Cold regions hydrology

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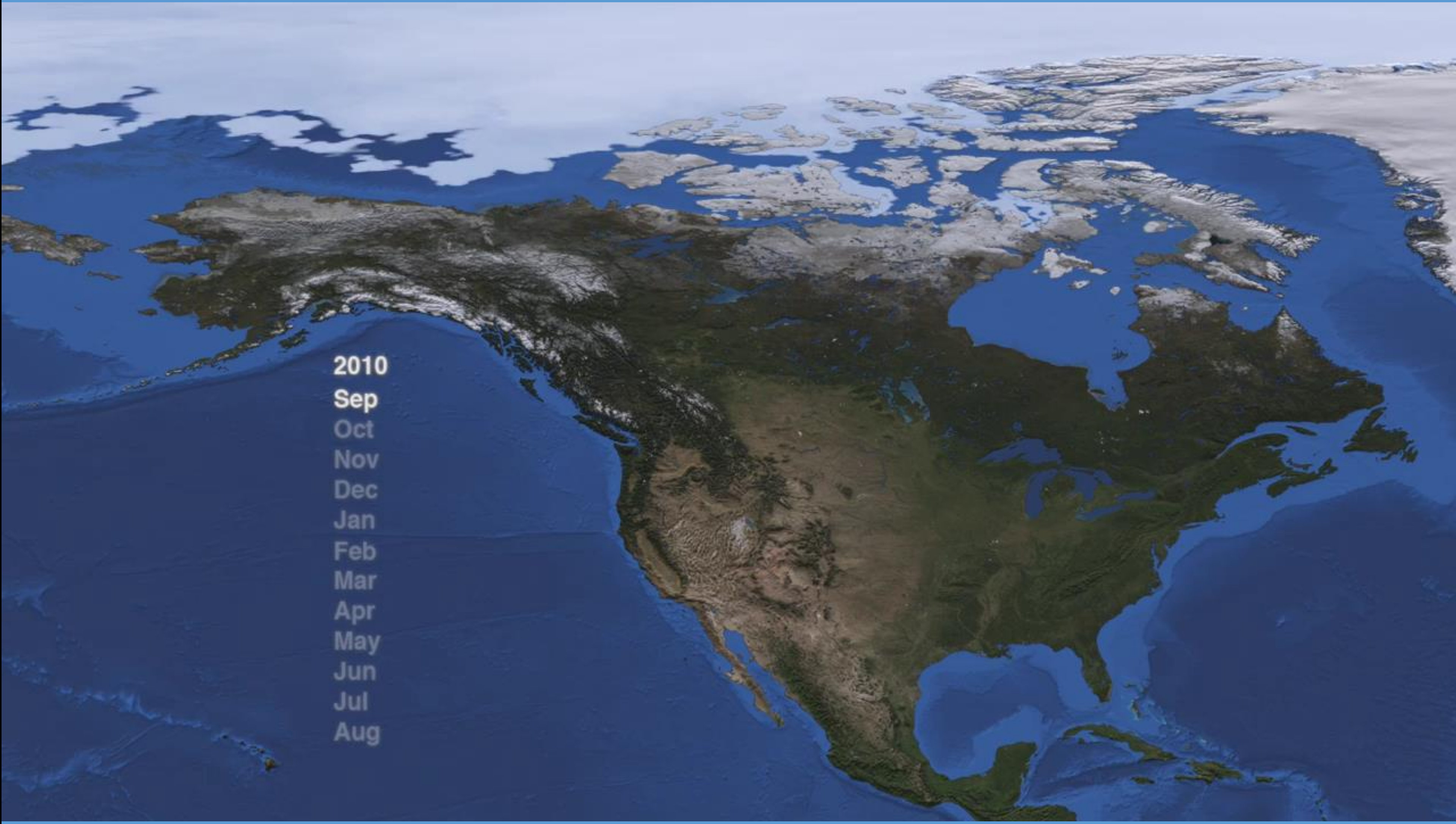
3. Snow processes

Learning Objectives

You should be able to:

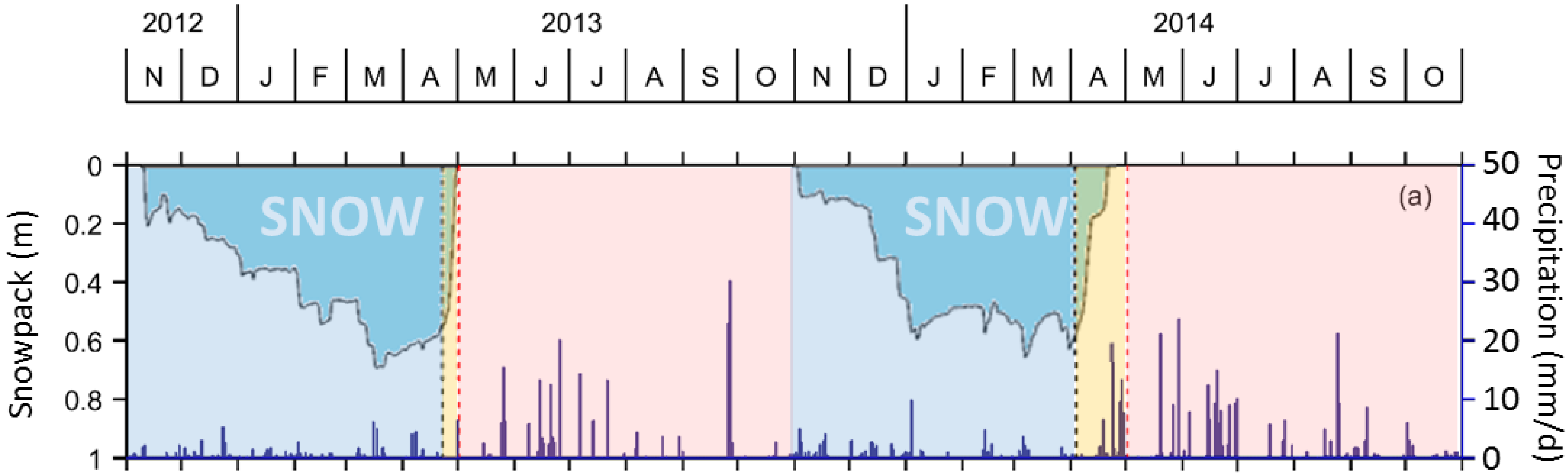
- Understand that snow is a porous medium
- Use snow depth, density and SWE to characterise the snowpack
- Explain how snow is measured
- Describe snow accumulation and ablation processes
- Describe the energy balance of snow and why it is important
- Calculate snowmelt using degree-day and energy balance methods

NASA/Goddard Space Flight Center Scientific Visualization Studio



NASA SVS: https://svs.gsfc.nasa.gov/3899

Snow seasonality



- Season 1: Snow accumulation (long and cold, slow hydrology)
- Season 2: Snowmelt (short and wet, dynamic hydrology)
- Season 3: Summer/growing season (variable)
- Northern-hemisphere “water year” typically Oct-Sept.

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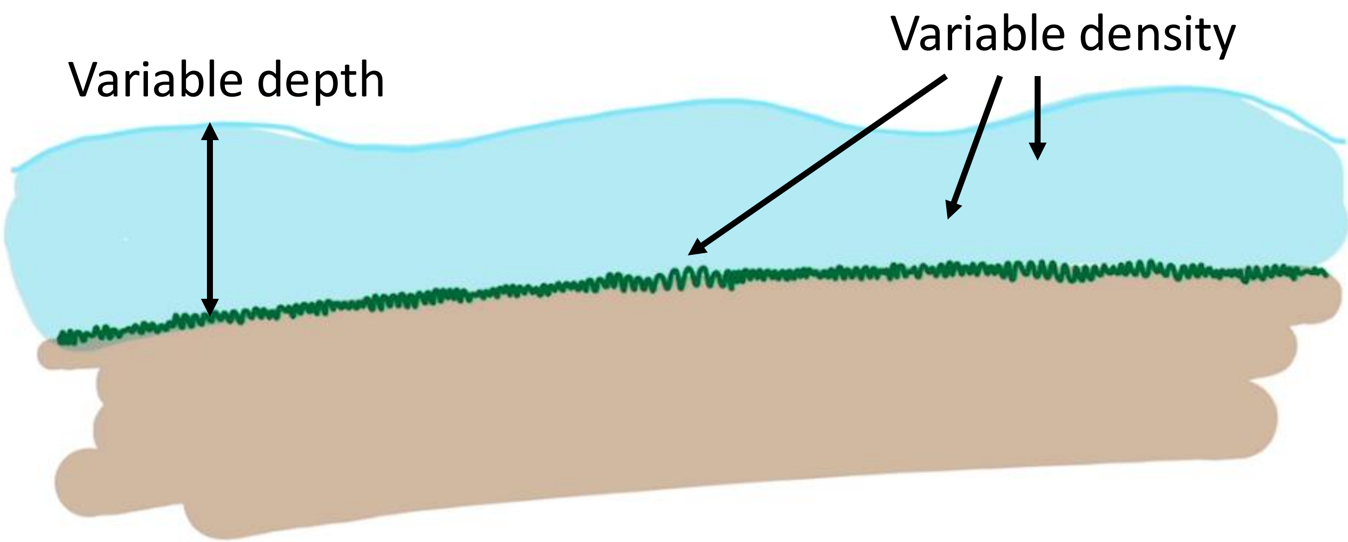
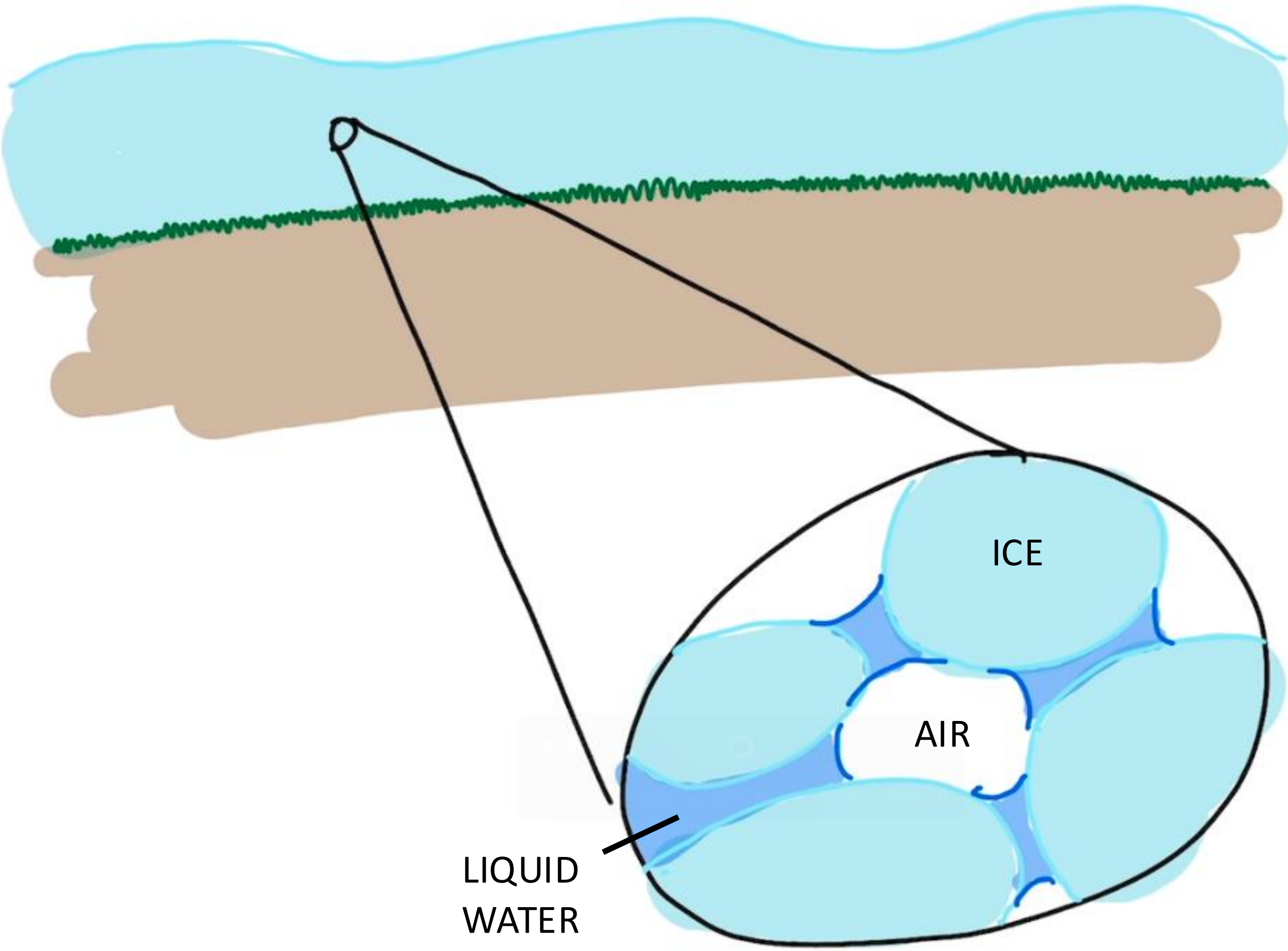
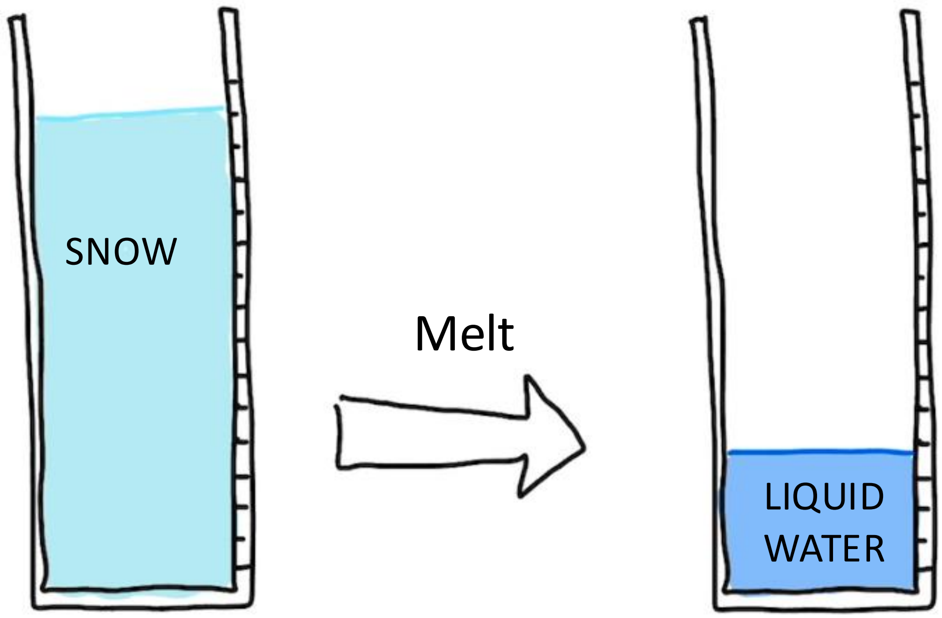
What is snow?



Snow is a porous medium



Snow water content

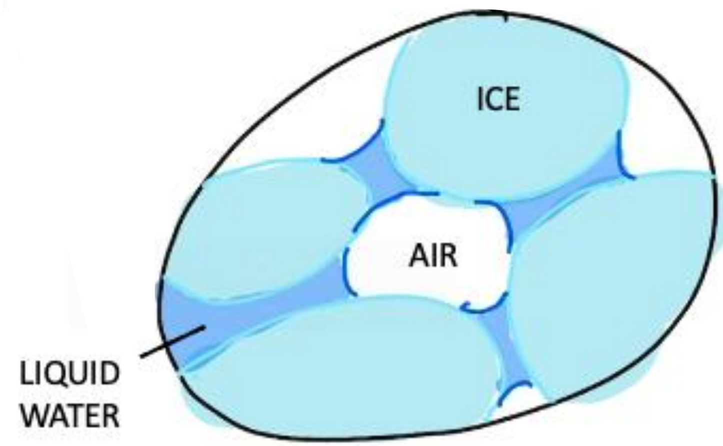


Mass, M_S (g)	=	Mass, M_L (g)
Depth, z_S (m)	>	Depth, $z_L = SWE$ (m or mm)
Density, ρ_S (kg/m^3)	<	Density, ρ_L= 1000 kg/m^3

Snow density

Recall density is the mass per volume, so

$$\rho_S = \frac{M_S}{V_S}$$



As we saw, snow is a porous medium, so

$$M_S = M_L + M_I + M_A$$

and

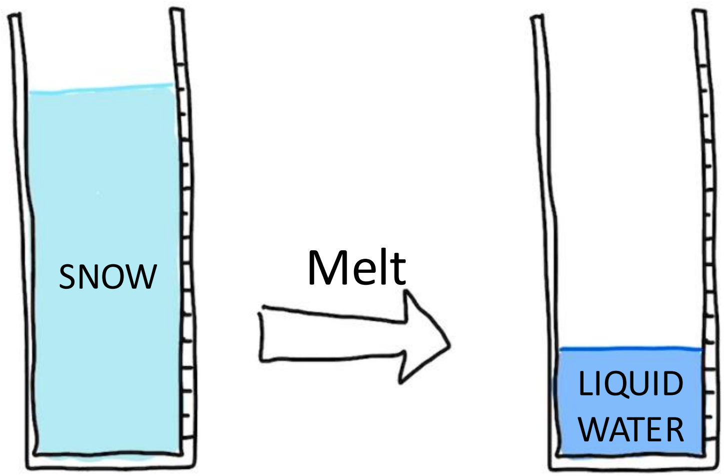
$$V_S = V_L + V_I + V_A$$

Note that

$\rho_L = \frac{M_L}{V_L} = 1000$ kg/m^3 $\qquad$ $\rho_I = \frac{M_I}{V_I} = 918$ kg/m^3

Because of the presence of air (negligible mass, large volume), the density of snow is much lower, $\mathbf{100 \le \rho_S \le 600}$ **kg/m³** (typical range)

Snow water equivalent, SWE



Consider, before and after melt, mass is conserved:

$$M_S = M_L$$

$$\rho_S V_S = \rho_L V_L$$

$$\rho_S z_S A = \rho_L z_L A$$

Cancel areas, and rearrange:

$$SWE = z_L = \frac{\rho_S}{\rho_L} z_S$$

So SWE is somewhere between 0.1 – 0.6 times the snow depth.

Snow density profile

As the snowpack goes through warm (melt) and cold (re-freeze) cycles over the winter, ice is redistributed over the profile.

Layers of higher/lower density can develop in the profile.

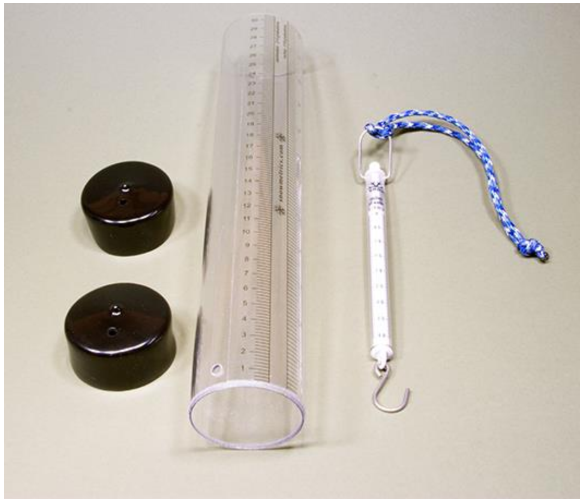
This is especially the case in deep snowpacks.

In this case, to calculate SWE you need to account for how density varies with depth.

USGS: https://www.usgs.gov/media/images/scientist-deep-snow-pit

Snow surveying

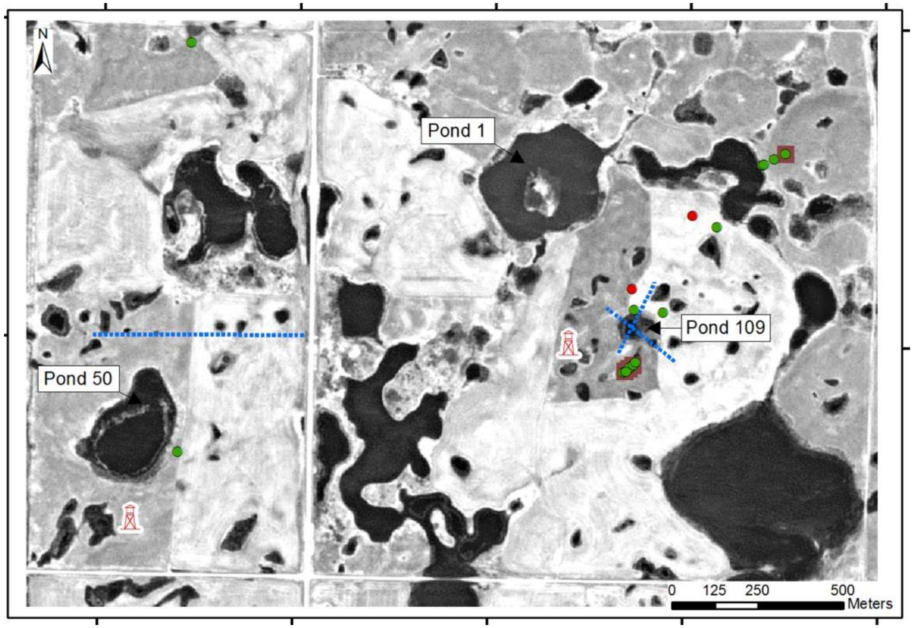
- Aim: measure the peak snowpack, in water equivalent units, just before melt
- Take lots and lots of measurements of snow depth, z_S, with a ruler/tape measure
- Take a smaller number of density measurements, ρ_S, by weighing a known volume with a snow tube/snow corer
- Very low tech! Very labour intensive! Best method we have!

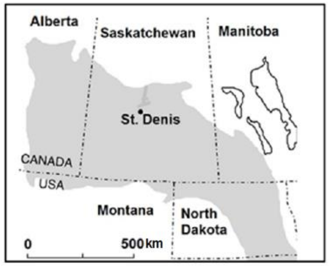


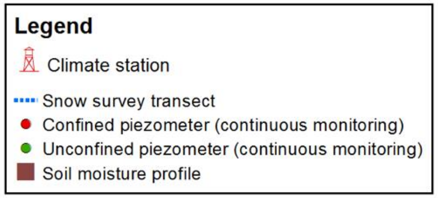
http://snowmetrics.com/shop/basic-12-kit/

Snow surveying at St Denis

Snow surveying at St Denis

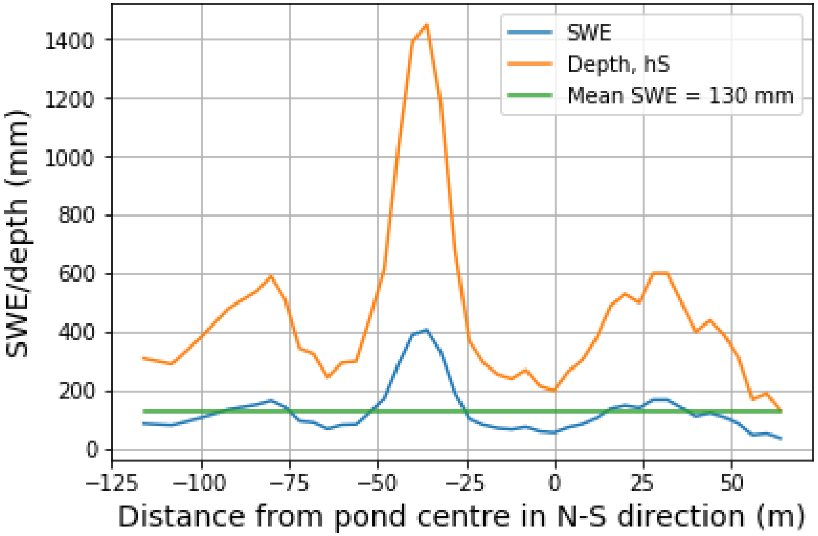




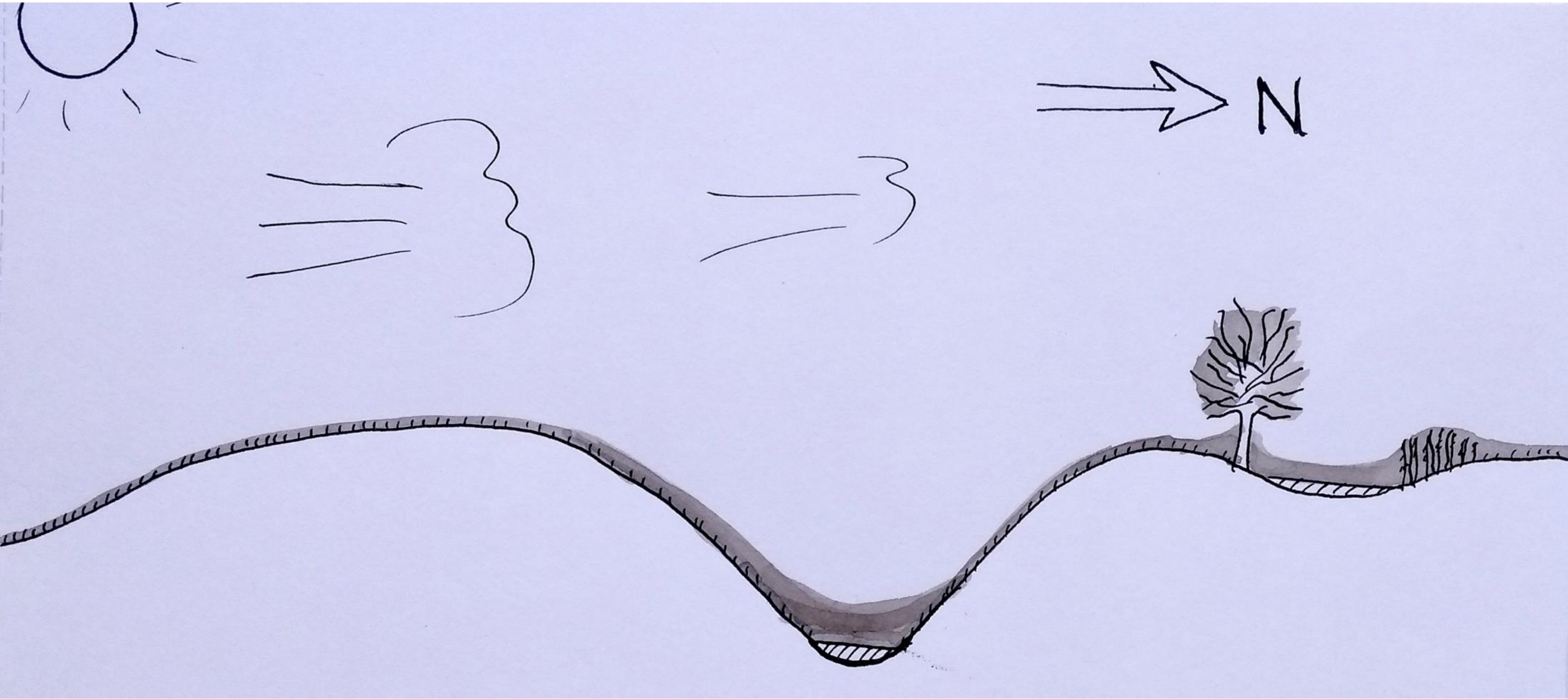


- Density measurements and transect survey data for 2007

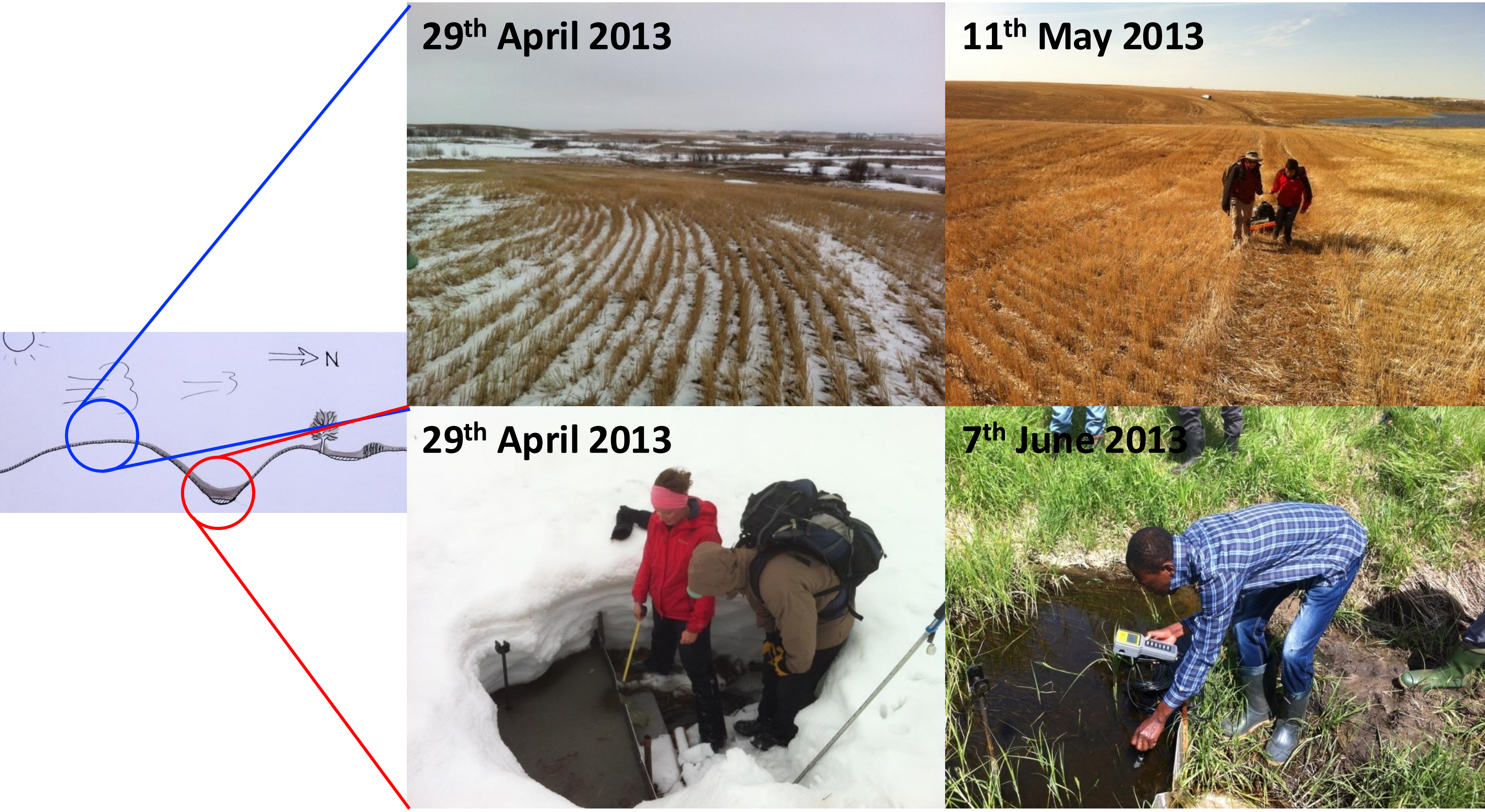
N-S transect about Pond 109 are shown for 2007:



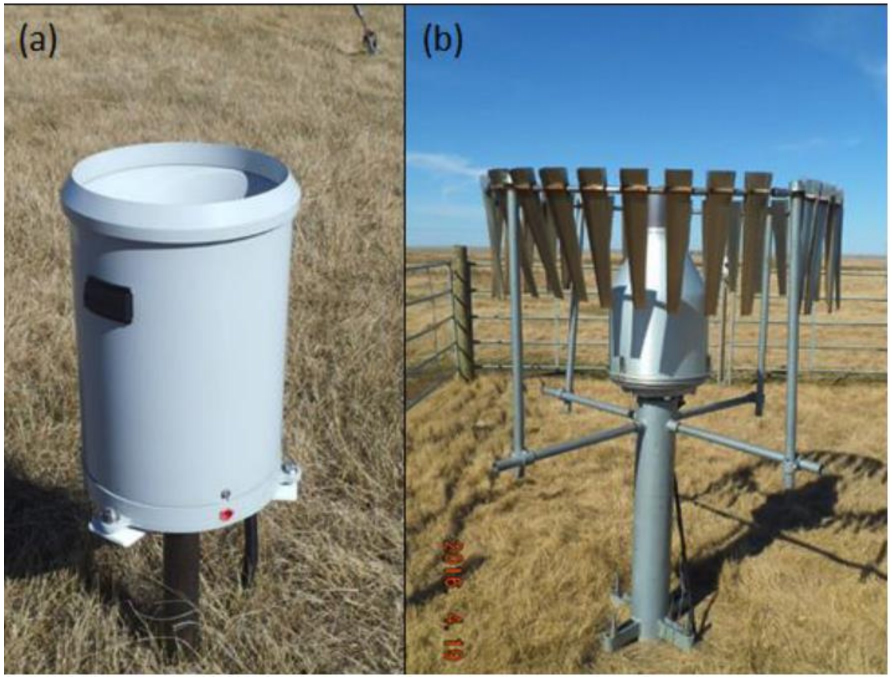
Snow accumulation



Snow accumulation



Measuring snowfall

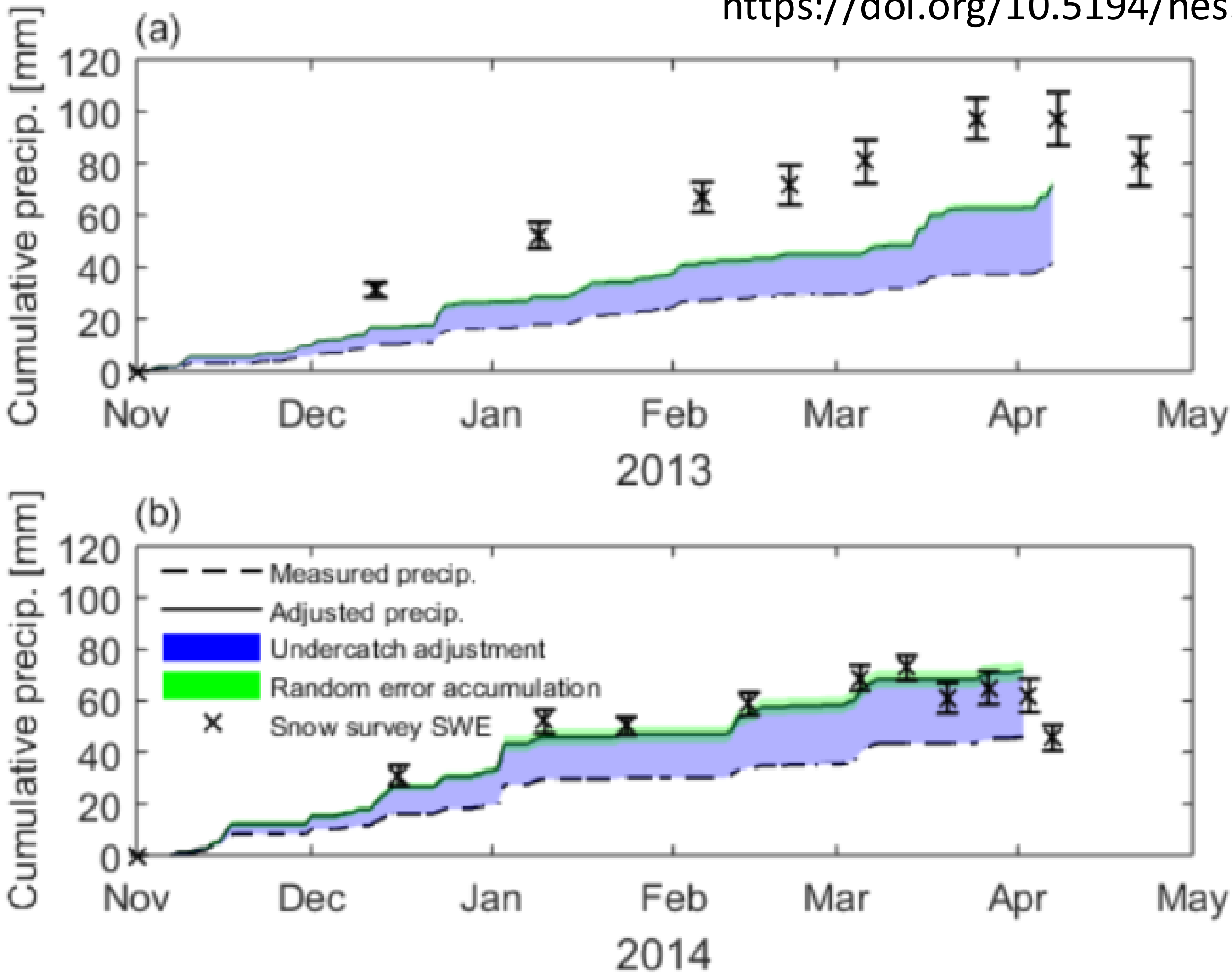


https://www.the-cryosphere.net/10/2347/2016/tc-10-2347-2016.pdf

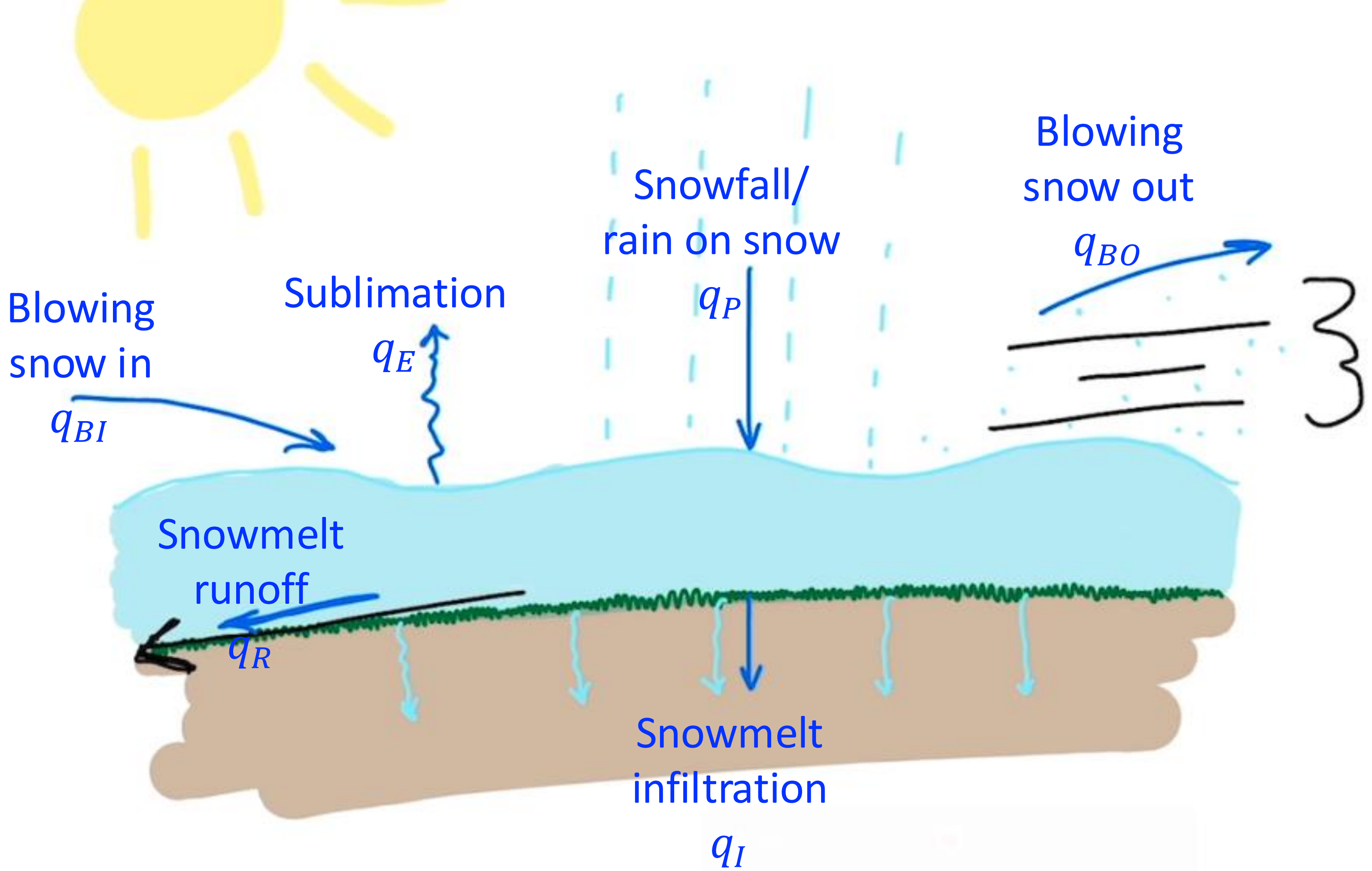
- Tipping bucket rain gauges (left, standard in most places) don’t work for snow
- Weighing precipitation gauges (right x2) work for rain and snow. Expensive, and complex data processing
- Wind under catch is a big problem – more significant for snow than rain
- For many practical applications, snowfall is not important – what the hydrologist really needs is peak SWE

Snowfall ≠ SWE

https://doi.org/10.5194/hess-21-5401-2017



Snow water balance



$$\Delta SWE = (q_P + q_{BI} - q_{BO} - q_E - q_M)\,\Delta t$$

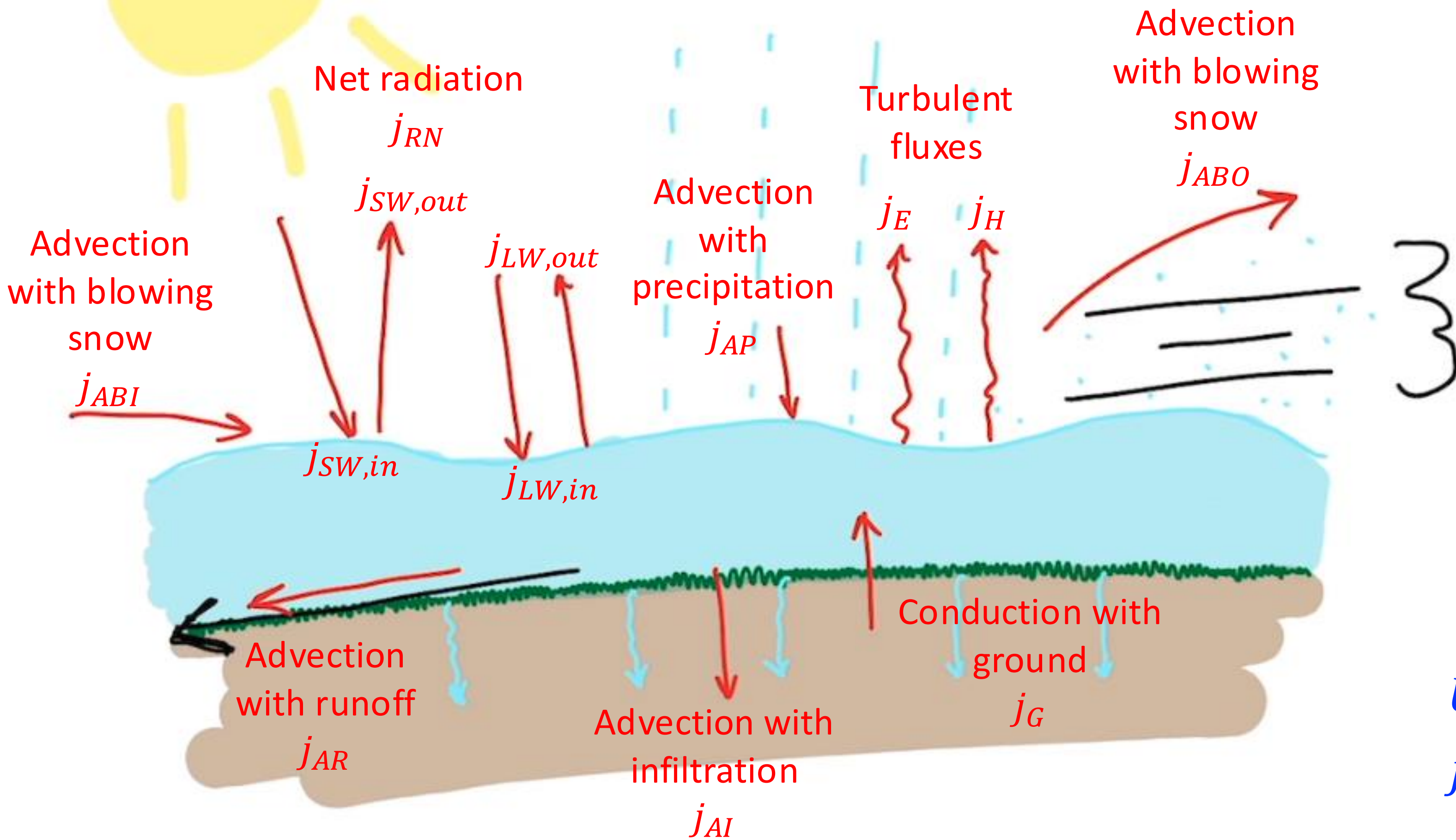
$$q_M = q_R + q_I$$

SWE = mm

q = mm/d

Δt = d

Snow energy balance



U = J

j = J/d

Δt = d

$$\Delta U_L + \Delta U_S = (j_{RN} + j_{AP} + j_{ABI} - j_{ABO} - j_E - j_H - j_G - j_M - j_{AR} - j_{AI})\,\Delta t$$

$$j_{RN} = j_{SW,in} - j_{SW,out} + j_{LW,in} - j_{LW,out}$$

Snow internal energy and melt

The internal energy of the snow is comprised of sensible heat, i.e.

$$U_S = m_i c_{p,i} T + m_L c_{p,L} T$$

and latent heat, i.e.

$$U_L = -\lambda m_i$$

So the change in internal energy is given by

$$\Delta U = \Delta U_S + \Delta U_L = \Delta\left(\left(c_{p,i} T - \lambda\right) m_i + m_L c_{p,L} T\right)$$

And this is equal to the net energy flux into the snowpack, shown previously.

The term

$$-\Delta \lambda m_i$$

represents the energy consumed for snow melt!

For example, if we melt 1 kg of water, we have a reduction in ice mass of 1 kg and we consume

$$334{,}000 \text{ J/kg} \times 1 \text{ kg} = 334{,}000 \text{ J of energy}$$

Snowmelt

Slightly more complicated than melting ice, since snow is a porous medium.

1. Warming phase:

Bring snowpack to a uniform temperature of 0°C

No change in latent heat!

Controlled by the specific heat capacity of snowpack:

$$\Delta U = (m_i c_{p,i} + m_L c_{p,L})\Delta T$$

2. Ripening phase:

Melt snow until snowpack reaches field capacity

No change in sensible heat (i.e. constant temperature)

Controlled by the latent heat of fusion:

$$\Delta U = -\Delta m_i \lambda$$

3. Output phase:

When the porous snow has a high water content, it yields the water as drainage from the snowpack.

Additional energy continues to contribute to phase change, i.e. $\Delta U = -\Delta m_i \lambda$

Models for snowmelt

Physically based models are based on the aforementioned ideas

Quantifying all the mass and energy fluxes is a huge undertaking, involving a lot of measurements.

There are a number of models established for this, notably John Pomeroy's *Cold Regions Hydrological Model*, CRHM, (http://www.usask.ca/hydrology/CRHM.php)

Most Land Surface Schemes also deal with this, with varying levels of sophistication.

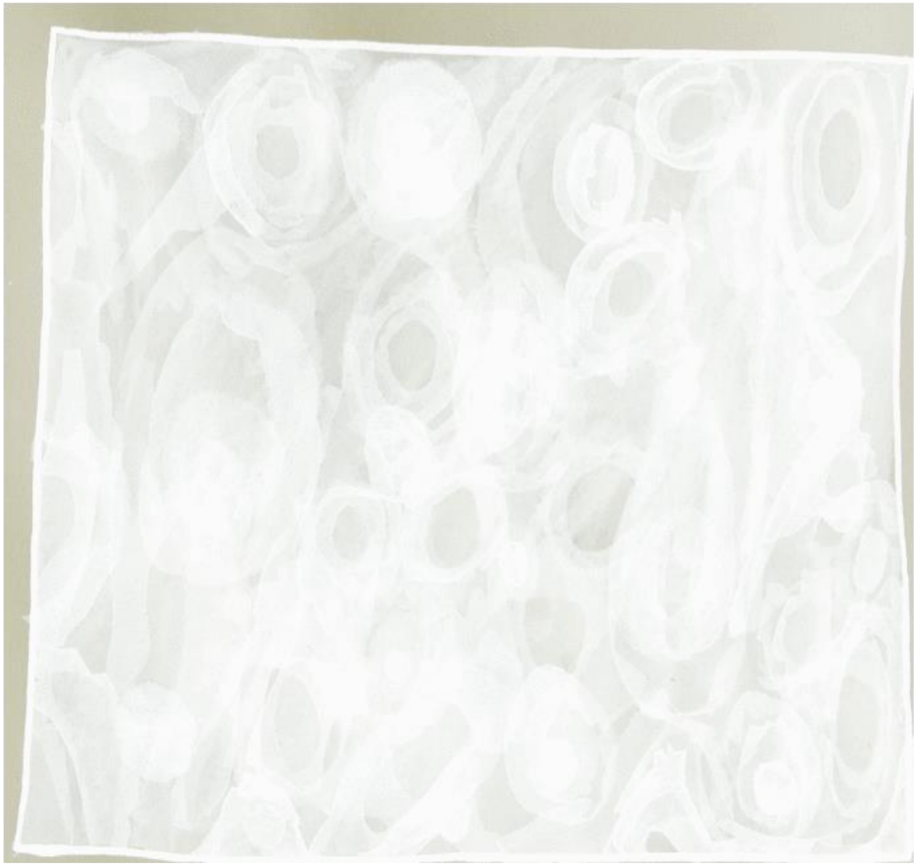
Another widespread, much simpler (arguably obsolete) method is the "temperature-index approach" (also known as the "degree-day" method):

$$m(t) = r.\,(T_A(t) - T_M) \qquad T_A(t) \geq T_M$$

$$m(t) = 0 \qquad T_A(t) < T_M$$

where r is a melt coefficient (i.e. empirical parameter), which takes a value similar to 3.6 mm/d (Dingman, p. 210).

Snow net energy – shortwave radiation

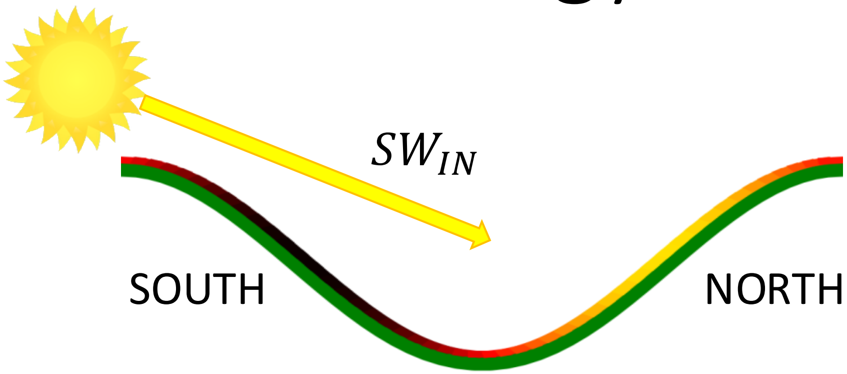


$$SW_{OUT} = \alpha \times SW_{IN}$$

Where α is the albedo:

	$\boldsymbol{\alpha}$
Fresh snow	0.8-0.9
Old snow	0.4-0.6
Trees	0.1-0.2
Snow covered trees	0.2-0.3
Bare ground	0.1-0.35
Grass	0.2

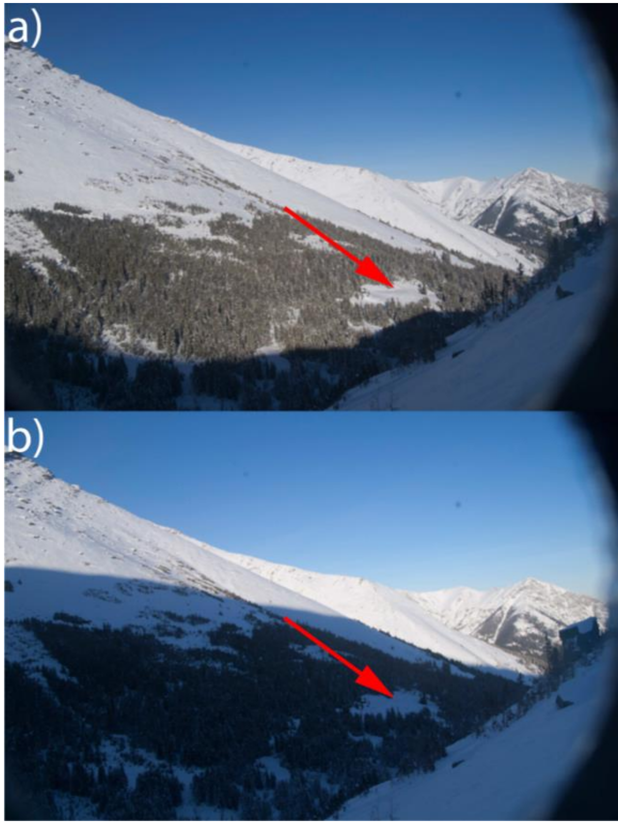
Snow net energy – slope and aspect



Slope angle	North facing	South facing
0	20.6	20.6
10	16.6	24.1
20	12.0	26.8
30	7.0	28.7
40	1.9	29.7

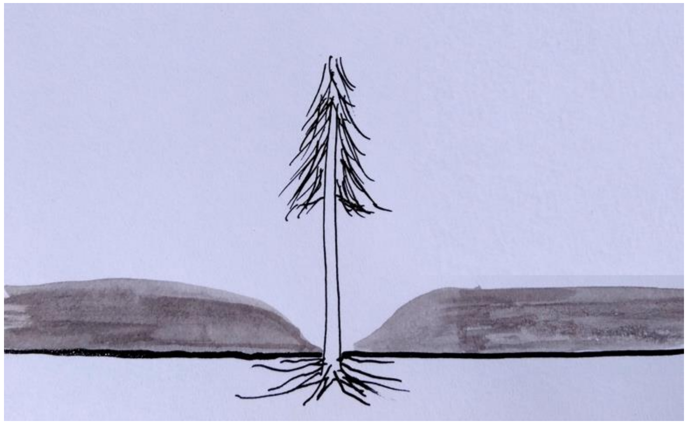
Incident radiation, SW_{IN}, at Danville, VT (44.5°N) on March 17 (MJ/m^2). Dingman, p. 194

In mountains we can also get shadowing effects:

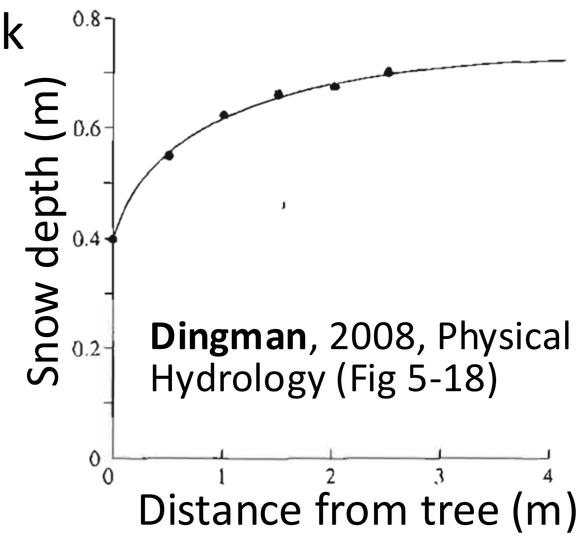


Marsh, C. 2012. MSc Thesis, U of Saskatchewan

Snow net energy – longwave radiation



Enhanced snow ablation due to melt by longwave radiation from tree canopy and trunk

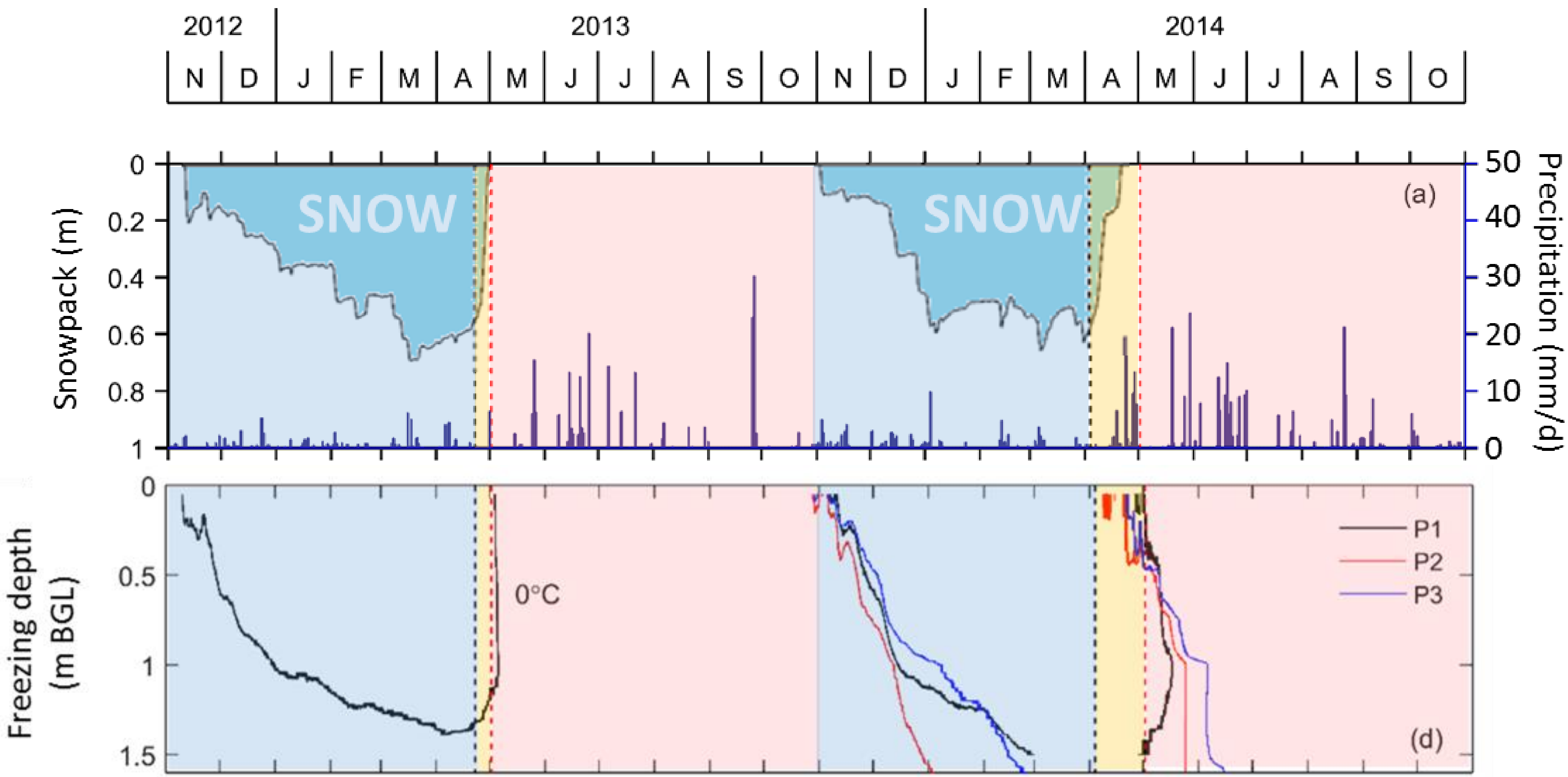


Dingman, 2008, Physical Hydrology (Fig 5-18)

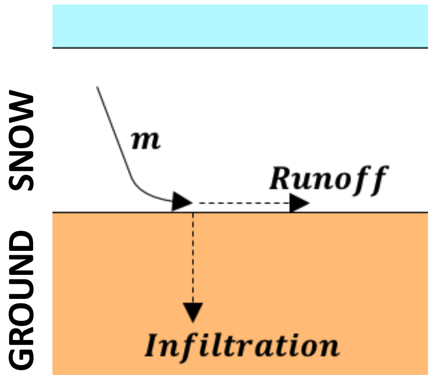
Image: John Pomeroy

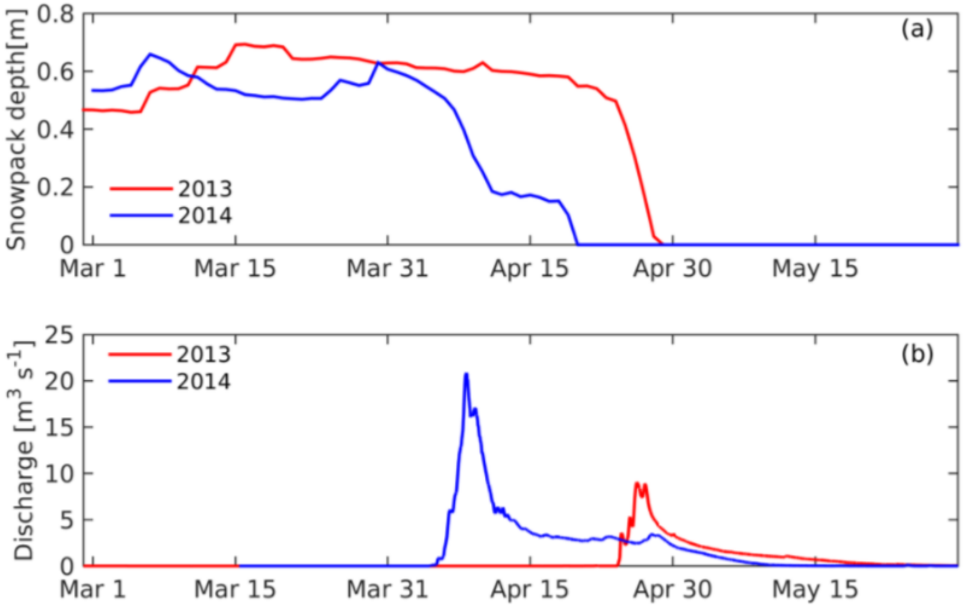
Snowmelt over frozen soils

https://doi.org/10.5194/hess-21-5401-2017



Melt to runoff vs infiltration





Snowmelt runoff

Modelling SWE

Model inputs:

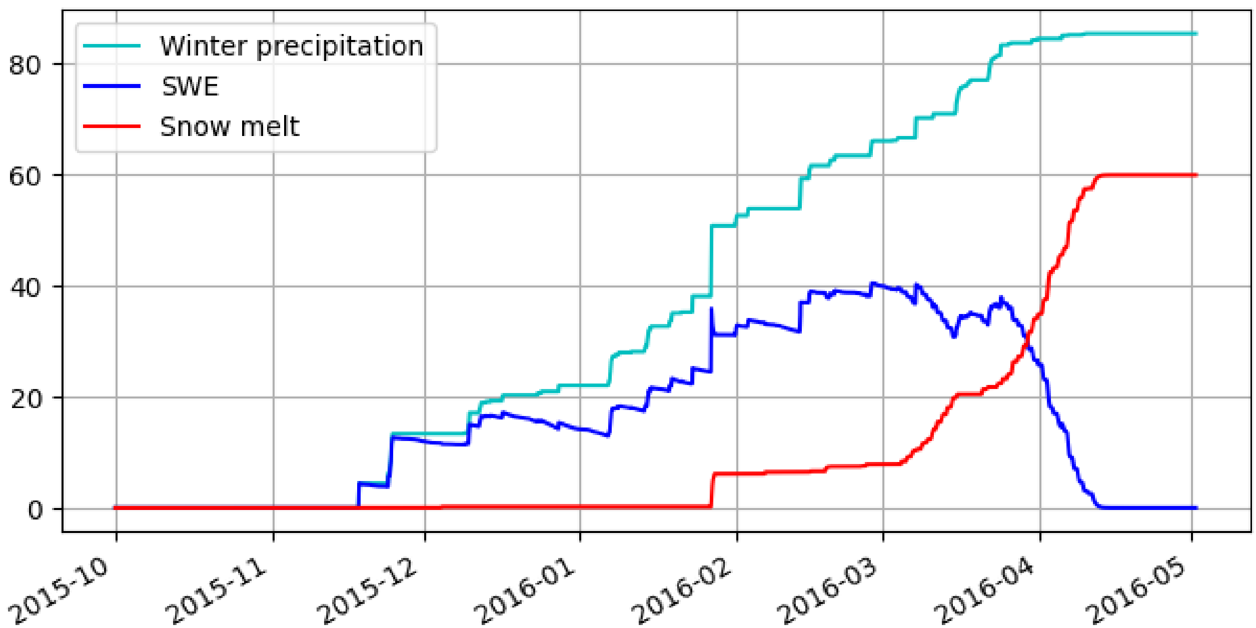
Shortwave rad in	$j_{SW,in}$
Longwave rad in	$j_{LW,in}$
Air temperature	T_A
Precipitation	P
Baro pressure	BP
Relative humidity	RH
Wind speed	U

Snow model

Solves the mass and energy balance equations

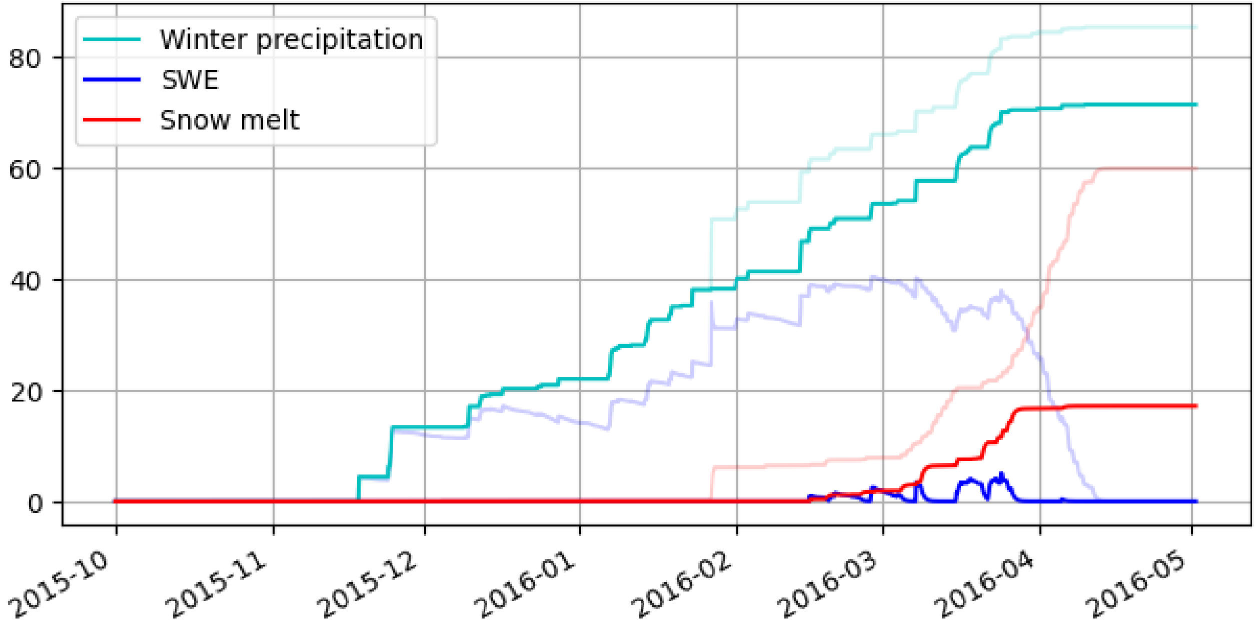
Model output:

Shortwave rad out	$j_{SW,out}$
Longwave rad out	$j_{LW,out}$
Snow mass	SWE
Snow melt	qM
Sublimation	qE
Snow temperature	T_S
Snow depth	z_S



Insights from SWE model:

Increase the air temperature by +1 deg C

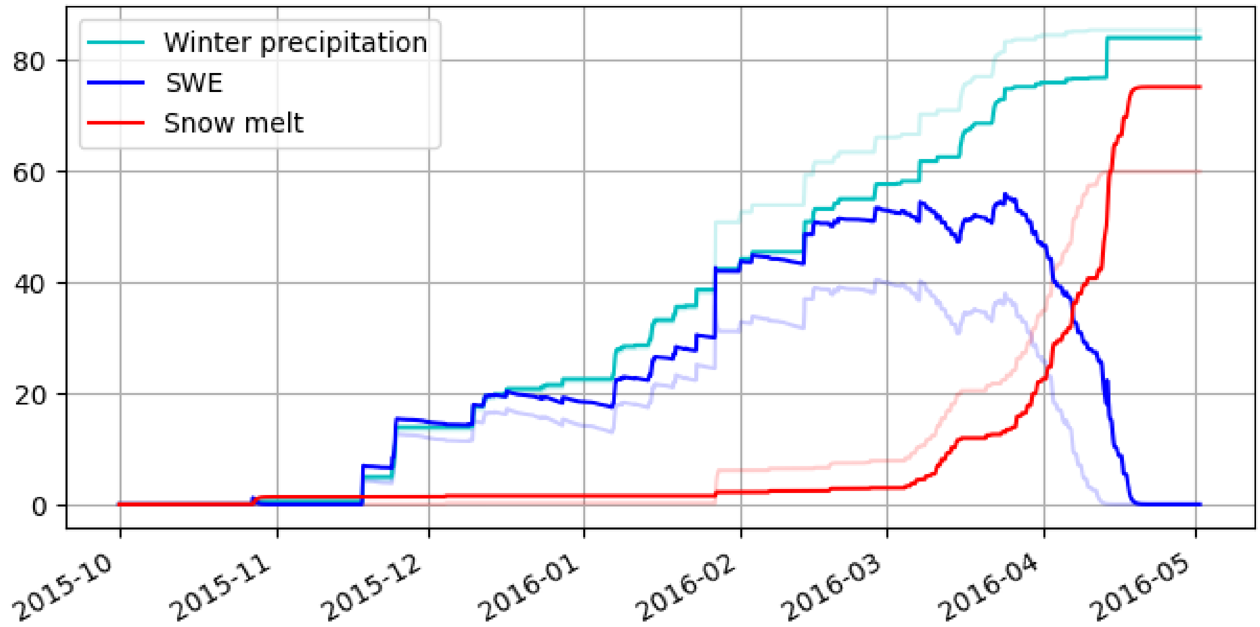


Result:

- Much less SWE and snowmelt
- Lots of snowfall melts without accumulating
- More rainfall, less precipitation on the snowpack

Insights from SWE model:

Reduce the air temperature by -1 deg C

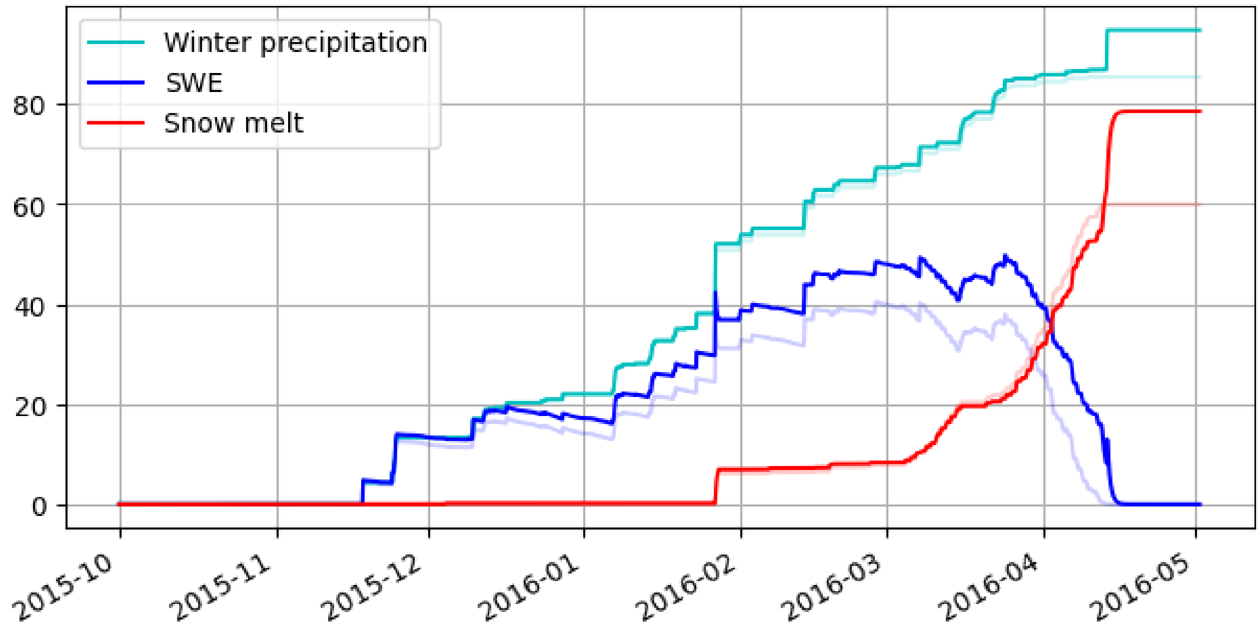


Result:

- More SWE and snowmelt
- Longer lasting SWE in the spring

Insights from SWE model:

Increase precipitation by +10%

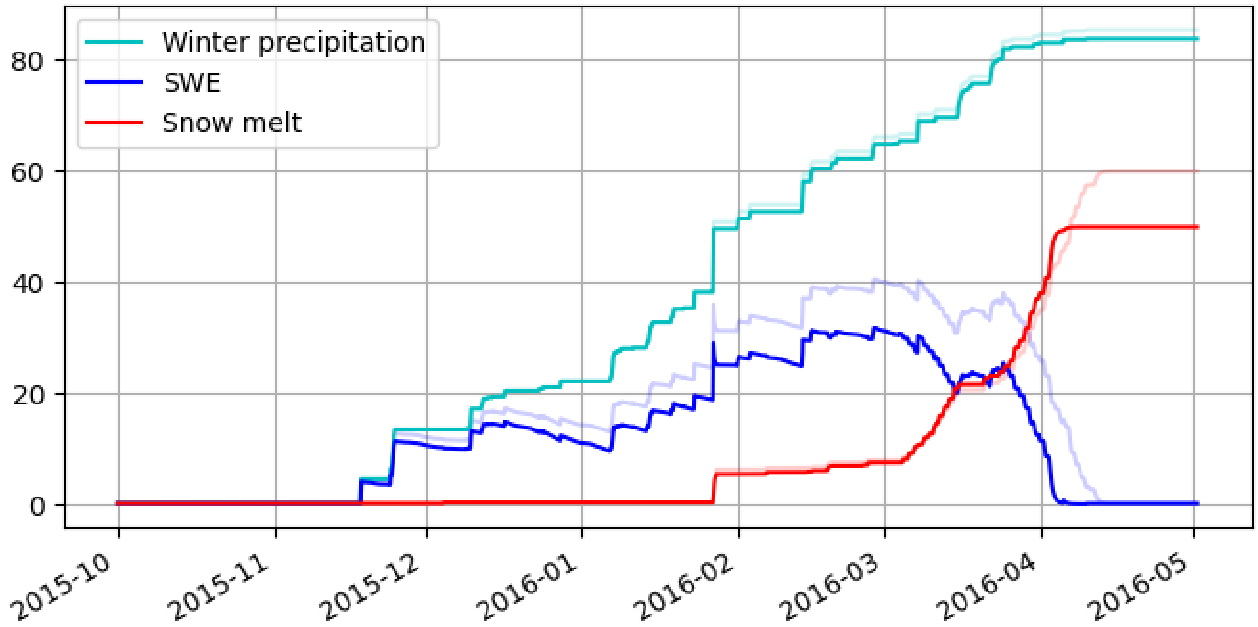


Result:

- More SWE and more snowmelt
- Timing of snowmelt is unaffected

Insights from SWE model:

Reduce precipitation by +10%

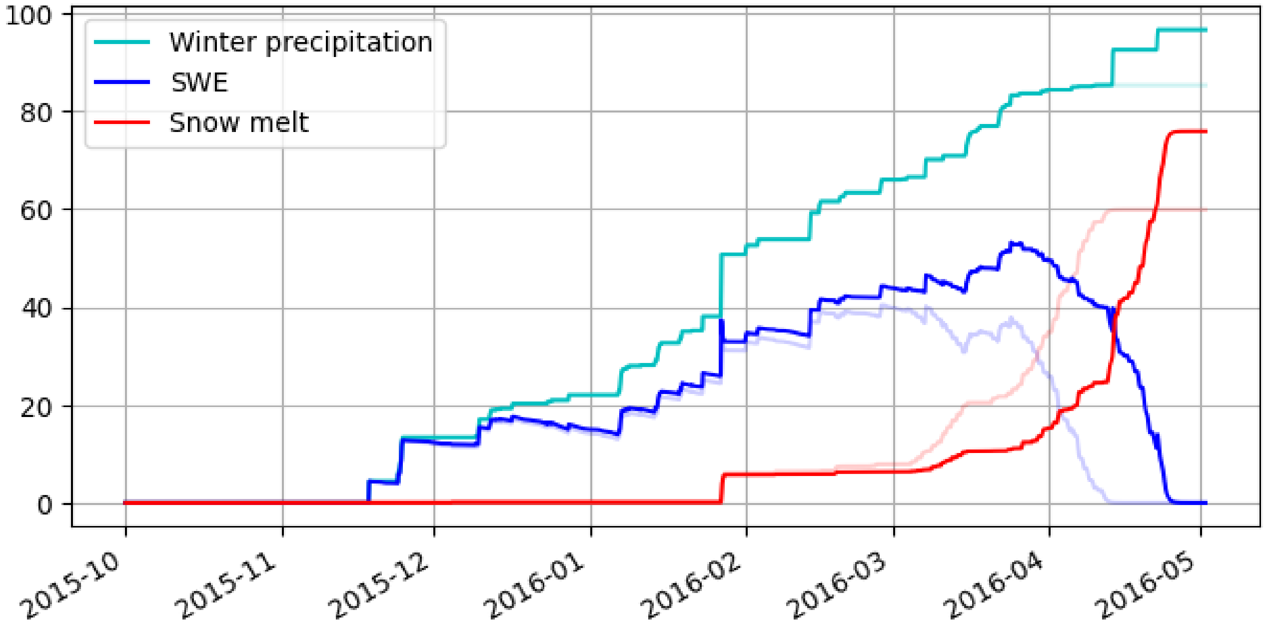


Result:

- Less SWE and less snowmelt
- Timing of snowmelt is unaffected

Insights from SWE model:

Increase shading, reduce $j_{SW,in}$ by 75%:

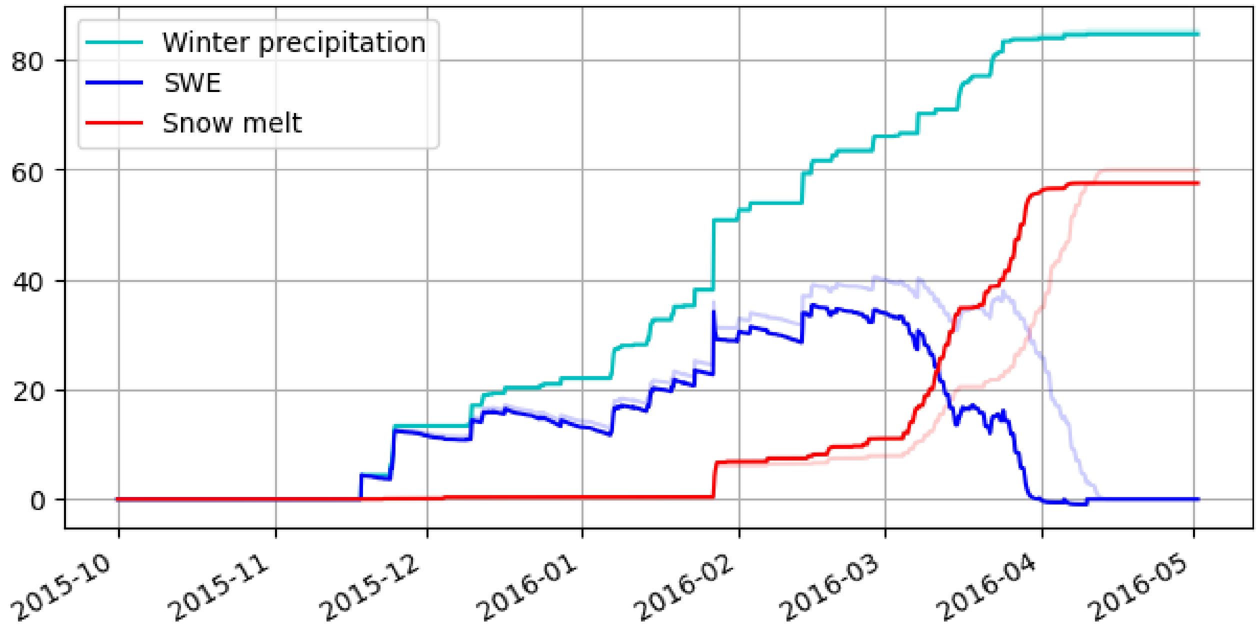


Result:

- Delayed snowmelt

Insights from SWE model:

Dirty snow, reduce albedo from 0.8 to 0.75:



Result:

- Snowpack absorbs more heat, and melts earlier

Worked examples
1) St Denis snow survey

You are provided with data from a snow survey conducted at St Denis, Saskatchewan, Canada, on 20th March 2007.

Explore the data to understand what is provided.

Calculate the snow densities for different landcovers. Decide the best way to distribute density across the entire site.

Estimate SWE for each individual landcover, and for the site as a whole.

For this activity you will need the file StDenisSnowSurvey2007.xlsx

Worked examples
2) Energy-based snow melt calculation

Consider a snowpack with 30 mm of SWE. The snow is 0.15 m deep. The snow temperature is -7^{o}C.

The sun is shining. The net input of energy over 1 day is 10 W/m^2

Calculate:

i) What is the snow density?

ii) What is the mass of ice and liquid water in the snow at the start of the day?

iii) How much energy (in MJ/m^2) does it take to get the snowpack to 0^{o}C.

iv) The excess energy goes to melt some of the snow. How much snow melts?

v) What is the final state of the snowpack in terms of mass of ice, mass of liquid and temperature.

Worked examples
3) Degree-day method snow melt calculation

Using the degree-day method, with the temperature data in the file 2007_Airtemp.csv, produce a time series of daily snowmelt for St Denis, based on snow survey data from Q1. Assume r=3.66 mm/d

Make a plot in Excel of SWE vs time and cumulative snowmelt vs time.

Worked examples
4) Snowmelt model comparison

Compare the energy-balance based snowmelt model (soilice) with the degree-day method.

Make a plots in python of SWE vs time and cumulative snowmelt vs time for each model.