Cosmic rays on snow: A combined analysis of fractional snow cover derived from Sentinel-2, MODIS and Cosmic Ray Neutron Sensors across Europe

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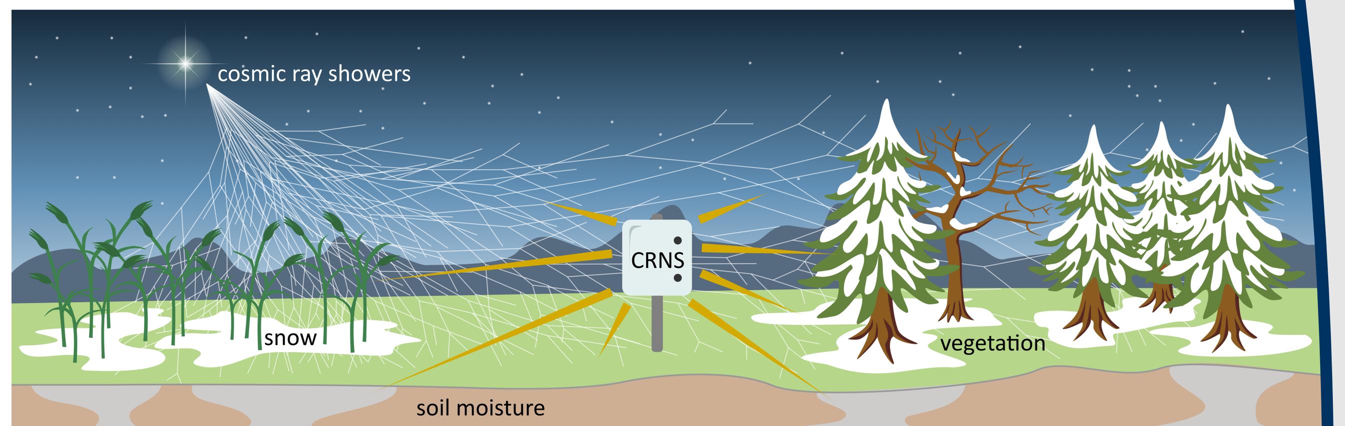
Introduction

- Cosmic Ray showers are slowed by **hydrogen sources** on the earth surface and in the atmosphere (e.g. vegetation, soil moisture and snow) to slow neutrons
- Above-ground **Cosmic Ray Neutron Sensing** (CRNS) detects the drop in fast neutron abundance when the hydrogen pool increases within a footprint of 10 to 20 hectares (e.g. through an increase in **Snow Water Equivalent** (SWE))
- CRNS holds the potential to close the gap between the coarse spatial resolution of remote sensing products and the conventional point-resolution of SWE field measurements
- This study compares the CRNS signal of **65 COSMOS-EU and Austrian stations** to the **Fractional Snow Cover** (FSC) indicated by the corresponding **Sentinel-2** (direct observation and gap-filled) and **MODIS** products



Methods

Data collection sources

- Sentinel-2 FSC On Ground (FSCOG) and Gap Filled FSC (GFSC): Copernicus data hub
- MODIS FSC: NSIDC data hub
- COSMOS-EU: Bogena et al., 2021
- Additional Austrian stations: Cosmic Sense affiliated CRNS network

CRNS & FSC data → **Classification** → **Interpretation**

Procession steps

1) The FSC-mean of all available raster points within a **250 m radius** around the specific station location has been computed (high quality raster points only)

2) Based on the **daily** FSC values, the lowest neutron count rate at no snow (FSC = 0) has been identified as 'summer' minimum

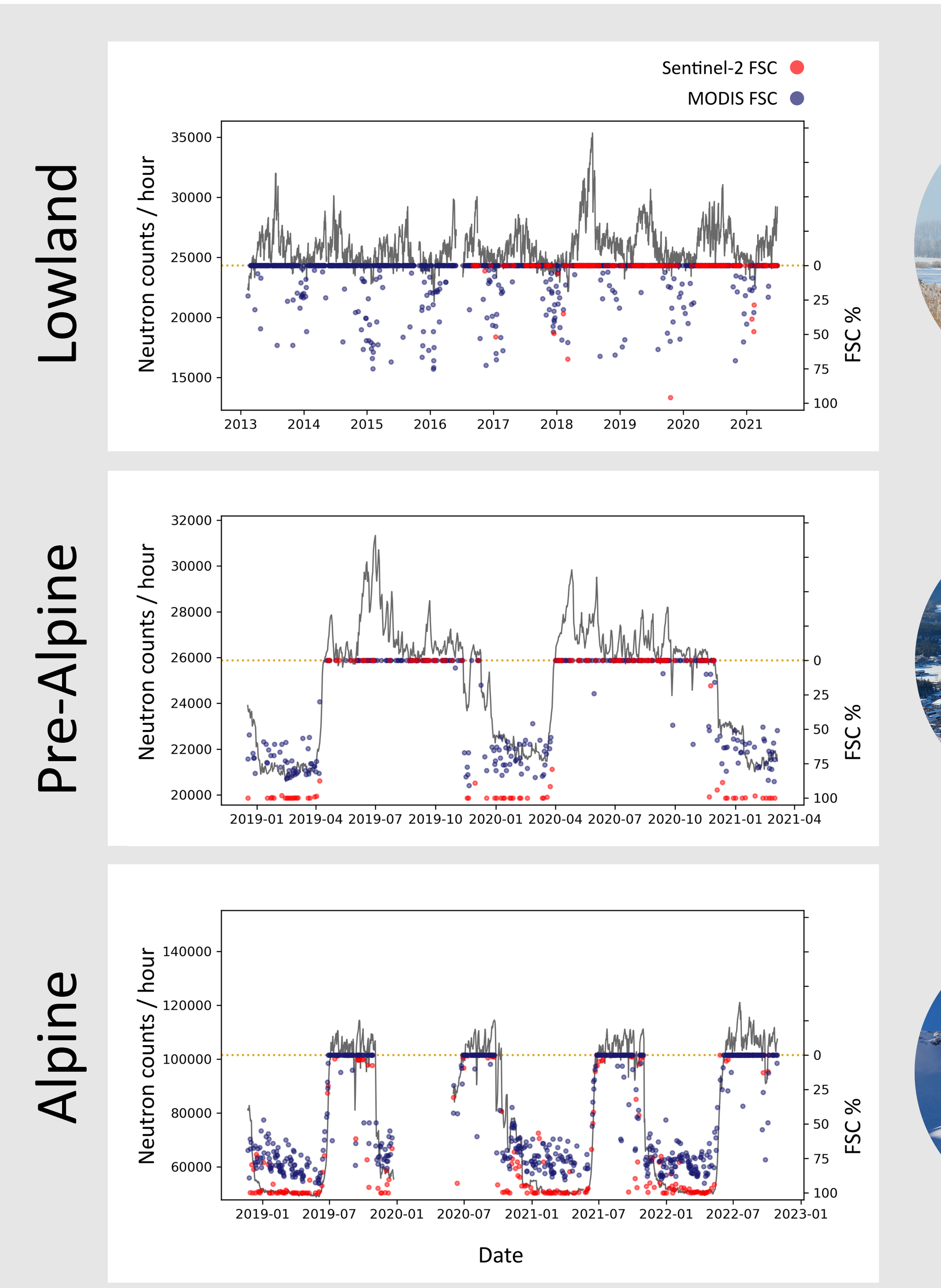
3) 'Summer' and 'winter' ranges of neutron counts have been computed based on the min and max of snow (**FSC > 0: 'winter'**) and no-snow (**FSC = 0: 'summer'**) neutron count values

4) The 'summer' and 'winter' neutron count ranges of all stations have been compared to **site specific properties**, like altitude

Remote Sensing Product Validation

- The **Sentinel-2 GFSC** product has been processed for the station Weissee (Austria) to compare against the **MODIS** and **Sentinel-2 FSCOG** products
- All remote sensing FSC values at Weisssee were compared against local **snow height** (HS) measurements and CRNS converted **SWE**

Results



- The left-hand graphs show **3 typical signal types** of lowland, pre-Alpine and Alpine stations
- The FSC = 0 line is located at the **'summer' minimum** neutron count rate

Remote Sensing FSC characteristics

- FSC estimations from Sentinel-2 and MODIS acquisitions show a striking **mismatch** at high FSC values
- FSC values are generally **higher at Alpine stations** than at Lowland stations

CRNS signal characteristics

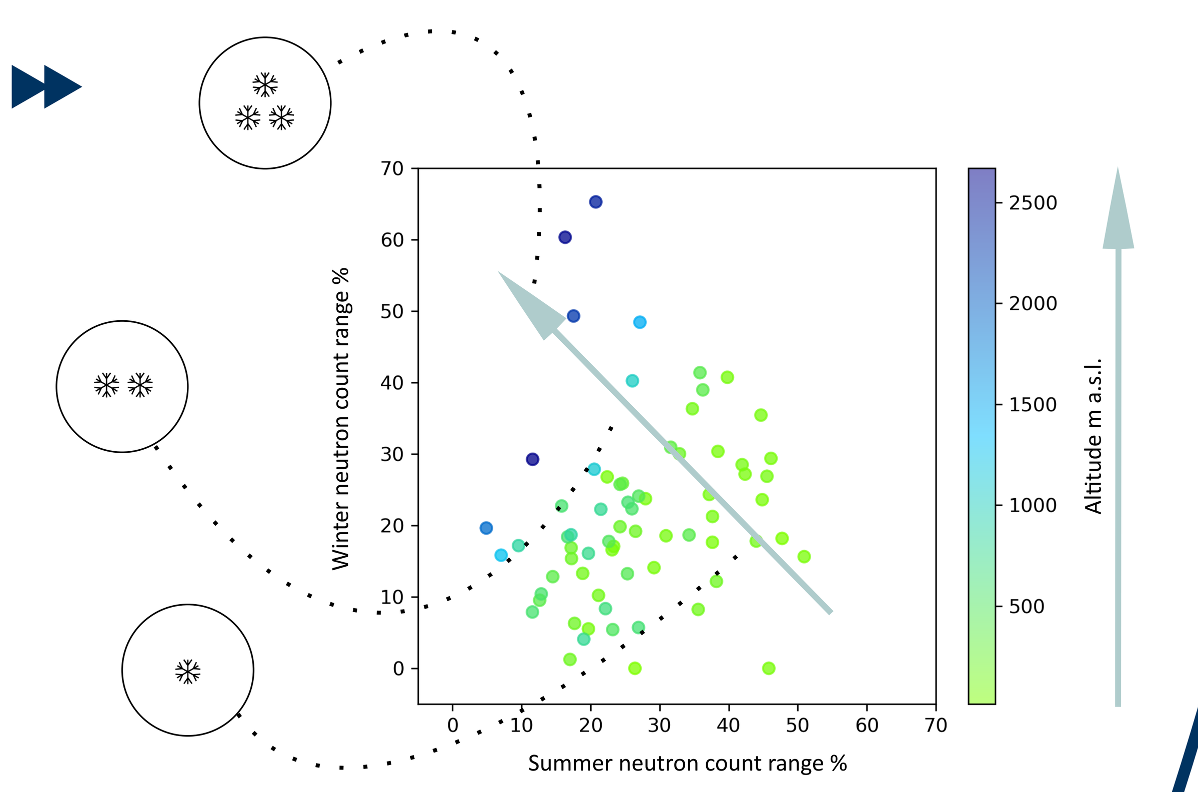
- Lowland: **high** variation of neutron count values in **'summer'**, **low** variation of neutron counts in **'winter'**
- Pre-Alpine: **high** neutron count variation in **'summer' and 'winter'**
- Alpine: **low** neutron count variation in **'summer'** and **high** neutron count variation in **'winter'**

Given station examples

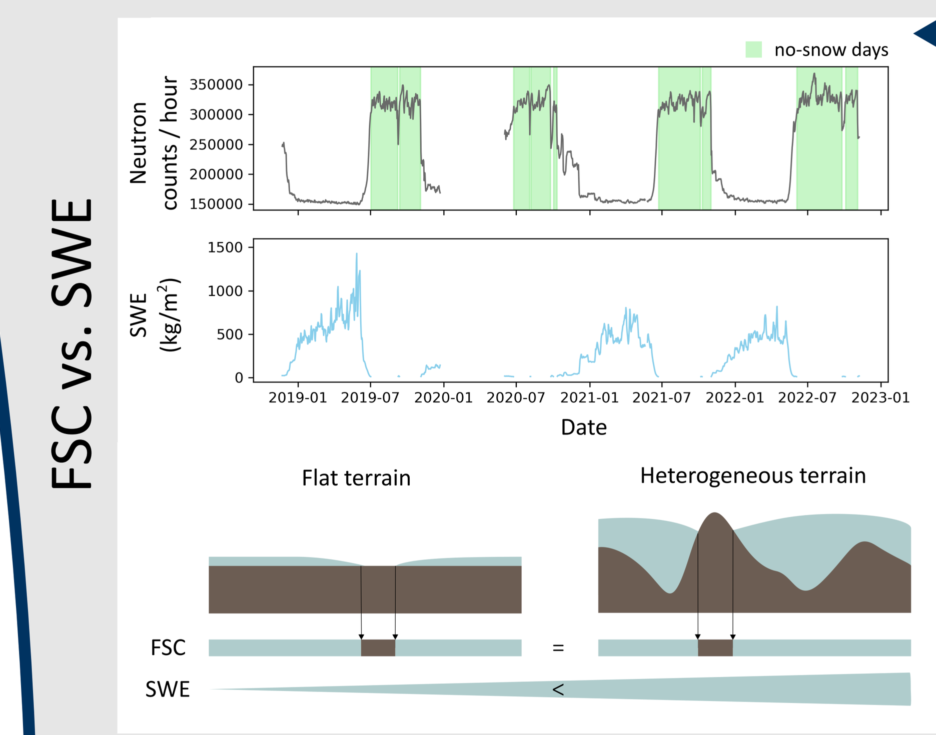
- **Lowland**: Voulund, Denmark
- **Pre-Alpine**: Leutasch, Austria
- **Alpine**: Weisssee, Austria

Correlation with altitude

- The right-hand graph contrasts the summer and winter ranges of **all 65 investigated stations**
- Results are given as the **share** of the summer and winter neutron count range in comparison to the all-year neutron count range at the corresponding station
- The range distributions show a strong **correlation with altitude**: low-altitude stations have high summer and low winter ranges, while the opposite is true for high-altitude stations

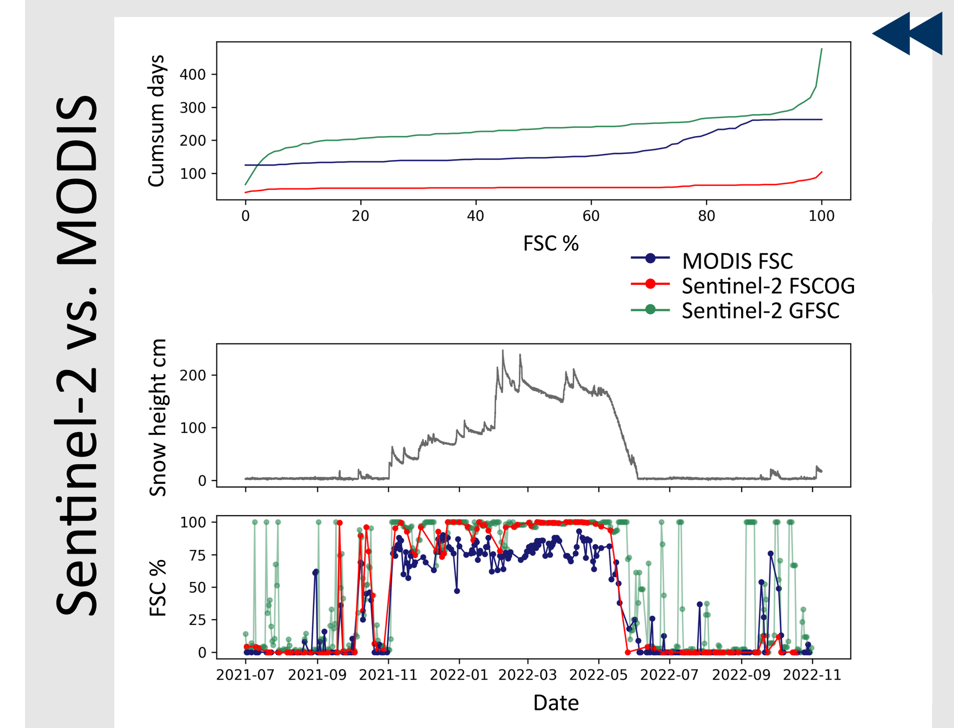


Discussion



Drawbacks of FSC

- The graphs shows the **SWE** signal, **converted** from CRNS at Weisssee
- **FSC** can be determined from **satellite** sensors, but it provides only an approximation on snow presence ('winter') and absence ('summer') and **not** on **SWE**
- The amount of **SWE at low FSC** can **vary** significantly, depending on the terrain (as illustrated in the lower figure)
- The presence of **snow-free patches** has a strong effect on the neutron count signal (Schattan et al., 2019), which calls for a correction especially in rough Alpine terrain

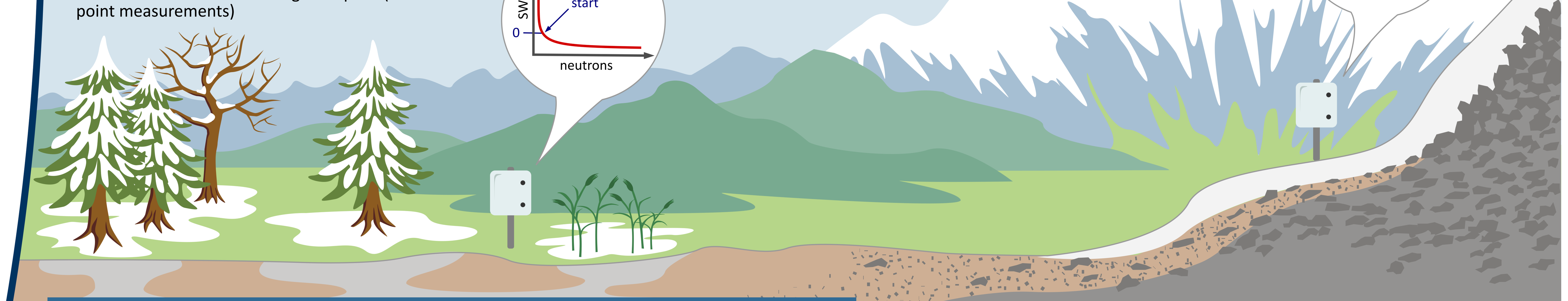


Remote Sensing products

- The graphs show the comparison between the FSC from **different remote sensing products** at Weisssee and a contrast to **snow height** (HS)
- Sentinel-2 FSCOG and MODIS show **good agreement** with the snow presence, indicated by HS
- Sentinel-2 GFSC shows **high data density** (cumsum), but many wrong FSC indications on no-snow HS days

Applicability of CRNS for SWE estimations

- **High summer** neutron count ranges at **low-altitude** stations are caused by a general **high moisture** level, sourced in additional hydrogen pools (e.g. vegetation, soil moisture, ...)
- The **hyperbolic** character of the 'neutron-count-to-SWE' **conversion function** introduces **high uncertainty** at **low-altitude** stations, where the high moisture abundance translates to low neutron counts even before an additional signal drop is initiated by snowfall
- SWE estimation from CRNS is more **suitable** at **high-altitude** stations, where general **moisture** levels are **low** and where the heterogeneous terrain and snow distribution calls for a SWE estimation within a large footprint (in contrast to point measurements)



Conclusions

- **High-altitude stations** with low general moisture abundance are **best suited** for SWE estimations with CRNS
- **Remote Sensing FSC** products can be used to **evaluate** the **suitability** of a station for SWE estimations, by determining the summer neutron count range, which is an indication for general moisture abundance and fluctuations
- Further investigations of the **effect of snow-free patches** on the neutron count signal are needed to make the range determination in heterogeneous terrain more reliable

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References: Bogena, H.R., Schrön, M., Jakobi, J., Ney, P., Zacharias, S., Andreasen, M., Baatz, R., Boorman, D., Duygu, M.B., Eguibar-Galán, M.A. and Fersch, B., 2022. COSMOS-Europe: a European network of cosmic-ray neutron soil moisture sensors. Earth System Science Data, 14(3), pp.1125-1151; **Schattan**, P., Köhli, M., Schrön, M., Baroni, G. and Oswald, S.E., 2019. Sensing area-average snow water equivalent with cosmic-ray neutrons: The influence of fractional snow cover. Water Resources Research, 55(12), pp.10796-10812; **E.U. Copernicus Land Service Information**: https://land.copernicus.eu/pan-european/biophysical-parameters/high-resolution-snow-and-ice-monitoring/snow-products/snow-cover; **NASA National Snow and Ice Data Center**: https://nsidc.org/data/modis/data (MODIS Terra & Aqua: MOD10A1.061 & MYD10A1.061)

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