The RHOSSA campaign: Multi-resolution monitoring of the seasonal evolution of the structure and mechanical stability of an alpine snowpack

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The Weissfluhjoch WFJ site

- ✓ Regular snow observations site of SLF (Meister 2009)
- ✓ Eastern Swiss Alps, above Davos, 2536m elevation
- ✓ Long time-series of snowpack observations, dating back to 1936
- ✓ Provide snow cover and atmospheric data
- ✓ Similar as e.g. Col de Porte in France (Lejeune 2019) or Sodankylä in Finland (Leppänen 2016)
- ✓ Indispensable datasets for evaluation of snowpack models (e.g. Fierz 1998; Essery 2016), research studies, instrument testing …

Context

Objective parameters

- density and specific surface area (SSA) for basic snow structure characterization
- critical crack length (CCL) for snow stability characterization

complement the semi-empirical indices from traditional stratigraphy

✓ New instrumental techniques and methods
  - Propagation saw test for CCL measurements (e.g. Gauthier & Jamieson, 2006)
  - Devices for SSA measurements (e.g. DUFISSS (Gallet 2009), IceCube (Zuanon 2013))
  - Statistical calibration to derive density and SSA from SMP measurements (Proksch 2015)

✓ New formulations in snow cover models for SSA (Carmagnola 2014, Vionnet 2012) or snow stability (e.g. Gaume 2017)

These new instrumental and modeling developments lead to **new demands for evaluations**

The RHOSSA campaign

- In winter 2015-2016, the standard program of snow measurements at WFJ − traditional profiling and compressions tests − was complemented with measurements of density, SSA, and CCL.
- From Dec. to end of March → in dry snow conditions
- We provide a dataset
  - ✓ Multi-instrument: from classical techniques to some newly-developed ones (PSTs, X-ray tomography, SnowMicroPen, IceCube)
  - ✓ Multi-resolution:
    - Temporal − from the classical bi-weekly or weekly snowpit measurements to daily SnowMicroPen measurements
    - Spatial − vertical resolution from the size of the layer (cm) to sub-m

The RHOSSA campaign

Check out our paper in TC

https://doi.org/10.5194/tc-2019-276
Preprint. Discussion started: 11 December 2019

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The RHOSSA campaign: Multi-resolution monitoring of the seasonal evolution of the structure and mechanical stability of an alpine snowpack

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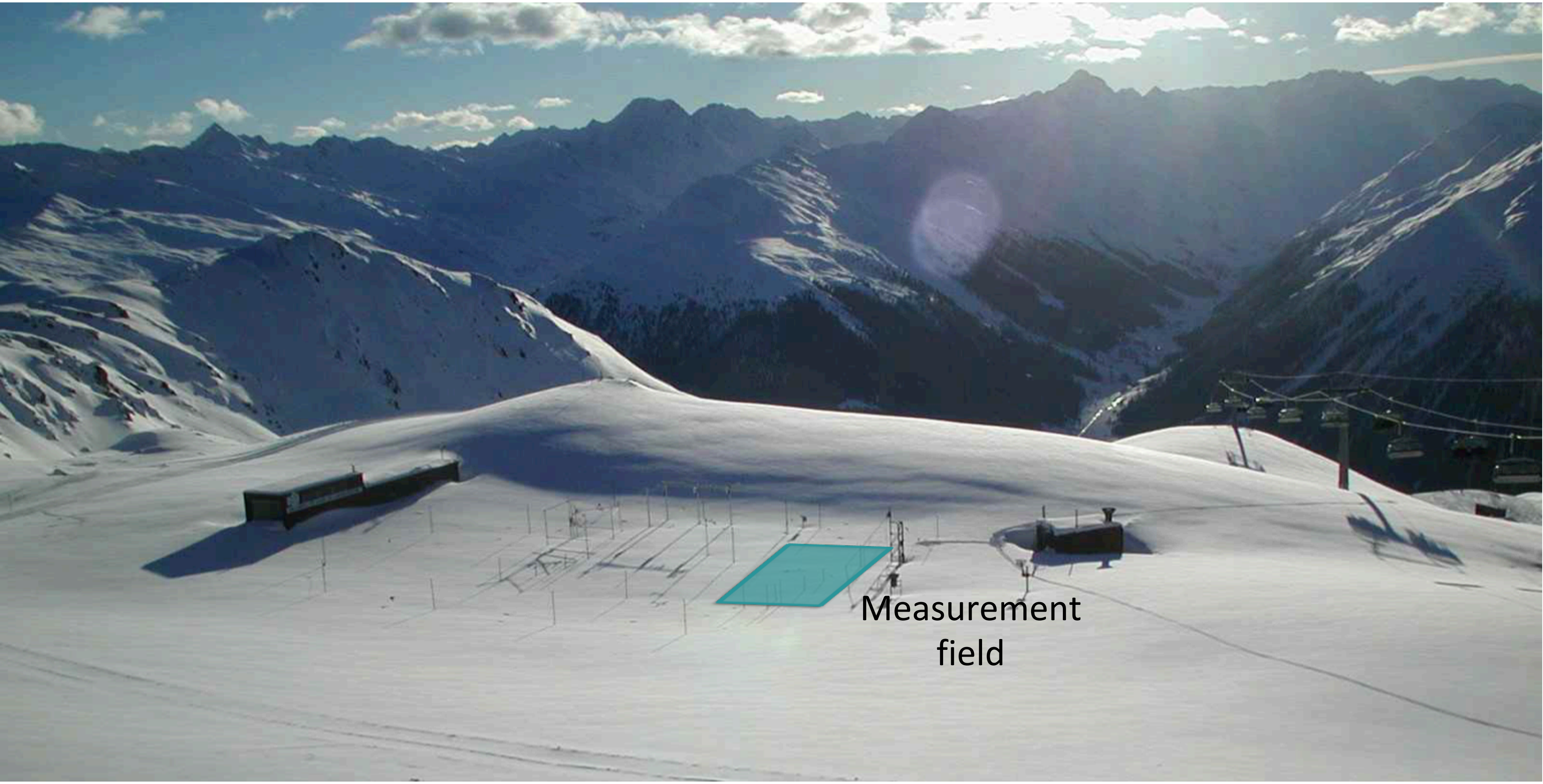
Outline

- Campaign design and protocol
- Deriving density and SSA from SMP measurements
- Results
  - Main stratigraphic features
  - Density evolution
  - SSA evolution
  - Comparisons
    - Inter-measurement comparisons
    - Comparisons of SNOWPACK and measurements
- Conclusions

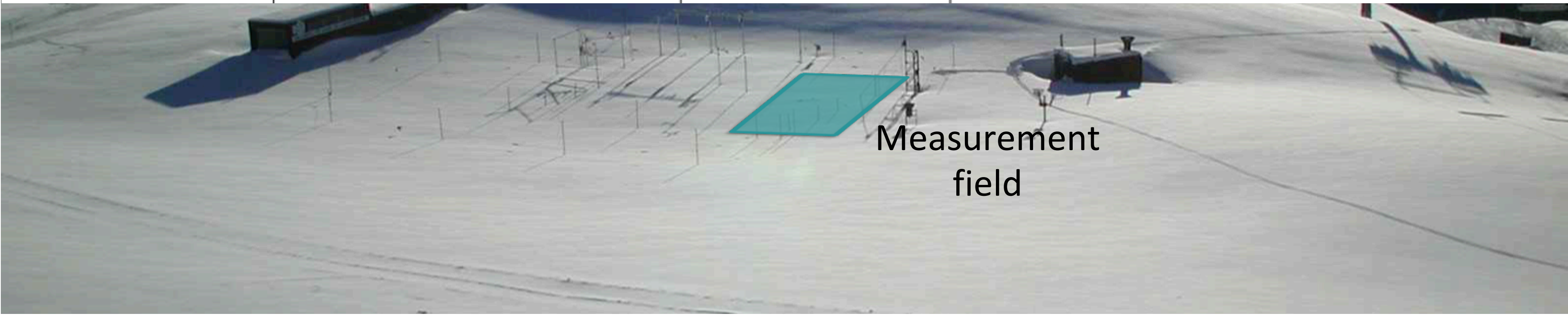
Campaign design & protocol



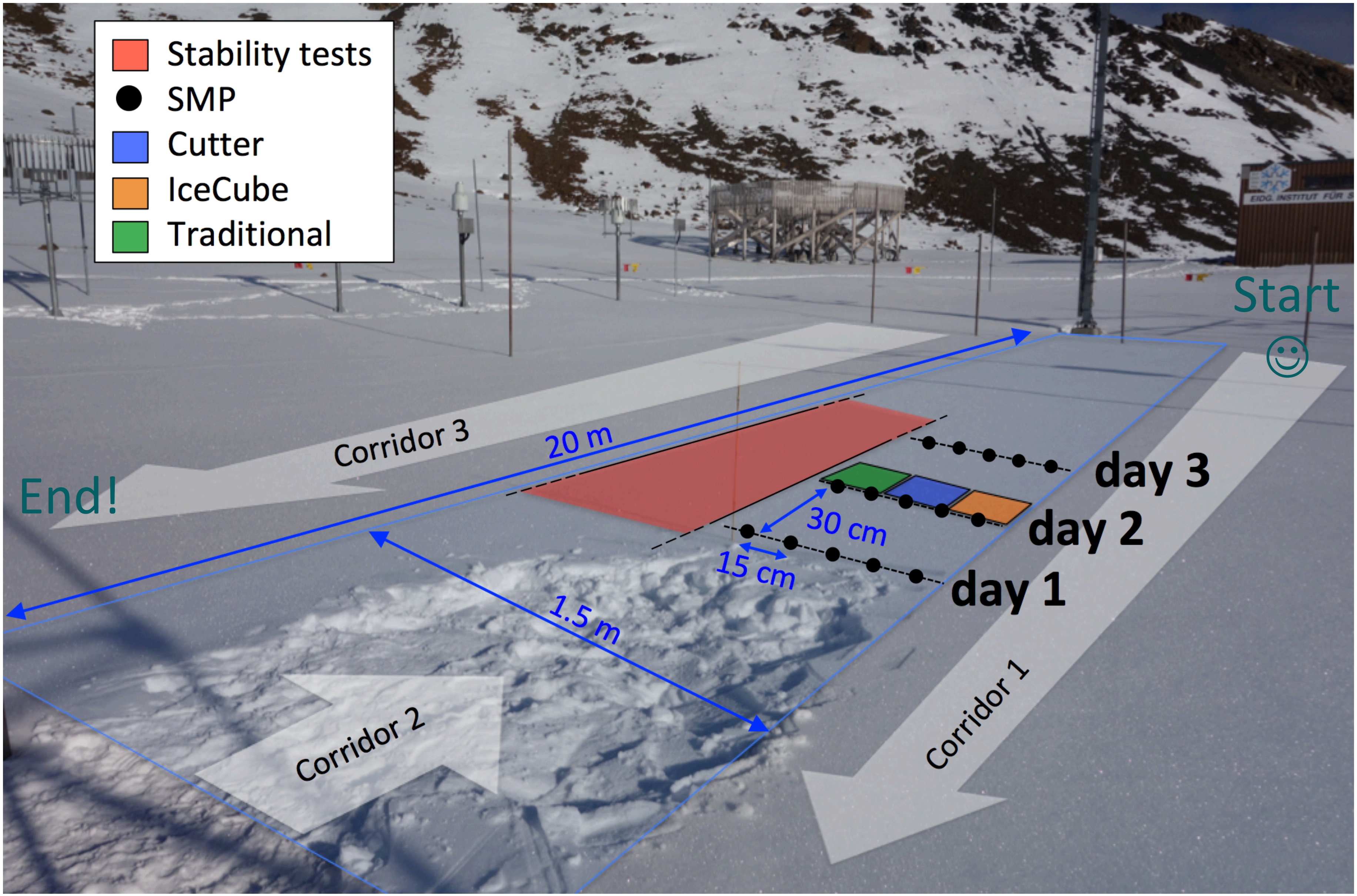
Campaign design & protocol

List of the measurements

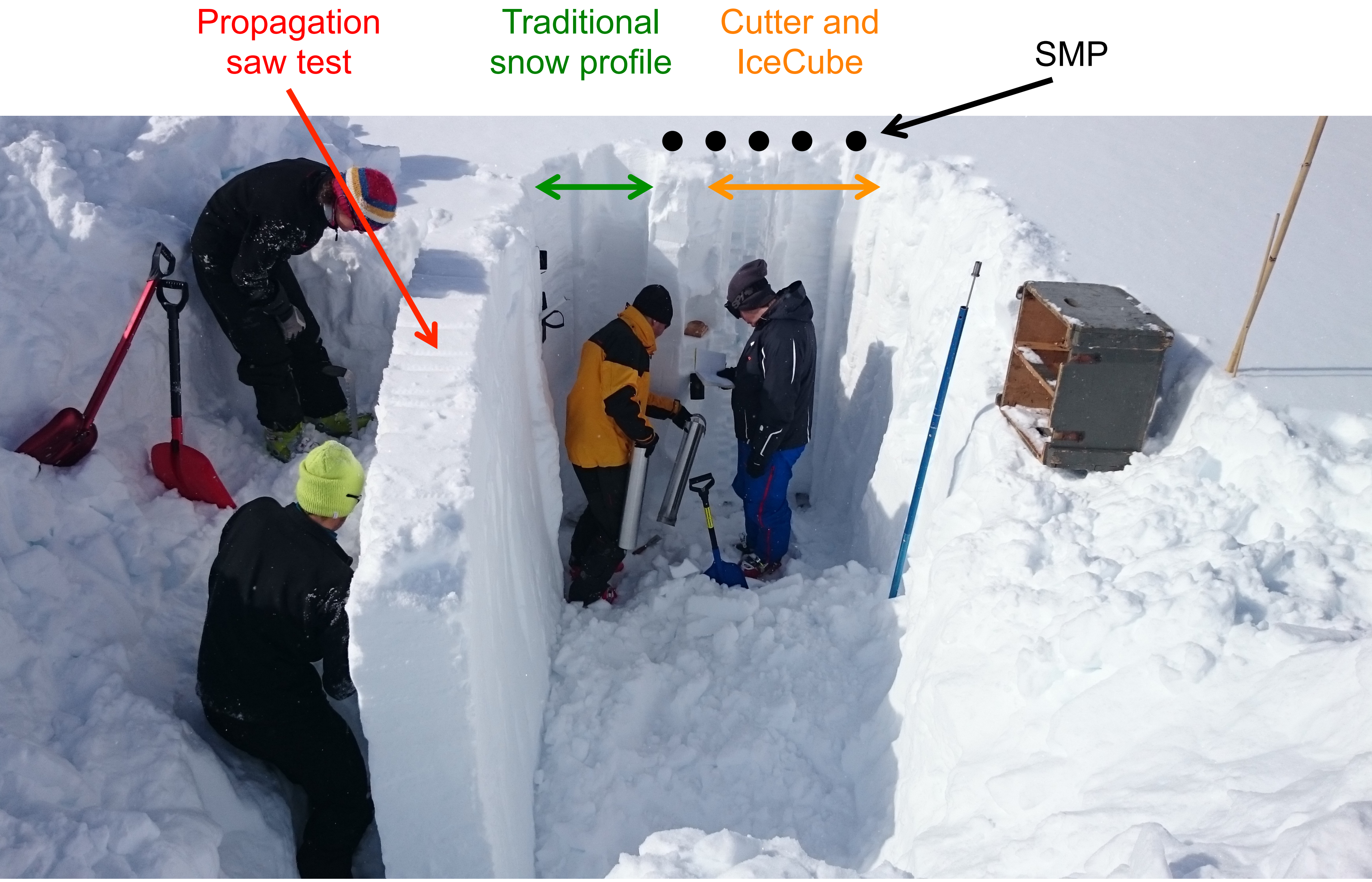
Method	Frequency	Vertical resolution	Measured or derived properties
SnowMicroPen	daily (100 profiles in total)	0.5 mm	penetration force (N), density (kg m^{-3}), SSA (m^2 kg^{-1})
Density cutter	weekly (15 profiles in total)	30 mm	density (kg m^{-3})
IceCube	weekly (13 profiles in total)	30 mm	SSA (m^2 kg^{-1})
Traditional profile	every 1 to 2 weeks (11 profiles in total)	variable	grain shape, grain size (mm), hand hardness, temperature (°C), ram resistance (N)
Stability tests	8 times over the season	-	critical crack length (m), #taps until failure
Tomography	6 times over the season	0.1 mm	density (kg m^{-3}), SSA (m^2 kg^{-1})



Campaign design & protocol



Campaign design & protocol



Deriving density and SSA from SMP

SnowMicroPen (SMP)

- Fast: 1 m profile ~ 1 minute
- High vertical resolution: 4 µm
- Output
  - *direct*: penetration resistance force
  - *derived*: microstructural parameters, density and SSA (Proksch et al, 2015)

Deriving density and SSA from SMP

We re-calibrated the model of Proksch 2015

- for SMP 4
- using our density cutter and IceCube measurements as reference (target)
- new calibrations

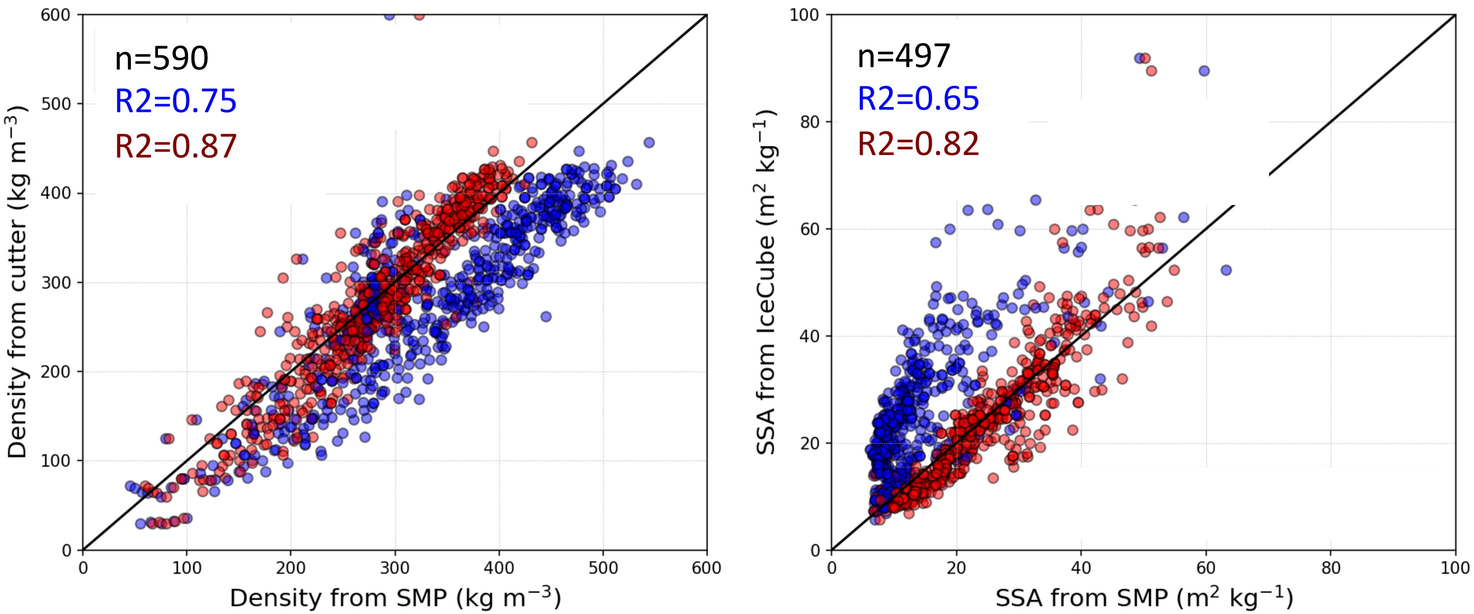
$$\rho_{\mathrm{SMP}} = a_1 + a_2 \times log(F) + a_3 \times log(F) \times L + a_4 \times L$$

$a_1 = 295.8 \pm 0.3$, $a_2 = 65.1 \pm 0.1$, $a_3 = -43.2 \pm 0.4$, and $a_4 = 47.1 \pm 0.7$,

$$\mathrm{SSA}_{\mathrm{SMP}} = b_1 + b_2 \times log(L) + b_3 \times log(F)$$

$b_1 = 0.57 \pm 0.05$, $b_2 = -18.56 \pm 0.04$, and $b_3 = -3.66 \pm 0.01$

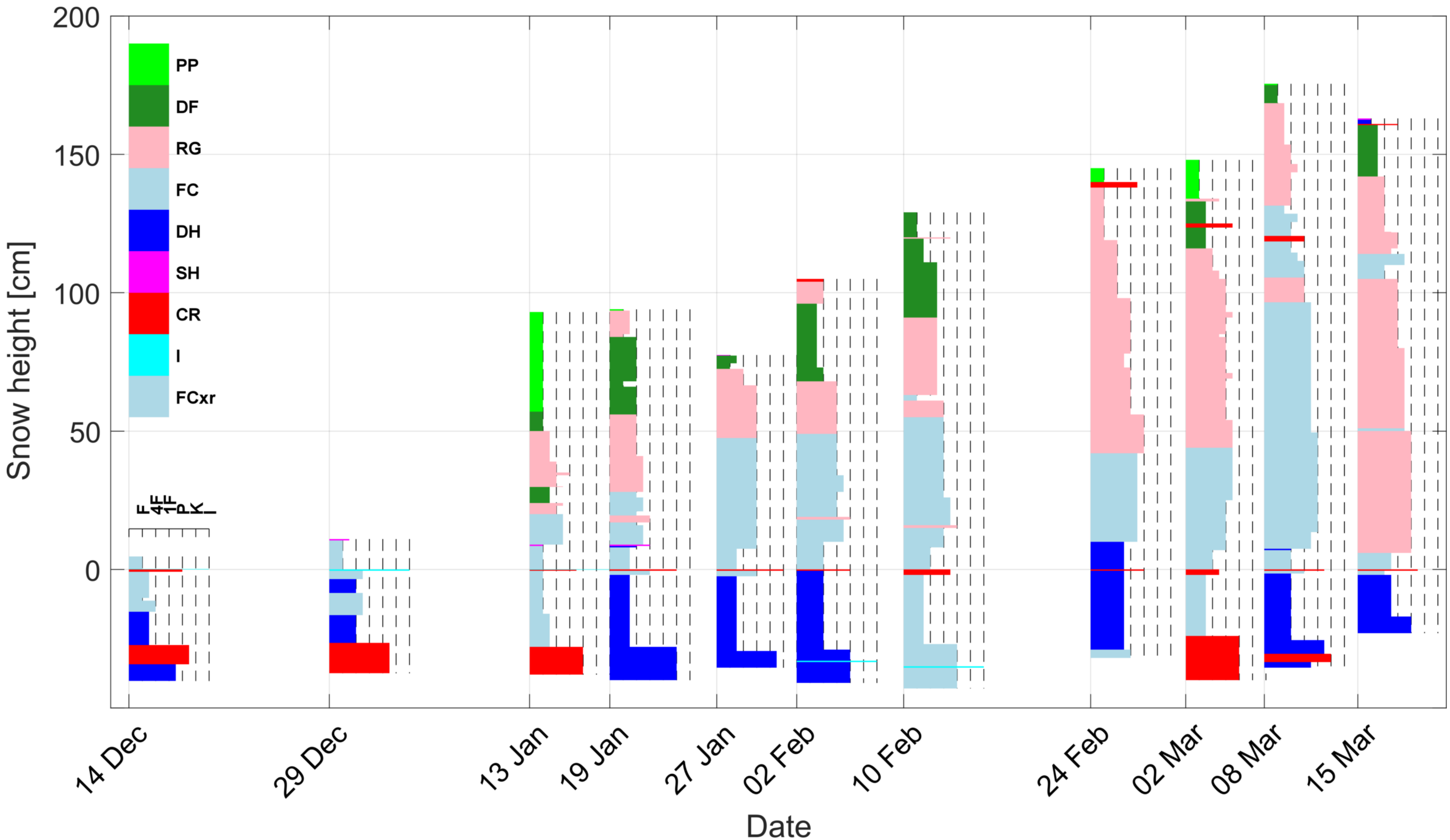
Calibration of Proksch et al. 2015
Calibration of Calonne et al. 2019



Let's look at the data…

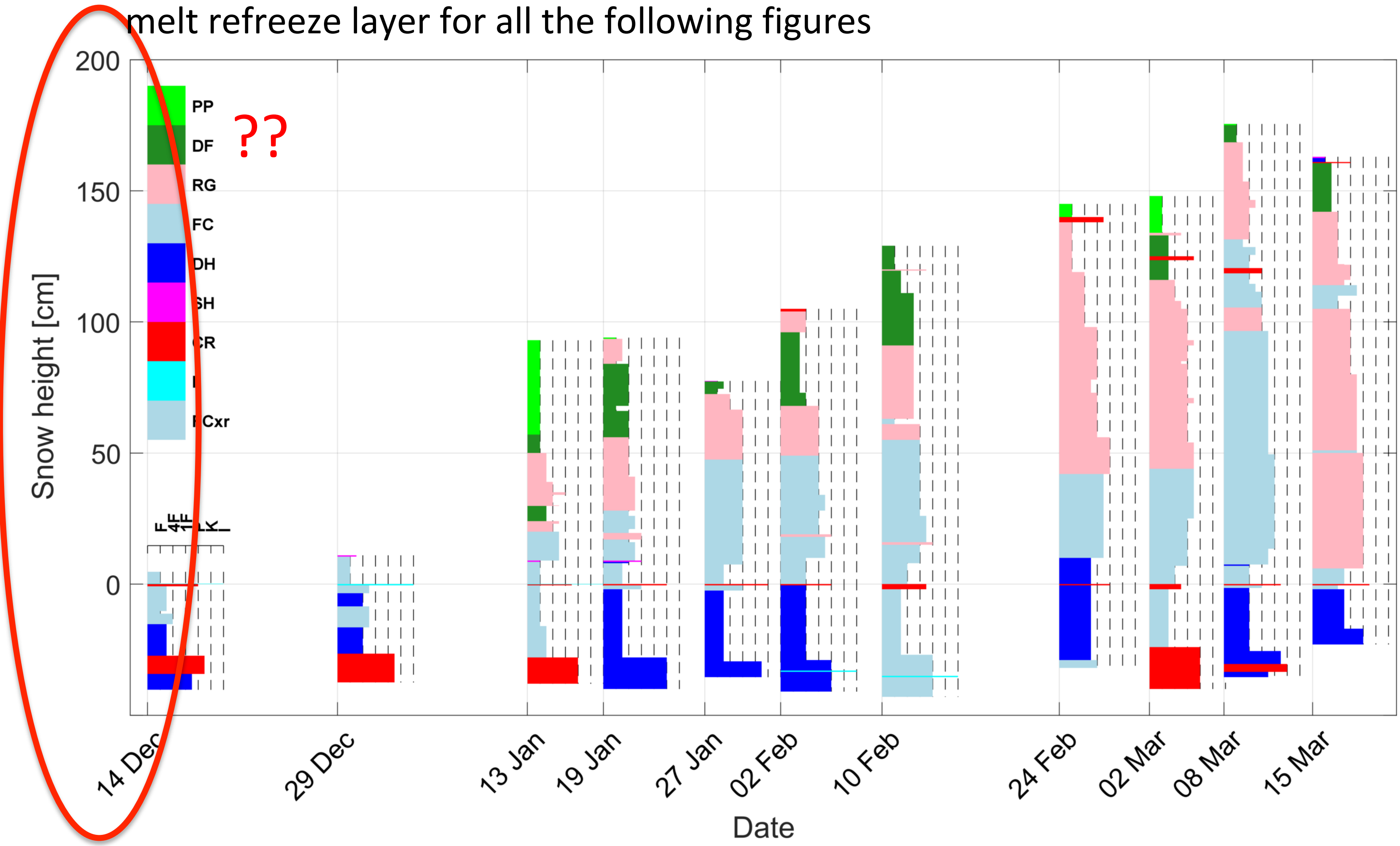
Results – Main stratigraphic features

Traditional snow profiles recorded over the season

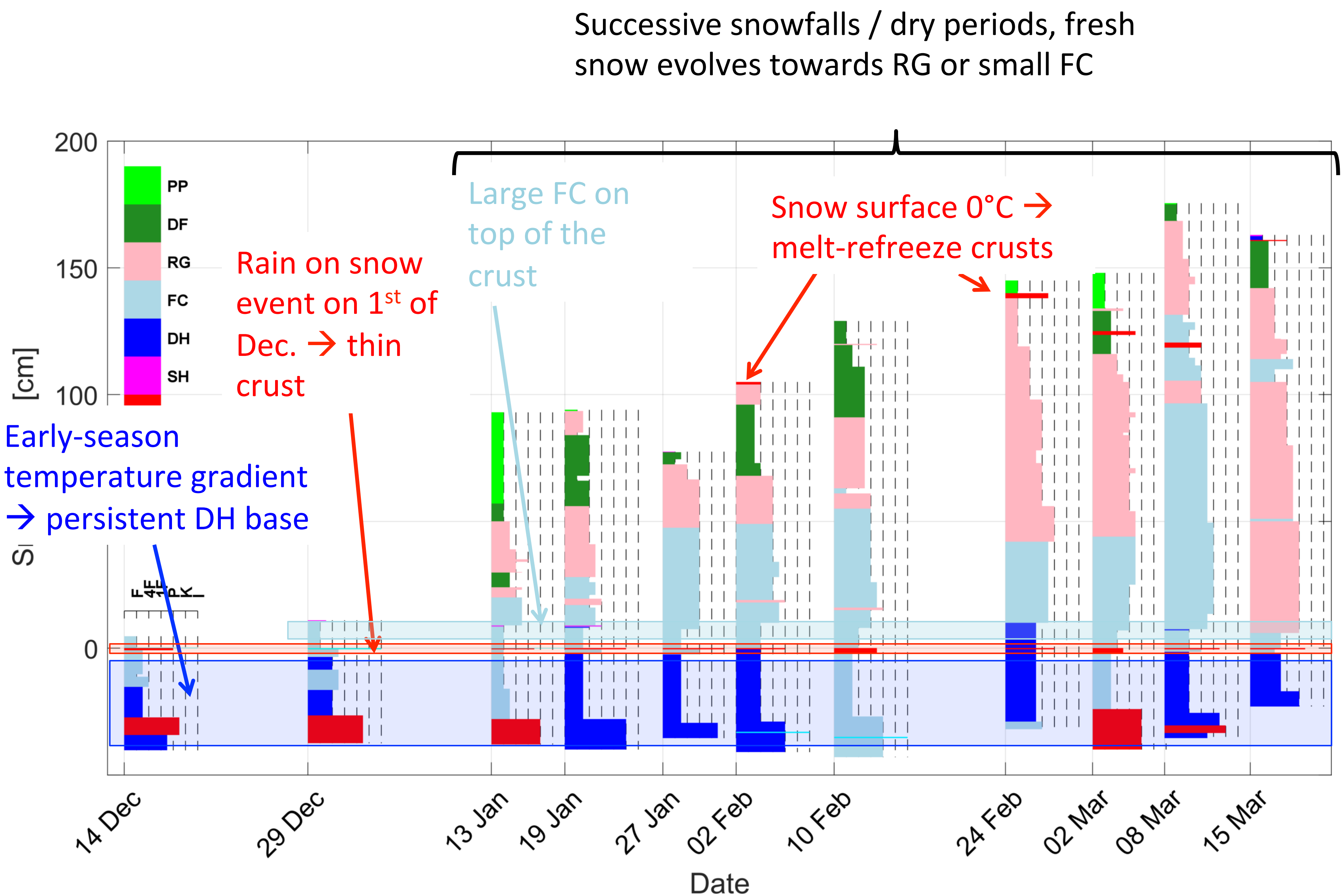


Results – Main stratigraphic features

- **Matching snow profiles:** alignment (z=0) based on a well-defined melt refreeze layer for all the following figures



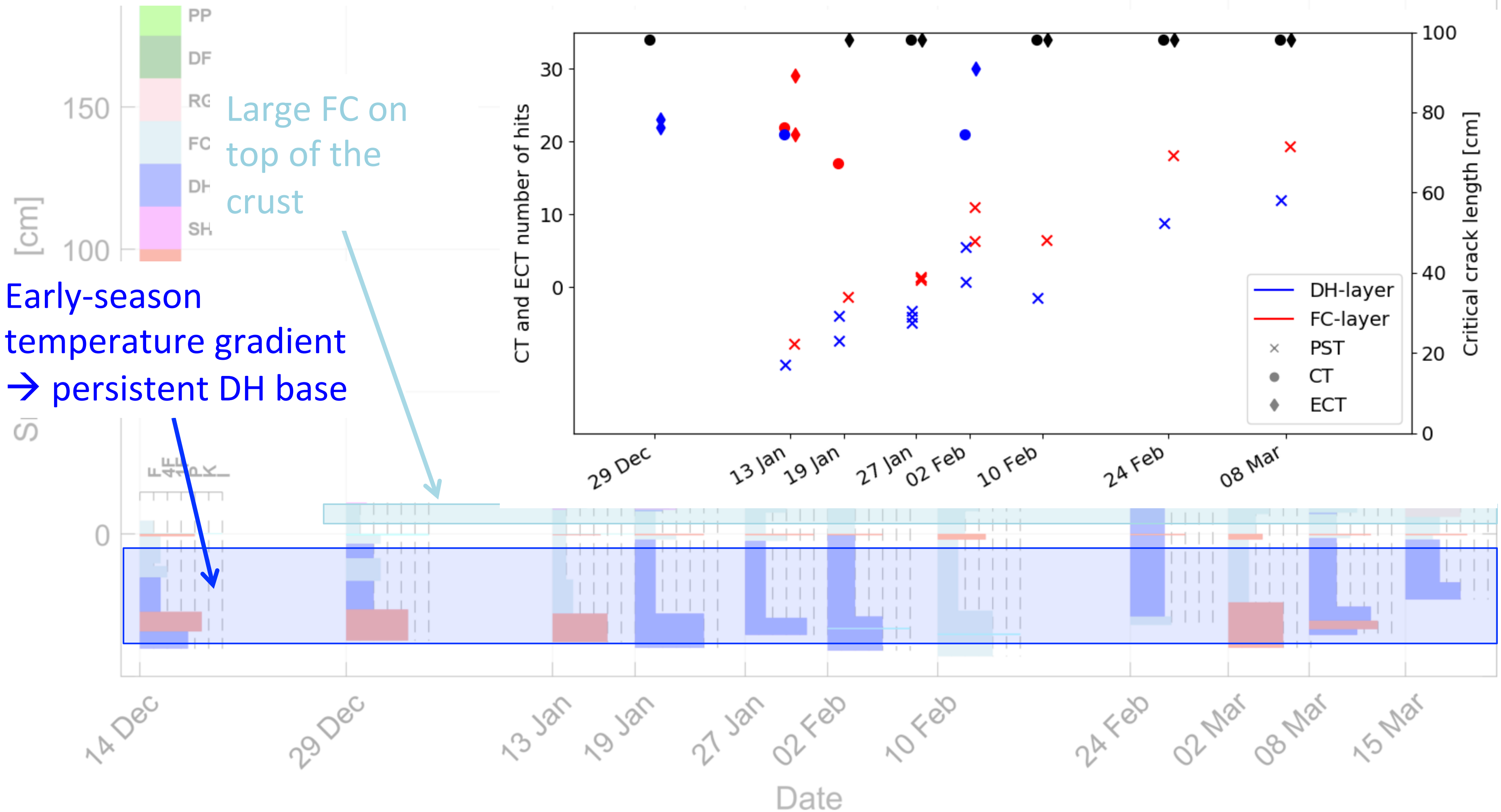
Results – Main stratigraphic features



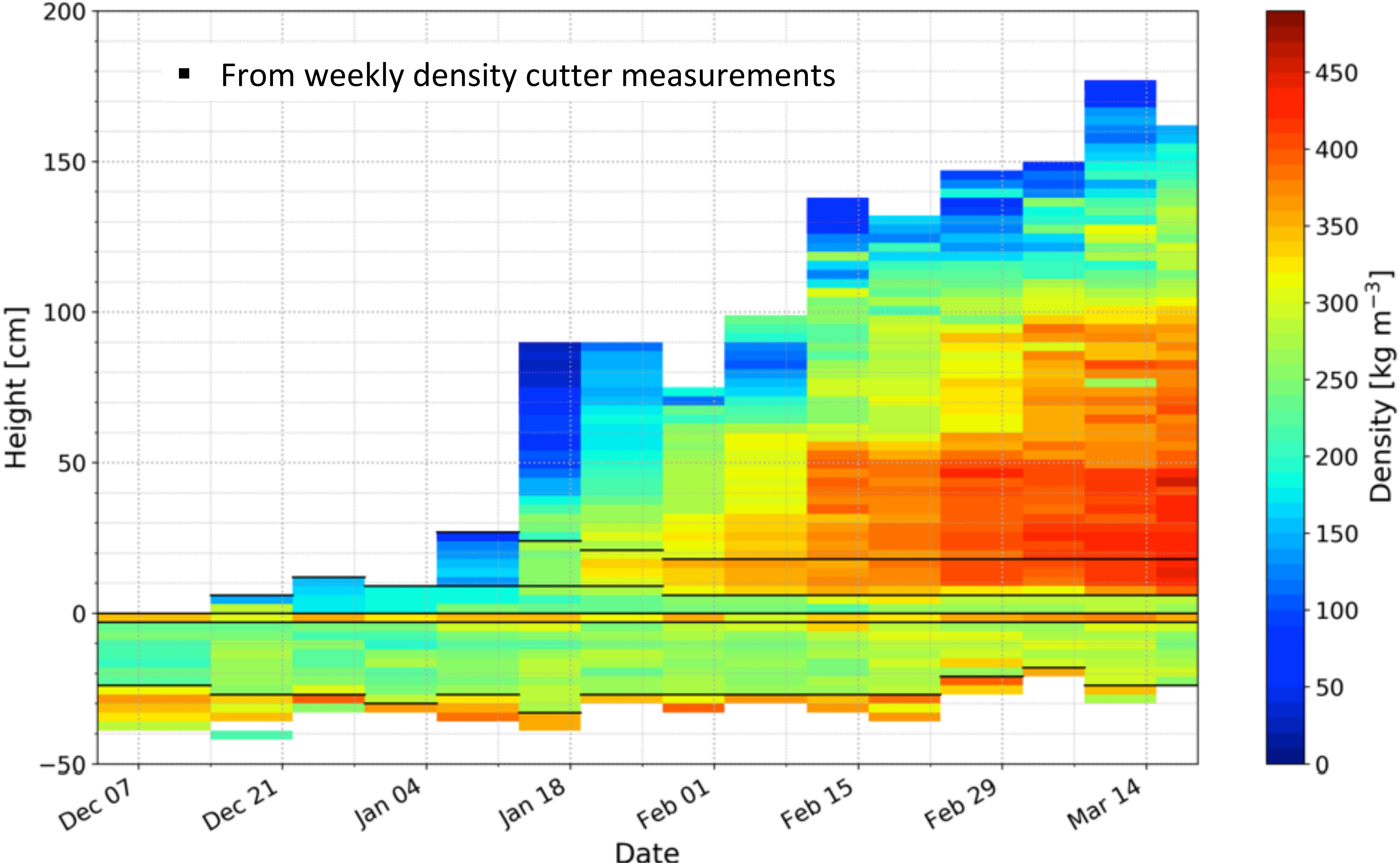
Results – Main stratigraphic features

Results of the stability tests performed over the season

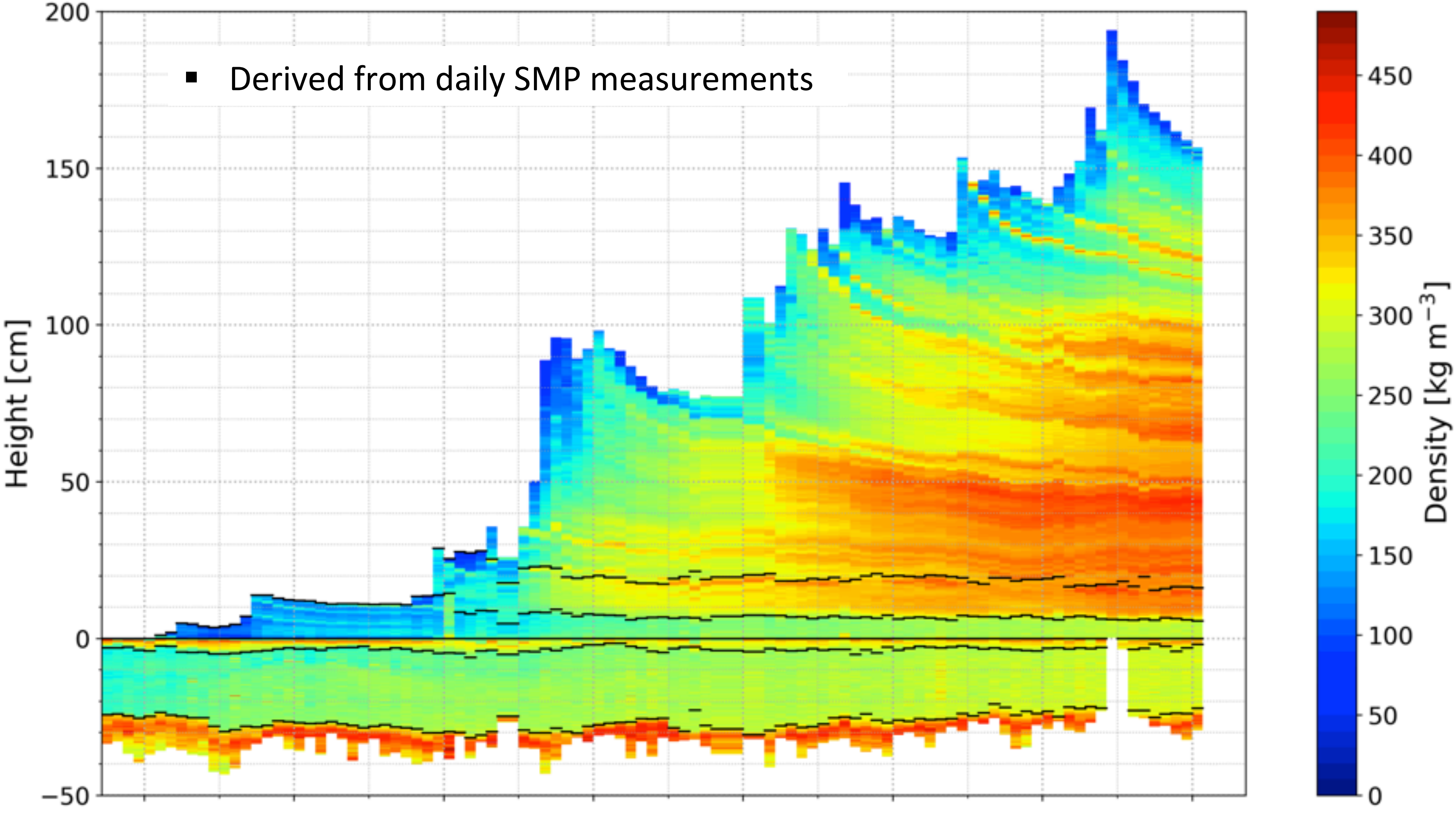
→ DH and FC layers, below and above the crust, were critical weak layers during most of the season



Results - Density evolution



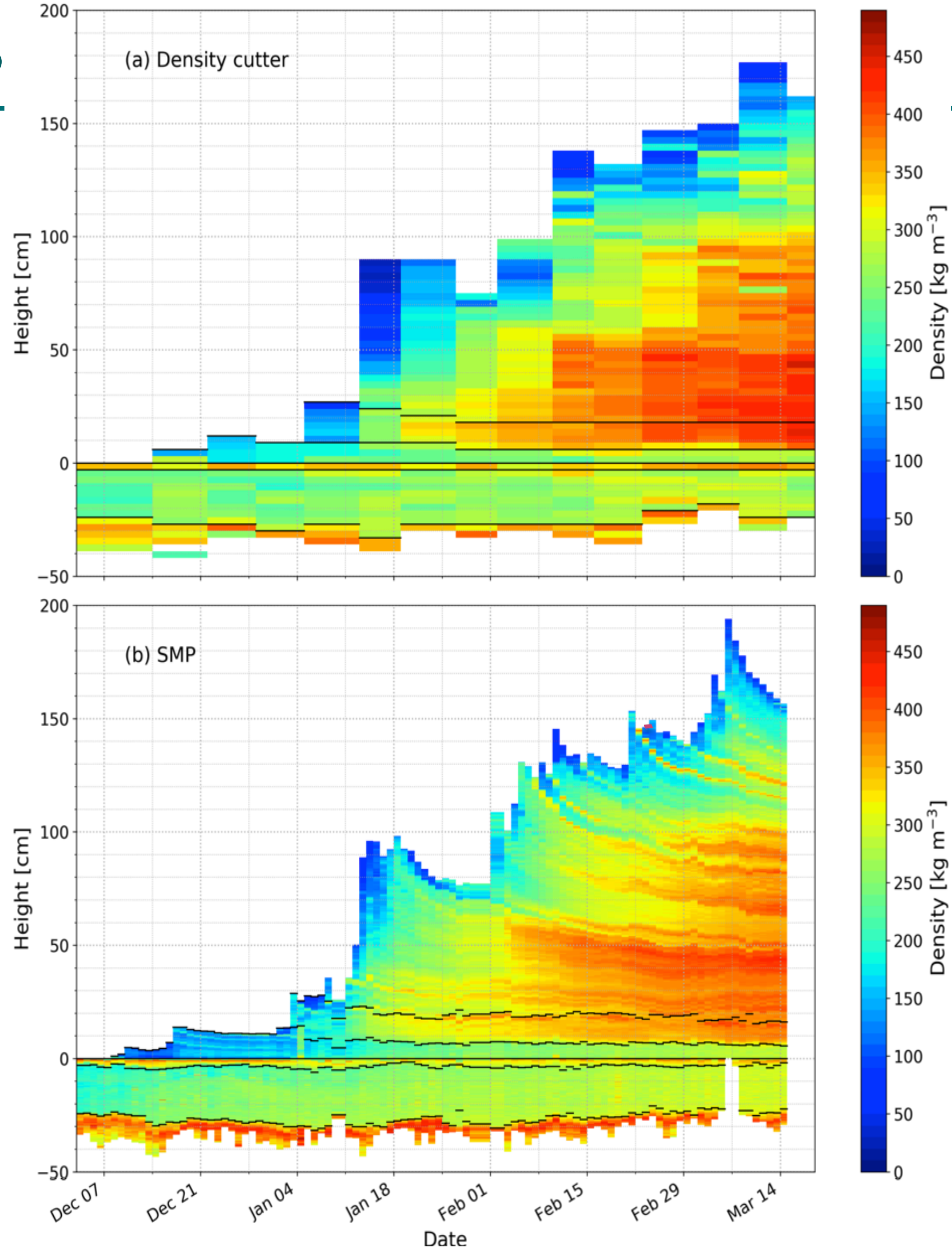
Results - Density evolution



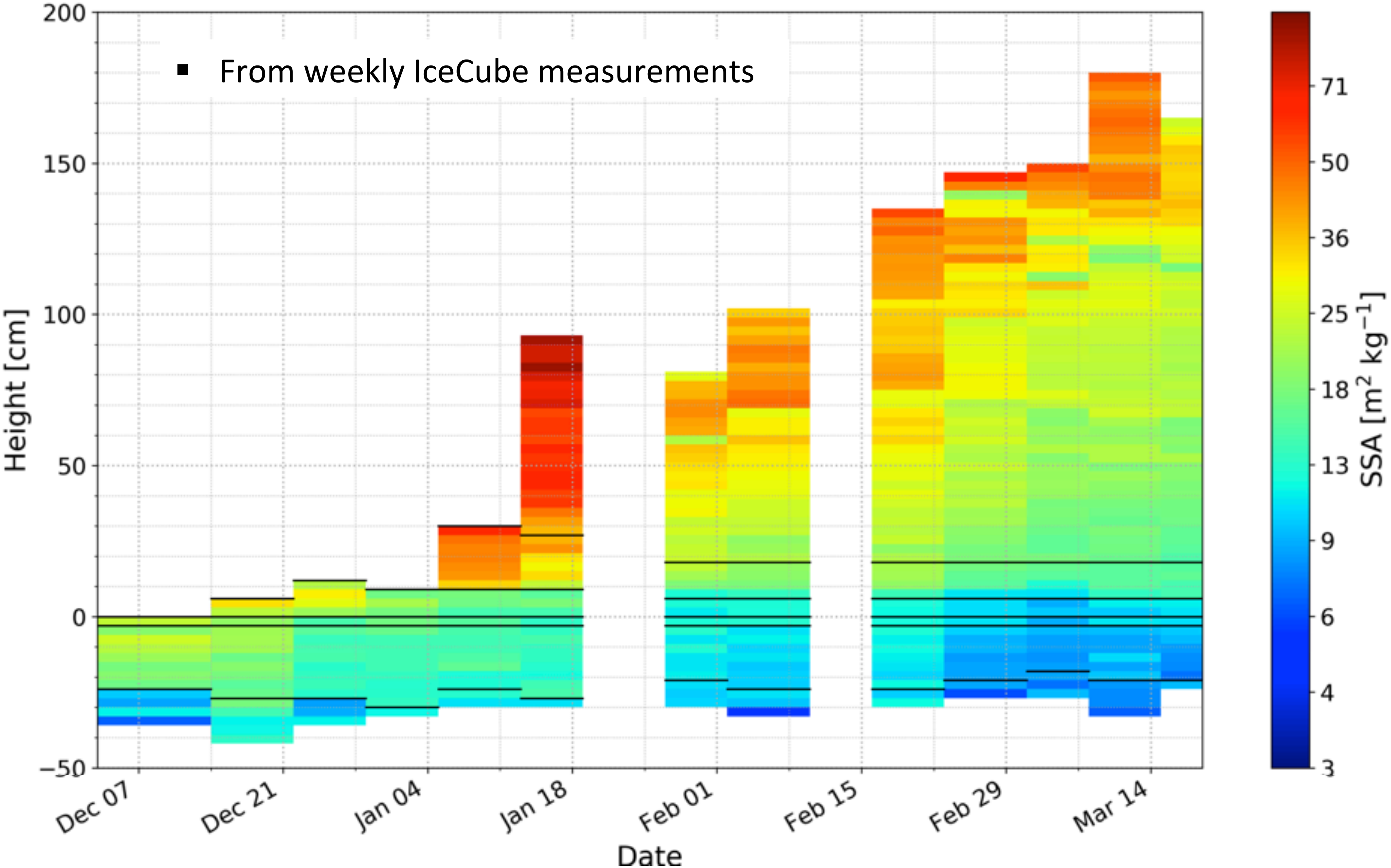
Results - Dens

- **Daily** vs. **weekly**
- **1 mm** vs. **3 cm** of vertical resolution

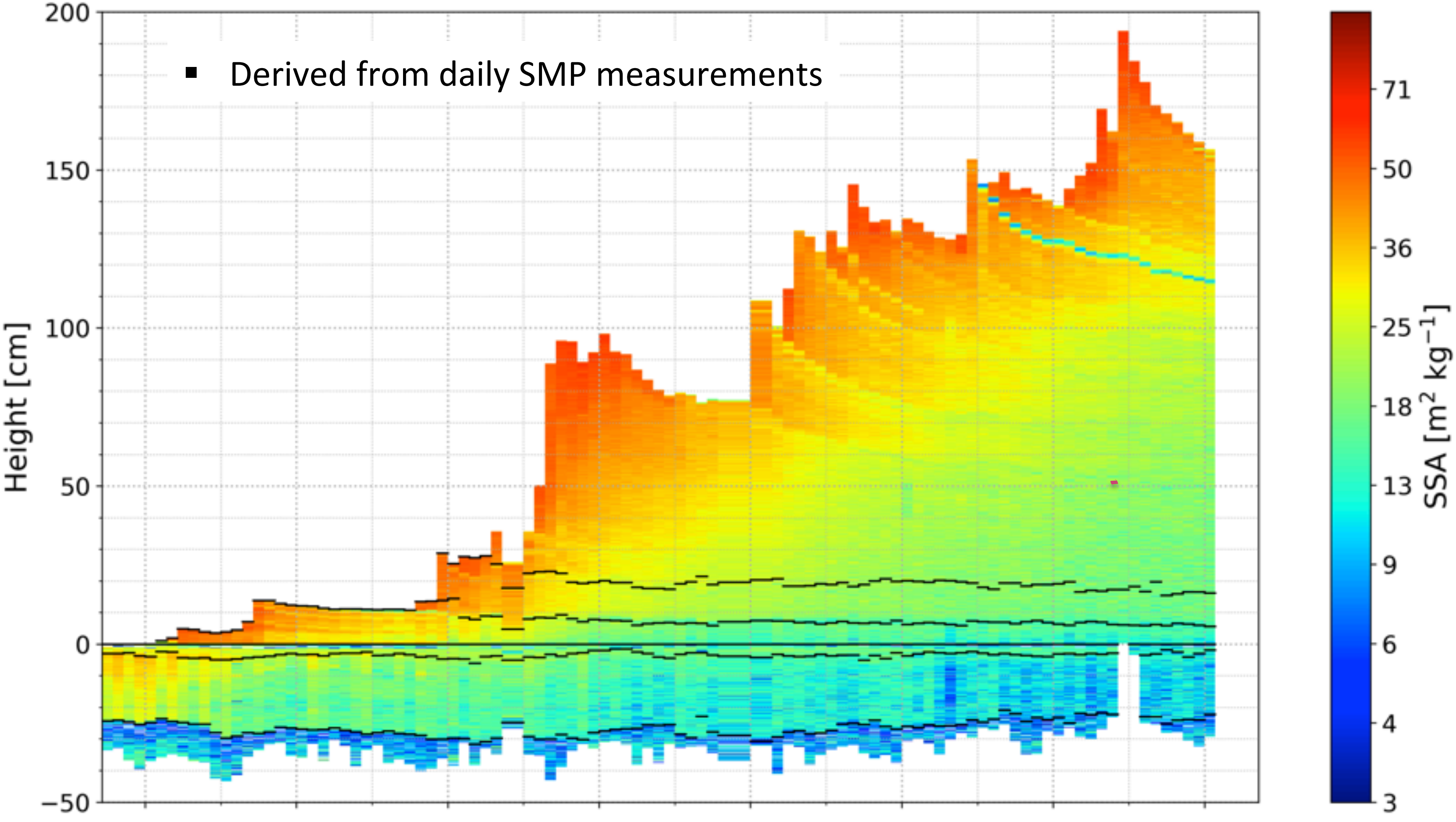
- Main features revealed by both methods
- High resolution data
  → Continuous picture of the density evolution
  → Allows tracking specific layer evolution



Results – SSA evolution



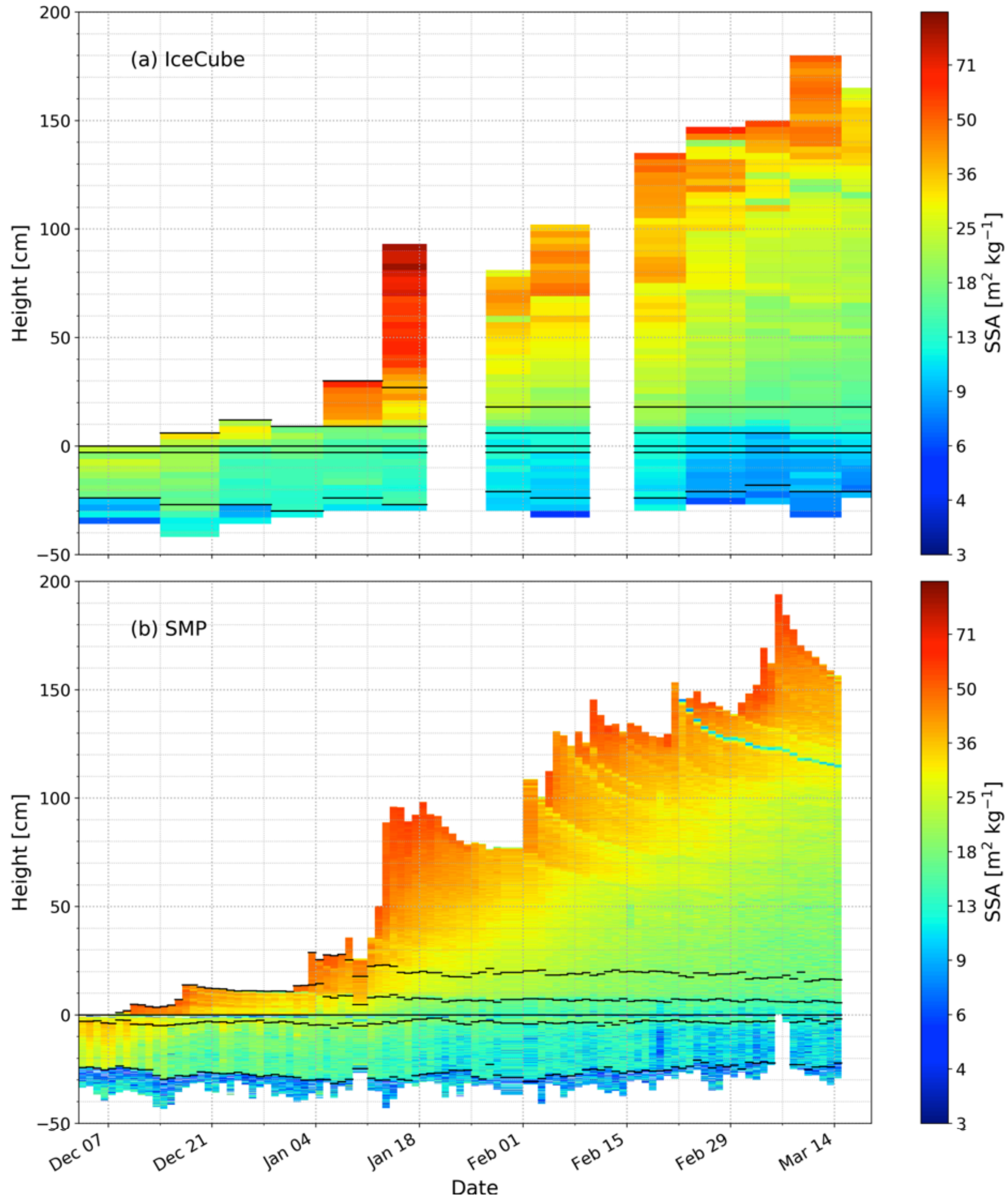
Results – SSA evolution



Results – SSA

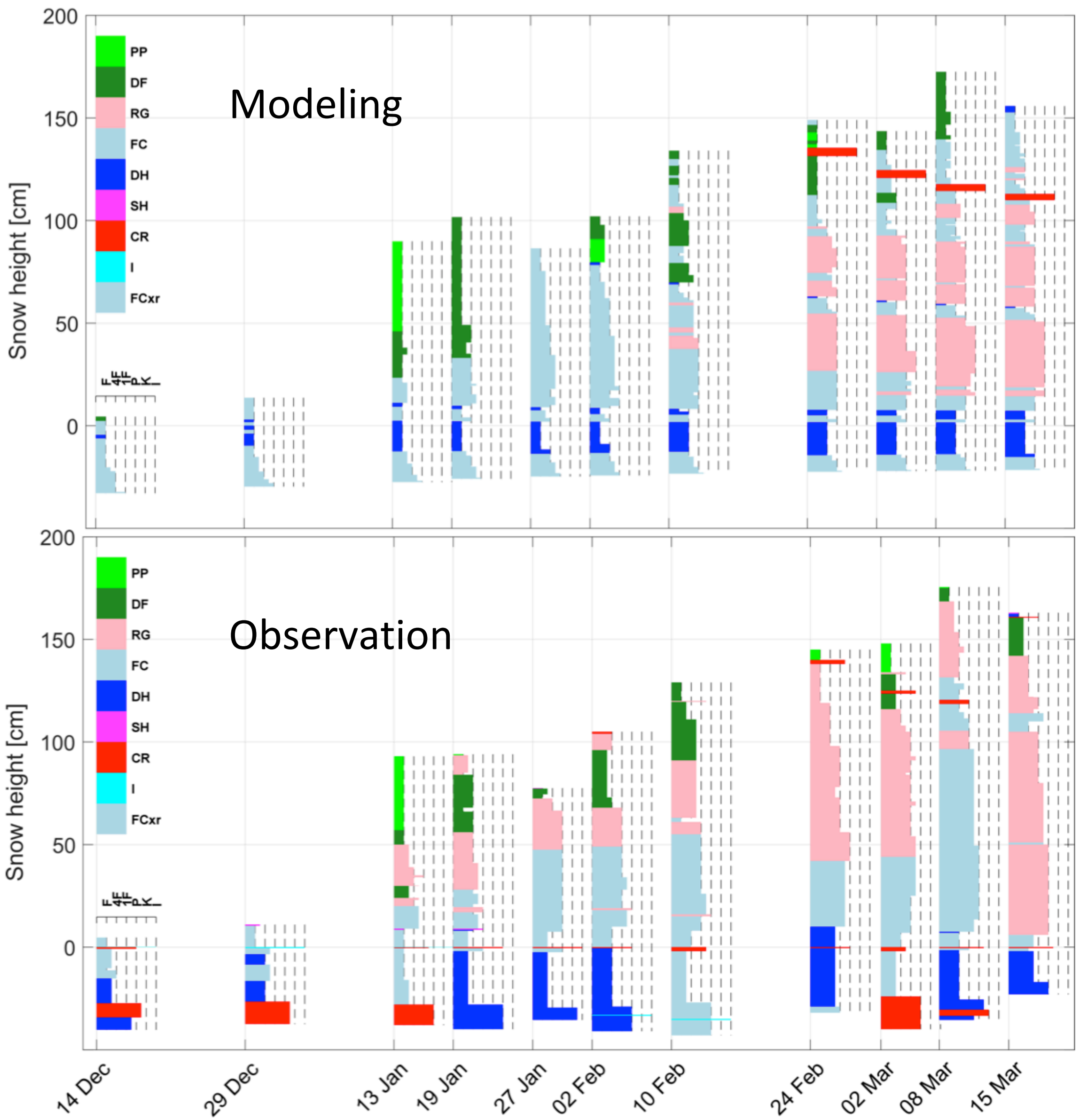
- **Daily** vs. **weekly**
- **1 mm** vs. **3 cm** of vertical resolution

- Main features revealed by both methods
- High resolution data
  - → Continuous picture of the SSA evolution
  - → Allows tracking specific layer evolution



Results – Comparisons

Traditional profiles



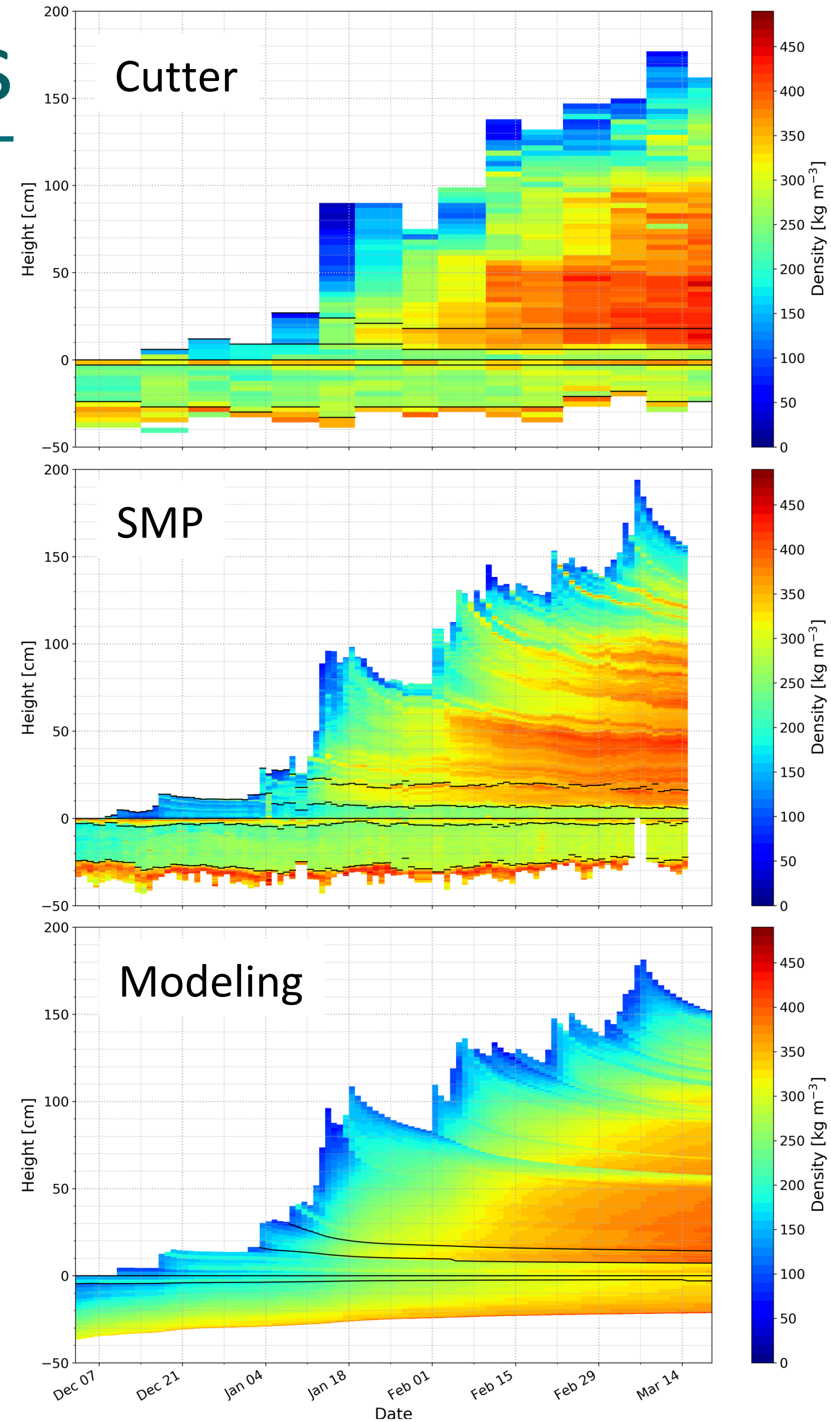
- SNOWPACK was driven with an optimized half-hourly dataset of meteorological and snow measurements from the automatic weather station at the WFJ site
- Early formation of the crust is not simulated → precipitation forcing scheme used does not allow representing rain fall events occurring at negative air temperatures (Quéno 2018)

Results – Comparisons

Density profile evolution over the season

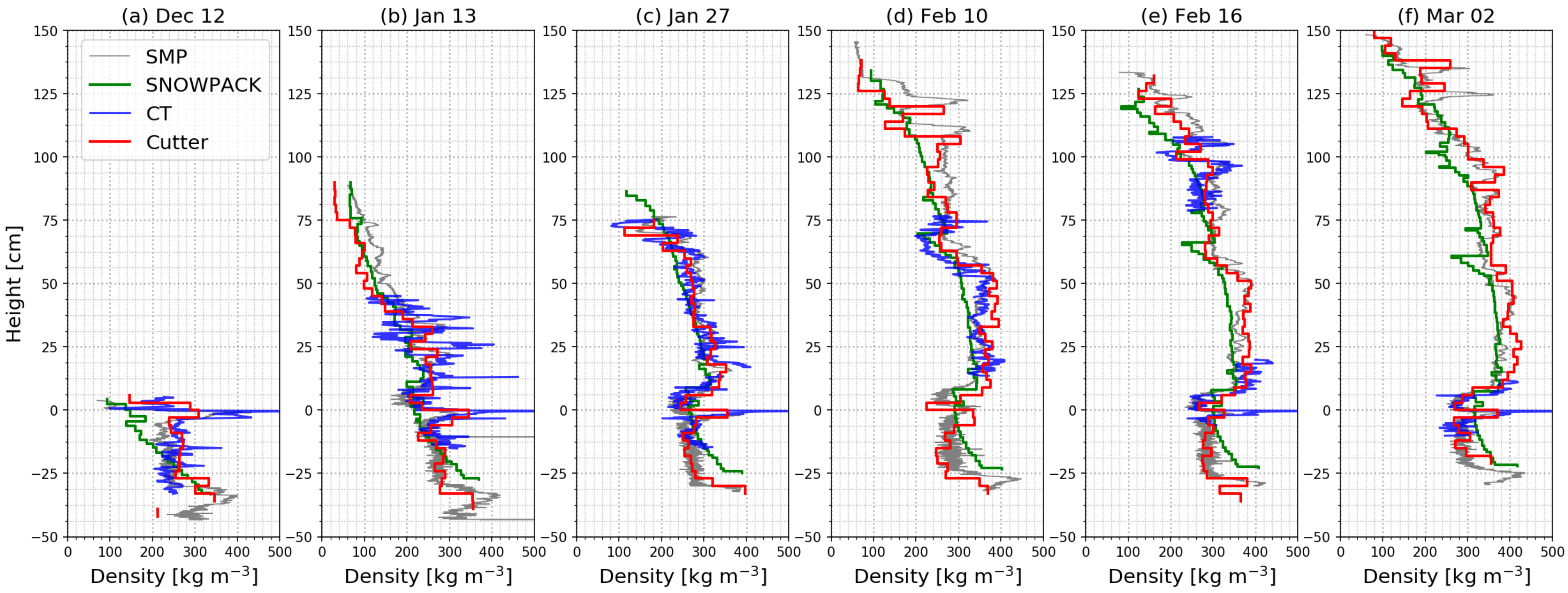
- Good agreement between measurements

- SNOWPACK simulation
  - Overall fair agreement
  - Crust formed on Dec. 1st is not simulated
  - Slight overestimation of the densification of the bottom depth hoar layer (similar findings with the model Crocus in Barrere 2017)



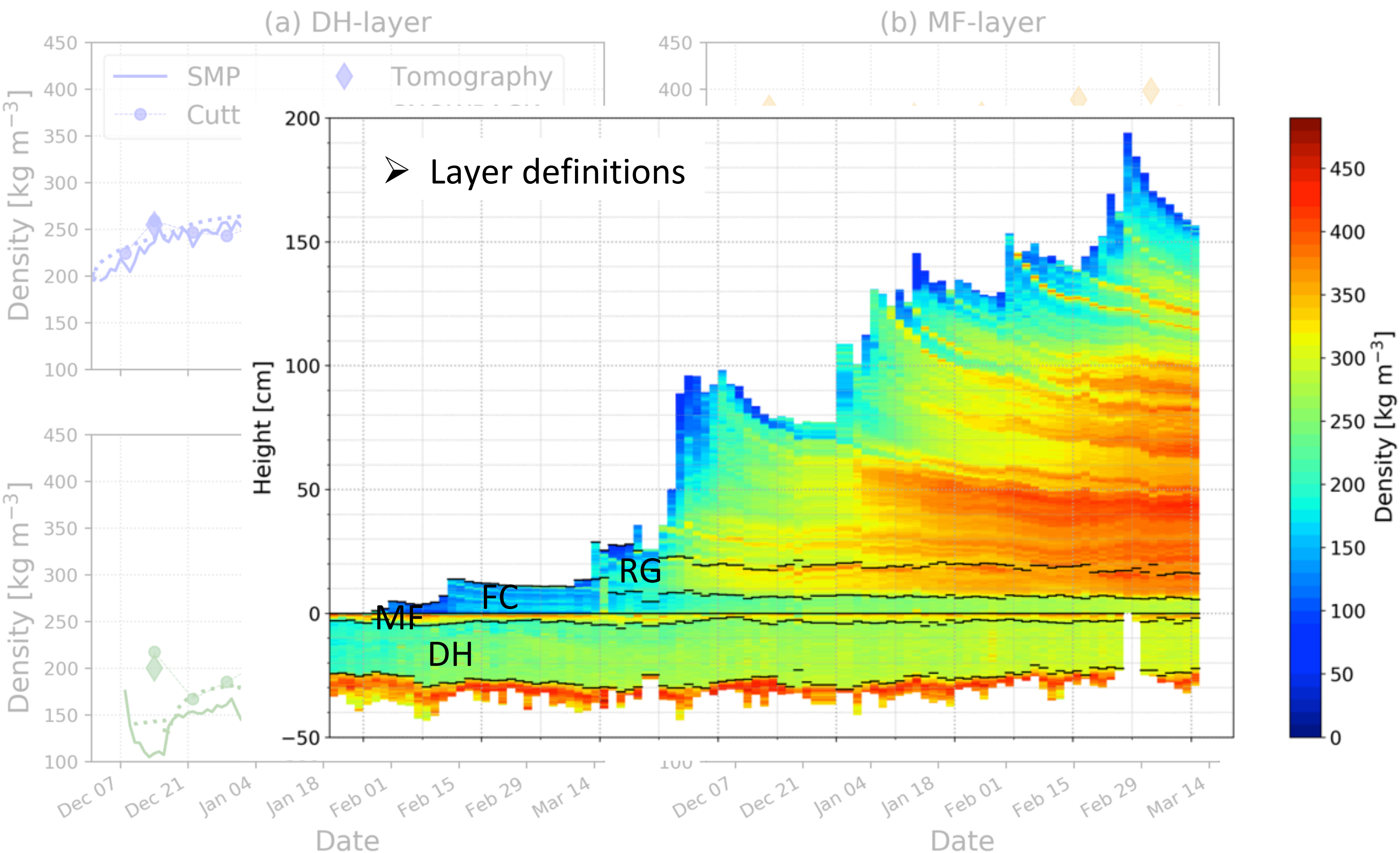
Results – Comparisons

Day by day comparison of density profiles



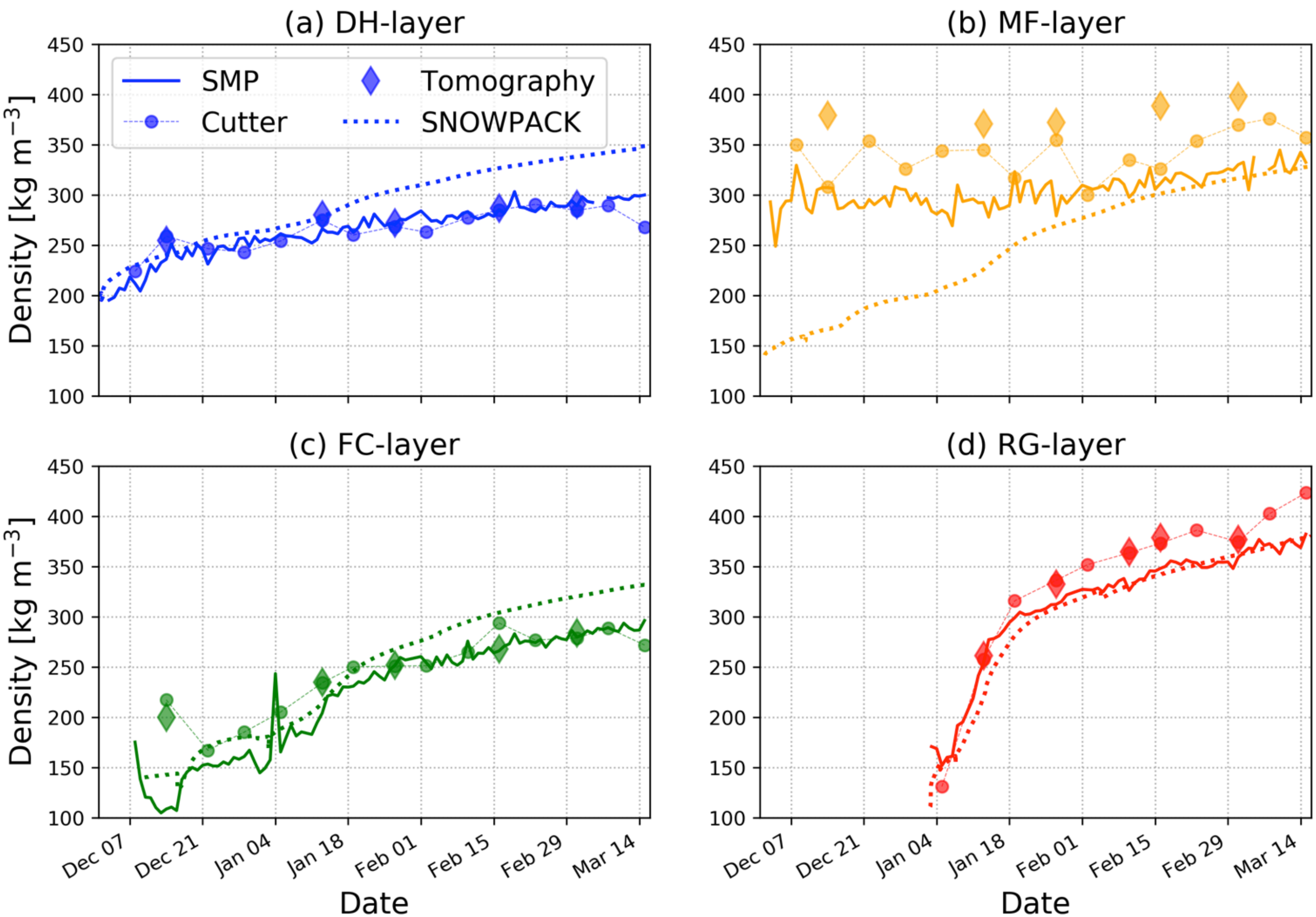
Results – Comparisons

Evolution of density for 4 tracked layers over the season



Results – Comparisons

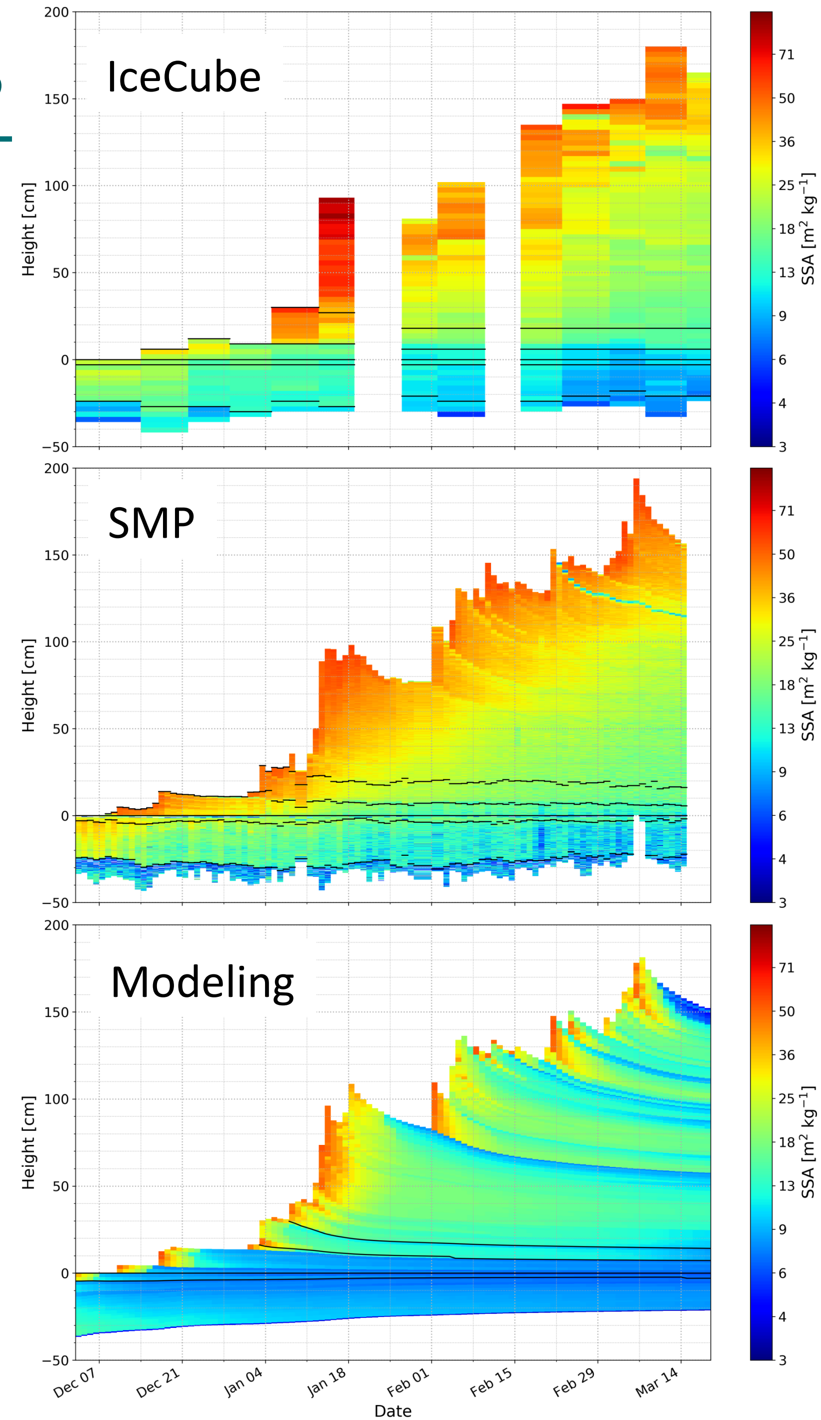
Evolution of density for 4 tracked layers over the season



Results – Comparisons

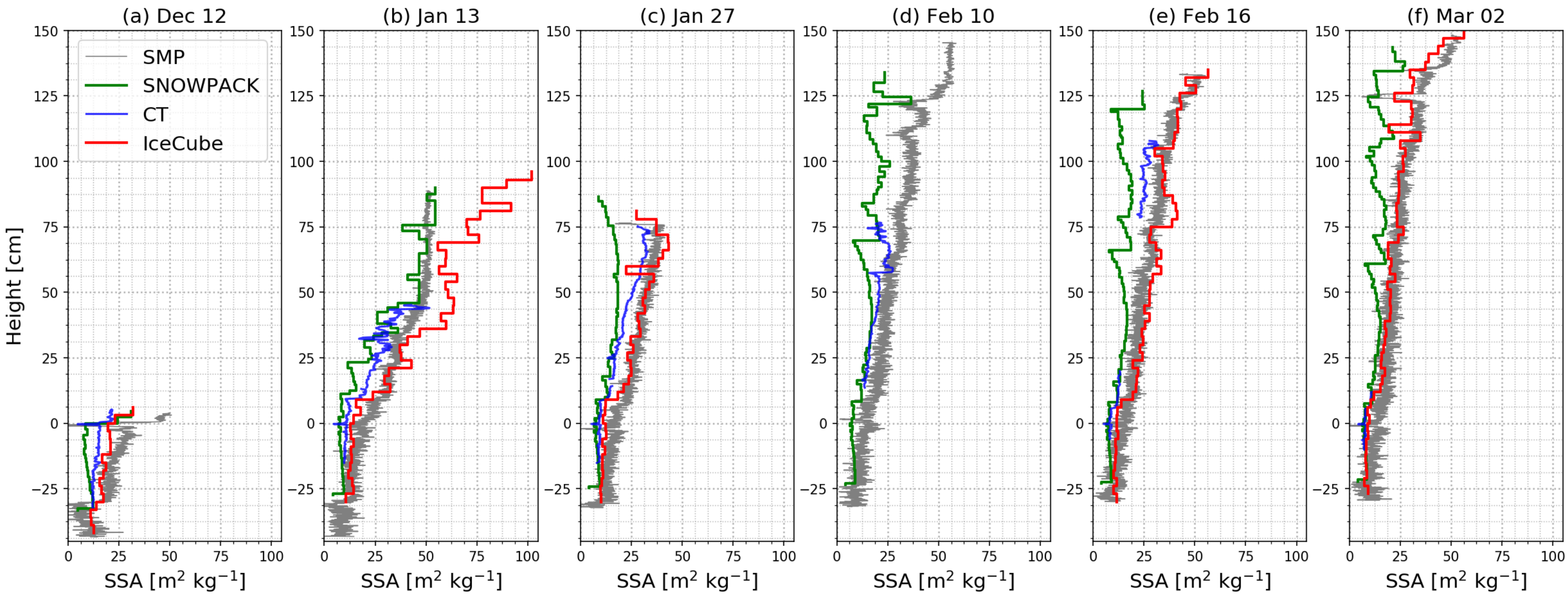
SSA profile evolution over the season

- Inter-measurement comparisons
  - significant and systematic deviations
  - IceCube and SMP derived values are higher than values computed on tomographic images
- SNOWPACK assessment
  - Crust formed on Dec. 1st is not simulated
  - overall underestimation of the SSA (similar bias reported at an arctic site by Leppänen 2015; on the contrary, a systematic overestimation of the SSA simulated by Crocus was reported by Tuzet 2017).



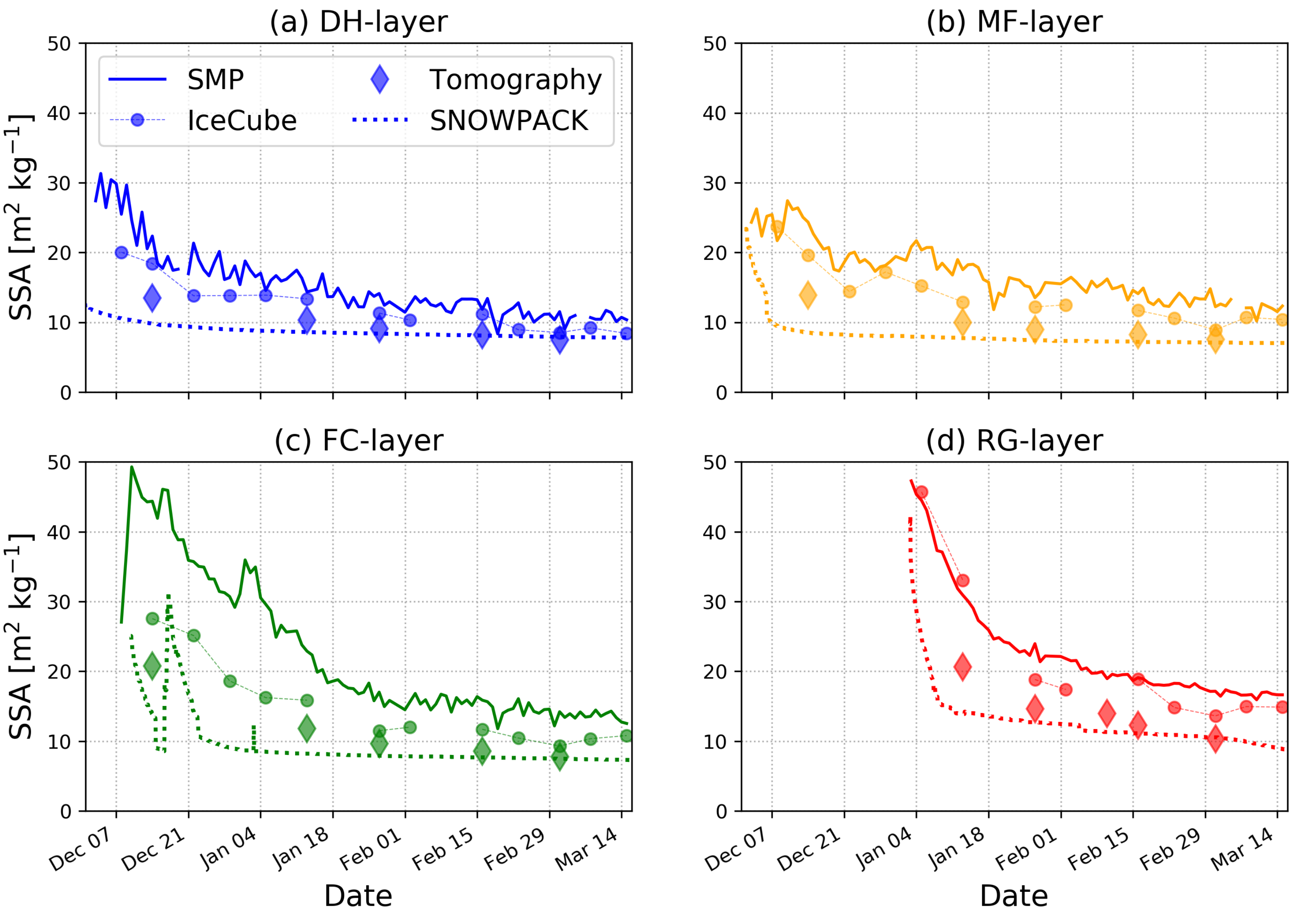
Results – Comparisons

Day by day comparison of SSA profiles



Results – Comparisons

Evolution of SSA for 4 tracked layers over the season



Conclusions

- The RHOSSA campaign included traditional profiling, stability tests, density cutter measurements, IceCube measurements, SMP measurements, and tomography.

- High-resolution data (daily profiles with a 0.5 mm vertical resolution) offers an unprecedented detailed and continuous picture of the snowpack evolution

- Our specific results comprise
  - Re-calibrated parameterizations to estimate density and SSA from SMP measurements for device version 4
  - Comparison of density and SSA estimates from state-of-the-art measurement methods (Cutter/IceCube, tomography, SMP-derived)
  - Comparison of SNOWPACK simulations and field measurements

- Our study demonstrates the potential of high temporal and spatial resolution dataset for the evaluation of the snow cover models as Crocus or SNOWPACK.

- In this view, the RHOSSA measurements campaign could be extended to other snow observation sites to cover different environments and conditions.

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