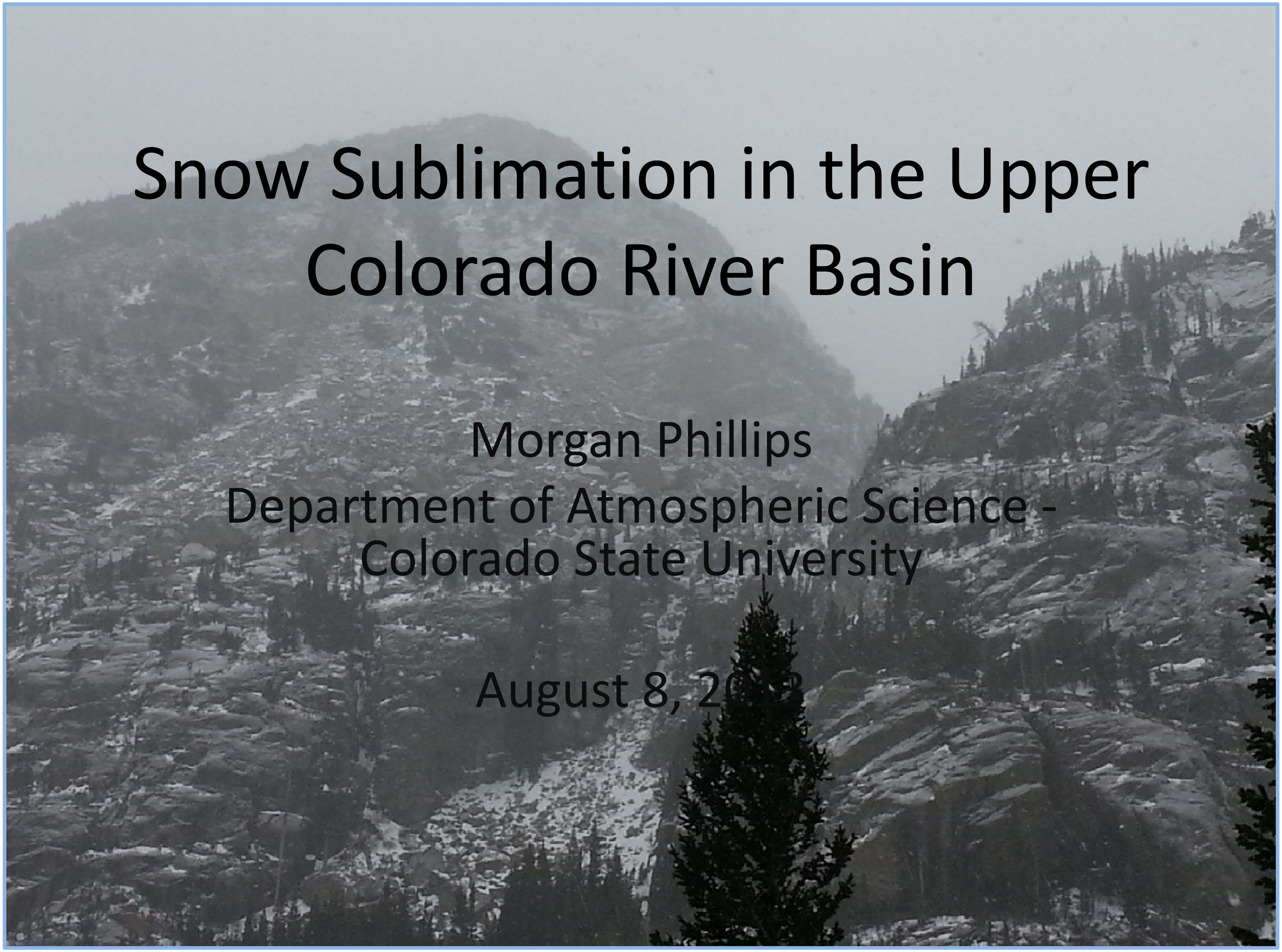

Snow Sublimation in the Upper Colorado River Basin

Morgan Phillips

Department of Atmospheric Science - Colorado State University

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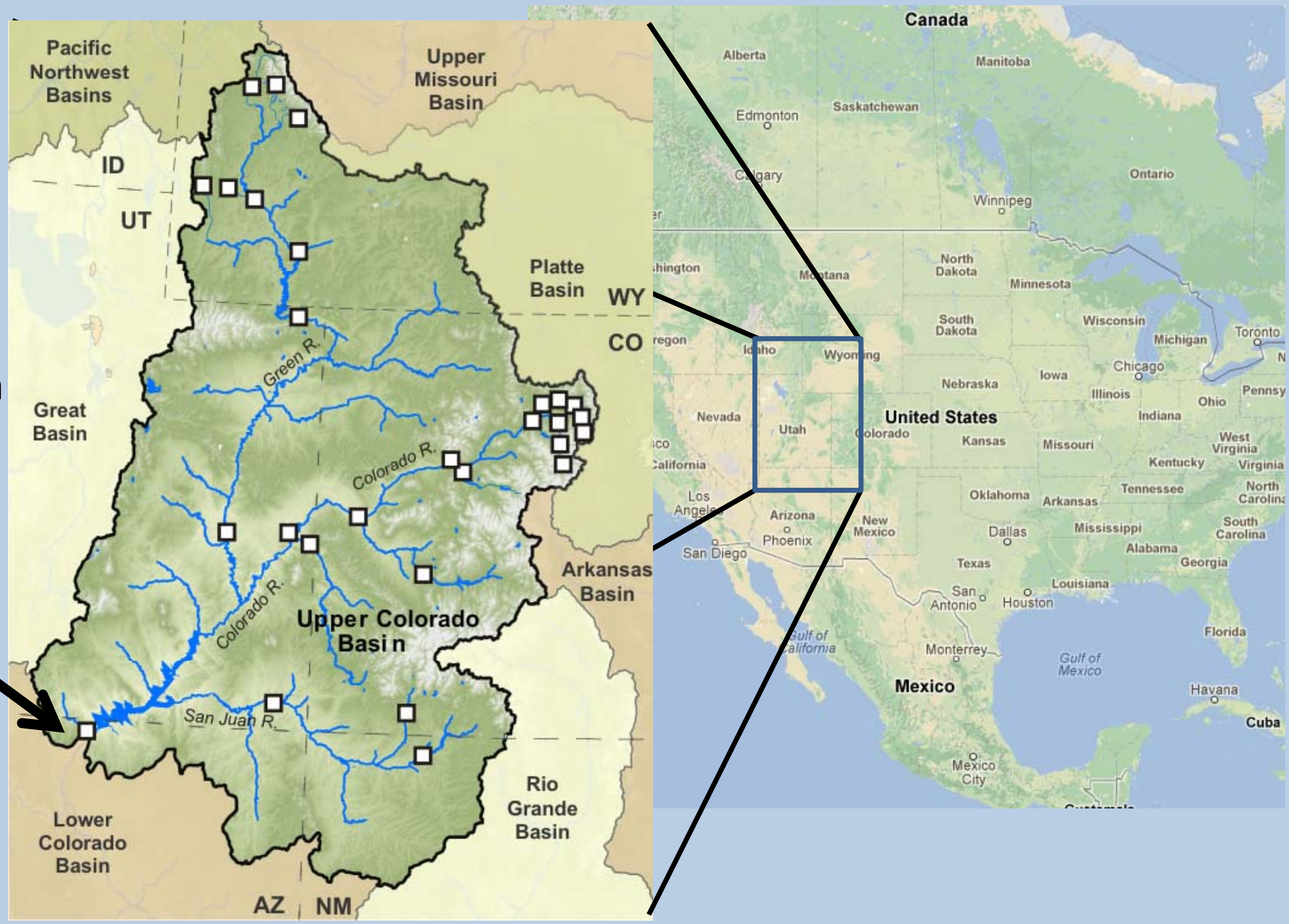
Upper Colorado River Basin (UCRB)

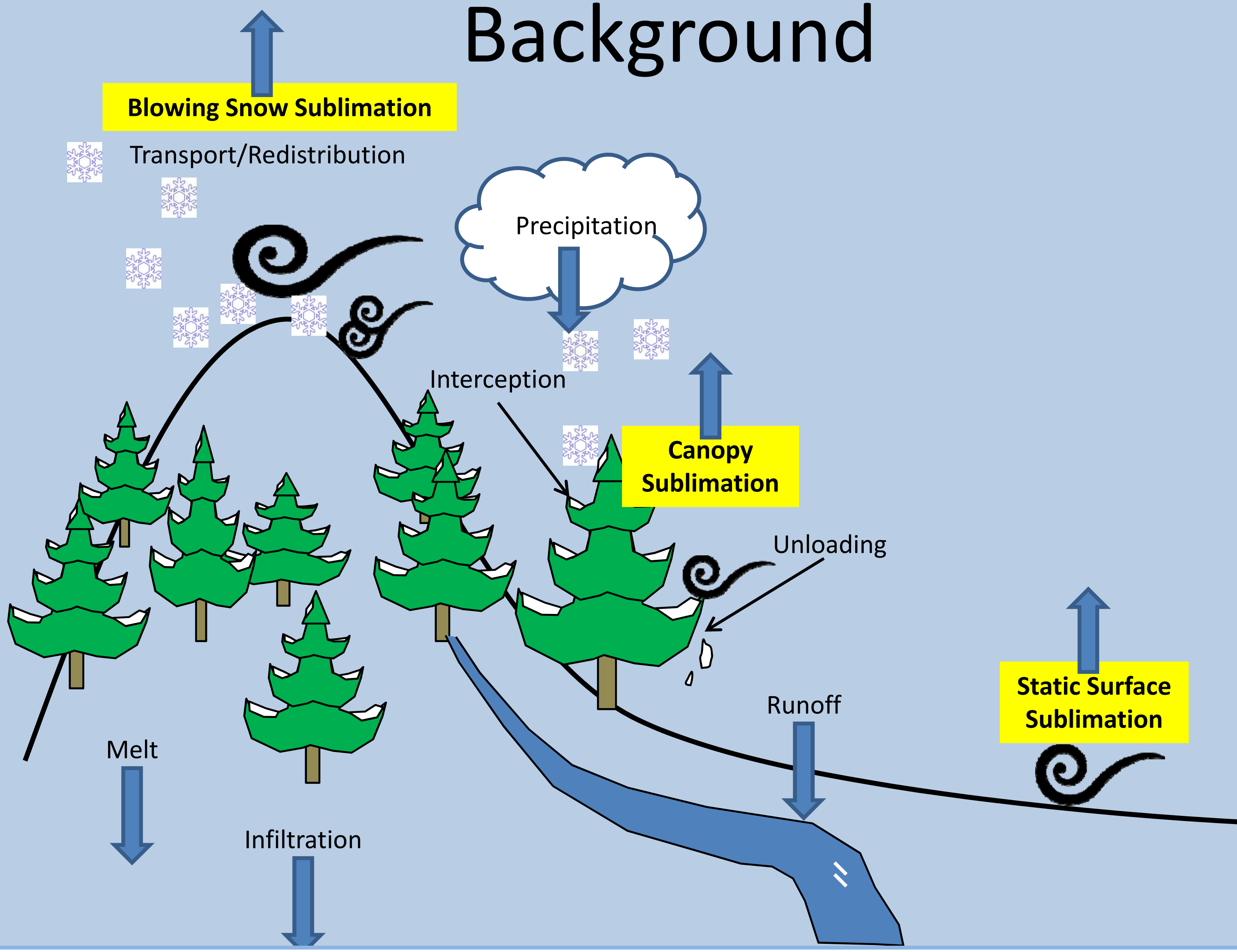
Lee's Ferry
Average annual Discharge ≈ **8.5 million acre-feet** (2004-2010 avg.)



Background

Up to 70% of annual flow in the UCRB originates from snowmelt (Christensen et al., 2007)

Background


Blowing Snow Sublimation
Transport/Redistribution
Precipitation
Interception
Canopy Sublimation
Unloading
Runoff
Static Surface Sublimation
Melt
Infiltration

Motivation

- National Integrated Drought Information System (NIDIS)
  - Expand on the Upper Colorado River Basin pilot project – Risk Assessment
    - Does sublimation play a significant role in the water balance?
    - Where/when is sublimation most important?

Previous Work

- Sublimation can consume 10%-60% of annual snowpack

Author	Type	Amount
Avery et al., 1992	Static	1.56 mm/day (max of 8.52 mm/day)
Harding et al., 1996	Canopy	4 mm in 36 hours
Hood et al., 1994	Static and blowing	15% annual precip.
Kattleman et al., 1991	Alpine	1-2 mm/day, 18% ann. Precip.
Lundberg et al., 1994	Canopy	0.3 mm/hr
Liston et al., 1998	Arctic, blowing only	22% of winter precipitation
MacDonald et al., 2010	Alpine	20-30% annual snowfal
Marks et al., 1992	Alpine	20% annual snowfall
Meiman et al., 1974	Forest/Alpine	40% annual precip. canopy, 60% annual precip. Alpine
Molotch et al., 2004	Canopy	0.41 (sub-canopy) - 0.71 (canopy) mm/day
Montesi et al., 2004	Canopy	20-30% annual snowfall
Schmidt et al., 1998	Canopy	20% annu. Snow, 0.52 mm/day
Schultz et al., 2004	Desert Alpine	44% Snowpack (3 mm/day)
Strasser et al., 2008	Total Sub.	10-90% annual precip
Schmidt et al., 1992	Total Sub.	46 mm annually

Goals

- Primary Tasks
  - Asses requirements and availability of data needed for estimating sublimation
  - Determine optimal methodology for estimating sublimation over a large mountain watershed
  - Compute regional estimates of snow sublimation over a period of several years

Goals

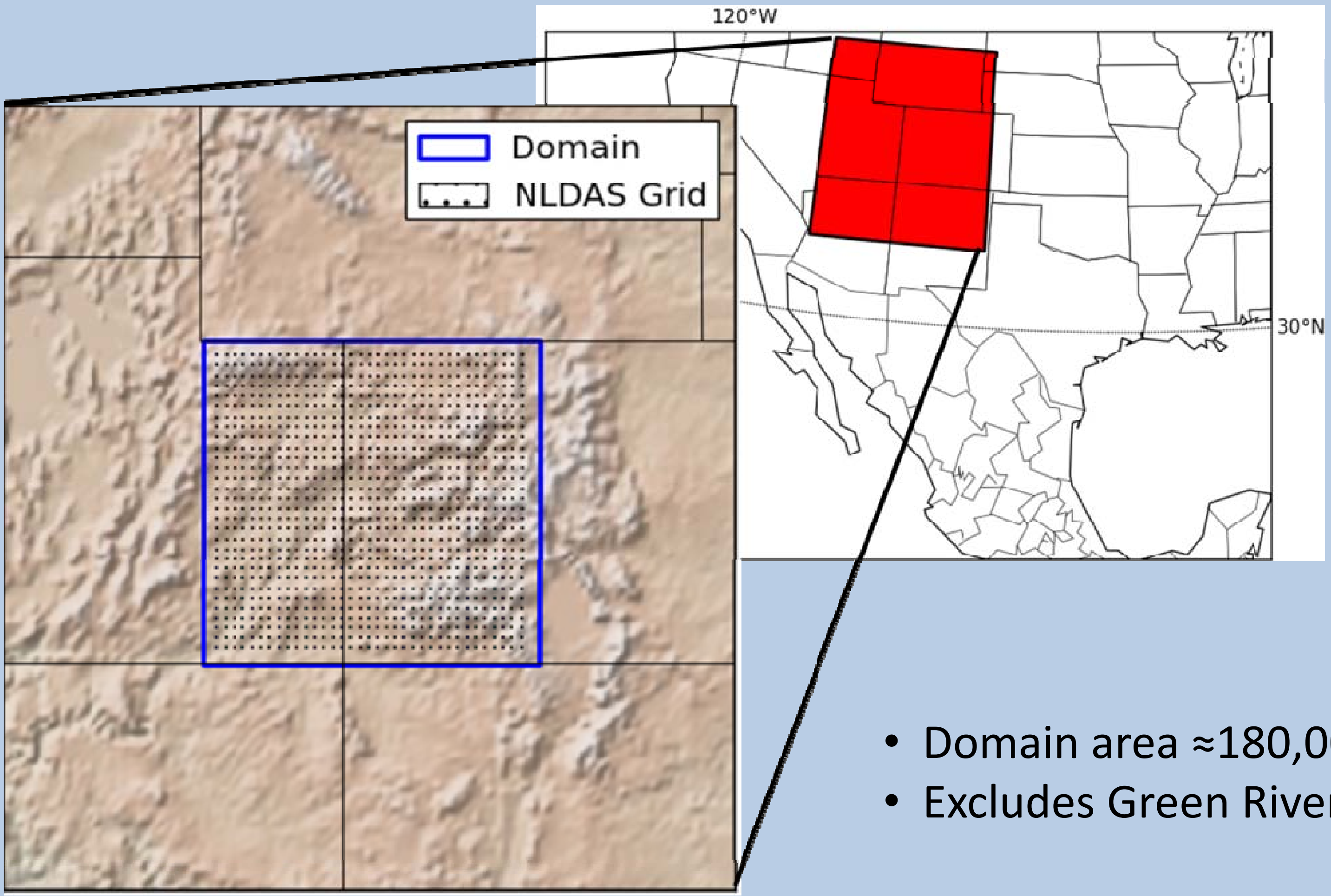
- Implement a snow evolution model for multiple years
- Think Big!
  - Most sublimation studies are on the order of 10-100 km^2
  - Study Domain ≈ 180,000 km^2
- Details
  - 250 m grid resolution
    - 1766 x 1666 grid points
  - Simulate blowing snow
  - Hourly time-steps

Model Description

- **SnowModel** – Spatially distributed snow evolution model (Liston et al., 2006)

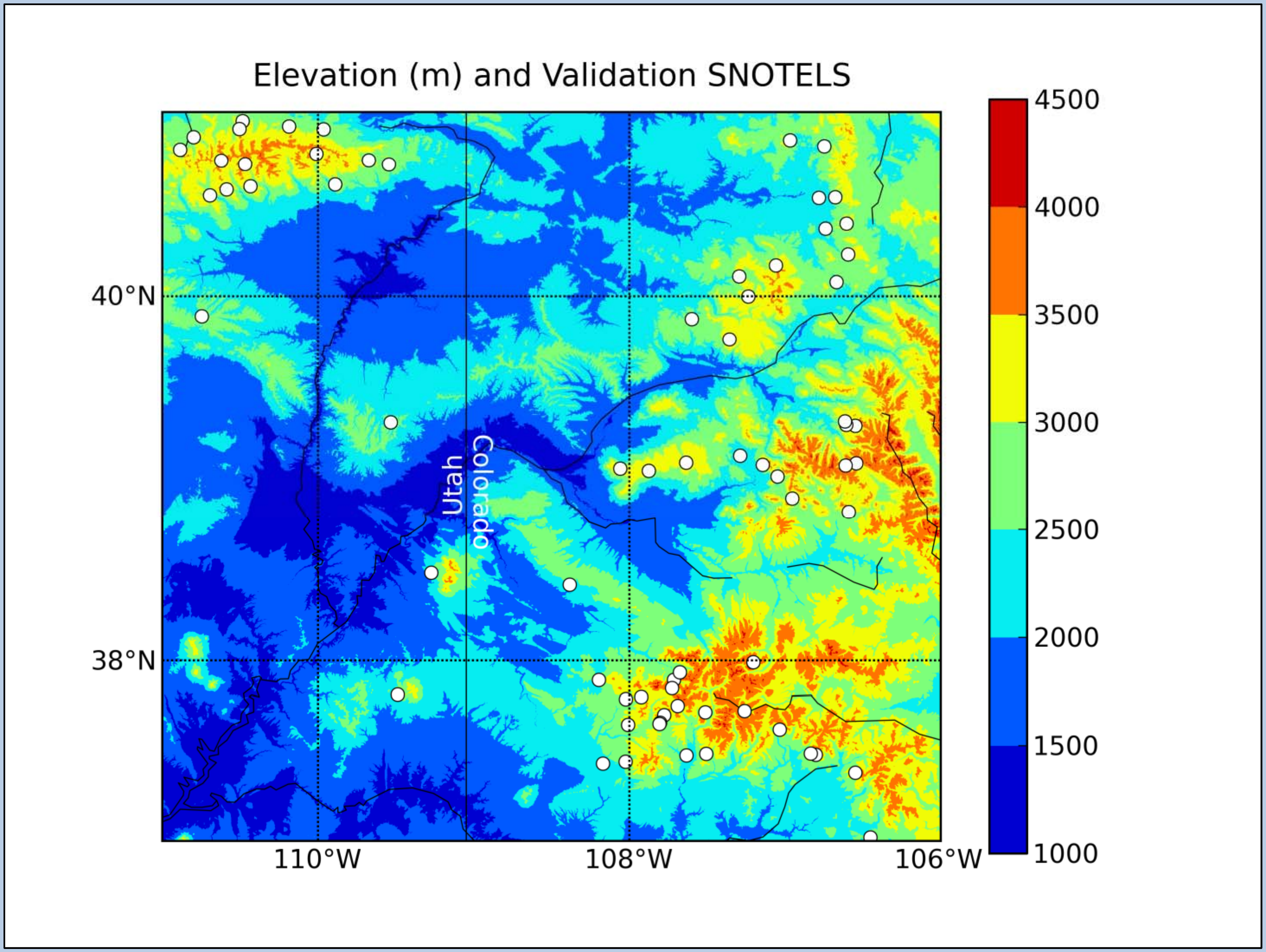
- Capable of simulating 3 components of sublimation
  - Static surface - Determined from calculations of latent heat flux from static snow surface
  - Canopy – Fully simulates sub-canopy environment and estimates sublimation loss from intercepted snow
  - Blowing snow - Transportation and 3D redistribution of snow
    - Sublimation of suspended snow particles

Study Domain



- Domain area ≈180,000 km^2
- Excludes Green River basin

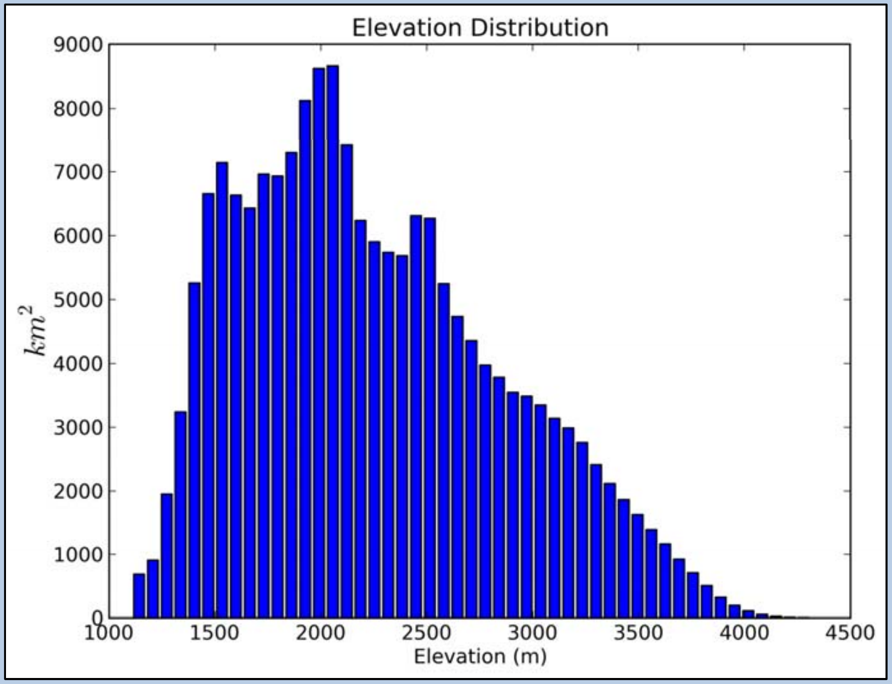
Elevation and Validation SNOTEL

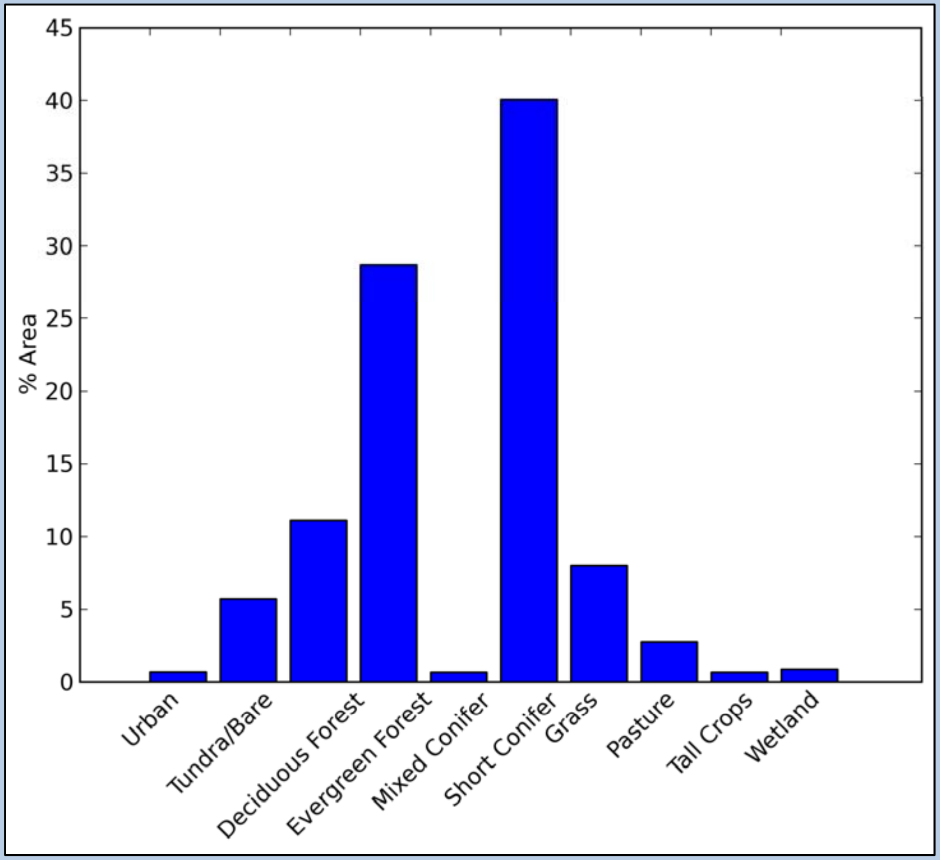


> 10 years of data

Study Domain

- Topography
  - National Elevation Dataset (Gesch et al., 2009)
- Land Cover Data
  - 2006 National Land Cover Dataset (Fry et al., 2011)





Forcing Data

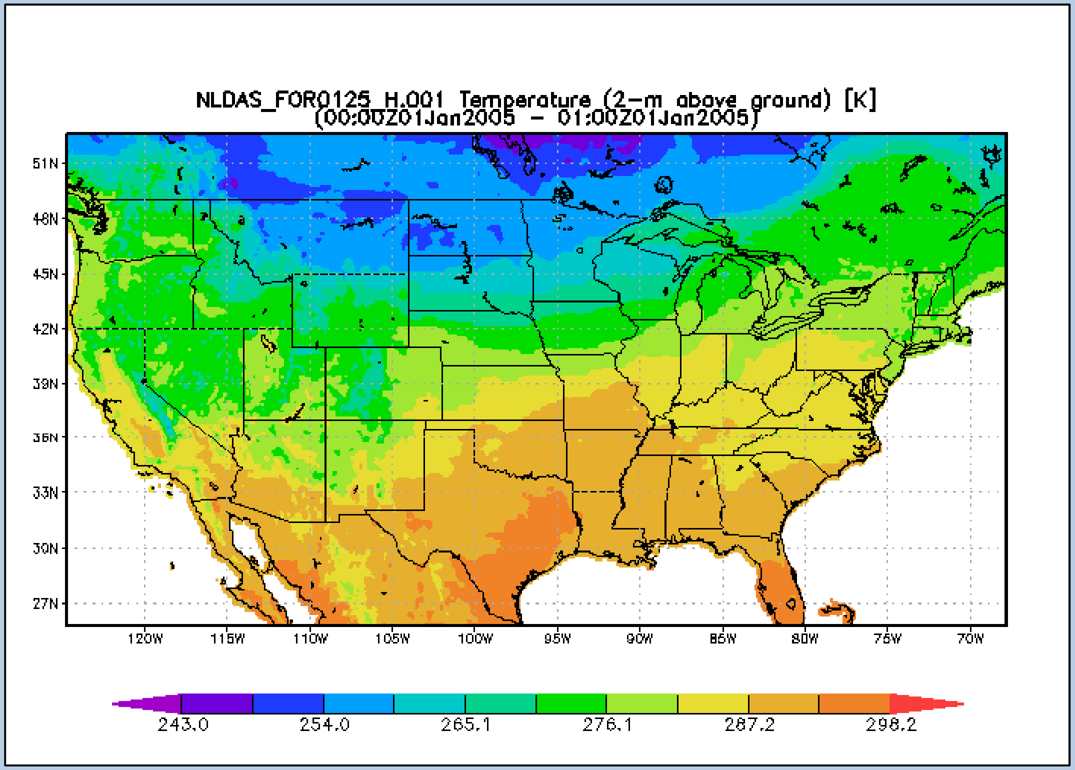
North American Land Data Assimilation Systems (NLDAS)

13 km gridded data, hourly output

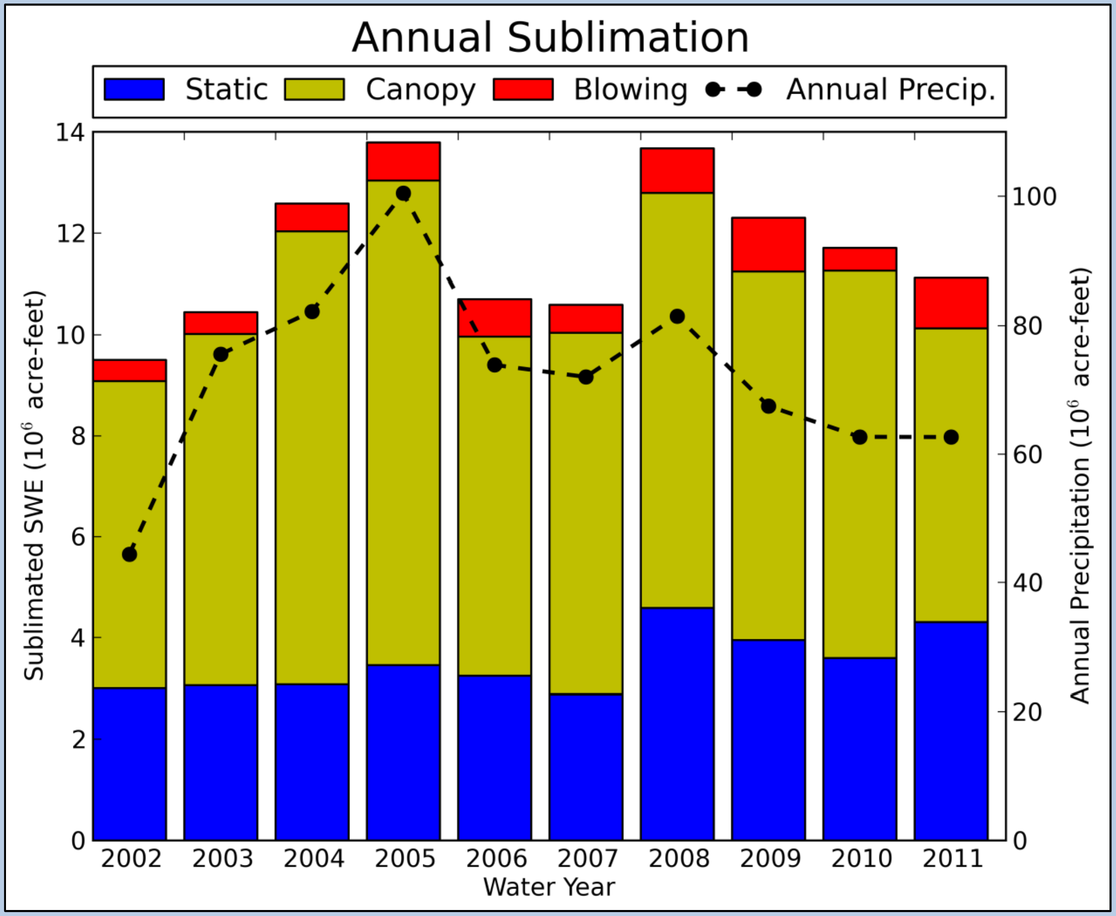
Non-precipitation fields derived from the North American Regional Reanalysis (NARR), downscaled to the hourly NLDAS domain

Precipitation data generated from

- Daily Gauge Precipitation
- NARR reanalysis
- Stage 2 precipitation data
  - WSR-88D Radar estimates

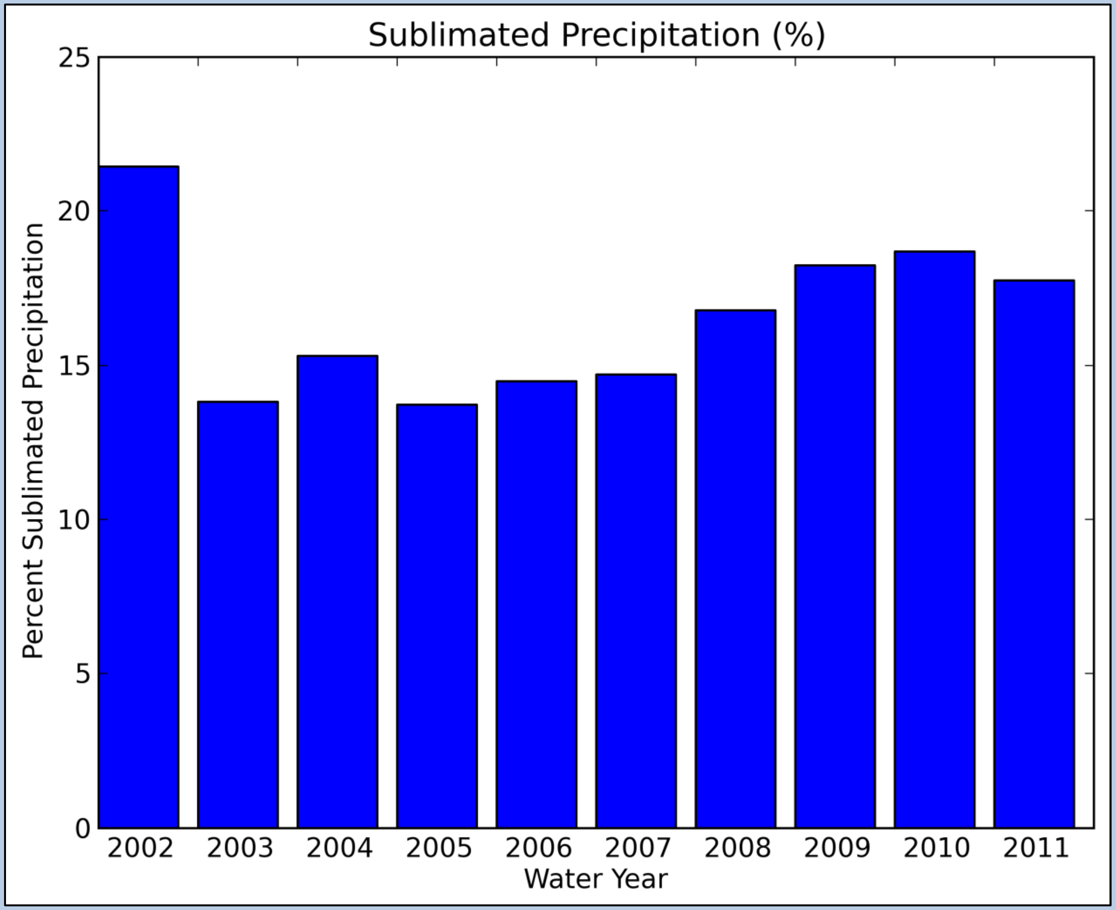


Results



Domain total sublimation from Oct., 1, 2001 through Sept., 30, 2011

Results



Domain total sublimated precipitation from Oct., 1, 2001 through Sept., 30, 2011

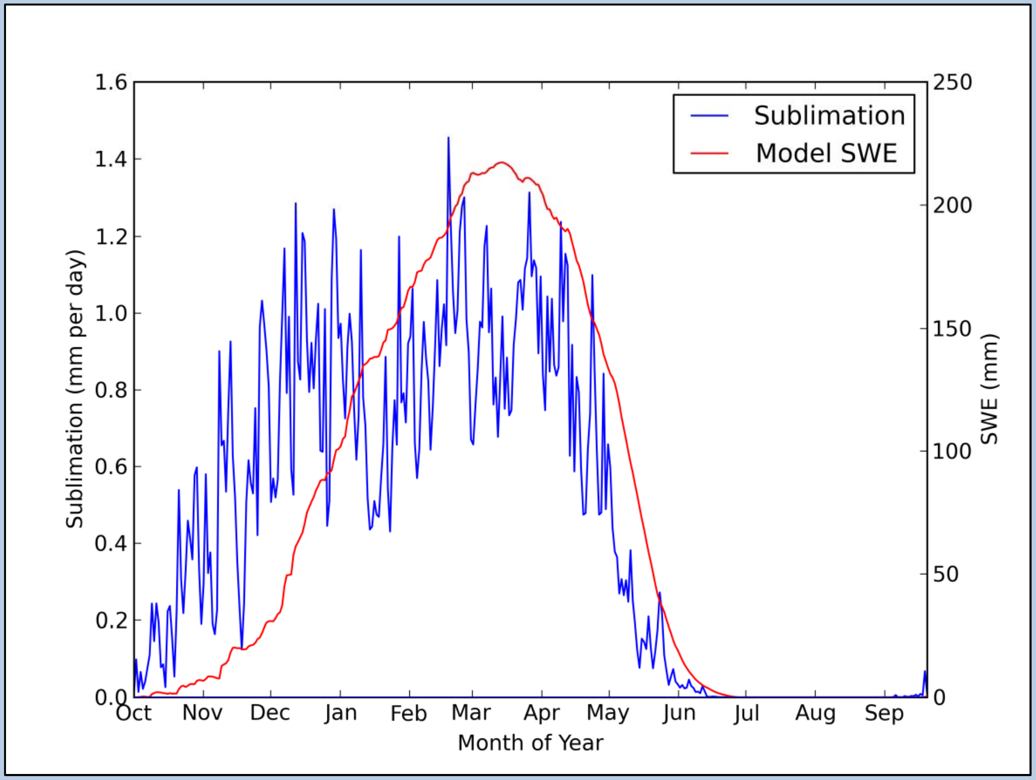
Temporal Variability

Sublimation rapidly increases with the increase in snow cover

Episodic in nature, with well defined 'events' of high sublimation (Hood et al., 1999)

Peaks during mid-winter when sub-freezing temperatures and strong winds drive moisture flux

Sublimation ends as snow-pack becomes isothermal and energy is used for melting



10 Year simulated average daily sublimation and 10 year average simulated SWE at 69 select grid cells corresponding to SNOTEL locations

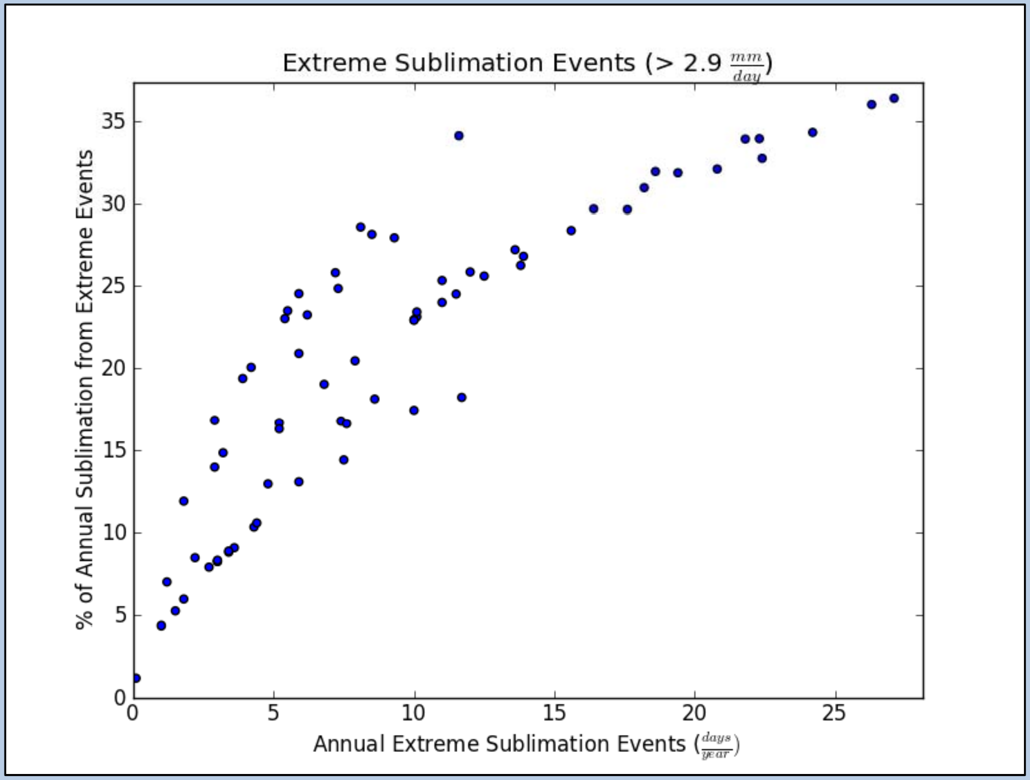
Temporal Variability

Extreme Events: Several periods of high sublimation occur throughout the year

Define an extreme sublimation event as one that exceeds the magnitude of 95% of daily sublimation amounts

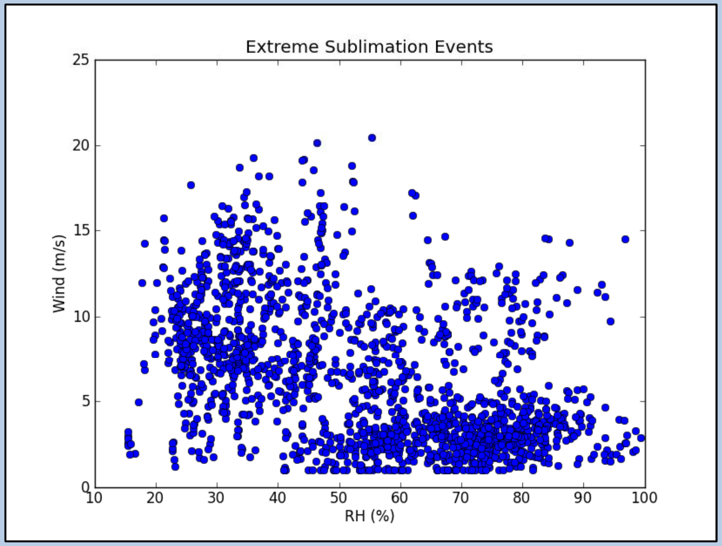
Interesting relationship between the amount of 'Event Driven' Sublimation and the number of Extreme Events

Note: No single forcing variable (e.g. wind, RH, ect.) strongly correlated with extreme events

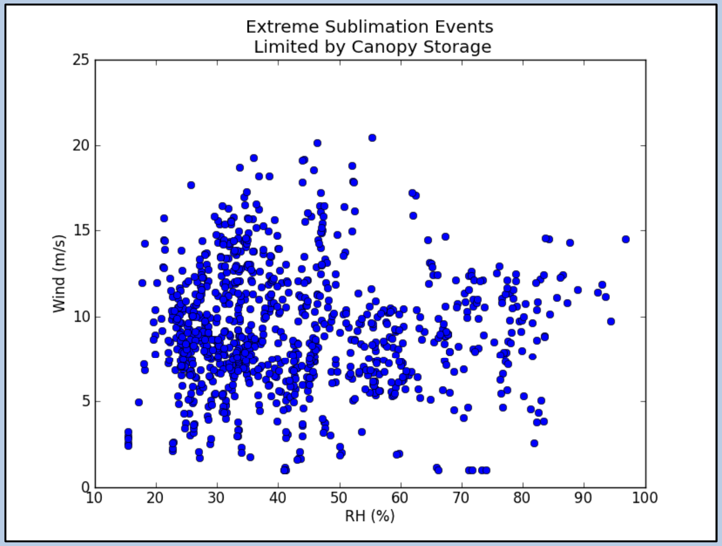


Percent of sublimation from extreme events vs. number of extreme events at 69 select grid cells corresponding to SNOTEL locations

Extreme Events: Hourly Analysis



Hourly extreme sublimation events from control domain



Extreme sublimation events when canopy storage was less than 1 mm

How is it possible to generate sublimation at high RH and low wind speeds?

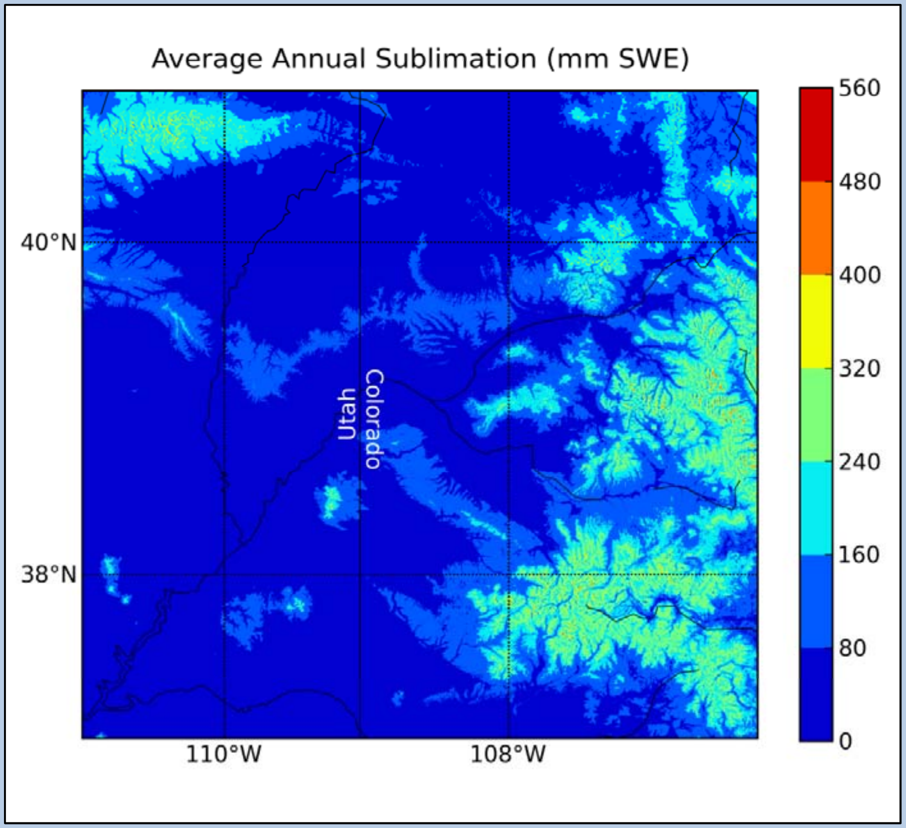
- Increase ventilation by increasing the surface area

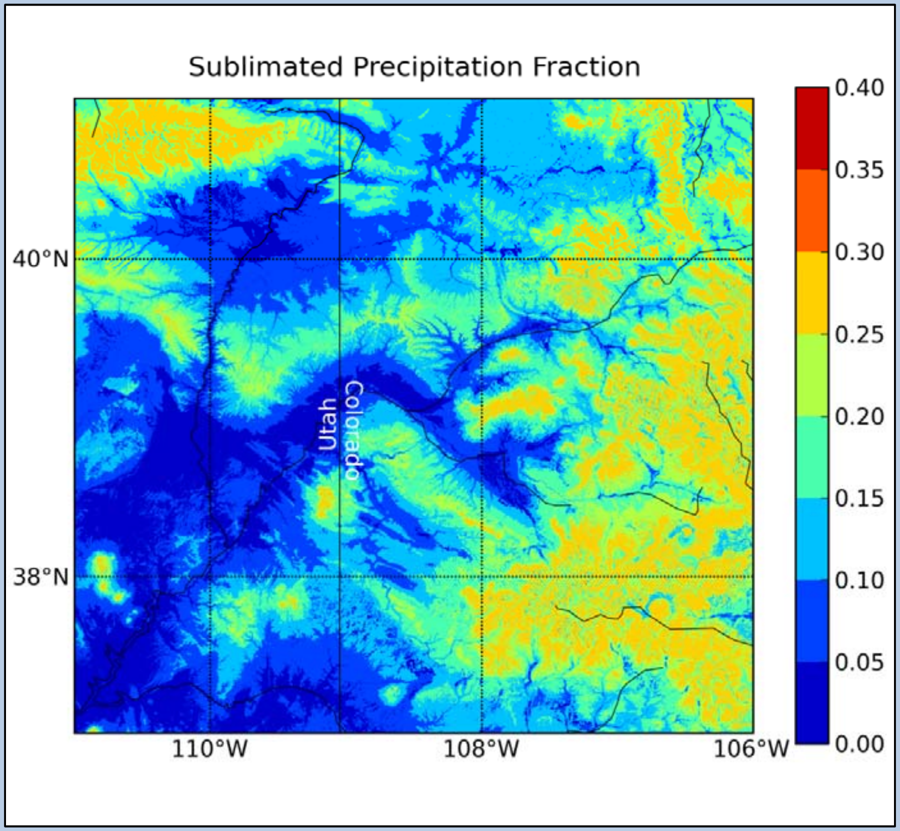
Extreme sublimation events require the correct combination of many factors

- Meteorological forcing
- Distribution of snow within different land cover types
- History of snow pack

<u>Event Driven Sublimation specific to each location based on land cover, exposure, ect..</u>

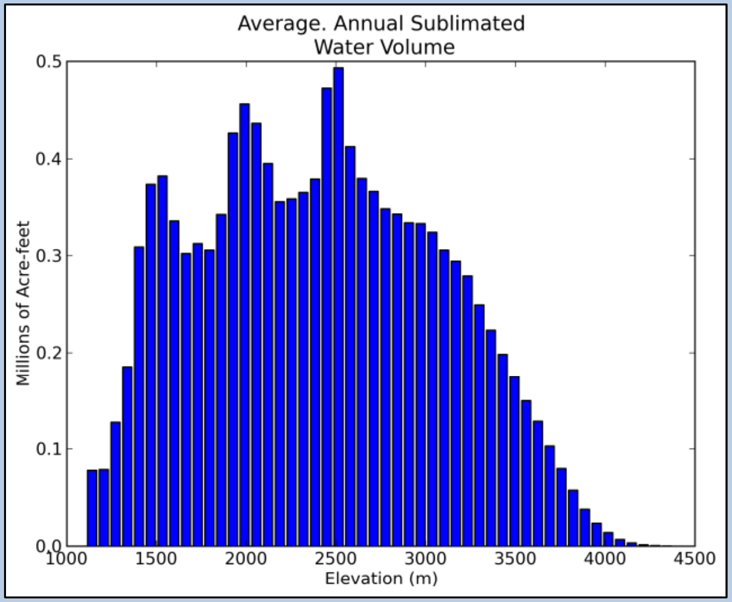
Spatial Variability

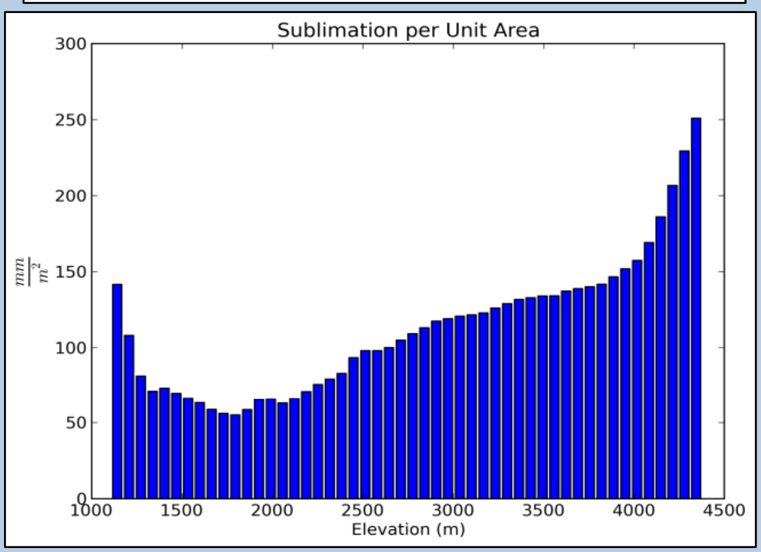




10 year simulation average, Oct. 1, 2001 through Sept. 30, 2011

Spatial Variability

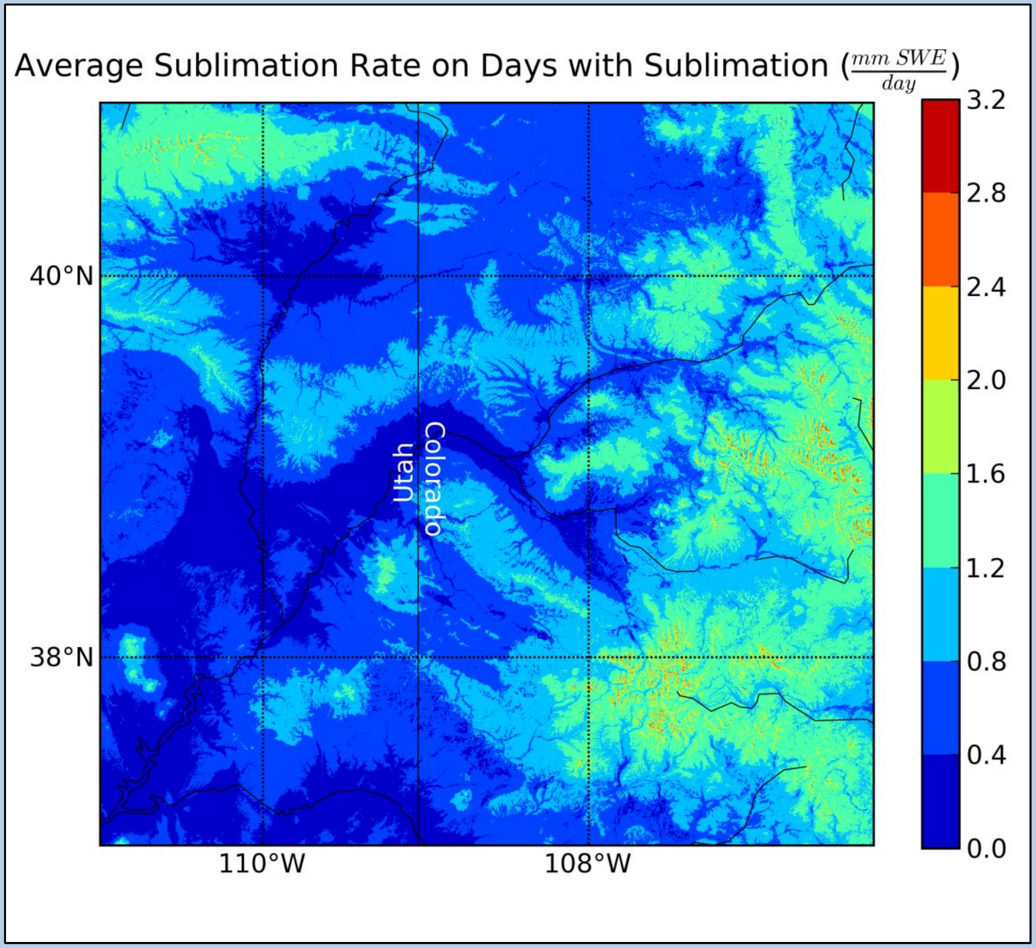




- Largest volume of sublimation occurs in middle elevations
  - Largest area
  - Dense forest canopy intercepts and sublimates snow
- Sublimation is most efficient at high elevations
  - Increased wind speeds
  - Blowing snow processes greatly increase sublimation amount

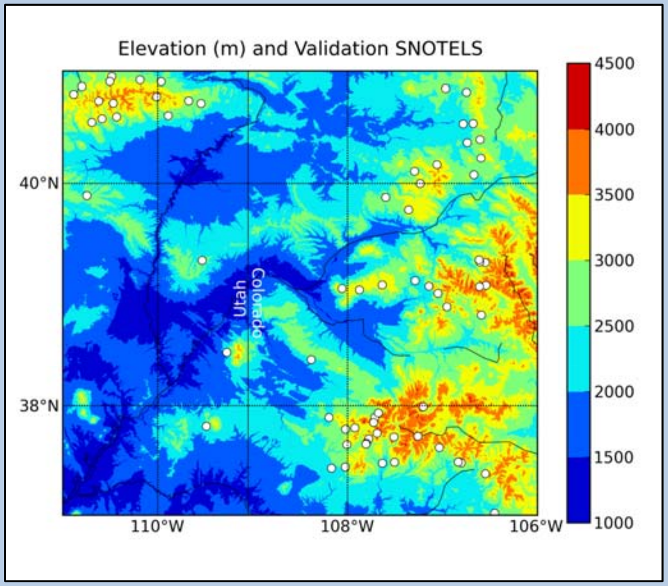
Top: 10 year average simulated sublimation
Bottom: 10 year average simulated sublimation per unit area

Spatial Variability



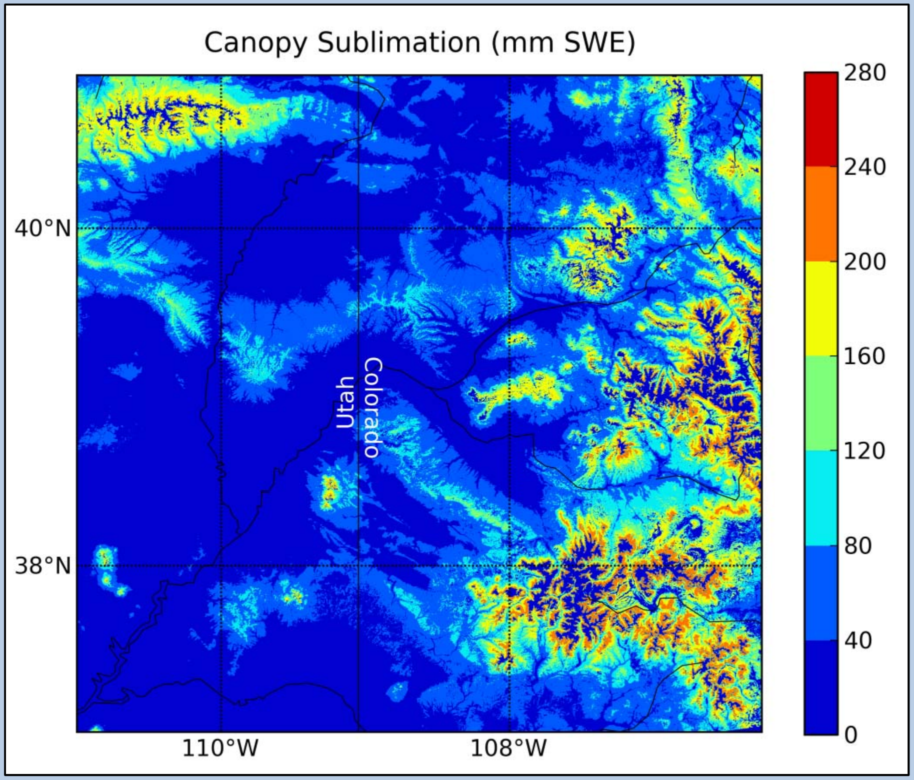
Calculated from daily sublimation totals from Oct. 1, 2001 through Sept. 30, 2011

Not only do high elevations accumulate the most snow, they are most susceptible to SWE loss via sublimation



Canopy Sublimation

- Accounts for the majority of sublimation in the simulations
- Results show 41 acre-feet km^{-2}
  - Compared to 37 acre-feet km^{-2} (Schmidt et al., 1992)
    - 10% more than Schmidt et al.



Annual average canopy sublimation from 10 years of simulations

Canopy Sensitivity

- How does changes in the Leaf Area Index (LAI) influence canopy sublimation

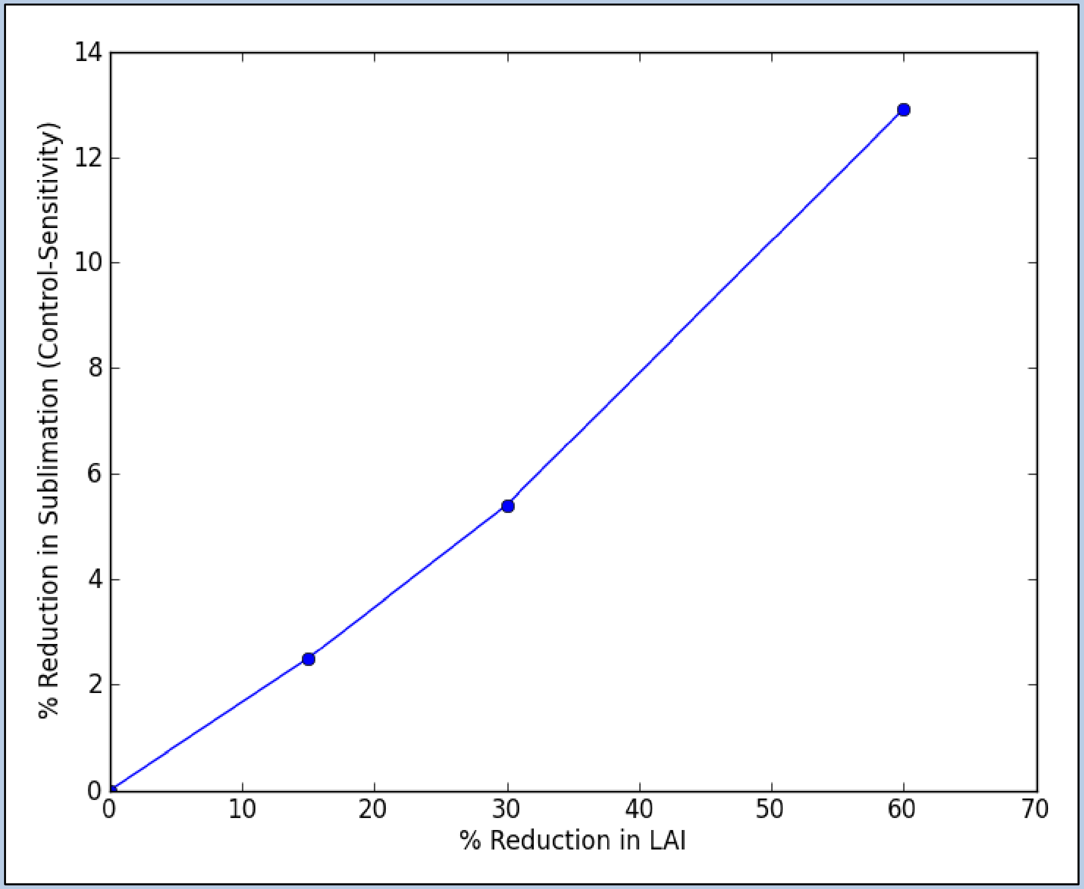
$$U_{subcanopy} = e^{\left(-(0.9\,LAI^*)\frac{\left(1-(0.6\,H_{veg})\right)}{H_{veg}}\right)} U_{grid}$$

  – Reduced LAI* increases sub-canopy wind speeds → greater sublimation
  – Reduced LAI* decreases interception → less canopy sublimation

Canopy Sublimation Sensitivity

Reduction in LAI values from Mountain Pine Beetle mortality as given by Pugh et al.

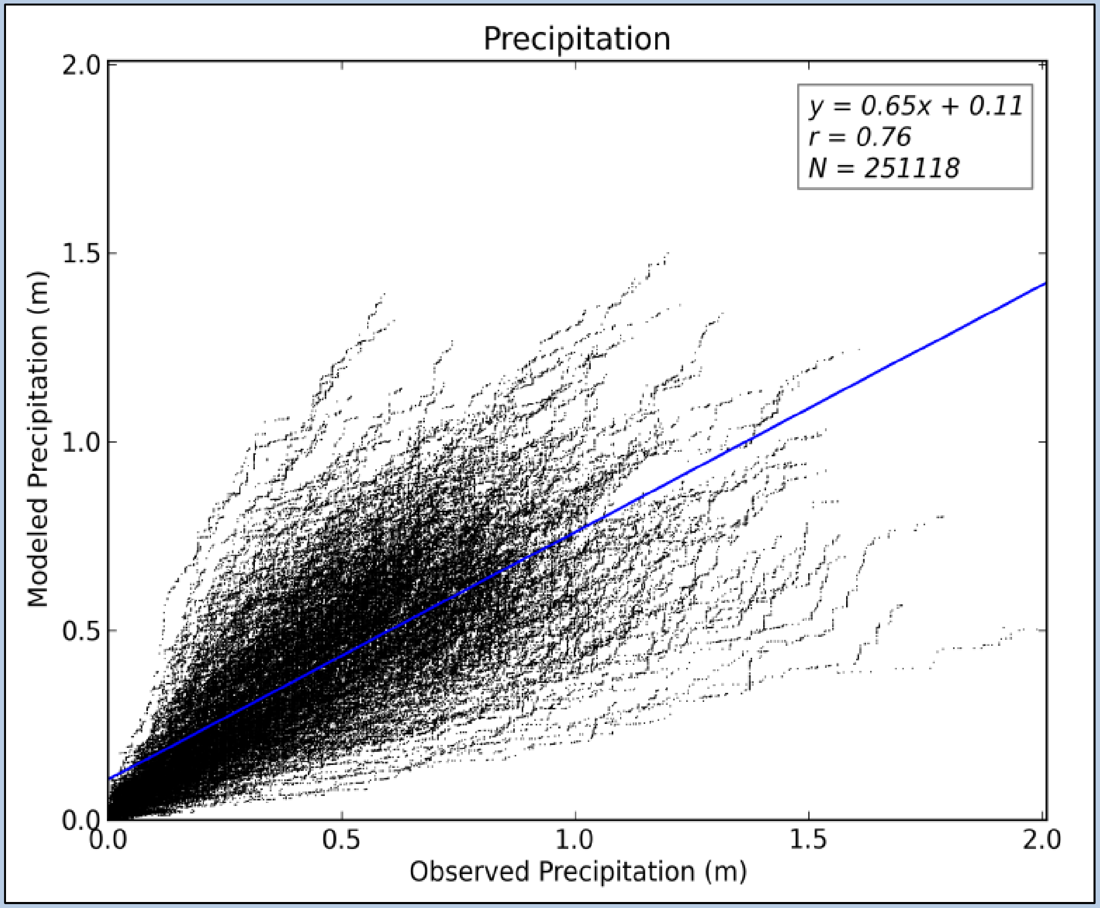
- 30% reduction in LAI*→5% reduction in total sublimation
    - Slight increase in static surface sublimation
    - Larger decrease in interception and canopy sublimation
    - Net decrease in sublimation water loss



Model Performance

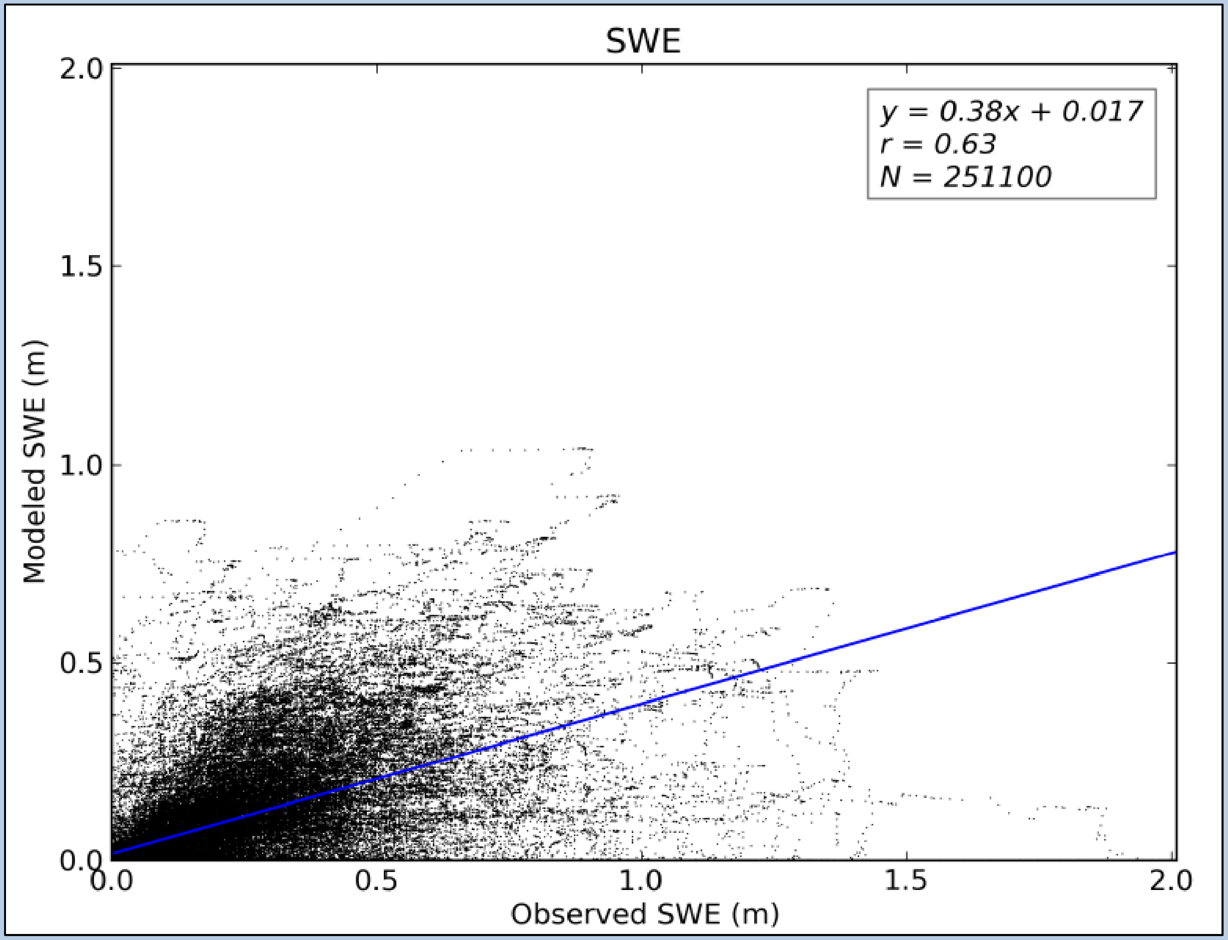
- Model under-estimated precipitation
  - Low bias noted in forcing data
- Snow accumulation was also under-estimated
  - Partially due to comparing grid-cell average to point measurements
  - Most notable in forested regions

Validation - Precipitation



Comparison of observed precipitation from 69 SNOTEL sites to model simulated precipitation for 10 years of simulations

Validation - SWE



Comparison of observed SWE from 69 SNOTEL sites to model simulated SWE for 10 years of simulations

Model Performance

- Snow accumulation
  - SNOTEL observations taken in forest clearings
    - Model provides grid-cell average over a forested area
    - Explains some snow accumulation errors
  - Could be due to inaccurate portrayal of precipitation phase
    - Not enough precipitation accumulating as snow
  - Canopy interception too high?
    - Unloading only a function of temperature

$$L_m = 5.8 \times 10^{-5}(T_a - 273.16)dt$$

Summary

- What did we learn?
  - Majority of sublimation occurs in forest canopy
    - Large area, large surface area from interception, available precipitation
    - Sublimation is very sensitive to land surface characteristics and vegetation
  - Sublimation efficiency increases with elevation
    - High elevations lose snow-pack water at the greatest rate, but cover a small area
      - Meiman and Grant, 1974

Summary Cont.

– Sublimation varies from year to year
  - Extent and longevity of snow cover
  - Vegetation type and land cover
  - Ambient meteorological conditions (wind, relative humidity)

– Sublimation is episodic

- Land surface models are computationally expensive to run!

Future Work

- Improve simulated SWE
  - Better precipitation forcing
    - Precipitation Amount
    - Precipitation Phase
- Better vegetation model
  - Need to address unloading as function of wind speed/LAI, not just temperature
  - More detailed vegetation types
- Increased resolution
  - Capture small scale heterogeneity
- Thermodynamic feedbacks
- **<u>Validation</u>**

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Thank You

The data used in this study were acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

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