MONITORING SNOW PROCESSES AND SNOW DENSITY BY THERMAL INERTIA

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Outline

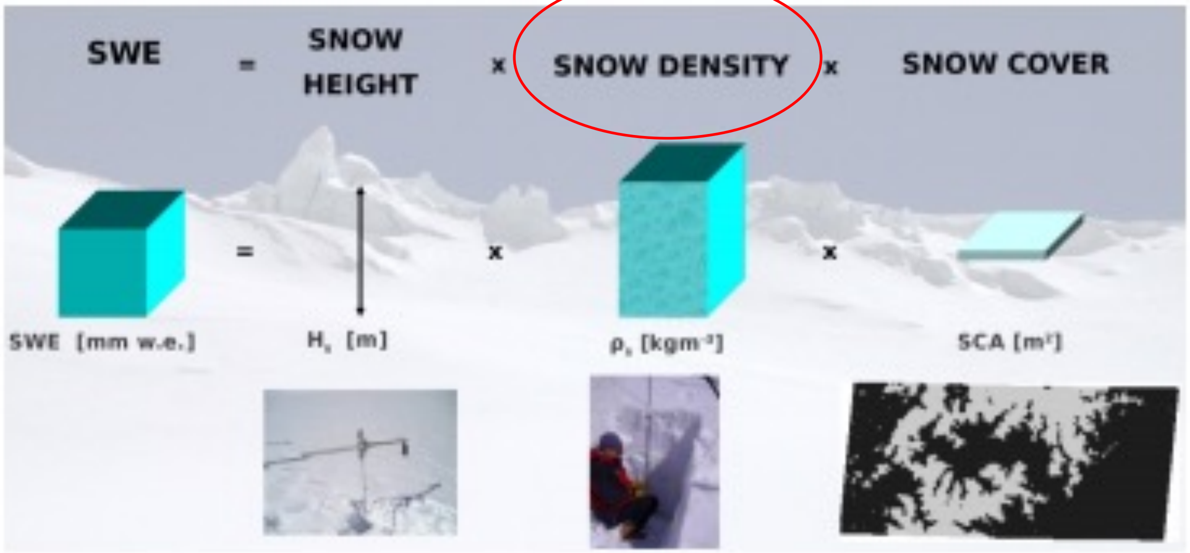
1. **Background;**
2. **Thermal inertia and snow dynamics;**
3. **Mapping snow density;**
4. **Conclusions**

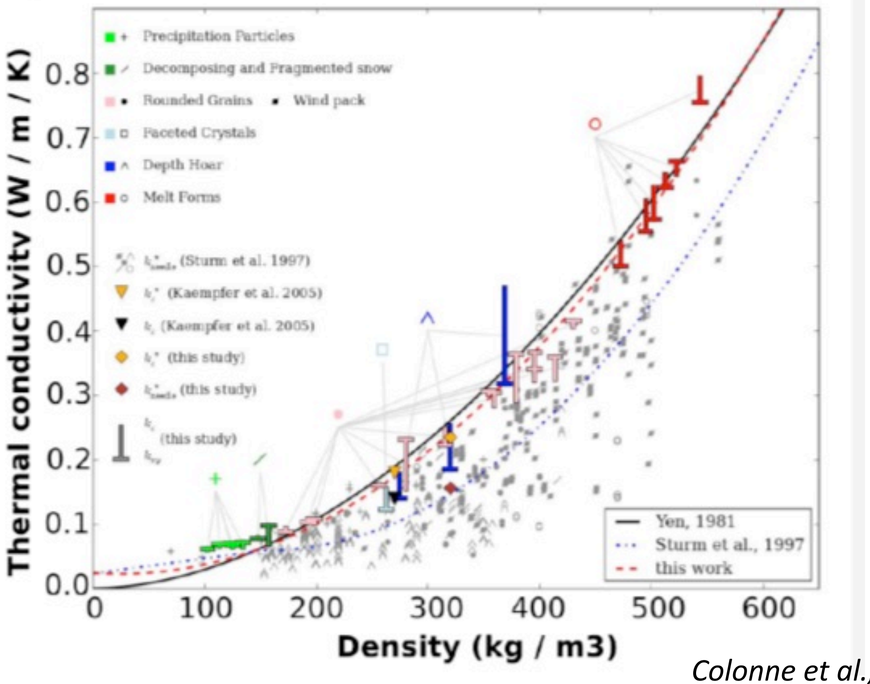
Background

Snow, as a fundamental reservoir of freshwater, is a crucial natural resource

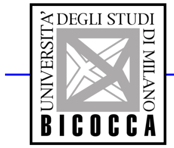
Snow density is a critical variable (e.g. for SWE)

- Thermal properties of snow vary primarily with density
- Density controls inertia and conductivity





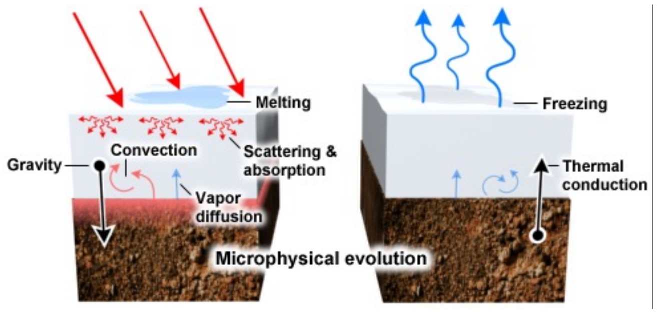
Colonne et al., 2010



Background

Snow/ice physical properties. A complex microstructure

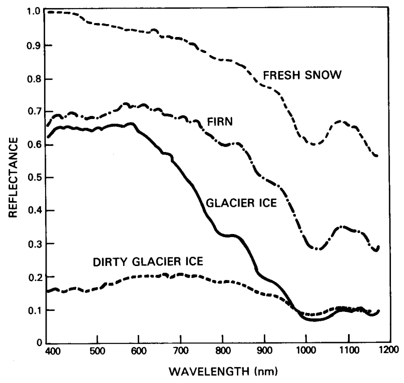
- A porous medium made of ice, air and liquid water
- Their relative proportion controls optical and thermal properties
- Weather conditions control metamorphism and compaction

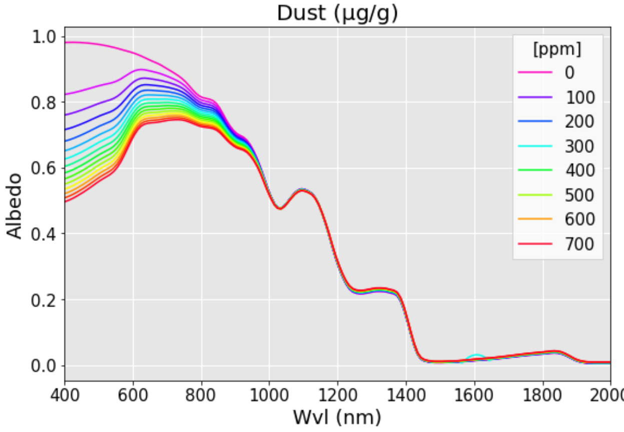


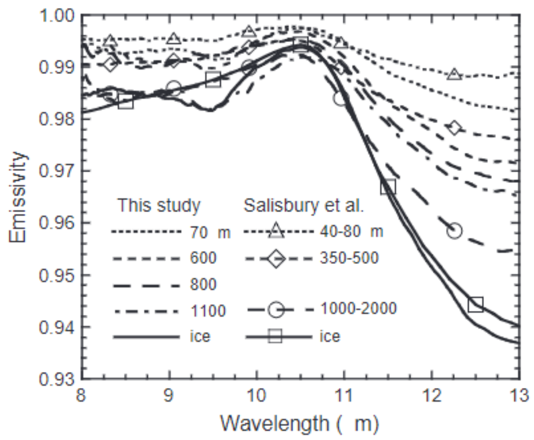
Unique radiative properties

- White in VIS, affected by light-absorbing impurities
- Grey in NIR, affected by snow grain size
- Almost a black body in TIR @λ = 11 μm. Affected by snow density. Emissivity is reduced with increasing snow grain size

→ *Very (spatial and temporal) rapid changes of its albedo and thermal properties*







Hori et al., 2006

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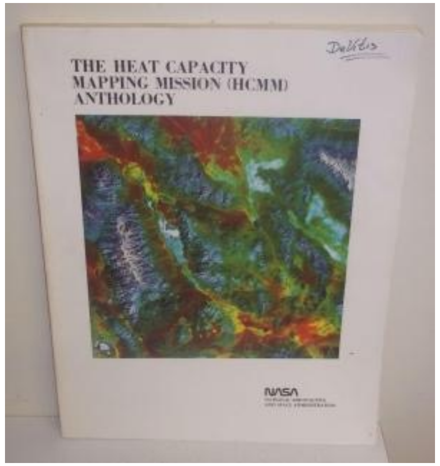
Contribution of thermal inertia for snow monitoring

- *Thermal inertia P is an indicator of the material resistance to changes in temperature* $P = \sqrt{k\,\rho\,c}$ $[J\,m^{-2}\,K^{-1}\,s^{-1/2}]$
- *Remote sensing of apparent thermal inertia was successfully used to track soil moisture, lithology and planetary surface geology, since 1980 by HCMM – NASA)*
- *Some attempts to retrieve snow density by active and passive microwave but the possibility to get accurate estimates of snow density still represents a great challenge*
- *Since changes of snow density and liquid water content continuously occur in the snowpack, spatial and temporal patterns of thermal inertia can theoretically reveal snowmelt processes. Never exploited to evaluate snow properties, such as snow density*

$$APs = \frac{(1-\alpha)\,SW_{in}\,A_1[\cos(\omega t_2 - \delta_1) \; - \cos(\omega t_1 - \delta_1)]}{\Delta T_{(t2-t1)}\sqrt{\omega}\sqrt{1 + \frac{1}{b} + \frac{1}{2b^2}}}$$



α = shortwave albedo [–];

SW_{in} = incoming shortwave radiation $[\mathrm{W\,m^{-2}}]$ averaged in day-time hours;

A_1 and b = coefficients of first-order approximation of the Fourier series, which depends on latitude and solar declination and azimuth, computed according to Xue and Cracknell (1995);

ω = Earth's rotation angular velocity $[7.2921150 \, x \, 10^{-5} \; \mathrm{rad\,s^{-1}}]$;

δ_1 = phase difference between surface temperature and shortwave incoming radiation, [rad]. $\delta_1 = \omega t_{max}$=3.794, with t_{max}=14:30

ΔT = surface temperature difference between the night-time and the day-time temperatures measured at times t_1 (04:00) and t_2 (11:30), respectively [K].

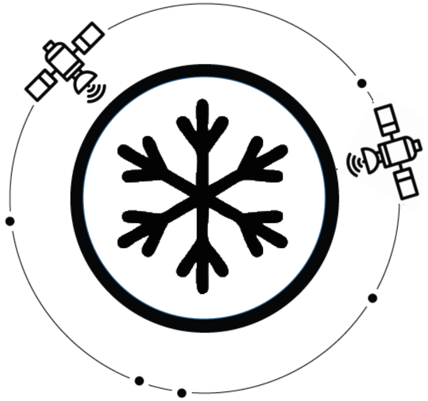
Short and Stuart (1982)
Price, 1980

Maltese et al., 2013

Main objectives

- **To exploit thermal Inertia for monitoring snowmelt processes;**

- **To infer snow density through thermal inertia observations**

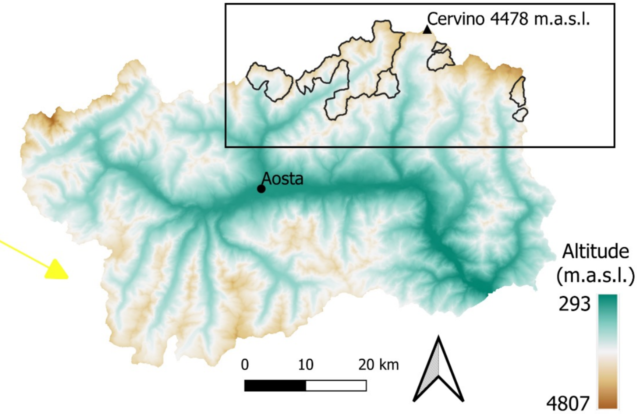


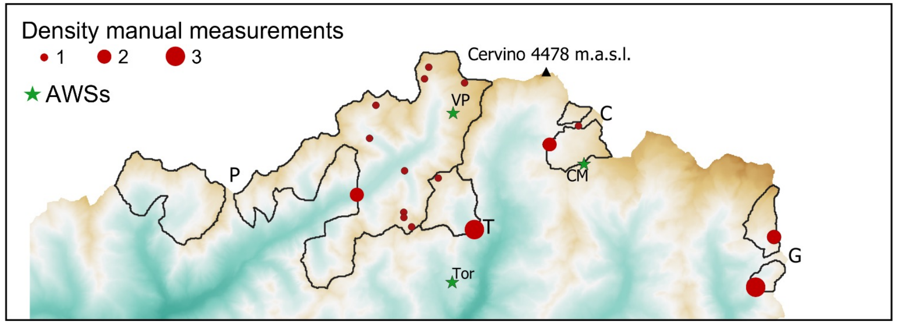
Test sites – Alpine catchments, temporal and spatial analysis

• Temporal analysis

Torgnon AWS and fully equipped ICOS site – Northwestern Italian Alps Altitude 2,160 m a.s.l. Subalpine unmanaged grassland area covered by snow from the end of October to late May. (2012-2017 hydrological years).

• Spatial analysis





Four alpine basins. Valpelline, Gressoney, Cervinia and Val Tournenche catchments

Data and methods

• Temporal analysis

Input variables (in situ AWS measurements)

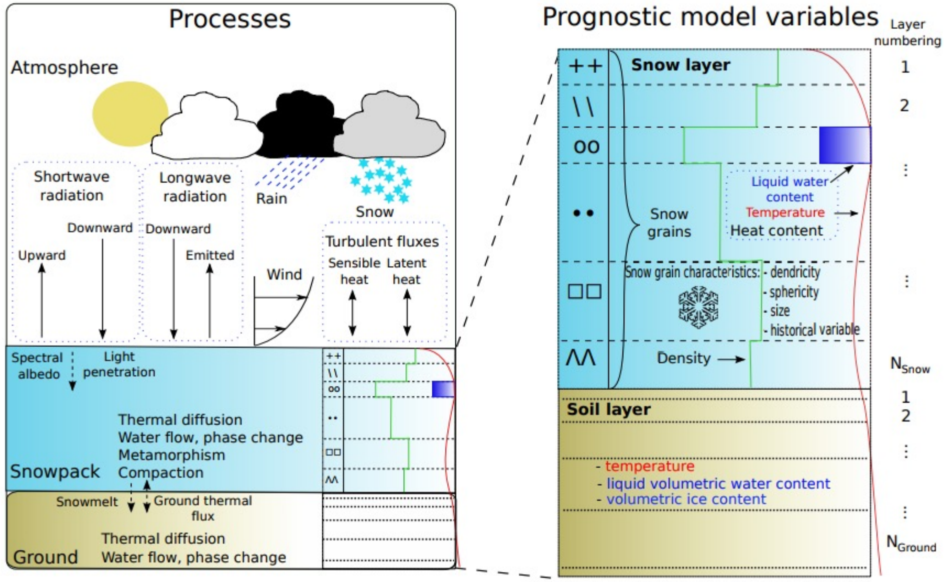
- Air temperature and pressure
- Wind speed
- Air humidity
- Precipitation
- Direct and diffuse SW_{in} and LW_{in}

→ **Crocus model** →

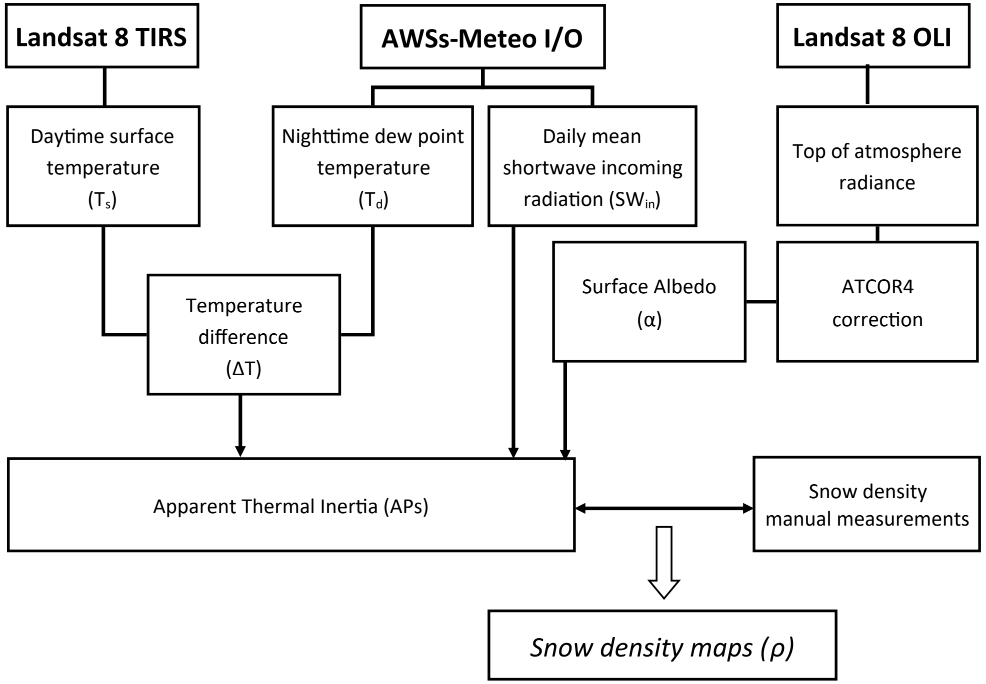
Output variables

- Snow height
- Snow Water Equivalent
- Liquid Water Content
- Snow Density
- Snow melt
- Temperature
- Albedo

CROCUS snowpack model for snow density simulation



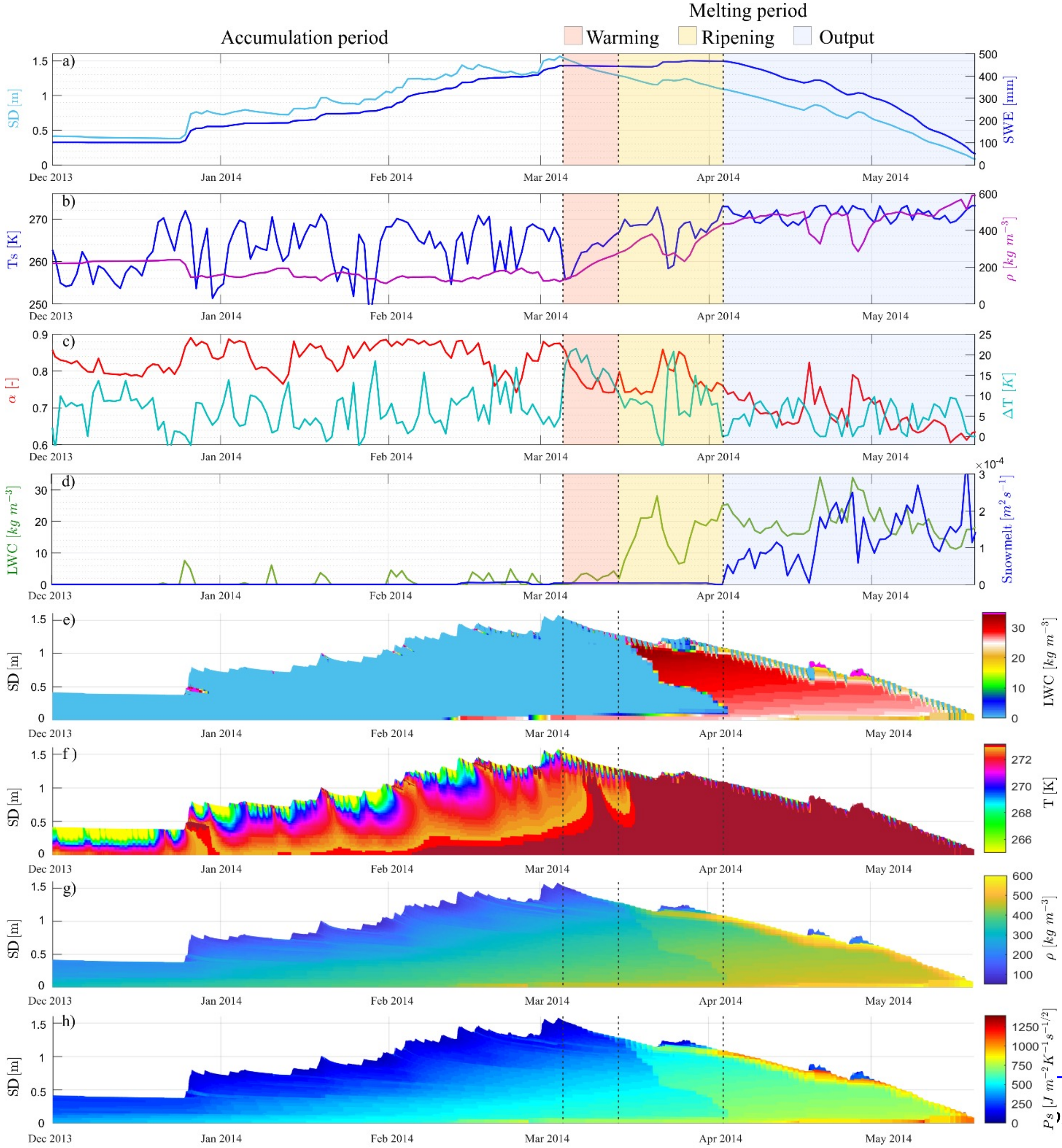
• Spatial analysis

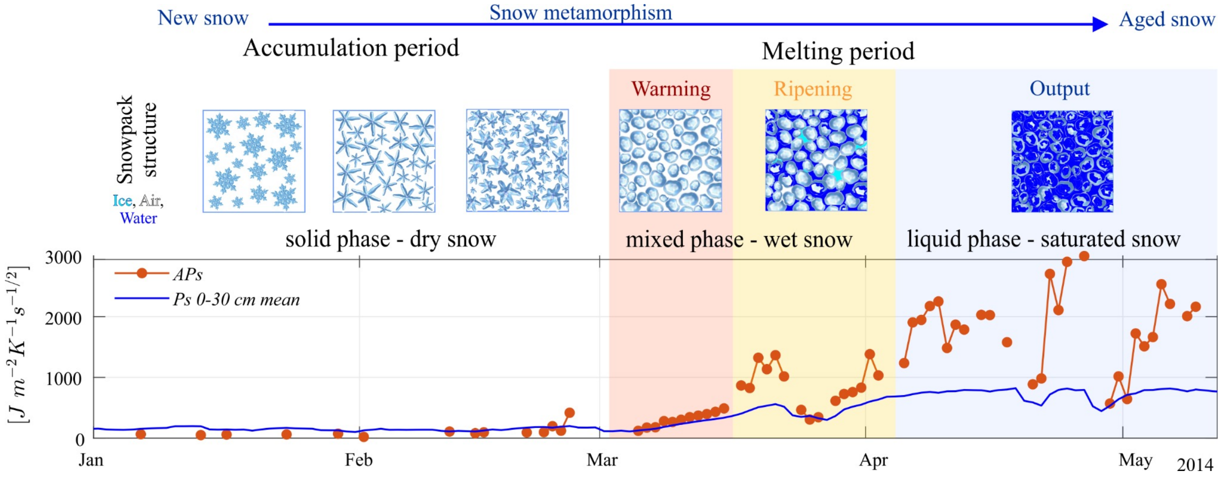


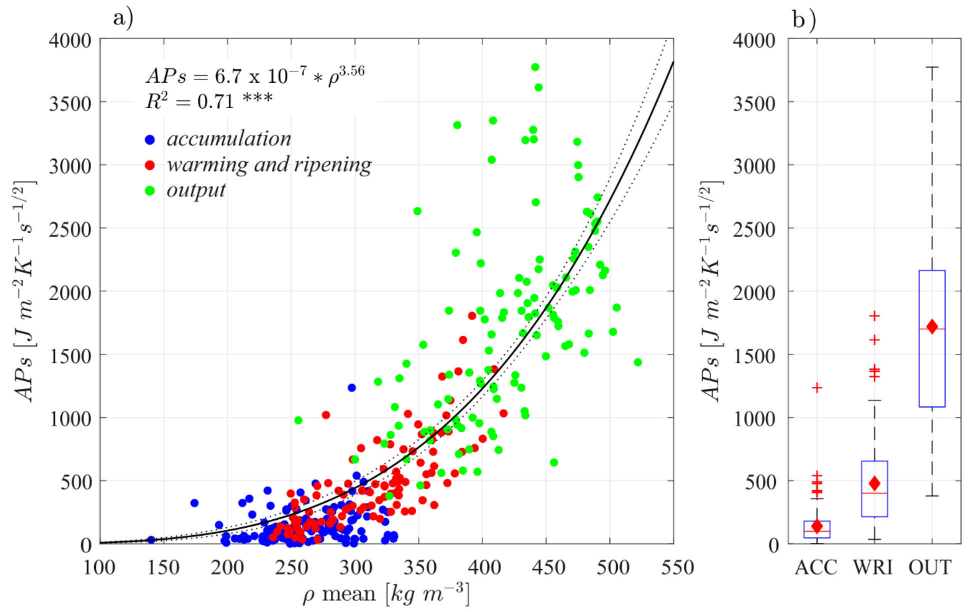
Landsat images	Manual measurements (n°)	Snow density range 30cm (Kg/m³)	Snow density range snowpack (Kg/m³)	Snow depth range (cm)
10/05/2015	3	405-532	405-532	85-150
13/04/2017	9	300-485	314-505	70-390
29/01/2019	3	212-270	212-375	40-220
16/01/2020	4	260-320	260-335	65-180
04/03/2020	3	173-300	173-390	95-155
05/04/2020	2	312-410	223-410	53-142

Snowpack development and snow density

- **Temporal analysis (example 2013-2014 season)**



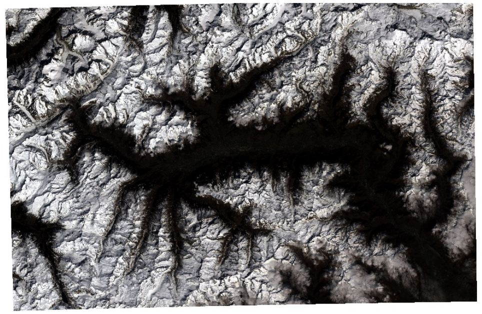


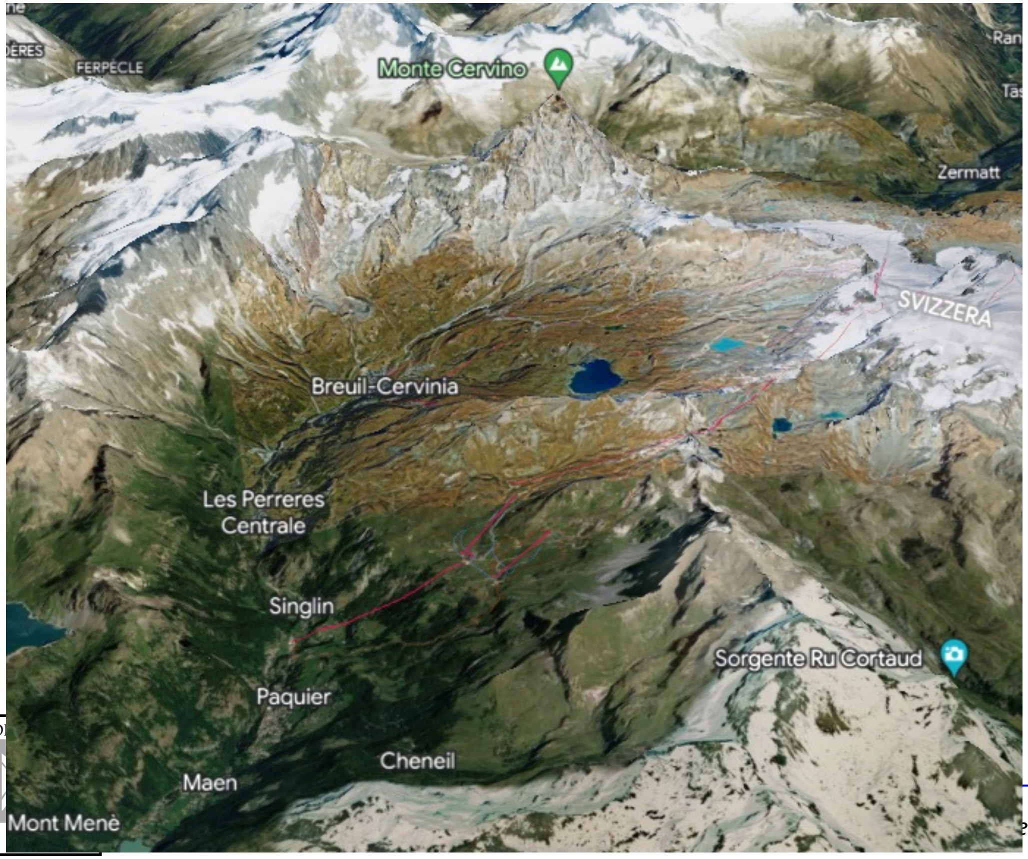


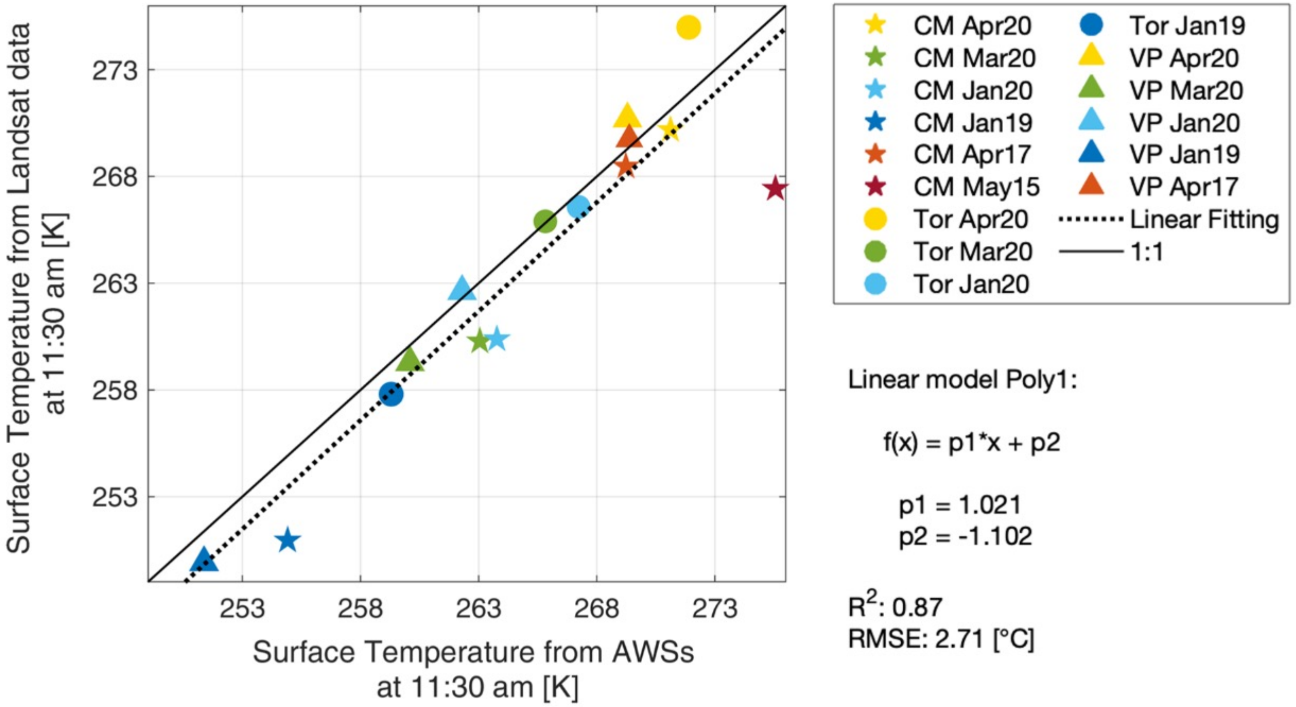
Power law relationship between AWS estimated APs and simulated snow density (all years, mean values of the whole snowpack)

Snow temperature comparison

- **Spatial analysis**





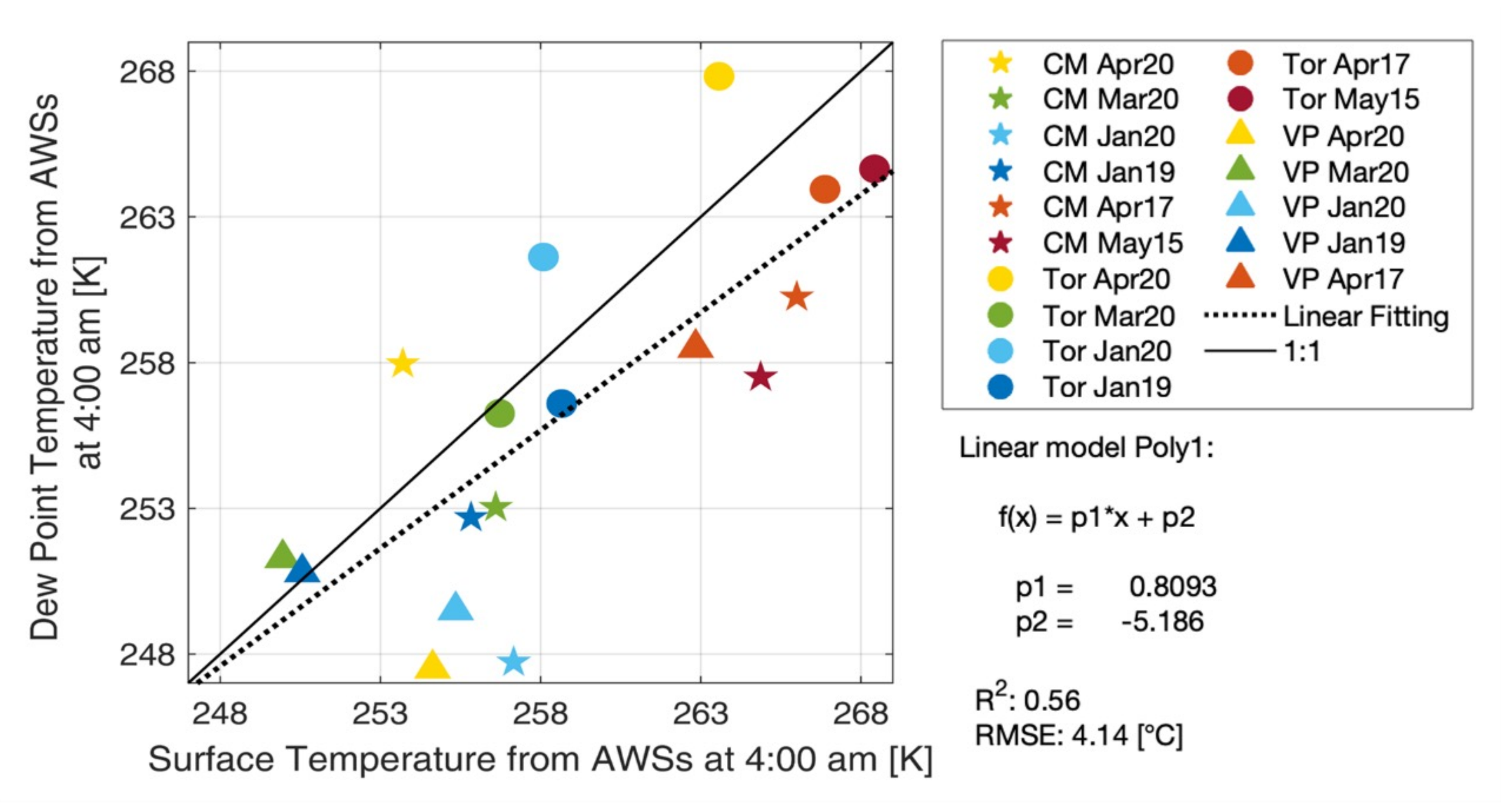


Validation of input data (midday surface temperature)

Night time surface temperature

A critical point: dew point temperature as a surrogate of night time temperature

$$T_d = \frac{c\left[\ln(RH) + \frac{bT_a}{c+T_a}\right]}{b - \ln(RH) - \frac{bT_a}{c+T_a}}$$



! Importance of night time measurements by LSTM, SBG-TIR and TRISHNA !

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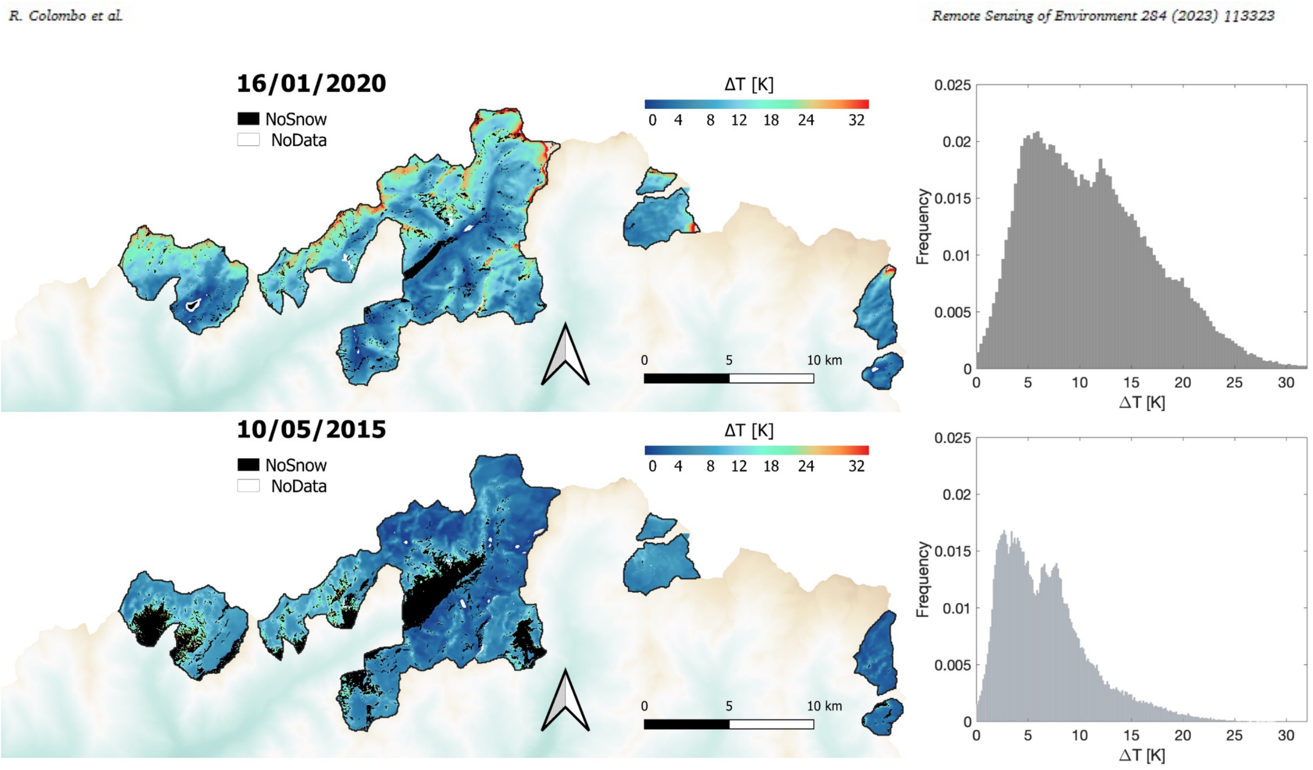
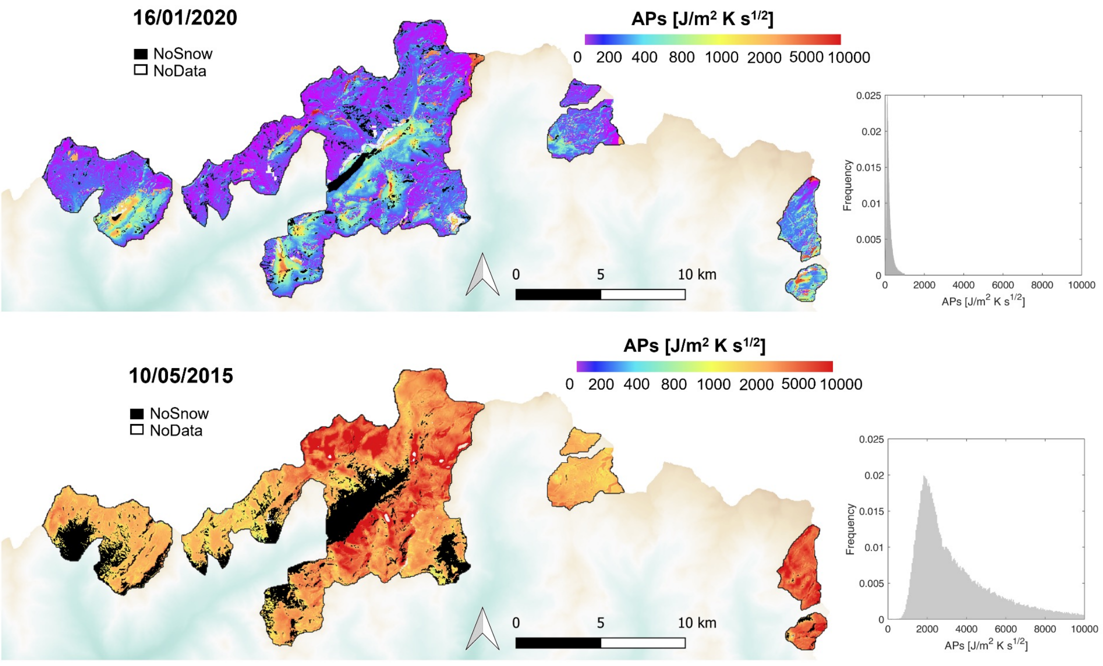
ΔTs and thermal inertia

- **Spatial analysis**



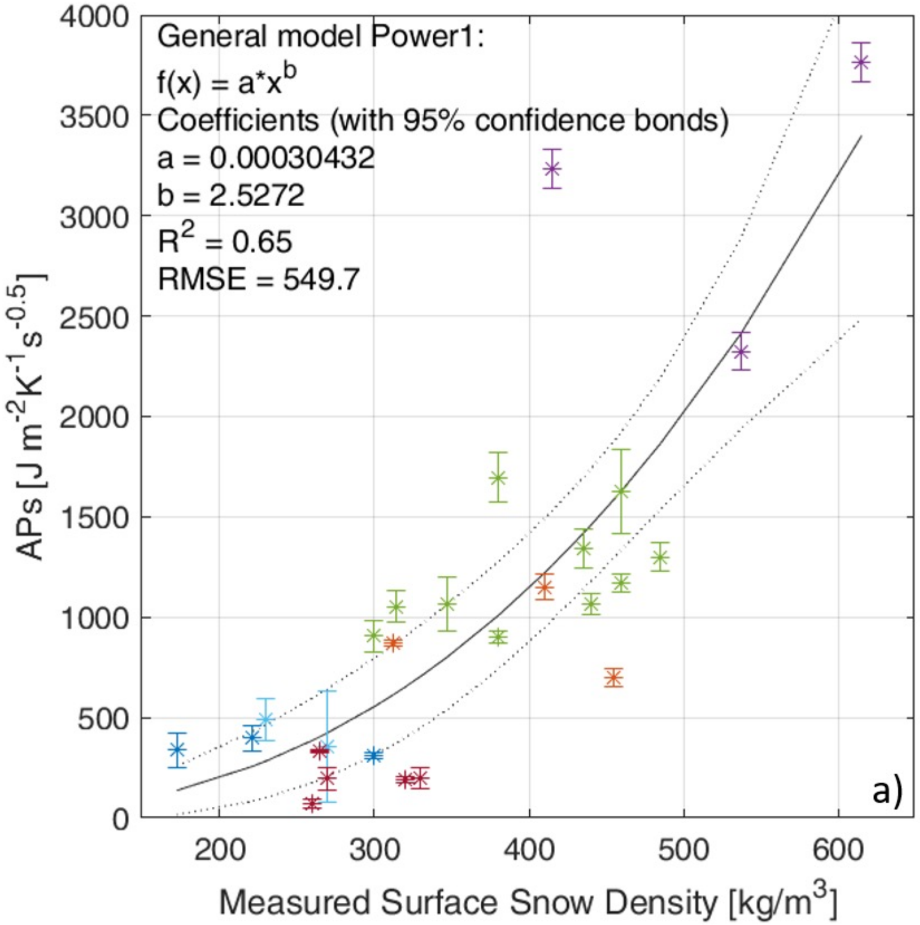


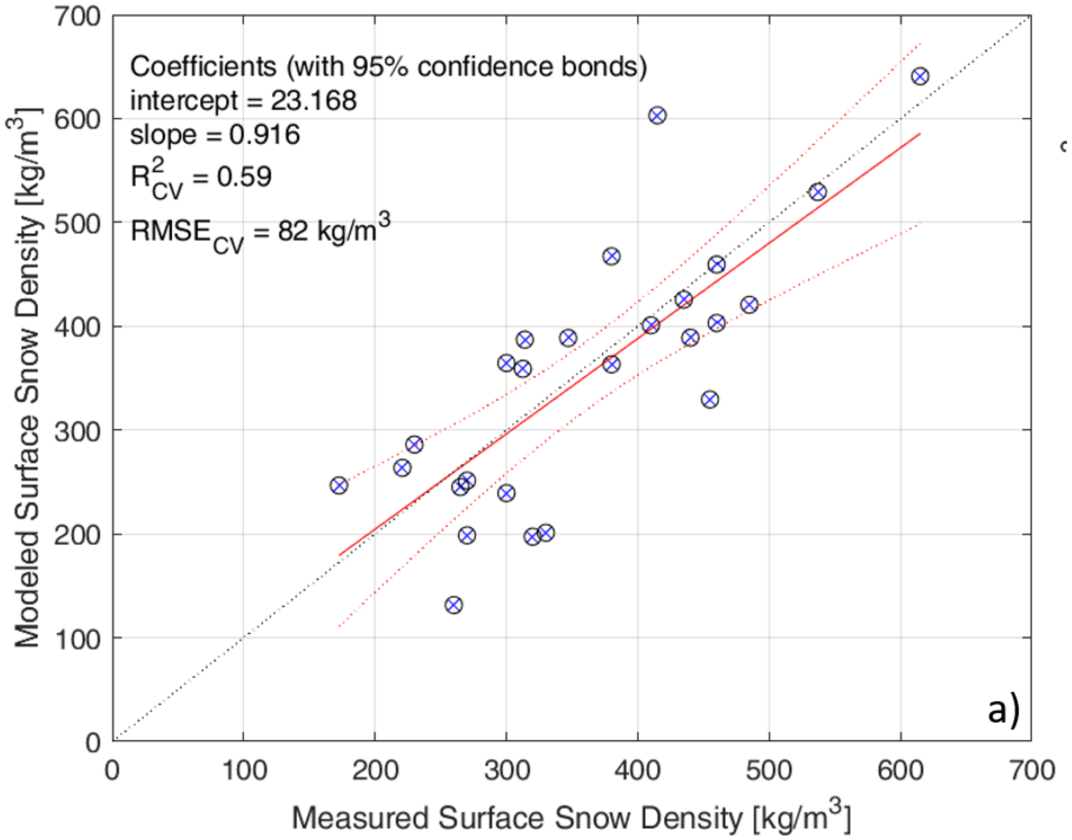
The snow surface temperature difference depends on the two selected instantaneous measurement times, meteorological conditions and heat exchanges occurring in the selected timeframe

Snowpack exhibits high spatial and temporal variability of thermal inertia. In accumulation, fresh and pristine snow, mean values are around 220 $J\ m^{-2}K^{-1}s^{-0.5}$*, while during snowmelt inertia increases up to 2000* $J\ m^{-2}K^{-1}s^{-0.5}$

Overall, ΔT values are higher in January than in May. Snow temperatures are limited by 0 °C and this explain why ΔT decreases through the season. In January, ΔT shows a higher spatial variability with values that reach up to 30 K, in some cases. The highest values seem to occur for fresh snow along the ridges, which are the first to be illuminated in the early morning. A considerable dependency on altitude and aspects can be also noted. For example, at higher altitudes, where we encounter fresh snow, the ΔT is generally higher. Spatial variability is also related to snow exposure and shadowed slopes during the satellite overpasses. These are, in general, north-facing slopes and they exhibit lower ΔT since they have received less solar radiation.

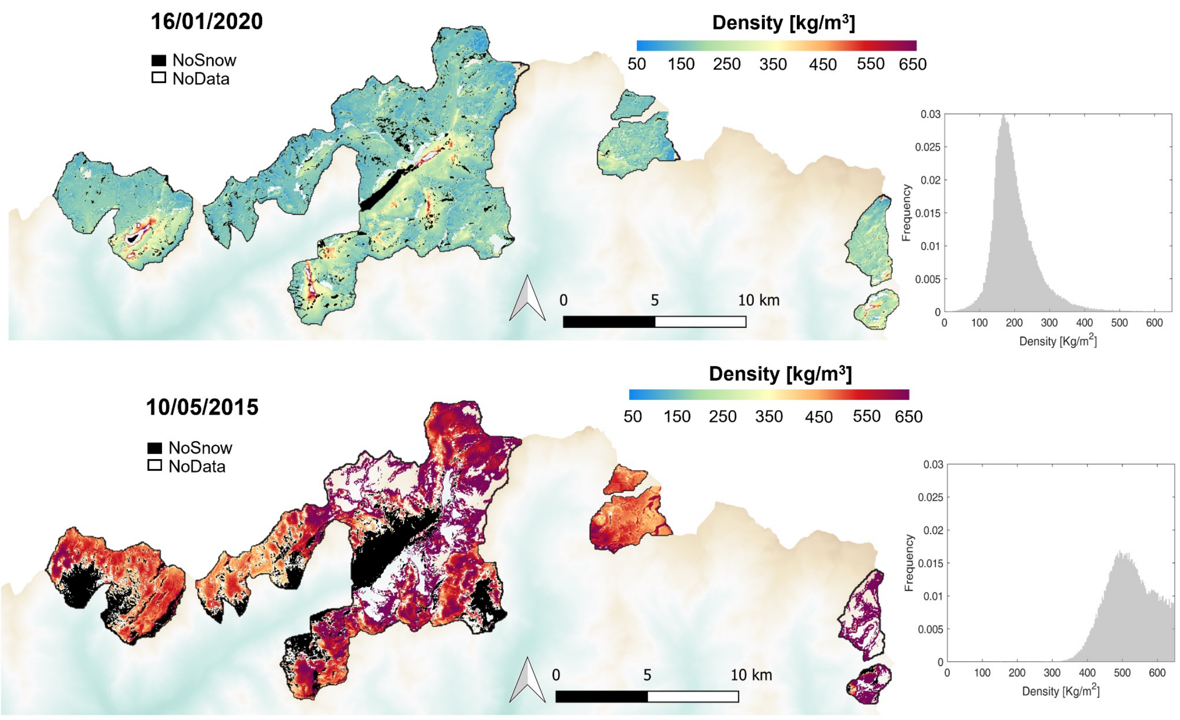
Snow density estimation from thermal inertia



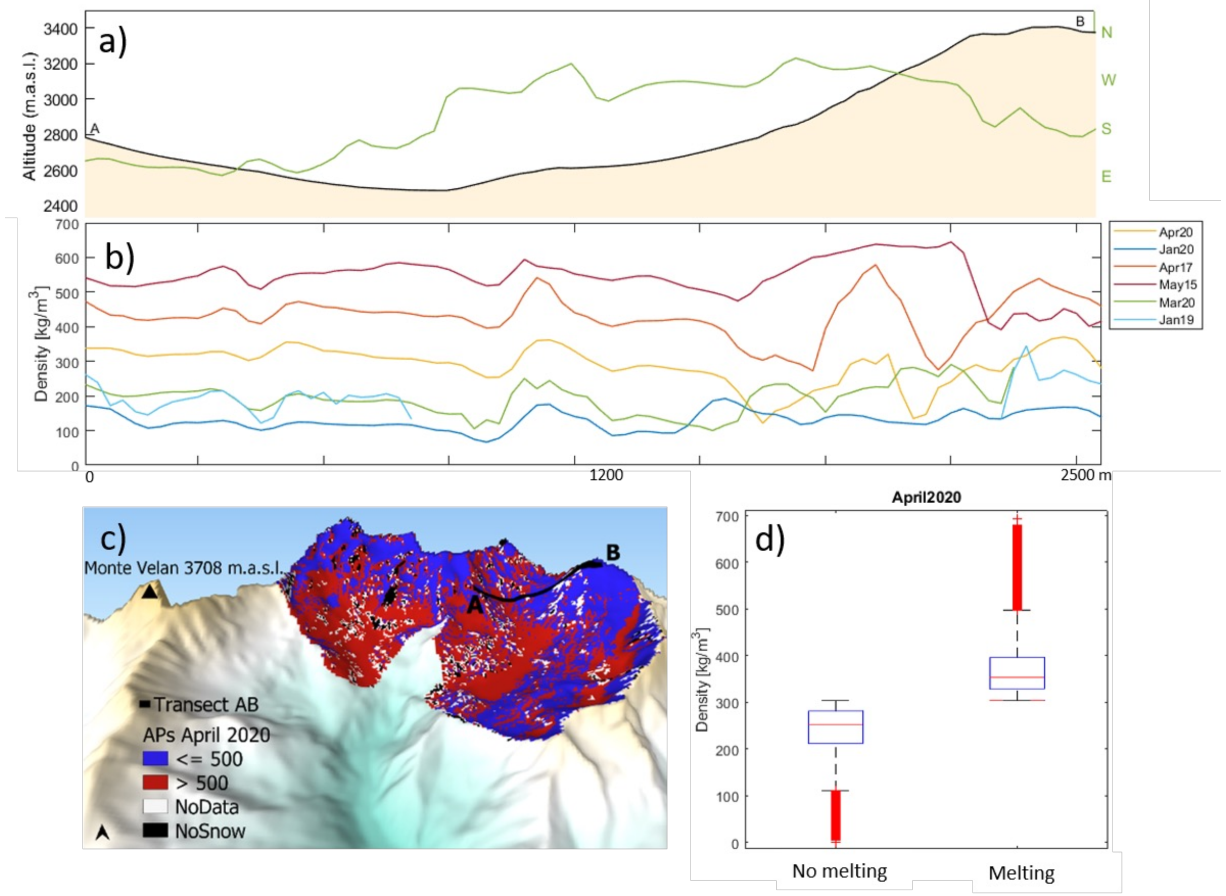


The model allows for estimation of snow density with R^2_{CV} and $RMSE_{CV}$ of 0.59 and 82 kg m^{-3}, respectively

Snow density monitoring from space



Snow density maps exhibit coherent seasonal patterns, with higher variability during the spring with respect to winter



A threshold of 500 $Jm^{-2} K^{-1}s^{-0.5}$ in the APs maps allow for distinguishing cold dry snow and melting snow

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Conclusions

1. Results provide evidence that snow thermal inertia is sensible to snowmelt phases. Snowpack exhibits high spatial and temporal variability of thermal inertia for fresh pristine snow and wet snow;

2. Average snowpack density can be estimated reasonably well from thermal inertia observations (still empirical approach). Possibility to retrieve mean and upper snowpack density with errors around 80-90 $kg\ m^{-3}$ and uncertainty of 10-15%;

3. There is potential to improve this study. There are different sources of uncertainties and further research are needed;

4. This study is the first attempt at the exploitation of thermal inertia for snow monitoring and it may contribute to open new applications in Earth Observation in the study of the cryosphere;

5. New perspectives can be provided by LSTM, SBG-TIR and TRISHNA, by exploiting their combined temporal resolution, nighttime images and a spatial resolution consistent with mountain landscape.

Thank you

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