Snow hydrology: remote sensing, ground measurements, modeling & applications

Roger Bales, Professor, University of California, Merced

Ground-based measurements
Remote sensing of snow
Data integration & modeling
UCM/SNRI faculty: Earth science & environmental engineering

Roger Bales - mountains, polar
Tom Harmon - groundwater, embedded sensors
Martha Conklin - catchment & riparian biogeochemistry
Peggy O’Day - geochemistry
Sam Traina - soil chemistry
Some other things that I do

• Biogeochemical response of seasonally snow-covered mountain catchments to climate variability & change
• Polar climate & atmospheric chemistry
  - Accumulation over the Greenland ice sheet from ice cores
  - Time history of reactive chemical species in Greenland & Antarctic cores
  - Effect of snow on atmospheric chemistry
• Regional climate applications & assessment
Other research: N cycle at Emerald lake

plant uptake

leached

denitrification

net mineralization

discharge

Meixner & Bales, 2002
Other research:

Polar atmospheric chemistry & glaciology
Other research:

Greenland accumulation map

Bales et al., JGR 2001
Other research: Polar atmospheric chemistry

Temperature driven degassing of $H_2O_2$ increases boundary layer $H_2O_2$ concentrations ~7 fold (Summit, Greenland)

- OH +70%
- HO$_2$ +50%

Increased oxidation capacity in (firn) air & fog

Hutterli et al., JGR 2001
Snow cover & climate change
Snow contributions to annual precipitation

Serreze et al., 1999

Most runoff & recharge comes from snowmelt
The questions
- How much snow is out there?
- How fast is it melting?
1. Measure snow water equivalent (SWE) distribution on the ground
2. Measure snow covered area (SCA) using remotely sensed data
3. Model snowmelt & snow cover depletion using energy balance data
4. Evaluate model performance
Current operational forecasting for seasonal water supply

- Precipitation forecast
- Empirical & regression methods
- Ground data
- Volume forecasts
- Decision making
Snow telemetry sites

- Point measurements of SWE
- Established as index sites
SWE distribution: SNOTEL bias

1. Del Norte Gauge
2. Colorado
3. New Mexico
4. Utah
5. Arizona
6. Wyoming

[Map showing the SWE distribution in the Western United States with numbered locations and state borders indicated.]
SWE distribution: SNOTEL bias

April: 2001

Slumgullion SNOTEL site, Colorado

April: 2002

Snow depth, cm

0 0.5 1 1.5

2km

Snow water equivalent

2001 2002 historical mean

Molotch et al., in preparation
April SWE at 4 sites

2001

2002

SNOTEL

survey
sdev & range
Optimal locations for measuring mean SWE

1. Slumgullion

April deviance = 0.61 cm

April and May deviance = 7 cm

4. Upper San Juan

April deviance = 2 cm

April deviance = 1 cm

5. Wolf Creek Summit

April deviance = 8 cm

6. Lily Pond

April deviance = 1 cm
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Resolution</th>
<th>Domain</th>
<th>Purpose</th>
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<tr>
<td>MODIS</td>
<td>moderate</td>
<td>full</td>
<td>snow cover</td>
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<tr>
<td>AVHRR</td>
<td>moderate</td>
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<tr>
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<td>AMSR-E</td>
<td>low</td>
<td>full</td>
<td>dry snow cover</td>
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<td>SWE correlation</td>
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Snow cover mapping process

- Scene evaluation:
  - degree of cloud cover
  - Coverage over study basins

- Build Cloud Masks using several spectral-based tests

- AVHRR bands

- Build thermal mask

- Geographic mask

- Composite cloud mask

- Topography

- Ground measured snow water equivalent

- AVHRR (HRPT FORMAT) pre-processed at UCSB [NOAA-12,14,16]

- Execute atmospheric corrections, conversion to engineering units using AVREF

- Execute sub-pixel snow cover algorithm: AVTREE using bands 1,2,3 (reflectance) as input

- Snow map algorithm output: mixed clouds, high reflective bare ground, & sub-pixel snow cover

- Application of cloud, thermal & geographic masks to raw AVTREE output

- Georegister image using GEOREG script

- Masked fractional snow covered area map

- Interpolate using hypsometric method

- Combine sub-pixel SCA and ground-based interpolated SWE to produce total basin water maps

- Total snow water equivalent map
Sierra Nevada 1998
SCA animation

Red: clouds
Black: no snow
Greyscale: SCA

R. Davis, CRREL
Mar % SCA - 2000 ApR

1-25

26-99
Snow products, April 6, 1999

Total snow water equivalent

$\text{SCA} \times \text{SWE}_g = \text{Total SWE (m/km}^2\text{)}$

Legend:
- 0
- 0.001 - 0.2
- 0.2 - 0.4
- 0.4 - 0.6
- 0.6 - 0.8
- 0.8 - 1
- 1 - 1.2
- No Data
Rio Grande SCA & SWE: average for March

Red is more snow, white is no snow
Energy balance modeling scheme

Data cube with variables:
- SWE
- Albedo
- SCA
- Incident solar
- Longwave
- Air temp
- Relative humidity
- Wind speed

Outputs:
- Energy balance
- LSM
- SWE & SCA
- Pixel by pixel runoff potential
- Basin potential runoff

Inputs:
- Time
- Vegetation
- Topography
- Soils
Tokopah basin: 19.1 km²
2629 – 3487 m.a.s.l.

Topaz lake basin: 1.5 km²

Emerald lake basin: 1.2 km²

stream gage
**SWE distribution: field methods**

- **Snow depth**
  - 6 people
  - 8 days
  - 400+ measurements

- **Snow density**
  - 11 measurements
SWE distribution: binary regression tree

Snow depth, cm

- elevation
- solar radiation
- wind exposure
- vegetation density
- slope

Molotch et al., 2004
Approach: melt flux modeling

\[ \text{melt flux} = (R_n \times m_q + T_d \times a_r) \times SCA \]

Where:

- \( m_q \) = Energy-to-water depth conversion, 0.026 cm W\(^{-1}\) m\(^2\) day\(^{-1}\)
- \( a_r \) =
  \[
  m_q \rho C_h k^2 (\ln z / z_0)^{-2} u \left[ C_p + RH_a \frac{L}{2 \rho} \left( \frac{d*e}{dt} \right) \right]_0 - \frac{(1 - RH_a) L}{T_a \rho} e^* \]

- net radiation > 0
- degree days > 0
- Snow covered area
Estimating distributed daily net radiation

\[ R_n = S_{\downarrow} \times (1 - \alpha) + L_n \]

Where \( L_n = \) net longwave, estimated from air temp. & RH
Spatial variability of snow surface albedo

May 05

May 21

June 18, 1997

\(\alpha_{\text{mean}} = 0.664\)

age = 11 dy

\(\alpha_{\text{mean}} = 0.693\)

age = 1 dy

\(\alpha_{\text{mean}} = 0.686\)

age = 4 dy
Approach to estimating albedo

No update

With update

AVIRIS interpolation

USACE

albedo

snow age, days

AVIRIS interpolation

USACE

time step

0 25 50 75 100
Modeled snow water equivalent (SWE) and snow covered area (SCA)

\[ SWE_j = SWE_0 - \sum_{j=1}^{n} M_j \]

- initial SWE
- daily snowmelt
Spatial snowmelt modeling: albedo parameterization

day of year: 112

empirical  observed  AVRIS

snow:  no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 125

empirical  observed  AVRIS

snow:  no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 128

empirical  observed  AVRIS

snow:  no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 141

empirical  observed  AVRIS

snow:  no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 160

empirical    observed    AVRIS

snow:  no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 176

empirical  observed  AVRIS

snow: no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 192

empirical  observed  AVRIS

snow:  no snow:
Spatial snowmelt modeling: albedo parameterization

day of year: 208

empirical  observed  AVRIS

snow:  no snow:
Index model evaluation: snowmelt timing

- $r^2$ of 0.59 vs. 0.73 using USACE vs. AVIRIS albedo
- Modeled peak 18 vs. 2 dy before observed peak
Index model evaluation: snowmelt magnitude

modeled - observed SWE

Improvement greatest in areas dominated by solar component

SWE difference, cm

-250 -105 -35 35 105 240

index-USACE  index-AVIRIS
Physical vs. index model: snowmelt timing

- $r^2$ of 0.62 vs. 0.73 using USACE vs. AVIRIS albedo
- No improvement in modeled peak using physical model
Index model evaluation: snowmelt magnitude

\[ \text{SWE}_j = \text{SWE}_0 - \sum_{j=1}^{n} \text{M}_j \]

modeled - observed SWE

index-USACE  index-AVIRIS  physical-USACE

SWE difference, cm

-250   -105  -35   35  105   240
Summary

Better snow estimates through better data
- new ground-based SWE measurements
- satellite SCA & albedo
- energy balance modeling

Tokapah example
- Timing improved: hydrograph $r^2$ increased from 0.59 to 0.73
- Magnitude error decreased from 36% to 2%
Snow: the way forward

demonstrate usefulness of RS products to research & applications communities
  - hydrologic forecasts
  - water resources decisions
  - biogeochemistry
create new demands for RS snow products within water resources community
integrate ground & space measurements for SWE estimation
enhance dialog between research & applications communities on topics of snow measurement & modeling
plot/hillslope

soil moisture
SWE distribution
micromet
fluxes

Water balance
snow distribution
\[\text{melting timing}\]
partitioning
infiltration
runoff
ET
recharge

basin
remote sensing
SCA
albedo
vegetation
ground/RS
SWE
precip
radiation
EB
topography
ground
soil moisture
bedrock
soils
Follow-up Gin Flat SWE studies