The Terrestrial Snow Mass Mission:
Status and lessons learned from the ongoing development of a snow-focused satellite mission

A partnership between Environment and Climate Change Canada, Natural Resources Canada, and the Canadian Space Agency supported by a consortium of 15 Canadian universities and international partners

Science readiness, Environment and Climate Change Canada:
Chris Derksen, Benoit Montpetit, Julien Meloche, Vincent Vionnet, Vincent Fortin, Marco Carrera, Nicolas Leroux, Courtney Bayer, Franck Lespinas

Technical readiness, Canadian Space Agency:
Jean Bergeron, Fauve Strachan, Nadhem Rojbi, Ralph Girard, Aurélien Fourmault, Patrick Plourde, Christopher Servant

Ground segment, Natural Resources Canada:
Roger De Abreu, Shawn MacArthur

Field activities:
Richard Kelly (U. Waterloo), Alexandre Langlois (U. Sherbrooke), Alexandre Roy (UQTR), Philip Marsh (WLU) John Pomeroy (U. Saskatchewan)



Environment and Climate Change Canada
Environnement et Changement climatique Canada
Canadian Space Agency / Agence spatiale canadienne
Canada

2002-2005

- NASA CLPX
- ESA EE-7 - CoReH2O spins up

2009-2012

- CoRe H2O Phase A
- Campaigns in Finland, Austria, and Canada
- Advancements in snow measurements and radiative transfer modelling

2012-2013

- SnowSAR campaigns, NWT, Canada
- CoReH2O not selected for EE-7 implementation

2015-2019

- ECCC – CSA start to develop TSMM
- SMRT is published (open source)

2021-Present

Recent TSMM activities:

- Phase 0 completed/revisited
- Dual Ku-band sub-array built
- TSMM simulator completed
- CryoSAR campaigns
- SVS2/Crocus LSM published
- SWE retrieval concept published

The TSMM Concept

- TSMM will acquire two frequencies of Ku-band radar measurements (13.5/17.25 GHz), both of which are sensitive to snow mass
- These measurements have not been acquired from space before
- Measurements at 500 m resolution will cover all the Northern Hemisphere every 5-7 days, independent of cloud cover and darkness
- When and where needed, a 50 m stripmap mode will acquire measurements across a 30 km swath
- Free and open access planned for TSMM data and products

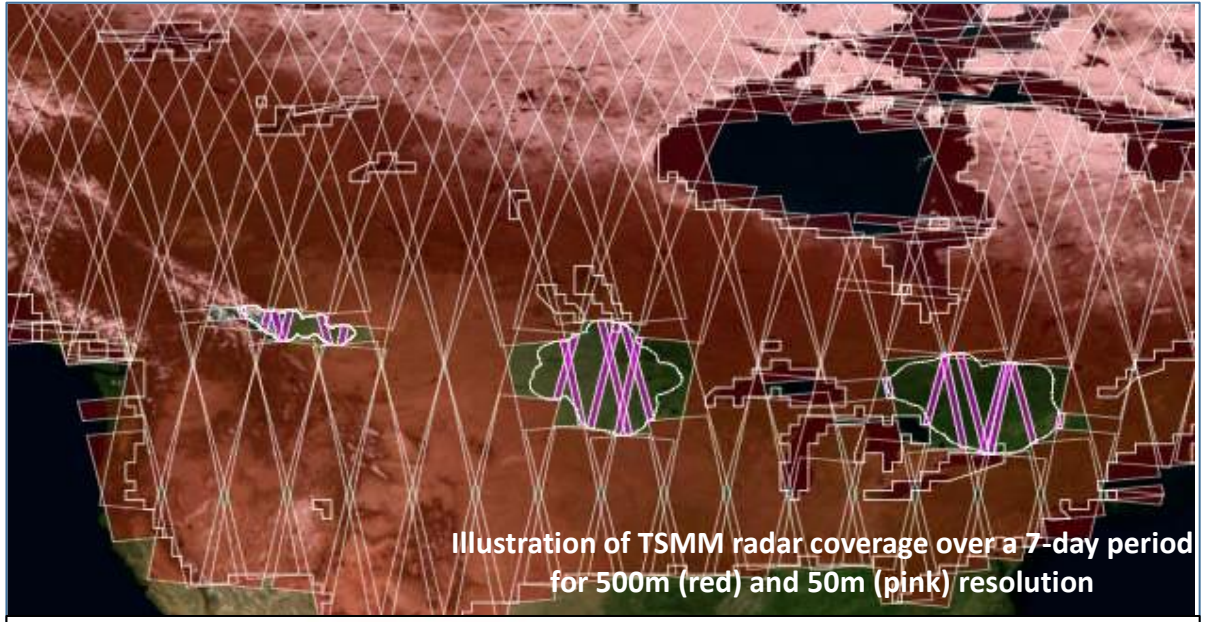
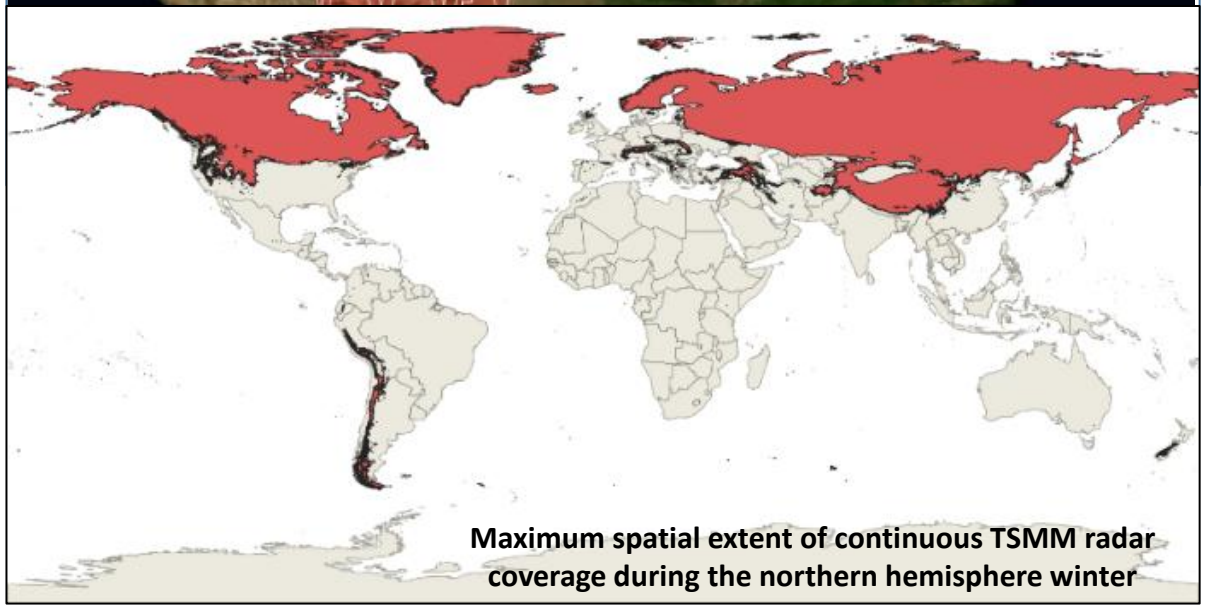


Illustration of TSMM radar coverage over a 7-day period for 500m (red) and 50m (pink) resolution

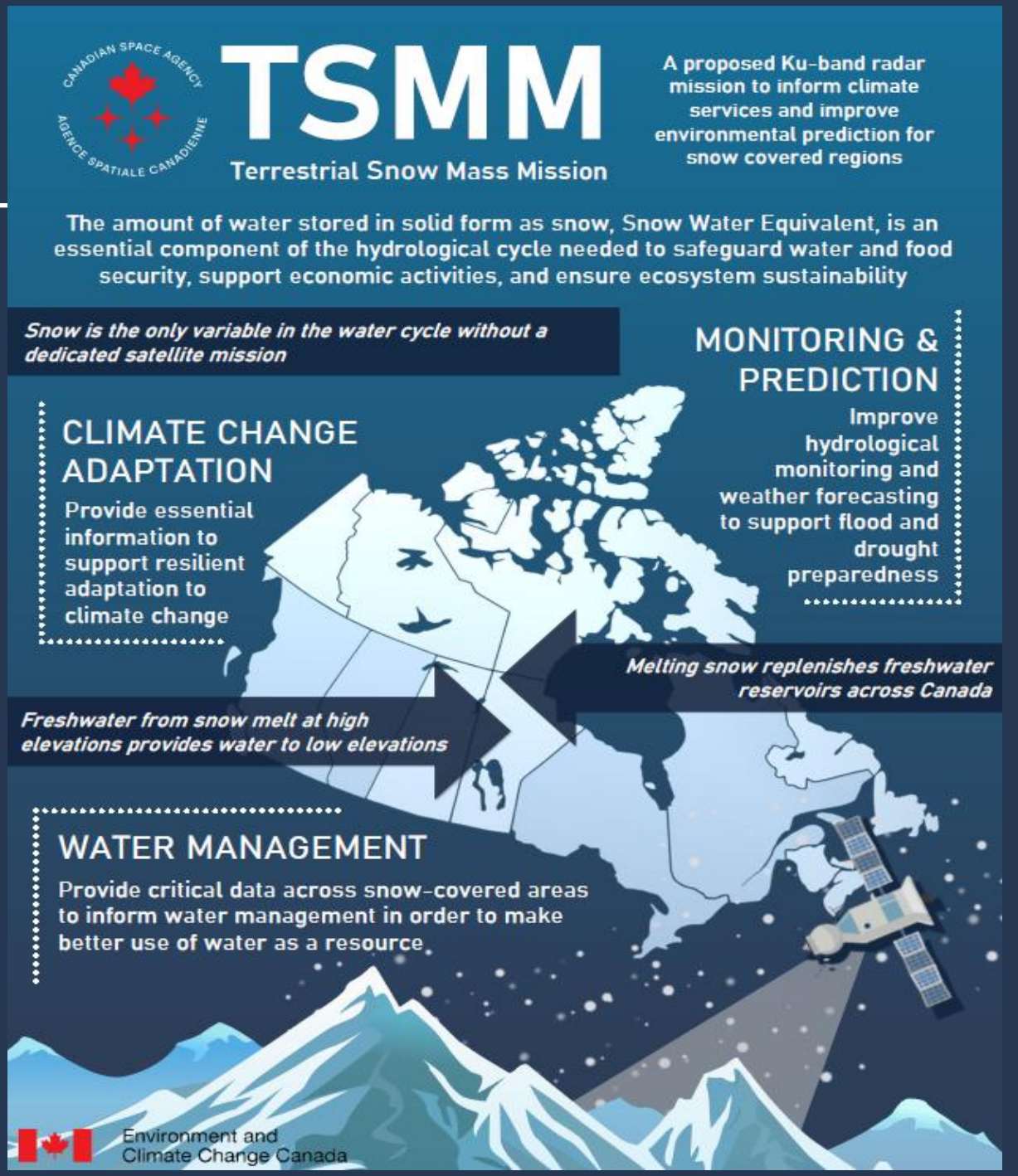


Maximum spatial extent of continuous TSMM radar coverage during the northern hemisphere winter

Terrestrial Snow Mass Mission

First and only satellite EO mission to *continuously* monitor snow nationally and globally … because water availability and security matters to Canadians everywhere

- ✓ TSMM will provide the first Ku-band SAR measurements from space over global snow-covered areas
- ✓ Will deliver a snow mass product (the amount of water stored in solid form by snow) at 500m resolution, across all of Canada, updated weekly
- ✓ TSMM will utilize improved surface analysis system including data assimilation for operational applications at ECCC
- ✓ Improved snow mass information will be used at ECCC to inform analysis of freshwater availability in a changing climate and improve weather and streamflow prediction
- ✓ Many other sectors require snow mass information, including agriculture, hydropower, and municipal water resource management
- ✓ Climate change is altering freshwater supply across Canada, including seasonal snow cover, and so understanding impacts on water availability is essential for adaptation planning



Benefits From Improved Snow Mass Information From Space



STREAMFLOW FORECASTING

Better understanding of snow melt can improve situational awareness and preparedness for flood events due to changing river flow

HABITAT MONITORING

Keystone wildlife populations of economic and social value, such as caribou, are influenced by snow distribution and properties

WATER RESOURCE SECURITY

Management of water from snow melt is important to ensure water availability for human consumption and to maintain healthy aquatic ecosystems

NUMERICAL WEATHER PREDICTION

Snow mass measurements can reduce errors in medium-range weather forecasts

AGRICULTURAL PLANNING & FOOD SECURITY

Water from snow safeguards food security by providing essential moisture and mitigating drought risks

INFRASTRUCTURE

Snow mass observations can be used to improve disaster resilience and protect the build environment through improved flood forecasting and snow load assessments

HYDROPOWER & CLEAN ENERGY

Information on snow melt is a strategic requirement to support hydropower generation, a vital economic commodity and key pillar to achieving a net zero energy system

Evolution of the TSMM Policy Narrative

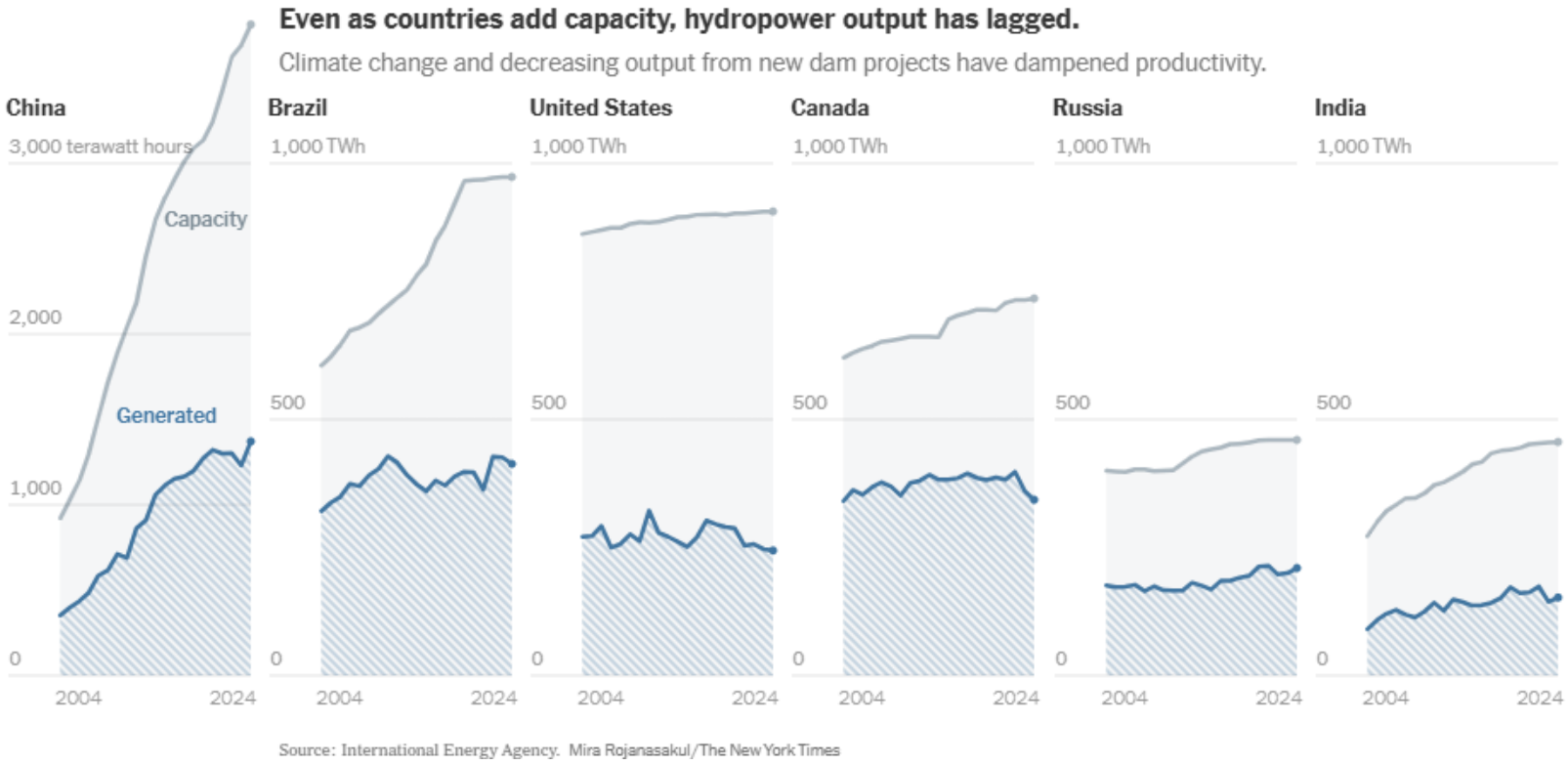
- Over the decade-long period of TSMM development, the domestic policy narrative has continually evolved, and international partnership opportunities have changed

- Water security has emerged as the predominant theme

- In Canada, we see:
  - less snow upstream of major Western rivers
  - reduced snowfall and drier winters in Quebec
  - low spring runoff; summer droughts

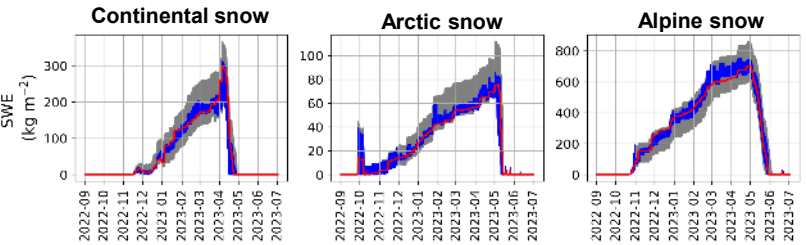
- Hydropower infrastructure is producing notably less energy than capacity worldwide

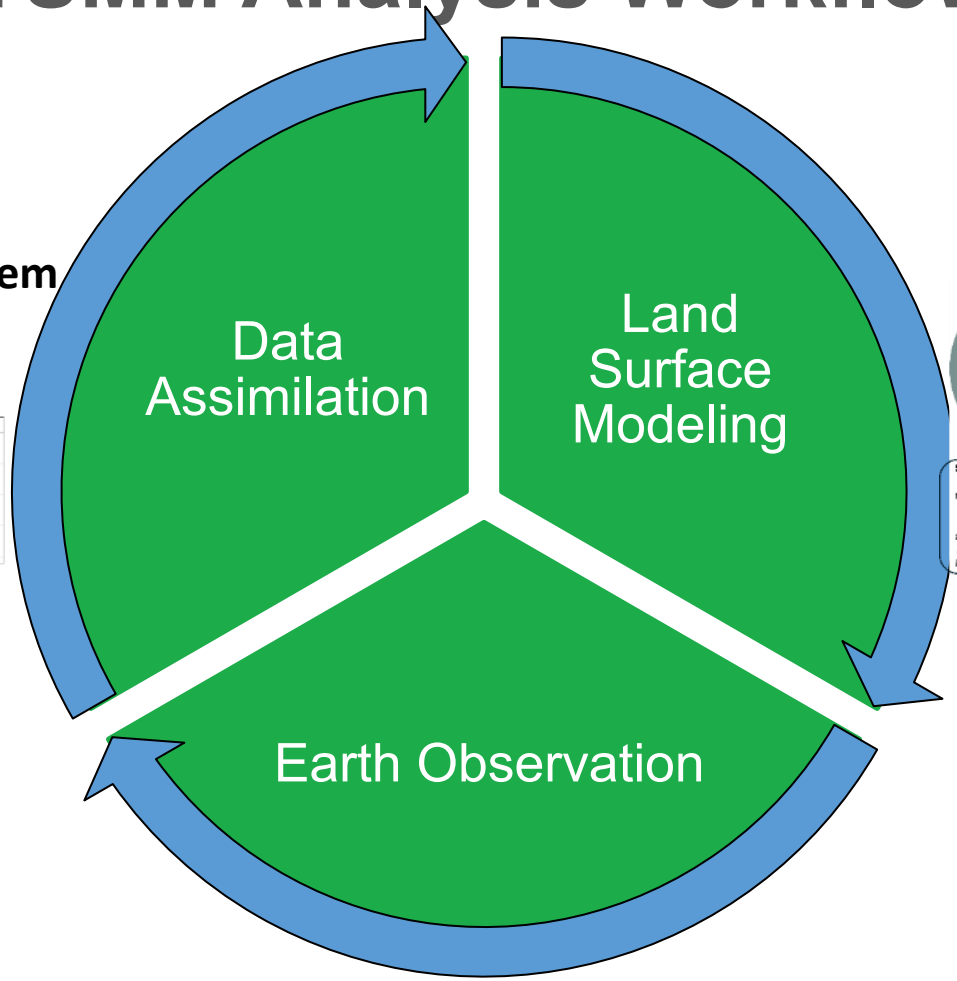
- Better snow information is needed to optimize hydropower production and support industry in meeting new clean energy regulations



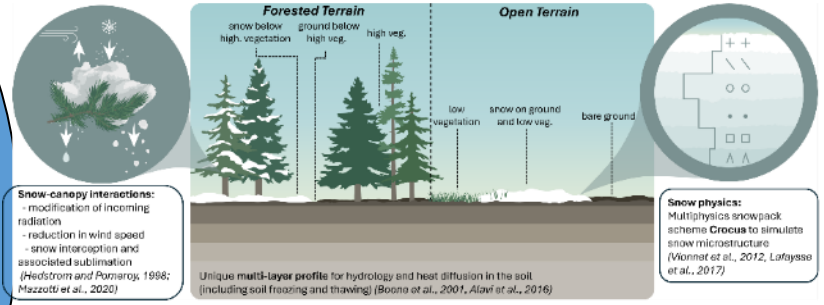
TSMM Analysis Workflow

CaLDAS
Canadian Land Data Assimilation System





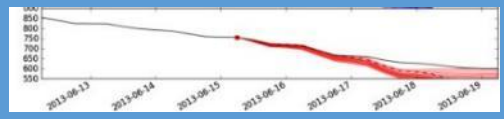
SVS-2
ECCC Soil Vegetation Snow V2



- **CIMR**
- **TSMM**

Treatment of Snow in ECCC's National Surface & River Prediction System

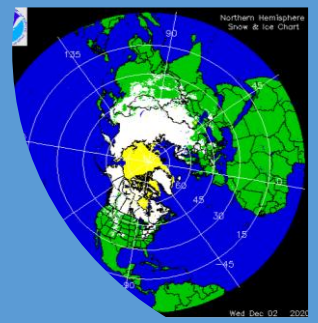
Snowpack forecasts



- Deterministic and ensemble forecasts
- Up to 16 days (up to 32 days every week)

Snow data assimilation

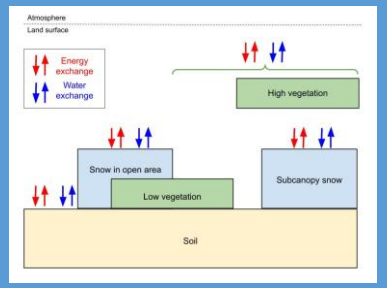
IMS snow cover data



Snowpack modelling

Simple 1-layer snowpack
(Leonardini et al., 2021)

Land Surface Scheme
SVS



Met. Forecasts
HRDPS

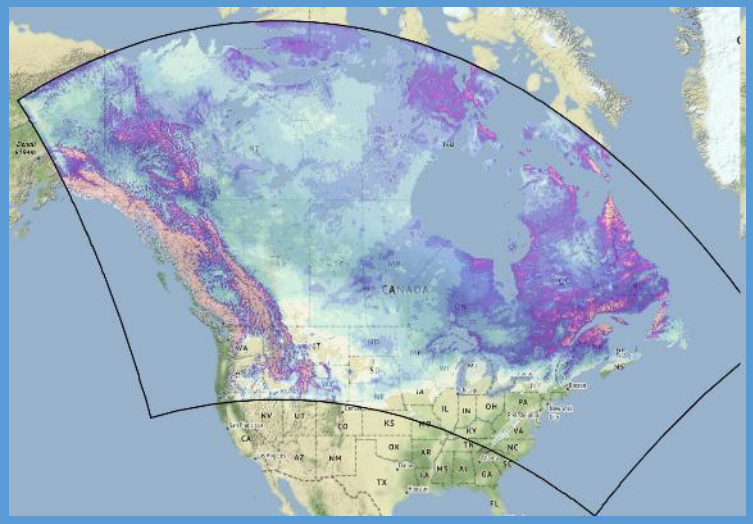
Precip. Analysis
CaPA

Atmospheric forcing
(resolution 2.5 km)

Surface Analysis: Canadian
Land Data Assimilation System

Optimal interpolation
(Garnaud et al, 2021)

Snowpack analysis



- Resolution: 2.5 km
- Variables: snow depth and SWE
- Updated every 6 hours

What R&D is Needed to Deliver the Snow Mass Analysis Required by Users?

Core Components	Key Considerations	Tools
Microwave remote sensing (TSMM; Metop-SGB; CIMR)	• Volume scattering (incl. snow microstructure) • Soil background	Snow Microwave Radiative Transfer (SMRT) model
Physical snow modeling	• Ability to simulate SWE, microstructure, and stratigraphy for initialization	Soil Vegetation and Snow version 2 (SVS2) including the snowpack model Crocus
SWE retrieval	• Retrieval constraints to ensure plausible values • Estimation of the complete snow profile	Markov Chain Monte Carlo (MCMC)
Data assimilation	• Approach to ensure improved snow state updates	Multiple Snow Data Assimilation System (MUSA) Canadian Land Data Assimilation System (CaLDAS)

Future Treatment of Snow in ECCC's National Surface & River Prediction System

Met. Forecasts HRDPS

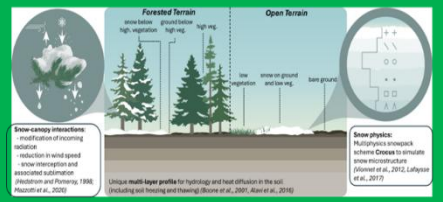
Precip. Analysis CaPA

Atmospheric forcing (resolution 2.5 km)

Snowpack modelling

Multi-layered snowpack (Vionnet et al., 2025)

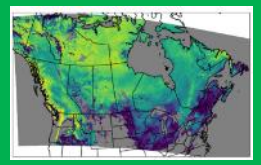
Land Surface Scheme SVS2



Snow data assimilation

TSMM radar &SWE products

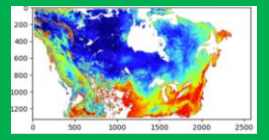
Resolution: 500 m

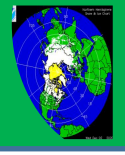


Passive Microwave

AMSR2/3 (12.5 km) & CIMR (5 km)

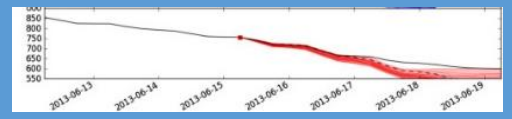
IMS snow cover data





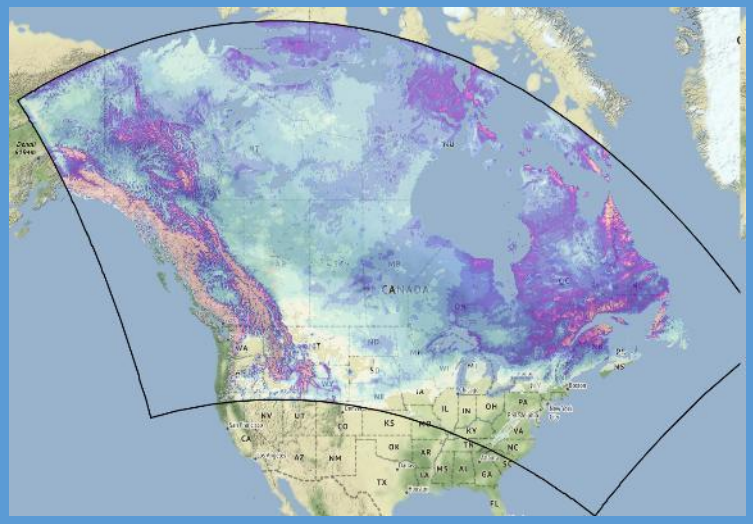
Surface Analysis: Canadian Land Data Assimilation System

Snowpack forecasts



- Deterministic and ensemble forecasts
- Up to 16 days (up to 32 days every week)

Snowpack analysis



- Resolution: 2.5 km
- Variables: snow depth and SWE
- Updated every 6 hours

Soil Vegetation and Snow (SVS) Version 2

- A **major upgrade** of the existing SVS land surface model, with a special focus on **cold-region hydrological processes**

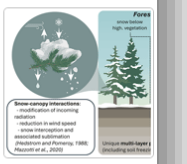
https://doi.org/10.5194/gmd-18-9119-2025
© Author(s) 2025. This work is distributed under the Creative Commons Attribution 4.0 License.

Article | Assets | Peer review | Metrics | Related articles

Model description paper | 27 Nov 2025

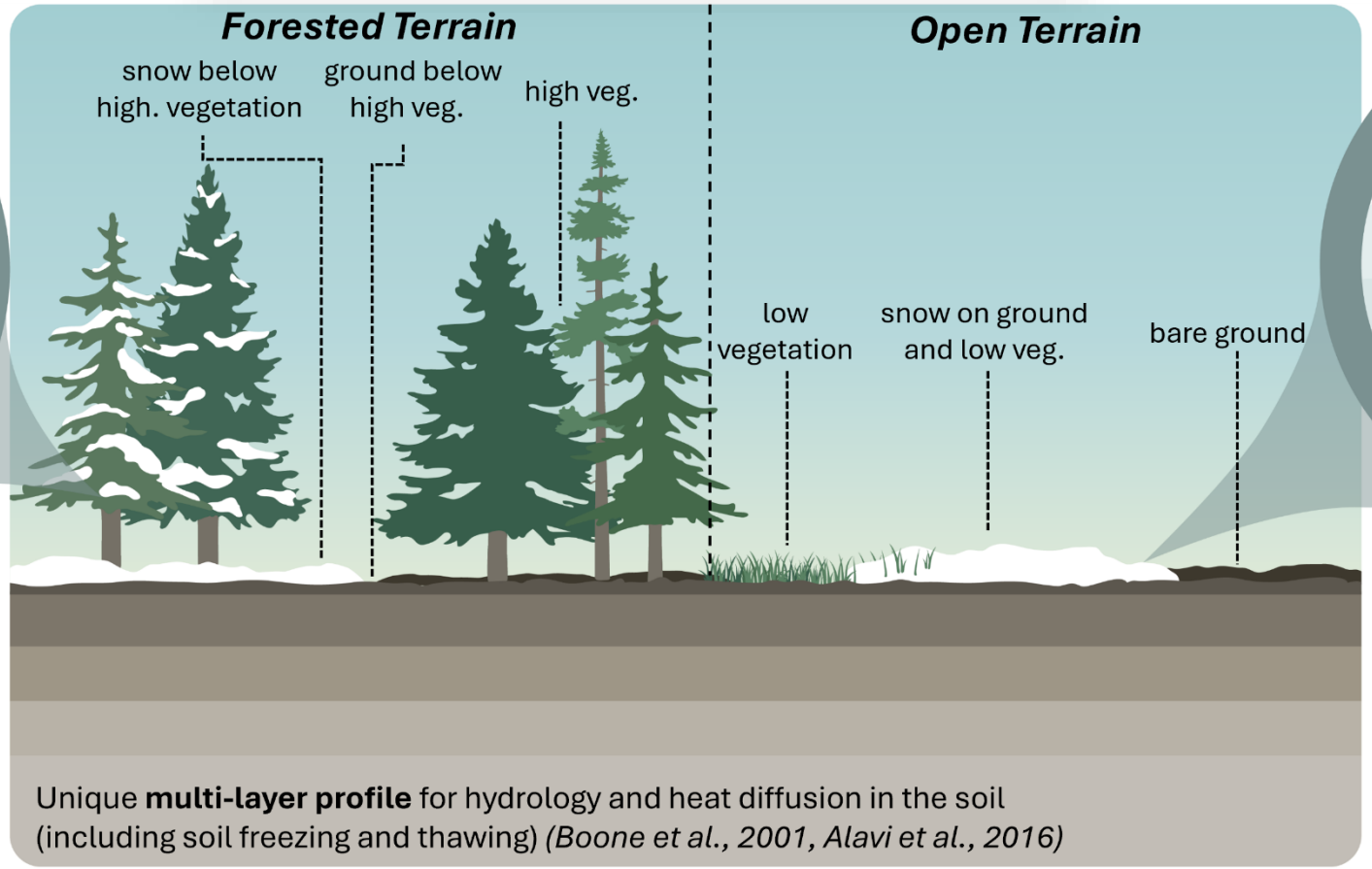
Enhancing simulations of snowpack properties in land surface models with the Soil, Vegetation and Snow scheme v2.0 (SVS2)

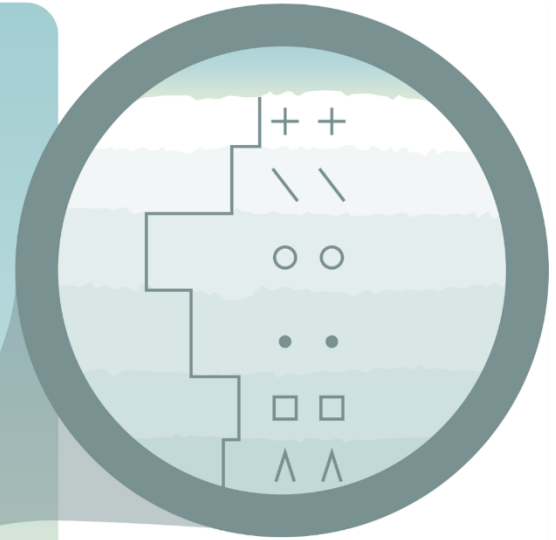
Vincent Vionnet, Nicolas R. Leroux, Vincent Fortin, Maria Abrahamowicz, Georgina Woolley, Giulia Mazzotti, Manon Gaillard, Matthieu Lafaysse, Alain Royer, Florent Domine, Nathalie Gauthier, Nick Rutter, Chris Derksen, and Stéphane Bélair



- Makes distinction between **snow** in **open** and **forested terrain**







Snow-canopy interactions:
- modification of incoming radiation
- reduction in wind speed
- snow interception and associated sublimation
(Hedstrom and Pomeroy, 1998; Mazzotti et al., 2020)

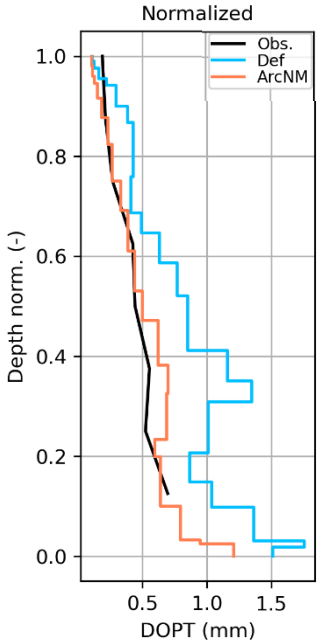
Unique **multi-layer profile** for hydrology and heat diffusion in the soil (including soil freezing and thawing) *(Boone et al., 2001, Alavi et al., 2016)*

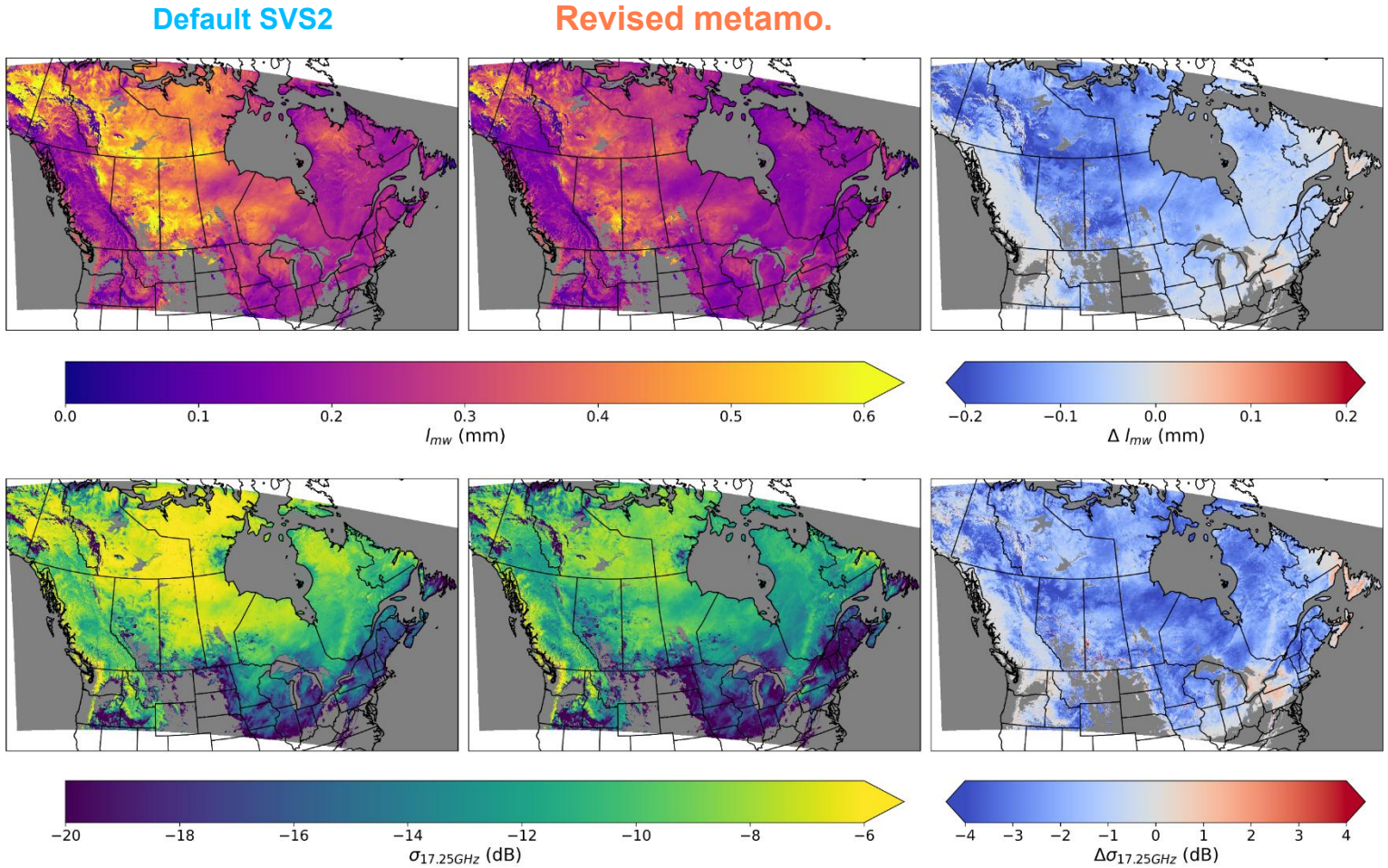
Snow physics:
Multiphysics snowpack scheme **Crocus** to simulate snow microstructure *(Vionnet et al., 2012, Lafaysse et al., 2017)*

Revised Snow Metamorphism Scheme in Crocus

- SVS2 simulations (winter 20/21):
  - default version of Crocus (alpine version)
  - Version with revised metamorphism (on going work, *Braun et al. (2025)*)
  - Crocus optical diameter converted to microwave grain size (l_{mw})

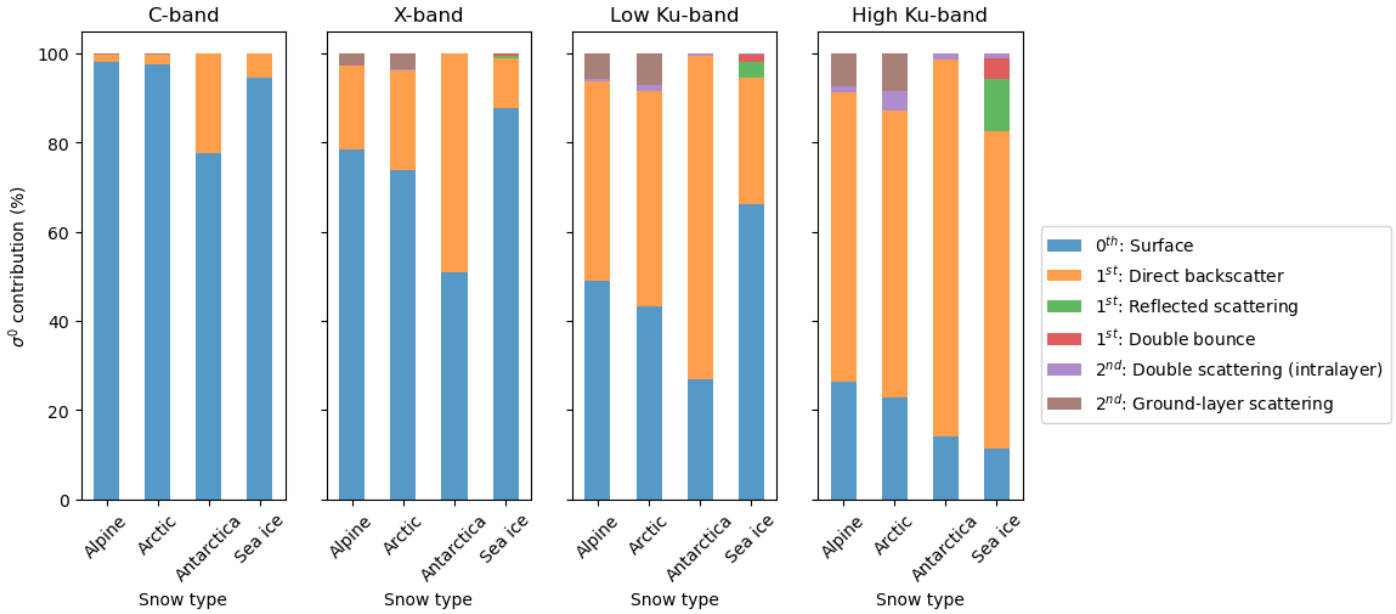
$$l_{mw} = K d_{opt} \frac{2(\rho_{ice} - \rho_{snow})}{3\rho_{ice}}$$



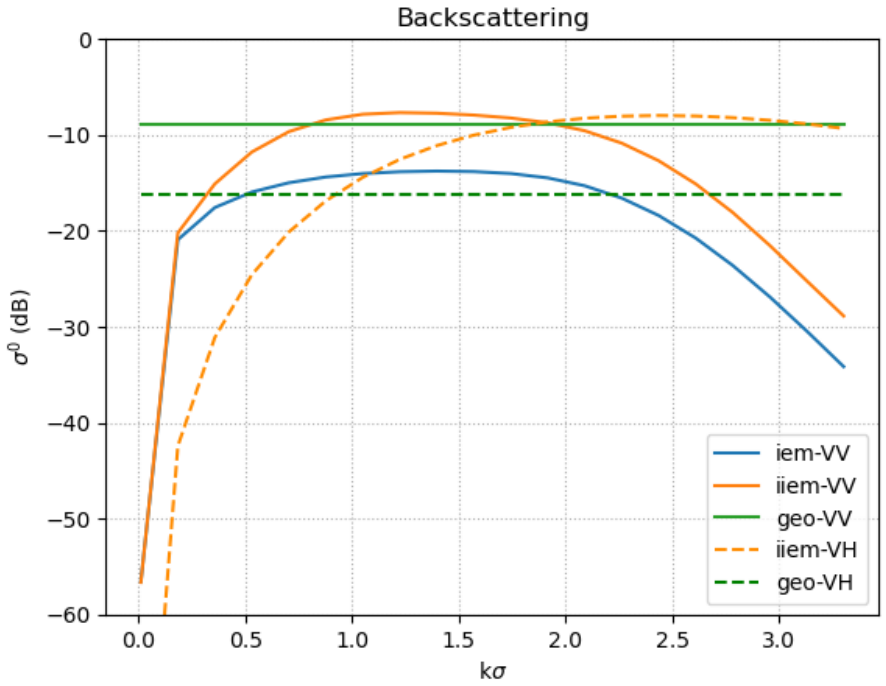


Improved Snow Radiative Transfer Modeling

- Iterative solver now implemented in SMRT
  - Faster computation
  - Allows signal contributions to be isolated
  - Available in the latest release of SMRT on GitHub



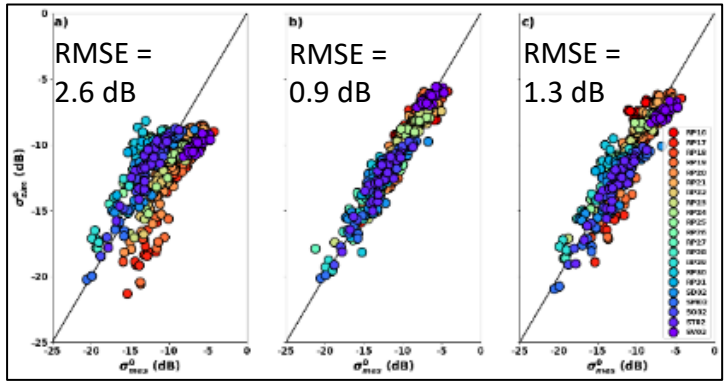
- IIEM surface model implemented in SMRT
  - Allows simulation of the X-pol signal compared to previous surface model
  - Soon to be officially released on SMRT GitHub



https://github.com/smrt-model/smrt

Forward Modeling of the Microwave Signal with SMRT

Step 1



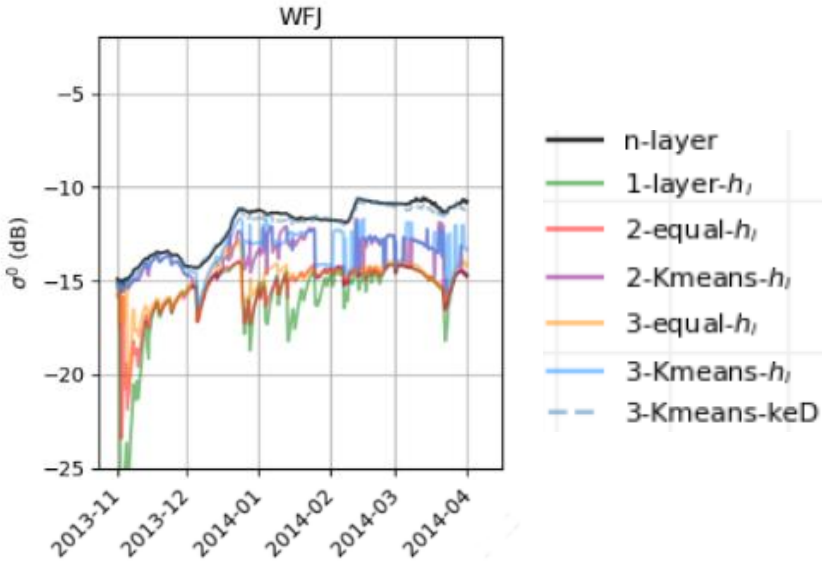
Validated forward modeling of **Ku-band measurements**





Montpetit et al (2024)

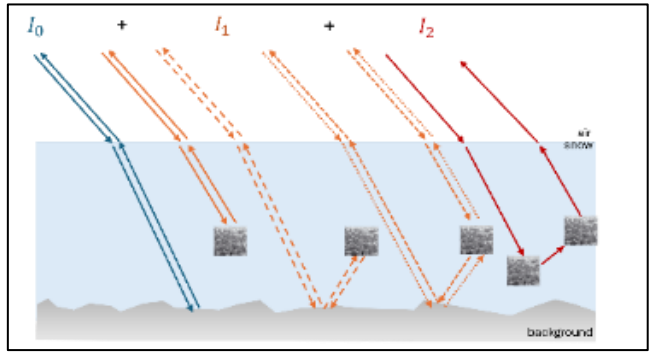
Step 2



Reduce n-layer Crocus simulations to "**Radar Equivalent**" layers improving computation while conserving snowpack mass

Meloche et al (2024)

Step 3



Implement new radiative transfer equation solver to improve computation and better discriminate scattering mechanisms

GitHub Snow Microwave Radiative Transfer Model (SMRT) Picard et al.

Environment and Climate Change Canada | Environnement et Changement climatique Canada


Research article | 28 Aug 2024

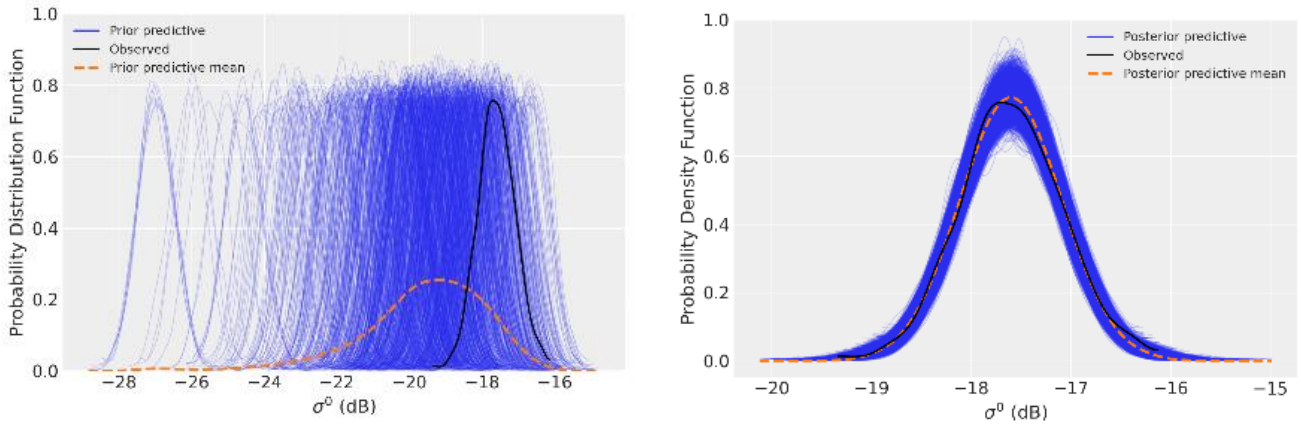
Retrieval of snow and soil properties for forward radiative transfer modeling of airborne Ku-band SAR to estimate snow water equivalent: the Trail Valley Creek 2018/19 snow experiment

Canada

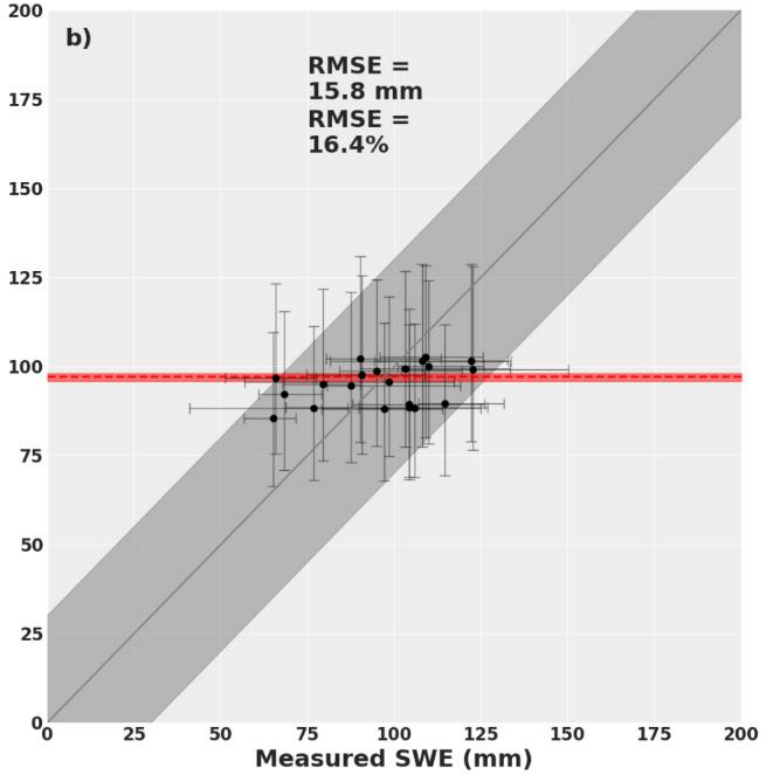
SWE Algorithm Concept

Markov Chain Monte Carlo (MCMC):

- Optimizes SSA, Density, Thickness for each layer (3 x N-layer parameters total)



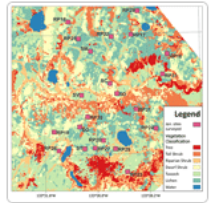
- SWE retrieval concept shown to work in Arctic environment within the desired accuracy of 30 mm RMSE



Research article | 07 Nov 2025

Snow Water Equivalent from airborne Ku-band data: the Trail Valley Creek 2018/19 snow experiment

Benoit Montpetit, Julien Meloche, Vincent Vionnet, Chris Derksen, Georgina Woolley, Nicolas R. Leroux, Paul Siqueira, J. Max Adam, and Mike Brady



Airborne Ku-band Radar Measurements

- ‘CryoSAR’ (L- and Ku-band radar) instrument consortium led by U. Waterloo, funded by CFI and NSERC
- Approval from Transport Canada for installation on any Cessna-208 allows for flexible low-cost deployment



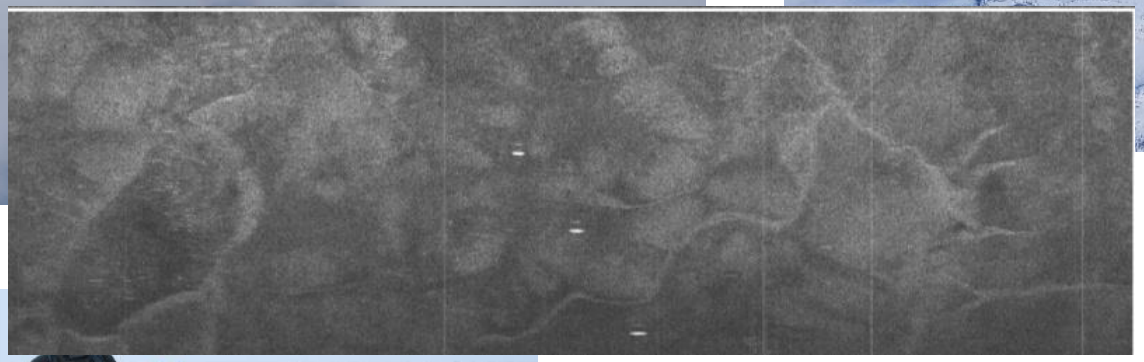


Arctic Landscape: Trail Valley Creek NWT, 2018/19





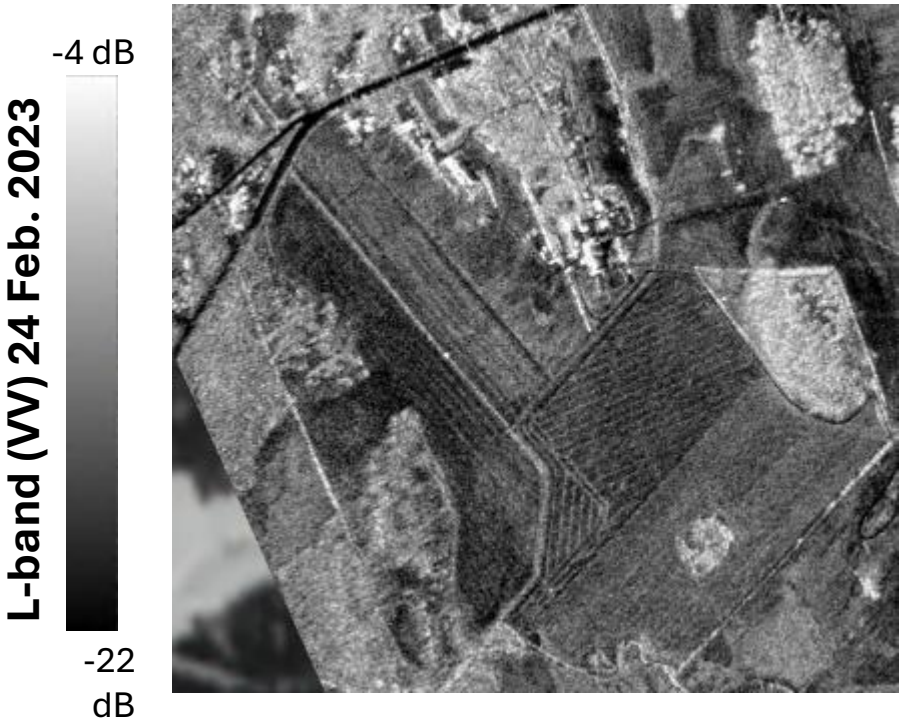




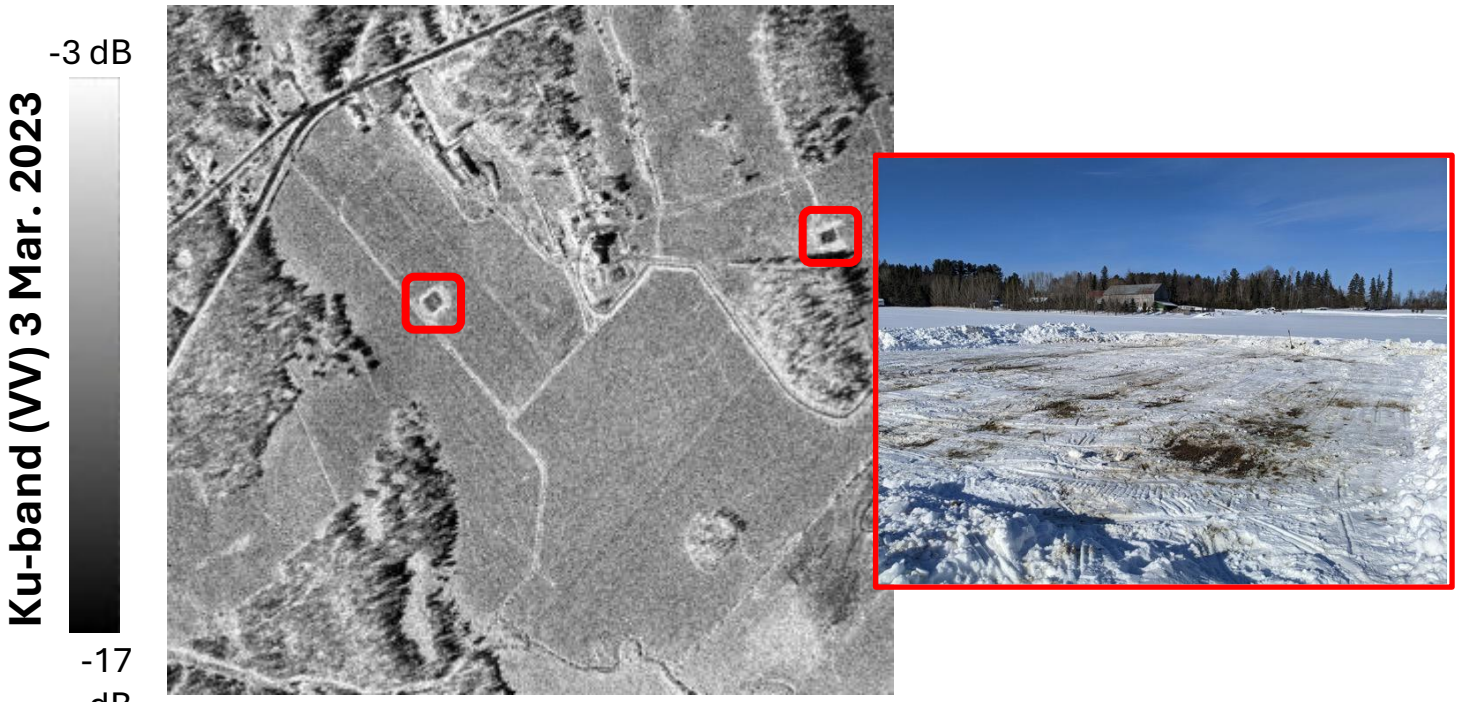




Agricultural Landscape: Powassan Ontario, 2022/23



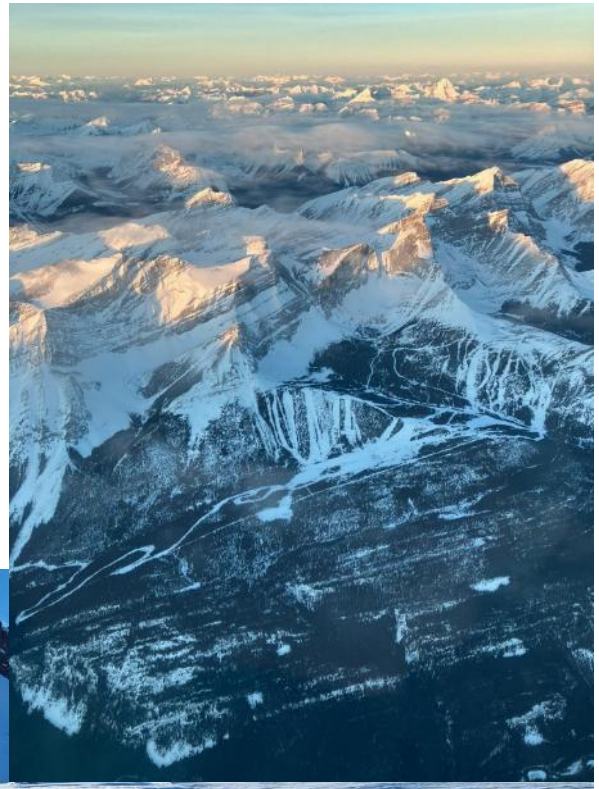
- At L-band, soil surface roughness features in agricultural fields are clearly evident because the snow is ‘invisible’ to radar



- At Ku-band, soil surface features disappear because the radar signal is scattered by the overlying snowpack
- Note clear response to areas with snow removed

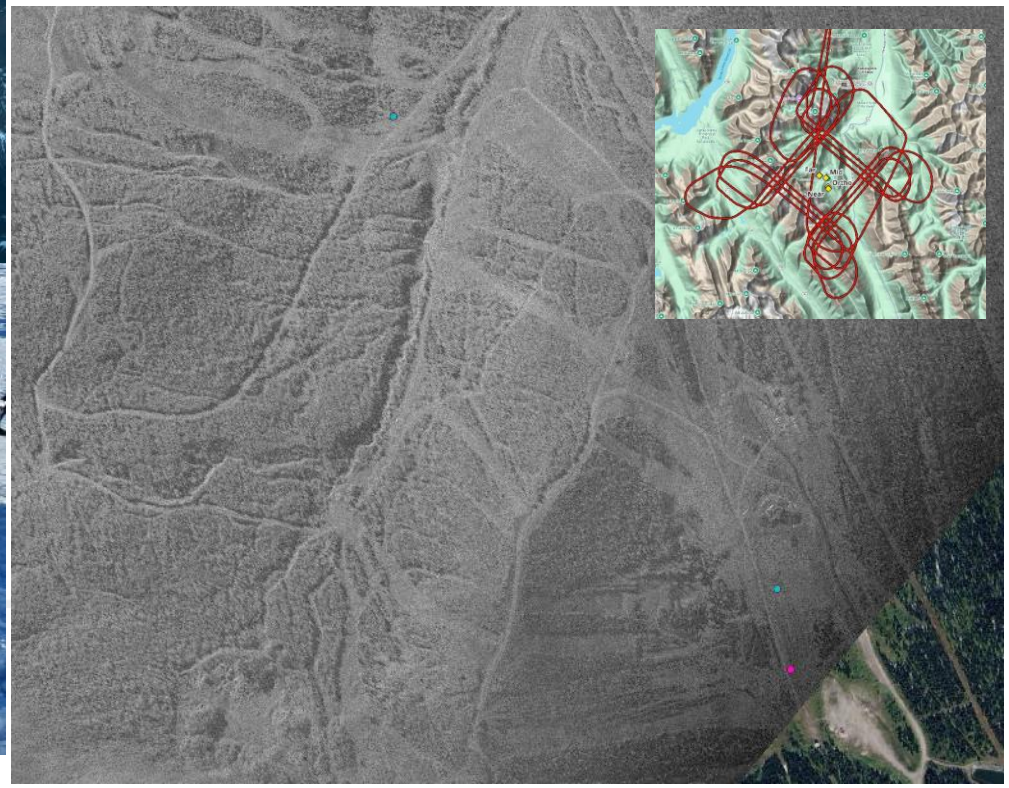
Alpine Snow: Fortress Mountain, 24/25 and 25/26











Ground-Based Dual Ku-Band FMCW radars





Environment and Climate Change Canada | Environnement et Changement climatique Canada

Canada

Synthetic Experiment of Backscatter Assimilation

- At **3 locations** spanning different climates
  - TVC, Rogers Pass, Powassan
- Assimilation using the **particle filter method**
- Weekly assimilation of **synthetic observations of backscatte**r at 13.5 GHz, 17.25 GHz, and **SWE** when snowpack is dry



https://doi.org/10.5194/egusphere-2025-5790
© Author(s) 2025. This work is distributed under
the Creative Commons Attribution 4.0 License.

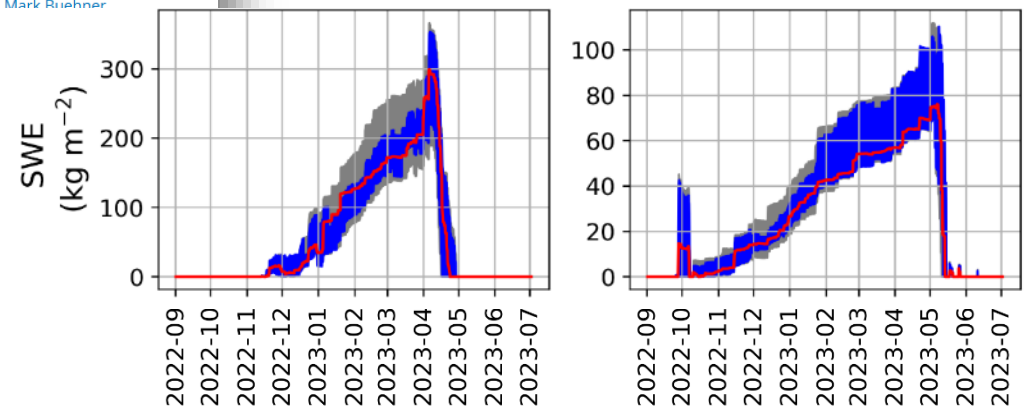
Abstract | Assets | Discussion | Metrics

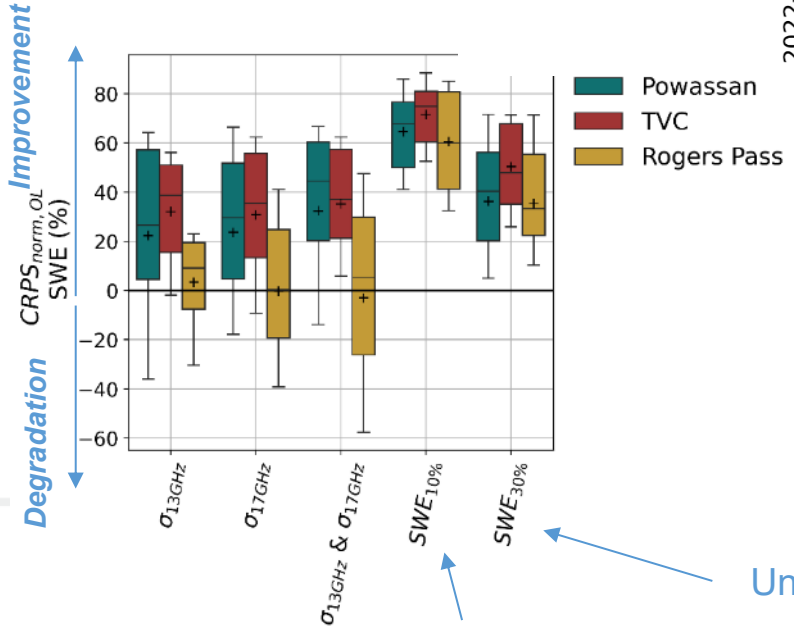
10 Dec 2025

Assimilation of synthetic radar backscatters at Ku-band improves SWE estimates

Nicolas R. Leroux, Vincent Vionnet, Courtney Bayer, Julien Meloche, Arlan Dirkson, Franck Lespinas, Mark Buehner, Marco Carrera, Benoit Montpetit, Bernard Bilodeau, Maria Abrahamowicz, and

Assim. σ 17 GHz





- At TVC and Powassan:
  - Assimilating σ **improves SWE estimates** compared to the open loop
- At Rogers Pass in **alpine terrain**:
  - No **improvement** in SWE when assimilating σ due to **saturation** of the simulated synthetic signal

Future Remotely-Sensed Snow Mass Products: Streamflow Prediction

Treatment of Snow in ECCC's National Surface & River Prediction System

Met. Forecasts HRDPS

Precip. Analysis CaPA

Atmospheric forcing (resolution 2.5 km)

Snowpack modelling

Multi-layered snowpack (Vionnet et al., 2025)

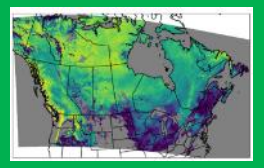
Land Surface Scheme SVS2



Snow data assimilation

TSMM radar &SWE products

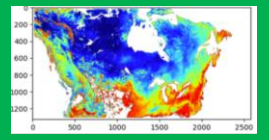
Resolution: 500 m

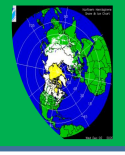


Passive Microwave

AMSR2/3 (12.5 km) & CIMR (5 km)

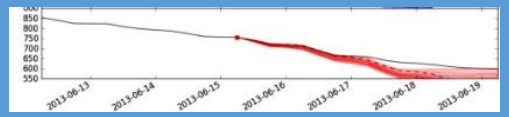
IMS snow cover data





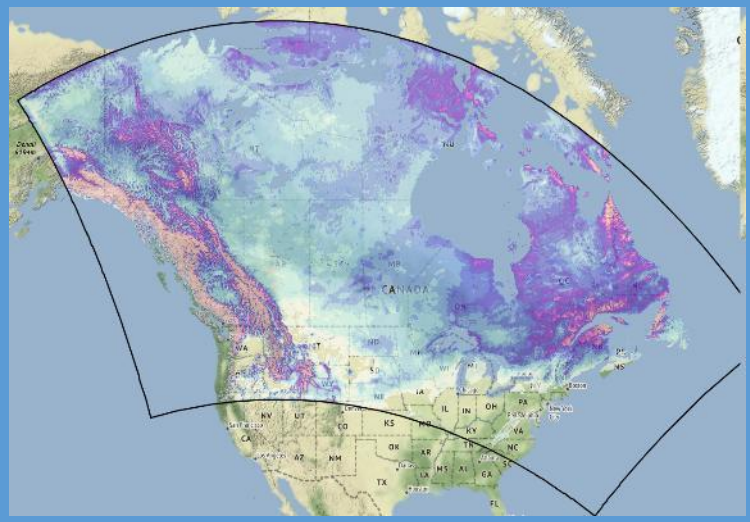
Surface Analysis: Canadian Land Data Assimilation System

Snowpack forecasts



- Deterministic and ensemble forecasts
- Up to 16 days (up to 32 days every week)

Snowpack analysis



- Resolution: 2.5 km
- Variables: snow depth and SWE
- Updated every 6 hours

TSMM Simulator

- Uses SVS2/Crocus as inputs to SMRT for scene generation
- Generates L1 product using Phase 0 orbital information
- Flexible SAR performance parameters
- Currently running on ECCC HPC collaboration system
- Current projects using TSMMS:
  - Canadian Mosaic
  - MCMC SWE retrieval
  - Alaska SWE retrievals (SnowEx 2023)



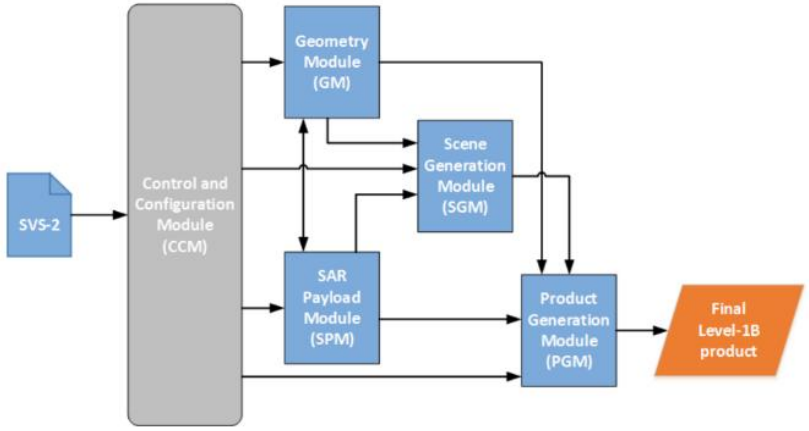
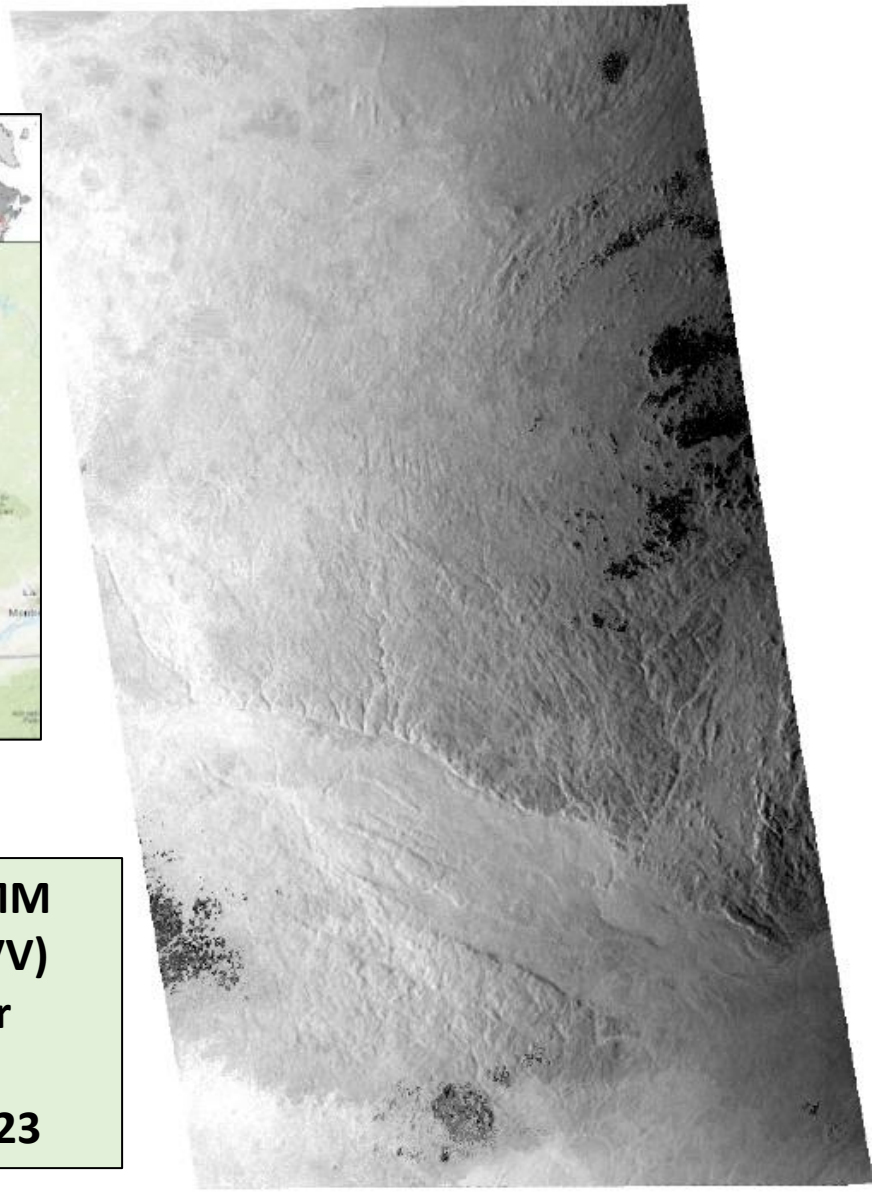


Figure 1. Simplified TSMM software architecture diagram.



Simulated TSMM radar image (VV) Ottawa River watershed 3 February 2023

TSMM Status

1. Science readiness continues to advance; new snow analysis system at ECCC will be implemented with CIMR data
2. Urgency to fund Phase A so industry can address remaining technological risks related to Ku-band TRM's
3. Mission costing and policy narrative continue to be refined

TSMM Status

1. Science readiness continues to advance; new snow analysis system at ECCC will be implemented with CIMR data
2. Urgency to fund Phase A so industry can address remaining technological risks related to Ku-band TRM's
3. Mission costing and policy narrative continue to be refined

Lessons Learned (in the Canadian Funding Context)

- Strong policy hooks are essential
- Must explain the mission in a non-technical way
- Find impactful expressions of support
- 'Made in Canada' industrial solution is required
- Remain ready – timing is everything, and some good luck is needed
- 'Champions' needed at all levels (but higher is better…)
- Continuity/evolution in the science vision – we are approaching 25 years since CLPX