Monitoring Soil Water Content by Cosmic Ray Neutron Sensing in the Tibetan Plateau

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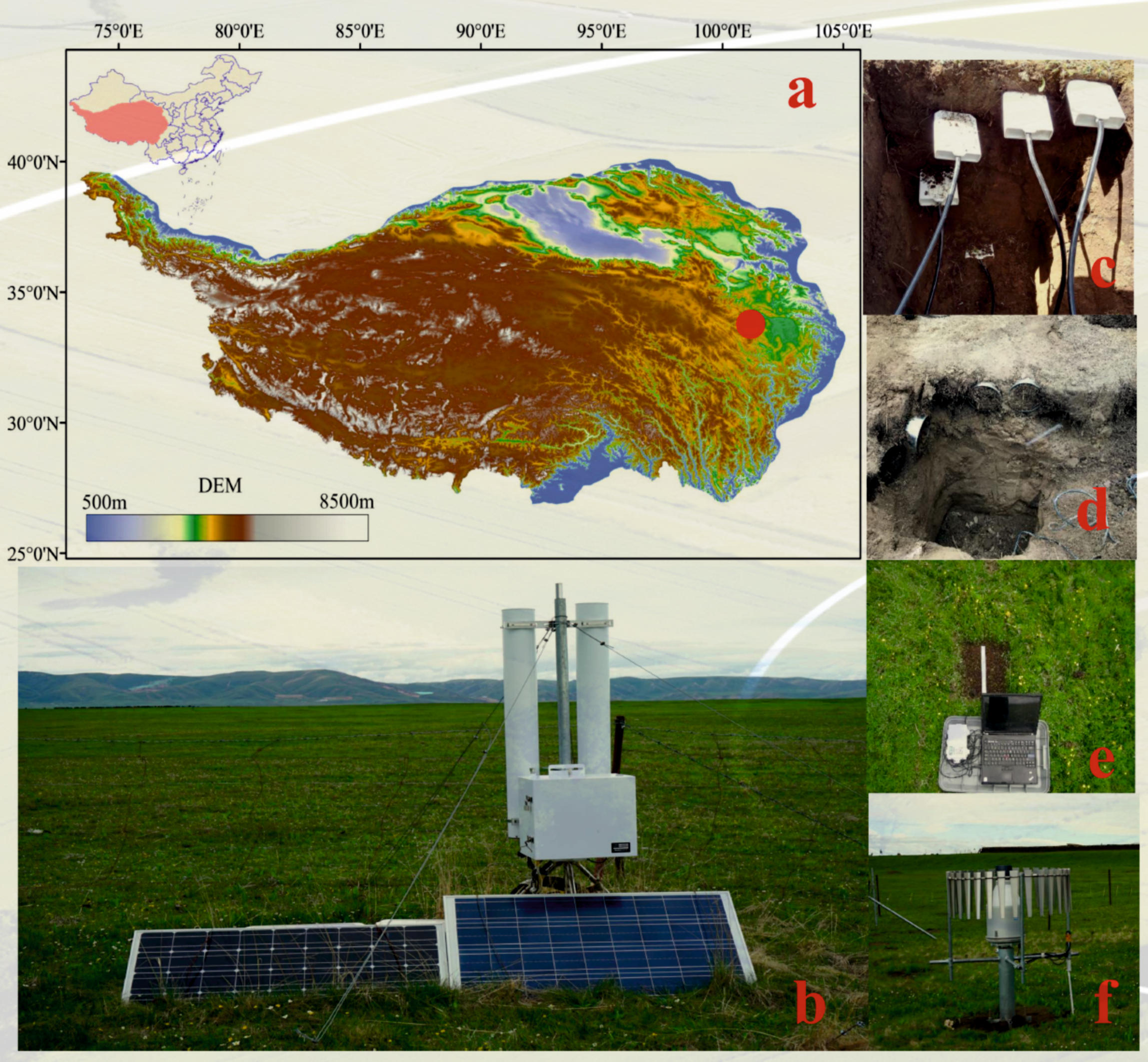
Soil moisture is one of the key variables controlling the exchanges of water and energy at the land surface. One particularly interesting climate zone is the Eastern Tibetean Plateau with its dry cold winters and wet monsoon summers at high altitudes. To better understand hydrological processes and the response of the hydrological cycle to climate change the novel method of Cosmic-Ray Neutron sensing had been tested in the northeast of the Qinghai-Tibet Plateau with a highly hetereogeneous organic soil profile. Using this technique one can relate the flux density of albedo neutrons generated in cosmic-ray induced air showers to the amount of water in the environment on the scale of several hectares. Instrumented with in-situ sensors and cosmic ray probes we discuss the effective measurement depth of CRNS retrieval and vertical weights of different layers up to 50 cm depth in this semi-humid alpine meadow. During the non-frozen period we analyzed and validated the representativeness of CRNS in an extensive comparison of in-situ data, two soil moisture retrieval algorithms and full-scale neutron Monte Carlo simulations using the transport model URANOS. As the CRNS method gains traction and evolves towards large-scale applications, the findings from this study are pivotal for the understanding of the technology and ist limitations.

Study Site

northeast of the Qinghai–Tibet Plateau



(a) The location of the cosmic-ray probe
(b) cosmic-ray probe (at the beginning of April),
(c) SWC profile (CS616 measurements),
(d) soil sampling,
(e) vegetation sampling,
(f) precipitation observation (rain gauge).

Mixing in Air

Neutrons are able to travel hundreds of meters from origin (contact with the soil) to detection.

Detection

A moderated He detector counts **low-energy** neutrons.

Sensitivity to Water

High-energy neutrons are comparatively insensitive to water. At lower energies, particularly in the **blue** domain, hydrogen can effectively moderate neutrons. **Thermal** neutrons are slow and sensitive also to other chemical compontents.

The novel method of Cosmic-ray Neutron Sensing (CRNS) allows for non-invasive soil moisture measurements at a hectometer scaled footprint. This technique relies on the measurement of neutrons originating from cosmic-ray induced air showers. The key characteristic of the method is the exceptionally high moderation strength of hydrogen. It slows down fast neutrons whereas other heavier elements independent of the chemical composition rather reflect them. The result is an inverse relation of the above-ground neutron intensity to soil moisture. Due to neutrons being transported over the air over hundreds of meters, the measurement is representative for an area on the scale of hectares. In the recent years the focus shifted to understanding signal generation by Monte-Carlo simulations for complex environmental topographies. The remarkable performance of CRNS in signal interpretation allows for a promising prospect of more comprehensive data quality.

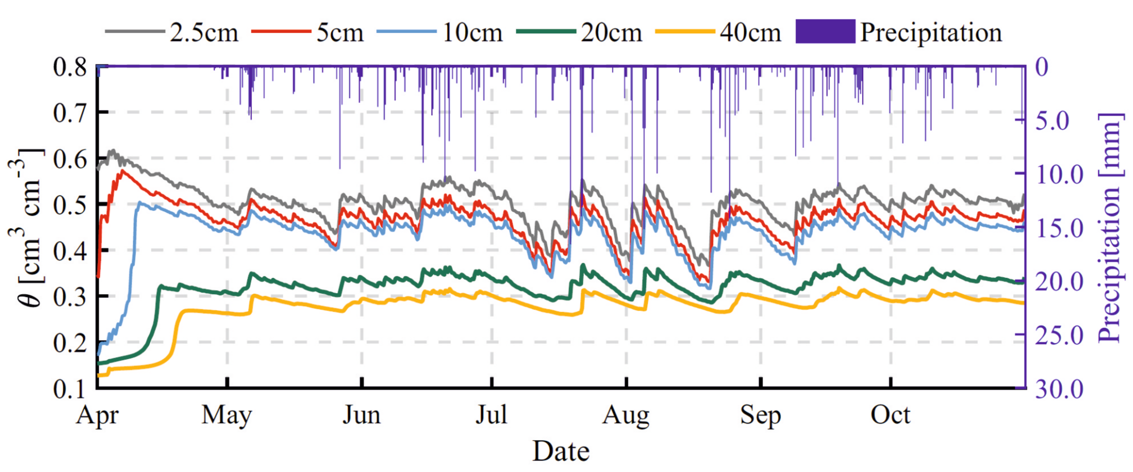
Measurement
average over
10 ha and 0.5 m depth

Integration
non-invasive sensors

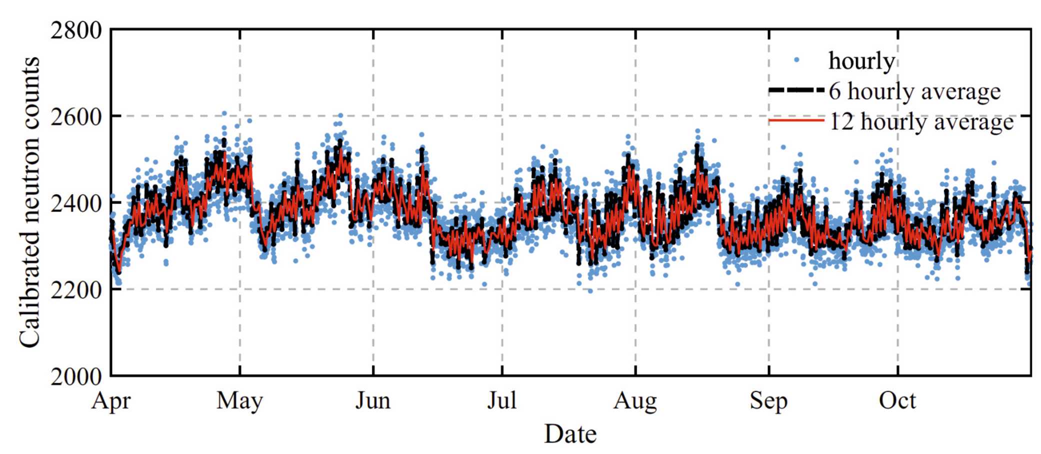
Operation
PV powered stations

Connection
real-time data transmission

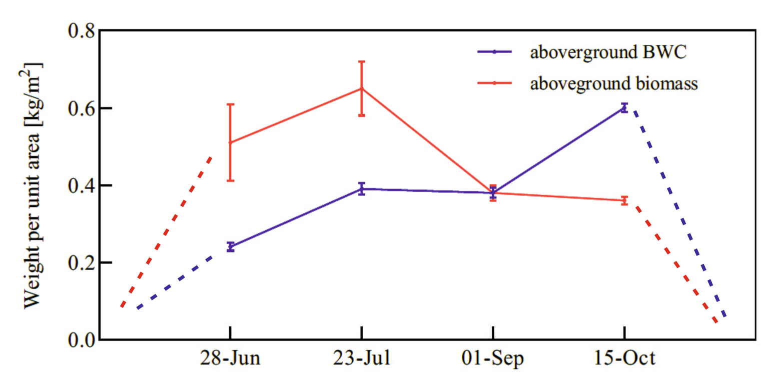
Data



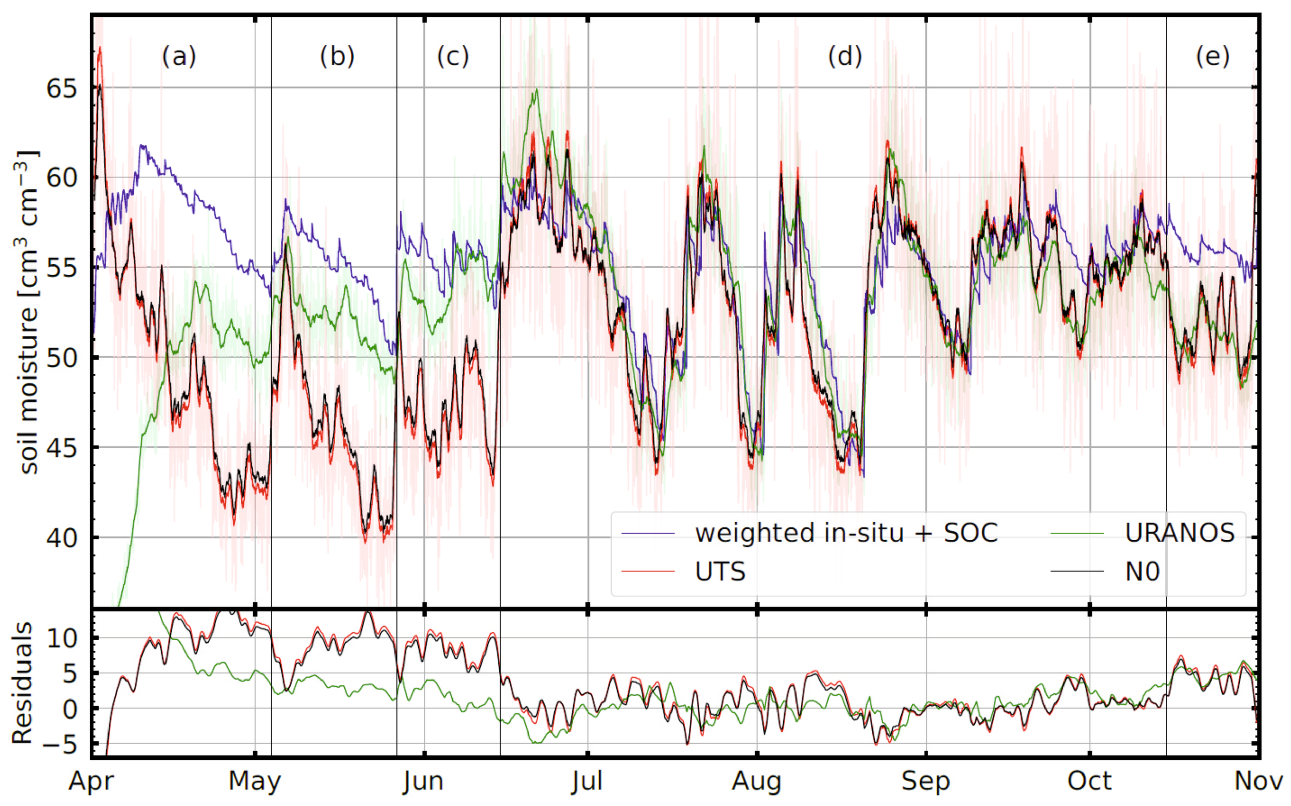
Soil layer (cm)	Bulk density (g cm^{-3})	Porosity	SOC (g g^{-1})	Clay content (%)	Textural class (USGS)
0–5	0.5	0.61	0.24	1.8	Sand
5–10	0.85	0.55	0.12	3.6	Sand
10–20	0.96	0.47	0.06	9.2	Sandy loam
20–40	1.51	0.37	0.008	17.3	Sandy loam



(Top) Time series of 6-h averaged precipitation and in situ SWC profile measurements. (Bottom) Raw and calibrated neutron count rates measured at the PAWM site from April to October 2019. The time series are hourly, 6 hourly (black line) and 12 hourly (red line).



Analysis



Comparison of weighted in situ measurements including the equivalent water of SOC in comparison to retrieved soil moisture from CRNS and the full-scale Monte Carlo simulation. The deviations of each of the methods are given compared to weighted in situ measurements (blue). All data are smoothed by a 24-h rolling mean. Periods of quantitatively distinct deviations are marked by letters. The delimiters are (a) 01.04.–04.05., (b) 04.05.–27.05., (c) 27.05.–15.06., (d) 15.06.–15.10., and (e) 15.10.–31.10.

Consistency with weighted profiles

The variations in soil water content retrieved by the UTS method were generally consistent during periods of low and high precipitation. There were obvious peaks during the study period, which coincided with periods of low precipitation and low SWC and the neutron flux was indeed negatively correlated with SWC, as expected.The CRNS SWC estimation responded to essentially all precipitation events. consistent with the on-site in-situ SWC measurements during the summer period marked by (d).

Pressure correction

$$N_p = N_{\mathrm{raw}} \cdot e^{[(P-P_0)/L]},$$

Humidity correction

$$N_{\mathrm{pih}} = N_{\mathrm{pi}} \cdot [1.0 + 0.0054 \cdot (\rho_{\mathrm{wv}} - \rho_{\mathrm{ref}})],$$

Incoming correction

$$N_{\mathrm{pi}} = N_p \cdot \left(\frac{N_{\mathrm{avg}}}{N_{\mathrm{nm}}}\right),$$

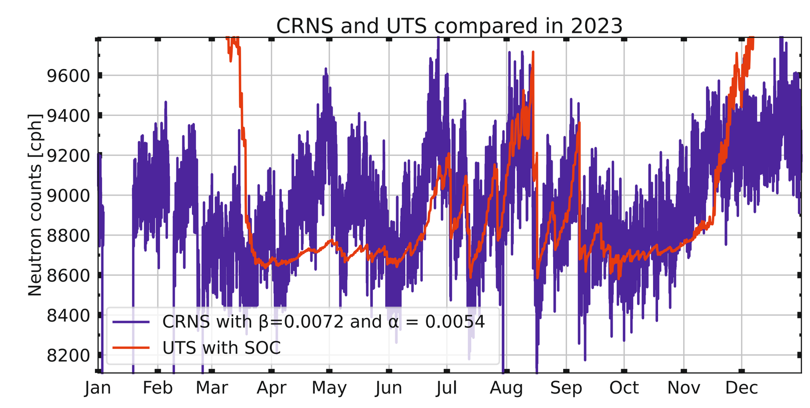
UTS soil mositure retieval

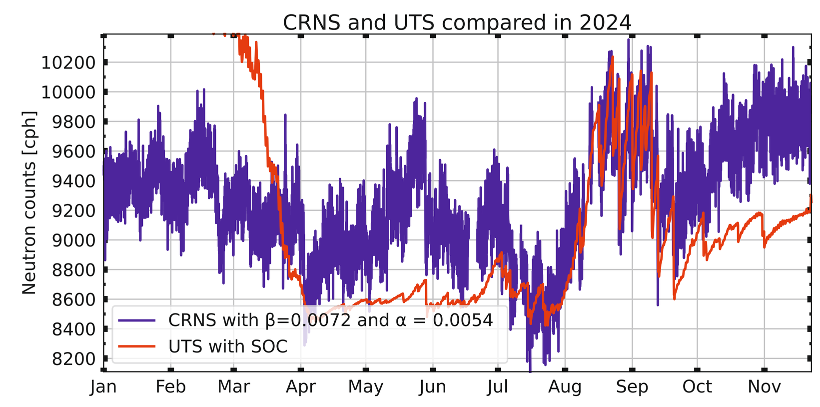
$$I(\theta, h) = N_D\left[\frac{p_1 + p_2\theta}{p_1 + \theta}(p_0 + p_6 h + p_7 h^2) + e^{-p_3\theta}(p_4 + p_5 h)\right],$$

UTS depth weighting

$$Z^* = \rho_{\mathrm{bd}}^{-1}[8.32 + 0.14\,(0.97 + e^{-r/100})]\frac{26.42 + \theta}{0.057 + \theta},$$

Questions





Time series of hourly averaged CRNS data for the following years in comparison to analytically derived CRNS counts from in-situ data. Counts are inversely related to soil moisture.

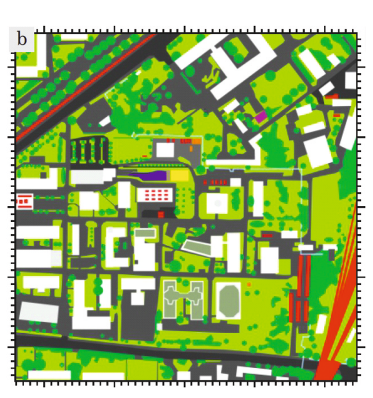
Seasonal Effects

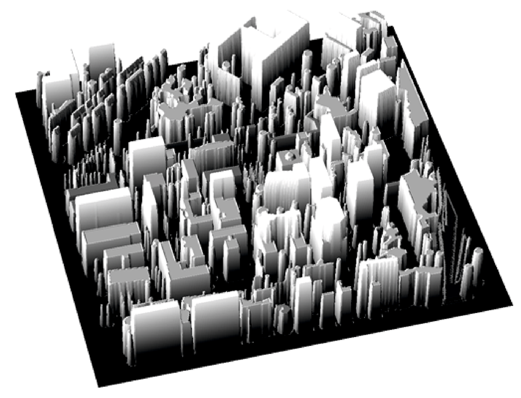
We could find a good agreement for matching the CRNS signal in summer with the in situ–derived soil moisture. At the beginning of the year and in the end we observe significant deviations. While frost and thaw can explain the offset for the very cold periods, from May to mid- June, this deviation is most likely caused by another effect. While the vegetation itself has a negligible effect on the CRNS signal, it may influence the CRNS signal in a different way. We can hypothesize that evaporation effects of the highly porous topsoil would not directly be visible even in the topmost in-situ sensor. The first layer of the ground would get significantly drier by the strong solar radiation and wind than the in-situ observations would be able to show. We tested this theory by artificially reducing the moisture in the top 2 cm. In the first drying period (a) it would need to be 30% drier than measured - a questionable large difference. For the second drying period (b), the top 2 cm would need to be 25% drier and for (c) 15% drier. The offset in soil moisture for (c) could be reasonable. URANOS simulations seem to close the gap partially, i.e., a full-scale more detailed simulation provides a more close agreement to in situ data than analytical models. This indicates a potentially stronger effect for surface-near inhomogeneities on CRNS measurements. Although the cause of this discrepancy remains open for discussion, we are able to quantify it.

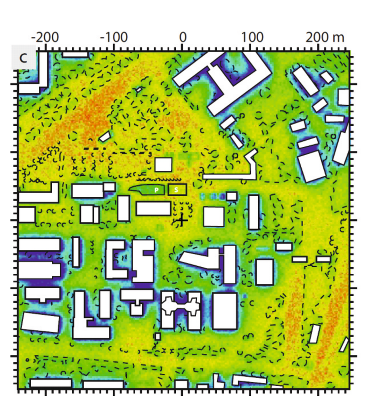
URANΦS
Cosmic-Ray Neutrons for Environmental Research

- Neutron Transport Monte Carlo Simulation
- Voxel Engine
- Ray-Casting
- Cosmic Neutron Source Option
- written in C++
- linked against ENDF data bases


topography example


simulation model


3D model



result

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