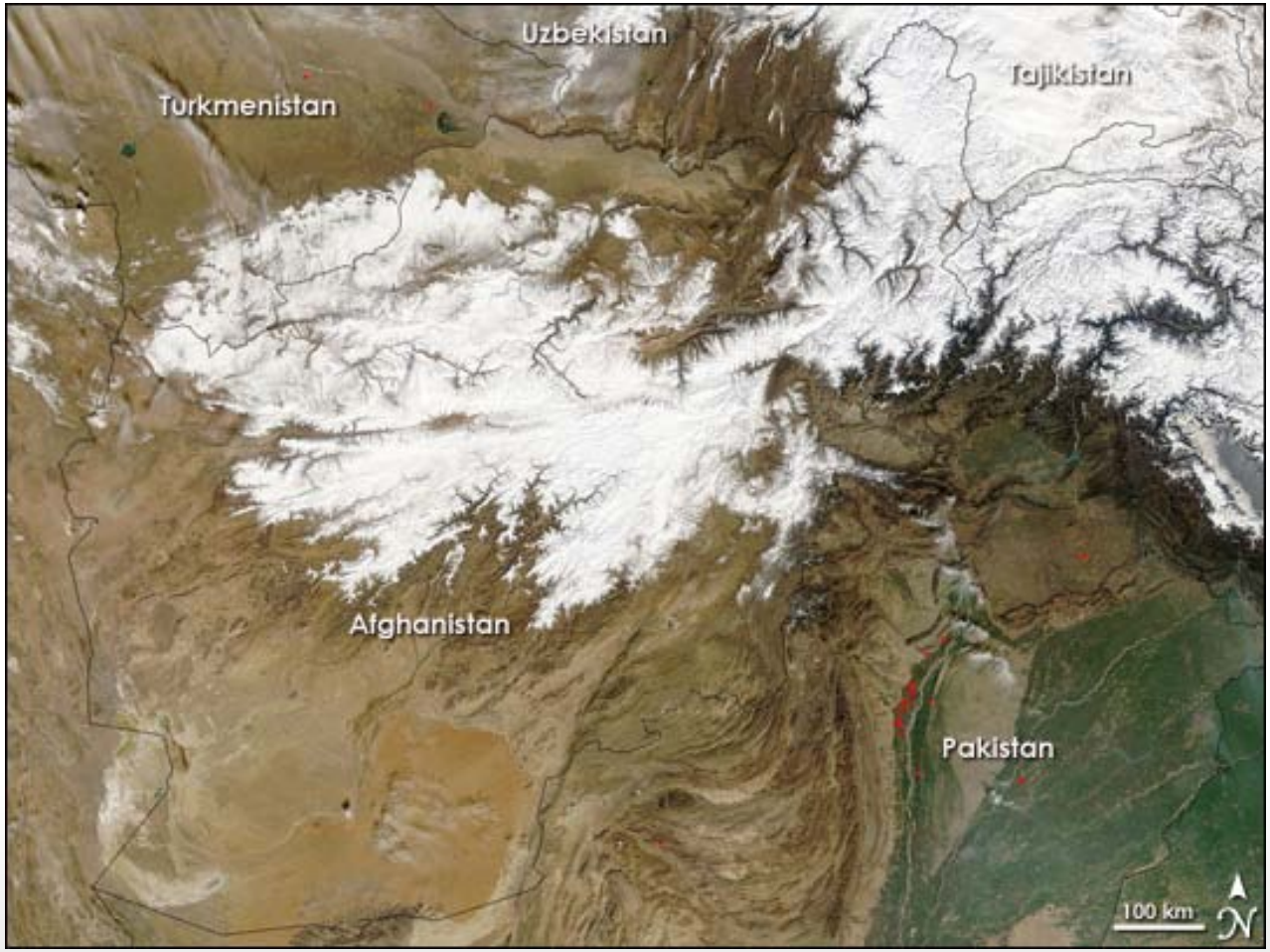



# Why is reconstruction important in the Sierra?

- Good, but not complete coverage with pillows and surveys
- ASO is great but it doesn't cover the whole Sierra and it's unclear how long it will last
- Areas with good pillow and survey coverage and Airborne Snow Observatory can be used for model verification

Rittger, K., and J. Dozier (submitted), Spatial estimates of snow water equivalent from reconstruction, *Advances in Water Resources*.

# Why is reconstruction important in other regions?




- Many areas in the world have little or no ground-based snow measurements, e.g. Afghanistan's Hindu Kush Mountains

# Reconstruction model

- Using remotely sensed snow disappearance (snow covered area is zero), back calculate the energy needed to melt snow.
- $SWE=\sum M$
- $M=R+H+L+G$
  - M is energy to melt
  - R is net radiation
  - H is sensible heat
  - L is latent heat
  - G is heat flow into the snowpack
- Assumptions
  - No significant accumulation after peak SWE
  - G=0 since snowpack is melting; i.e. pack is 0 ˚C
  - Snow surface is lesser of air temp or 0 ˚C
  - Model resolution is constrained by snow covered area resolution (~500 m)

# Energy for melt, M=R+H+L

- $M = fsca * M_p$
  - fsca is smoothed fractional snow covered area (MODSCAG, Painter et al., 2009 or MOD10A1, Hall et al., 2006)
  - $M_p$ is potential melt (100% snow covered pixel)
- Net radiation, $R = S_{\downarrow}(1-a) + F_{\downarrow} + F_{\uparrow}$
  - $S_{\downarrow}$ is incoming solar (downscaled from NLDAS-2, 1/8th˚, Cosgrove et al. 2003)
    - $S_{\downarrow}$ is split into direct and diffuse using an empirical formula based on transmission (Erbs et al., 1982; Olyphant, 1984)
    - Direct solar is scaled by the cosine of the local zenith angle, or shadowed if below the local horizon (Dozier and Frew, 1990) and scaled by elevation
  - a is albedo (inversion from MODSCAG grain size and MODDRFS)
    - Gardner Sharp (2010) model
  - $F_{\downarrow}$, $F_{\uparrow}$ is incoming/outgoing longwave (downscaled from NLDAS-2)
    - Corrected for topography and vegetation

# Energy for melt, M=R+H+L

- Sensible heat, $H(\zeta,T_a,T_s)$ and latent heat, $L(\zeta,Q,T_s,P)$
  - $\zeta(w,T_a,T_s)$ stability function
  - w is wind speed (downscaled wind speed from NLDAS-2)
    - Scaled based on terrain curvature, wind slope, and vegetation (Liston et el., 2007)
  - $T_a$ is air temp (downscaled from NLDAS-2)
  - $T_s$ is surface temp, lesser of air temp or 0 ˚C
  - Q is specific humidity (downscaled from NLDAS-2)
  - P is air pressure (downscaled from NLDAS-2)

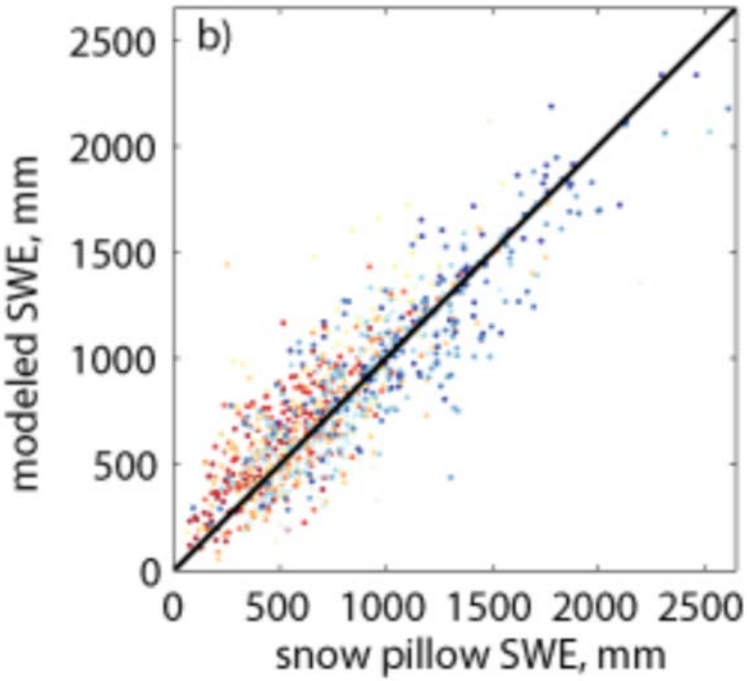
# Brubaker et al. (1996) model

- Since wind speed and other turbulent terms are difficult to estimate, Brubaker et al. suggest a radiation/degree-day model
  - $M=aR+bT$
    - M is melt
    - R is average <u>daily</u> net radiation above 0 W $m^{-2}$
    - T is the average <u>daily</u> air temperature above 0 ˚C.
    - a is a constant (0.26 mm $W^{-1}$ $m^2$ $day^{-1}$) that converts R to melt
    - b is an empirical coefficient (e.g. 1.5 mm $C^{-1}$ $day^{-1}$) that converts T to melt, thus it varies by location.

Brubaker, K., A. Rango, and W. Kustas (1996), Incorporating radiation inputs into the snowmelt runoff model, *Hydrological Processes*, *10*, 1329-1343.

# Rittger (2012) model, the basis for this model

- Rittger (2012) reconstructed SWE in the Sierra Nevada for 2000-2011 using the Brubaker et al. (1996) method
- For the maximum SWE accumulation at a snow pillow:
  - Bias (model-pillow) averaged 38 mm, ranging from -78 to 214 mm.
  - The RMSE averaged 249 mm, ranging from 175-329 mm
  - Dry years had greater errors than wet years




Rittger, K. (2012), Spatial estimates of snow water equivalent in the Sierra Nevada, Ph.D. thesis, 225 pp, Unversity of California, Santa Barbara.

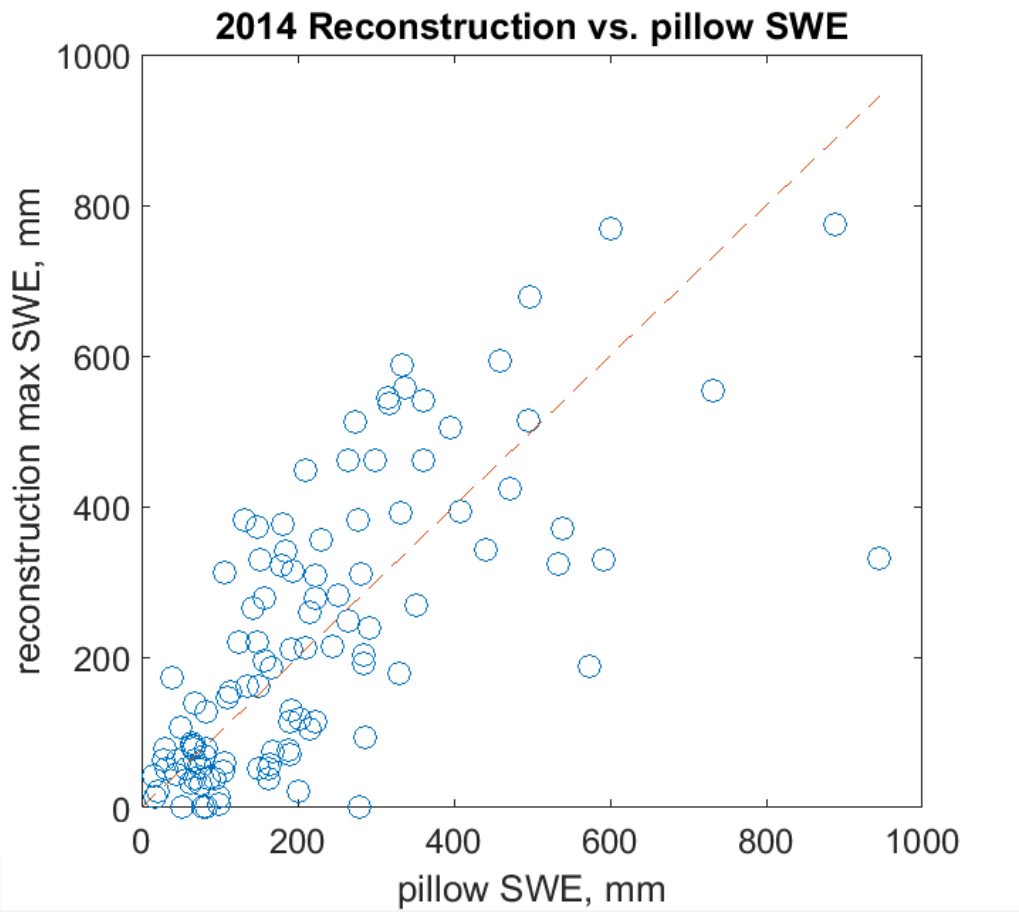
# Specific changes to reconstruction model from Rittger (2012)

1. Full e-balance vs. Brubaker et al. model
   - Melt summed hourly rather than daily since Brubaker requires daily average air temperatures
   - Added wind, latent, and sensible heat functions
2. Downscaling run at 500 m rather than 100 m
   - Limited by fSCA at 500m, thus 100 m is unnecessary and could cause errors
   - Allows parallelization to be done on days rather than tiles
3. Used our own shortwave bias correction rather than the one provided by NLDAS.
   - Uncorrected shortwave available in NLDAS-2 Forcing B dataset.
   - Issues with snow/cloud discrimination in NLDAS-2 shortwave Forcing A causes an underestimate.

# Specific changes to reconstruction model from Rittger (2012)

4. Treatment of ephemeral snow
   - SWE is only summed during contiguous periods of positive fSCA
5. Improved albedo estimates
   - Snow albedo calculated hourly and adjusted by half of “deltavis” term from MODDRFS
   - Previously, albedo was fixed throughout the day and decreased by a constant (0.12) to account for impurities in the snow and MODSCAG grain size errors.
6. Other computing changes
   - HDF5 support, block level compression to read individual days
   - image resampling changes

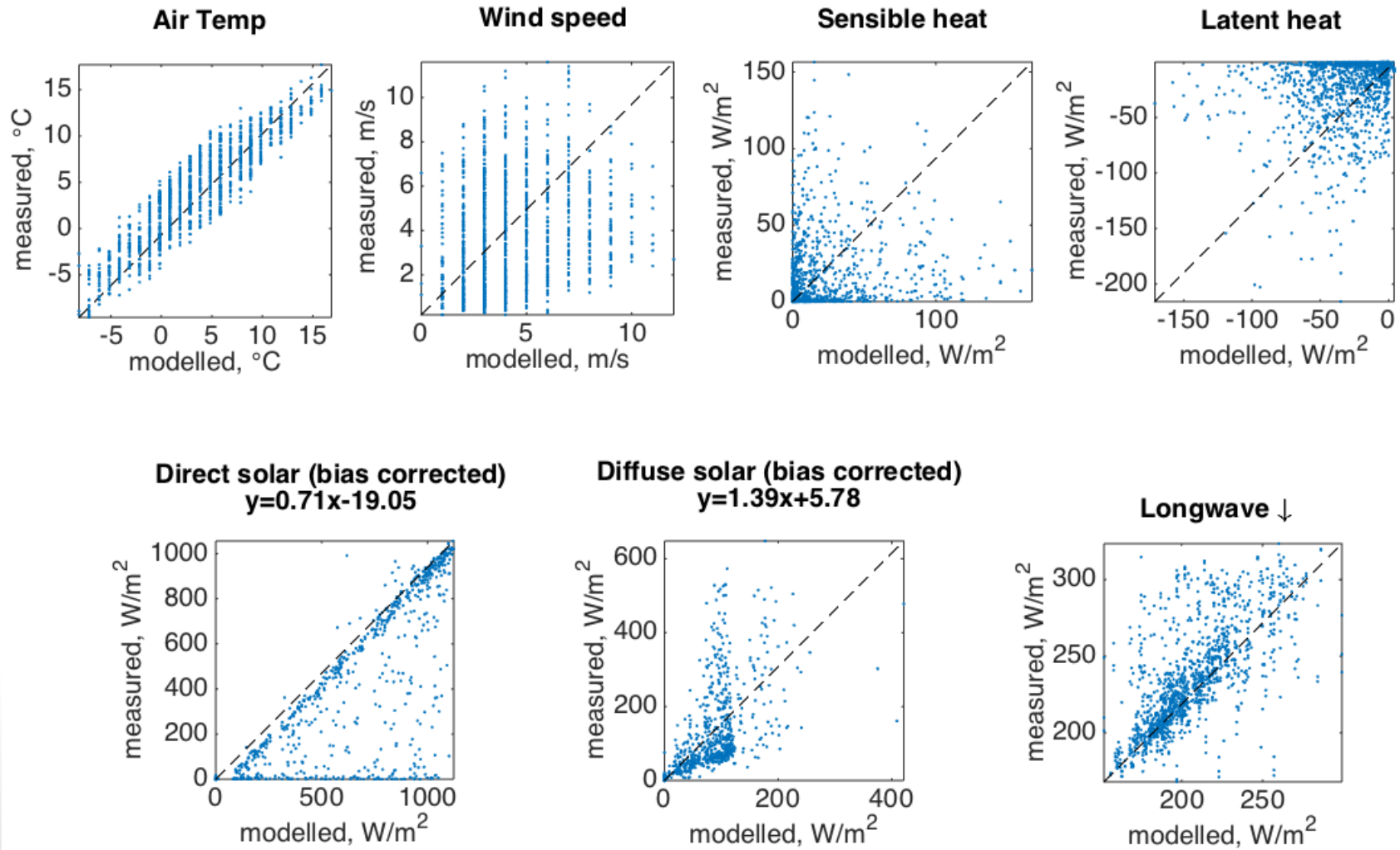
# Using maximum pillow SWE for verification




- N = 104 pillows
- Tiny bias, 3 mm
  - Compare with 38 mm average for the old model
- RMSE is 140 mm
  - compare with 249 mm average for the old model
- Low RMSE could be related to an exceptionally dry year, but since RMSE increased in drier years in the old model, this is a sign that the model is more accurate, but it still needs to be run for the same years.

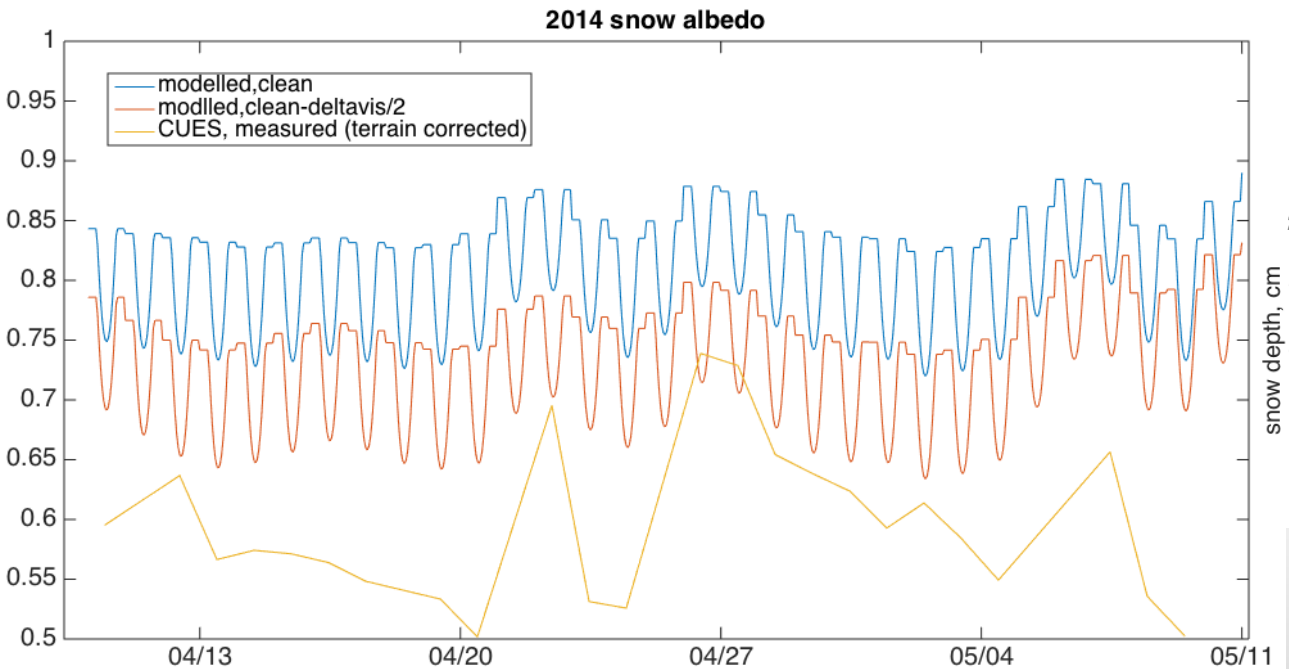
# CUES and the Upper Tuolumne

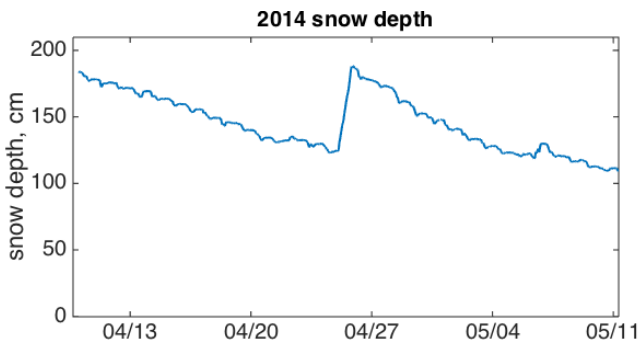
# Hourly energy balance components compared to CUES, 4/10-5/30/14



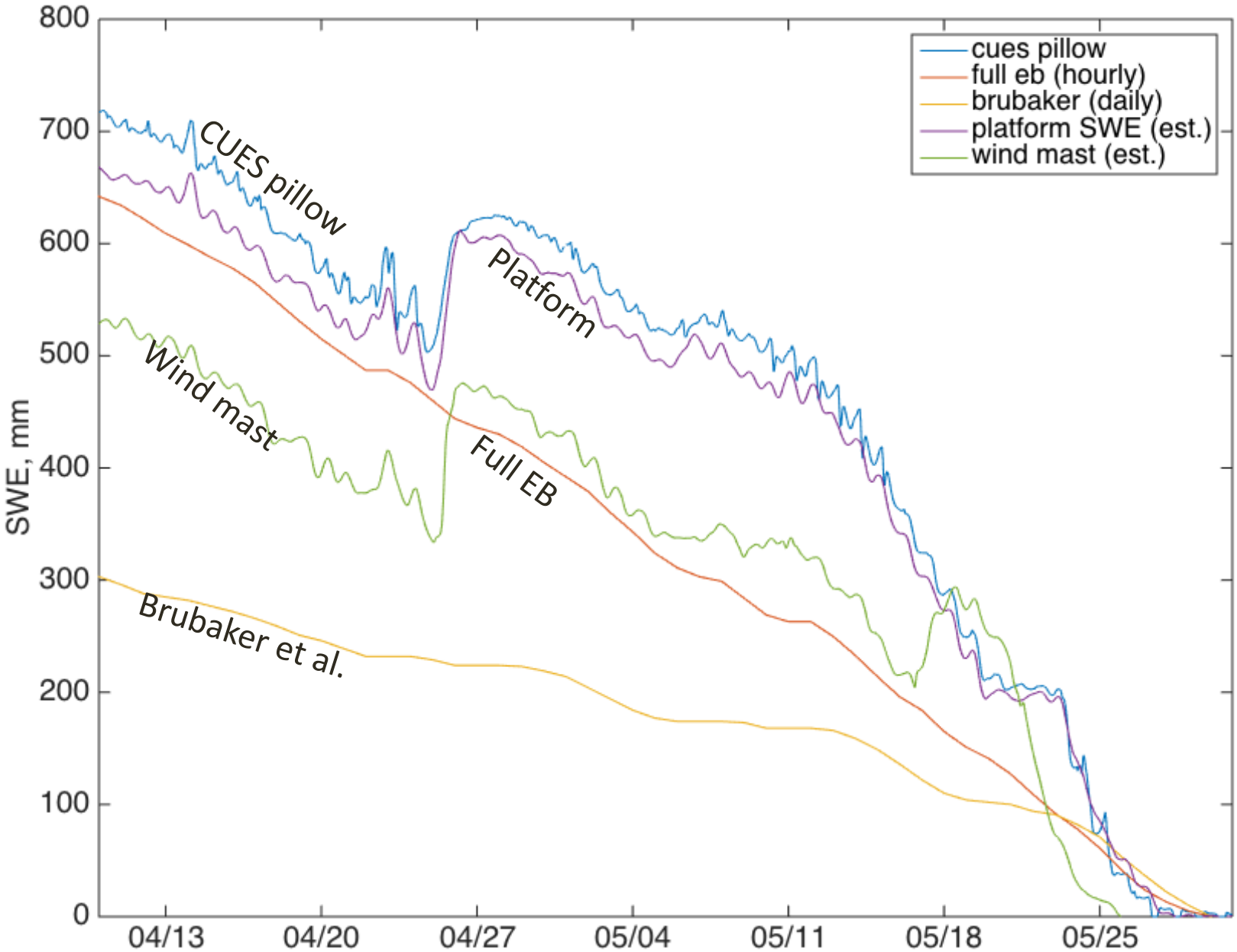
# Difficulty in verifying snow albedo

- Currently, ASO snow albedo is not broadband and still has errors, so we can't use that.
- Even with terrain correction from a terrestrial LiDAR, the snow albedo measured at CUES appears too low, e.g. < 0.75 for clean new snow. We may need to get the downlooking radiometer closer to the snow surface.
- Thus, we cannot currently verify our albedo estimates.

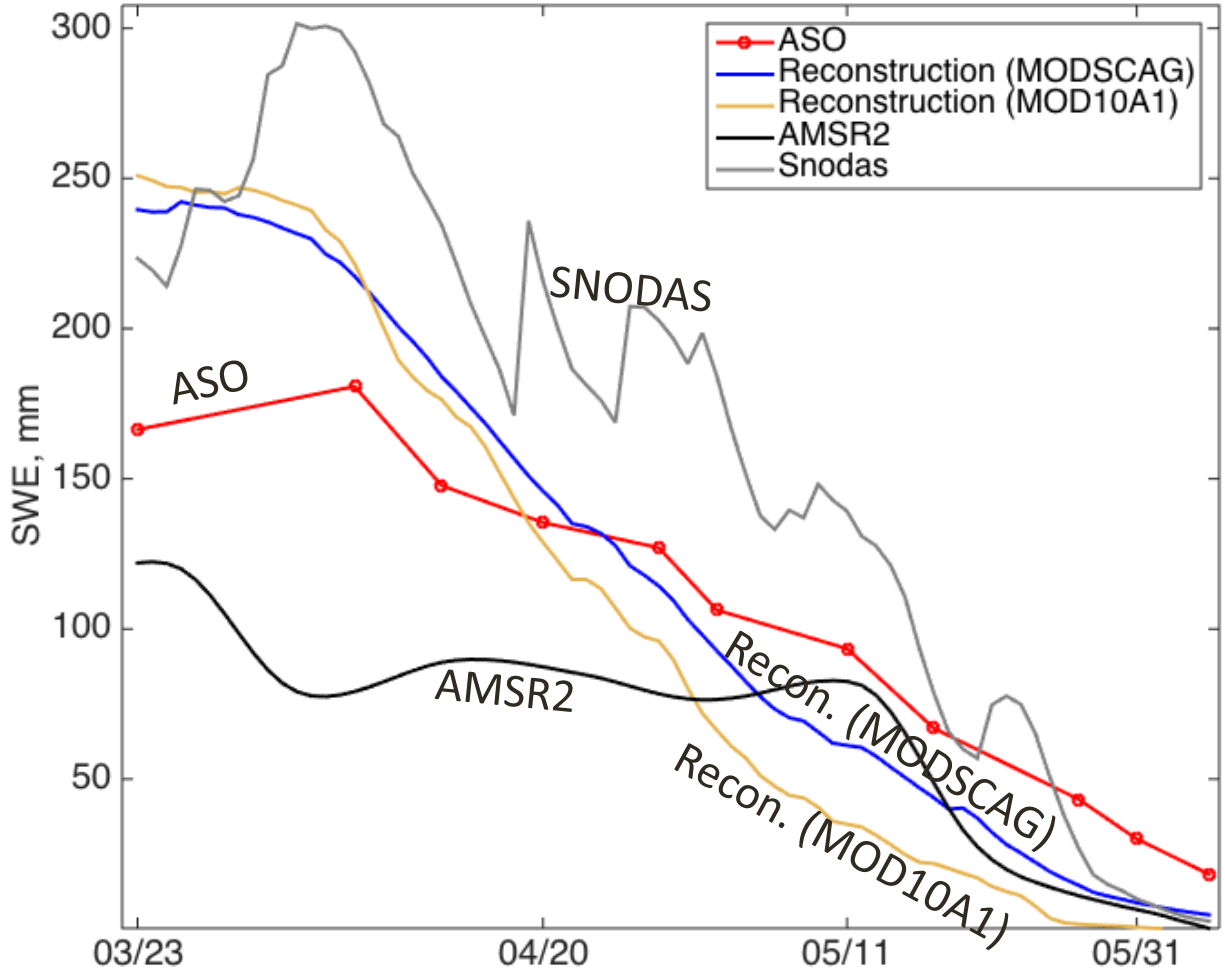


# 2014 SWE at CUES with known SCA

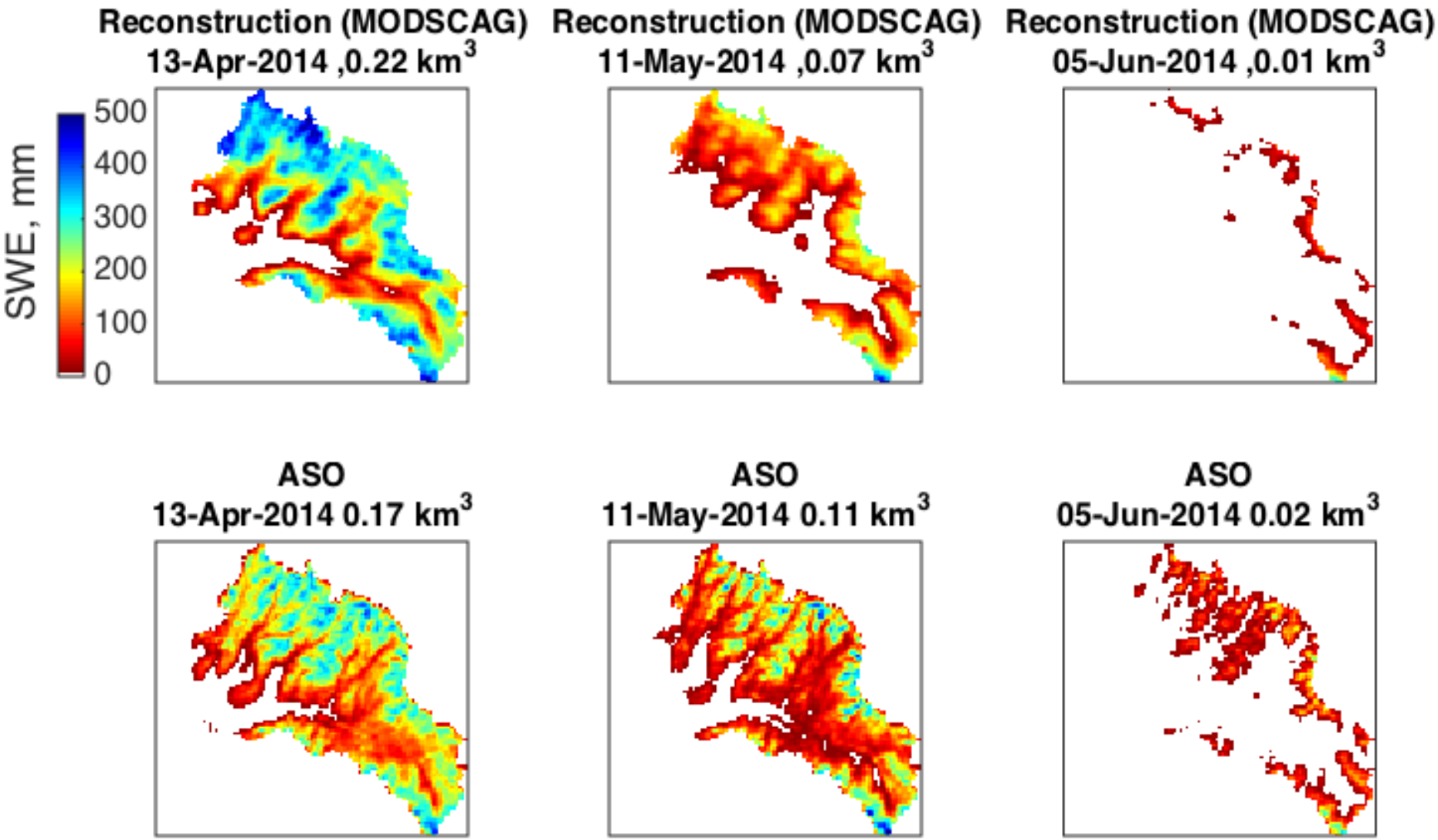


# 2014 Upper Tuolumne SWE

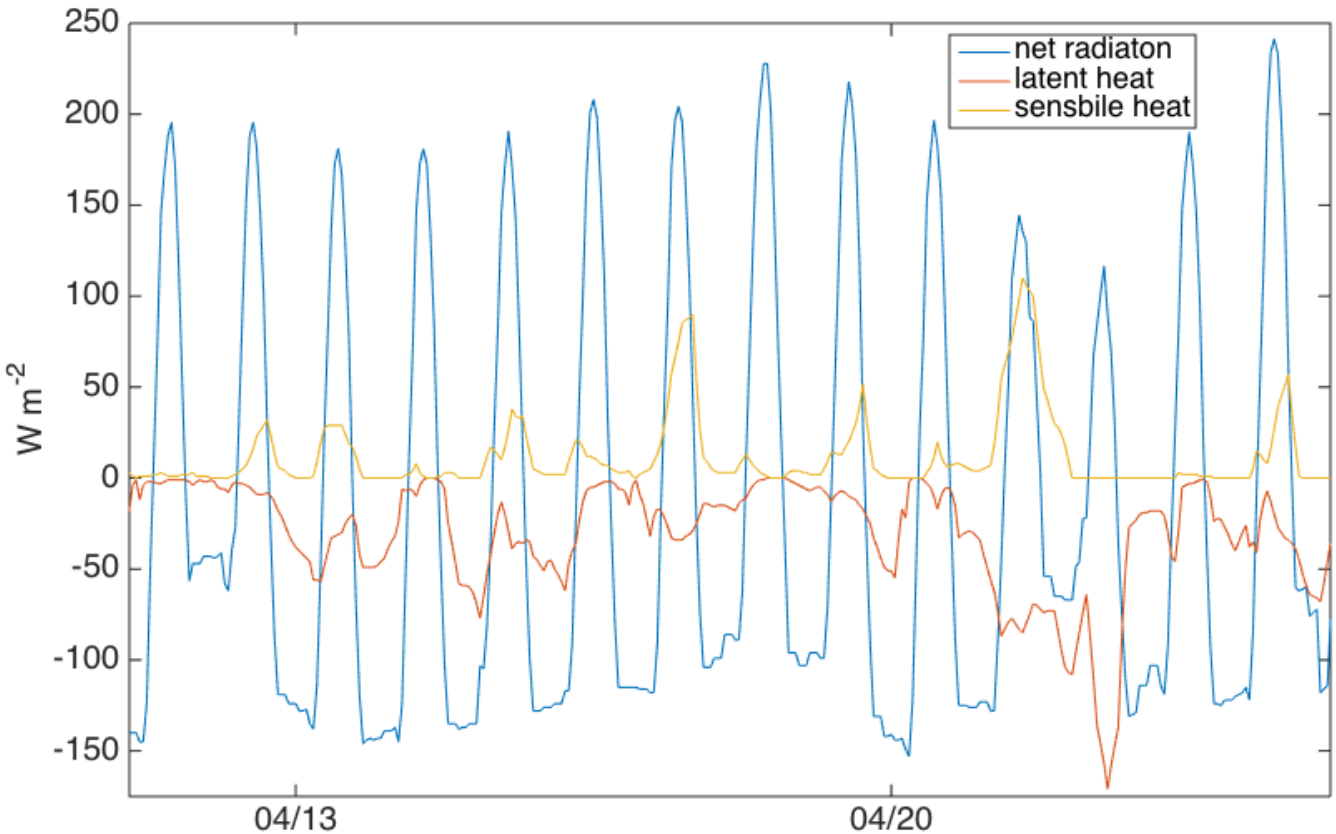



| | For peak SWE on 4/7/14 | | For all ASO dates |
|---|---|---|---|
| **Method** | **Mean SWE, mm** | **Bias, mm** | **RMSE, mm** |
| ASO | 181 | 0 | 0 |
| Reconstruction (MODSCAG) | 217 | 36 | 32 |
| Reconstruction (MOD10A1) | 221 | 40 | 43 |
| AMSR2 | 79 | -102 | 46 |
| Snodas | 292 | 111 | 64 |

# Spatial distribution of reconstructed SWE vs. ASO

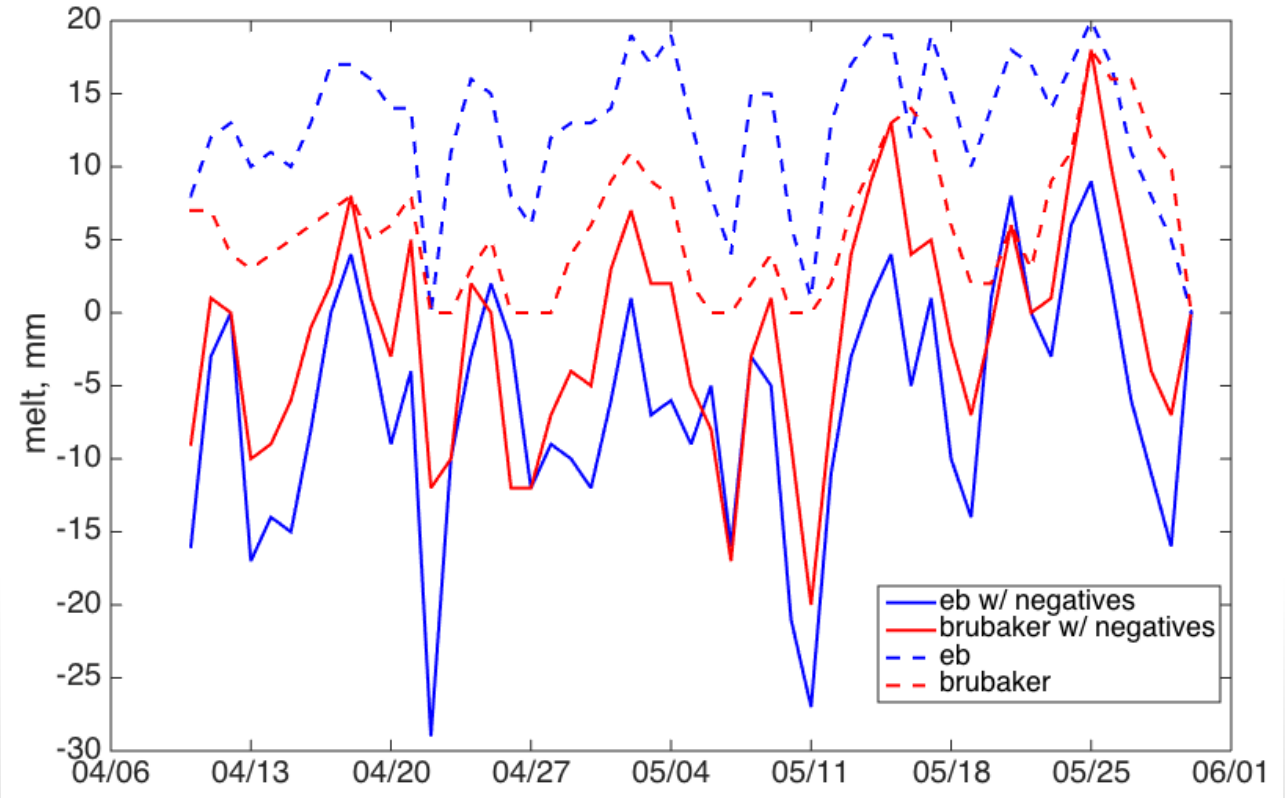


# Model time step is very important




- In both models, the snowpack does not lose/store energy
- This is a good assumption since snow (except for its surface) is isothermal during the melt.
- In the Brubaker et al. model, we only sum positive <u>daily</u> averages.
- In the energy balance model, we sum only positive <u>hourly</u> values.

# Daily melt if:
# 1) melt can be negative
# 2) melt can only be positive




- 1) Neither model would produce much positive melt, but the Brubaker et al. model would produce <u>more</u> melt than the eb model (red > blue, solid curves)
- 2) Results are reversed, eb produces more melt than the Brubaker et al. (blue > red, dashed curves)
- In other words, the reason the EB model produces more SWE is because it's an <u>hourly</u> rather than <u>daily</u> model.

# Take home points

- Reconstruction was the most accurate method for estimating peak SWE in the Upper Tuolumne
- Changes to the reconstruction model yielded more accurate results
- EB model produces more SWE than Brubaker et al. model because of hourly (rather than daily) melt time step
- Using MODSCAG fSCA over MOD10A1 barely improved SWE accuracy in the Upper Tuolumne