

Improved representation of forest snow processes in coarse-resolution models: Lessons learnt from upscaling hyper-resolution simulations

Giulia Mazzotti, Clare Webster, Richard Essery, Johanna Malle, Tobias Jonas

EGU21-15226 | HS2.1.7 | 29. April 2021



vPICO navigation shortcuts:



*to previous
slide*



*back to
overview*



*to next
slide*



*direct link to
section / topic*



WSL Institute for Snow
and Avalanche Research SLF



Overview

1. Introduction

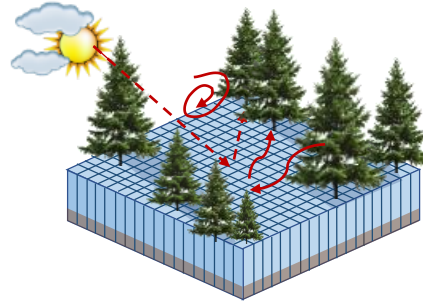
*Why forest snow?
Why process-based
modelling?*

2. Observations



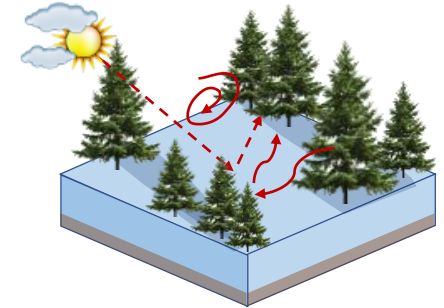
*Mobile multi-sensor setups
designed to measure forest snow
process variability*

3. Hyper-resolution model



*Model to capture small-scale
forest snow process variability
evaluated at the process level*

4. Coarse-resolution model



*Model with sub-grid representation
of forest snow processes derived
from upscaling experiments*

References

Contact

5. Conclusion

*Recap of main findings
Outlook*

Motivation

- Snow cover is a key element of our climate system: It controls land surface energy exchange through its high albedo and affects eco-hydrological processes by acting as freshwater storage and insulating material.
- Forests and seasonal snow overlap over large areas. Both snow cover regimes and forest structure are experiencing rapid changes (climate warming, wildfires, ...)
- Snow cover dynamics is shaped by complex processes that are over-simplified in conceptual models. Process-based models are thus necessary 1) for snow-hydrological forecasting and 2) to predict the impact of ongoing environmental change.



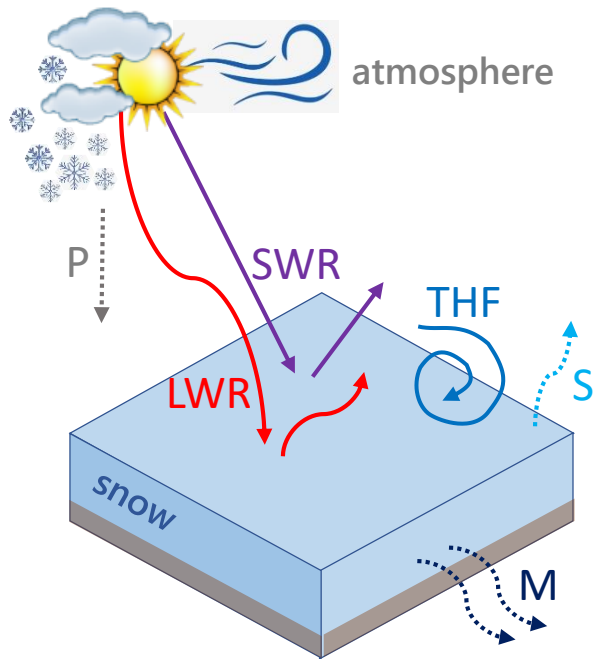
Background on forest
snow processes

Research challenges
and objectives

East Troublesome Fire, Fall 2020 – the Denver Post

Background

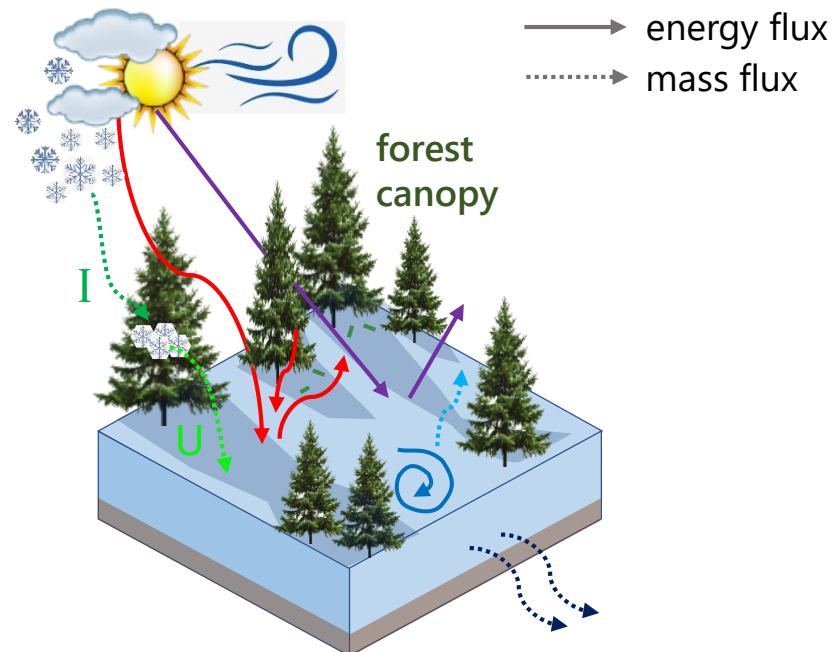
OPEN TERRAIN



$$\Delta M_{\text{snow}} = P - M - S$$

$$\Delta E_{\text{snow}} = \text{SWR}_{\text{net}} + \text{LWR}_{\text{net}} + \text{THF}$$

FOREST TERRAIN



$$\Delta M_{\text{snow}} = P + U \left[-S - M \right] - I$$

altered energy balance

$$\Delta E_{\text{snow}} = \left[\text{SWR}_{\text{net}} \right] + \left[\text{LWR}_{\text{net}} \right] + \left[\text{THF} \right]$$

shading canopy emittance reduced wind

- Trees impact all mass and energy exchange processes in forests
- Snow cover dynamics below forest canopy are therefore fundamentally different from those seen in open areas
- Process-based models need to adequately represent forest-snow processes

Background

- Forest snow processes exhibit strong variability at very small spatial and temporal scales
- Forest snow process dynamics thus result in heterogeneous snow accumulation and melt patterns and in complex, time-varying land surface properties

shaded snow:

- low radiative energy input
- little reflected solar radiation



intercepted snow:

- high reflectivity
- reduced accumulation



sunlit snow

- high radiative energy input
- high reflected solar radiation

snow-free canopy

- high absorption of solar radiation
- emission of thermal radiation



snow-free ground

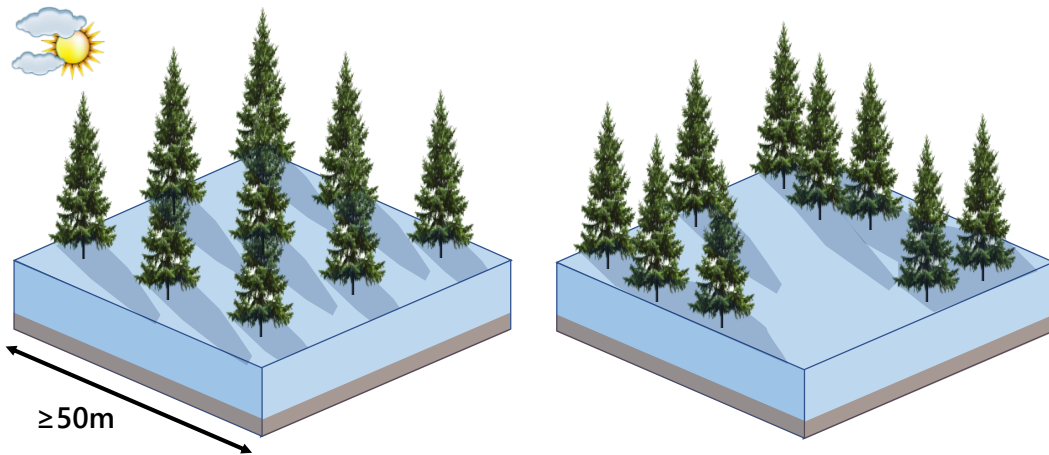
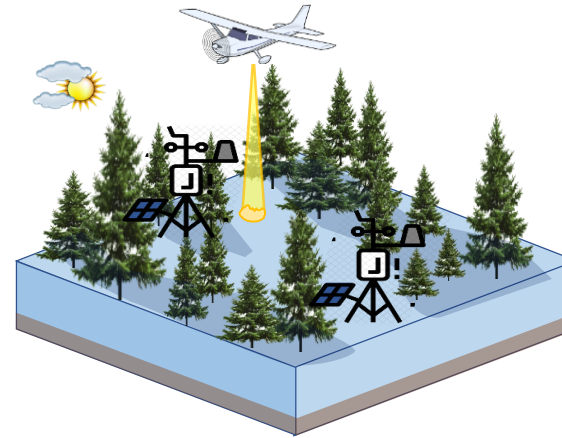
- high absorption of solar radiation
- reduced reflectivity

Research challenges

Typical model grid cells are larger than the spatial scale at which forest snow processes vary and interact (> 50 m vs. < 5 m). This scale mismatch entails two major research challenges:

1. Observational challenge

- It is very difficult to obtain process-level observations representative of entire grid cells
- Stationary sensors capture only limited areas
- Airborne LiDAR captures snow distribution, which is the sum of many processes



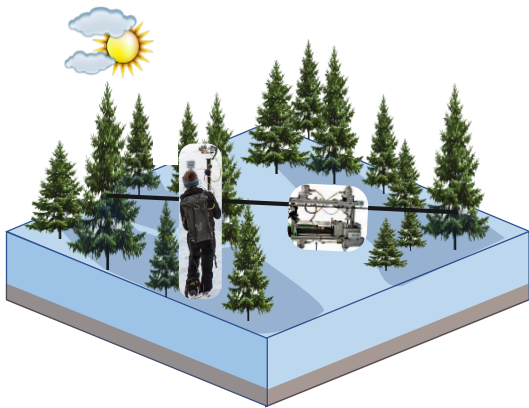
2. Modelling challenge

- Two grid cells with equal 'amount' of canopy but different horizontal arrangement are treated equally in most models
- However, their snow cover dynamics have been shown to be different based on snow distribution datasets from airborne LiDAR (Mazzotti et al. 2019a)

Research goals / approach

Bridge the gap between observed small-scale variability of forest snow processes and their representation in coarse-resolution models, using hyper-resolution modelling as intermediary step.

1. Process observations

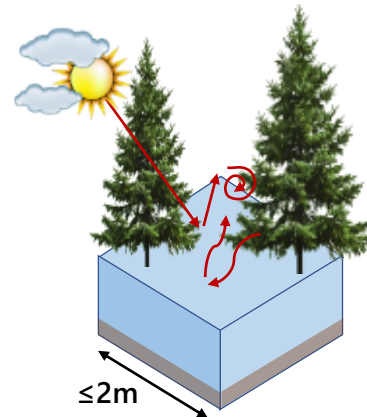


- Understand true process variability
- Small spatial scales
- Link to canopy structure

*process level
evaluation*



2. Point-scale / hyper-resolution modelling

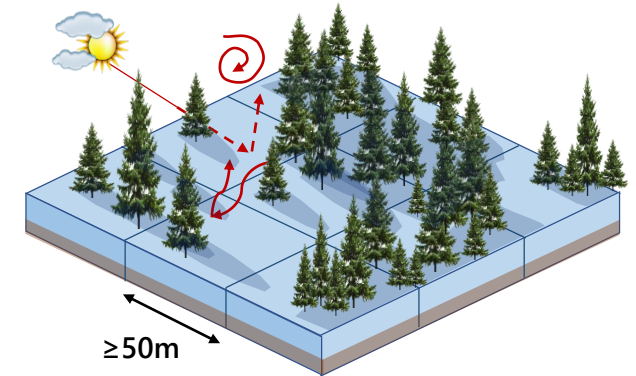


- Each process = $f(\text{meteo, canopy structure})$
- Explicit representation of process variability
- Direct comparison to measurements possible

*model
upscaling*



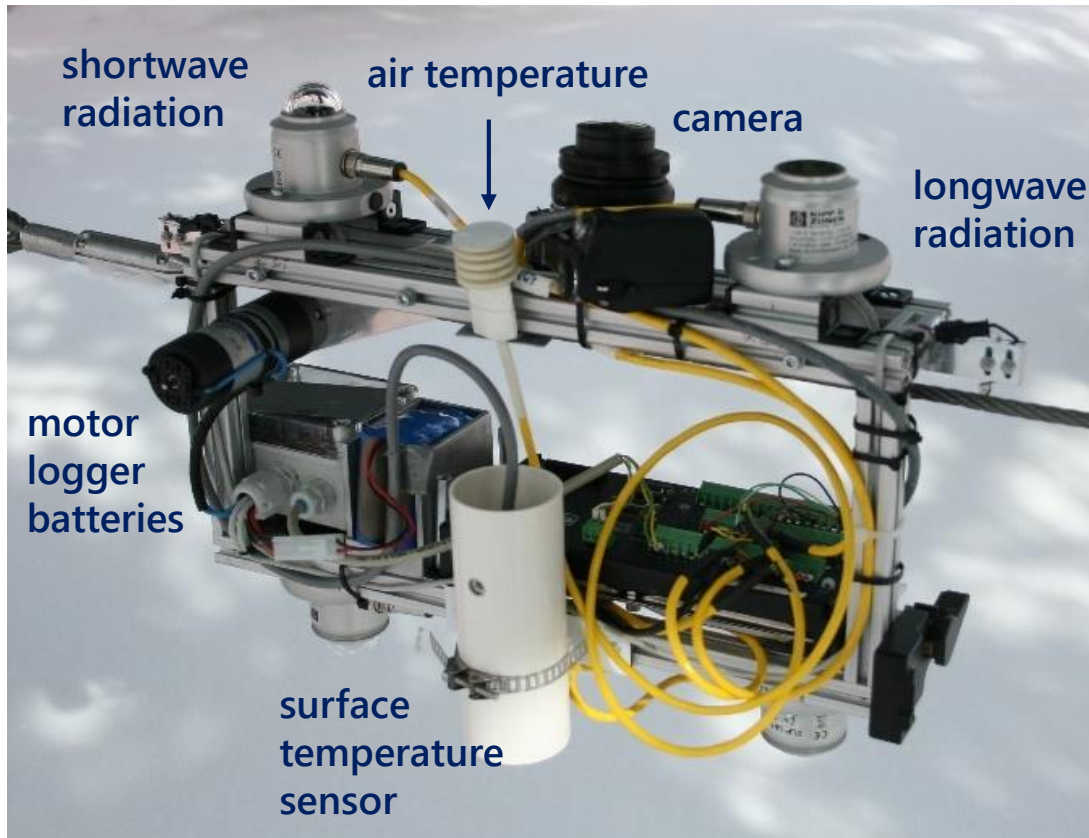
3. Large-scale / coarse-resolution modelling



- Spatially averaged processes
- Strategy to implicitly represent process variability
Inferred with model upscaling experiments

Mobile multi-sensor platforms

- Motorized cable car system
- Spatio-temporal variability along forest transects



Malle et al. (2019); Mazzotti et al. (2019b, 2020a)

- Handheld 'gimbal' system
- Snapshots of 2D spatial patterns

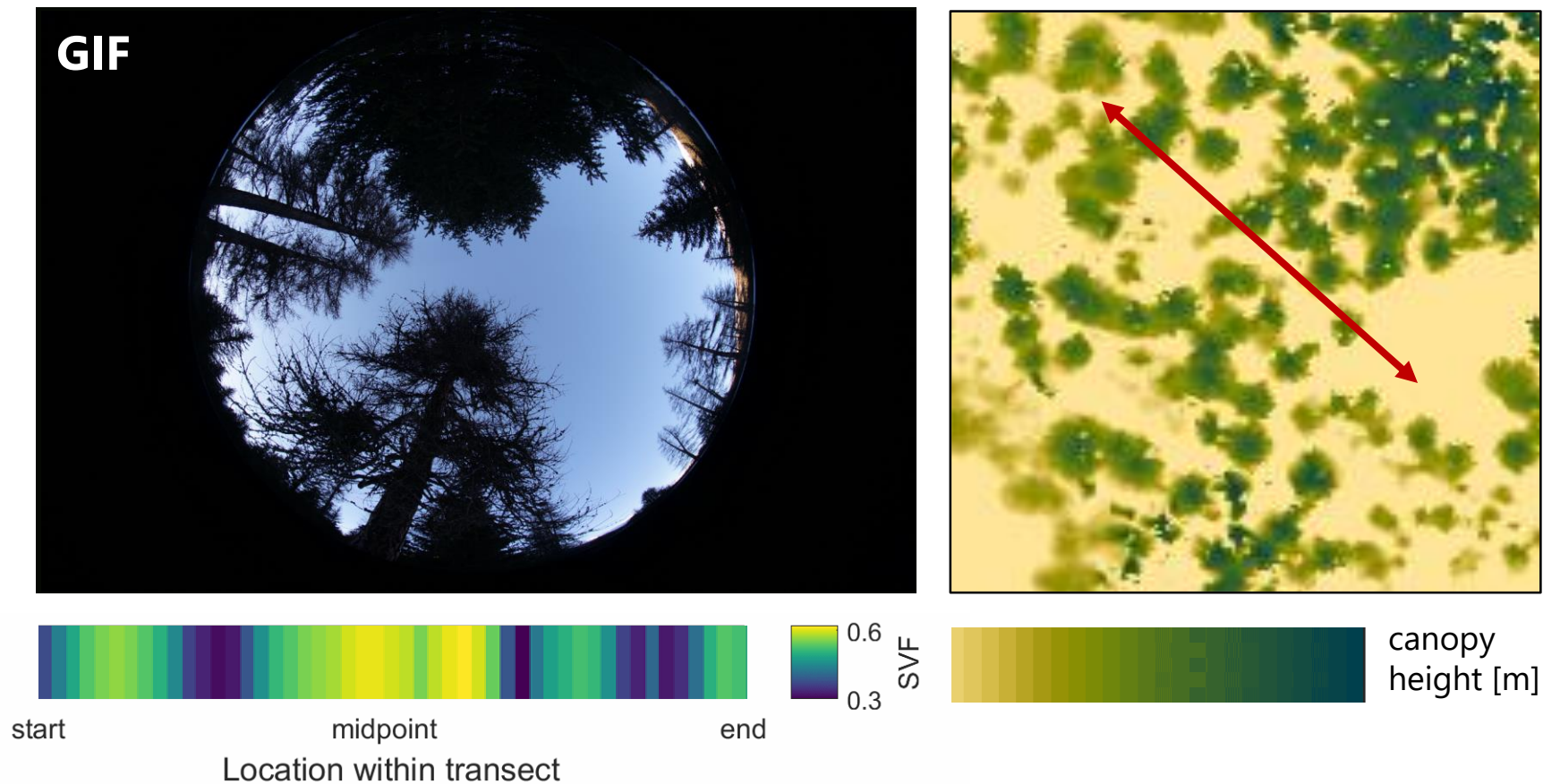


Example
cable car
dataset

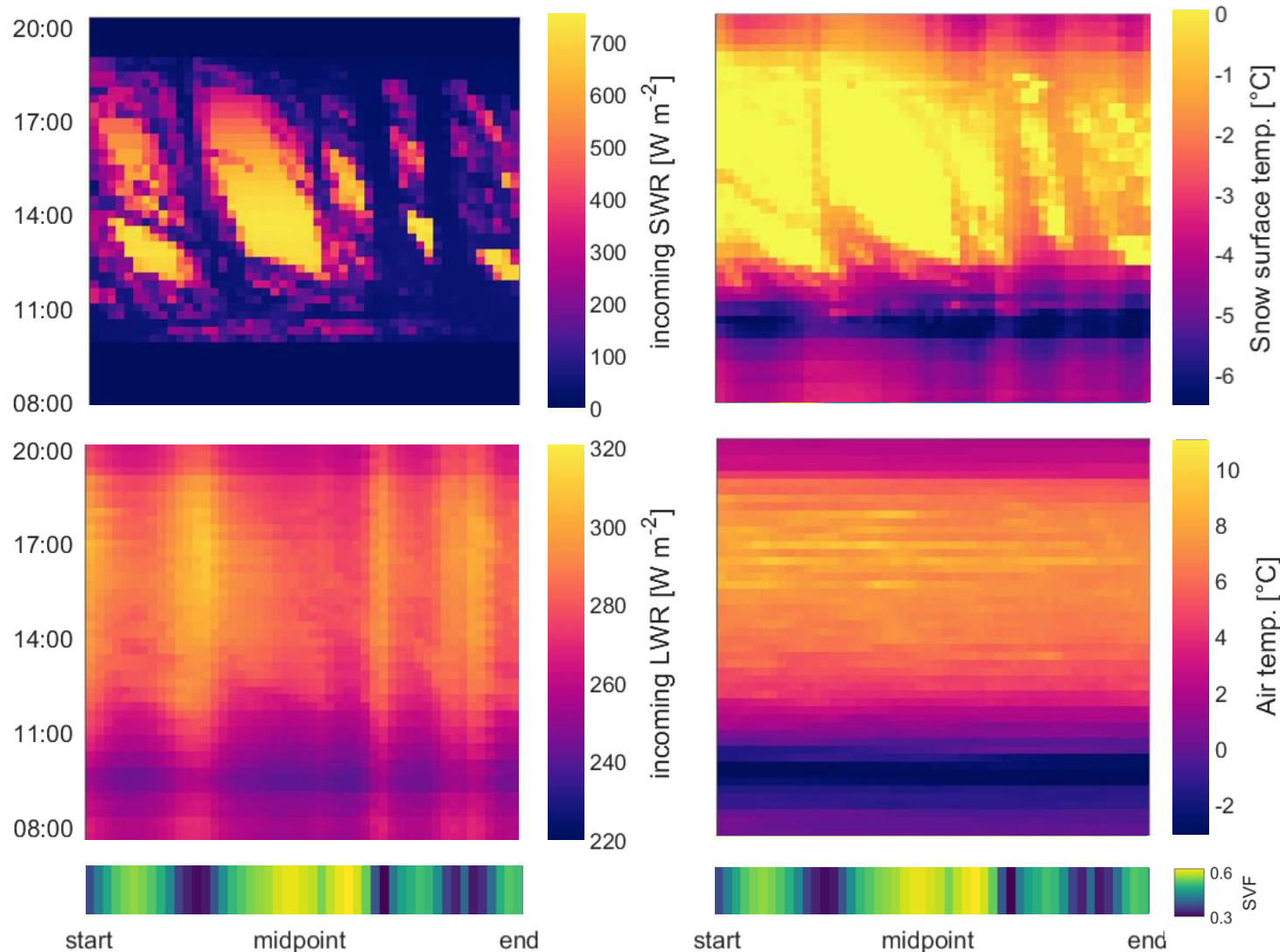
Example
gimbal
dataset

Canopy structure variability

- Example: larch/fir stand in the Engadine, 60m transect
- Within-transect variability: sky-view fraction extracted from hemispherical photography; canopy cover fraction from canopy height model

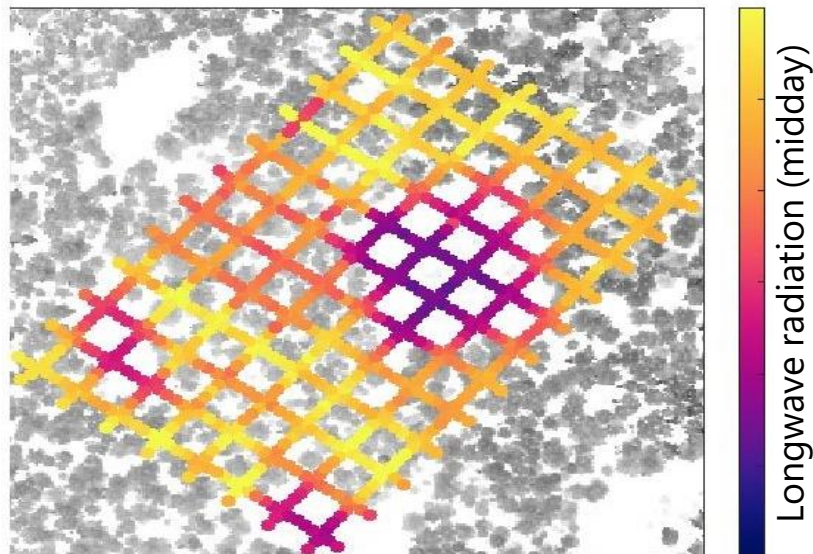
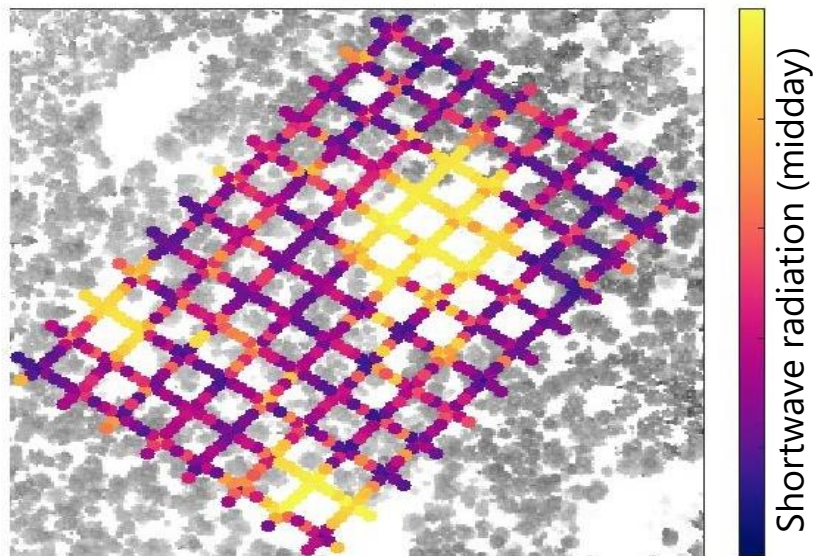
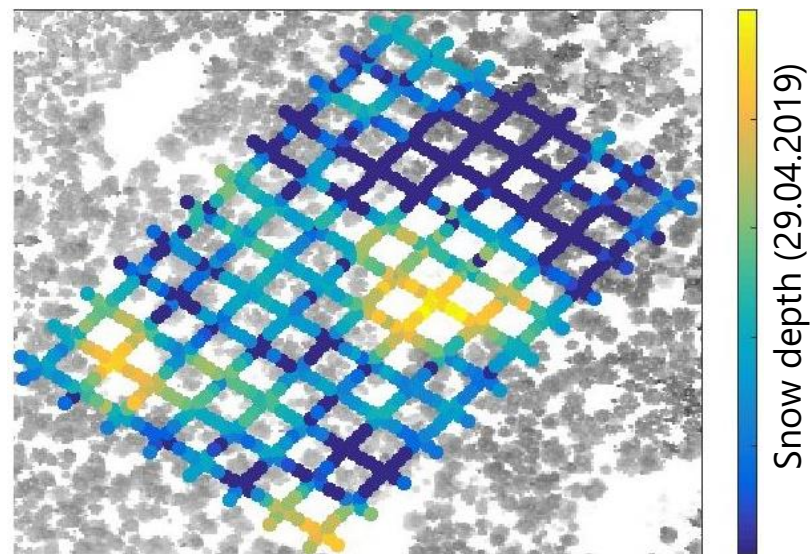
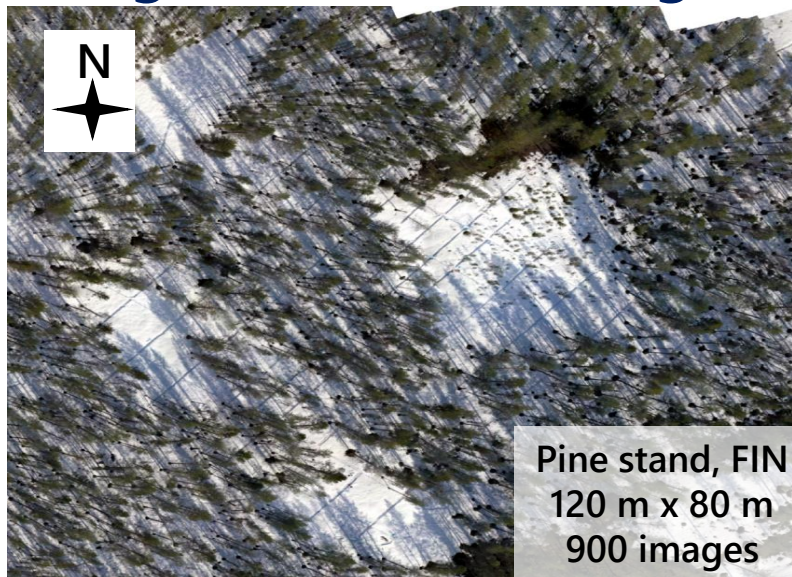


Spatio-temporal variability of energy balance components



- Example: larch/fir stand in the Engadine, 60m transect, clear-sky day Different energy balance components exhibit different variability patterns
- Interactions between processes evident (e.g. imprints of incoming sub-canopy shortwave radiation on snow surface temperature patterns)

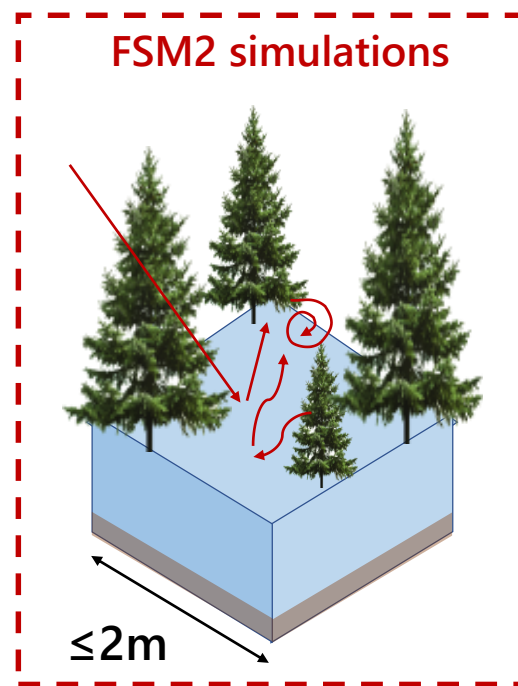
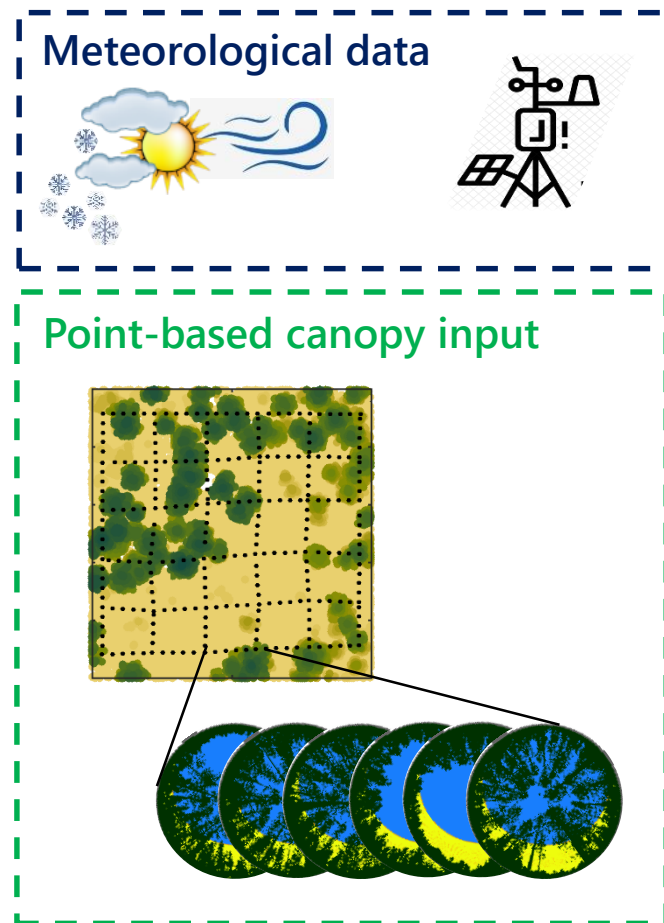
2D-grid dataset from gimbal setup



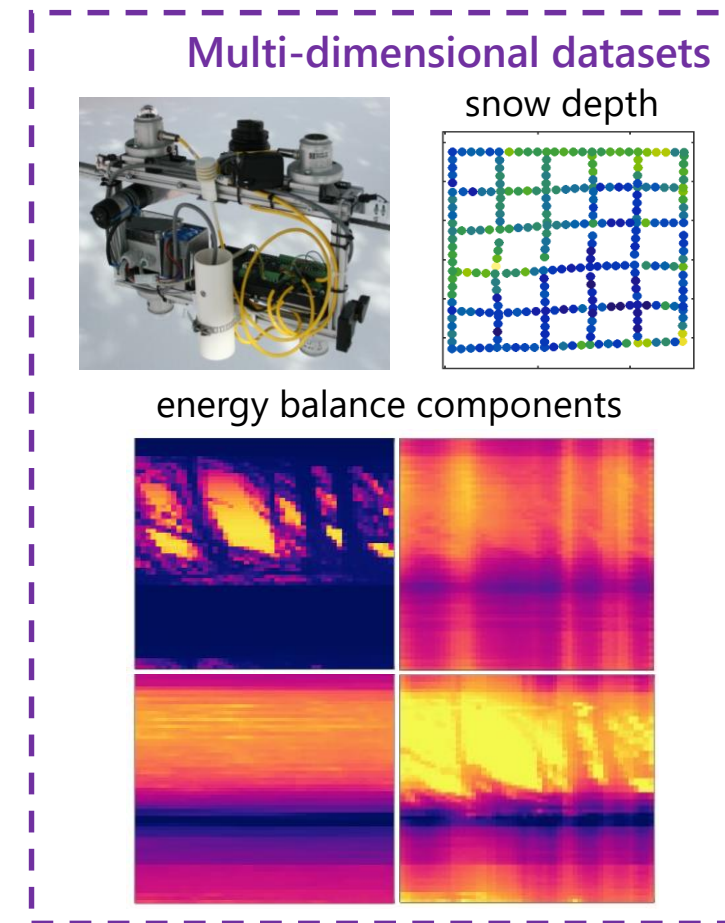
- Pine stand, Sodankylä, Finland
- Large and small artificial gaps
- 120 m x 80 m, 20 transects
- 900 surveyed locations
- Co-located hemispherical images, temporal snapshots of energy balance components, snow depth

Hyper-resolution forest snow modelling with FSM2

FSM2 structure and input



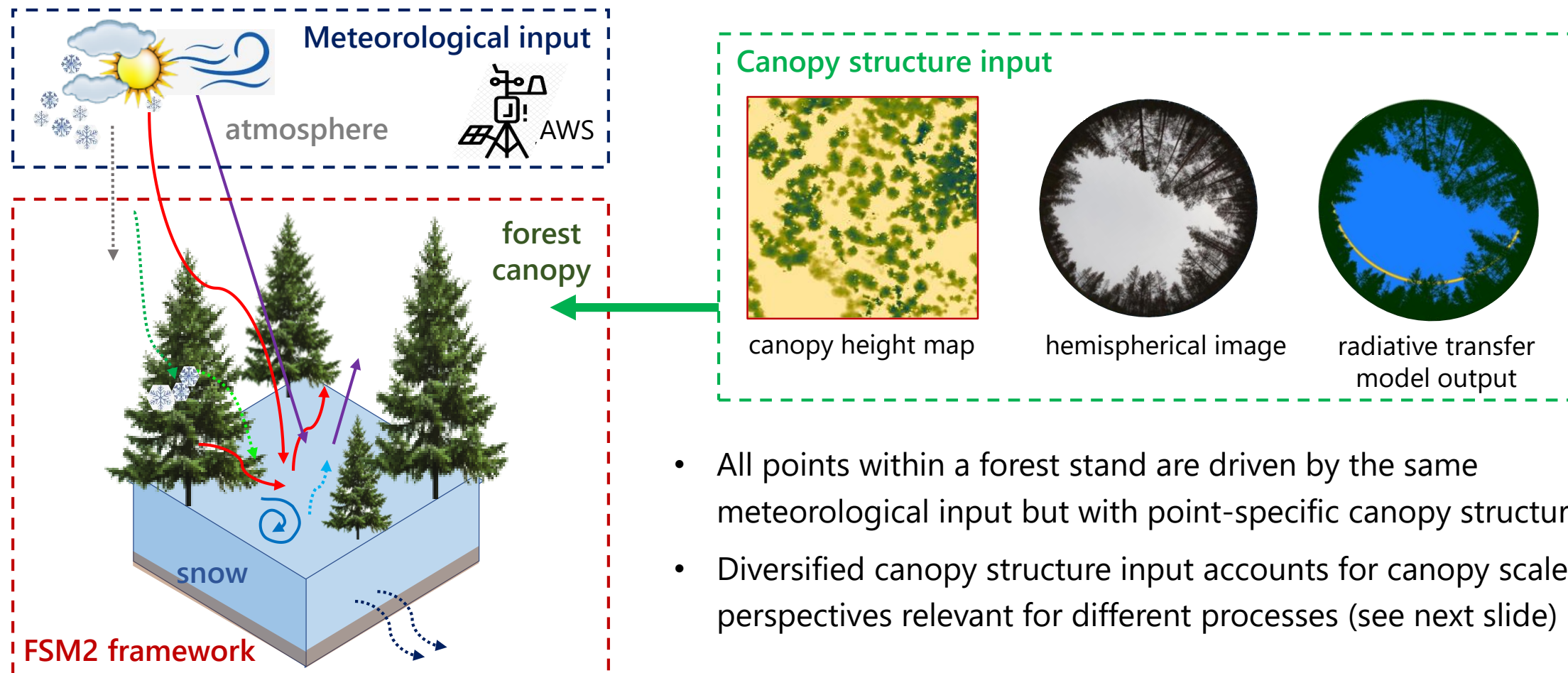
Process-level FSM2 evaluation



Mazzotti et al. (2020a,b)

The Flexible Snow Model (FSM2)

- FSM: Point energy balance model for open areas, few layers (*Essery 2015*)
- FSM2: Added a canopy implementation for application to forested environments (*Mazzotti et al. 2020a,b*)

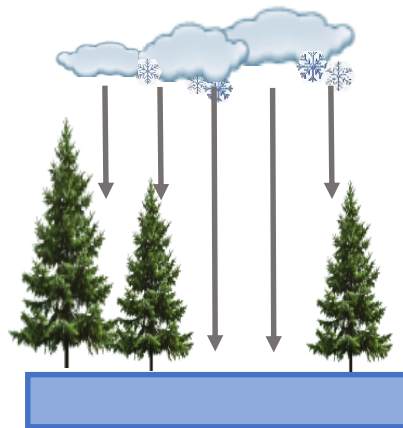


- All points within a forest stand are driven by the same meteorological input but with point-specific canopy structure data
- Diversified canopy structure input accounts for canopy scales and perspectives relevant for different processes (see next slide)

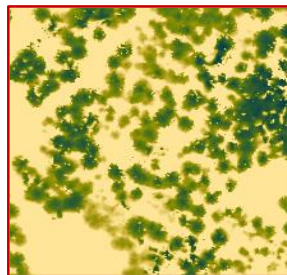
Process-specific canopy scales and perspectives

- In a first 'standard' version of FSM2, we use LAI as only canopy density descriptor (as many common models do)
- However, different processes 'see' different portions of the canopy. In an upgraded ('enhanced') FSM2 version, we use process-specific canopy input to account for these differences

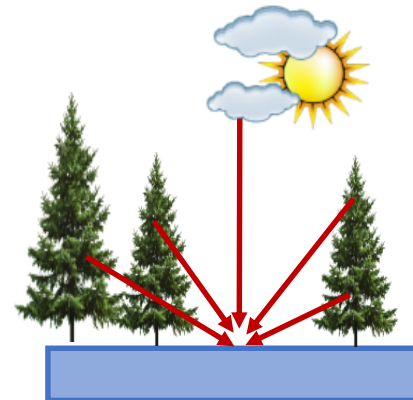
precipitation



vertical, local
canopy height map



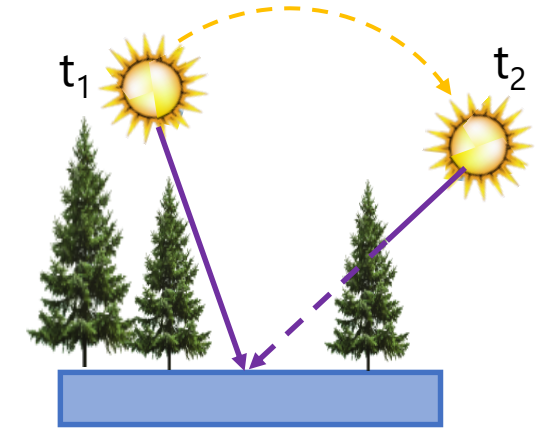
thermal + diffuse solar radiation



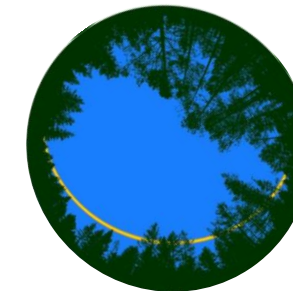
non-directional
hemispherical image



direct solar radiation

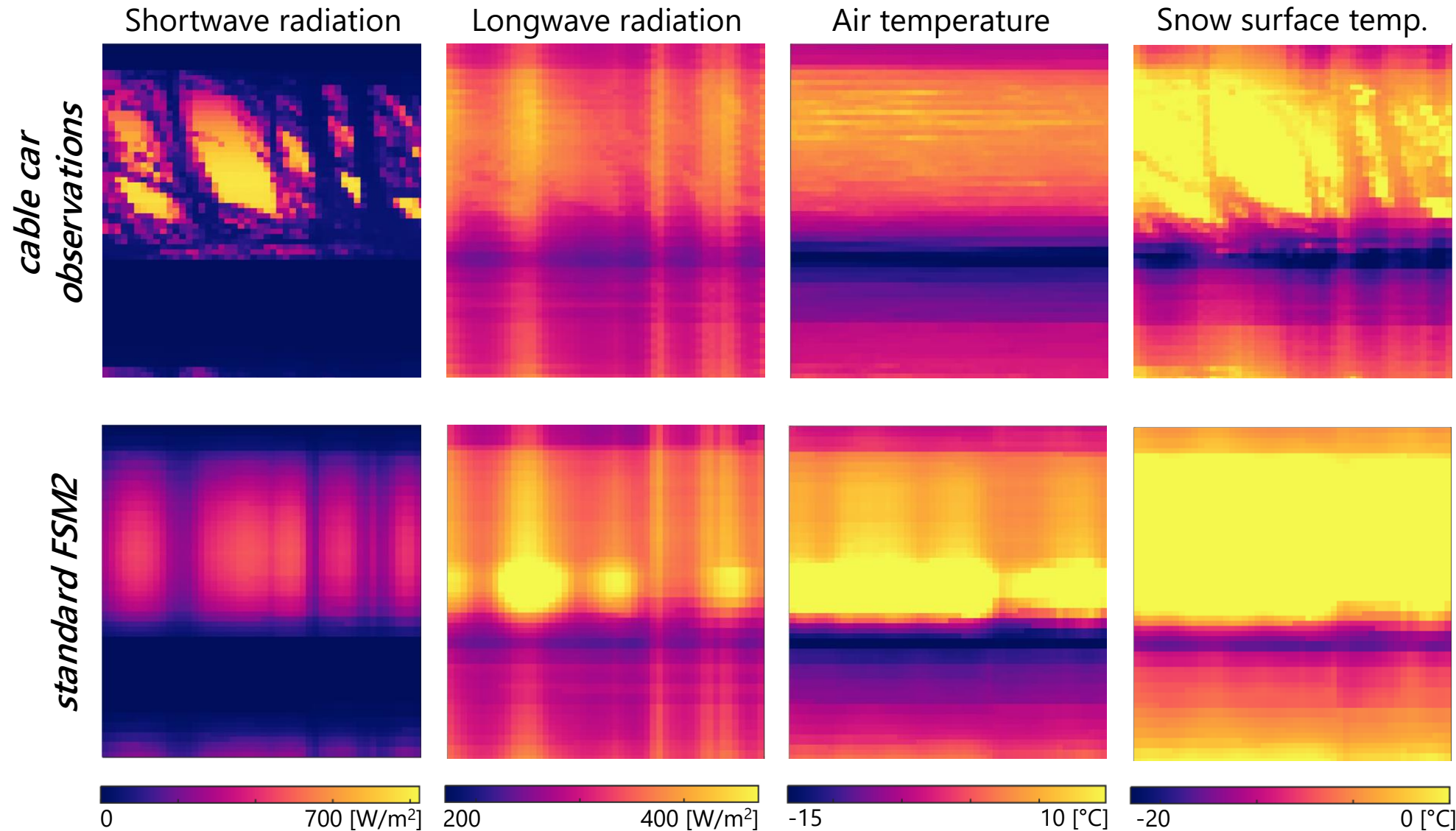


directional, time-varying
external radiation transfer model*



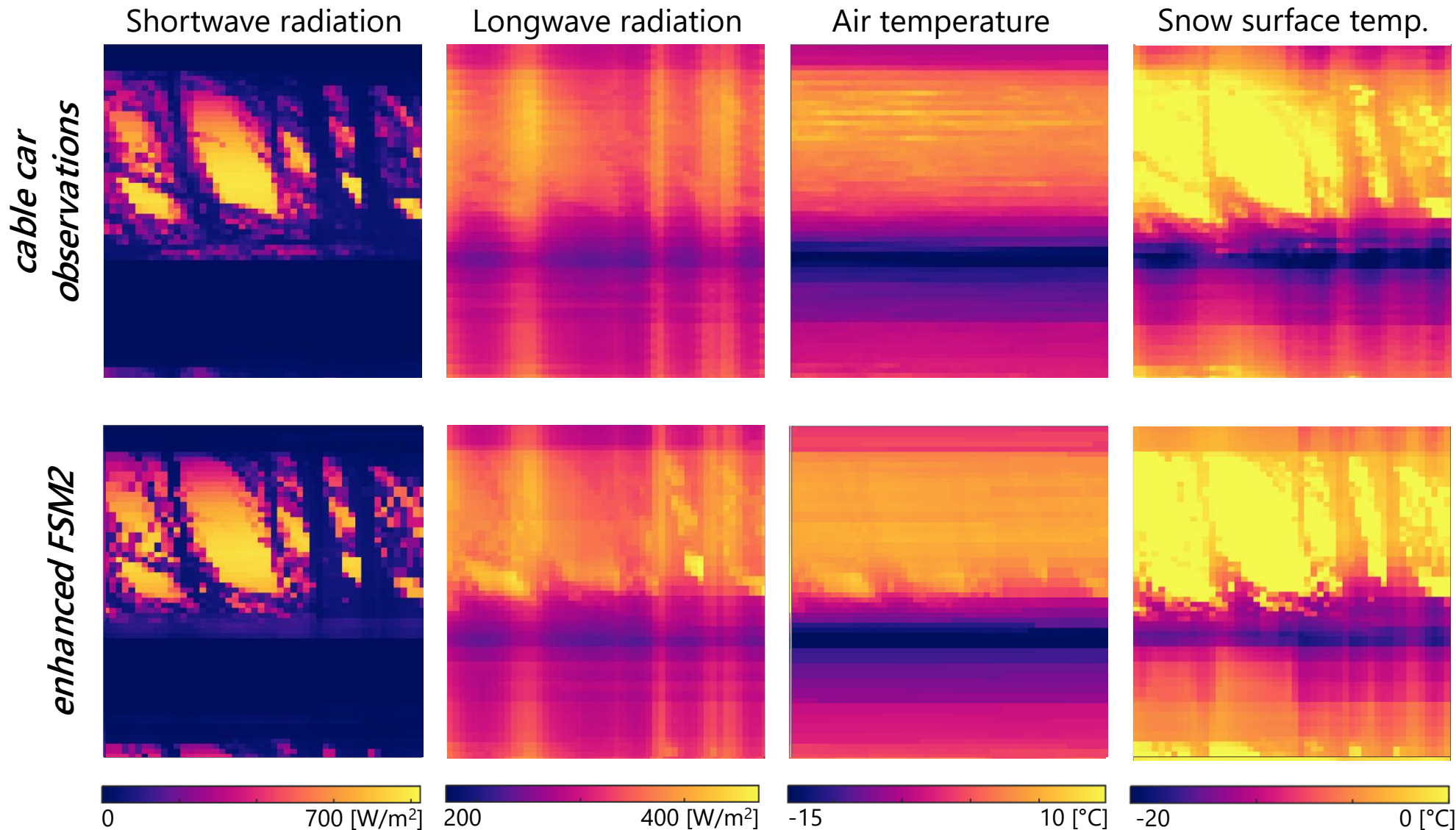
* based on
hemispherical
image analysis
(Jonas et al. 2020)

Energy balance simulations



- Simulations on 50 points along cable car transect, one diurnal cycle
- Spatio-temporal variability captured by standard FSM2 does not match observations

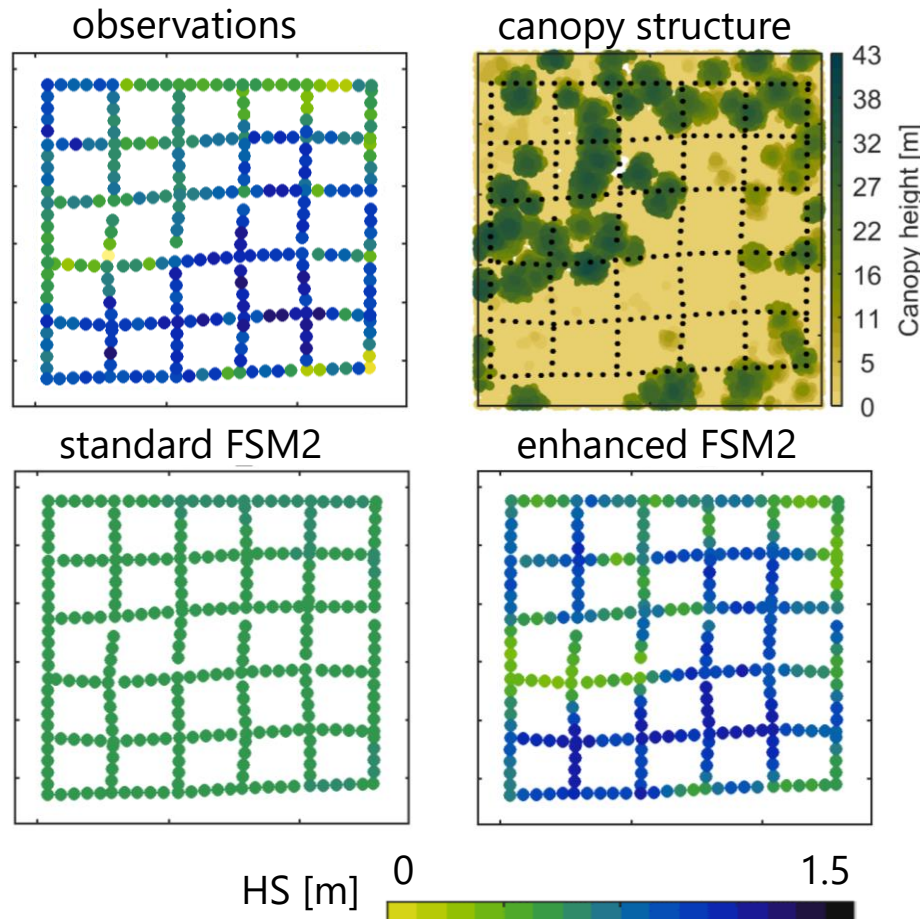
Energy balance simulations



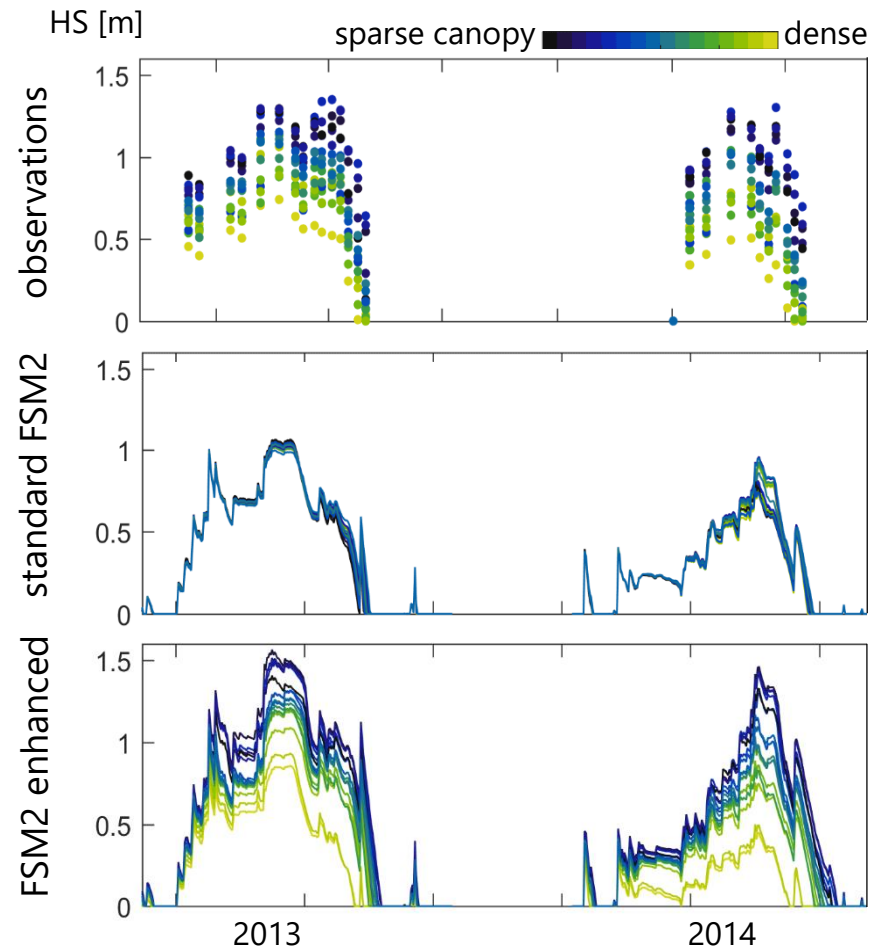
- Enhanced FSM2 captures spatio-temporal patterns of individual processes well
- Process interactions are also represented

Simulation of spatio-temporal snow cover evolution

Spatial patterns on a 50x50m plot
(snapshot on 12 March 2013)



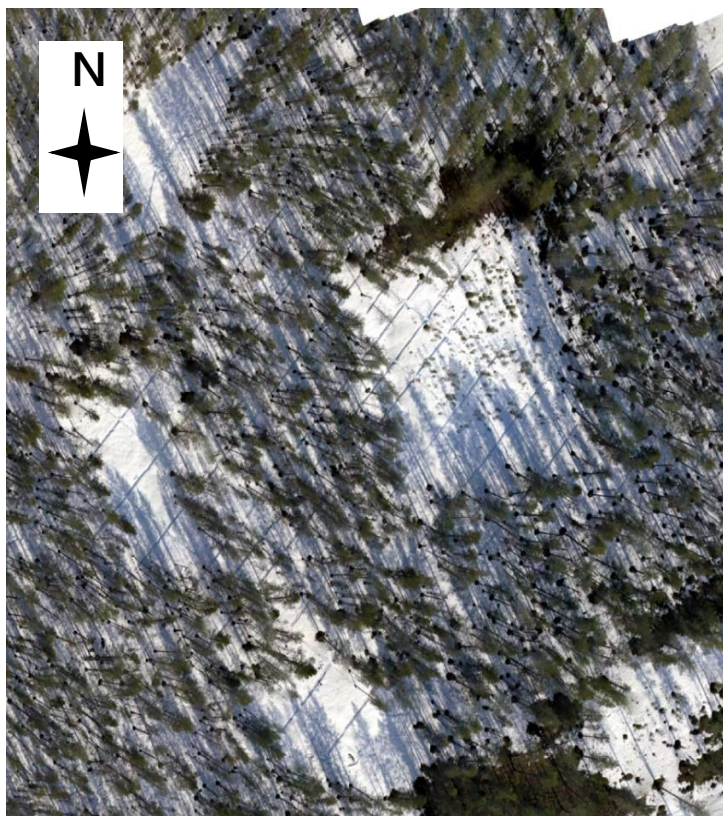
Temporal evolution



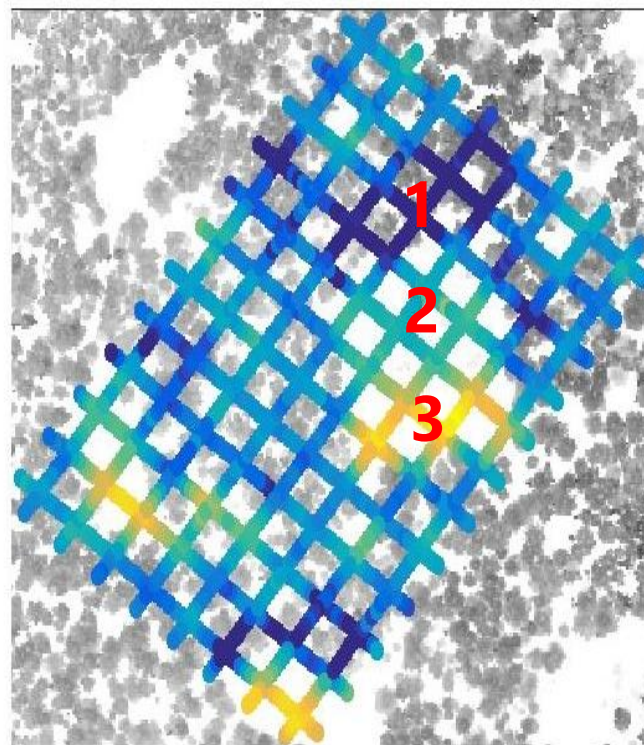
- Basic canopy representation (standard FSM2) underestimates spatio-temporal variability over entire season
- Diversified canopy representation (enhanced FSM2) improves simulated forest snow cover dynamics

Snowmelt distribution simulations

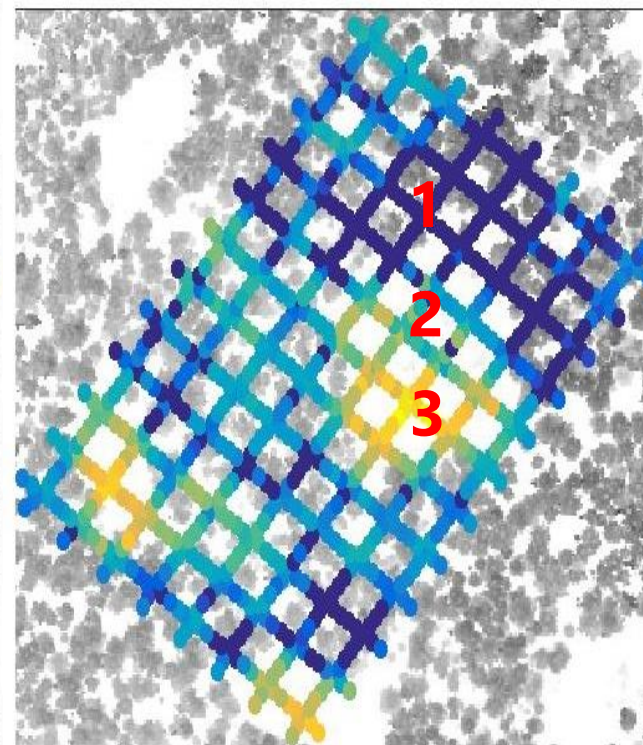
- Patterns well captured in complex canopy settings (meltout gradient N → S of gap)
- Patterns linked to radiation dynamics (see hemispherical images: direct SWR vs. LWR)



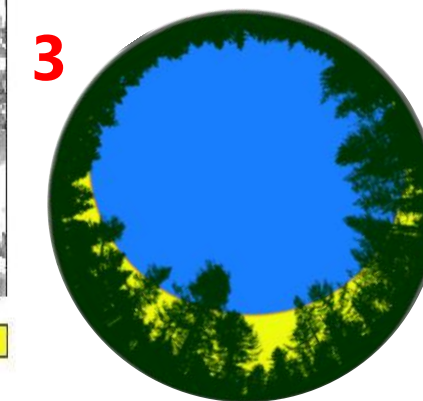
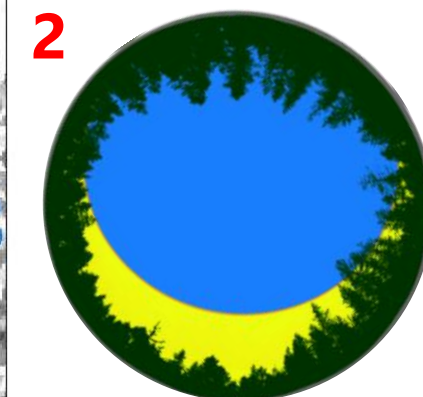
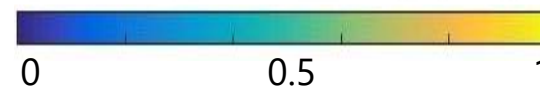
enhanced FSM2



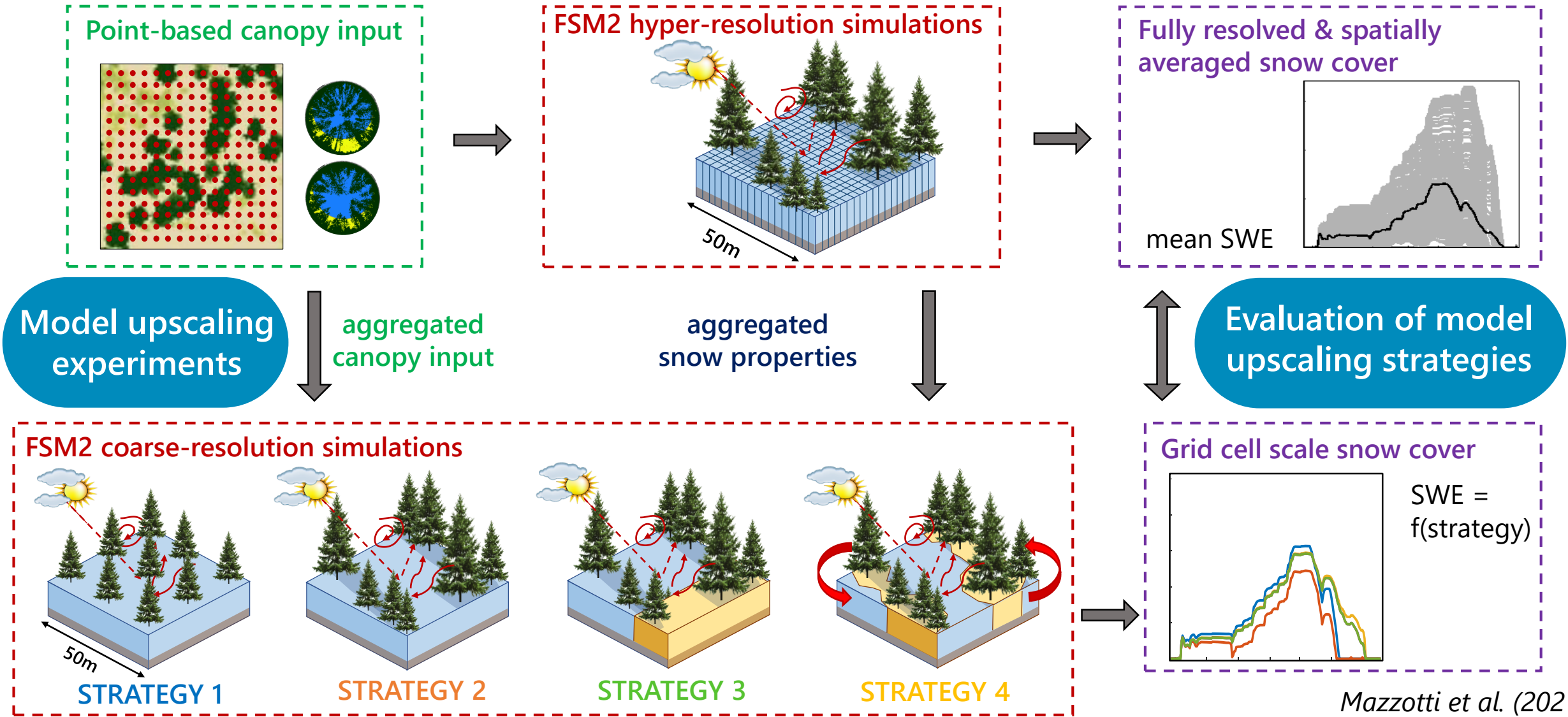
observations (29.4.2019)



normalized snow depth [-]

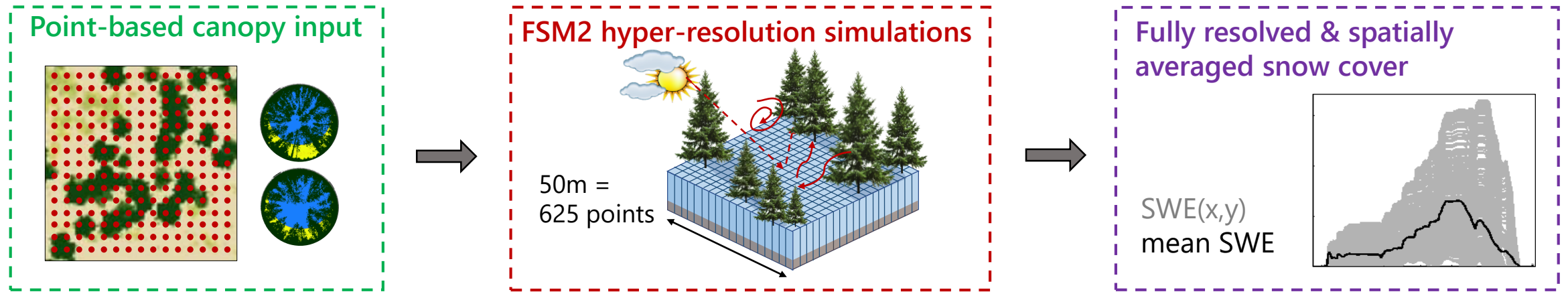


Exploring coarse-resolution modelling strategies with upscaling experiments

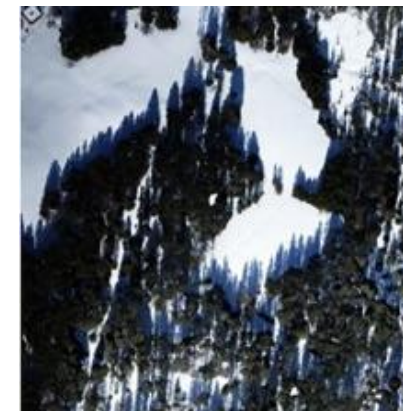


Design of model upscaling experiments

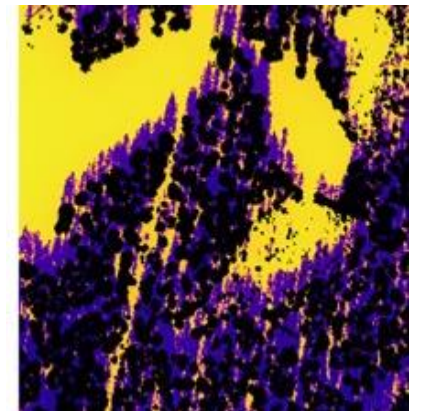
- Fully distributed point simulations with the enhanced FSM2, 2 m spacing, 150 000 m² domain (37 500 points)
- Simulations are taken as best estimate of fully resolved spatial variability and thus act as 'synthetic observations', which can then be used to derive spatial averages



- Sky-view fraction and canopy radiative transfer calculations rely on synthetic hemispherical images derived from airborne LiDAR at every modelled location
- Application of point cloud enhancing methodology to arrive at realistic canopy structure representation for radiation transfer modelling (see comparison to UAV image; *Webster et al. 2020*)



UAV image

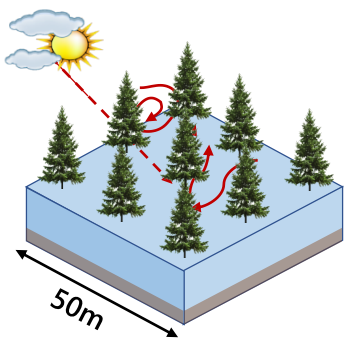


SWR transmissivity

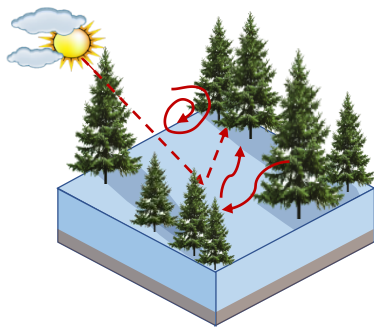
Coarse-resolution modelling strategies

- Spatially lumped simulations at 50 m resolution
- Explore which coarse-resolution model features are important for successful simulations
- Strategies differ by how they implicitly account for sub-grid variability of canopy structure and snow properties
- Idealized simulations: aggregated canopy and snow properties derived from hyper-resolution simulations

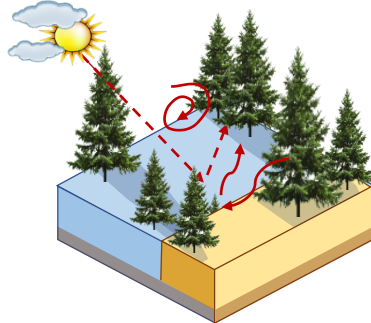
FSM2 coarse-resolution simulations



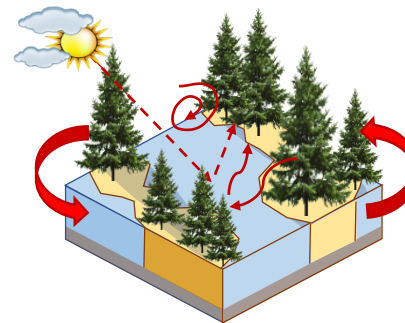
STRATEGY 1
homogeneous canopy
homogeneous snow



STRATEGY 2
heterogeneous canopy
homogeneous snow

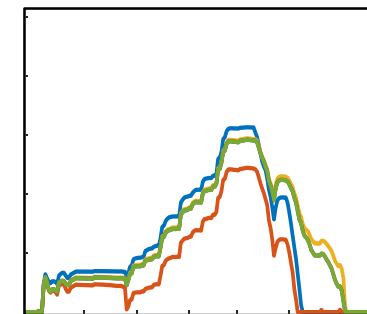


STRATEGY 3
heterogeneous canopy
heterogeneous snow
no interactions



STRATEGY 4
heterogeneous canopy
heterogeneous snow
with interactions

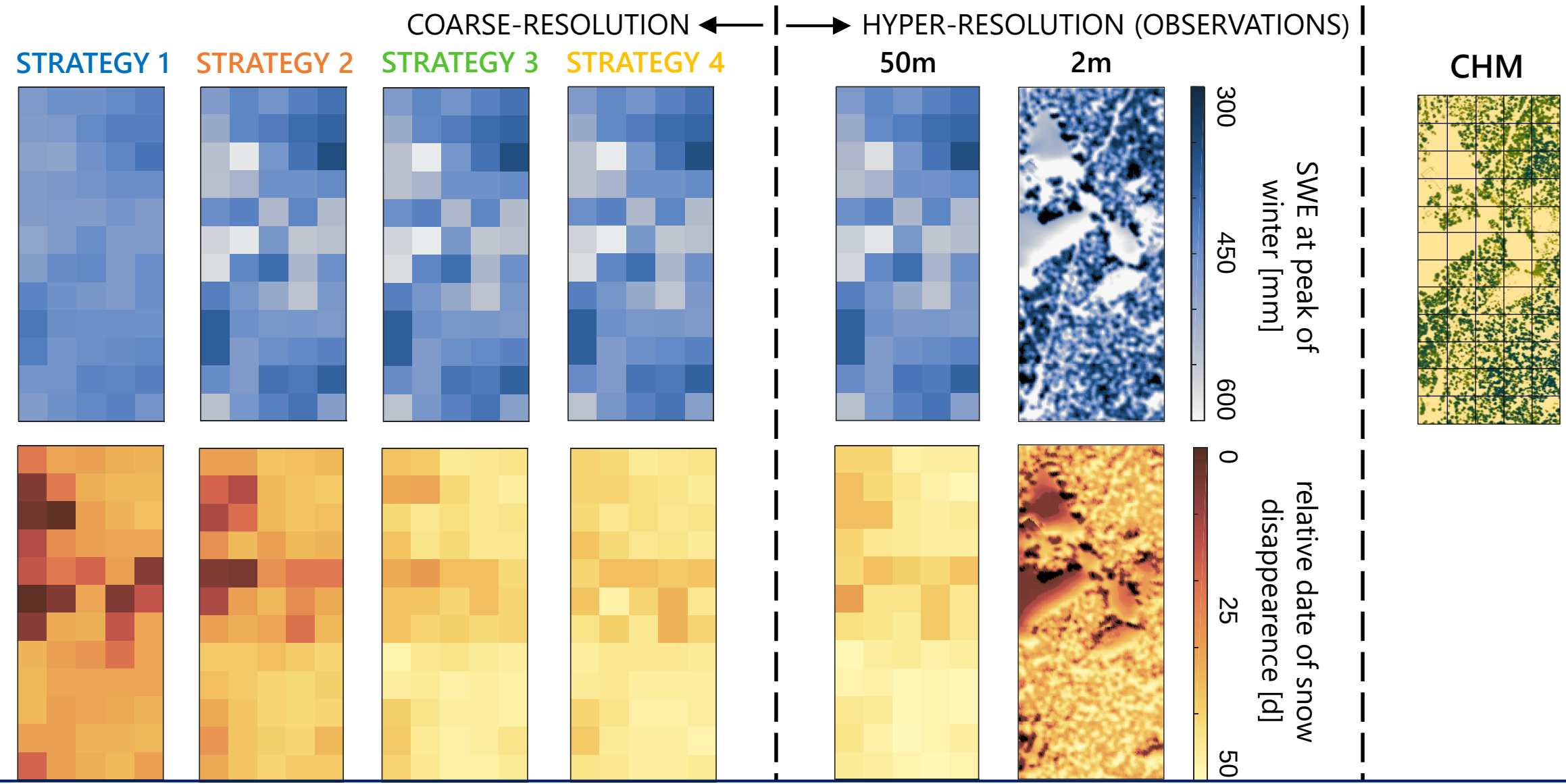
Grid cell scale snow cover



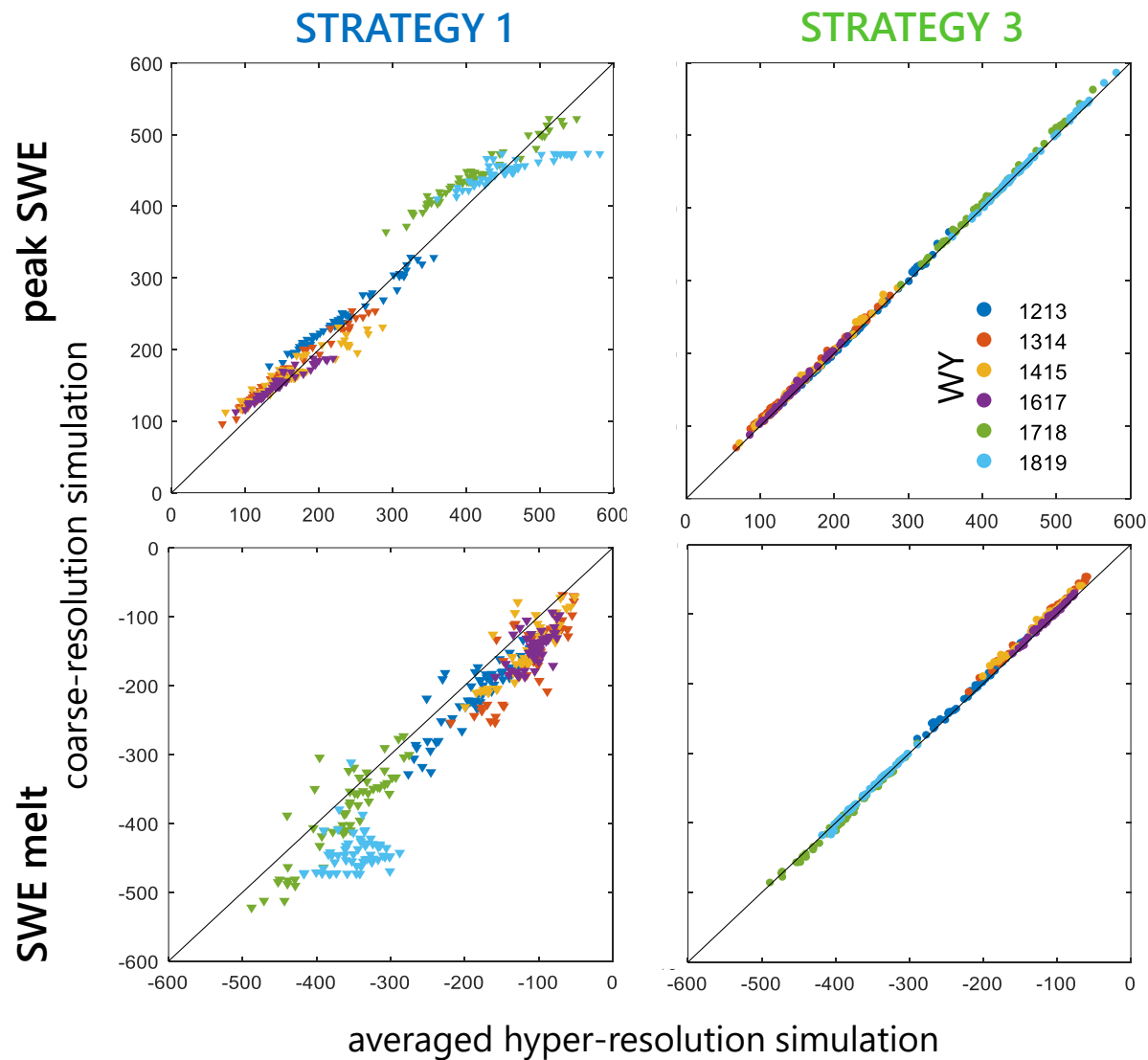
SWE =
 $f(\text{strategy})$

→ Evaluated against
spatially averaged hyper-
resolution simulations

Evaluation of coarse-resolution modelling strategies: spatial snow cover dynamics

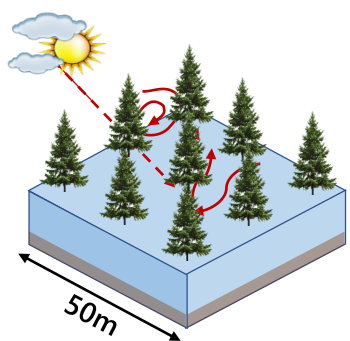


Multi-year evaluation



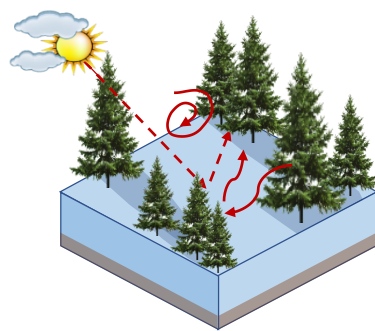
- Simulations for 6 years
- Consistent improvements with **Strategy 3** in simulating grid-cell scale snow cover dynamics (both for peak SWE and for snowmelt)
- Strategy 3 stands out as the best trade-off between model complexity and performance

Practical implications for model application



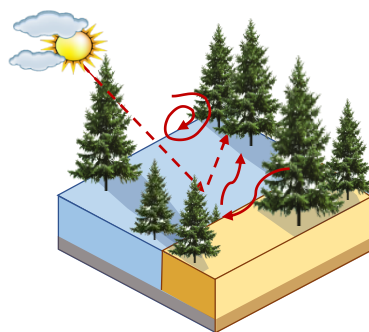
STRATEGY 1

homogeneous canopy
homogeneous snow



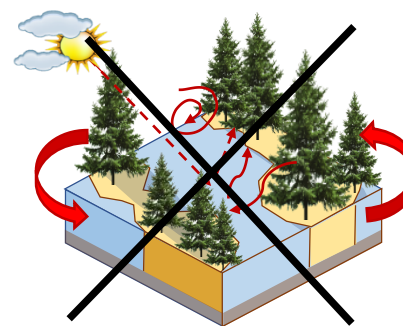
STRATEGY 2

heterogeneous canopy
homogeneous snow



STRATEGY 3

heterogeneous canopy
heterogeneous snow
no interactions



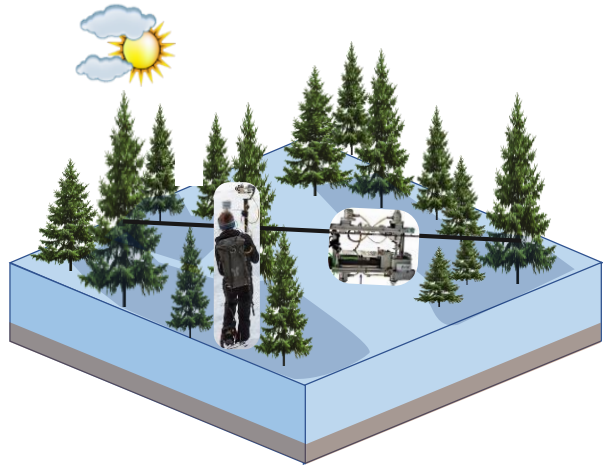
STRATEGY 4

heterogeneous canopy
heterogeneous snow
with interactions

- Detailed process-specific canopy structure input & radiative transfer properties necessary (**Strategy 2**)
... but can be calculated *outside* the snow modelling framework (i.e. 'offline')
- Accurate estimates of snow-covered fraction necessary (**Strategy 3**)
... parametrizations for forested areas to be developed
- Hyper-resolution snow modelling not necessary (~~**Strategy 4**~~)
... coarse-resolution models can *implicitly* represent the same level of detail

Summary of main achievements

1. Process observations

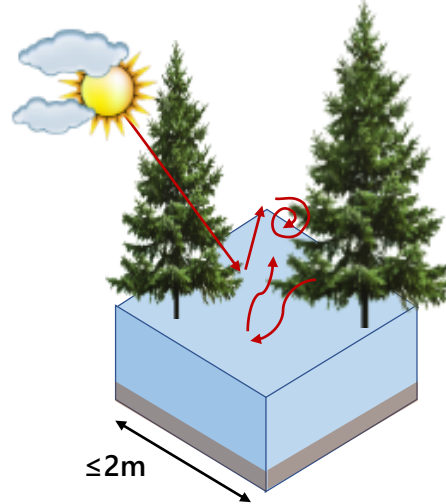


*Process-level
evaluation*



- Novel multi-sensor platforms for process-level observations were developed
- Different variability patterns were observed for different processes

2. Point-scale / hyper-resolution modelling

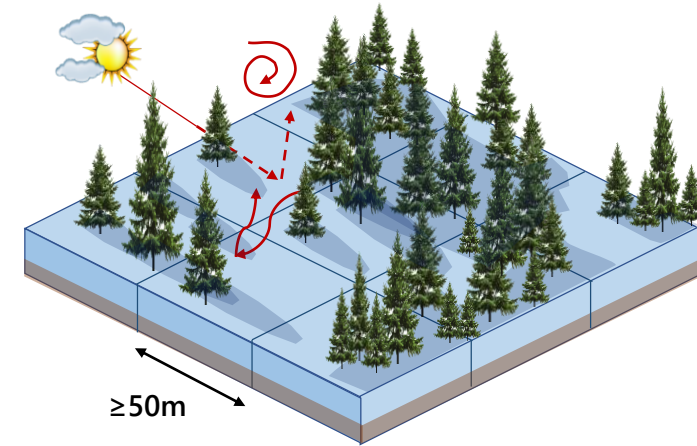


- Enhanced FSM2 with process-specific canopy input and detailed radiative transfer properties
- Accurate representation of forest snow cover dynamics and individual processes

*Model
upscaling*



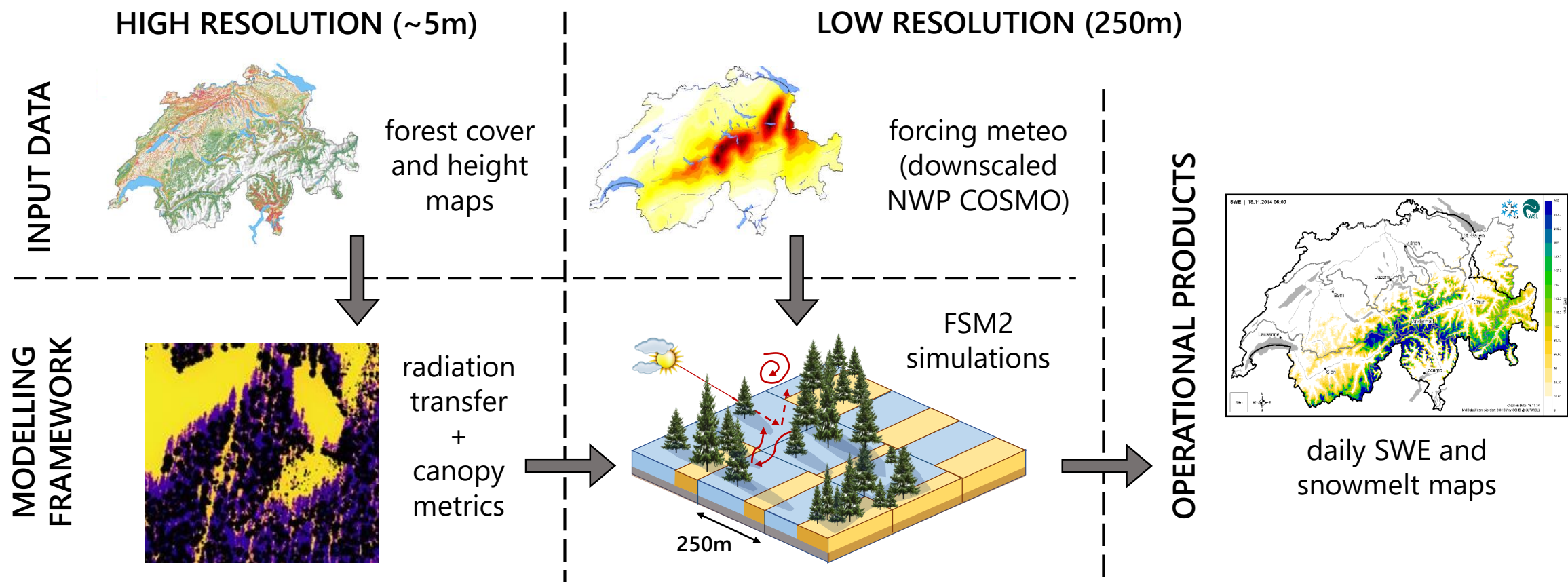
3. Large-scale / coarse-resolution modelling



- Process-specific canopy input and fractional snow cover are important at coarse resolutions as well
- Computationally expensive radiation transfer calculations can be outsourced.

Outlook

- Improved forest snow process representation currently being integrated in the modelling chain of the Swiss operational snow-hydrological service @ SLF
- Multi-resolution approach: high-resolution canopy properties (offline), coarse-resolution snow modelling (operational)

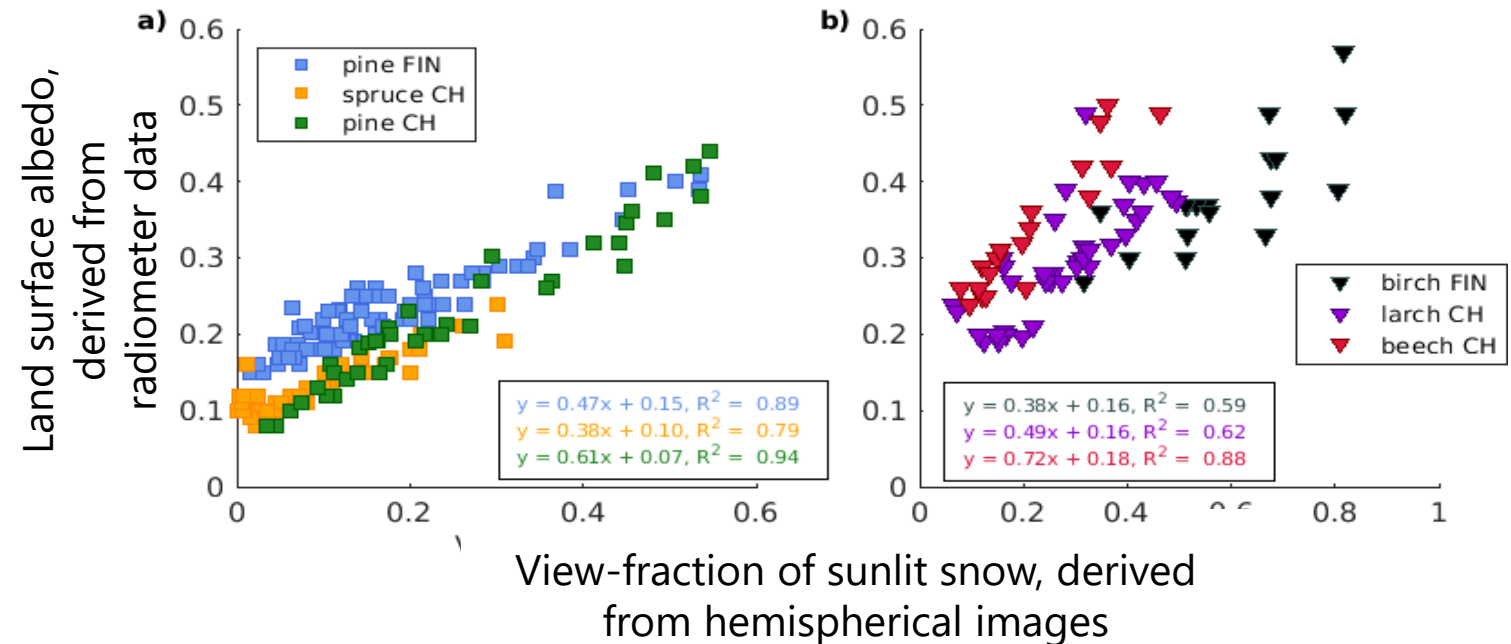


Outlook

- Drone-based data demonstrate the importance of snow surface shading for wintertime land surface albedo of forested environments. This effect is likely unaccounted for in land surface models (*Malle et al. 2021*)



'Albedo drone' with up-and down-looking shortwave radiometers and down-looking hemispherical camera



- Forest snow process modelling approaches derived in this study may therefore benefit land-surface models as well
- Improved quantification of snow albedo masking by vegetation would reduce a current major uncertainty in climate simulations

Check out our publications if you're curious to learn more about this research!

Distributed forest snow process observations

- Mazzotti et al. (2019a) Revisiting snow cover variability and canopy structure within forest stands: Insights from airborne LiDAR data. doi: 10.1029/2019WR024898
- Malle et al. (2019) Shading by trees and fractional snow cover control the sub-canopy radiation budget. doi: 10.1029/2018JD029908
- Mazzotti et al. (2019b) Spatially continuous characterization of forest canopy structure and sub-canopy irradiance derived from handheld radiometer surveys. doi: 10.1175/JHM-D-18-0158.1

Point-scale / hyper-resolution radiation and snow modelling

- Jonas et al. (2020) HPEval: a canopy shortwave radiation transmission model using high-resolution hemispherical images. doi: 10.1016/j.agrformet.2020.107903
- Essery (2015) A factorial snowpack model (FSM 1.0). doi: 10.5194/gmd-8-3867-2015
- Mazzotti et al. (2020a) Process-level evaluation of a hyper-resolution forest snow model using distributed multi-sensor observations. doi: 10.1029/2020WR027572
- Mazzotti et al. (2020b) Resolving small-scale forest snow patterns using an energy-balance snow model with a 1-layer canopy. doi: 10.1029/2019WR026129

Large-scale / coarse-resolution radiation, forest snow and land surface modelling

- Webster et al. (2020) Enhancing airborne LiDAR data for improved forest structural representation in canopy shortwave transmission modelling. doi: 10.1016/j.rse.2020.112017.
- Mazzotti et al. (2021) Improving the physical representation of forest snow processes in coarse-resolution models: lessons learnt from upscaling hyper-resolution simulations. doi: 10.1029/2020WR029064
- Malle et al. (2021) Effect of forest canopy structure on wintertime Land Surface Albedo: Evaluating CLM5 simulations with in-situ measurements. doi: 10.1029/2020JD034118



Contact

Giulia Mazzotti

Snow hydrology group

WSL Institute for Snow and Avalanche Research SLF

Davos Dorf, Switzerland



giulia.mazzotti@slf.ch



Giulia Mazzotti (@snoe_giulia)



Thank you for your interest in this research.

If you have any questions, don't hesitate to get in touch!