Beyond Binary: Continuous Freeze–Thaw from L-band Missions

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NASA Jet Propulsion Laboratory
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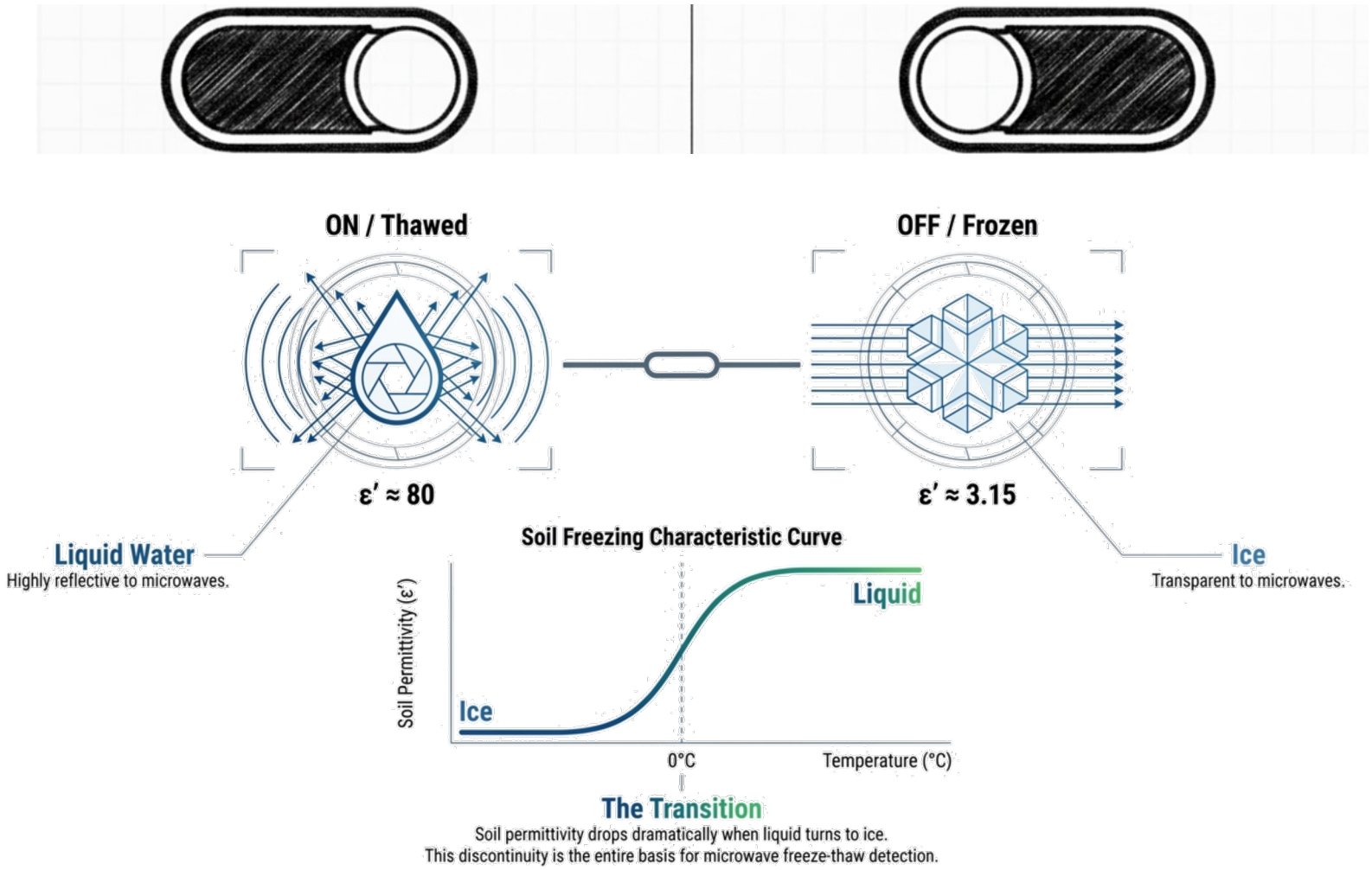
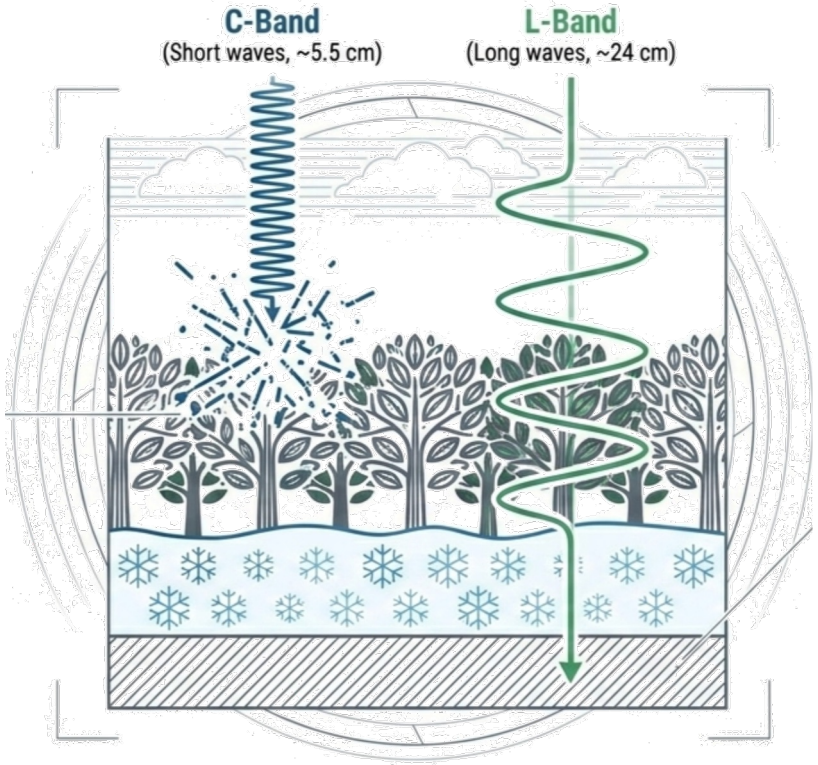
Microwave Remote Sensing: Why L-band?





SMAP mission vision: From Active Baseline to Dual-channel Passive Backbone

Jan 2015 | Jul 2015 | 2015-2025 | Oct 2025

Active L3_FT_A (3 km)
Detailed, but the radar failed after 3 months.

Passive L3_FT_P (33 km native)
Wide-angle, survived.

The Original Vision

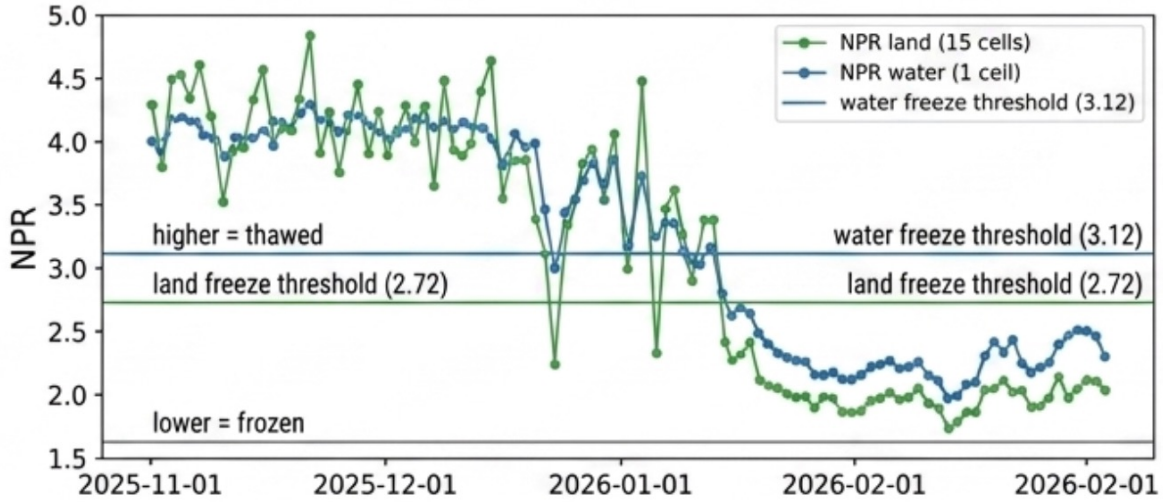
SMAP launched to measure the identical state using two methods.

The Pivot

Radar failure forced reliance on the passive radiometer.

The Result

NPR cancels physical temperature to read the pure dielectric state.



SMAP was designed active and passive

Two L-band observables of the same state, on one shared 6 m antenna (launched Jan 2015).

ACTIVE · RADAR

L3_FT_A

σ^0 backscatter · 3 km · the high-resolution product

$$\Delta(t) = (\sigma^0 - \sigma^0_{fr}) / (\sigma^0_{th} - \sigma^0_{fr})$$
frozen when $\Delta \leq 0.5$

A seasonal threshold on backscatter — designed to resolve freeze at 3 km.

PASSIVE · RADIOMETER

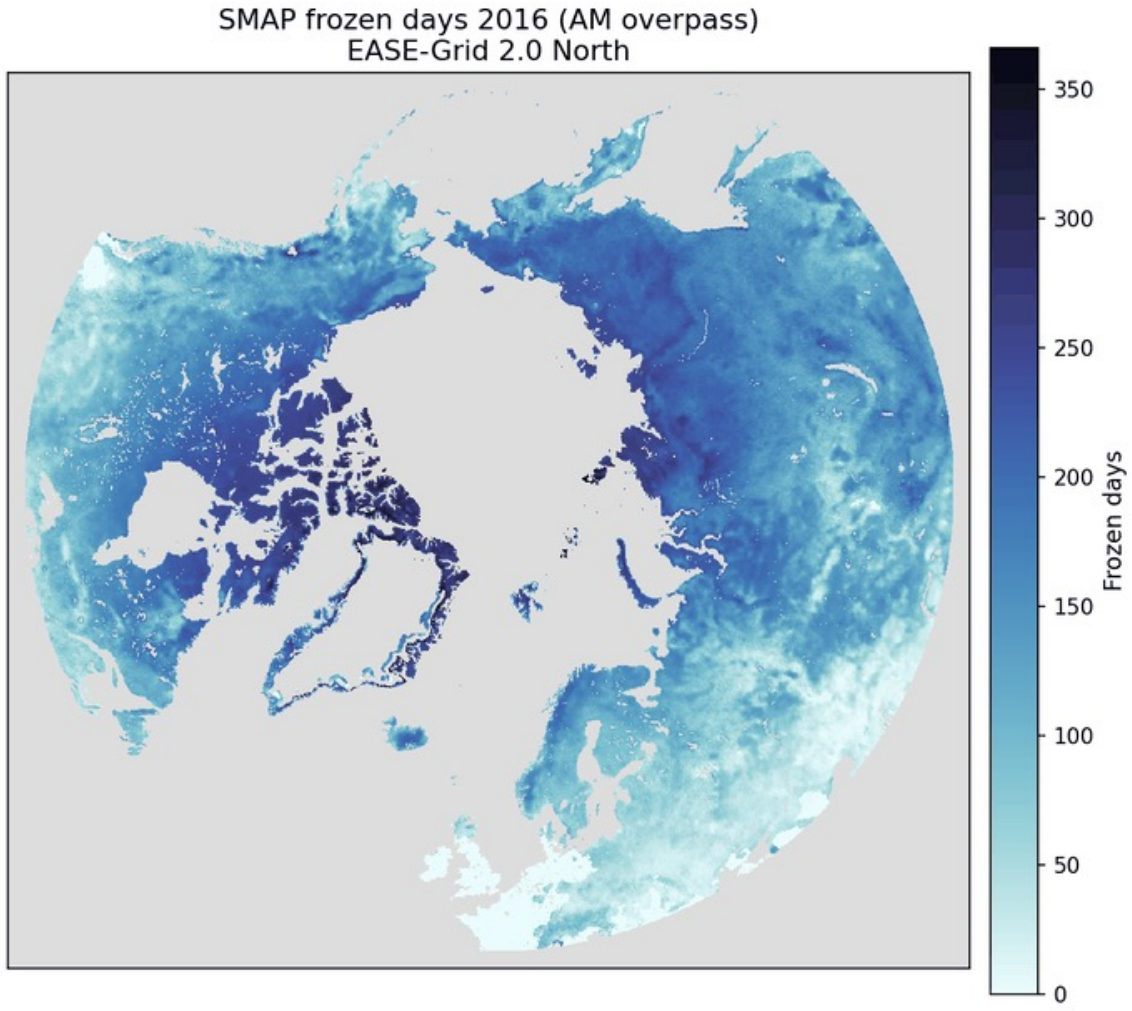
L3_FT_P

NPR polarization ratio · 33 km native · 9 km grid

$$NPR = (Tb_V - Tb_H) / (Tb_V + Tb_H)$$
cancels physical temperature → reads state

Reads the dielectric state directly, independent of physical temperature.

What a decade SMAP FT product enable



Tracking key climatological metrics:

✓ spring-onset timing, interannual variability, fall freeze, long-term trends, and carbon-cycle phenology.

Advancing non-binary freeze-thaw modeling:

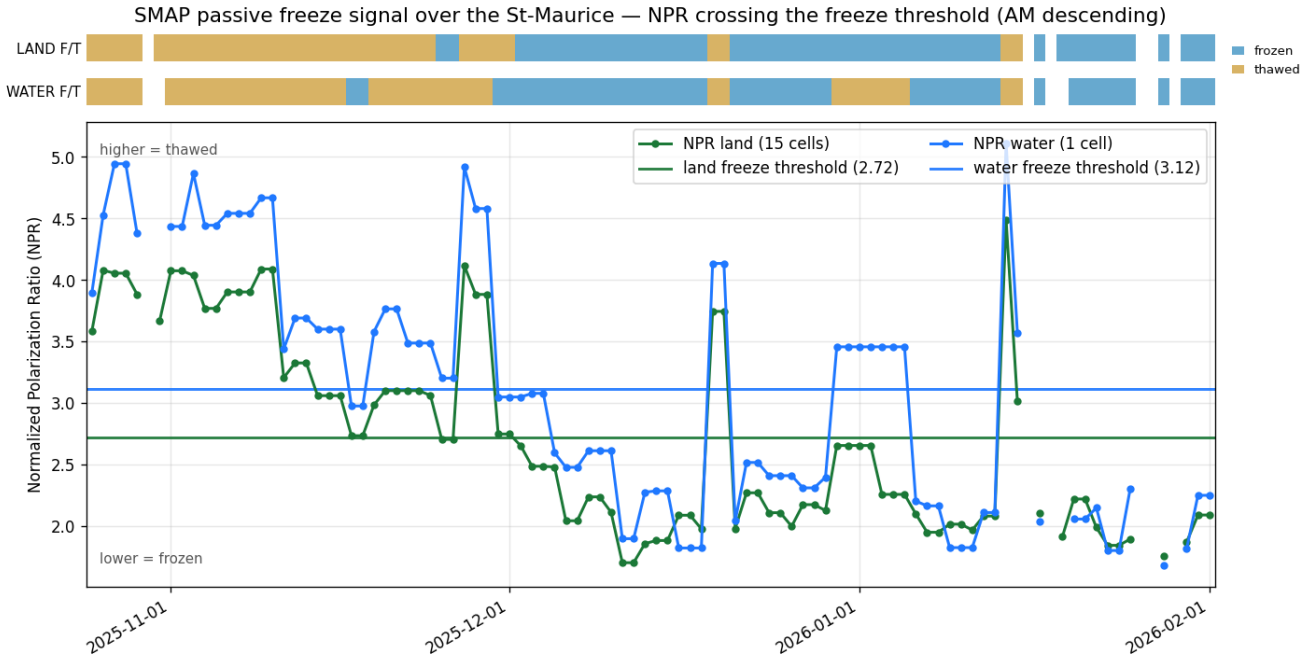
✓ Baseline algorithm: Binary product

✓ **transitional "zero-curtain" phase** where liquid water and ice coexist.

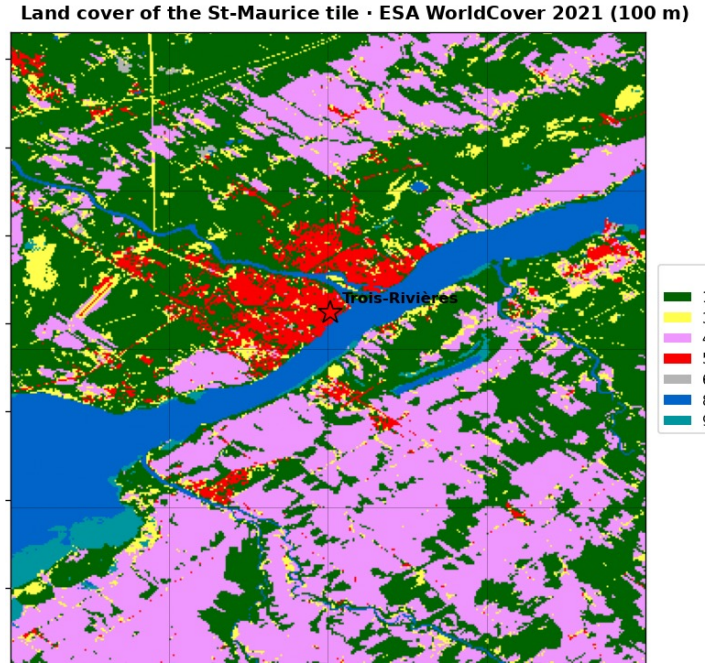
Supporting continental-scale ecological research:

✓ northern hydrology, ecosystem dynamics, and carbon cycling

Passive FT @ local scale

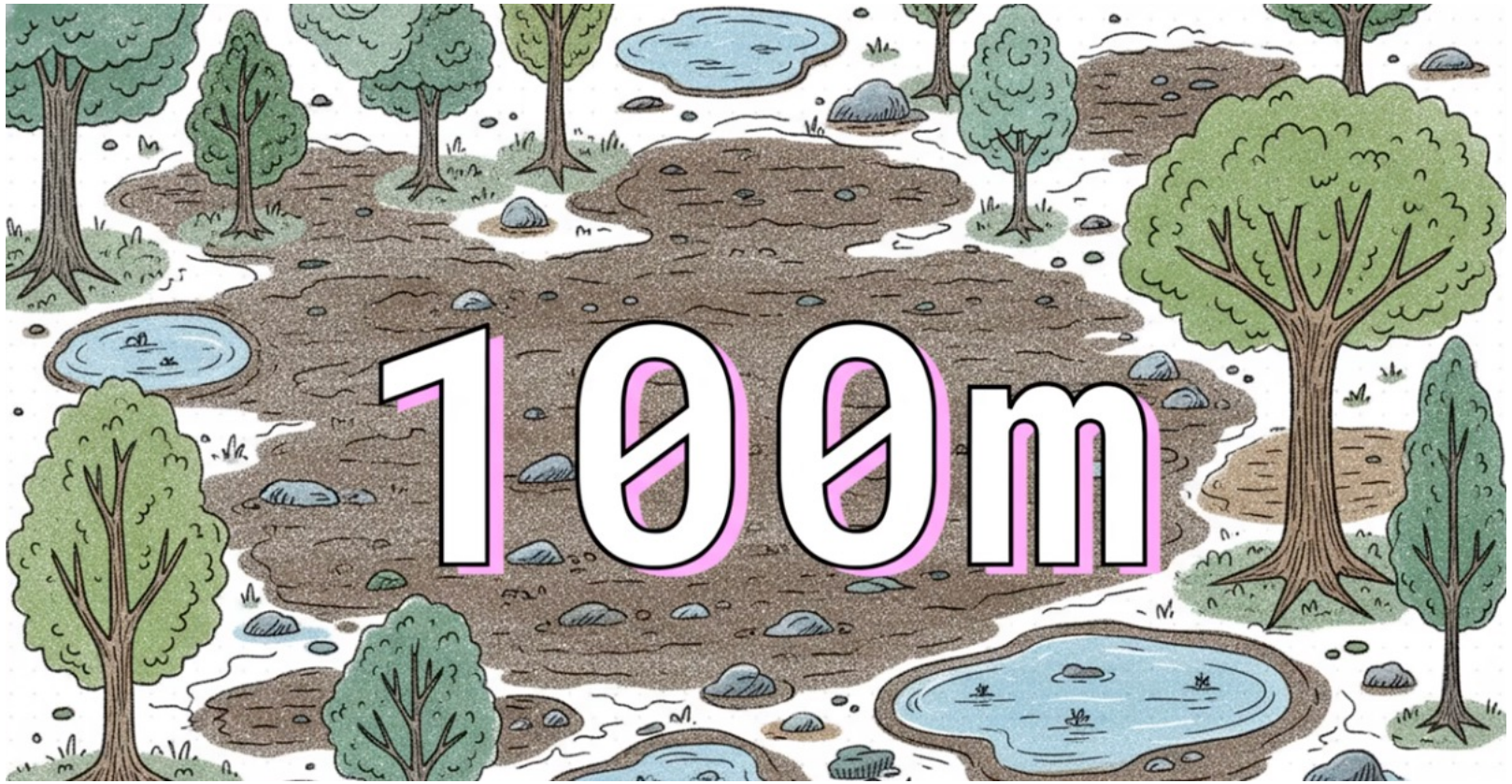


NPR crosses the freeze threshold (land vs water)



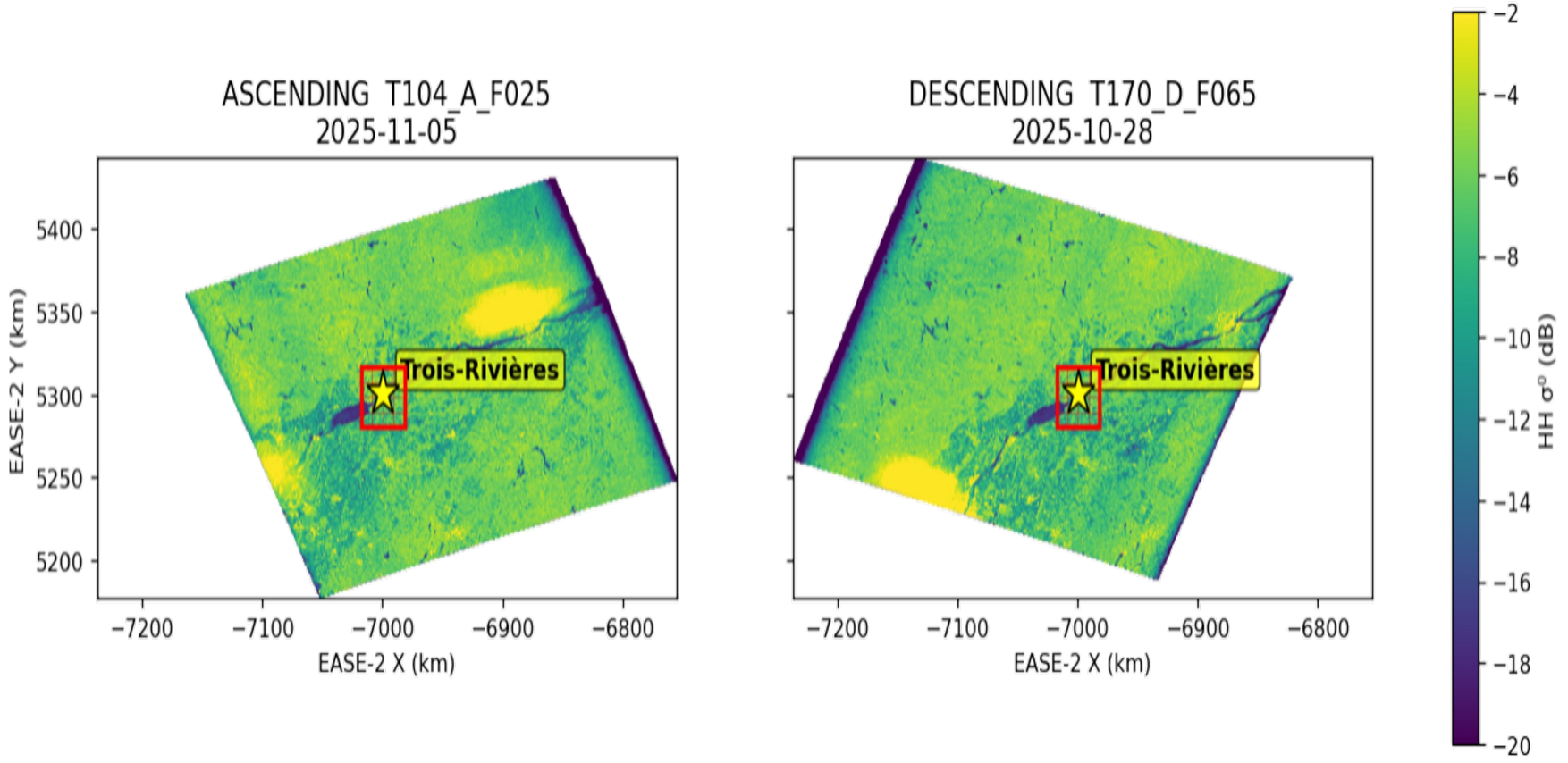
Tile land cover: forest 44% · cropland 34%

L-band SAR is collecting again (NISAR mission)



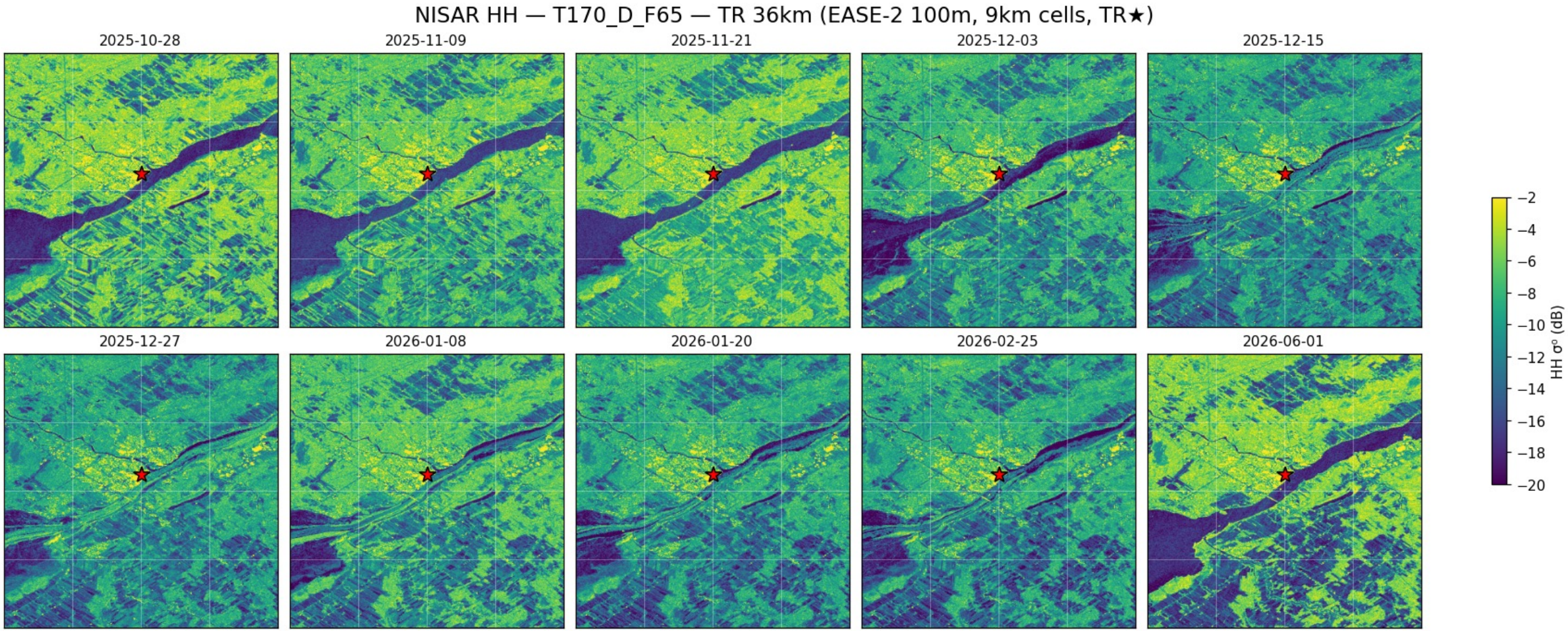
NISAR image over the St-Maurice

Over ~6 weeks the surface changes state — and that state controls the water budget.

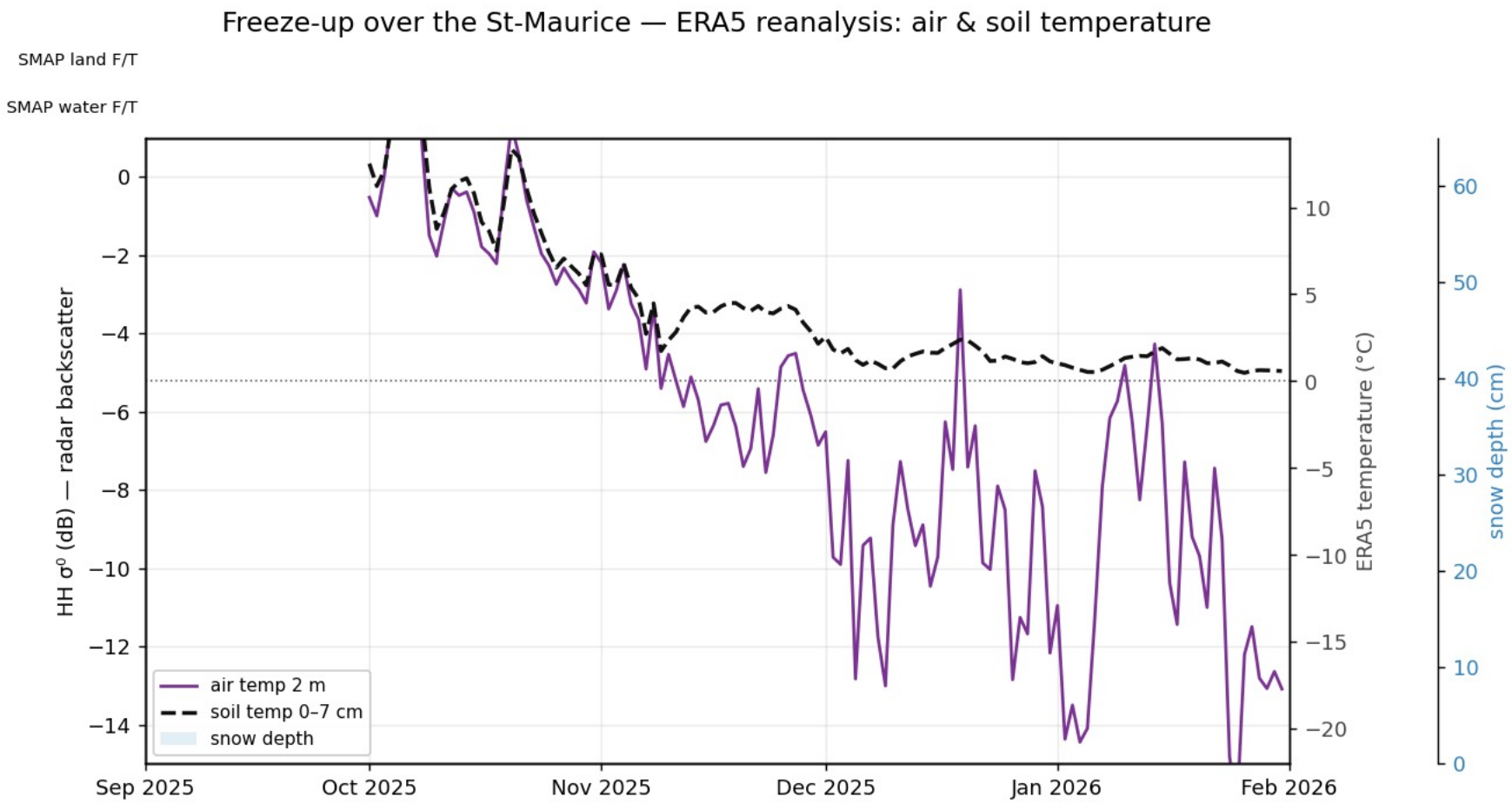


L-band SAR scene · Réservoir Gouin → the St-Lawrence at Trois-Rivières. Can a satellite see this state at the scale that matters?

Let’s zoom in a 36km area



Freeze-up varies by land cover



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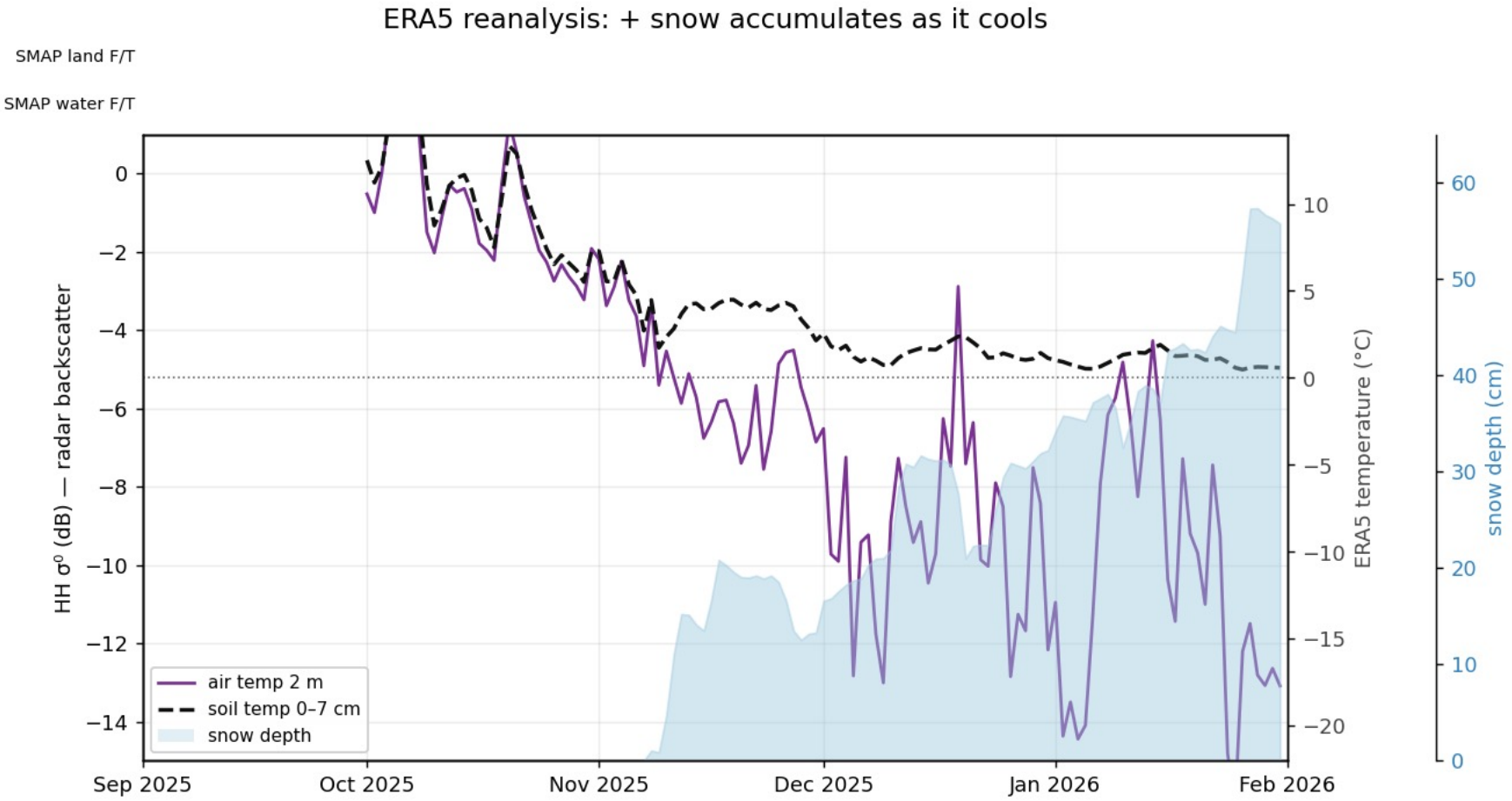
ERA5 reanalysis sets the seasonal frame — air & soil temperature.

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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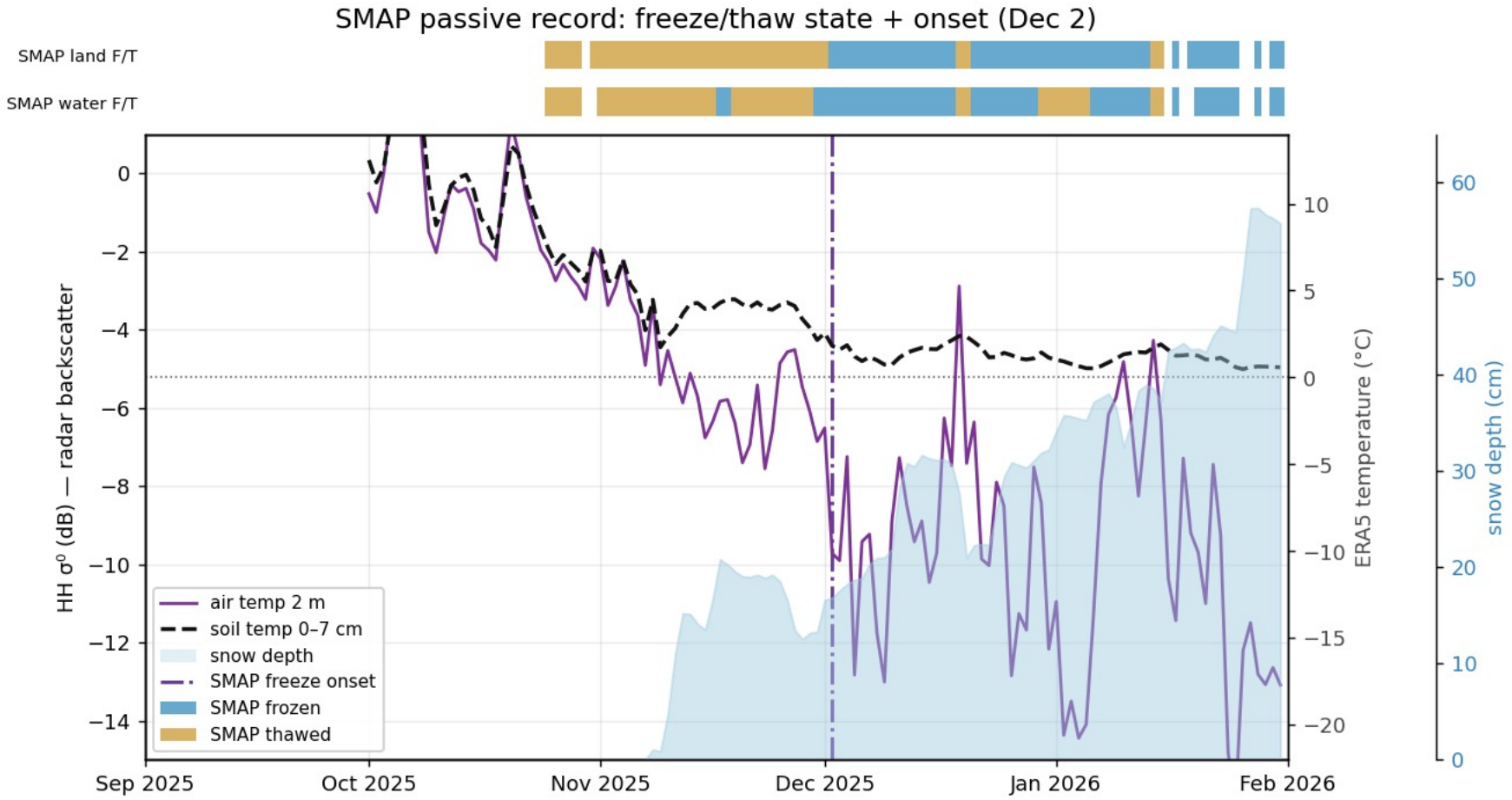
Snow accumulates as it cools.

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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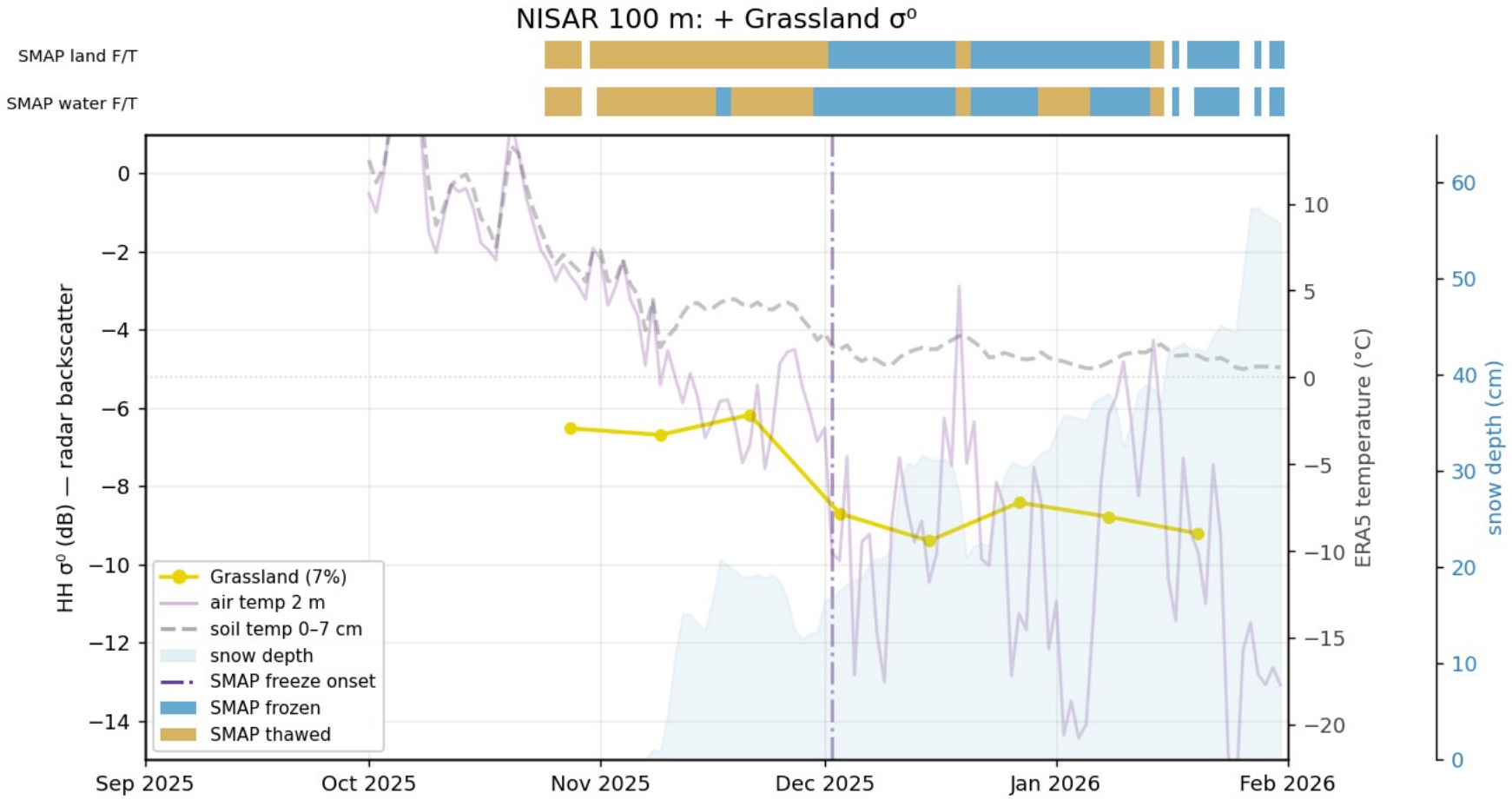
SMAP passive record: the coarse binary state, freeze onset ~Dec 2.

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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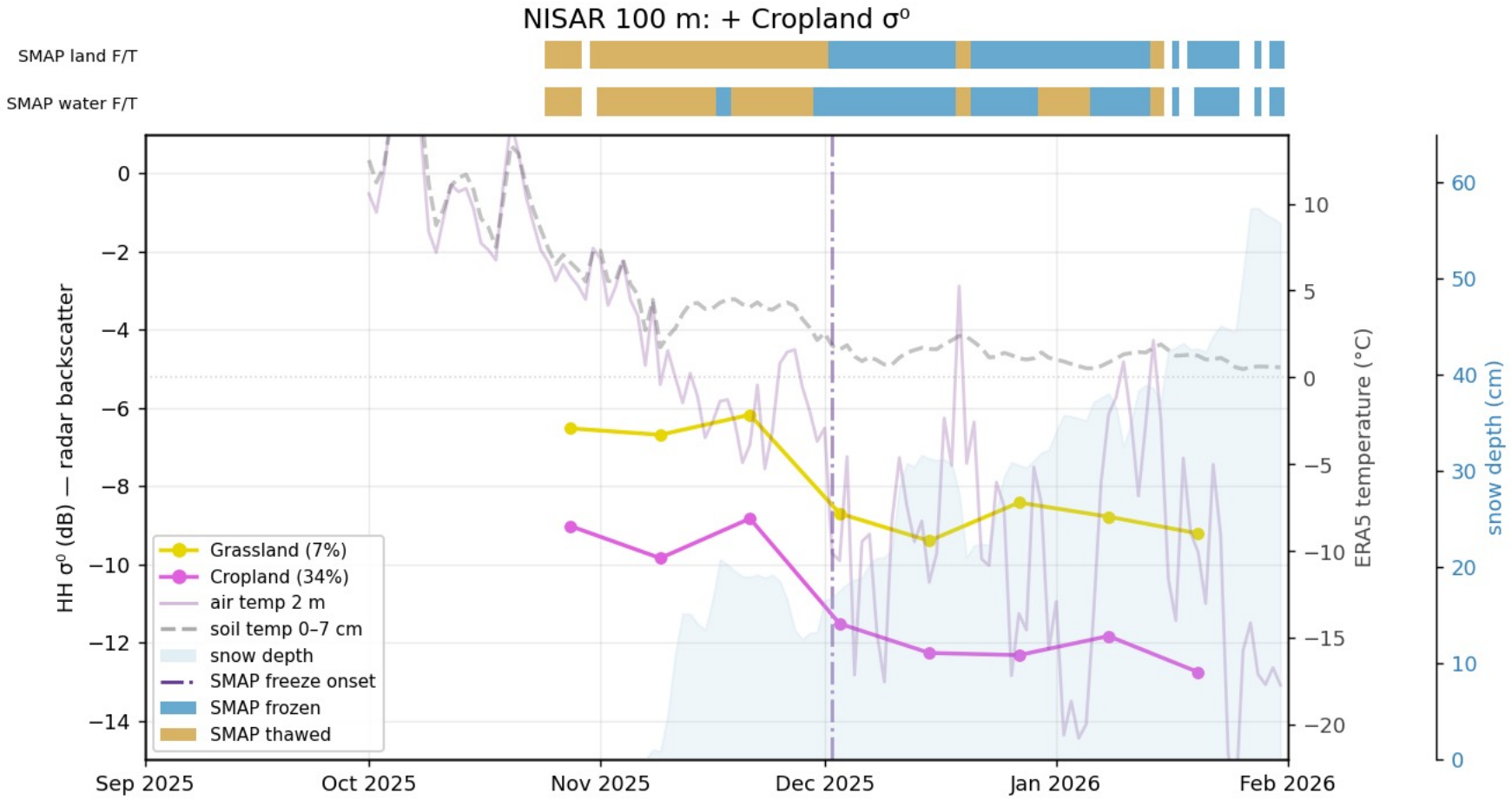
Zoom to 100 m — grassland's σ⁰ freeze-down (7% of the cell).

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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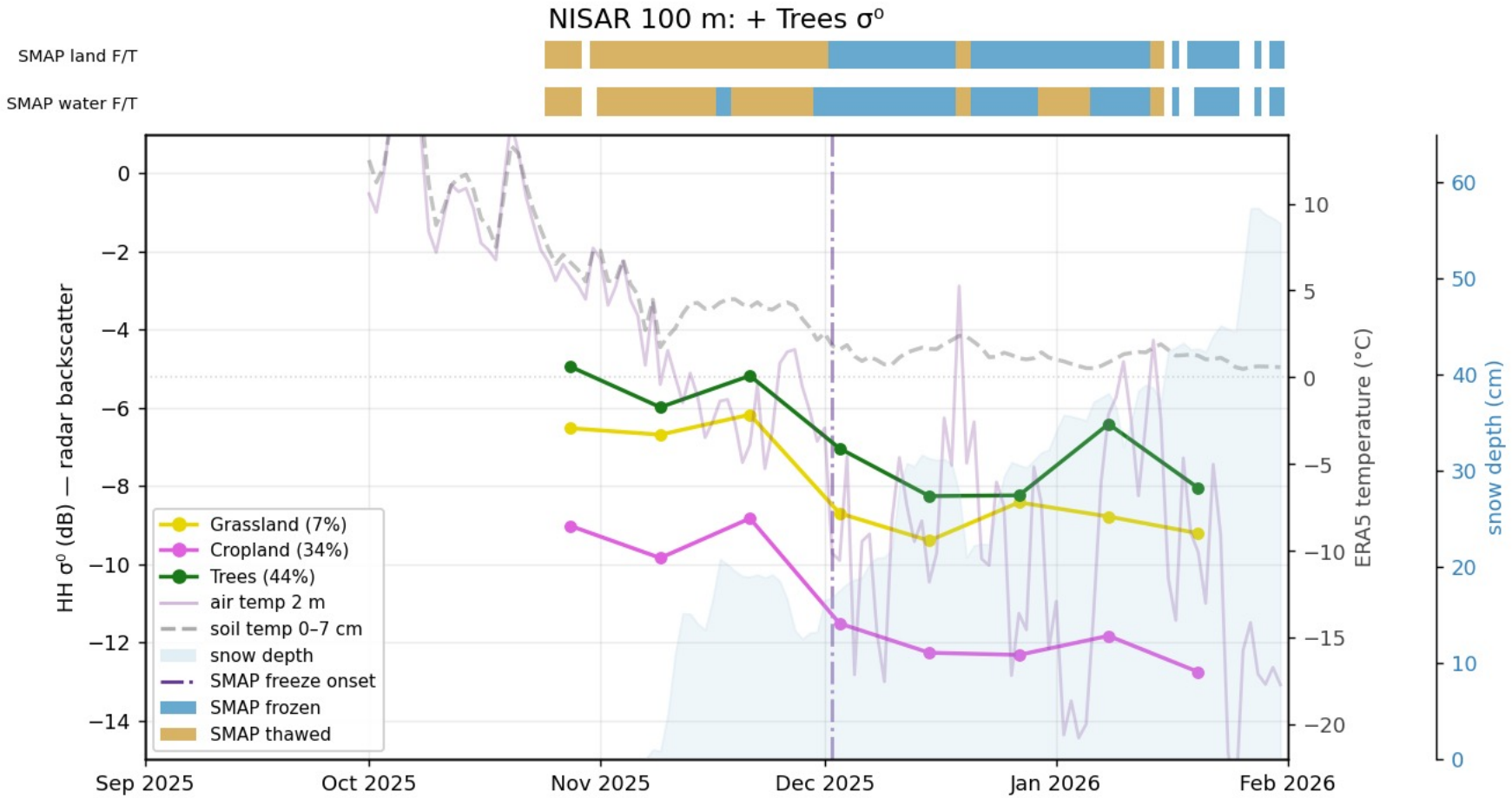
Cropland adds its own timing and magnitude (34%).

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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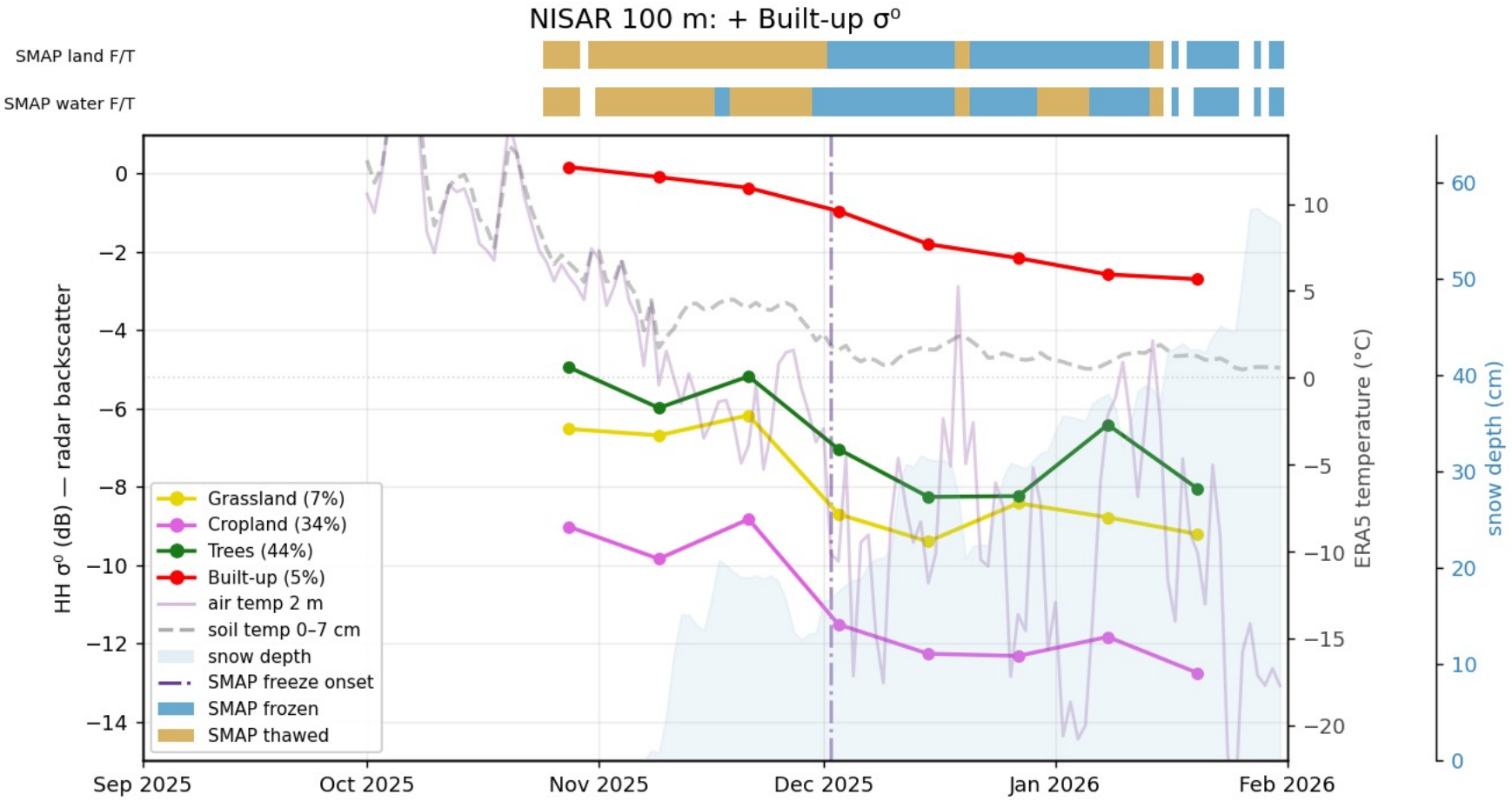
Trees — the largest class (44%) — a coherent freeze-down.

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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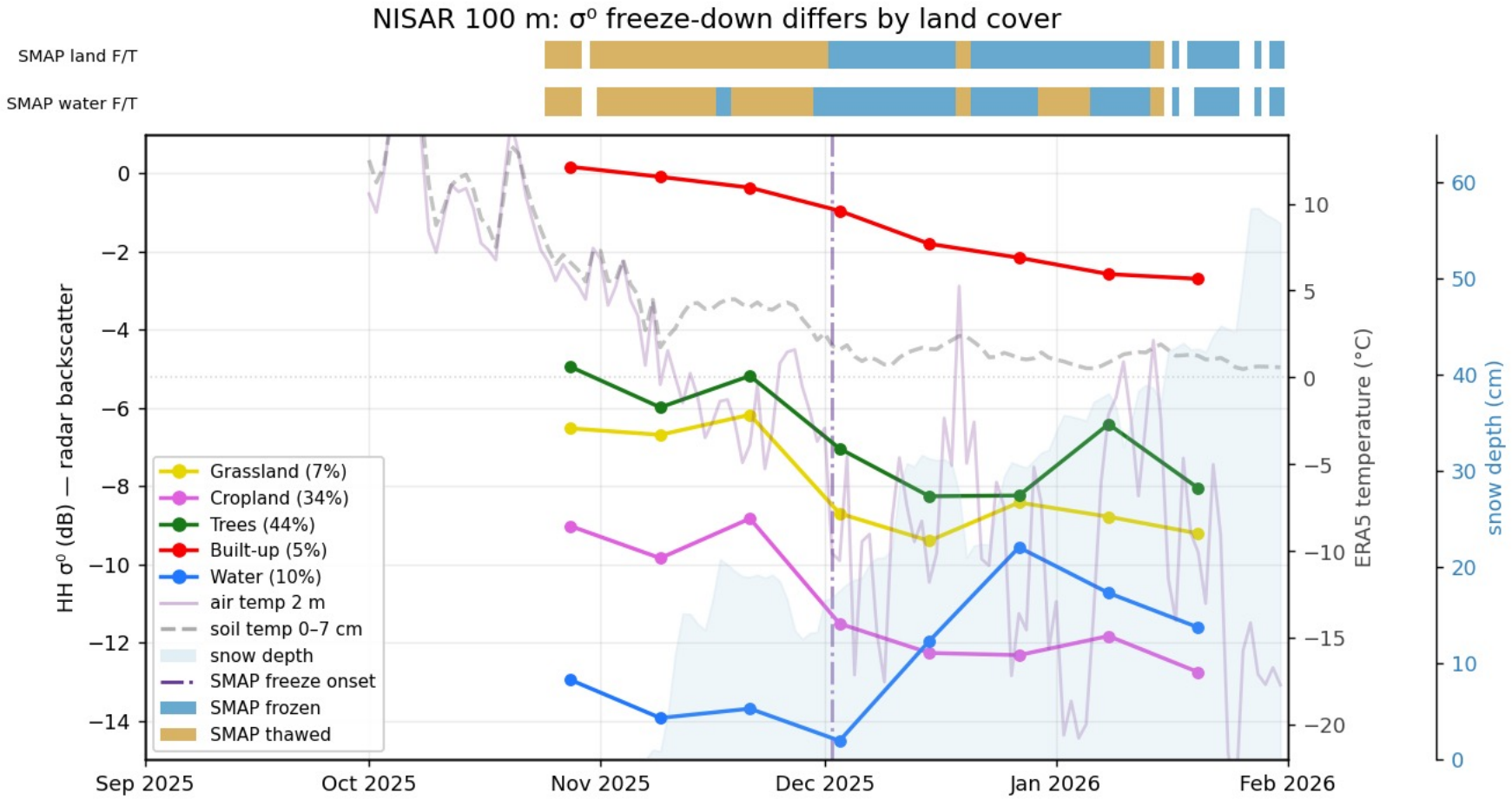
Built-up changes least (~3 dB swing).

· INSIDE ONE SMAP CELL

Freeze-up varies by land cover



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One SMAP cell hides land-cover-specific freeze timing and magnitude.

To know if σ^0 resolves freeze, SFCC you need ground truth

ALASKA · HAS IN-SITU

Ground truth lets you test σ^0

- 37 SNOTEL/SCAN stations across Alaska
- 760 (σ^0, soil-temp, liquid-water) triplets at the 100 m pixel, Oct 2025 – Jan 2026
- Freeze defined from ts crossing 0 °C (≥7 d) and the liquid-water collapse
- → a verdict on each pixel

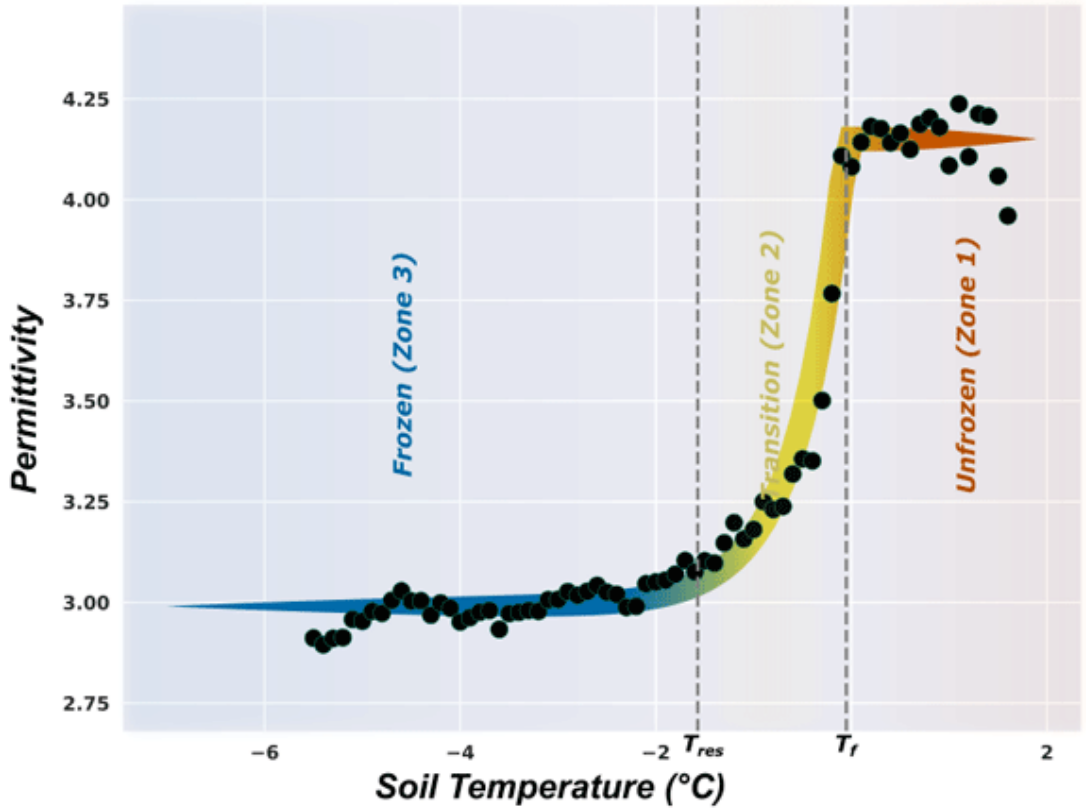
ST-MAURICE · NO IN-SITU

Same σ^0 — but no validation

- The L-band σ^0 analog exists over the basin
- No co-located in-situ to draw or confirm the freeze characteristic
- Half-solved on its own
- → the collaboration ask (next sections)

Beyond binary: continuous freeze state

Soil Freezing Characteristic Curve



The SFCC captures the zero-curtain and partial-freeze states a binary scheme erases.

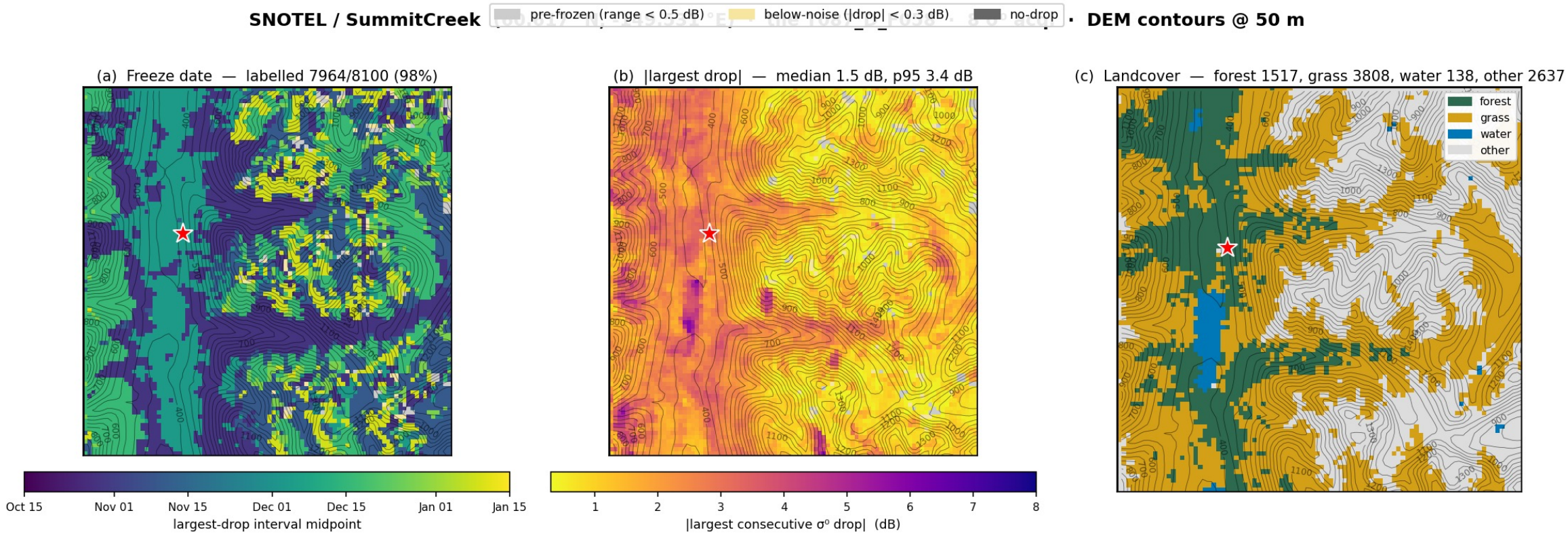
The measurement question

What does σ^0 represent physically at each pixel — and how does it map through the SFCC to hydraulic conductivity (hydrology) and respiration breakpoints (ecosystems)?

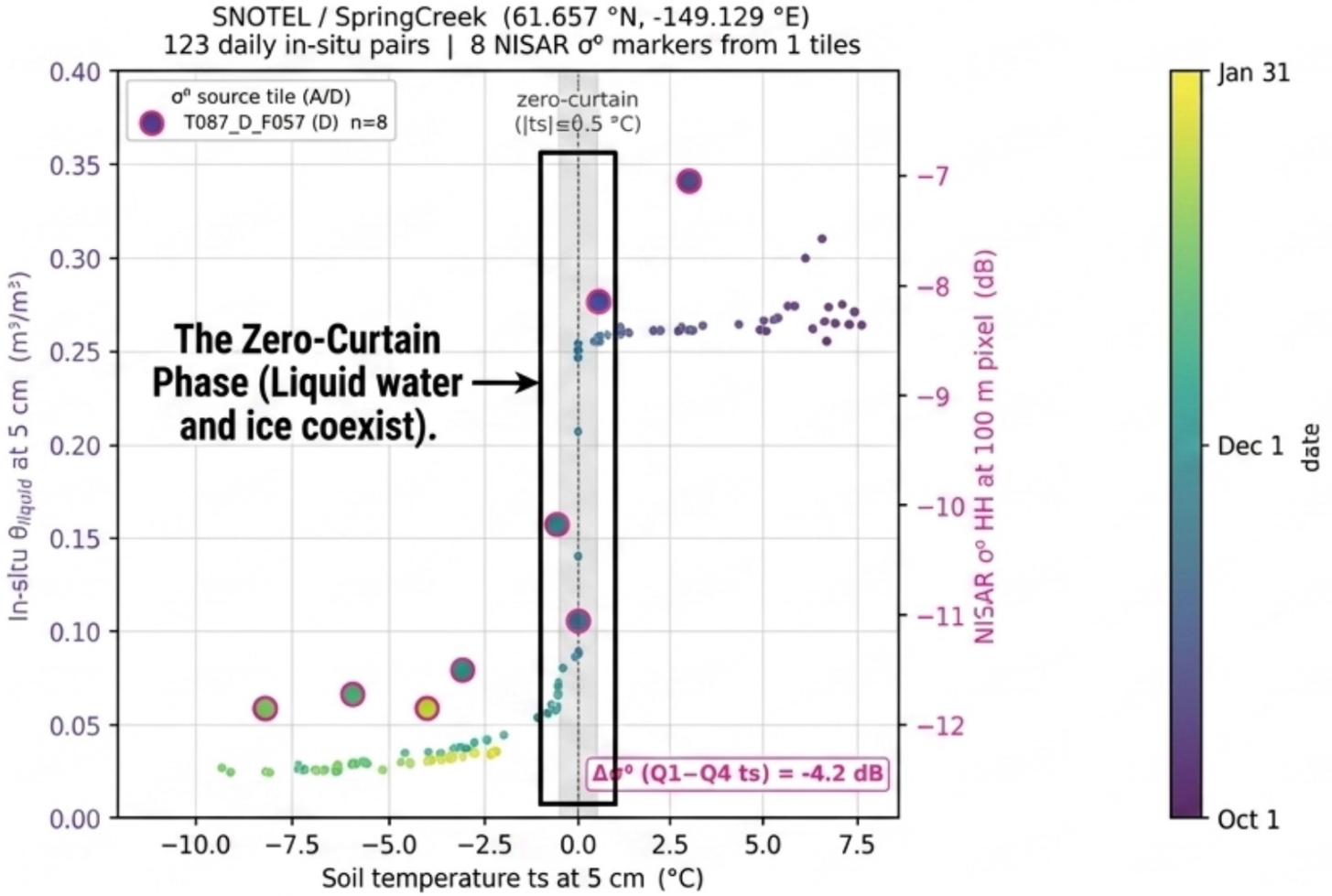
Salmabadi, Hesam, Renato Pardo Lara, Aaron Berg, Alex Mavrovic, Chelene Hanes, Benoit Montpetit, and Alexandre Roy. "In situ monitoring of seasonally frozen ground using soil freezing characteristic curve in permittivity–temperature space." *The Cryosphere* 20, no. 3 (2026): 1635-1654.

One SMAP cell = 8,100 NISAR pixels

SummitCreek, 9×9 km: four land-cover regimes freeze weeks apart — a 7× range in $\Delta\sigma^0$ (median 1.5, p95 3.4, max 6.1 dB).



Surface Freeze Characteristic Curve (Alaska)



The Biological Link

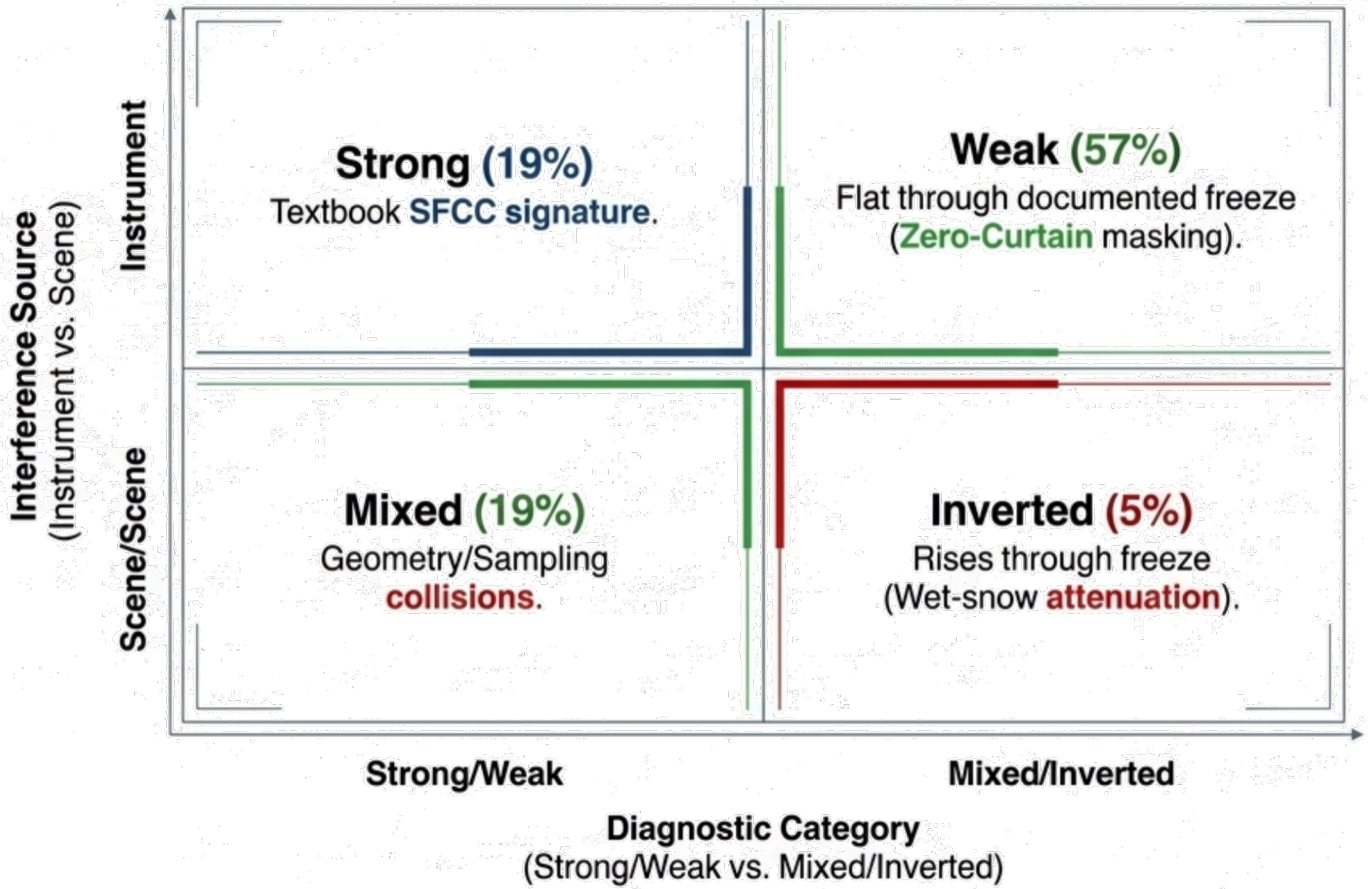
By tracking precise liquid-water transitions rather than just temperature thresholds, satellite data now maps directly to carbon flux and respiration breakpoints.

The Open Question

The remaining ambiguity is a forward-model problem. Linking radar backscatter through the SFCC to hydraulic conductivity requires localized field validation—the next great collaborative frontier.

At 100 m, σ^0 is clean only part of the time

37 Alaska stations, sorted by response. The trajectories are mutually indistinguishable from σ^0 alone.

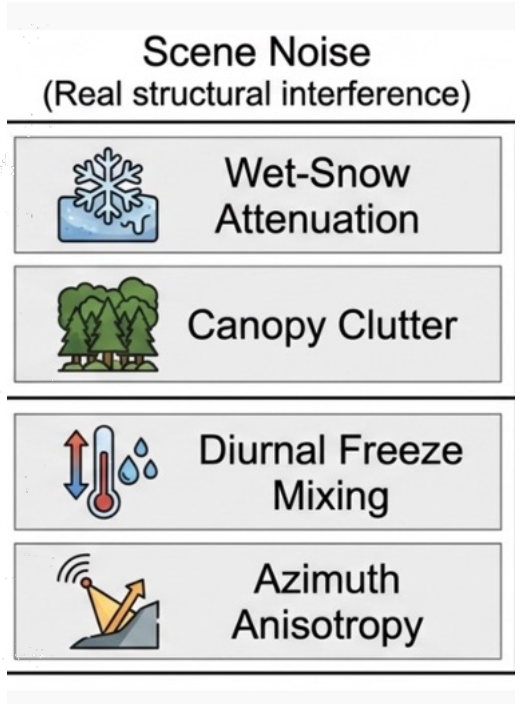


Instrument Noise
Random. We can average it away.

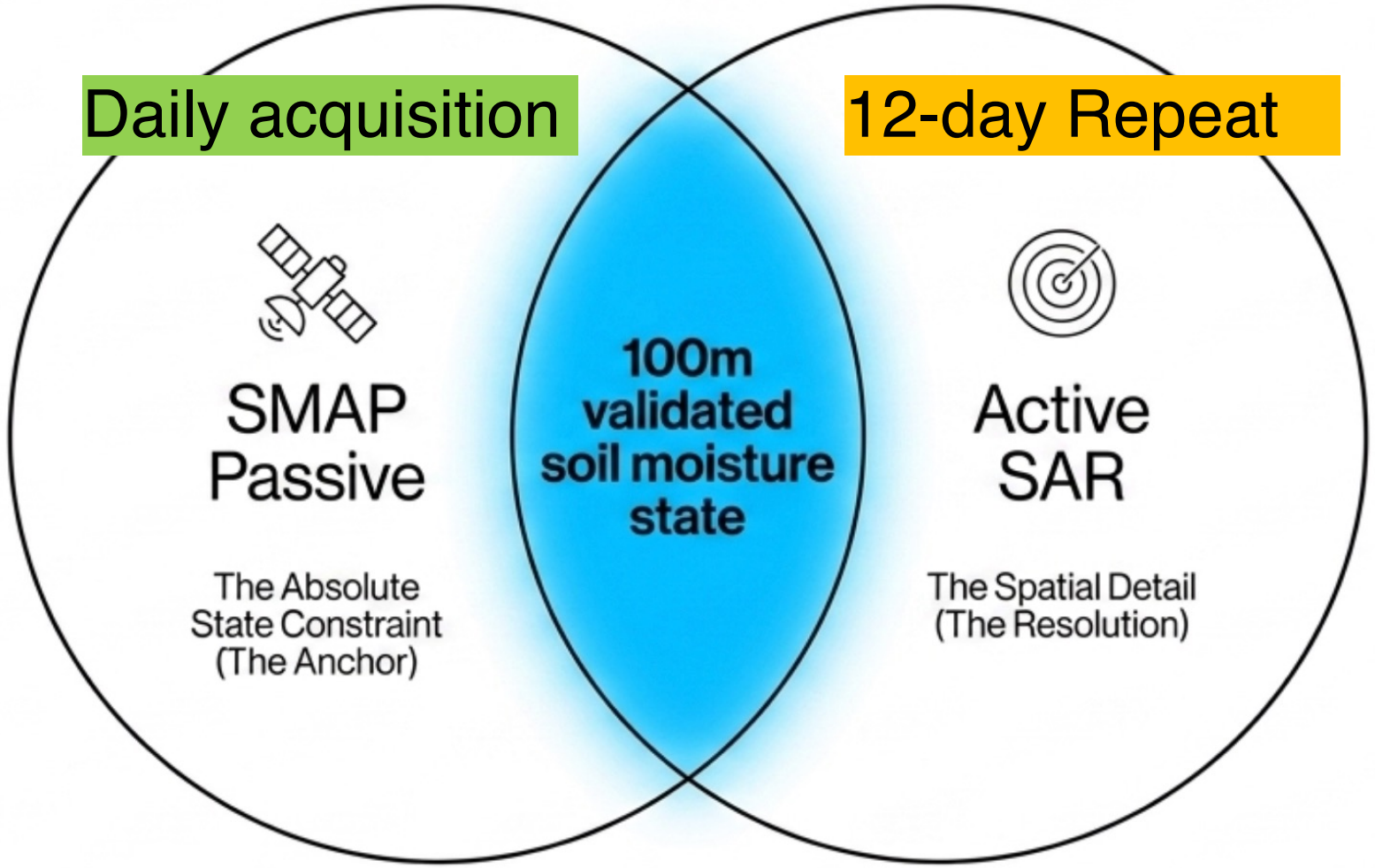
Scene Noise
Physical reality (snow, trees). Averaging fails here.

Sampling Geometry
Ascending vs. descending inconsistencies.

Scene Noise
(Real structural interference)



Active-Passive Synergy:
Can we Fulfill the SMAP Freeze/Thaw Vision?



10 years of wide-angle SMAP passive data provides the accurate, absolute baseline.

Active SAR provides the 100m spatial resolution.

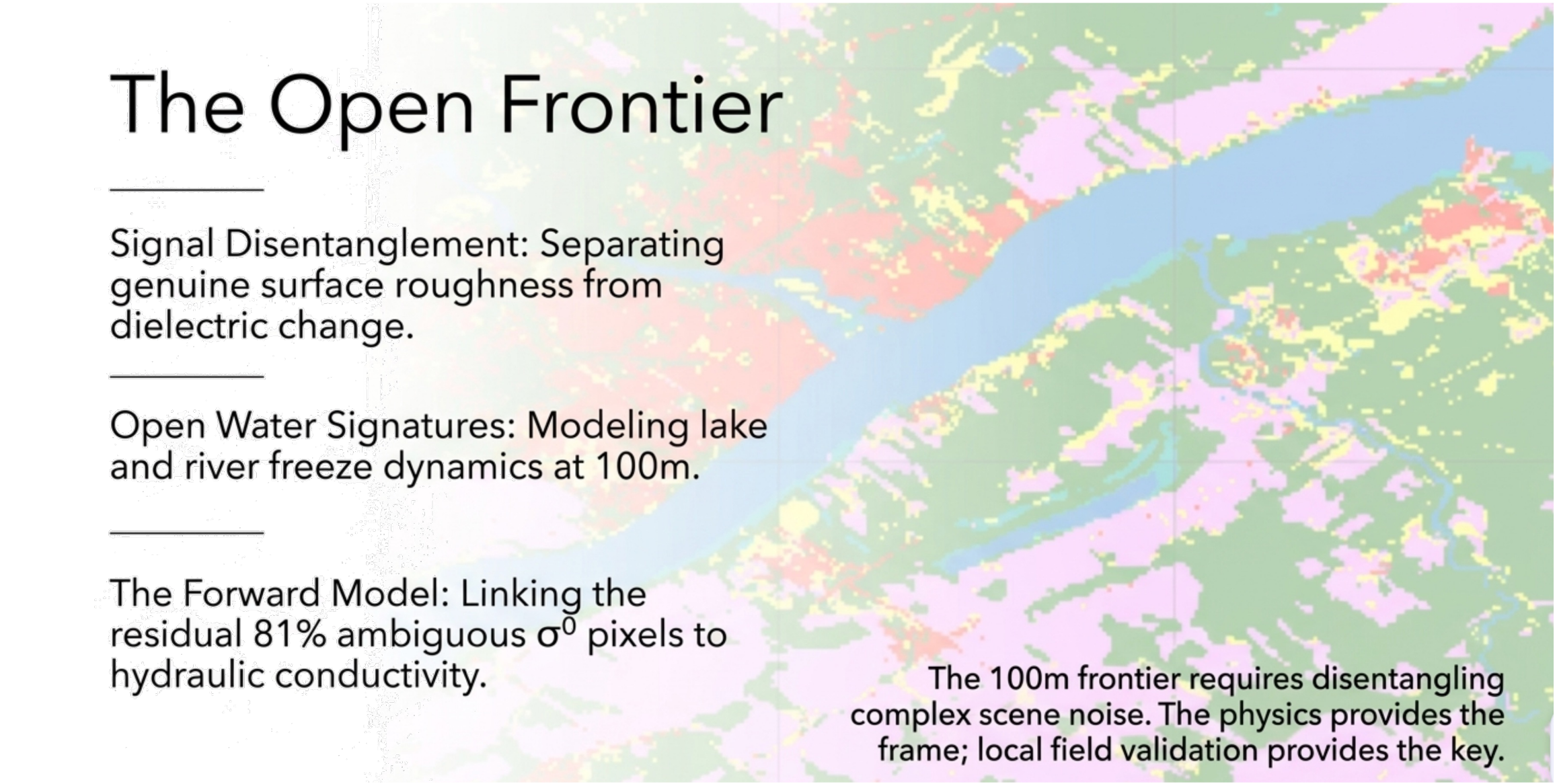
Together, they act as a lock-and-key mechanism to disentangle complex high-resolution radar returns.

The Open Frontier

Signal Disentanglement: Separating genuine surface roughness from dielectric change.

Open Water Signatures: Modeling lake and river freeze dynamics at 100m.

The Forward Model: Linking the residual 81% ambiguous σ^0 pixels to hydraulic conductivity.



The 100m frontier requires disentangling complex scene noise. The physics provides the frame; local field validation provides the key.

Acknowledgments

This work builds on SMAP mission leadership and a close Canadian collaboration.

SMAP · NASA LEADERSHIP

Simon Yueh
SMAP Project Scientist
NASA JPL

Dara Entekhabi
SMAP Science Team Lead
MIT

Craig Ferguson
SMAP Program Scientist
NASA Headquarters

CANADIAN COLLEAGUES

Alexandre Roy & group
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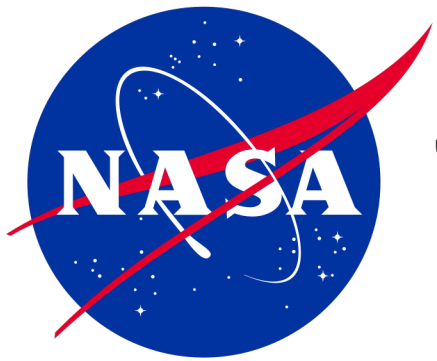
Université du Québec à Trois-Rivières (UQTR)

Chris Derksen
Freeze–thaw collaborator
Environment and Climate Change Canada

Xiaolan Xu · NASA JPL · SMAP L3 Freeze/Thaw · SMAP L3_FT_P open at NSIDC (nsidc.org/data/smap)



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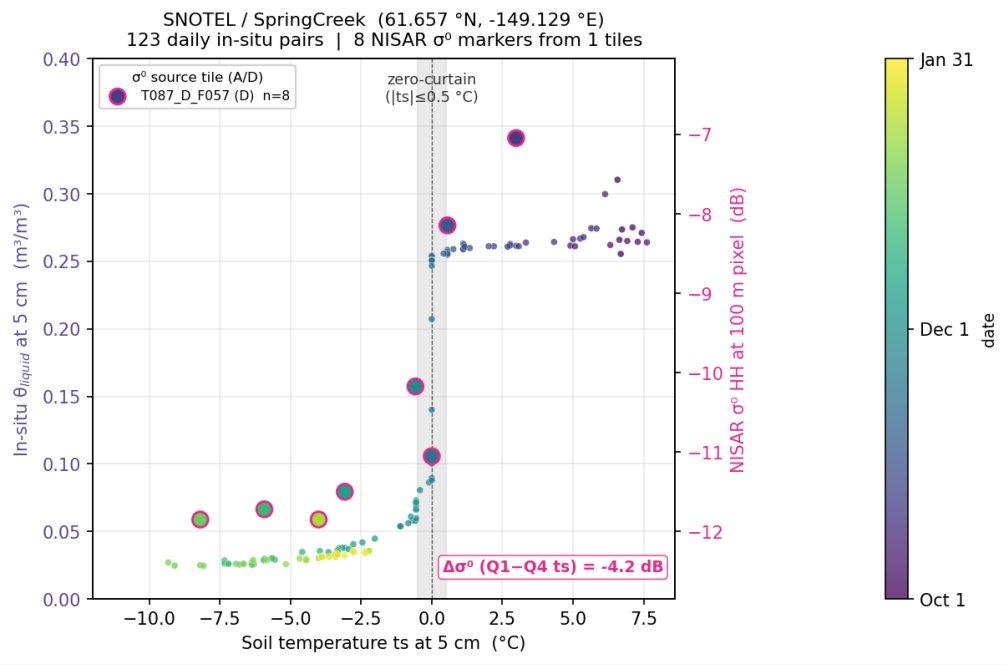
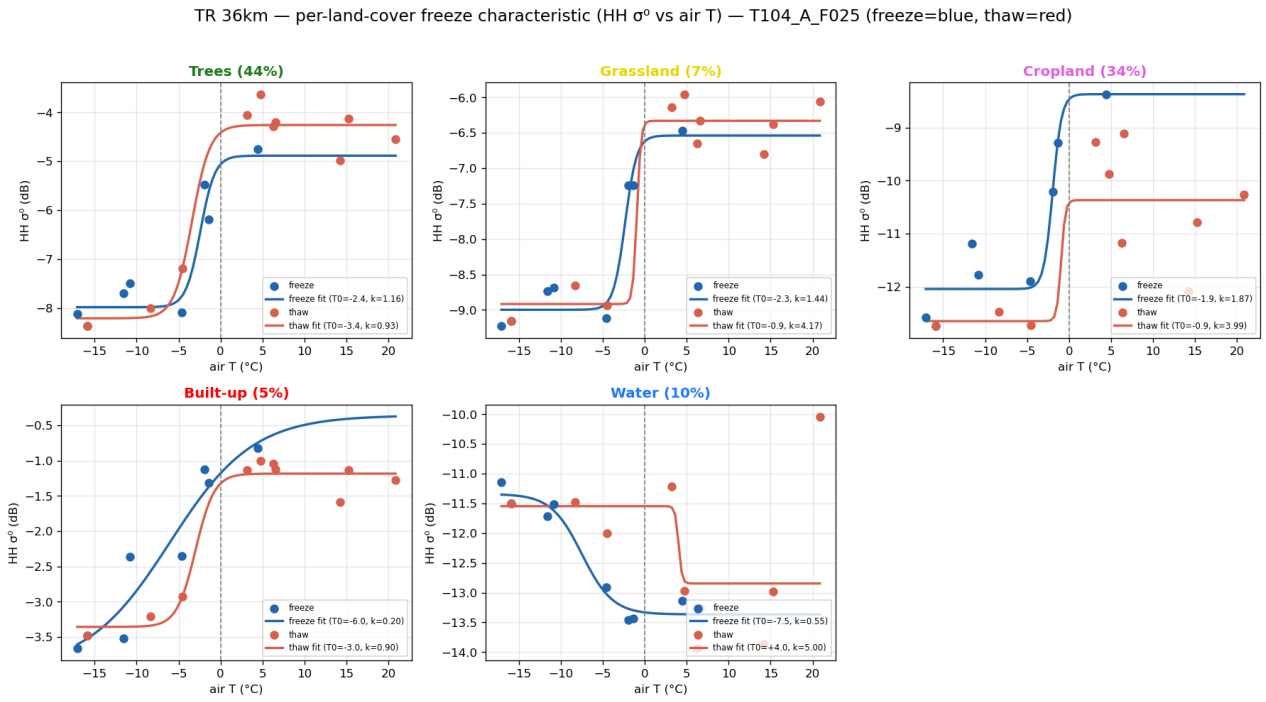
The σ⁰–temperature freeze characteristic





Alaska (SpringCreek): in-situ liquid water draws & validates the SFCC — σ⁰ is the L-band replica.

St-Maurice: the σ⁰ analog exists, but no in-situ → the collaboration ask.

Building on the C-band foundation

The host group already showed FT is retrievable over this landscape from SAR. That's the starting point.

C-BAND · SENTINEL-1

Carries open agriculture

- EFTA probabilistic framework, strong agricultural accuracy
- Real in-situ network (2 & 10 cm soil temp, Borealis)
- ~70 m effective after speckle filtering

L-BAND · NEW SAR

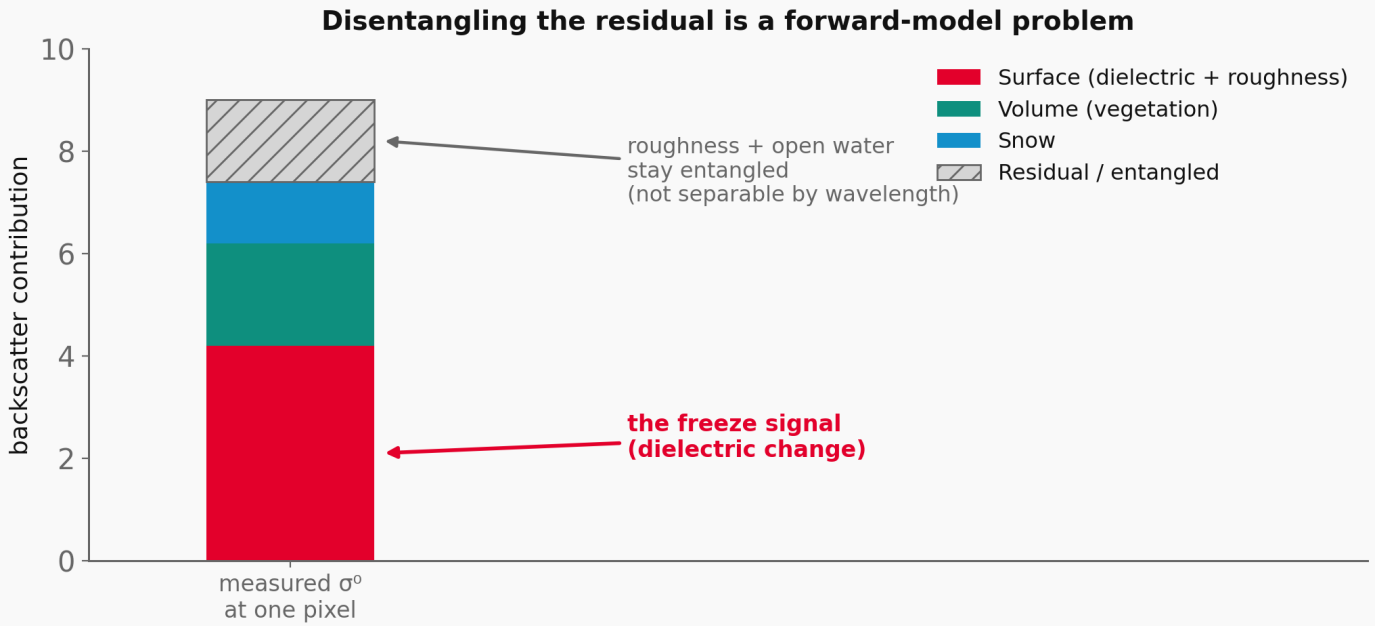
Reaches the forested basin

- Longer wavelength → lowest canopy scene noise
- 100 m tile — same scale as C-band ~70 m
- Bands combine directly, and across passes (prev slide)

The natural step: process L-band over their sites and work the forest problem together.

Credit: Taghipourjavi, Kinnard & Roy 2024

Disentangling the residual



Constrained today

- A decade passive record
- A sub-km active observable
- L-band's scene-noise advantage
- 100 m heterogeneity

Open

- The ambiguous pixels (roughness + open water entangled)
- Validation at watershed scale
- FT → SFCC → conductivity linkage
- Lake / river freeze–thaw