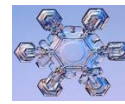


© Ernesto Trujillo



Snow and Vegetation

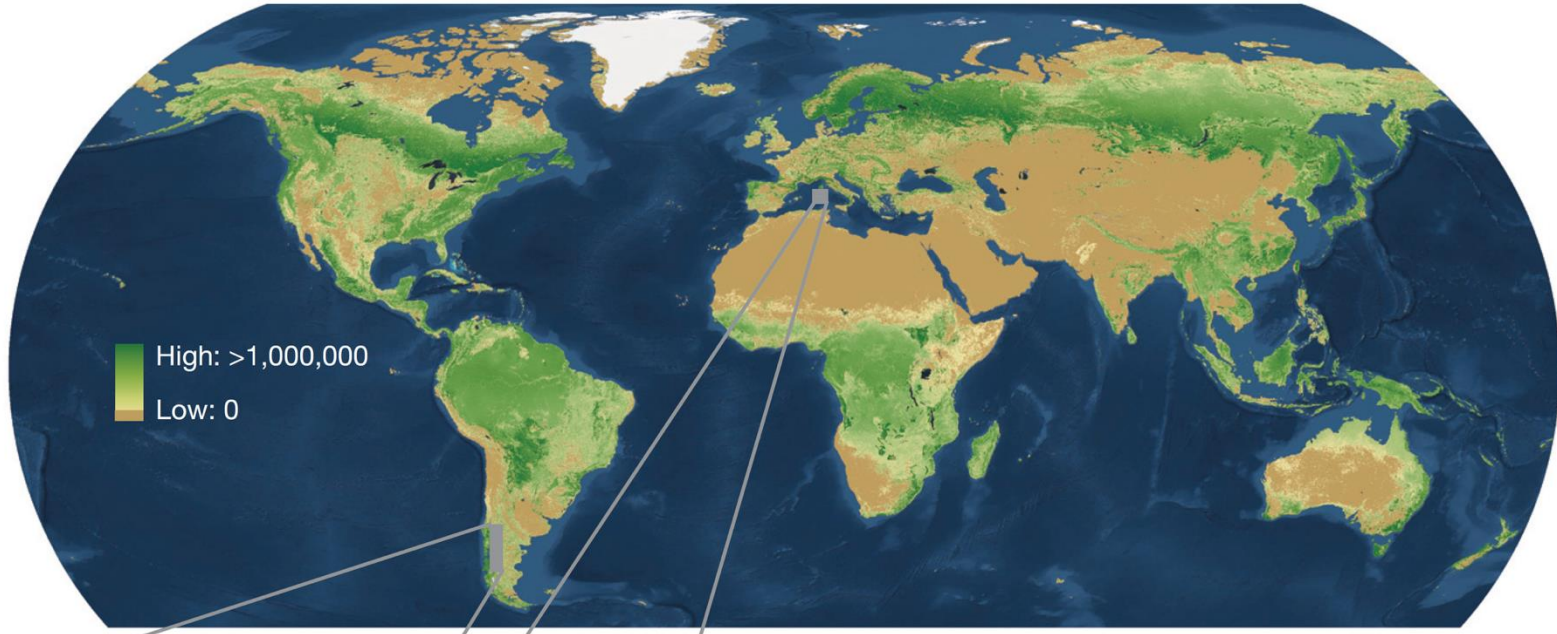
Snow and Vegetation interactions



2

How important are Snow and Vegetation interactions and associated processes?

The global map of tree density at the 1-km² pixel scale.

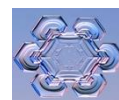


TW Crowther *et al.*: Mapping tree density at a global scale, *Nature*, 1-5 (2015) doi:10.1038/nature14967



- Snow-Vegetation Interactions/Processes
 - Canopy interception
 - (Sublimation and Melt)
 - Below Canopy Snow
 - SNOWPACK Canopy Modelling (Mass- and Energy Balance)
 - Introducing Spatial Heterogeneity (Below Tree and Gaps)

How important?

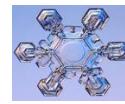
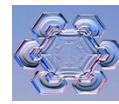


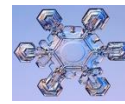
4

Estimates of the total tree number for each of the biomes that contain forested land, as delineated by The Nature Conservancy

Biome	% Total Land Area	n	Total Trees (Billions)	± 2 SD (Billions)	% Total Trees
Boreal Forests	11.49%	8688	749.34	50.07	24.28%
Deserts	21.01%	14637	52.95	2.92	1.75%
Flooded Grasslands	0.79%	271	64.58	14.19	2.13%
Mangroves	0.23%	21	8.18	0.26	0.27%
Mediterranean Forests	2.43%	16727	53.42	1.20	1.76%
Montane Grasslands	3.88%	138	60.3	24.04	1.99%
Temperate Broadleaf	9.32%	278395	362.6	2.90	11.98%
Temperate Conifer	3.18%	85144	150.57	1.34	4.97%
Temperate Grasslands	7.18%	17051	148.29	4.93	4.90%
Tropical Coniferous	0.48%	0	22.21	0.40	0.73%
Tropical Dry	2.85%	115	156.37	63.42	5.17%
Tropical Grasslands	14.66%	999	318.01	35.52	10.51%
Tropical Moist	14.81%	5321	799.45	23.98	26.41%
Tundra	5.25%	2268	94.89	6.31	3.14%
Total		429775	3041.17	96.07	

Forest in Switzerland – 31% of Total Area





Up to 60% of snowfall is intercepted





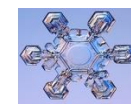
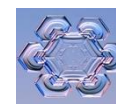
Up to 50% of intercepted snow is sublimated



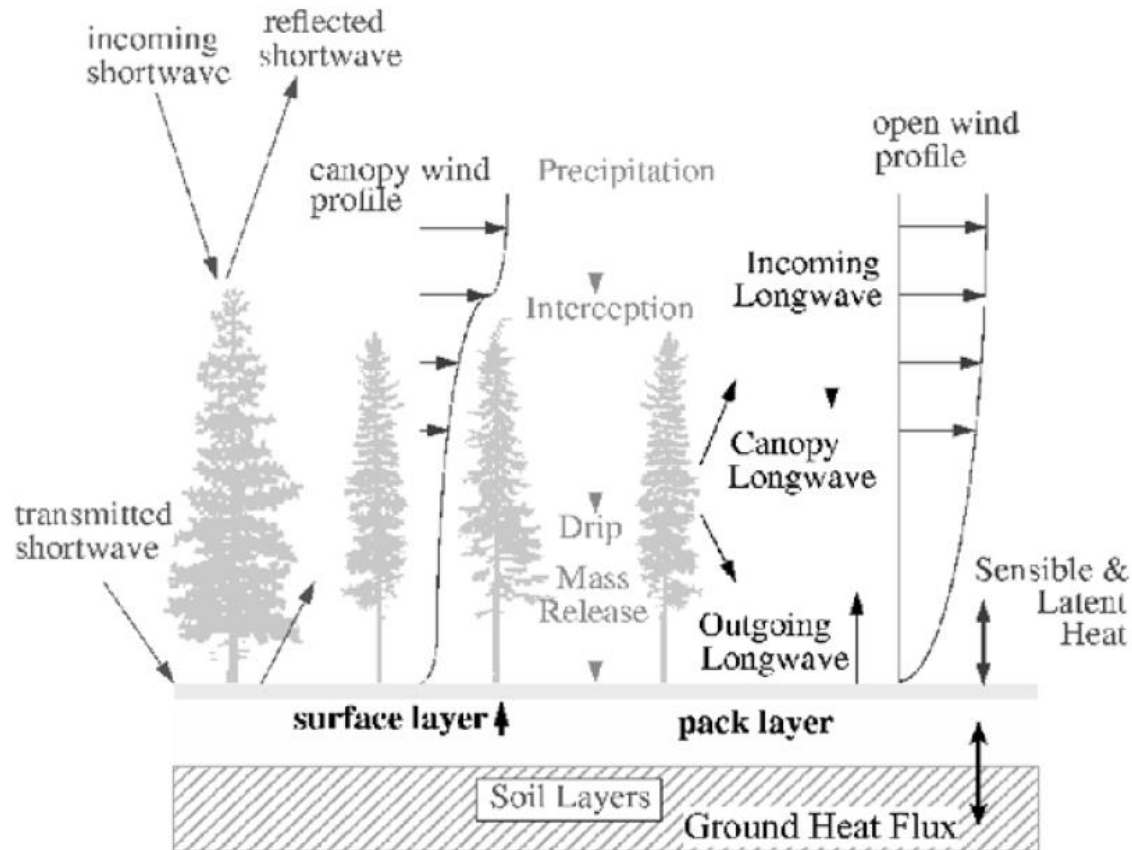


- The magnitude of snow accumulation and timing/rates of melt are very different between forested and non-forested areas
- Sub-canopy snow is sheltered from the wind, decreasing turbulent transport and snow redistribution
- Vegetation significantly alters the energy balance through shading, direct radiation intercepted by trees, and tree temperatures affect the longwave radiation transmittance and emittance
- Vegetation strongly relies on snowmelt water, soil temperatures (related to snow accumulations) affect root temperatures and tree activity
- More water (moisture) is lost back to the atmosphere via increased sublimation

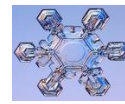
Snow Processes in a forested environment



9

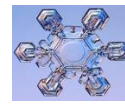


Source: *Andreadis et al., 2009*



- Snowfall is partitioned into:
 - Canopy Interception
 - Throughfall to the ground
- Canopy interception can account for significant portions of annual precipitation. Under-canopy snow accumulations can be just 60% of surrounding open areas [*Hardy et al.*, 1997]. Other studies indicate that as much as 60% of snowfall can be intercepted by canopy
- Interception amounts vary according to:
 - Vegetation type (e.g., deciduous or evergreen, species, age, height, Leaf Area Index (LAI), health, fires, etc.)
 - Snow characteristics (e.g., cohesiveness, density, water content)
 - Atmospheric and weather conditions (e.g., wind speeds, temperature)

Heterogeneous Snow Cover

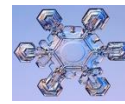


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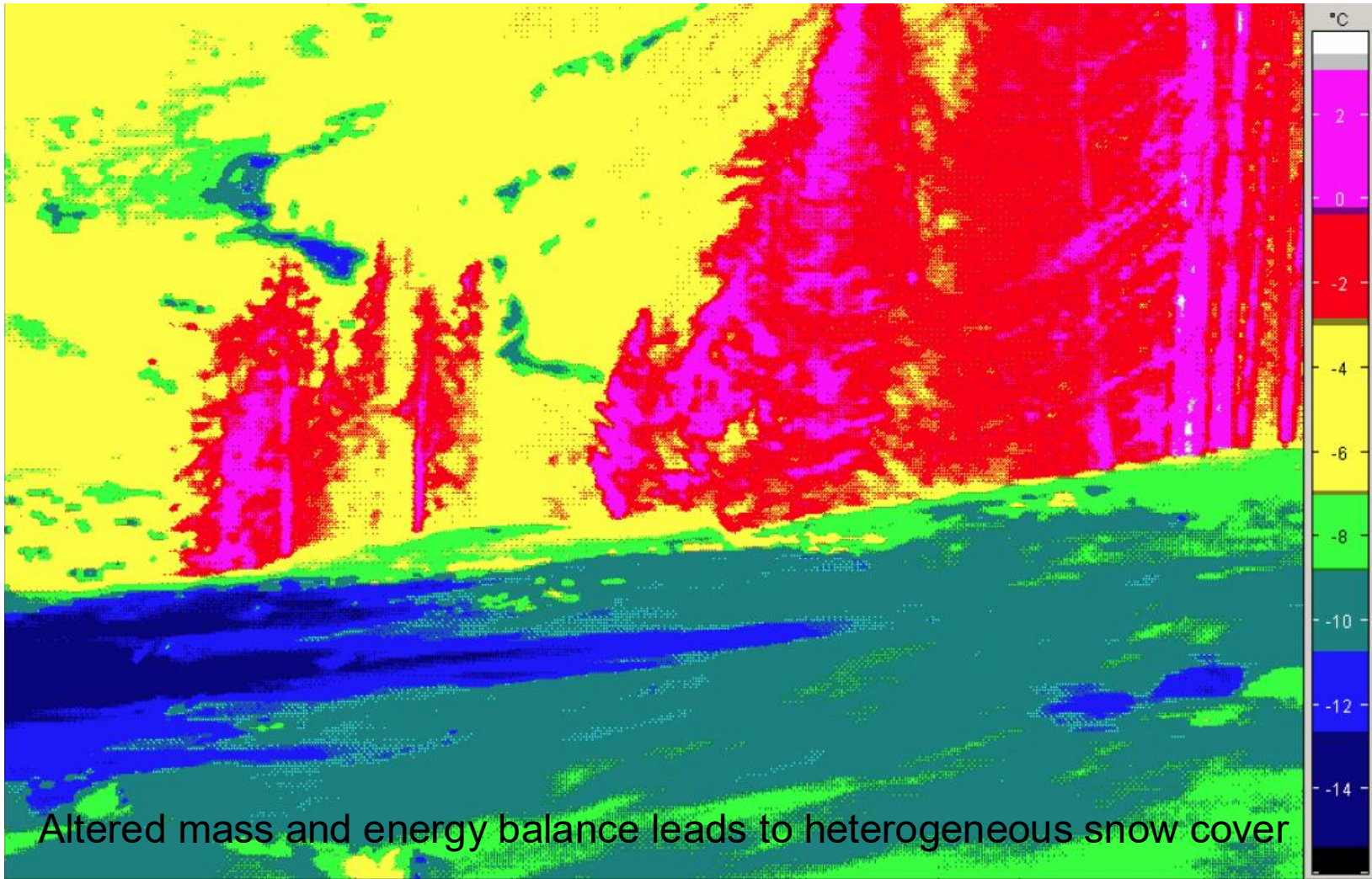


Altered mass and energy balance leads to heterogeneous snow cover

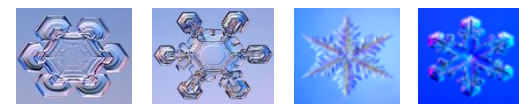
Surface Temperature -> IR input to snow



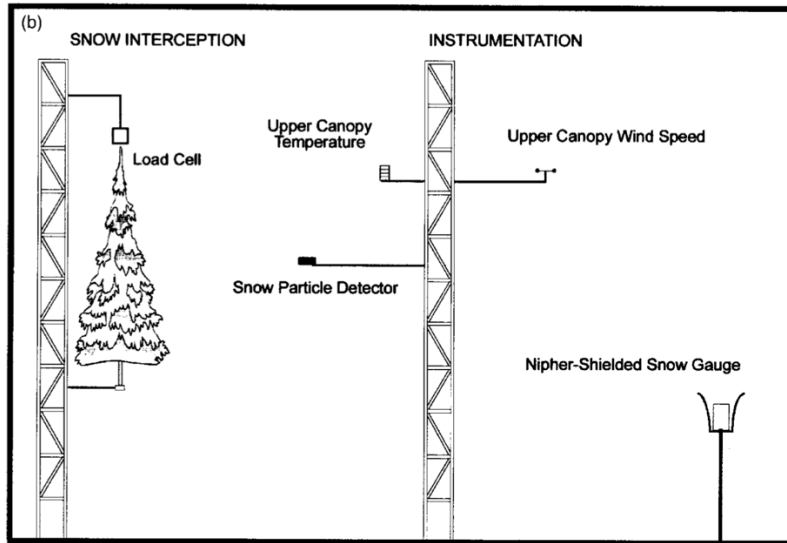
12



Tree-stand scale studies



13



(a) Experimental site location. (b) Tower design and instrumentation. The schematic conceptualizes the basis for the towers used at the jack pine and black spruce sites. [Hedstrom and Pomeroy, 1998]

The weight of intercepted snow was measured for a single tree per season.

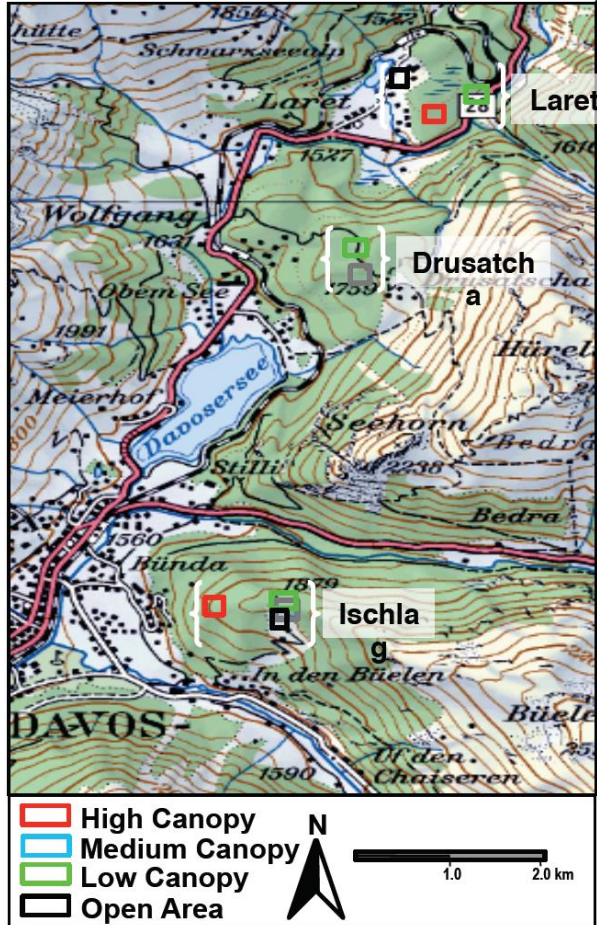
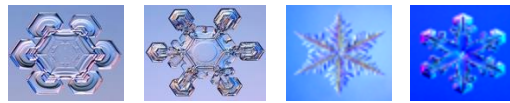
Black Spruce: 1992-1993 (1 season)

Jack pine forest: 1992-1997 (5 seasons)

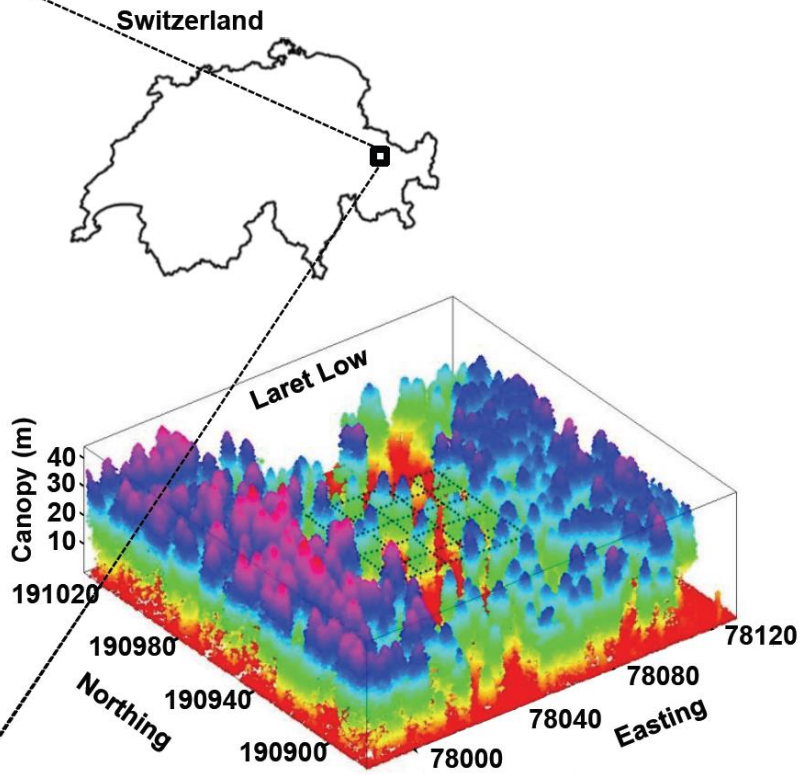
Weekly measurements of intercepted snow

Model was formulated from the hypothesis that:

- Interception efficiency decreases with canopy snow load and increases with canopy density
- Snow unloading increases with time

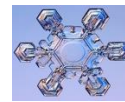
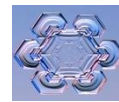


Field Areas



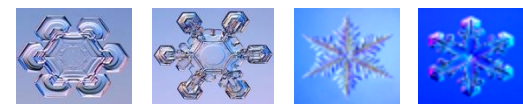
[Moeser et al., 2015]

Good old hand measurements have been made

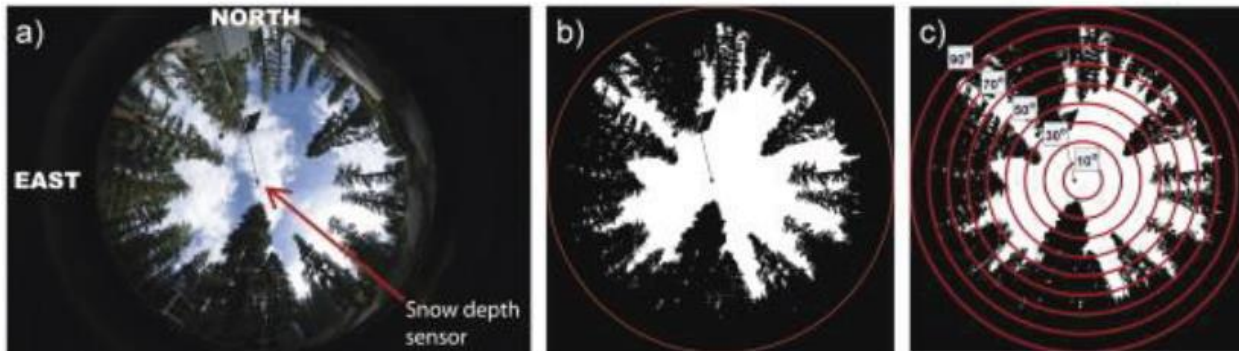


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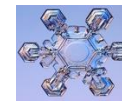
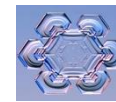




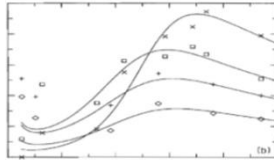
- Leaf area index (LAI) is a dimensionless ratio (leaf area per unit ground area) of the layered area of vegetation leaf content (needles, branches and stems) occupying the space above the same area of ground cover
- Canopy coverage/closure (CC) is the fraction of sky not visible from under the canopy (i.e. $1 - \text{SVF}$).
- Calculated with hemispherical photos



Improved Model (Old Knowledge)

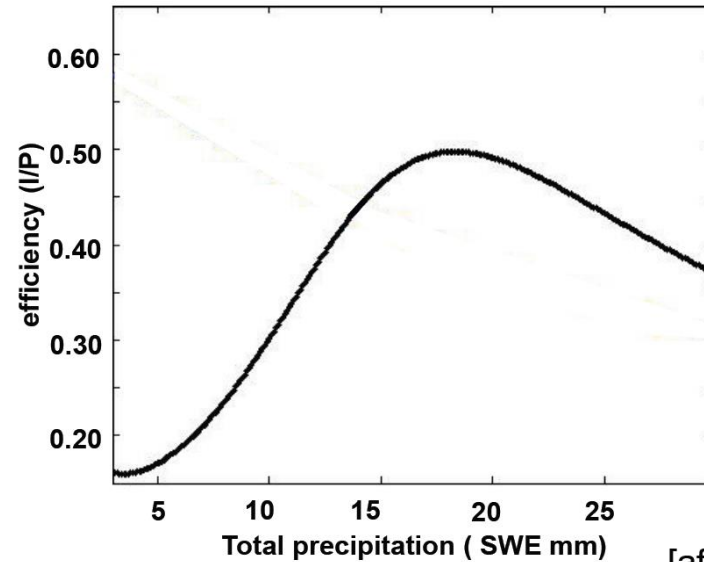


17

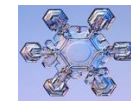
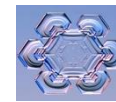


← (Satterlund et al 1967)
Sigmoidal distribution

$$I = \frac{I_{max}}{1 + e^{-0.3(P-13.3)}}$$

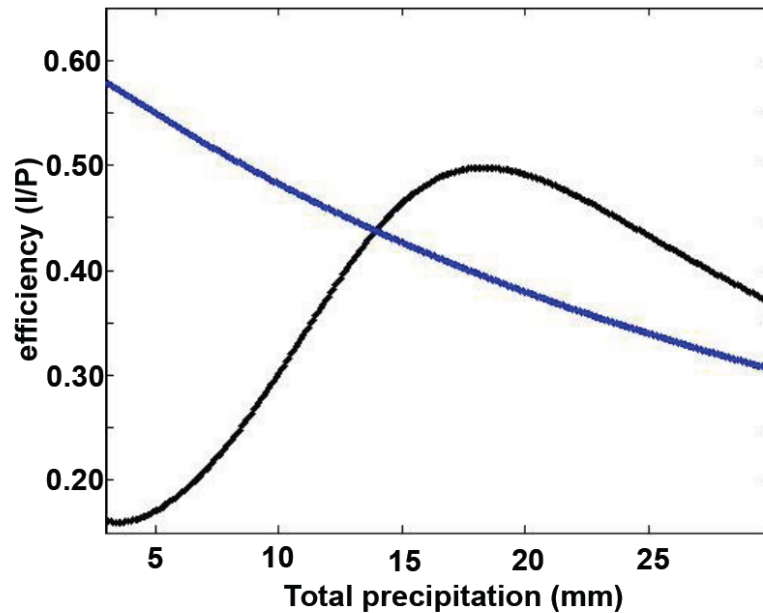


[after Moeser et al., 2016]



Comparison of distributions using mean canopy parameter values

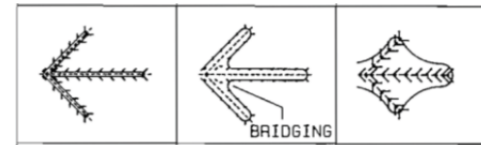
- - > Compared to the most used snow interception model



— Moeser et al. — Hedstrom and Pomeroy

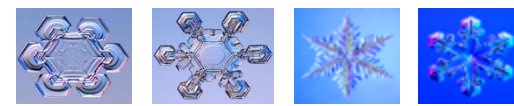
... ..

SNOW BRIDGING



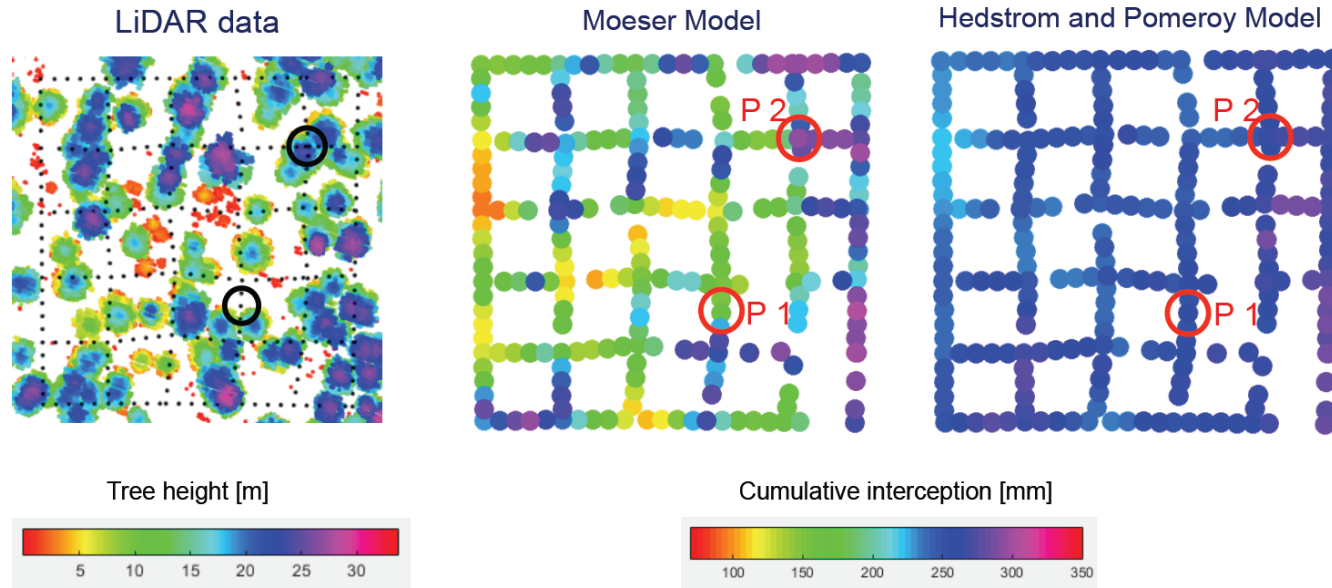
VS.
NO
SNOW
BRIDGING...

[after Moeser et al., 2016]



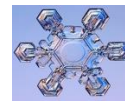
Spatial variability of model results

Cumulated seasonal interception at the Drusatscha medium field area, 2013-14



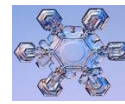
[after Moeser et al., 2016]

Fate of Snow on the Trees



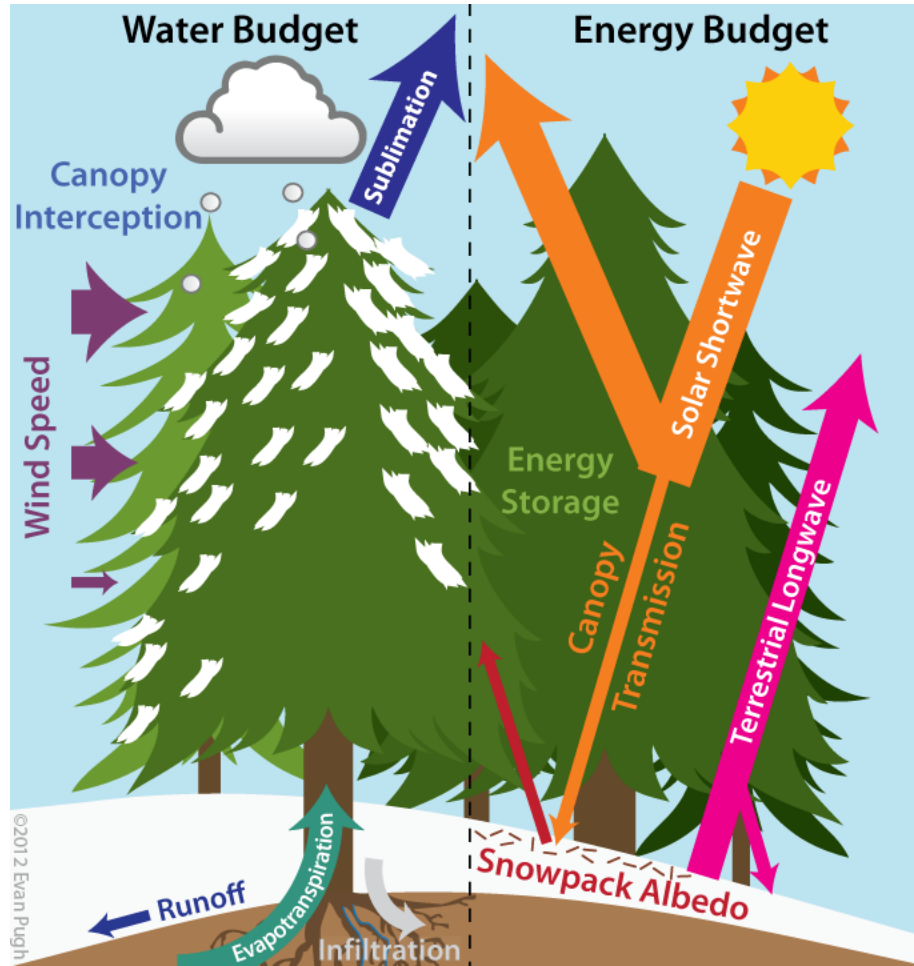
20

- Intercepted snow can fall to the ground/snowpack, sublimate, evaporate, and/or melt
- Sublimation of ice to water vapor at 0° C requires 2838 kJ per kilogram of ice and standard atmospheric pressure which is a high amount of energy in winter [*Hobbs, 1974; Pomeroy and Gray, 1995*]
- The rate of sublimation is controlled by the local energy balance – turbulent heat fluxes, conduction and radiation
- Limiting factors: available energy and the relative humidity
- Maximum sublimation rates at air temperatures slightly below 0° C, at low relative humidity, and high wind speeds.
- In cold regions snow may remain for several days or weeks in the canopy which favors large amounts of snow to be sublimated.



- Vegetation canopy is represented by a single big leaf with:
 - Temperature T_{can} (K)
 - Storage of intercepted water I (mm)
- Leaf is characterized by 3 parameters:
 - Canopy height z_{can} (m)
 - LAI ($m^2 m^{-2}$) or Plant index area (PIA) ($m^2 m^{-2}$)
 - Direct throughfall fraction c_f (-)
- Water and Heat (energy) balances are calculated in three steps:
 - Preliminary mass balance (I and c_f)
 - T_{can} is obtained solving energy balance of canopy (Radiation transfer, turbulent exchange of sensible and latent heat)
 - Mass balance of canopy is updated by evaporation/sublimation/condensation from previous step

Coupled Mass and Energy Budget



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Source: <http://hydroproc.evanpugh.com/>

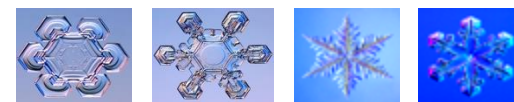
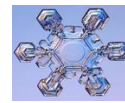


Table 1. Parameters used by the SNOWPACK canopy module.

	Parameter (unit)	Description	Value
Model internal parameters	i_{\max} (mm m ⁻²)	Coefficient for the maximum interception capacity	Spruce: 5.9; pine: 6.6
	i_{LAI} (mm m ⁻²)	Maximum interception of water by canopy per unit of LAI	Rain: 0.25; snow: $i_{\max} (0.27 + 46/\rho_{s,\text{int}})$
	k_{LAI} (-)	Extinction coefficient for SW and LW radiations	[0.4–0.8] default: 0.75
	f_{LAI} (-)	Fraction of LAI in the uppermost canopy layer. For 2LHM only.	Default: 0.5
	D_{can} (m)	Average canopy diameter	1
	$\alpha_{\text{wet,snow}}$ (-)	Snow-covered canopy albedo	0.3
	$\alpha_{\text{dry}} = \alpha_{\text{wet,rain}}$ (-)	Dry and wet canopy albedo	0.11
	α_{trunk} (-)	Lower canopy-layer albedo	0.09
	f_d (-)	Ratio d/z_{can}	2/3
	$f_{z0\text{m}}$ (-)	Ratio $z_{0\text{m}}/z_{\text{can}}$	0.1
	$f_{z0\text{h}/z0\text{m}}$ (-)	Ratio $z_{0\text{h}}/z_{0\text{m}}$	0.999
	$r_{\text{a,LAI}}$ (-)	Parameter for the excess resistance introduces by canopy between surface and reference level.	3
	$f_{\text{ra,snow}}$	Factor for increased aerodynamic resistance for evaporation of intercepted snow	10
	ρ_{biomass} (kg m ⁻³)	Bulk biomass density	900
	$C_p, \text{biomass}$ (J kg ⁻¹ K ⁻¹)	Bulk biomass heat capacity	2800
e_{leaf} (m)	Mean leaf (or needle) thickness. For 2LHM only.	0.001	
User provided parameters	z_{can} (m)	Mean canopy height	
	LAI (m ² m ⁻²)	One-sided mean stand leaf area index	
	c_f (-)	Direct throughfall fraction	
	B (m ² m ⁻²)	Stand basal area. For 2LHM only.	



$$dI / dt = \Delta I - E_{int} - U$$

Fluxes: Interception storage of precipitation/snow ΔI (mm day⁻¹), Evaporation E_{int} (mm day⁻¹), Water unloading from the canopy U (mm day⁻¹)

Stage: I (mm) is the interception storage

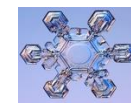
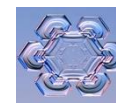
$(1-c_f)$ of the precipitation P (mm day⁻¹) is available for interception at each time step . $c_f(-)$ is the direct throughfall fraction

$$\Delta I = c(I_{max} - I) \left(1 - \exp \left\{ - \frac{(1 - c_f) P}{I_{max}} \right\} \right)$$

$c(-)$ is the unloading coefficient. It is time dependent ($c = 0.7$ suggested for hourly time steps).

$$I_{max} = i_{LAI} LAI$$

i_{LAI} (mm m⁻²) is set to a constant corresponding to the interception capacity for liquid precipitation for air temp > 1.2 ° C, or parameterized for snow.

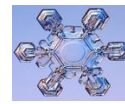


Below $T_{\text{air}} < 1.2^\circ \text{ C}$. ρ is the snow density

$$i_{LAI} = i_{max} \left(0.27 + 46 / \rho_{s,int} \right)$$

Table 1: Interception capacity of rain and snow, typical values reported in literature.

Quality of precipitation	i_{LAI} (mm m ⁻²)	Source
Rain	0.1-0.3 mm m ⁻²	Commonly used in GCMs
Snow	$i_{LAI} = i_{max} (0.27 + 46 / \rho_s)$	(Pomeroy1998#99)
	where	
	$i_{max} = \begin{cases} 5.9 & \text{Spruce} \\ 6.6 & \text{Pine} \end{cases}$	(Schmidt & Gluns, 1991)
	4.4 mm m ⁻²	Coniferous, average ρ_s (Essery2003)
	30/LAI	Norway spruce (Koivusalo2002)
	5	Coniferous (Stähli2005)

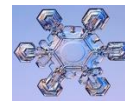


Water unloading from the canopy U (mm day⁻¹) only when the interception storage exceeds the actual interception capacity:

$$U = \max[0, I - I_{max}] / \Delta t$$

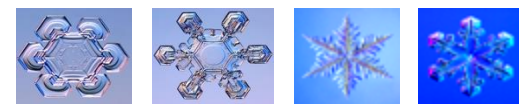
Throughfall T (mm day⁻¹) is then:

$$T = P - \Delta I + U$$



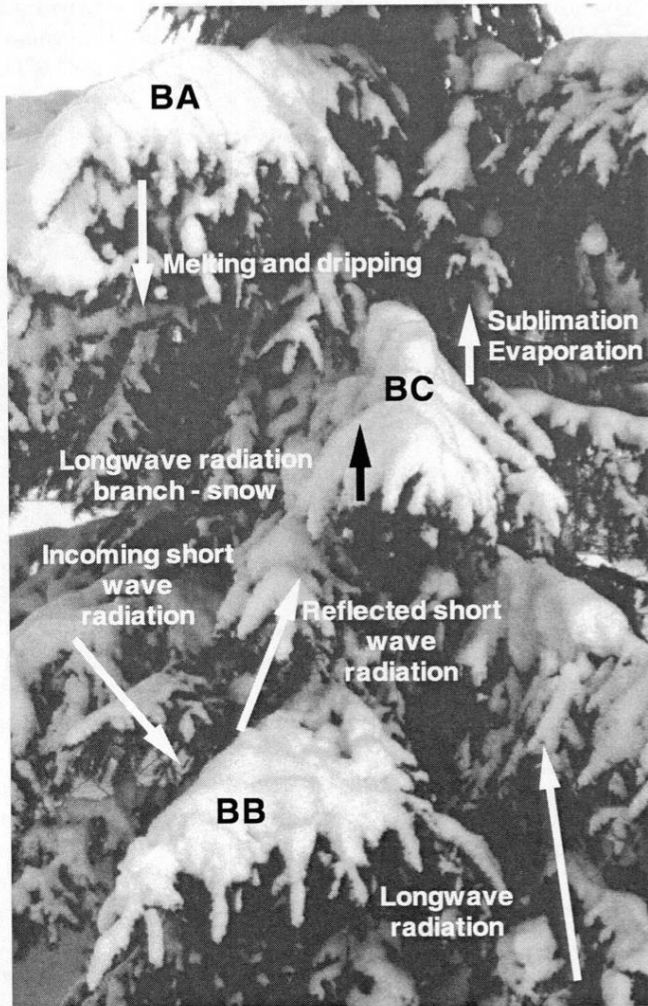
During accumulation (snow canopy interception):

- Albedo is continuously increasing
- Coniferous forests have an albedo of 5-15%. Fresh snow has an albedo > 90%
- Representative daily average albedo values in summer are 20% over grass, 15% for aspen, and 8% for conifer Boreal forests [Betts and Ball, 1997]
- During the initial phase of the accumulation process snow covers only a part of the branch
- The albedo of a snow-covered canopy will never be the same as snow because parts of the canopy are not covered with snow
- *Guttenberger* [1994] suggests an albedo of 30% for a fully snow-covered canopy
- The albedo of the conifer sites in winter rarely reaches 0.3 [*Betts and Ball*, 1997]



Radiation fluxes in a snow-covered canopy are complex:

- Direct and reflected shortwave radiation from trunks, branches, twigs, and needles
- Longwave radiation emitted by trees/intercepted snow
- A portion of the direct incoming short wave radiation is reflected by the snowpack on the ground
- Albedo of intercepted as well as albedo of snow on the ground decreases with age
- The albedo of the snowpack on the ground changes due to needles and twigs which falls from the canopy.



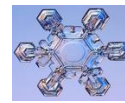
[Michael Bründl, 1997]



Net radiation of the canopy $R_{net,can}$ (W m^{-2}) is assumed to equal the sum of sensible H_{can} (W m^{-2}) and latent LE_{can} (W m^{-2}) heat fluxes
Neglects any storage or sources/sinks of heat within the canopy

$$R_{net,can} = H_{can} + LE_{can}$$

All terms are expressed as non-linear functions of the canopy temperature, and are solved by linearization using the temperature from the preceding time step



Turbulent sensible and latent heat fluxes

$$H_{can} = \frac{\rho c_p}{r_H} (T_{can} - T_{air})$$
$$LE_{can} = \frac{0.622L}{R_a T_{air}} \frac{1}{r_E} (e_{sat}[T_{can}] - e_{air})$$

Where

ρ and c_p are the density and heat capacity of air

T_{can} (K) is the canopy layer temperature

T_{air} (K) is the air temperature in the canopy

e_{air} (Pa) is the actual vapour pressure in the air of the canopy

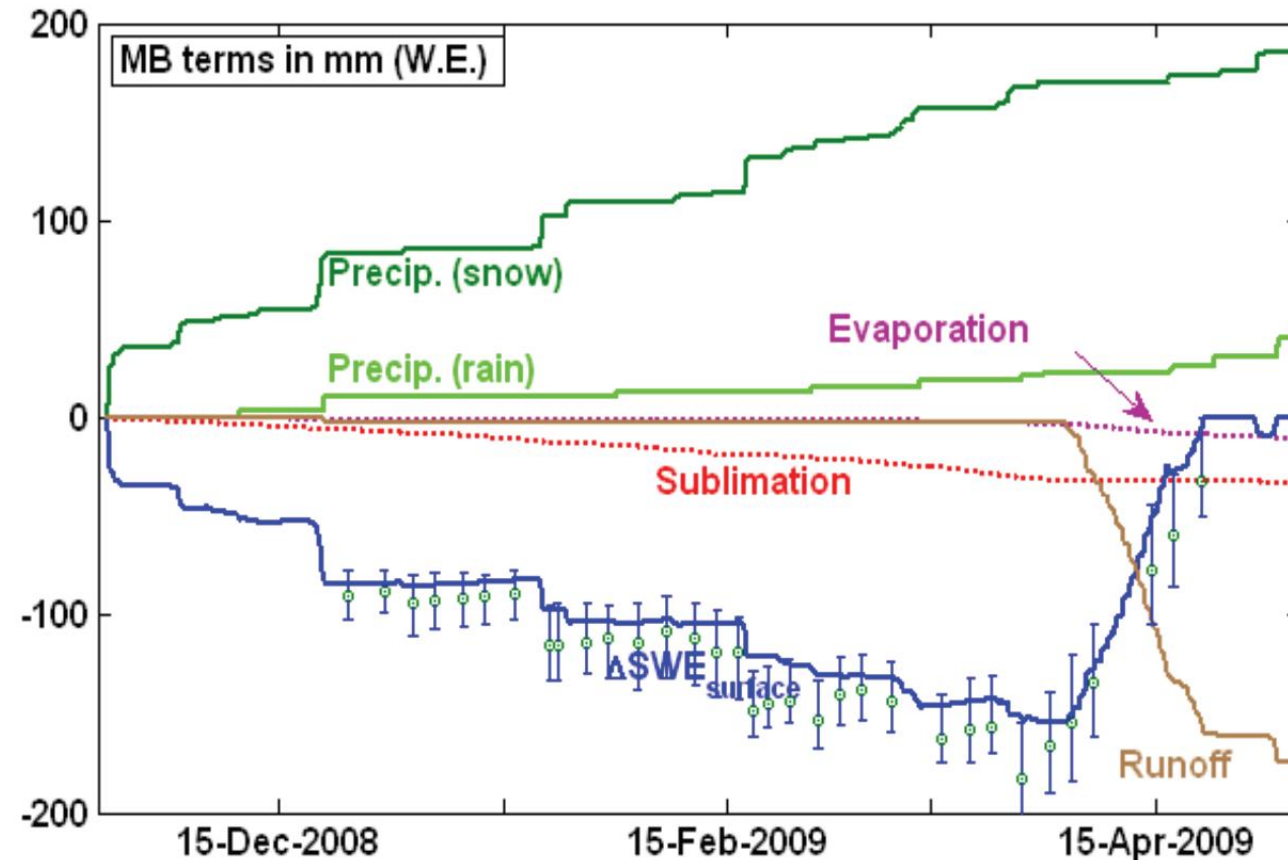
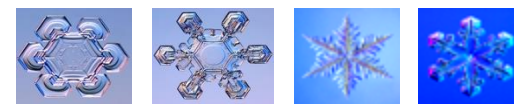
L (*unit*) is the latent heat of vaporization (or sublimation when $T_{air} < 273.15$ K)

R_a is the gas constant for air

$e_{sat}[T_{can}]$ (Pa) is the saturated vapour pressure corresponding to the canopy temperature

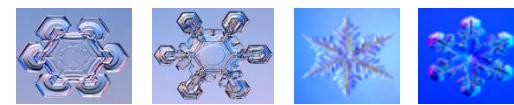
r_H (sm^{-1}) and r_E (sm^{-1}) are the canopy resistances for sensible and latent heat and should be equal

Snow below Canopy

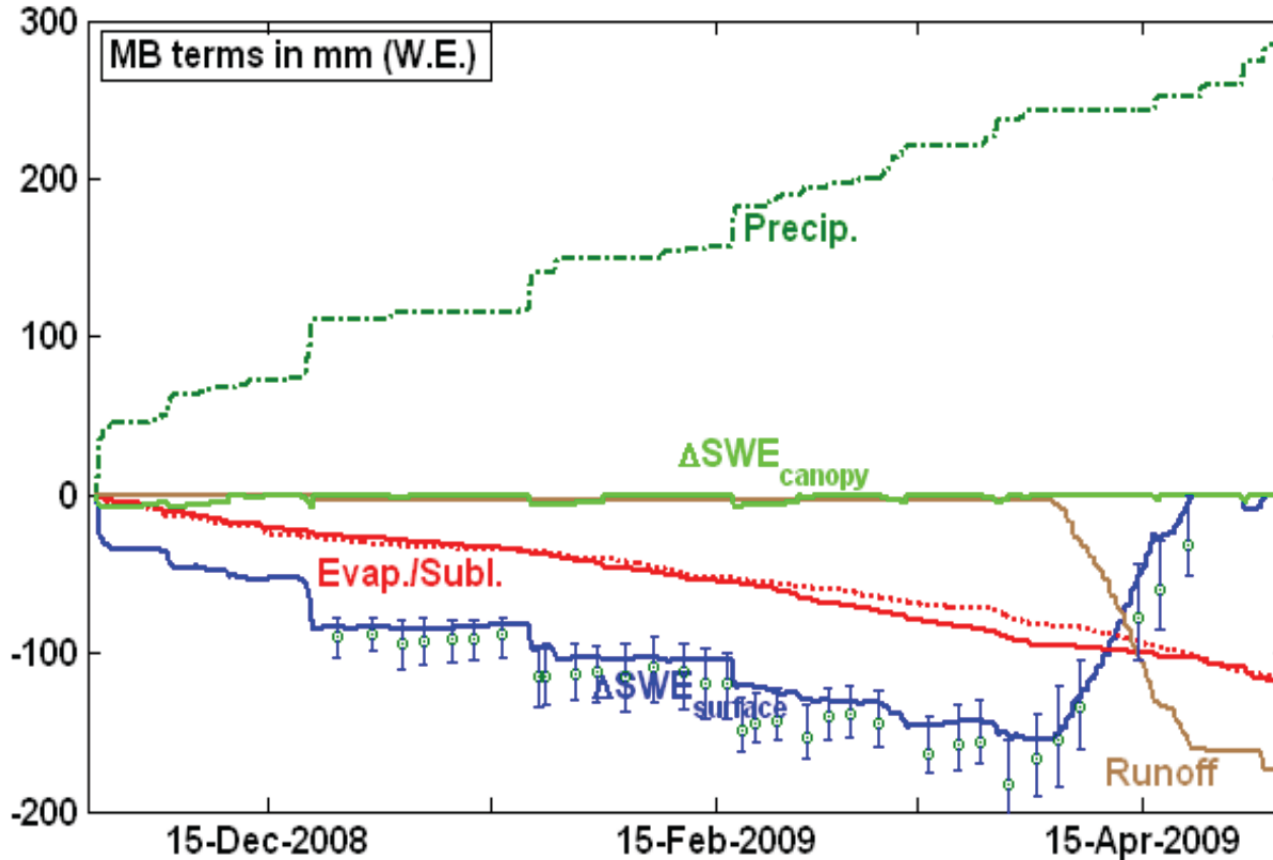


Cumulative mass balance terms for a below-canopy SNOWPACK simulation. The blue (negative) curve can be interpreted as the total SWE of snow below the tree (which is of course positive).

Snow including on Canopy

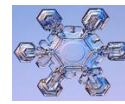


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Cumulative mass balance terms for a below-canopy SNOWPACK simulation including the snow on the tree. The blue (negative) curve is the total SWE of snow on and below the tree (which is of course positive).

But: Snow in forests is not uniform



33

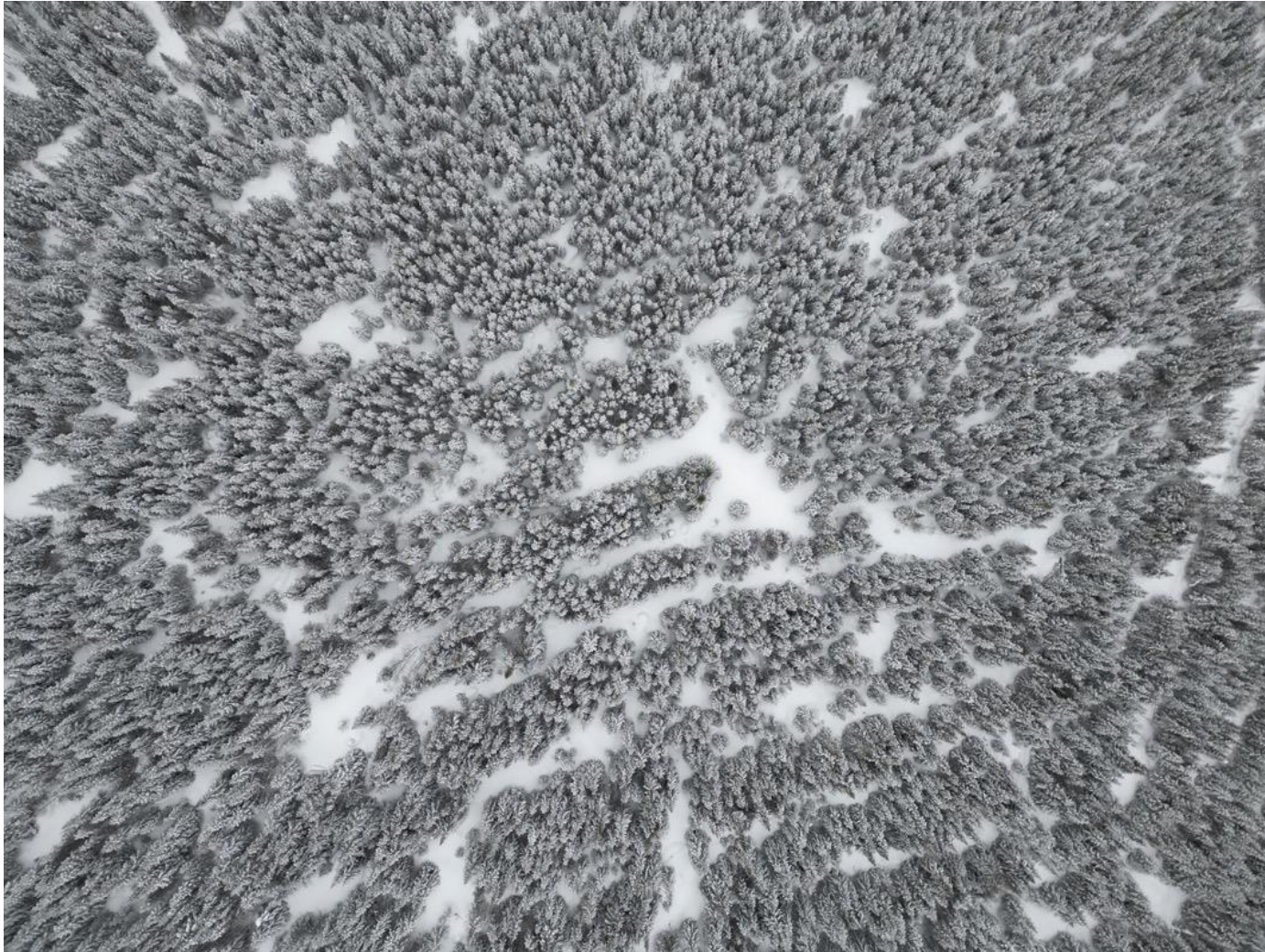
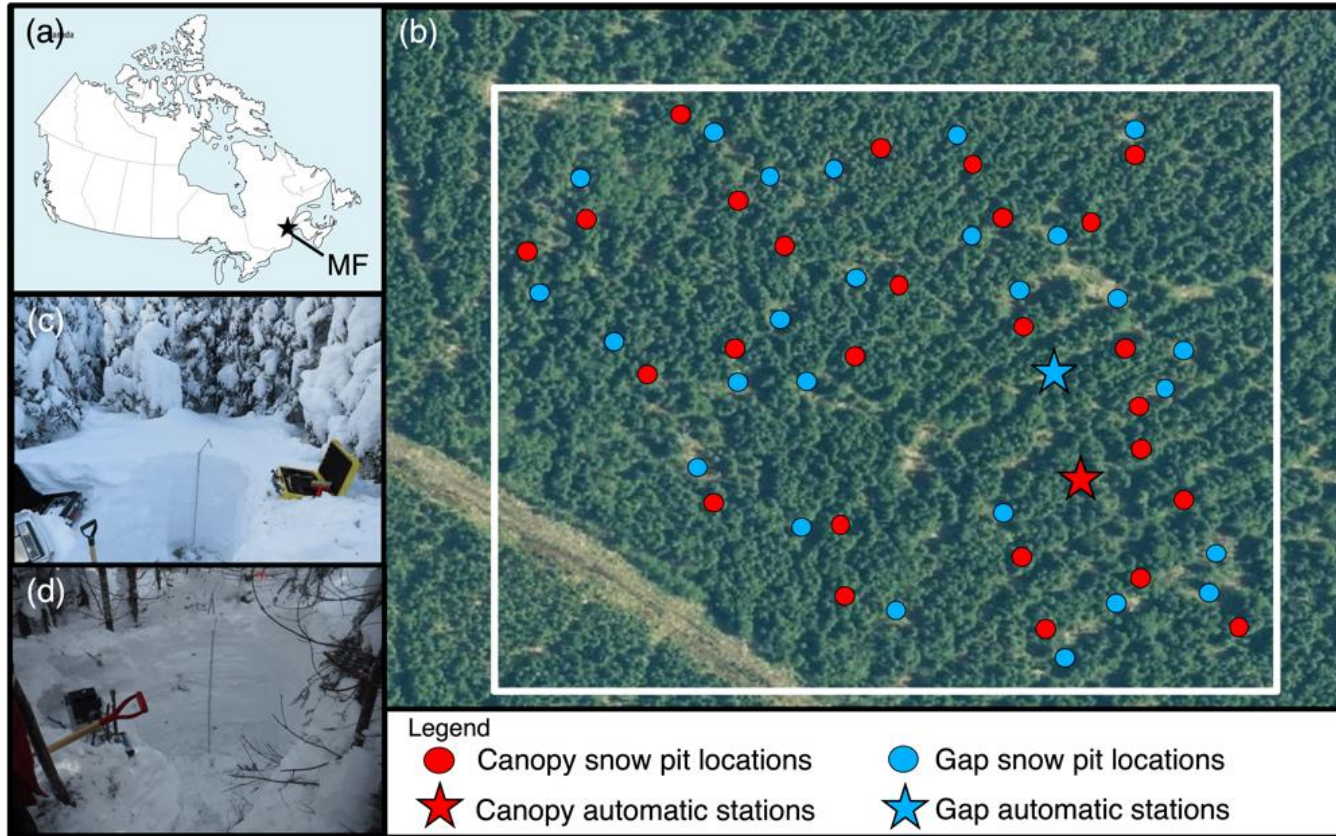
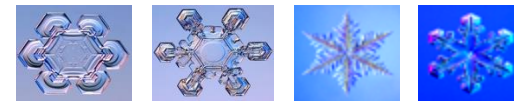


Photo: Montmorency Forest, Qc
(Bouchard, B, 2023)

New measurements in the Boreal Forest



Montmorency
Forest (~ 60 km
north of Quebec
City)

Weekly snow profile measurements (gaps and under the canopy)

Snow temperature

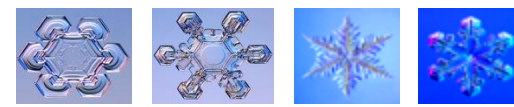
Snow density

Grain shape

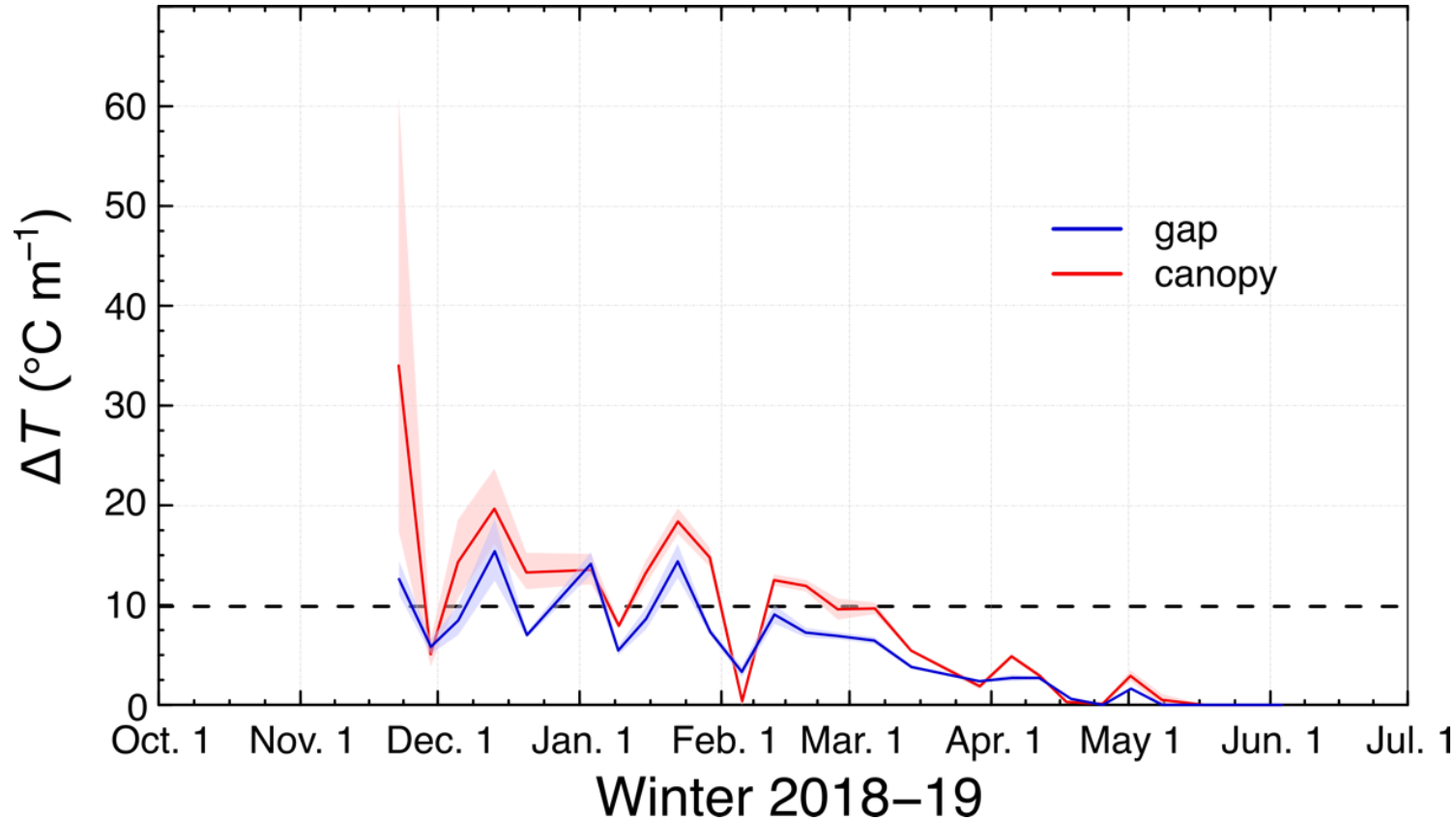
SSA

Winter 2018-19

Different Temperature Gradients



Vertical temperature gradient (ΔT)

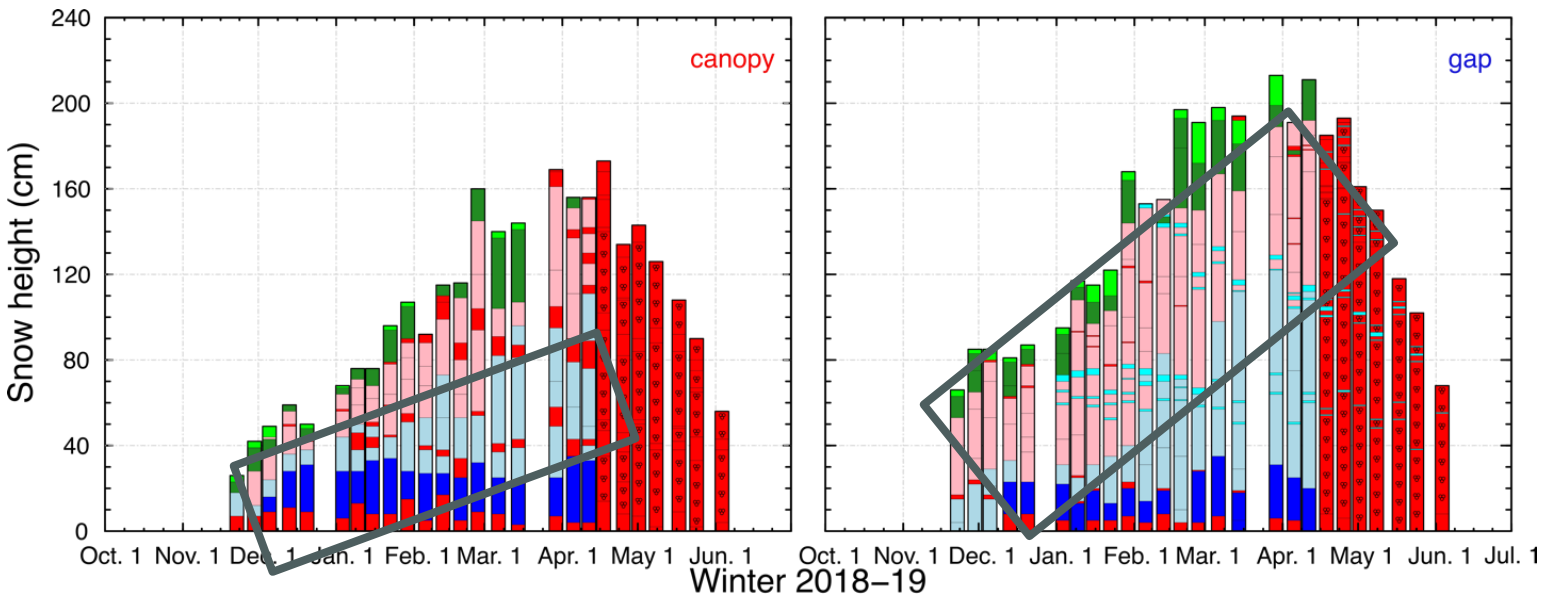
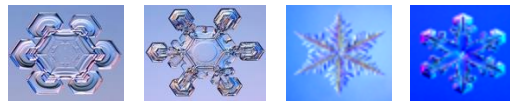


Less snow accumulation
under the canopy



Stronger vertical temperature
gradient (ΔT)

Observed Snow Structure for Canopy and Gap



- Precipitation Particles (PP)
- Decomposed and Fragmented precipitation particles (DF)
- Rounded Grains (RG)
- Faceted Crystals (FC)
- Depth Hoar (DH)
- Ice Layers (IL)
- Rounded Polycrystals (MFpc)
- Clustered Rounded Grains (MFcl)

Stronger ΔT under the canopy



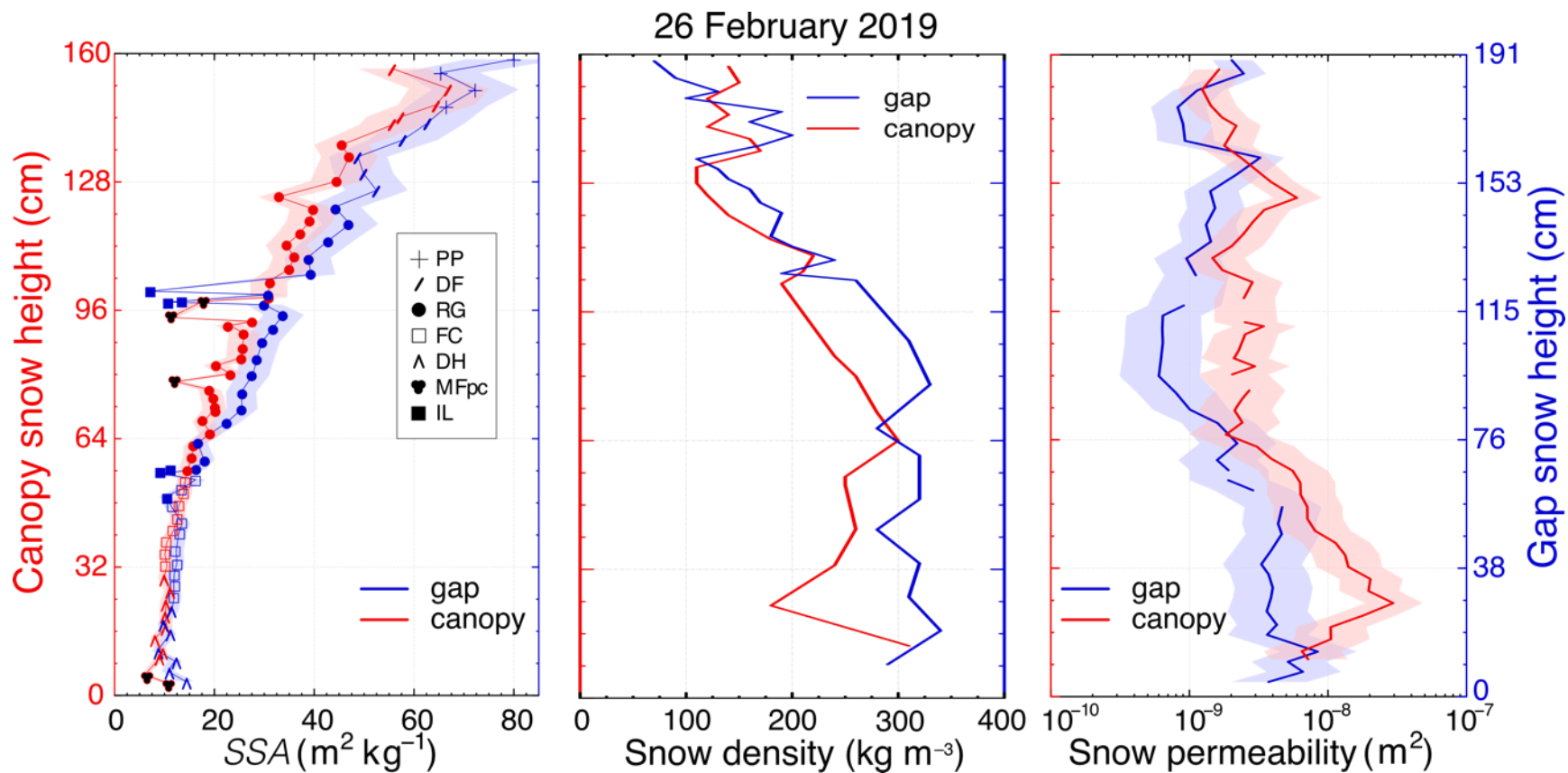
Faceting, depth hoar
(gradient metamorphism)

Weaker ΔT inside gaps



Rounded grains
(equi-temperature metamorphism)

Observed Structure Differences (SSA and Permeability)

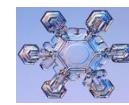
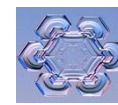


Lower SSA (larger grains) and lower density under the canopy

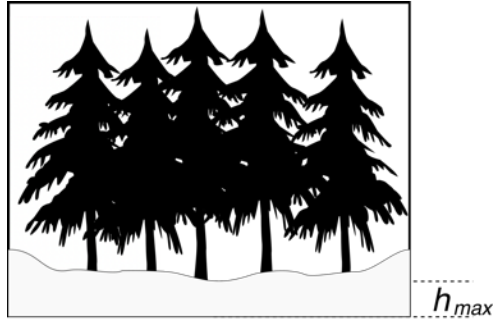


Higher permeability

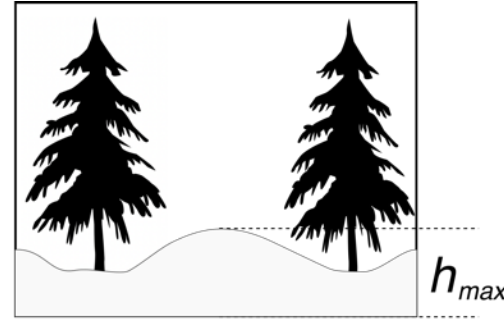
Influence on Permeability (K_s) and Thermal Conductivity



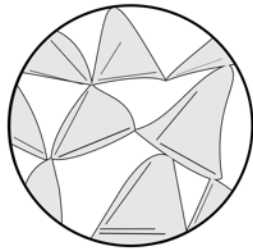
Canopy



Gaps

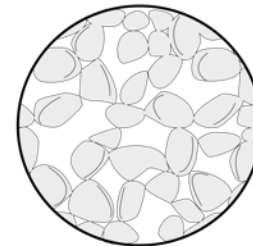


$\Delta T \uparrow$

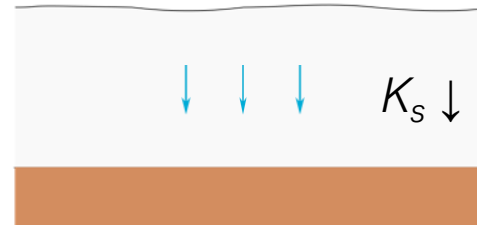
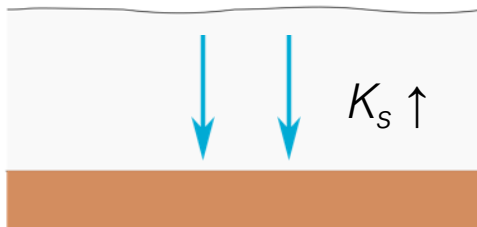


$\rho_s \downarrow, r_g \uparrow$

$\Delta T \downarrow$

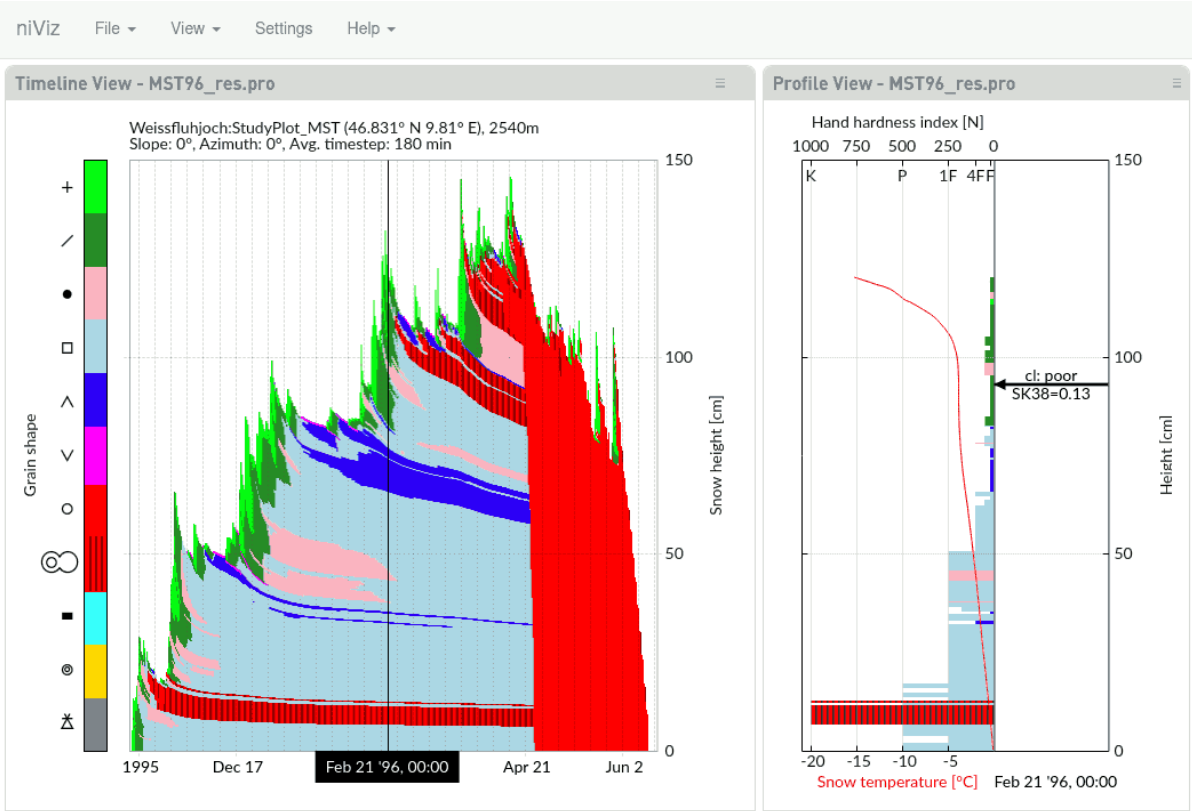
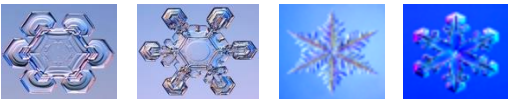


$\rho_s \uparrow, r_g \downarrow$



Question: What is the influence on thermal conductivity and consequently soil temperatures?

Can we simulate canopy with gaps for on runoff prediction?



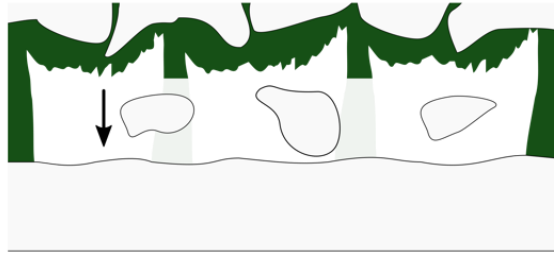
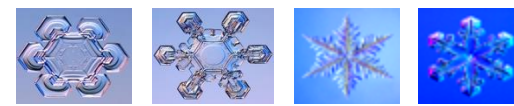
Resolution of Richards equations for matrix and preferential flow (Wever et al. 2016)



Canopy module resolving mass and energy exchanges between snow and vegetation (Gouttevin et al., 2015)



Introducing Canopy Snow Metamorphism

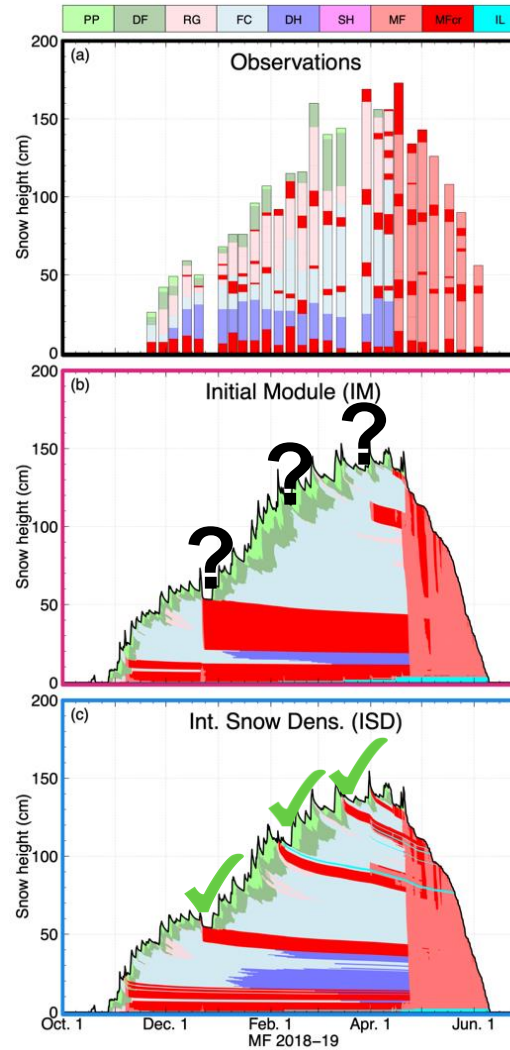


Original model

Unloading of **fresh** snow:
low density
precipitation particles

Modified model

Unloading of **metamorphized** snow:
intercepted snow densification
small rounded grains



The improved consideration of higher density and grain shape (more rounded) for snow that unloads improves the simulations of snow structure including ice lens formation and runoff timing.

Acknowledgement Ben Bouchard:

<https://doi.org/10.5194/tc-18-2783-2024>
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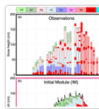
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20 Jun 2024

Impact of intercepted and sub-canopy snow microstructure on snowpack response to rain-on-snow events under a boreal canopy

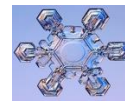
Benjamin Bouchard, Daniel F. Nadeau, Florent Domine, Nander Wever, Adrien Michel, Michael Lehning, and Pierre-Erik Isabella



RESEARCH ARTICLE

Comparison of snowpack structure in gaps and under the canopy in a humid boreal forest

Benjamin Bouchard, Daniel F. Nadeau, Florent Domine



- Processes are highly complex and variable, and quantitative understanding of energy and mass exchanges is limited
- Recent progress in observations, understanding and modelling
- There is less snow below trees but it does not melt earlier; Below – canopy climate is rather cooler (soil temperatures)
- Snow below the canopy is denser at the surface partly because of unloading and has strong spatial variability, higher permeability but also more crusts and ice lenses
- A modified SNOWPACK reproduces gap and canopy snow reasonably well; however full variability is hard to capture