Liquid water in ice sheet firn: detection, infiltration depth, and path towards a quantitative approach

Pierre Zeiger – IGE

08/03/2025

Introduction

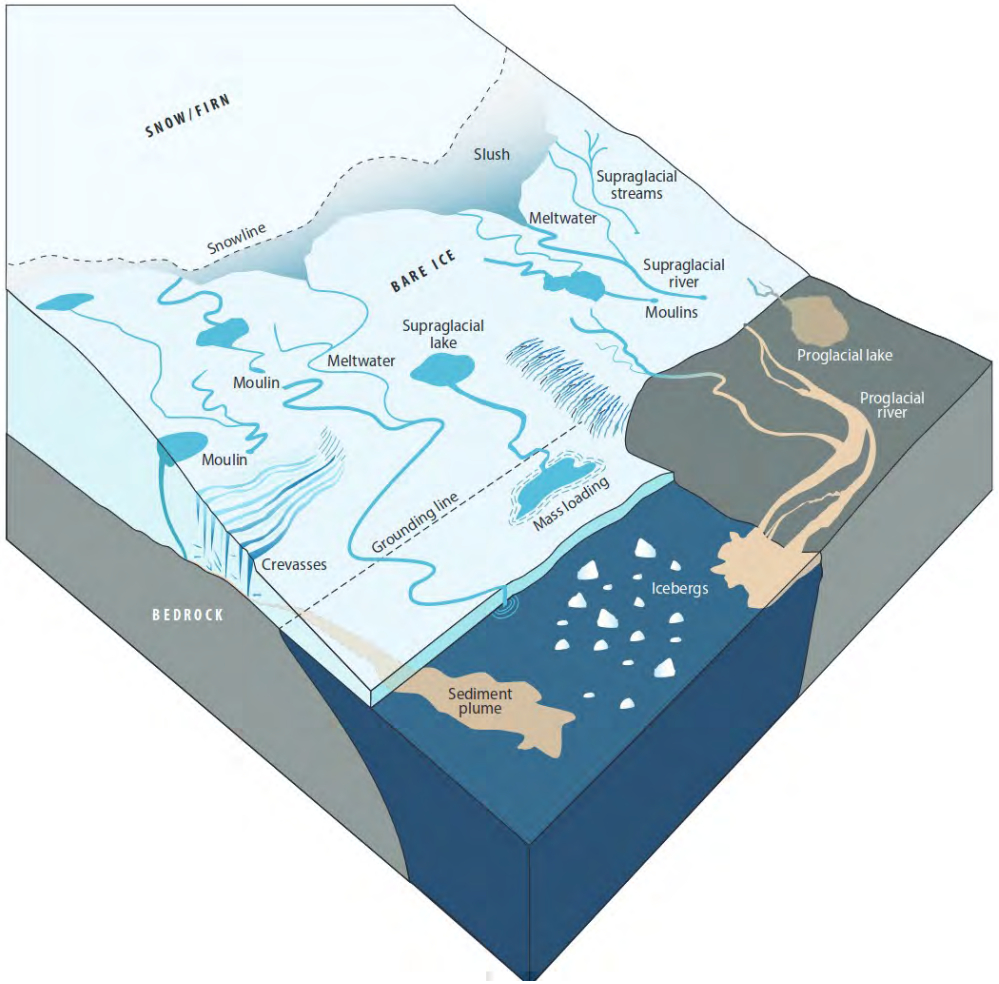
Ice sheet hydrology: impacts on mass balance

→ Runoff from ablation and firn zones

→ Accumulation, ponding and drainage

→ Ice fracturation and velocity increase

→ High uncertainty in SMB projections



From Pitcher and Smith, 2019

Introduction

Ice sheet hydrology: impacts on mass balance

→ Runoff from ablation and firn zones

→ Accumulation, ponding and drainage

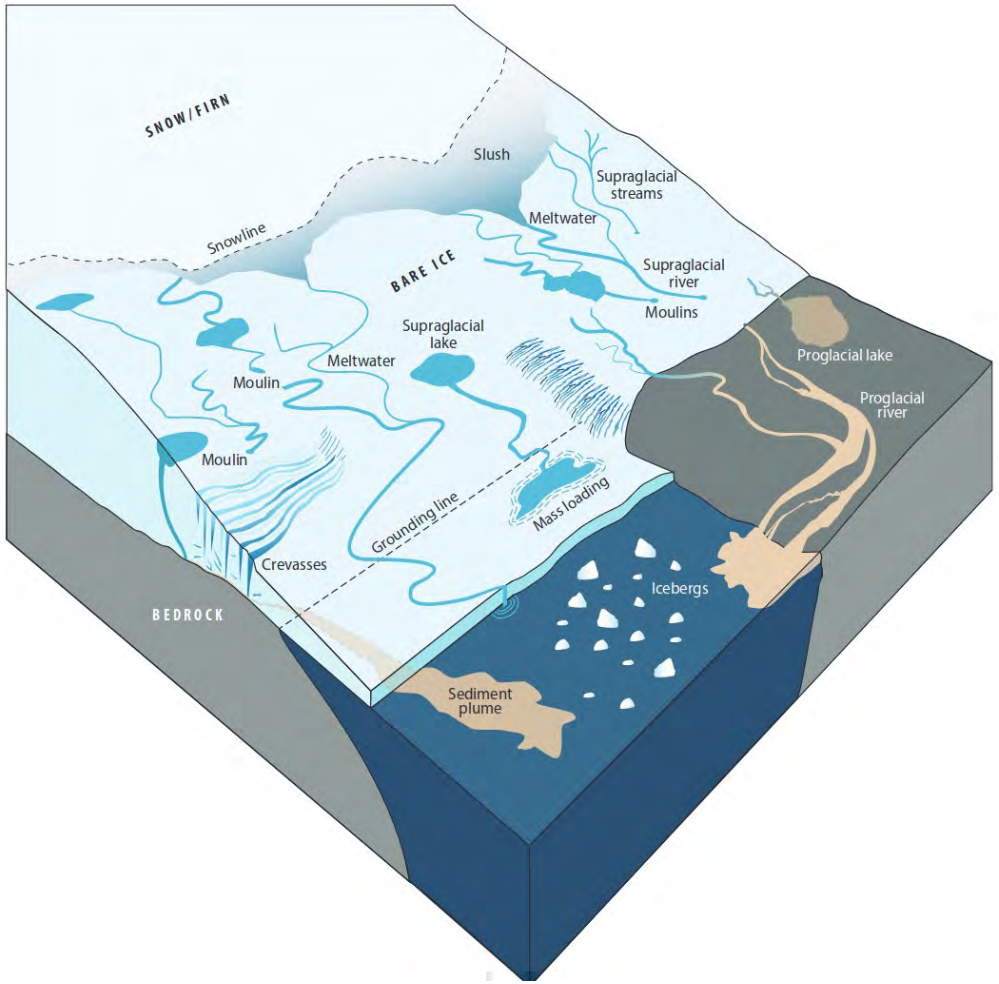
→ Ice fracturation and velocity increase

→ High uncertainty in SMB projections

Spaceborne observations of ice sheet hydrology

→ Firn hydrology (microwave radiometers, SAR);

→ Supraglacial (optical, SAR) and subglacial (inSAR, altimetry) networks



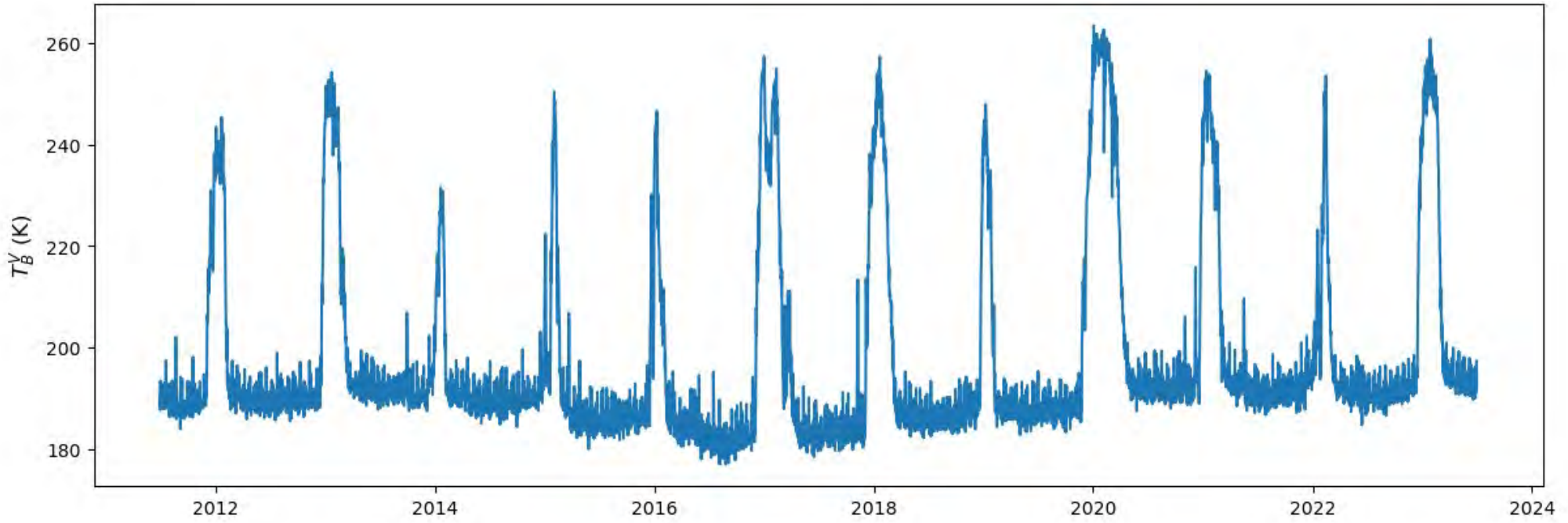
From Pitcher and Smith, 2019

Introduction

Liquid water detection using microwave radiometers

- Emission from the surface and subsurface
- Very high sensitivity to liquid water

- Climate timescale (1978-)
- <daily observations in polar regions



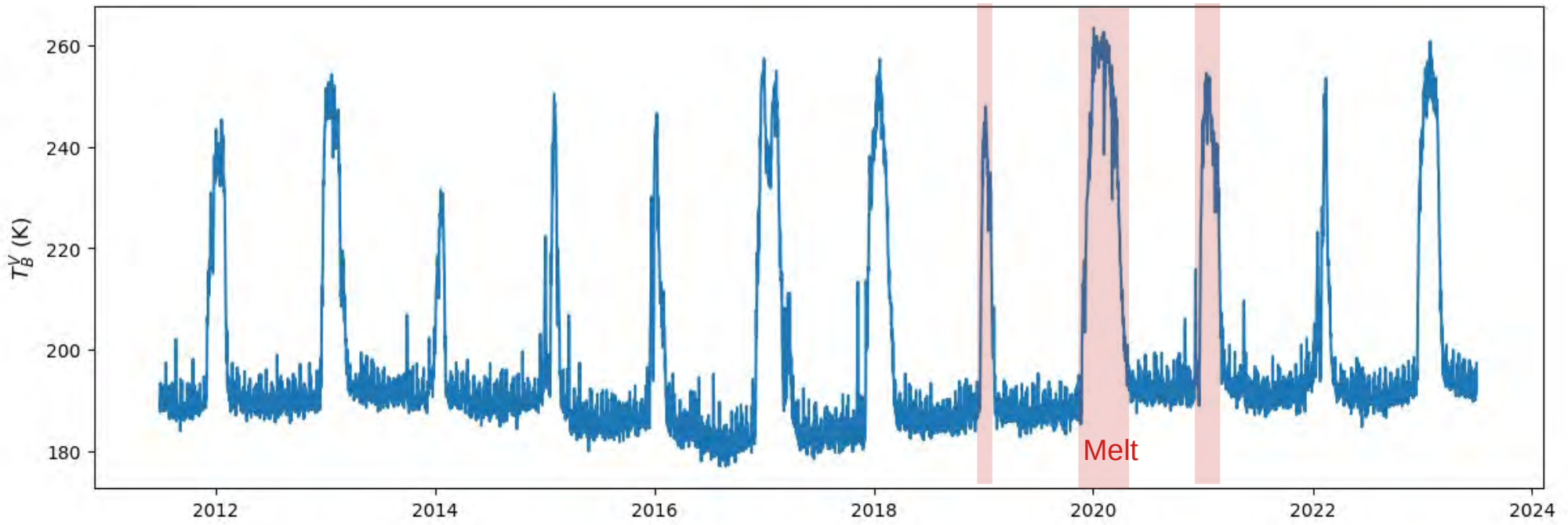
SMOS vertical polarization time series on the George VI ice shelf, Antarctica

Introduction

Liquid water detection using microwave radiometers

- Emission from the surface and subsurface
- Very high sensitivity to liquid water

- Climate timescale (1978-)
- <daily observations in polar regions

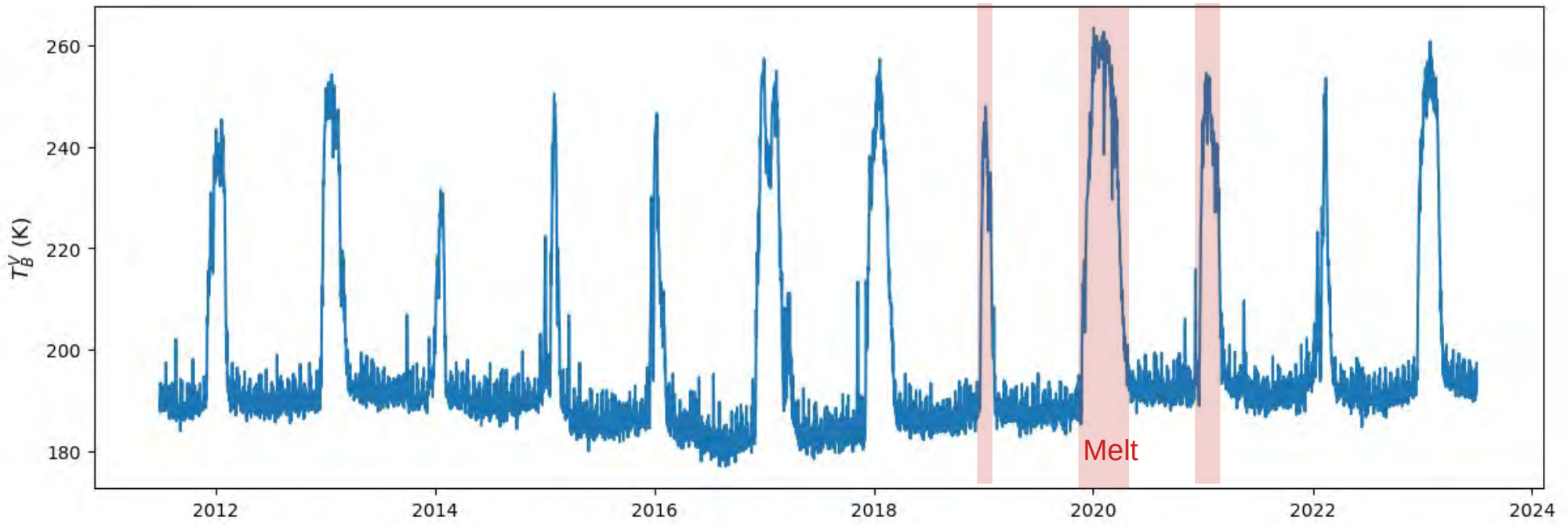


SMOS vertical polarization time series on the George VI ice shelf, Antarctica

Introduction

Liquid water detection using microwave radiometers

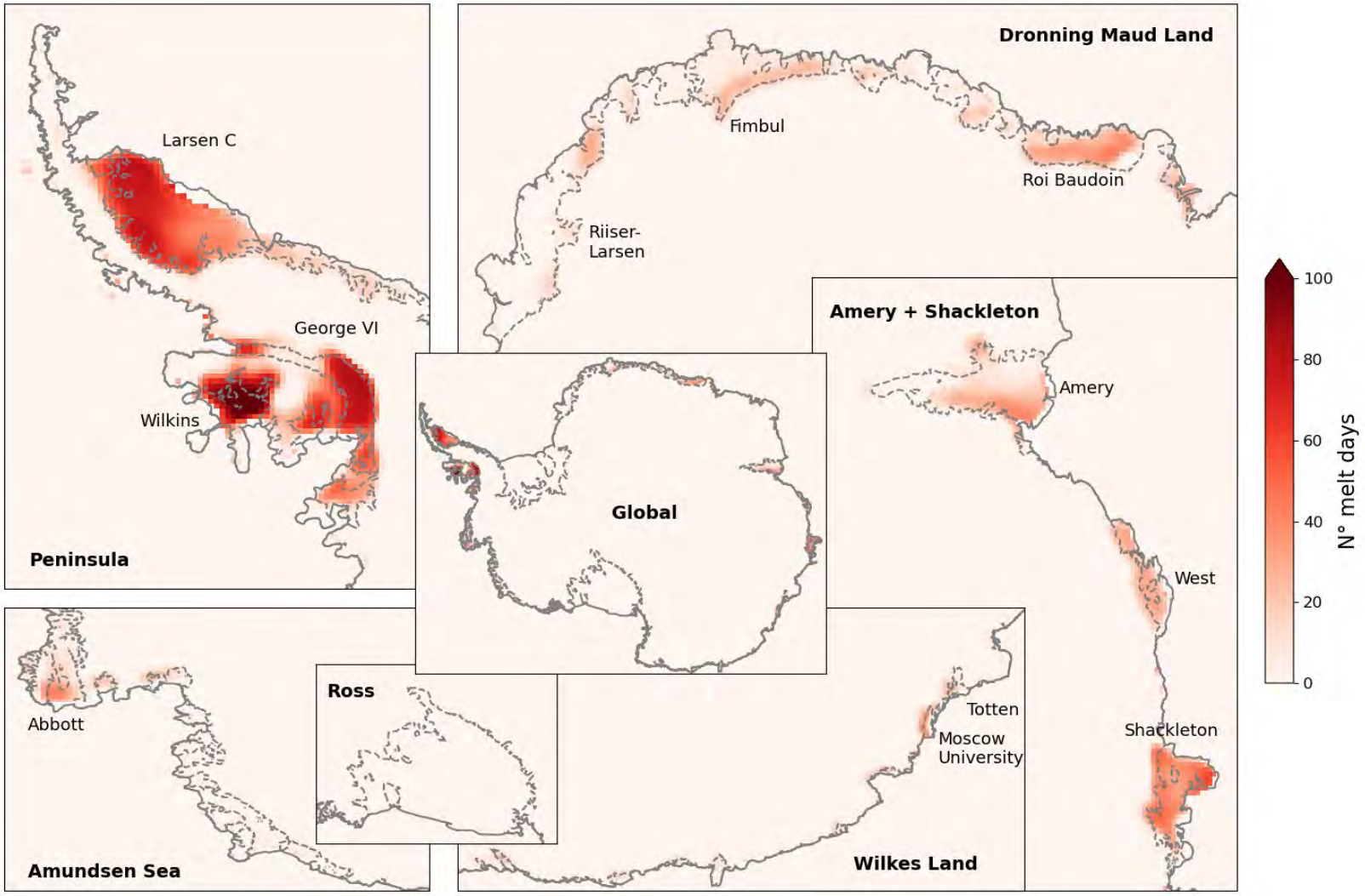
- Emission from the surface and subsurface
- Very high sensitivity to liquid water
- Climate timescale (1978-)
- <daily observations in polar regions



SMOS vertical polarization time series on the George VI ice shelf, Antarctica

- Does not measure melt fluxes
- Coarse spatial resolution (10s of km)

Detection of liquid water using SMOS



SMOS L-band binary dry/wet snow detection

→ 12.5 km grid

→ 30 km effective resolution

→ Antarctica and Greenland

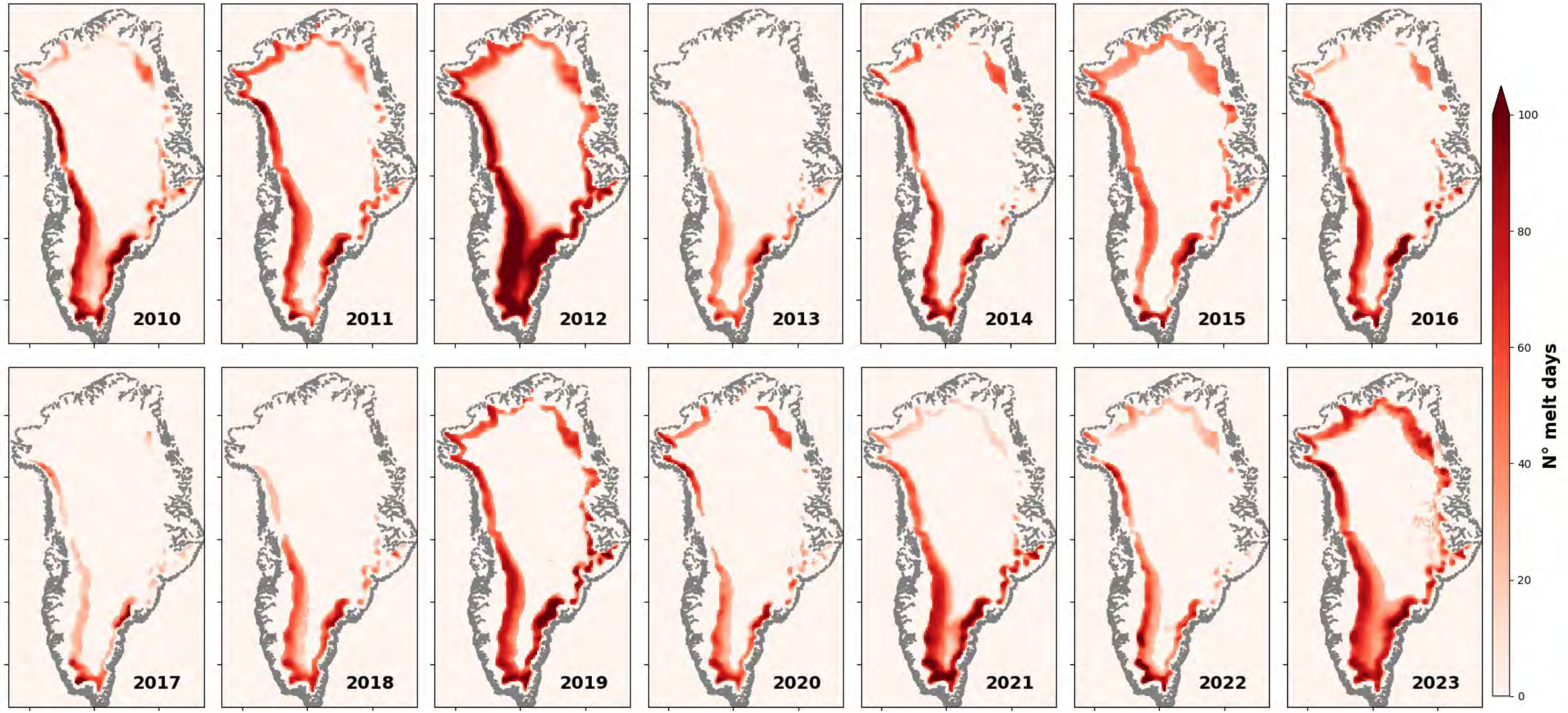
→ 2010 -

→ Twice-daily

→ > 98% of the pixels covered daily

Zeiger, P. et al. (2024), Resolution enhancement of SMOS brightness temperatures: Application to melt detection on the Antarctic and Greenland ice sheets, RSE, Vol 315

Detection of liquid water using SMOS



Zeiger, P. et al. (2024), Resolution enhancement of SMOS brightness temperatures: Application to melt detection on the Antarctic and Greenland ice sheets, RSE, Vol 315

Physical background

Microwave emission in layered snowpack

L-band: 1.4 GHz (λ~20 cm) → SMOS, SMAP

C-band: 6 GHz (λ~5 cm)

K-band: 18.7 GHz (λ~1 cm)

Ka-band: 36.5 GHz (λ~0.5 cm)

} AMSR2/3

Physical background

Microwave emission in layered snowpack

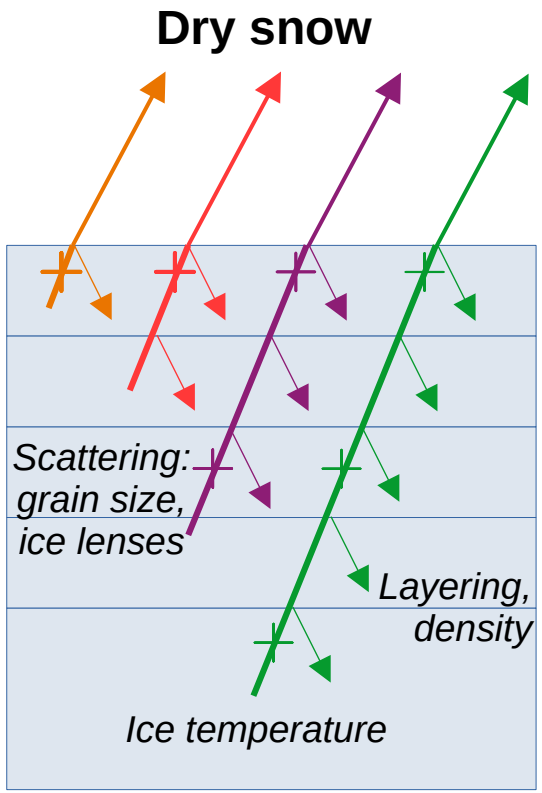
L-band: 1.4 GHz (λ~20 cm) → SMOS, SMAP

C-band: 6 GHz (λ~5 cm)

K-band: 18.7 GHz (λ~1 cm)

Ka-band: 36.5 GHz (λ~0.5 cm)

} AMSR2/3



Physical background

Microwave emission in layered snowpack

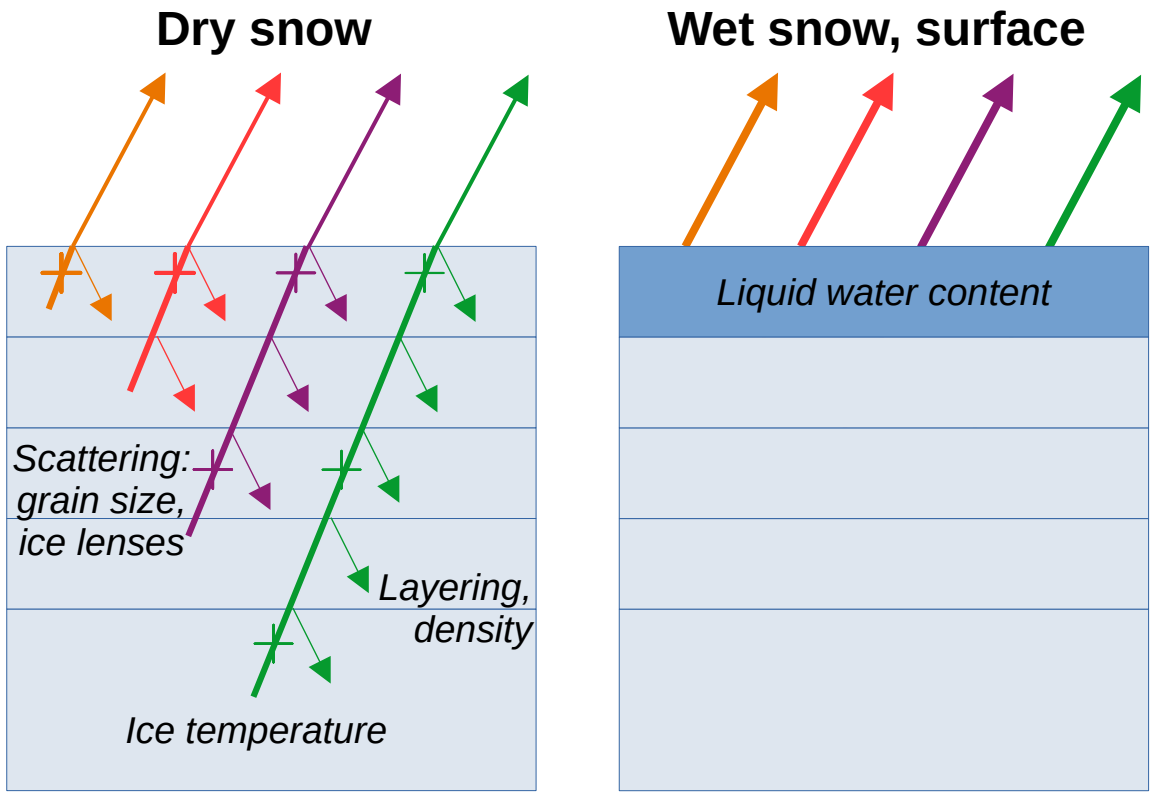
L-band: 1.4 GHz (λ~20 cm) → SMOS, SMAP

C-band: 6 GHz (λ~5 cm)

K-band: 18.7 GHz (λ~1 cm)

Ka-band: 36.5 GHz (λ~0.5 cm)

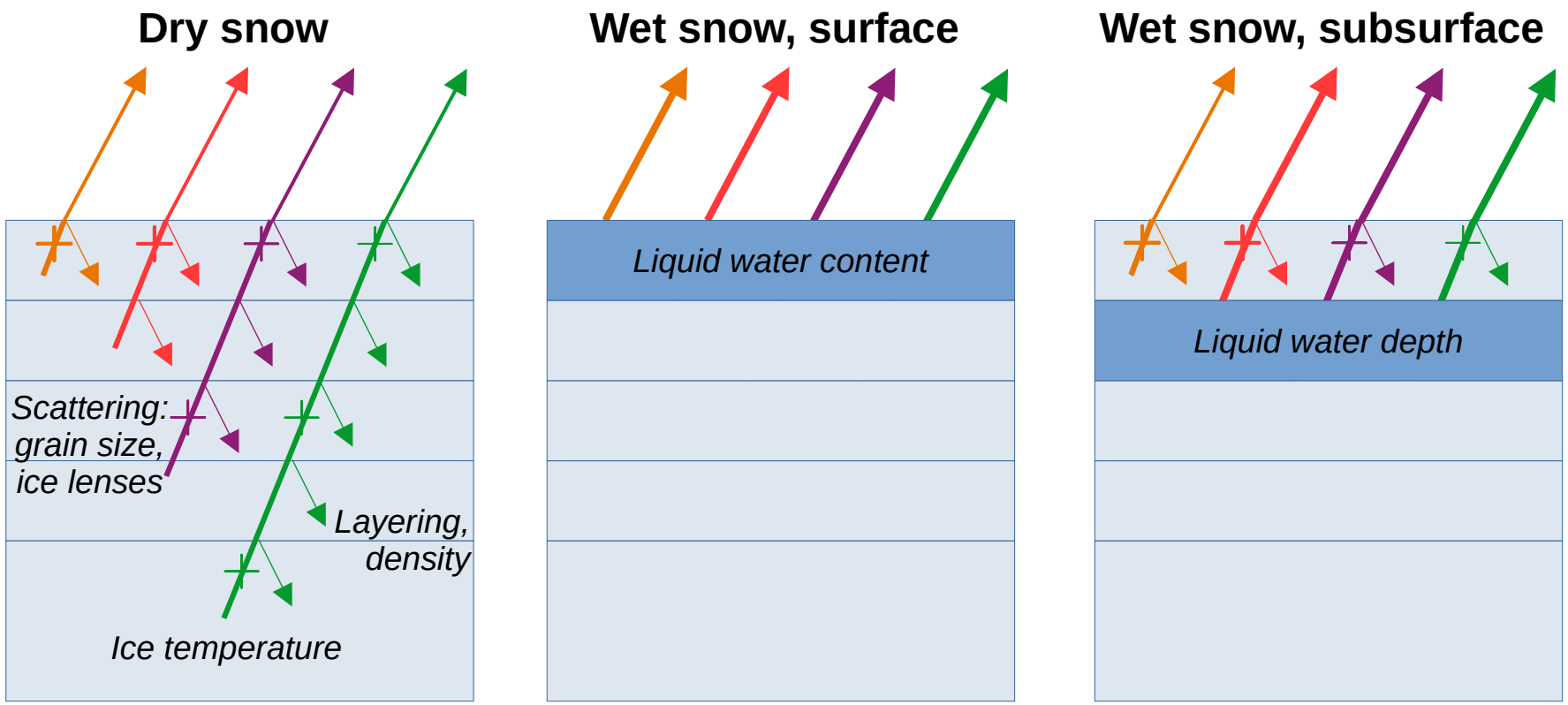
} AMSR2/3



Physical background

Microwave emission in layered snowpack

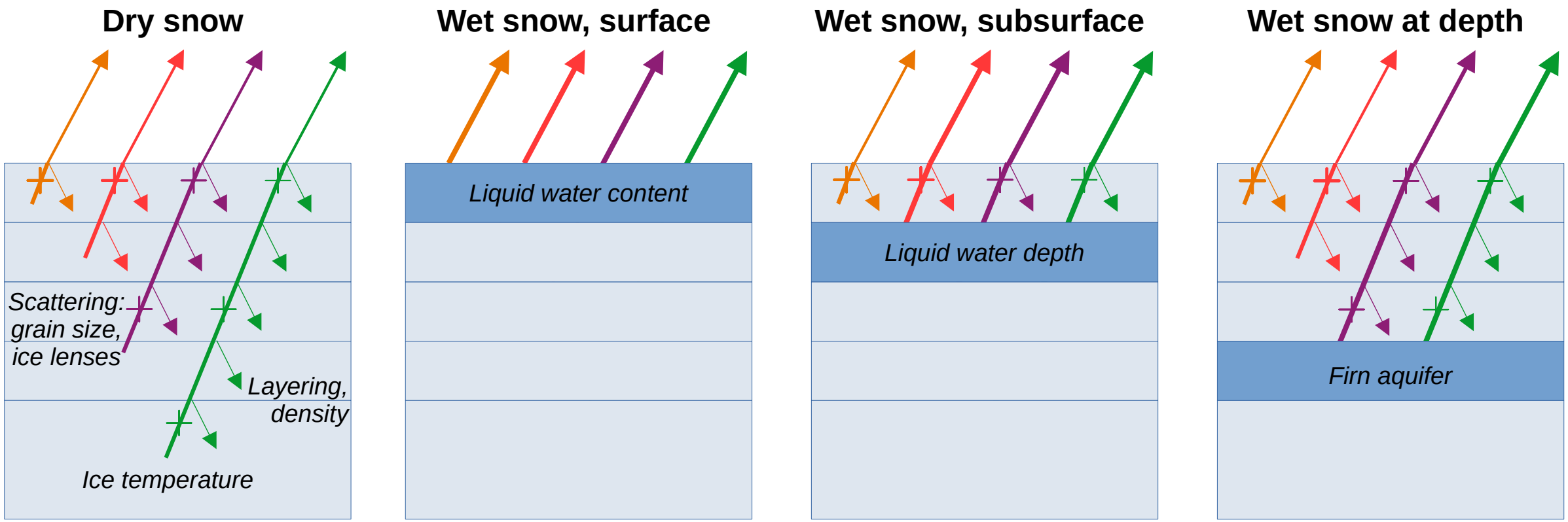
L-band: 1.4 GHz (λ~20 cm) → SMOS, SMAP
C-band: 6 GHz (λ~5 cm)
K-band: 18.7 GHz (λ~1 cm)
Ka-band: 36.5 GHz (λ~0.5 cm)
} AMSR2/3



Physical background

Microwave emission in layered snowpack

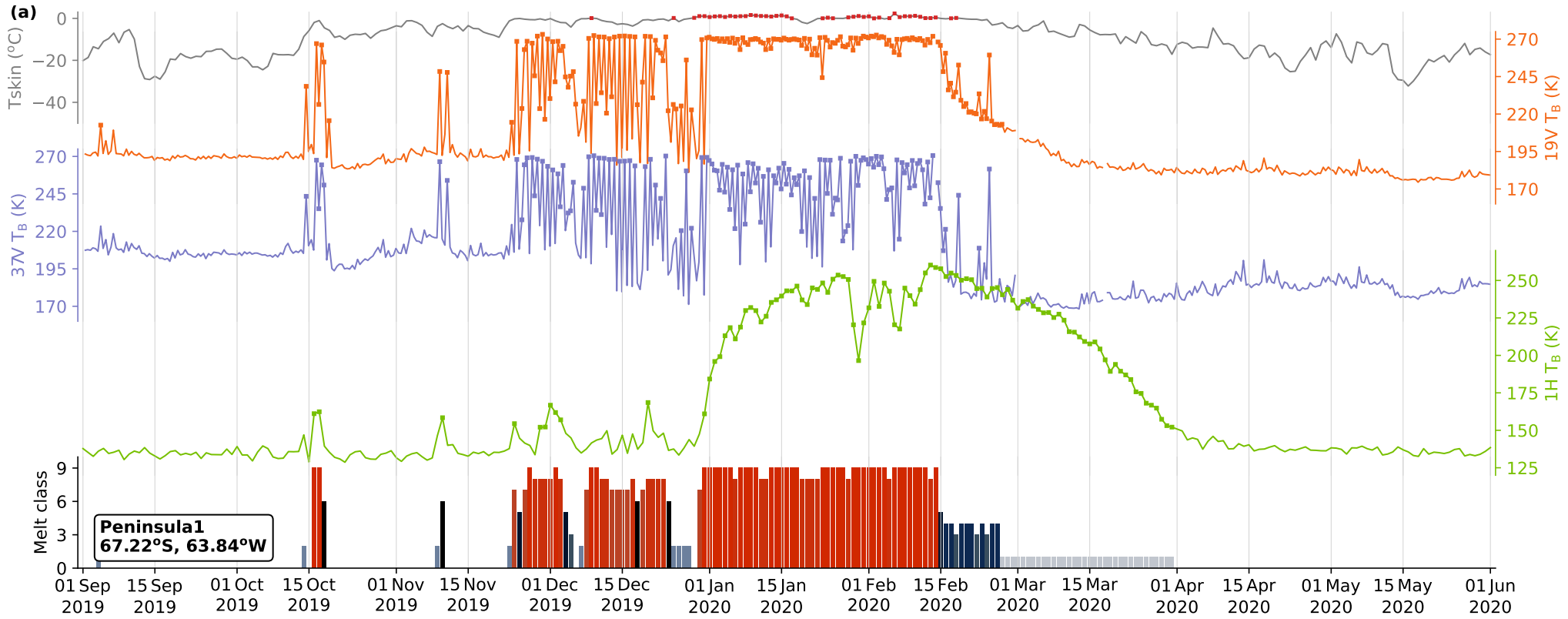
L-band: 1.4 GHz (λ~20 cm) → SMOS, SMAP
C-band: 6 GHz (λ~5 cm)
K-band: 18.7 GHz (λ~1 cm)
Ka-band: 36.5 GHz (λ~0.5 cm)
} AMSR2/3



Depth to liquid water: infiltration and refreezing

Multi-frequency empirical classification in Antarctica

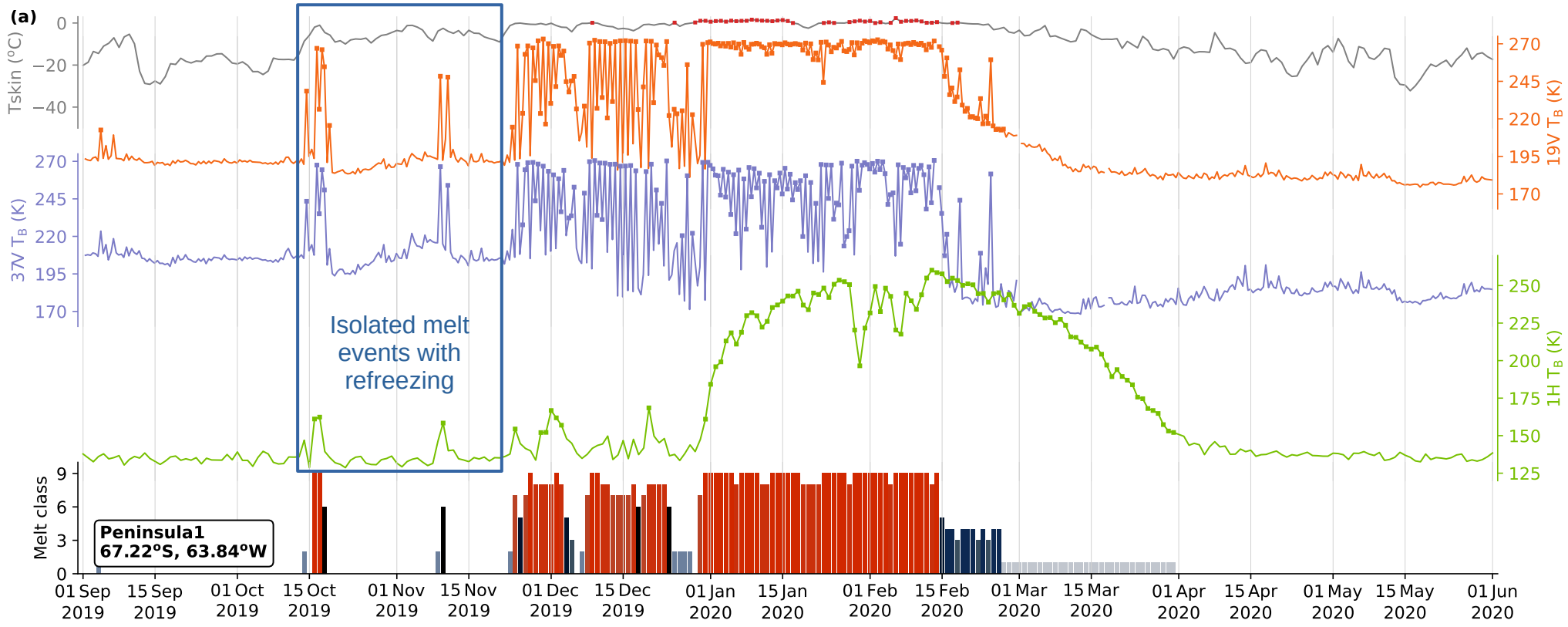
- 6 binary indicators: 1.4 GHz daily, 19 GHz twice-daily, 37 GHz twice-daily + « full melting »
- 64 « dry-wet signatures » combined into 10 output classes



Depth to liquid water: infiltration and refreezing

Multi-frequency empirical classification in Antarctica

- 6 binary indicators: 1.4 GHz daily, 19 GHz twice-daily, 37 GHz twice-daily + « full melting »
- 64 « dry-wet signatures » combined into 10 output classes

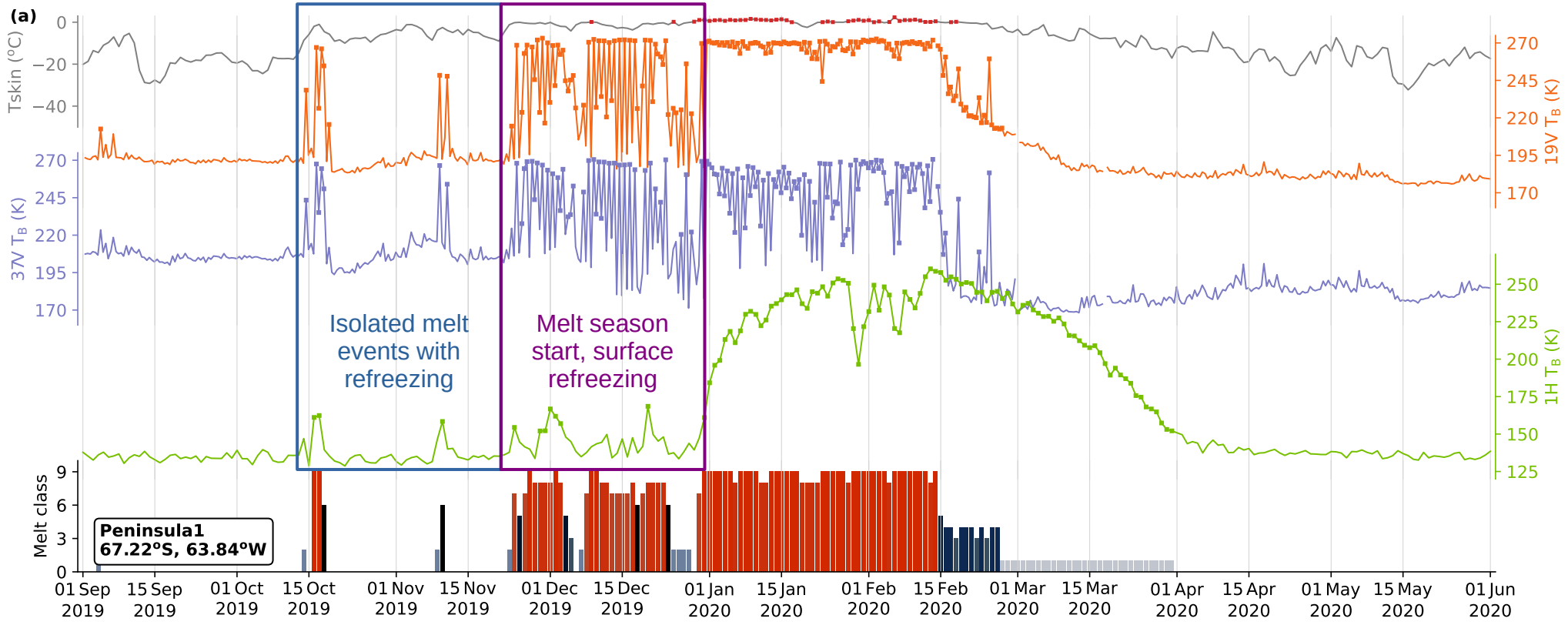


M. Leduc-Leballeur et al. (2026), Empirical classification of dry-wet snow status in Antarctica using multi-frequency passive microwave observations

Depth to liquid water: infiltration and refreezing

Multi-frequency empirical classification in Antarctica

- 6 binary indicators: 1.4 GHz daily, 19 GHz twice-daily, 37 GHz twice-daily + « full melting »
- 64 « dry-wet signatures » combined into 10 output classes

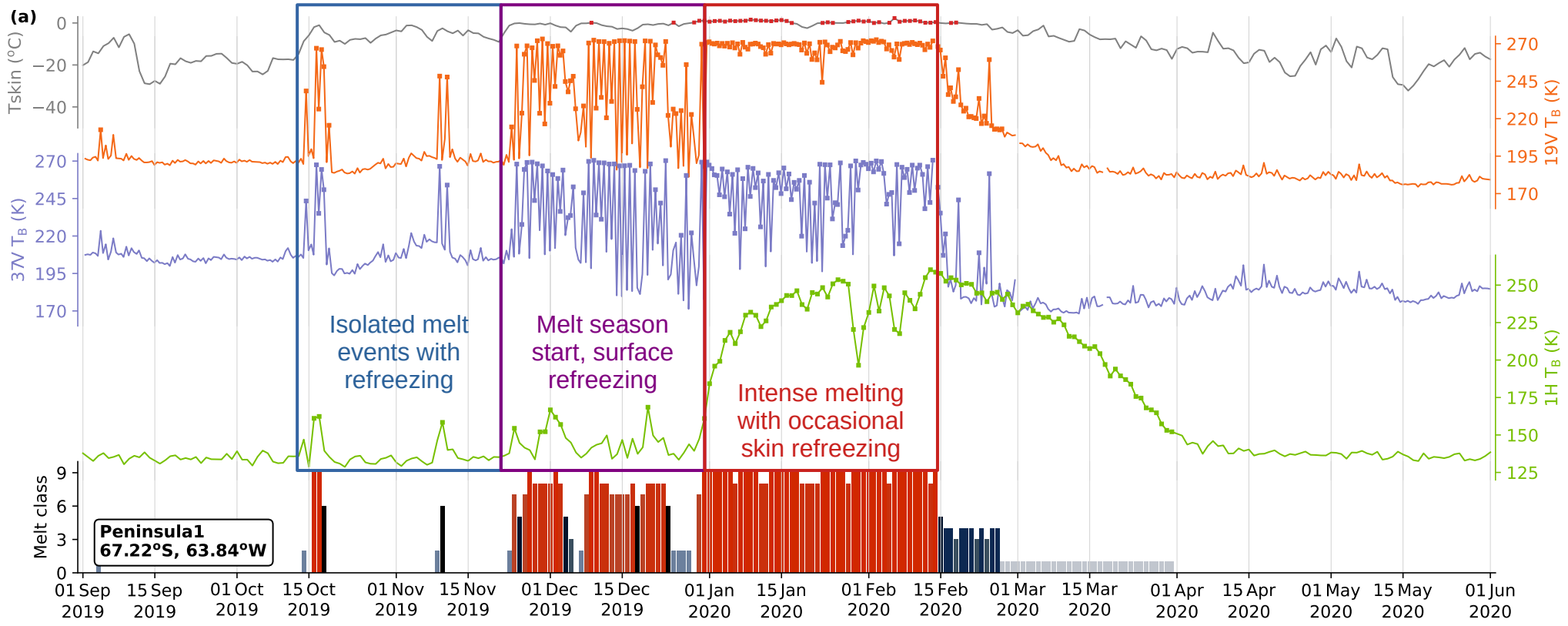


M. Leduc-Leballeur et al. (2026), Empirical classification of dry-wet snow status in Antarctica using multi-frequency passive microwave observations

Depth to liquid water: infiltration and refreezing

Multi-frequency empirical classification in Antarctica

- 6 binary indicators: 1.4 GHz daily, 19 GHz twice-daily, 37 GHz twice-daily + « full melting »
- 64 « dry-wet signatures » combined into 10 output classes

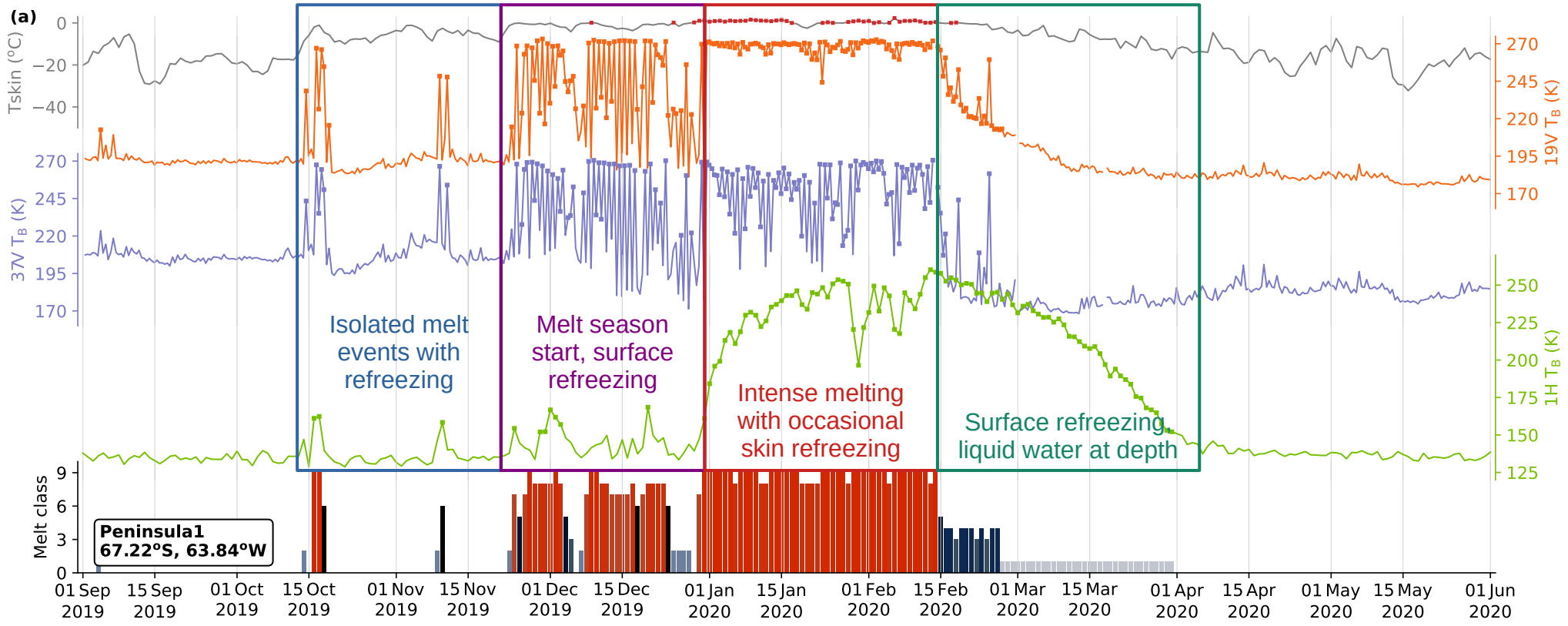


M. Leduc-Leballeur et al. (2026), Empirical classification of dry-wet snow status in Antarctica using multi-frequency passive microwave observations

Depth to liquid water: infiltration and refreezing

Multi-frequency empirical classification in Antarctica

- 6 binary indicators: 1.4 GHz daily, 19 GHz twice-daily, 37 GHz twice-daily + « full melting »
- 64 « dry-wet signatures » combined into 10 output classes



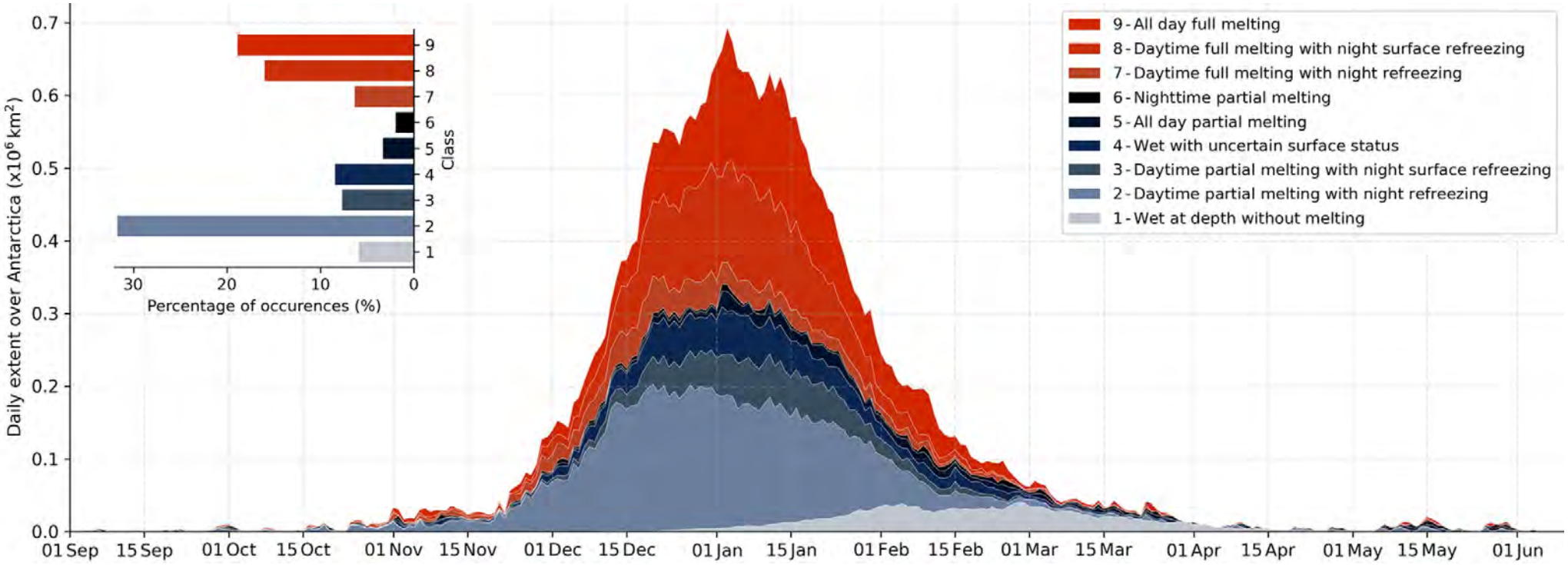
M. Leduc-Leballeur et al. (2026), Empirical classification of dry-wet snow status in Antarctica using multi-frequency passive microwave observations

Depth to liquid water: infiltration and refreezing

Multi-frequency empirical classification in Antarctica

- Antarctic-wide aggregated melt status (2012-2023 average)

M. Leduc-Leballeur et al. (2026)



- Next steps: → Operational monitoring (ESA 5D Antarctica)
  → Application to CIMR (2028/29)

Depth to liquid water: infiltration and refreezing

Depth to liquid water (DLW) in Greenland

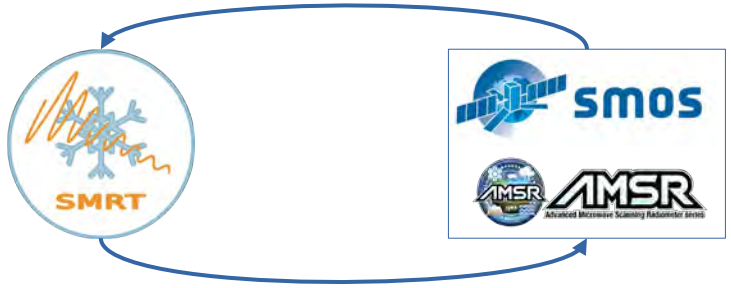
- Modeling chain, radiometer observations and machine learning

Depth to liquid water: infiltration and refreezing

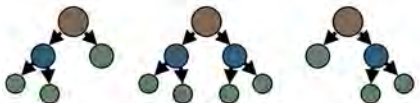
Depth to liquid water (DLW) in Greenland

- Modeling chain, radiometer observations and machine learning

1. Snow profiles from GEUS firn model (forced by CARRA)
2. Forward modeling of radiometer obs (using radiative transfer model)



3. Training and evaluation of a random forest ensemble



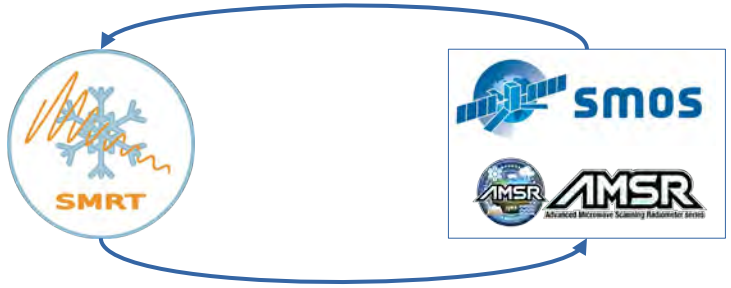
4. Output: Depth to Liquid Water (DLW)

Depth to liquid water: infiltration and refreezing

Depth to liquid water (DLW) in Greenland

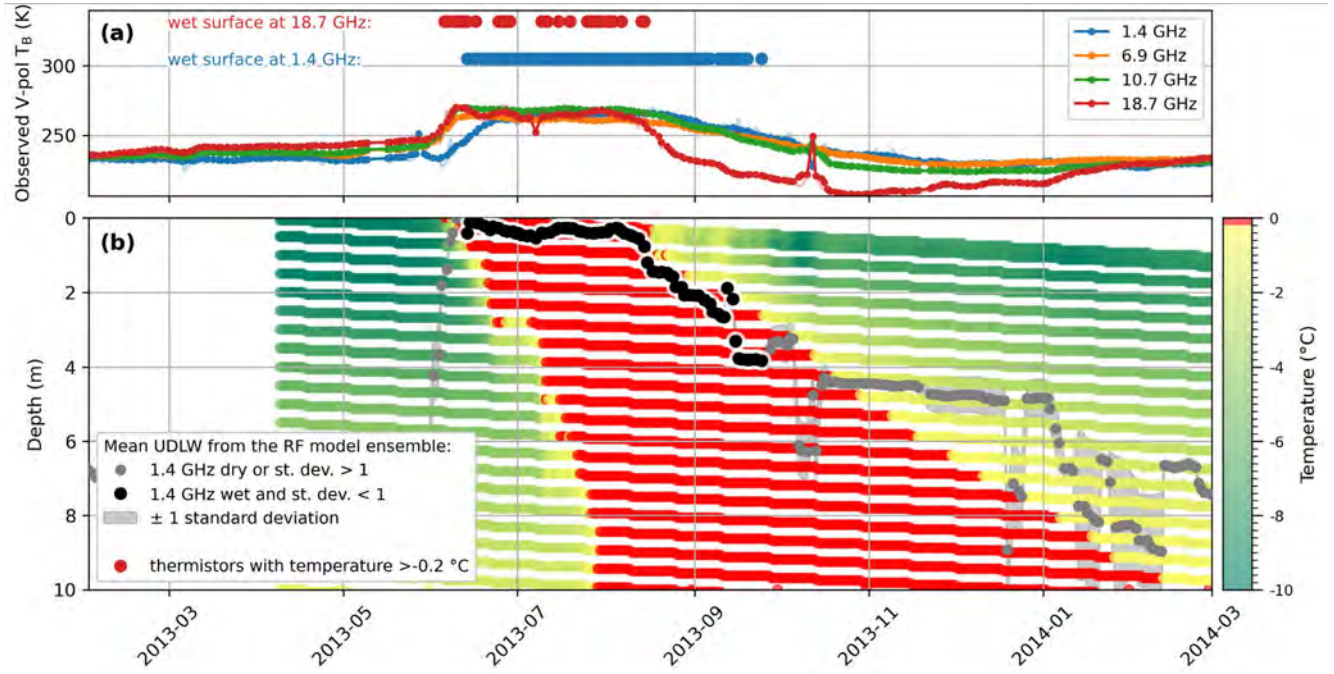
- Modeling chain, radiometer observations and machine learning

1. Snow profiles from GEUS firn model (forced by CARRA)
2. Forward modeling of radiometer obs (using radiative transfer model)



3. Training and evaluation of a random forest ensemble

4. Output: Depth to Liquid Water (DLW)

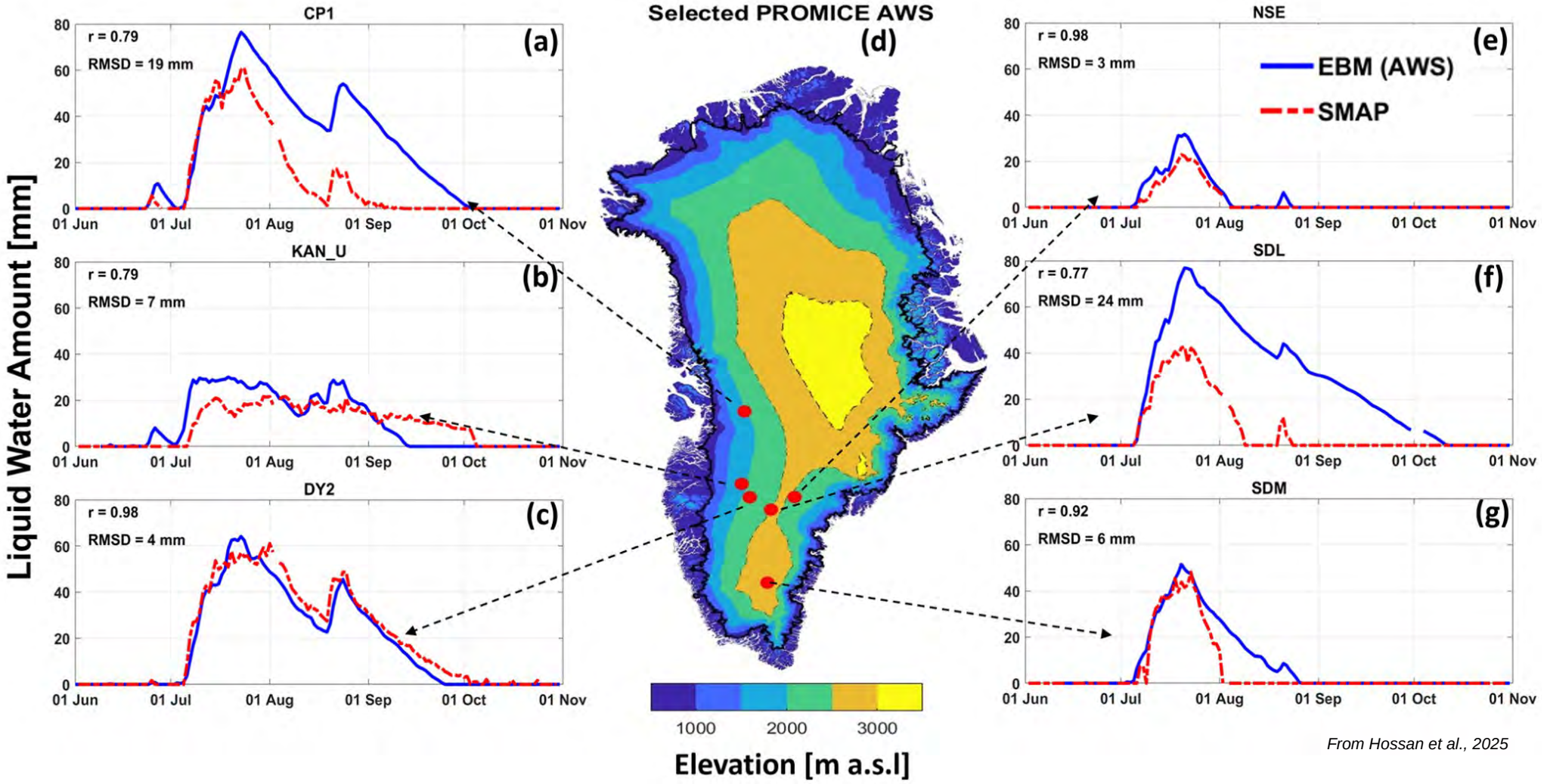


B. Vandecrux et al., (2026). Estimating the depth of subsurface water on the Greenland Ice Sheet using multi-frequency passive microwave remote sensing, radiative transfer modeling, and machine learning. Remote Sensing of Environment

Can we quantify liquid water?

Can we quantify liquid water?

Recent advances: Houtz et al., 2021; Hossan et al., 2025 → « Hot topic »

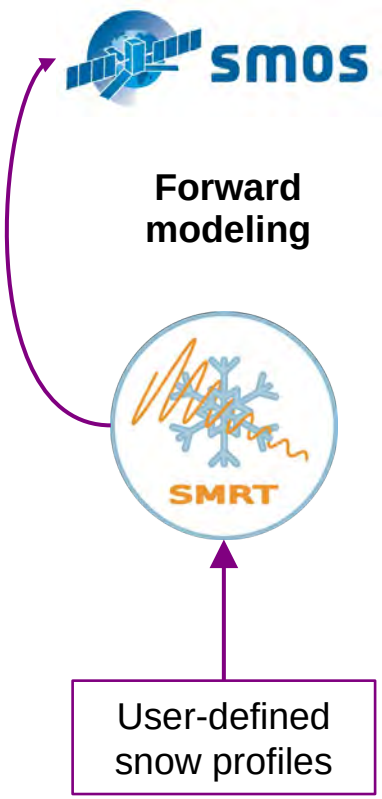


From Hossan et al., 2025

Can we quantify liquid water?

Recent advances: Houtz et al., 2021; Hossan et al., 2025

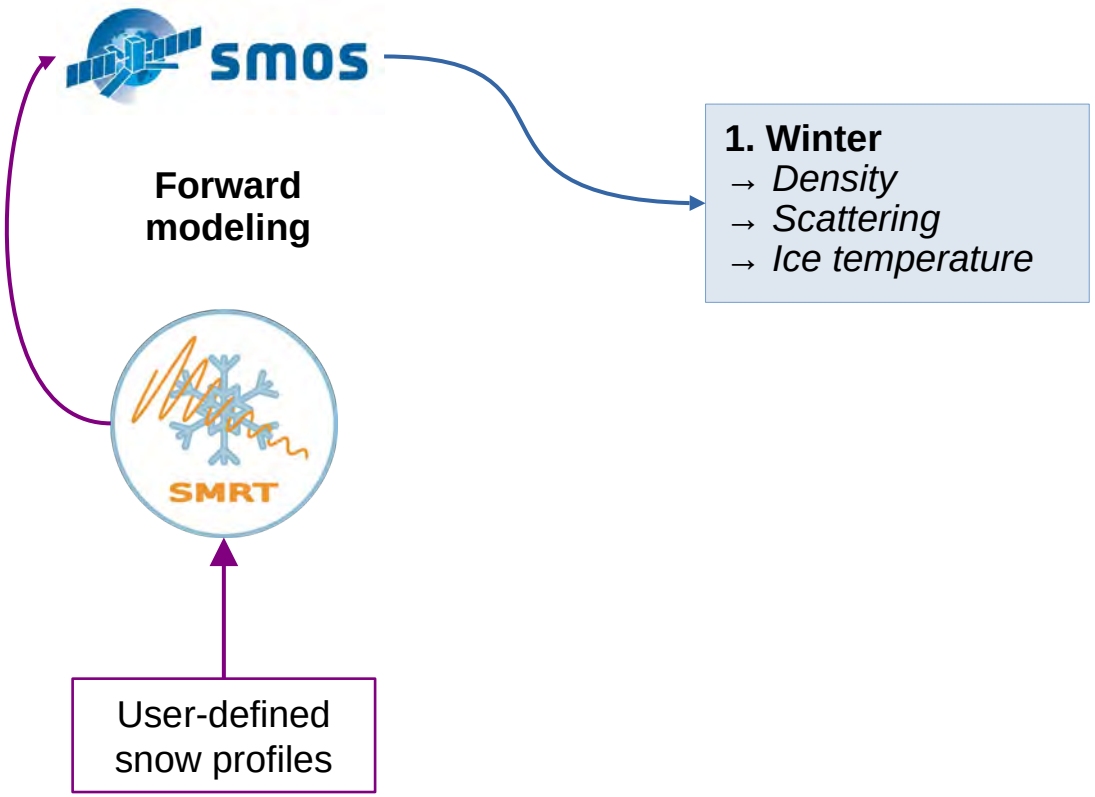
→Forward modeling using radiative transfer models



Can we quantify liquid water?

Recent advances: Houtz et al., 2021; Hossan et al., 2025

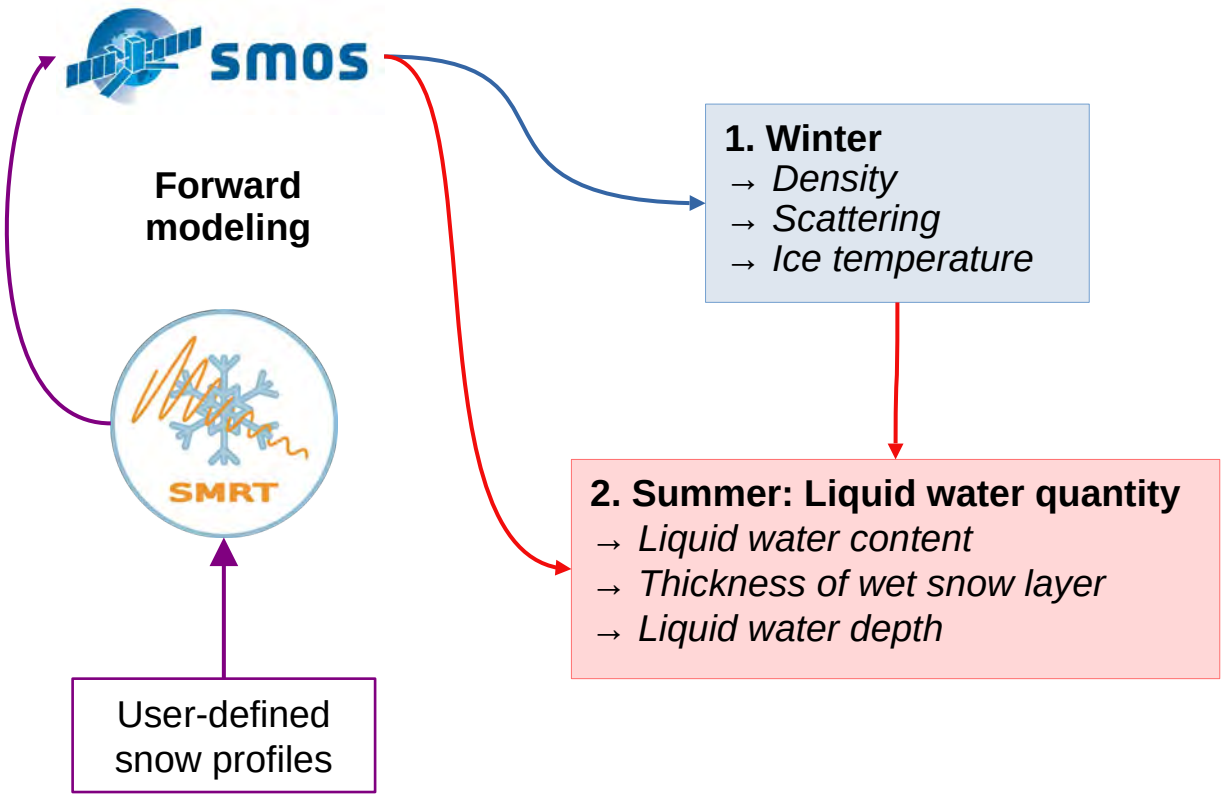
→ Forward modeling using radiative transfer models



Can we quantify liquid water?

Recent advances: Houtz et al., 2021; Hossan et al., 2025

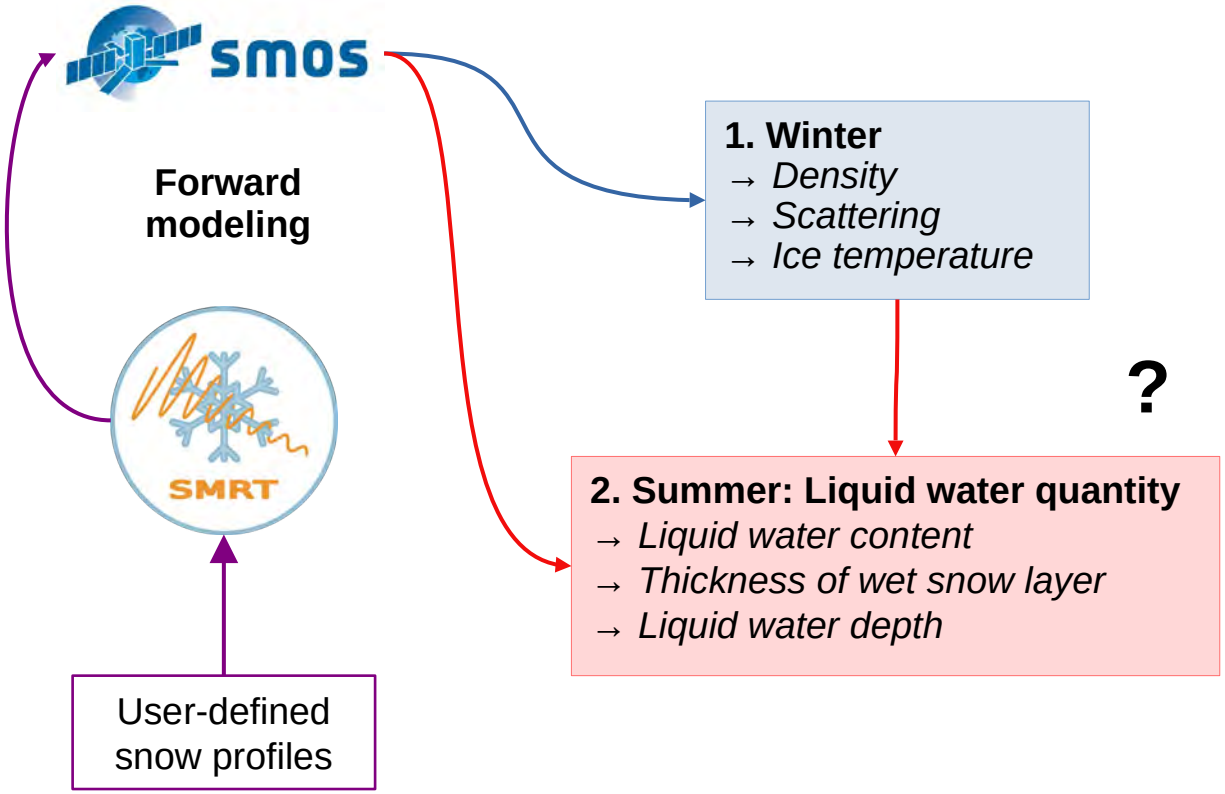
→ Forward modeling using radiative transfer models



Can we quantify liquid water?

Recent advances: Houtz et al., 2021; Hossan et al., 2025

→ Forward modeling using radiative transfer models



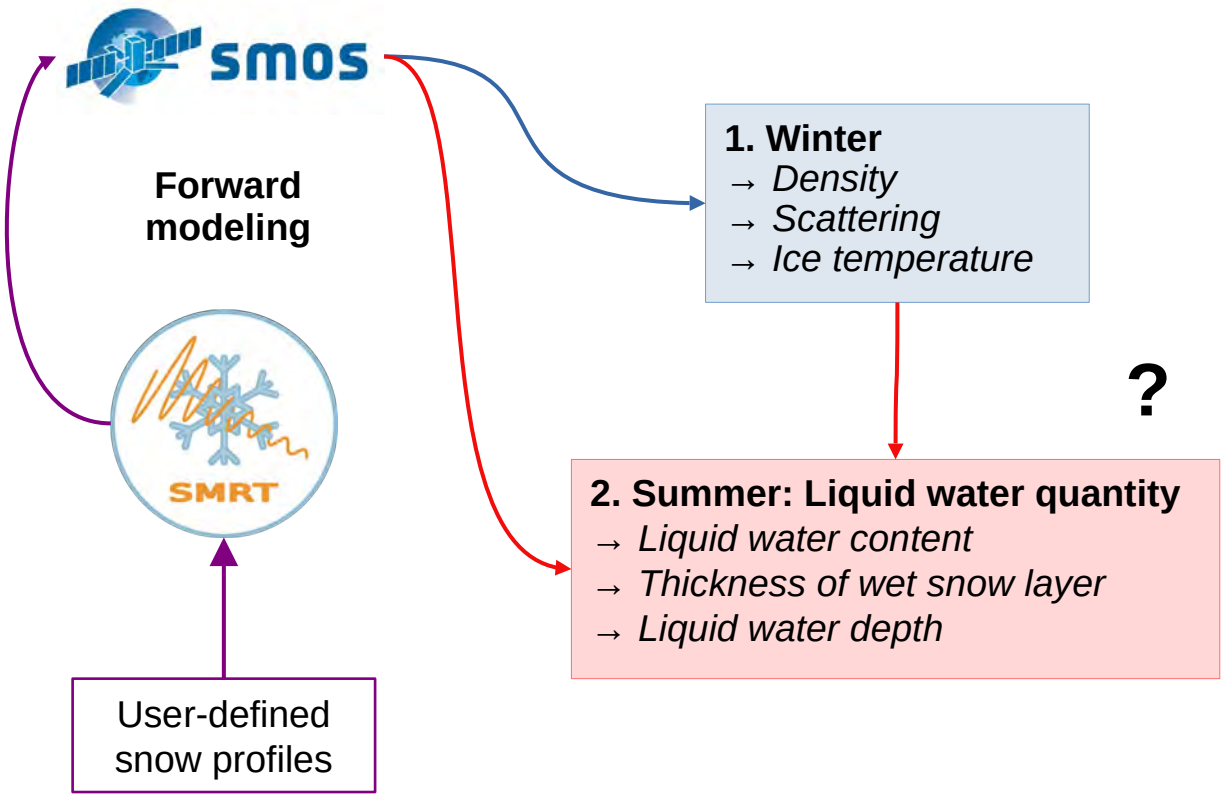
What parameters should be free?

The inversion problem is underdetermined

Can we quantify liquid water?

Recent advances: Houtz et al., 2021; Hossan et al., 2025

→ Forward modeling using radiative transfer models



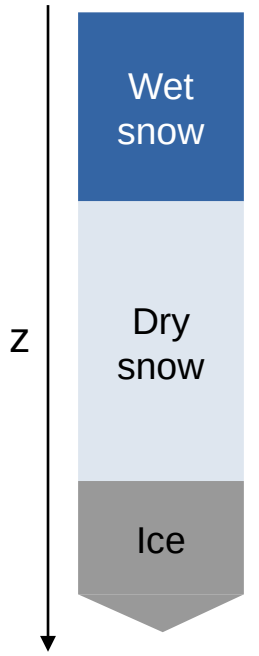
What parameters should be free?

The inversion problem is underdetermined

Current limitations:

1. 3-layer profile (wet snow, dry snow, ice)
   Fitting average density and temperature
   No layering/scattering in the firn
2. Homogeneous pixel
   But 30 km effective spatial resolution...

Can we quantify liquid water?



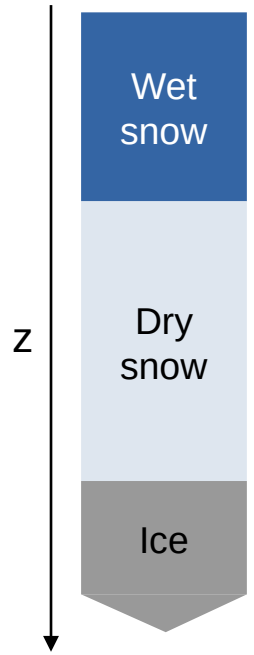
Baseline

Current limitations:

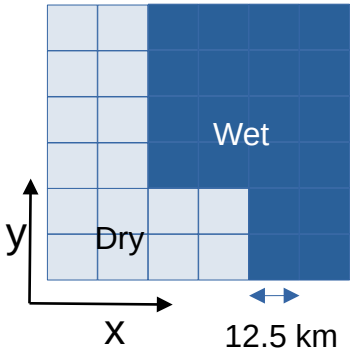
1. 3-layer profile (wet snow, dry snow, ice)
   Fitting average density and temperature
   No layering/scattering in the firn

2. Homogeneous pixel
   But 30 km effective spatial resolution...

Can we quantify liquid water?



Baseline

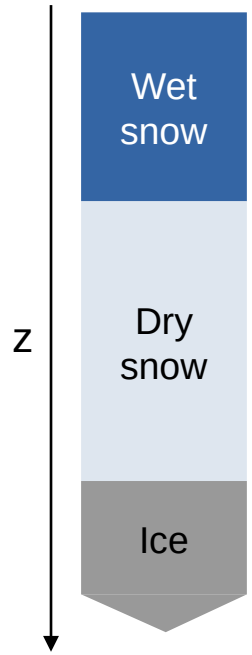


<u>Current limitations</u>:

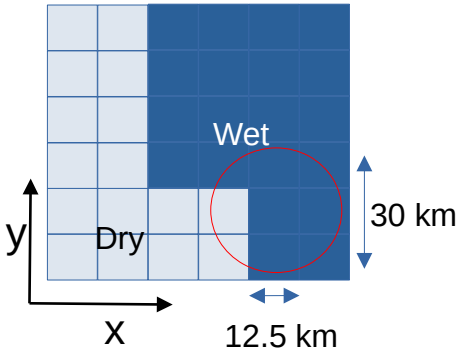
1. 3-layer profile (wet snow, dry snow, ice)
   Fitting average density and temperature
   No layering/scattering in the firn

2. Homogeneous pixel
   But 30 km effective spatial resolution...

Can we quantify liquid water?



Baseline

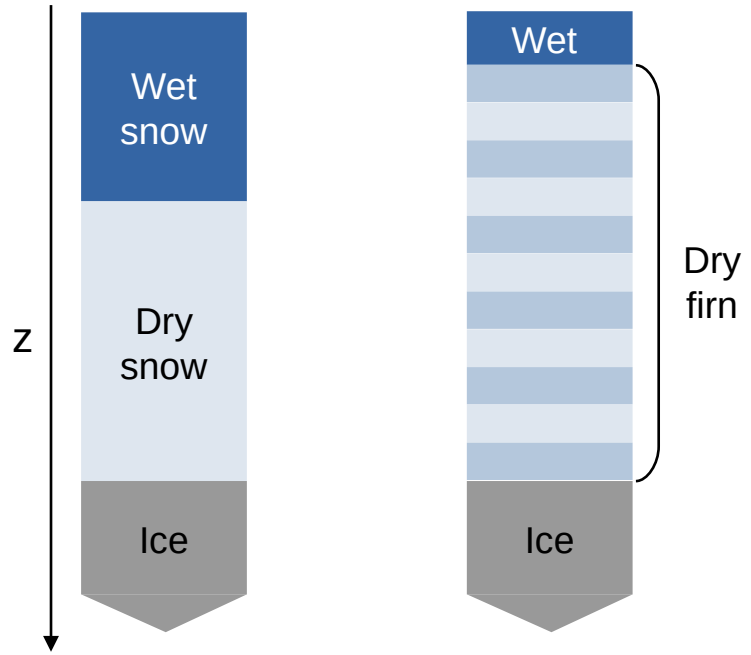


<u>Current limitations</u>:

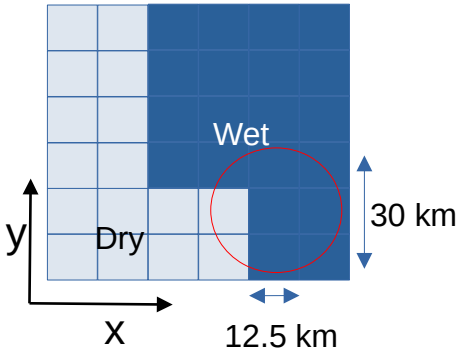
1. 3-layer profile (wet snow, dry snow, ice)
   Fitting average density and temperature
   No layering/scattering in the firn

2. Homogeneous pixel
   But 30 km effective spatial resolution...

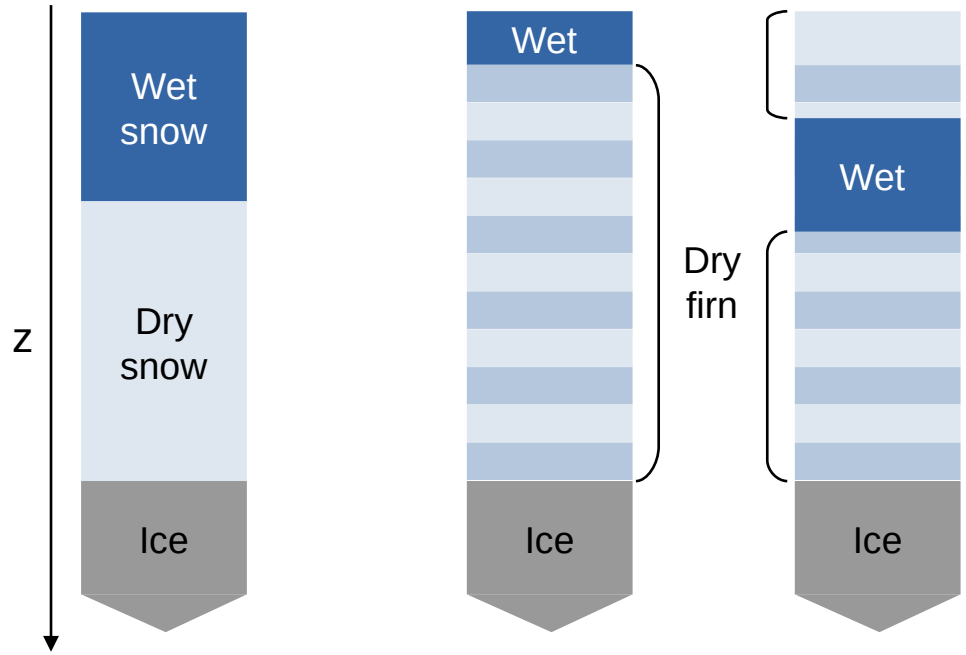
Can we quantify liquid water?



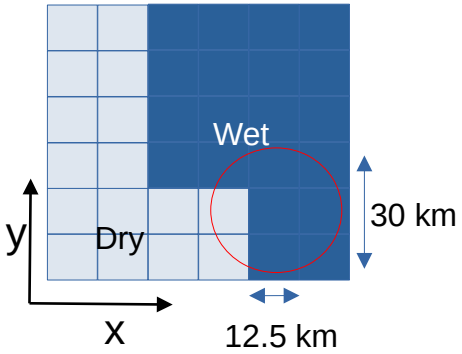
Baseline → 1. Add layering



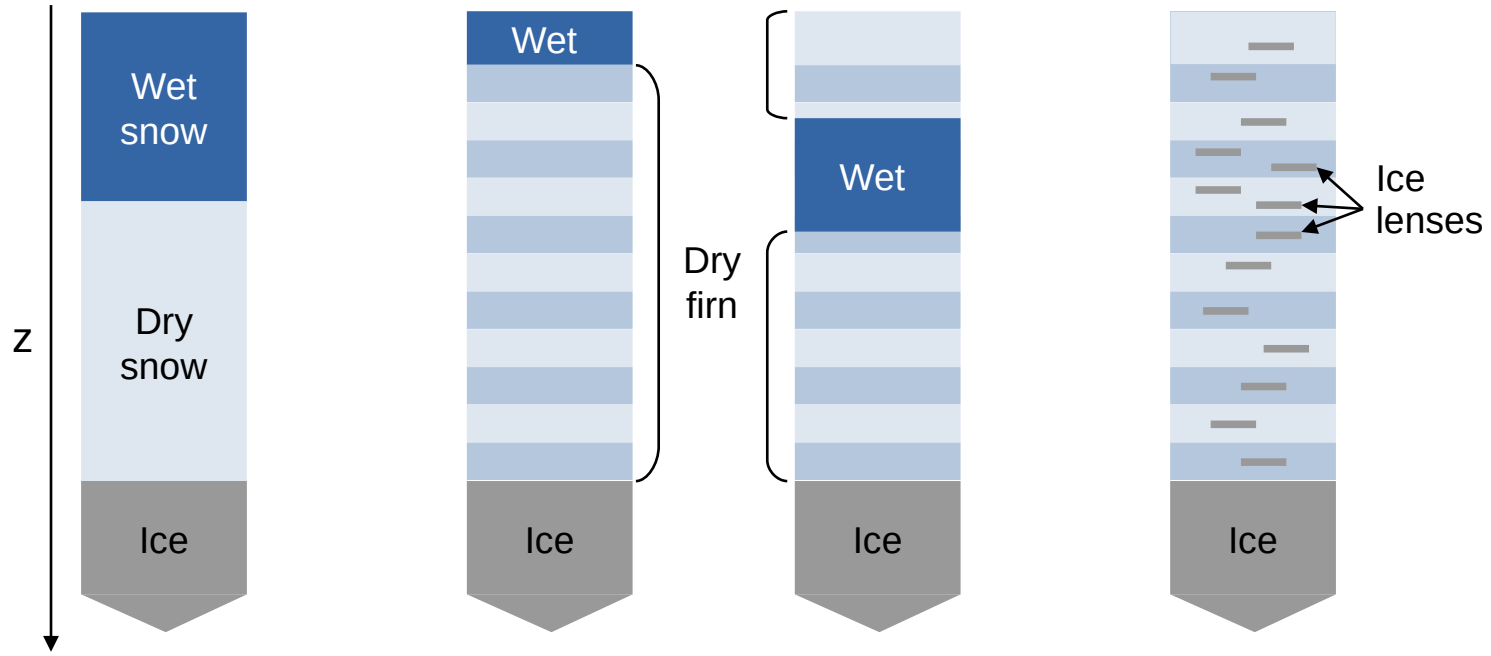
Can we quantify liquid water?



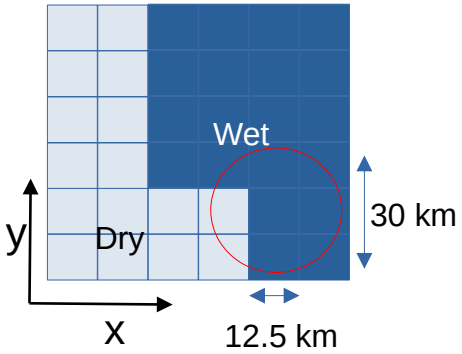
Baseline → 1. Add layering



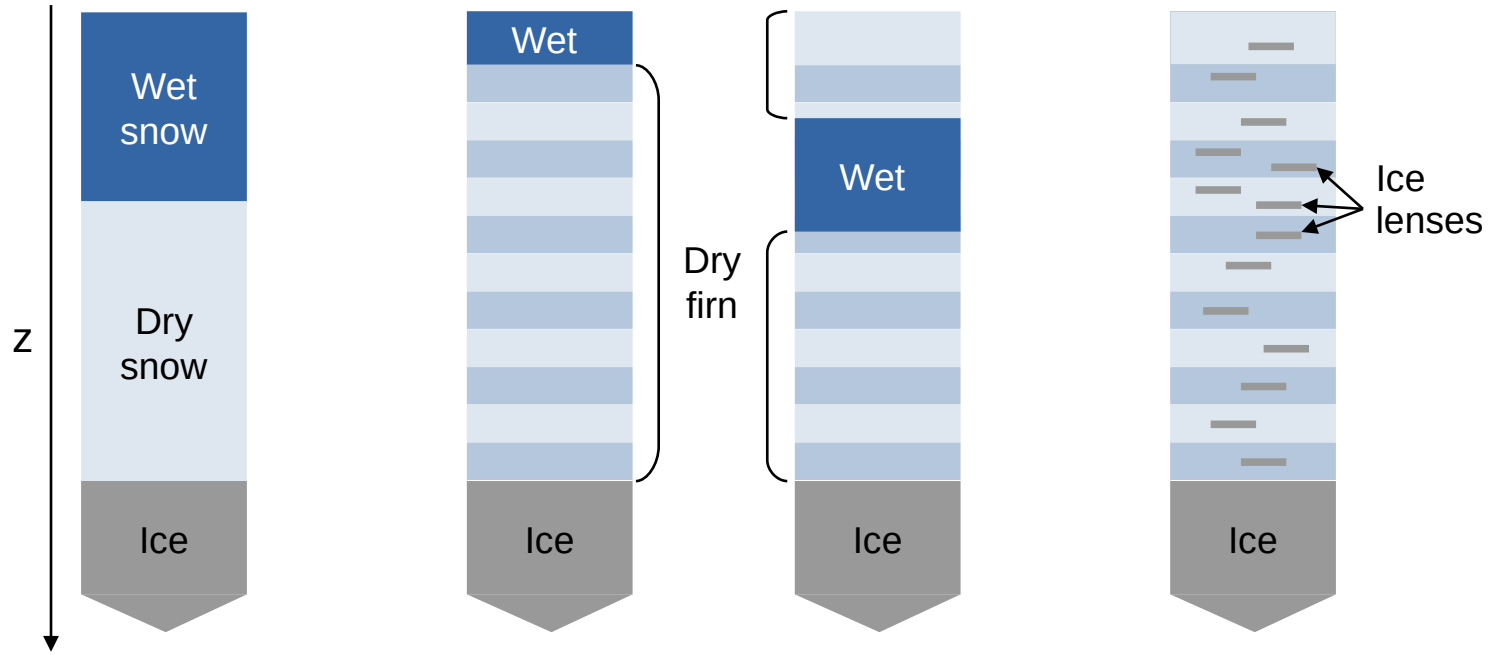
Can we quantify liquid water?



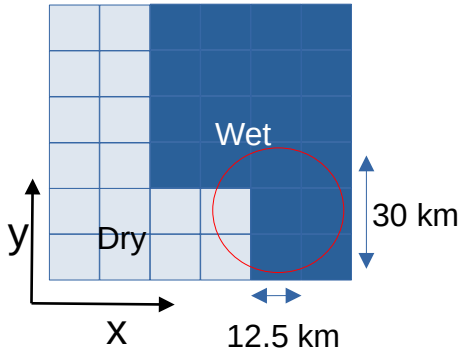
Baseline → 1. Add layering → 2. Add scattering

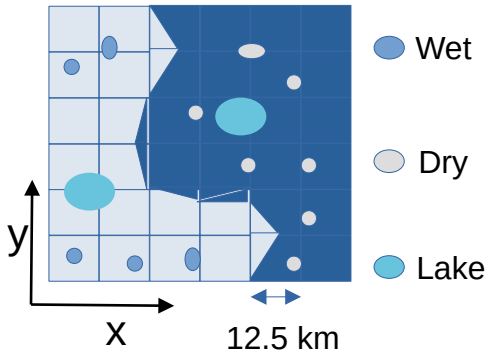


Can we quantify liquid water?

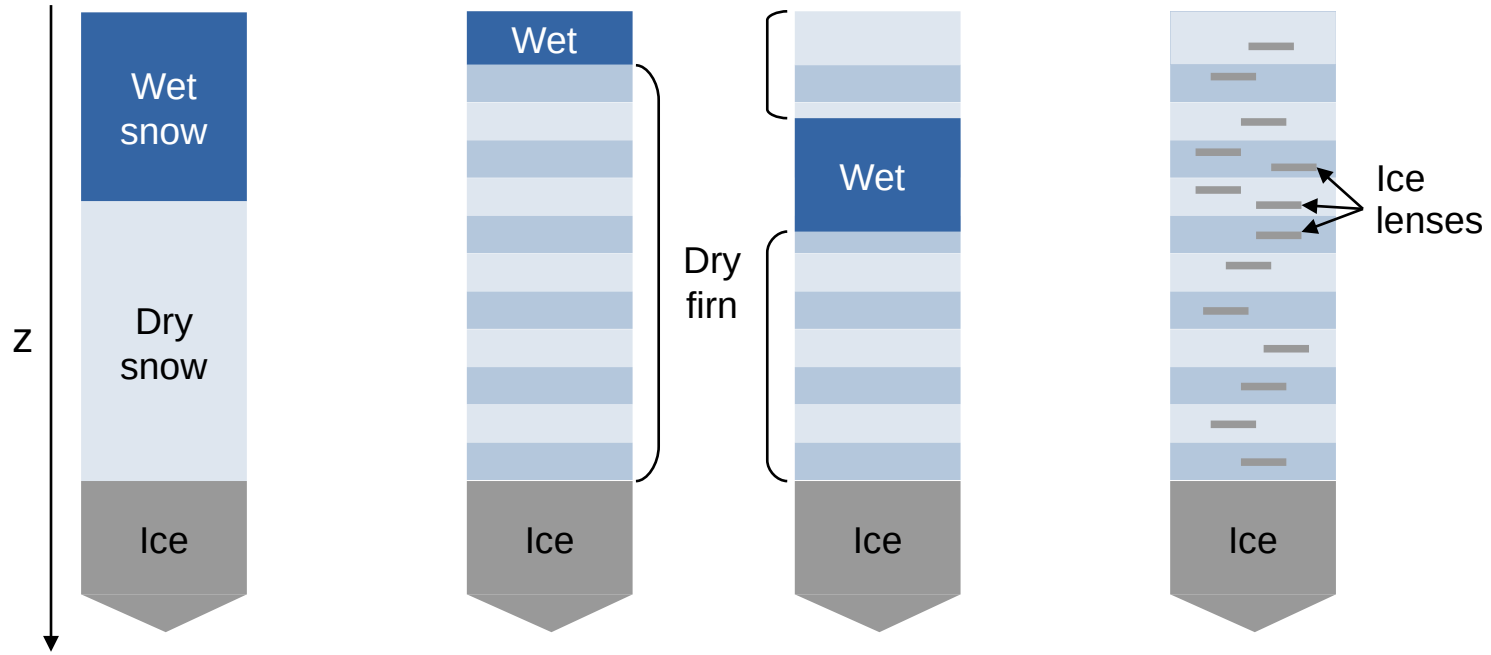


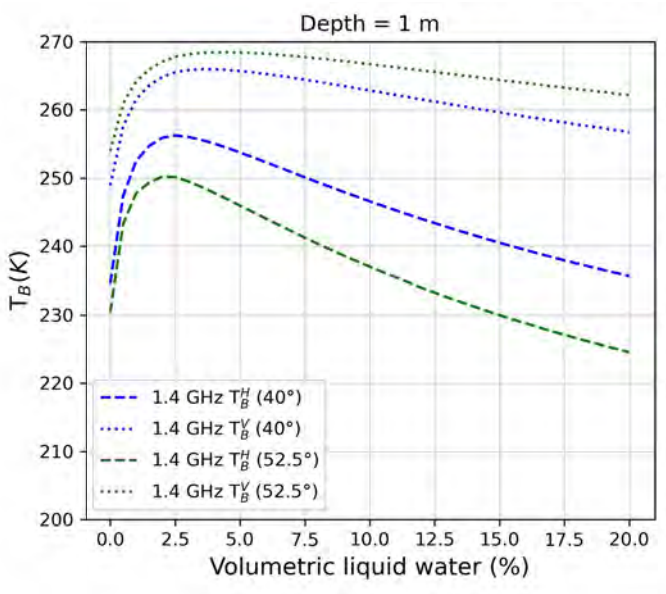
Baseline → 1. Add layering → 2. Add scattering → 3. Mixed pixel





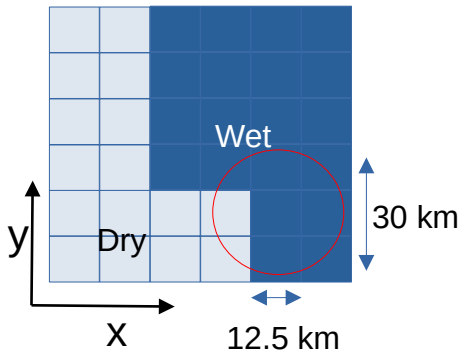
Can we quantify liquid water?

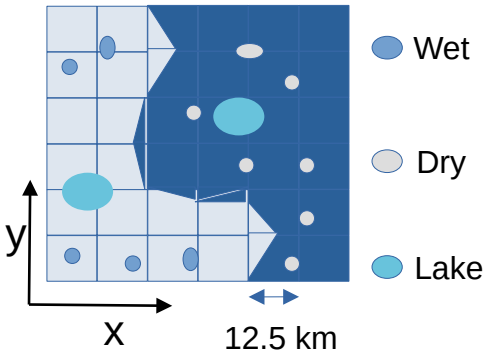




Sensitivity experiments

Baseline → 1. Add layering → 2. Add scattering → 3. Mixed pixel





Conclusion & Perspectives

- **Detection of liquid water using microwave radiometers**
  - Very high sensitivity → binary detection
  - Combination of frequencies → qualitative assessment of liquid water depth
  - Forward modeling & machine learning → quantification of liquid water depth

Conclusion & Perspectives

- **Detection of liquid water using microwave radiometers**
  - Very high sensitivity → binary detection
  - Combination of frequencies → qualitative assessment of liquid water depth
  - Forward modeling & machine learning → quantification of liquid water depth
- **Quantification of liquid water in the firn**
  - « Hot topic », possible using forward models but strongly underdetermined
  - Accurate retrieval requires parameterization of sub-pixel variability, layering and scattering
  - Under development...

Conclusion & Perspectives

- **Detection of liquid water using microwave radiometers**
  - Very high sensitivity → binary detection
  - Combination of frequencies → qualitative assessment of liquid water depth
  - Forward modeling & machine learning → quantification of liquid water depth
- **Quantification of liquid water in the firn**
  - « Hot topic », possible using forward models but strongly underdetermined
  - Accurate retrieval requires parameterization of sub-pixel variability, layering and scattering
  - Under development...
- **Perspectives:**
  - Future spaceborne missions, especially CIMR, Cryorad. Multi-mission retrieval
  - Spatial resolution improvement: data fusion (L-band SAR: SAOCOM, NISAR), sub-pixel parameterization…
  - Compare with snow/climate models