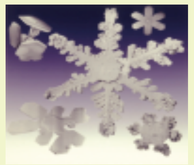
Airborne Snow Observatory:
A Research Partnership between
NASA - JPL and USDA - ARS
Northwest Watershed Research Center

Northwest Watershed Research Center
USDA
Agricultural Research Service

A Comprehensive Snow Density Model for Integrating Lidar-Derived Snow Depth Data into Spatial Snow Modeling



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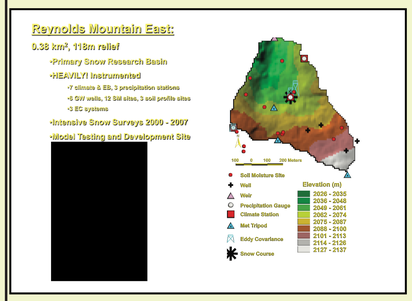
Transforming Snow Science

z_s *from Remote Sensing*

ρ_s *from modeling*

$$SWE = z_s \times \rho_s$$

The Holy Grail of Snow Hydrology



Owhyee Mountains, Idaho

RME: 1 snow pillow site, 18 years of hourly data for both z_s and SWE.

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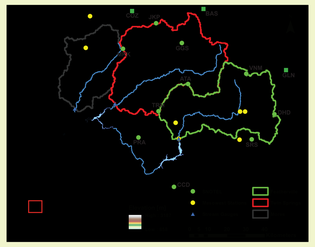
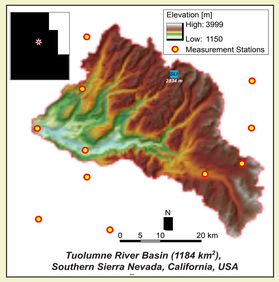


Boise River Basin (6977 km^2), Sawtooth Mountains, Idaho

13 NRCS SNOTEL sites, 15 years both z_s and SWE.



Tuolumne River Basin (1188 km), Southern Sierra Nevada, California;

ASO test basin, 2013 - 2017.
2015 - lowest snow year ever;
2017 - highest snow year ever;

1 viable SWE measurement site (Slide Canyon, 2834 m) with co-located z_s in 2017

[redacted]

Upper San Joaquin, March 17, 2017

Shasta Lake, 2014 & 2015

Oroville Dam Spillway March 3, 2017

[redacted]

Modeling Snow Density

Mechanisms that determine Snow Density:

0) Temperature and Humidity conditions during snowfall

1) Mechanical Compaction due to Wind
2) Compaction and Settling due to Temperature
3) Compaction due to Snow Load or Overburden
4) Compaction due to Liquid Water from Melt or Rain

Equations derived from experimental work done 50 years ago:

Foundational References:

Yosida, Z., et al., 1963, Physical properties of snow, in Ice and Snow, W.D. Kingery, ed., MIT Press, Cambridge, Mass, 485 – 527. (Note that the original document was developed at Hokkaido University in 1955)

Mellor, M., 1964, Properties of Snow, Cold Regions Science and Engineering Monograph III-A1, Cold Regions Research and Engineering Laboratory, Hanover, NH, 105 pp.

Kojima & Kenji, 1967, Densification of Seasonal Snow Cover, in Physics of Snow and Ice, Proceedings of International Conference on Low Temperature Science -- Sapporo, 1(2), Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, 929 – 952.

Anderson, E.A., 1968, Development and testing of snow pack energy balance equations, Water Resources Research, 4(1), 19 – 37.

Mellor, M., 1975, A review of basic snow mechanics, IAHS monograph.

Colbeck et al., 1978, The compression of wet snow, CRREL Report 78-10, 25pp.

Herron, M., and C. Langway Jr., 1980, Firn densification: An empirical model, Journal of Glaciology, 25(93), 373 – 385.

Salm, B., 1982, Mechanical properties of snow, Reviews of Geophysics and Space Physics, 20(1), 1 – 19.

Davis, R., J. Dozier, E. LaChapelle and R. Perla, 1985, Field and laboratory measurements of snow liquid water by dilution, Water Resources Research, 21(9), 1415 – 1420.

Synthesis References:

Anderson, E.A., 1976, A Point Energy and Mass Balance Model of a Snow Cover, NOAA Technical Report NWS 19, 152 pp.

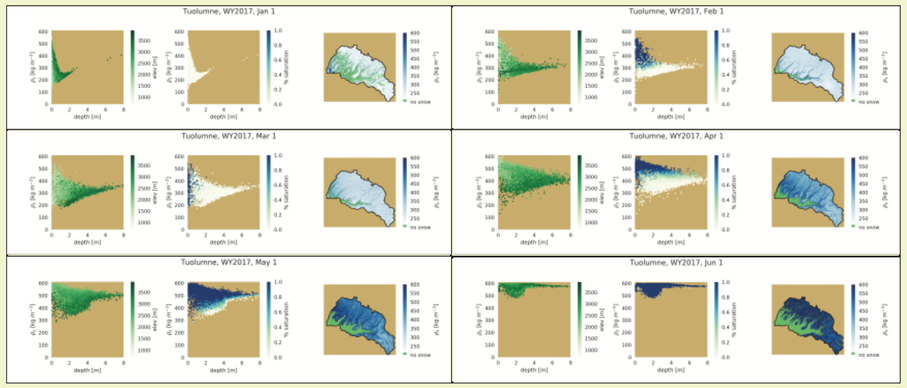
Yamazaki, T., J. Kondo, T. Sakuraoka and T. Nakamura, 1993, A one-dimensional model of the evolution of snow-cover characteristics, Annals of Glaciology, 18, 22 – 26.

Shapiro, L., J. Johnson, M. Sturm and G. Blaisdell, 1997, Snow Mechanics: Review of the state of knowledge and applications, CRREL Report 97-3, 40 pp.

Oleson, K.W., & others, 2013, Technical Description of version 4.5 of the Community Land Model (CLM), NCAR Technical Note, NCAR/NT-503-STR, 434 pp.

Model Behavior:

Density vs Depth & Elevation, Depth & Liquid Water Content, & Basin Density Distribution



Tuolumne River Basin, 50m Resolution, 2017 Snow Season

Snow Density Model Validation:

iSnobal Simulation vs Measured:

Model Fitting Statistics:
ME - Nash-Sutcliffe Model Efficiency
MBE - Mean Bias Difference
Mean Value
RMSD

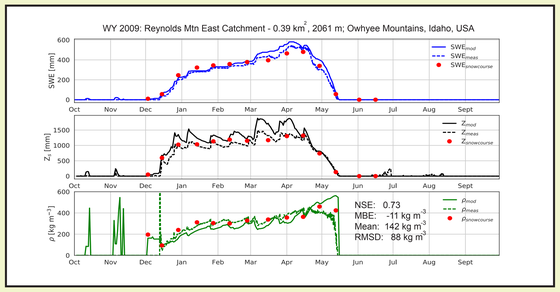
Snow Density Model Fitting Statistics

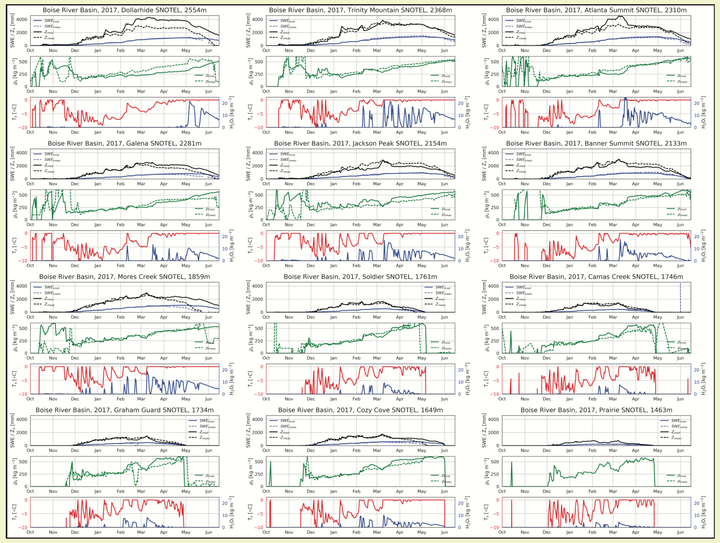
Watershed	Site & Elevation	ME:	MBE:	Mean:	RMSD:
Reynolds Creek, Idaho (WY2009)					
	RME (2043m):	0.86	+2	311	62
Boise River Basin, Idaho (WY2017)					
	DHD (2554m):	0.74	-57	339	84
	TRM (2368m):	0.87	-9	353	49
	ATA (2310m):	0.88	-15	348	44
	GLN (2281m):	0.92	-6	312	43
	JKP (2154m):	0.83	+47	334	67
	BAS (2133m):	0.93	+11	346	48
	MRK (1859m):	0.98	+2	348	27
	SRS (1761 m):	0.96	-3	312	35
	CCD (1749m):	0.92	+34	312	51
	GGS (1734m):	0.88	+31	348	58
	COZ (1649m):	0.94	+20	334	42
Tuolumne River Basin, California (2017)					
	SLI (2804m):	0.98	-7	373	27
Average over 13 sites		0.90	+5	336	49

Reynolds Creek Experimental Watershed

RCEW - RME

2009 Snow Season; Multi-Sensor Field Experiment





Boise River Basin, 2017 Snow Season

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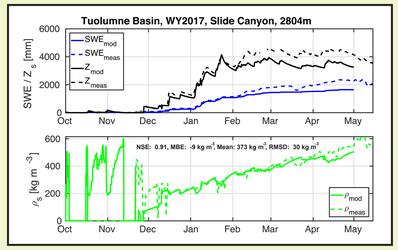

Tuolumne River Basin, 2017 Snow Season