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Monitoring Environmental Water with Ground Albedo Neutrons and Correction for Incoming Cosmic Rays with Neutron Monitor Data

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M. Schrön*[1], **S. Zacharias**[1], **M. Köhli**[2], **J. Weimar**[1,3], **P. Dietrich**[1]
[1] *Helmholtz Centre for Environmental Research - UFZ, Leipzig*
[2] *Physics Institute, Heidelberg University*
[3] *Institute of Environmental Physics , Heidelberg University*
E-mail: `martin.schroen@ufz.de`

Neutron monitors on the Earth's surface are usually used to track the dynamics of incoming cosmic-ray neutrons of high energy under the assumption that local environmental conditions do not influence the highly shielded flux. Oppositely, in a recently established research field the local dynamics of environmental water is monitored by detecting low-energy cosmic-ray neutrons. Water in soil, air, snow and vegetation determines the amount of ground albedo neutrons in the sensitive energy range from 1 eV to 100 keV. Plenty of small neutron detectors have been installed on natural or agricultural sites all around the world Climate research, hydrologic models and irrigation management rely on these measurements, which represent area-average water content within tens of hectares due to the fast diffusion of neutrons in air. A major issue is the modulation of the neutron flux by the dynamics of incoming cosmic-ray neutrons. Conventionally, independent data from neutron monitors are consulted to serve as a reference for the correction of the local detectors. However, the performance of this comparative correction approach is unreliable, because it does not account for geographical displacement, different energy windows of the detectors, or potential influence of atmospheric conditions on the referenced neutron monitor. In addition, neutron monitor stations are sparse on Earth, and occasionally signals from different locations appear to be significantly inconsistent. The presentation shows how ground albedo neutrons from cosmic-rays are used in environmental research and emphasizes the need for a reliable correction for the incoming flux.

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*Speaker.

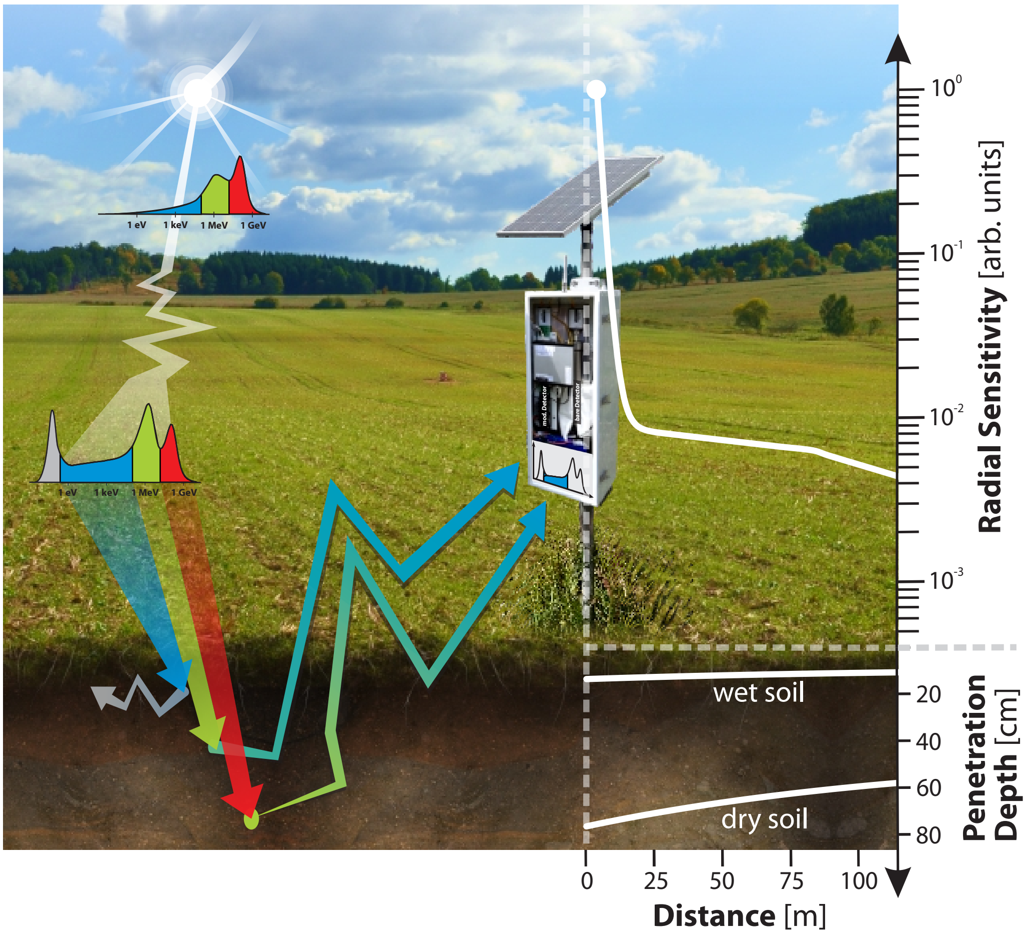

Figure 1: The method of the Cosmic-Ray Neutron Sensing (CRNS). High-energy neutrons (red) propagate through the atmosphere and generate low-energy neutrons by evaporation processes (green). The soil further slows neutrons down, especially when water is present they quickly moderate into the thermal regime (grey). Fast neutrons which are reflected from the soil travel large distances before they get detected. Most of the detected neutrons originate from the first tens of meters around the sensor and are able to penetrate the soil down to 90 cm. Calculations have been performed by the Monte Carlo neutron model URANOS [1].

1. Introduction

Neutron monitors all over the world are collecting data of incoming high-energy neutrons from cosmic-rays (see www.nmdb.eu). Local environmental effects to the incoming neutron signal can be minimized by rejecting low-energy particles with moderators like polyethylene. Therefore, neutron monitor stations can guarantee to measure only the pure incoming component of the cosmic radiation. On the other hand, cosmic-ray neutrons in the energy regime below 2 MeV are sensitive to oxygen, nitrogen, and most importantly to hydrogen. The hydrogen nucleus efficiently moderates fast neutrons down to thermal energies. Thus, a fast neutron detector would be able to monitor the variation of the neutron intensity caused by environmental water content. Knowledge about soil water content is important for efficient water management in arid regions, and a key variable for the prediction of floods and droughts with hydrological and climate models.

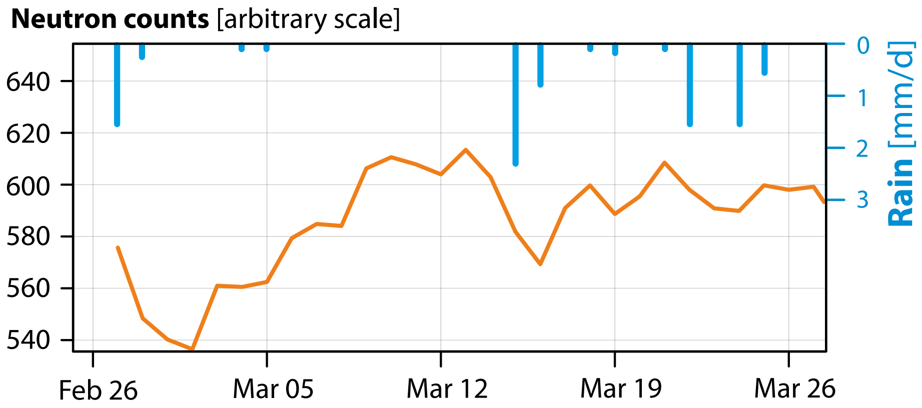

Figure 2: The relation between fast neutrons and precipitation water is demonstrated. Rain events (blue) lead to decreasing neutron intensity near the ground. In the days after rain events, the soil dries out and the neutron count rate increases.

2. Cosmic-Ray Neutron Sensing (CRNS)

The usage of neutron intensity as a proxy for snow and below-ground water content was first investigated by [2]. Then, [3] suggested to use the signal of albedo neutrons for water sensing in environmental sciences. First measurements and simulations with a detector above the ground where presented by [4], who thereby initiated intensive research in hydrological sciences. The uniqueness of this method compared to other soil moisture sensors is, that

1. neutrons penetrate the soil down to 90 cm depth, and
2. neutrons diffuse quickly in the air in distances of hundreds of meters,

as was shown by [1] using Monte Carlo simulations. Thus, a single cosmic-ray neutron sensor in the field is able to provide an area-average soil moisture signal of tens of hectares and tens of decimeters depth. Other soil moisture sensors are either unrepresentative local point measurements or only sensitive to the top-most few centimeters of the soil in a huge area.

2.1 Detection System

The so-called Cosmic-Ray Neutron Sensors are small neutron detectors developed by Hydroinnova, LLC of Albuquerque, New Mexico, USA (www.hydroinnova.com). The detector tubes contain ^{3}He or BF$_3$ gas and are either bare or shielded with 1 inch of polyethylene. The tubes, data logger and battery are mounted in a metal casing 1.5 m above the ground (see [5] for details).

2.2 Worldwide Measurement Network

The method to indirectly measure soil water content from fast neutrons is so reliable, that it lead to major investments in the research field of environmental and hydrological science. Since 2008 more than one hundred sensors have been installed in the USA, Europe, Asia, Africa and Australia (e.g. [5], [6]). Most of the data is freely available at http://cosmos.hwr.arizona.edu.

Moreover, groups in USA, Australia, and Germany acquired a mobile detector which can be carried on or in a car to perform large-scale neutron surveys (e.g. [7], [8]). Larger tubes and low

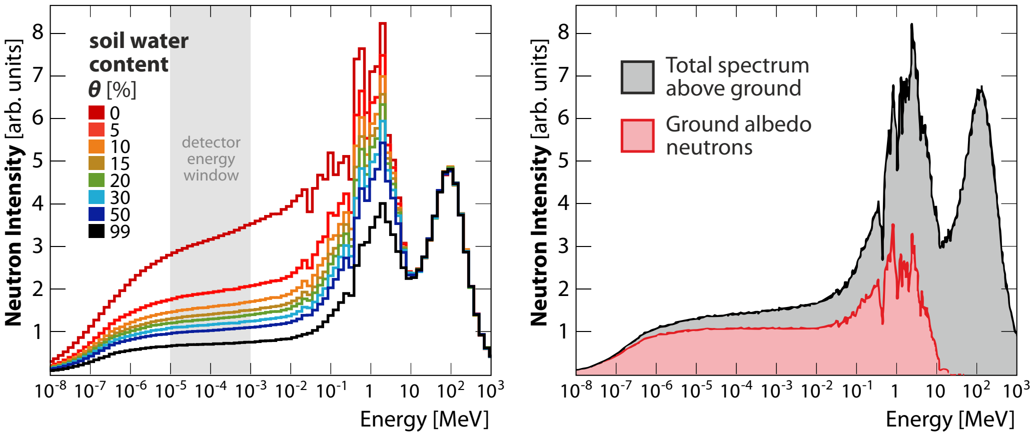

Figure 3: Left: The neutron energy spectrum near the ground is very sensitive to soil water content θ below 2 MeV and above 1 eV. Right: A significant component of the total spectrum (grey) are purely incoming neutrons that never had contact to the soil. In contrast, many neutrons have probed the soil (red) and thus carry information about its water content. Simulations have been performed with the Monte Carlo code URANOS [1]. Thermal neutrons are excluded in this simulation for the sake of computational efficiency.

driving speed allow high spatial resolution of neutron counts and thus the detection of soil moisture patterns in the investigated region. The rover can also be used to intercalibrate stationary sensors.

2.3 From Neutrons to Soil Moisture

The relation between fast neutron intensity and soil moisture is well understood. Figure 2 shows how the measured neutron abundance drops with rain events. In the following days the soil dries out which increases the neutron intensity. Three major approaches exist to determine the volume-average soil water content θ from the neutron counts N: (1) A Semi-empirical relation from [9] which depends on a single calibration parameter N_0:

$$\theta = \frac{0.0808}{N/N_0 - 0.372} - 0.115\,.$$

(2) The universal calibration function by [10], where exact estimations of every hydrogen pool in the surrounding is taken into account and a scaling parameter N_s is required to condition the neutron count rate over pure water. And (3) the analytical neutron-prediction model COSMIC by [11] which can run in inverse mode and accounts for variable water content in different soil layers. Depending on the individual application, each of these approaches has its advantages according to an extensive comparison study performed by [12].

3. Correction for other Influences on the Signal

The neutron intensity, however, is not only dependent on soil moisture. Other hydrogen sources in the environment as well as temporal variations of the atmosphere and incoming radiation have to be taken into account.

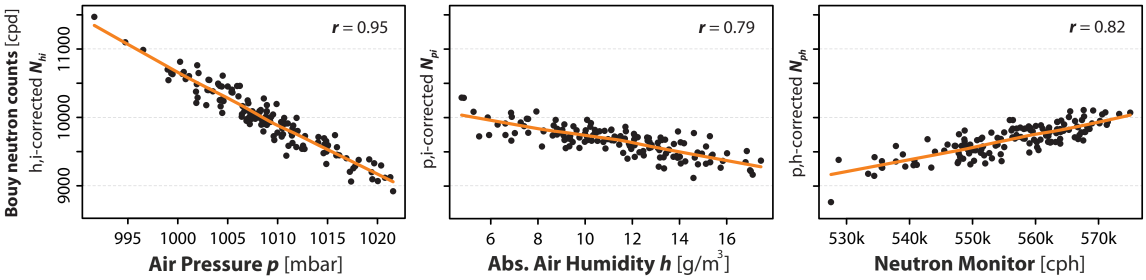

Figure 4: The signal of the CRNS low-energy detector shows clear correlations to air pressure p, air humidity h, and incoming radiation i, when corrected for the others, respectively.

3.1 Hydrogen Pools in the Soil and Vegetation

The soil can store hydrogen in many different forms of appearance. To take all of them into account, a simple approach introduced by [13] splits the total measured variable θ into three components: mobile accessable soil water θ_{sm} (the variable of interest), bound lattice water θ_{lw}, and hydrogen from organic material θ_{org}:

$$\theta = \theta_{\text{sm}} + \theta_{\text{lw}} + \theta_{\text{org}} \,,$$

where θ_{lw} and θ_{org} are to be determined independently. Vegetation stores a variable amount of water and it contains hydrogen in the organic material. Recent studies investigated the effect of crop and forest biomass by scaling the neutron counts with an estimation of the biomass water equivalent ([14], [15]).

3.2 Barometric Effect and Water Vapor

As the cosmic-ray shower passes the atmosphere, the intensity of the particles decreases according to the density profile of the air. The correction for temporal variations of the corresponding air pressure p is similar to the method applied by neutron monitors using the barometric coefficient β ([16]):

$$N_p = N \cdot e^{\beta(p - p_{\text{ref}})} \,.$$

Water vapor in the air needs to be treated separately, because the high cross-section of hydrogen contributes much more to neutron moderation than its mere mass. [17] investigated the effect of atmospheric water on low-energy neutrons with Monte-Carlo simulations. Knowing the absolute humidity of air near the surface, h, the correction is then given by:

$$N_h = N \cdot (1 + 0.0054(h - h_{\text{ref}})) \,.$$

3.3 Incoming Cosmic-Rays

Measurements by neutron monitors are important, because they are independent of environmental conditions and can be related to the pure incoming radiation only. The data is thus used to correct the incoming modulation in the water-dependent neutron signal of cosmic-ray neutron sensors.

The conventional method to remove the incoming variation is simply a relative scaling of the neutron monitor count rate M. However, other suggestions involve a rigidity-dependent rescaling with the factor g:

$$N_{\mathrm{i}}(g) = N \cdot \left(1 + g\left(\frac{M_{\mathrm{ref}}}{M} - 1\right)\right), \quad \text{or} \quad N_{\mathrm{i}}(1) = N \cdot \frac{M_{\mathrm{ref}}}{M},$$

where $g = 1 - 0.075(R - R_{\mathrm{NM}})$, R is the cutoff rigidity at the CRNS site, and R_{NM} is the cutoff rigidity at the neutron monitor station used ([5], [6]).

4. Residual Variations

The choice of the correction data has significant influence to soil moisture prediction from cosmic-ray neutron sensors. Therefore, a clarification is needed whether and how low-energy neutron signals can be corrected with the help of neutron monitor data.

4.1 Is the Incoming Correction Correct?

The correction with incoming radiation, N_{i}, assumes that the variation of N is the same as M in relative terms. However, cosmic-ray neutron sensors and neutron monitors measure completely different neutron energies. For example, it is possible that incoming cosmic-ray variations are only visible in the low-energy component (seen by the cosmic-ray neutron sensor), but have no or non-linear effect on high-energy neutrons (seen by the neutron monitor).

To test this hypothesis, we deployed the CRNS detector on a bouy in a lake. The surrounding water makes sure that no unknown changes of other hydrogen pools influence the signal. After the described corrections for air pressure and air humidity have been applied, the signal should be dependent on incoming variations only. However, in Fig 5 deviations to the different neutron monitors are obvious and beyond the counting error (grey).

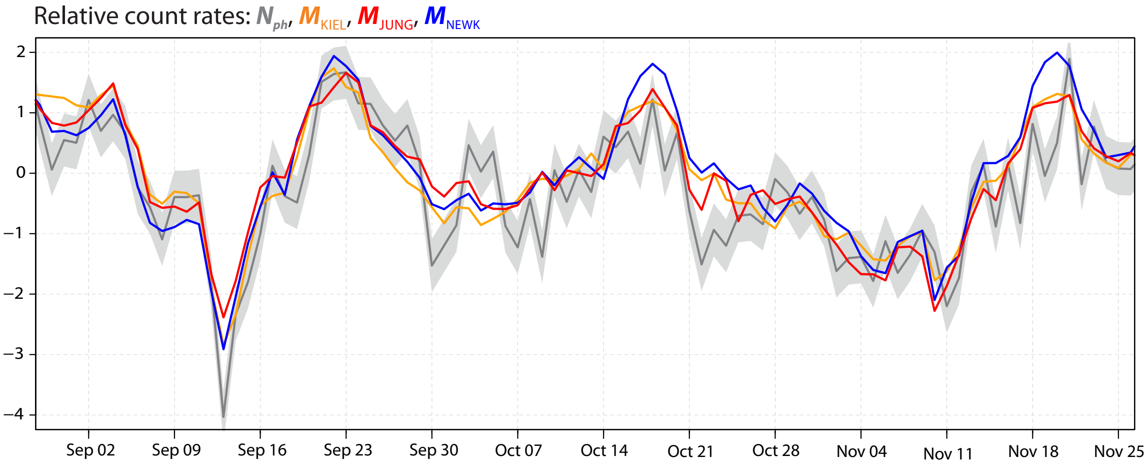

Figure 5: Neutron counts from a low-energy detector on a lake (dark grey, statistical error σ_{stat}, grey), corrected for air pressure and air humidity. The relative count rates of three different neutron monitors in Kiel (orange), Jungfraujoch (red) and Newark (blue) demonstrate: (1) the three monitors exhibit differences among each other, and (2) residuals to the bouy data are significant as their standard deviations are $\sigma_{\mathrm{res}} \approx 1.4\sigma_{\mathrm{stat}}$. The latter indicates that some effects from incoming radiation are still unrecognized.

4.2 Is the Choice of the NM Station Appropriate?

According to [18] the cutoff rigidity at the sensor location is 3.01 GV, while nmdb.eu shows 2.36 GV, 2.40 GV and 4.49 GV at neutron monitor stations Kiel, Newark, and Jungfraujoch, respectively. None of these stations fit perfectly to our site, but even Kiel and Newark show clear features of deviation. Figure 5 also demonstrates that signal correction would be sensitive to the chosen NM station, even when stations are located at similar rigidities. Differences in neutron counts indicate that potential effects exist that were not corrected, e.g. east-west anisotropy, local weather conditions, snow accumulation, or detector effects like temperature or moderation properties.

5. Conclusion

The method of environmental water sensing with cosmic-ray neutrons relies on the data from neutron monitors to provide the pure incoming component of the cosmic-ray neutron radiation. However, neutron monitor stations deliver different results at comparable rigidities. Furthermore, the energy windows of both detector systems are completely different. Is it possible to relate both intensities by a simple relative relation? We do not know yet whether changes in the incoming radiation are constant throughout the energy spectrum. Experiments with a cosmic-ray neutron sensor on a lake demonstrate that the low-energy signal shows features which might be related to incoming neutrons unrecognized by neutron monitors. A potential energy-dependent correction function from neutron monitors to cosmic-ray sensors needs to be discussed with respect to these findings.

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