6th international COSMOS workshop

Heidelberg University

October 8th - 10th, 2020

TOPICS

Fields of CRNS applications

Improved understanding of the signal

Integration of CRNS with hydrological modeling

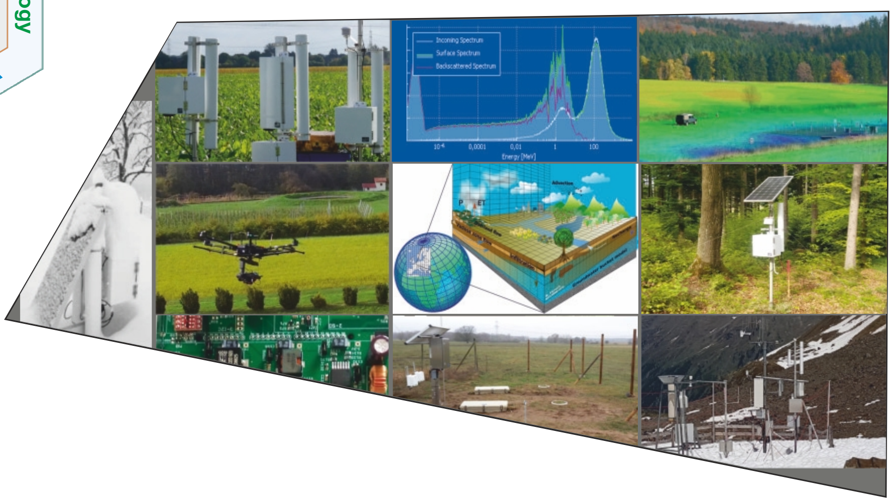
Cosmic-ray neutron sensing and lessons from applications

Development of a comprehensive strategy for CRNS worldwide

Design and improvement of neutron detectors

National and local COSMOS networks

Links to other communities



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Sascha Oswald (University of Potsdam)

Ulrich Schmdit (Heidelberg University)

Marek Zreda (University of Arizona)

Gold Sponsor

Quaesta Instruments is proud to have served the CRNS community since 2008. We are looking forward to learning of your recent progresses made in this continually blossoming field. Have a great Workshop!

Silver Sponsor

StyX Neutronica is a Heidelberg University startup company. Our focus is set to CRNS instruments based on boron-lined detectors as an inexpensive alternative to current systems. We appreciate your interest in working with us.

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CRNS Networks I Chair: H. Bogena

9:40

Cosmic Sense – a joint initiative engaging in interdisciplinary research on hydrological applications of cosmic-ray neutron sensing and its methodological improvements

S. Oswald [1], *Cosmic Sense - Consortium* [2]

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[2] *research unit Cosmic Sense, FOR 2694, www.uni-potsdam.de/en/cosmicsense/people/*

Soil moisture assessment is the main objective of Cosmic Sense as a research unit, in combination of field measurements and improvements of concepts, methods and equipment. This presentation will give an overview of the overarching objectives and methodological approaches and summarize the achievements and difficulties encountered so far.

A special focus of the research unit are joint field campaigns of about two months' duration combining devices and methods around cosmic-ray neutron sensing at particular field sites. The first one took place in summer 2019 in a small pre-alpine catchment in Bavaria, for example combining up to 25 cosmic-ray neutron sensing probes; while the second one is located in a low mountain range in western Germany and is on-going at the time of the Cosmos workshop 2020. Also, a densely-spaced cluster of cosmic-ray neutron sensing probes is operated for a longer period of time at a test site close to Potsdam.

Some highlights of the improvements and insights achieved will be indicated. Also, snapshots of special developments and ideas for new applications will be presented. The talk will close with a brief outlook on the next steps and on open questions that will have to be addressed.

10:10

An update from down-under – CosmOz: The Australian cosmic-ray soil moisture monitoring network

D. McJannet, A. Hawdon, M. Stenson, A. Sommer

CSIRO, GPO Box 2583, Brisbane, QLD, Australia

This presentation will provide an update on the state of play of the Australian cosmic-ray soil moisture monitoring network which is known as CosmOz. In recent years, research activity within the CosmOz network has been restricted due to lack of funds but recent investment from the Terrestrial Ecosystem Research Network (TERN) has reinvigorated the science in this space. TERN has an aim of monitoring terrestrial ecosystem attributes over time and providing the data in open access format. The new investment is facilitating an expansion to the existing network from 14 to 22 sensors and has also funded the development of a new data delivery system. This presentation will introduce the capabilities of the new data delivery portal with the aim of sparking discussions around the potential for a unified global approach to data delivery. The CosmOz network has now been established for 10 years and this presentation will look back over time to see how the systems have performed through droughts, floods, fires and cyclones. Finally, we will delve into the literature to reveal where the key areas of uptake of the cosmic-ray soil moisture data have been.

From above: Cosmic Ray Primaries and Principles — Chair: M. Schrön

10:40

Space Weather and its impact on the Earth's atmospheres

K. Herbst

Christian-Albrechts-Universität zu Kiel, Leibnizstr. 11, 24118 Kiel, Germany

It is commonly accepted that the terrestrial climate and chemistry is not only determined by anthropogenic influences but also by external parameters. The evidence for these influences derives from numerous studies revealing to what extent, in addition to astronomical causes, solar radiation and energetic particles, particularly cosmic rays, correlate with terrestrial observables, like, for example, the count rates of Neutron Monitors or the production of cosmogenic nuclides. However, determining whether solar radiation or cosmic rays are the primary agents regarding external climate driving requires quantitative modeling of all related processes. This talk will focus on the cosmic-ray transport from the interstellar medium to the Earth and the transport and interaction of cosmic rays with the Earth's magnetosphere and atmosphere.

11:00

The not so standard Neutron Monitor

C. Steigies [1], *C. Sarlanis* [2], *A. Papaioannou* [3], *G. Vasalos* [3]

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Neutron Monitors (NM) are standardized ground-based cosmic ray detectors. The IGY type has been in use since the International Geophysical Year 1957. In 1964 it has been succeeded by the NM64, which provides better count-rate statistics. Since the beginning, NMs deliver hourly count-rates to the World Data Center for Cosmic Rays (WDC-C) in a standardized format. With the creation of NMDB also a standard format for high-resolution data has been established. However, the data processing of NMs, that is the determination of count-rates of the whole monitor (which consists of typically 18 individual counter tubes) is not standardized. Single tubes may produce errors (spikes, dropouts, drifts, snow or wind effect) which deteriorate the high-precision measurement if this data is not properly corrected. We will present different types of measurement errors and a software package (PHENOMENON: PytHon corrEctioN algOrithMs for nEutroN mONitors) that we are creating as a possible standard data processing tool for all NM stations.

CRNS data: error estimation and combination — Chair: U. Schmidt

11:40

Error estimation for soil moisture measurements with cosmic-ray neutron sensing and implications for rover surveys

J. Jakobi [1], *J. A. Huisman* [1], *M. Schrön* [2], *J. E. Fiedler* [1], *C. Brogi* [1], *H. Vereecken* [1], *H. Bogena* [1]

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The cosmic ray neutron (CRN) probe is a non-invasive device to measure soil moisture at the field scale. This instrument relies on the inverse correlation between aboveground epithermal neutron intensity (1eV – 100 keV) and environmental water content. The measurement uncertainty of the neutron detector follows Poisson statistics and thus increases with decreasing neutron intensity, which corresponds to increasing soil moisture. In order to reduce measurement uncertainty (e.g. < 0.03 m^3/m^3), the neutron count rate is often aggregated over large time windows (e.g. 12h or 24h). To enable shorter aggregation intervals, the measurement uncertainty can be reduced either by using more efficient detectors or by using arrays of detectors, as in the case of CRN rover applications. Depending on soil moisture and driving speed, aggregation of neutron counts may also be necessary to obtain sufficiently accurate soil moisture estimates in rover applications. To date, signal aggregation has not been investigated sufficiently with respect to the optimisation of temporal (stationary probes) and spatial (roving applications) resolution. In this work, we present an easy-to-use method for uncertainty quantification of soil moisture observations from CRN sensors based on Gaussian error propagation theory. We have estimated the uncertainty using a third order Taylor expansion and compared the result with a more computationally intensive Monte Carlo approach and found excellent agreement. Furthermore, we used our method to quantify the dependence of soil moisture uncertainty on CRN rover survey design and on selected aggregation time. We anticipate that the new approach helps to quantify cosmic ray neutron measurement uncertainty. In particular, it is anticipated that the strategic planning and evaluation of CRN rover surveys based on uncertainty requirements can be improved considerably.

12:00

Combining thermal and epithermal neutron count rates for an improved soil moisture estimation under spatially heterogeneous soil moisture conditions

D. Rasche [1,2], *M. Köhli* [3,4], *M. Schrön* [5], *T. Blume* [1], *A. Güntner* [1,2]

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Since its invention about a decade ago, non-invasive soil moisture estimation using cosmic-ray neutron sensing (CRNS) at the field scale constantly advanced significantly through i.e. an improved understanding of the CRNS integration volume, weighting functions for reference soil moisture measurements and correction procedures of raw neutron counts. The derivation of field scale soil moisture is based on neutrons in the epithermal energy range, while further fields of application such as the determination of snow water equivalent and biomass dynamics partly rely on combinations of thermal and epithermal neutron count rates (i.e. neutron ratios). However, most approaches and processing techniques such as weighting functions are based on the assumption of rather homogeneous site conditions within the measurement footprint of the neutron detector. Consequently, state-of-art methodological processing procedures may not be suitable for the application of CRNS under heterogeneous site conditions and require further research.

On average, thermal neutrons have a substantially smaller measurement footprint radius (approx. 35 m) than epithermal neutrons (approx. 150 m). This may hamper the use of combinations of thermal and epithermal count rates under heterogeneous site conditions. However, this also offers the potential of a spatial discretization of the measurement footprint and may allow for a differentiation between near and far field soil moisture dynamics.

Against this background, we investigate the potential of combining thermal and epithermal neutron count rates for a spatial discretization of the CRNS footprint and its impact on the calibration accuracy against reference observations of soil moisture at a CRNS observation site with heterogeneous soil water dynamics in the near (mineral soils) and far field (organic peatland soils).

First analyses using URANOS neutron simulations to investigate measurement footprint dynamics under specific conditions of the study site located in north-eastern Germany revealed that the thermal footprint mainly covers mineral soils while the epithermal footprint also covers large areas with organic soils. Combining observed thermal and epithermal neutron count rates leads to an improved calibration in the near-field compared to using epithermal neutrons only. This illustrates the potential of combining epithermal and thermal neutron count rates for soil moisture estimation and footprint discretization under heterogeneous site conditions.

Thursday 11:40 - 12:40

12:20

Mapping soil moisture using Cosmic Ray Neutron Sensing and Sentinel 1, 2 and Landsat 8 TIRS data

V. Döpper [1], M. Förster [1], M. Heistermann [2], T. Francke [2], F. Arias [1], B. Kleinschmit [1]

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Several approaches exist to map soil moisture with remote sensing data. For that purpose, machine learning algorithms are a common approach. Such algorithms are typically trained and validated with point measurements. However, the scale of the remote sensing and such ground truth measurements differs markedly. In contrast, Cosmic Ray Neutron Sensing (CRNS) provides a volume-integrated measurement of soil moisture at the plot scale (a few hectares). So far, soil moisture has not been directly mapped via CRNS measurements as calibration and validation data, whose spatial scale coincide with remote sensing data. Therefore, we would like to model spatially CRNS measured soil moisture using Sentinel 1 (SAR), 2 (multispectral) and Landsat 8 TIRS (Thermal Infrared) data in a pre-alpine catchment area.
Since the remote sensing data has a higher spatial resolution than the CNRS measurement, we analyze the optimal size of a buffer around the cosmic ray probes for model training and validation. Furthermore, we analyze the benefit of a horizontal weighting of the remote sensing data corresponding to the horizontal CRNS footprint characteristics.
Since every type of remote sensing data indicates soil moisture properties at different scales and domains, we furthermore aim for identifying the optimal remote sensing sensor combination for empirical modelling of soil moisture using CRNS based soil moisture measurements.
The project is part of the DFG-funded research group Cosmic Sense, which aims to provide interdisciplinary new representative insights into hydrological changes at the land surface.

CRNS Networks II

Chair: U. Schmidt

14:00

Update on COSMOS and cosmic-ray hydrology

M. Zreda

Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA

The method of measuring soil moisture with cosmogenic neutrons was developed more than a decade ago. Since then hundreds of sensors have been installed, and our understanding of neutrons in the terrestrial environment has improved markedly. Here, I will provide an update on the COSMOS and other networks and present new technical developments in the sensor technology. Additionally, I will discuss progress in hydrologic applications of cosmogenic neutron sensing and propose ideas for future research.

14:30

What should we do with hundreds of cosmic-ray soil moisture sensors… as a community?

R. Rosolem

Department of Civil Engineering, University of Bristol, Bristol, United Kingdom

The cosmic-ray neutron sensing technique for soil moisture estimate has matured over the last decade. This has led to a positive adoption of such technology with the deployment of hundreds of sensors worldwide, and the establishment of a number of national scale monitoring networks. We now know more about key aspects of this measurement technique which have led to significant improvement on the quality of our soil moisture estimates. As a result, cosmic-ray neutron sensors continue to be a valueable asset to global land surface and hydrological modeling applications. Despite this significant increase in available sites, progress on understanding this vast amount of information has been somewhat slow, in part due to the lack of a common data processing protocol. This talk will (1) highlight the opportunities and challenges relating experimental work using the technology tailored to land surface and hydrological models; (2) introduce a newly-developed open-source Python package called ‘crspy‘ which is aimed to harmonize large datasets on cosmic-ray neutron sensors; (3) and discuss more open what we can do to take the steps forward and work collaborative on establishing a more open global COSMOS community to aid the evaluation and validation of current and future modeling developments.

Detectors I

Chair: M. Köhli

15:00

Neutron measurement and calibration capabilities at the Physikalisch-Technische Bundesanstalt

A. Zimbal, R. Nolte, E. Pirovano, D. Radeck, M. Reginatto, M. Zboril

Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig

The Physikalisch-Technische Bundesanstalt (PTB) is the national metrology institute of Germany, responsible for the realization of the units of the SI.

The main tasks of the Neutron Radiation Department, which belongs to the Ionizing Radiation Division, are the metrology, spectrometry, and dosimetry of neutron radiation. To accomplish these tasks, the department provides neutron reference fields, detectors, and methods of data analysis for traceable measurements of neutron radiation. We operate the accelerator facility PIAF (PTB Ion Accelerator Facility) for the production of monoenergetic neutron reference fields and an irradiation facility with radionuclide sources, including a thermal neutron reference field. Among other tasks, the infrastructure is used for the characterization and calibration of neutron measuring instruments. Our facilities are available for external partners in the frame of scientific cooperations.

We perform challenging measurements at our own facilities, in nuclear industry, at medical centers, and in the environment to support fundamental research, science, and industry. We offer advice on questions concerning measurements of neutron radiation and their radiological evaluation.

An important portable instrument that is used to characterize neutron fields is the PTB Bonner sphere neutron spectrometer NEMUS, capable of covering a large range of neutron energies from thermal to GeV. NEMUS serves as a secondary standard for the spectrometry and dosimetry of unknown neutron fields, traceable to PTB primary standards of the neutron fluence rate. With this system, we have performed measurements under extreme conditions ranging from low-level measurements at underground laboratories to high-intensity pulsed fields at hadron therapy facilities.

15:20

Local high-energy particles measurements for detecting primary cosmic-ray variations: application for soil moisture estimation

L. Stevanato [1], G. Baroni [2], M. Lunardon [1], S. Moretto [1], M. Polo [1]

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In the last decade the measurement of secondarycosmic ray neutrons has been established as a unique approach for intermediate scale observation of land surface hydrogen pools. Originally developed for soil moisture measurements, it has shown also promising applications for snow, biomass and canopy interception. The approach relies on the correlation between natural neutron background as created by cosmic-ray fluxes and local hydrogen pools. The measurements are generally performed based on moderated proportional counters filled with Helium-3 or Boron and the moderation is created by adding shielding material (mostly polyethylene) around the counter.
The signal is affected by the temporal variability of the incoming neutron fluxes. At first, the variability of neutron fluxes is due to solar activities. The neutrons are further attenuated by the mass of the air and air humidity.
Specific corrections have been proposed to account for these effects. Air pressure and humidity corrections rely on local measurements that could be easily collected. Incoming correction due to solar cosmic-ray fluctuation is based on a worldwide network monitoring station (NMDB). This network provides online access to their data in real-time. However, this approach showed some limitations in region where incoming fluxes could be not representative of local conditions introducing errors that could be relevant for the estimation of the targeted variable. In addition, it requires the need of post-processing of the data resulting in some difficulties to provide, e.g., soil moisture observations in real-time.
In the present contribution, we show the results of tests conducted on an alternative commercial sensor based on scintillators. The new probe has the capability to identify neutrons like proportional counter and, in addition, muons. These are high energy particles created from the same cascade of primary cosmic-ray fluxes that generate neutrons on the Earth. For this reason, they can be used for correcting the neutron signal by the variations of primary cosmic-ray fluxes. In addition to the pressure influence, however, temperature changes produce significant muon intensity variations. In fact, the temperature effect influences the creation and disintegration processes of muons in the atmosphere. For these reasons, both effects should be account for.
We present results from muon measurements at different locations and different heights in order to parametrize the pressure correction (attenuation length) that is not constant with the altitude as in the case of neutrons. Furthermore, we present a long-time measurement (1 year) of muon variations and how to manage in a simple way the extra dependence of the muons with air temperature profile. Finally, we show how the use of local high energy particles is a practical alternative to account atmospheric corrections and overcome the limitation of using data from NMDB.

15:40

Large-scale boron-lined neutron detection systems as a ^{3}He alternative for Cosmic Ray Neutron Sensing

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Cosmic-Ray neutron sensors are widely used to determine soil moisture on the hectare scale. Precise measurements, especially in the case of mobile application, demand for neutron detectors with high counting rates and high signal-to-noise ratios. For a long time Cosmic Ray Neutron Sensing (CRNS) instruments have relied on ^{3}He as an efficient neutron converter. Its ongoing scarcity demands for technological solutions using alternative converters, which are ^{6}Li and ^{10}B. Recent developments lead to a modular neutron detector consisting of several ^{10}B-lined proportional counter tubes, which feature high counting rates via its large surface area. The modularity allows for individual shieldings of different segments within the detector featuring the capability of gaining spectral information about the detected neutrons. This opens the possibility for active signal correction, especially useful when applied to mobile measurements, where the influence of constantly changing near-field to the overall signal should be corrected. Furthermore, the signal-to-noise ratio could be increased by combining pulse height and pulse length spectra to discriminate between neutrons and other environmental radiation. This novel detector therefore combines high-selective counting electronics with large-scale instrumentation technology.

16:00

Lithium Foil Neutron Detectors

A. Raymond [1], *A. Inglis* [1], *P. Taber* [1], *M. Zreda* [2]

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In response to a demand for alternatives to helium-3 (He-3) neutron detectors in the field of nuclear security, Silverside Detectors developed a novel thermal neutron detector with a goal of meeting He-3 performance and reliability at a lower cost (measured as cost per neutron counted). The design uses lithium-6 (Li-6) foil in a rectangular multi-wire proportional counter. The detectors are resistant to impact, vibration, and humidity, and may be used in a wide range of temperatures. The cost per neutron count of Li-6 panels is less than half that of He-3 tubes, with a comparable sensitivity. Silverside's detectors are currently deployed by the United States Departments of Defense and Homeland Security at airport and border locations.

Silverside's Li-6 detectors have also been tested for and incorporated into cosmic ray soil moisture sensors. Field tests with stationary units and rovers have demonstrated that the Li-6 sensors perform well compared with the standard COSMOS sensors employing He-3 or B-10 proportional gas tubes. The responses to changing moisture levels are nearly identical in sensors equipped with these three thermal neutron detectors. This result shows that the sensors are compatible and interchangeable. The lower cost of Li-6 relative to He-3 enables a scale-up of deployed units for new network-level research efforts. It also favors installation of additional detection capacity, which yields higher count rates and data with smaller uncertainties.

Detectors II Chair: M. Köhli

16:50

A downward-looking cosmogenic neutron sensor for measuring soil moisture at a horizontal scale of meters

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The standard cosmogenic neutron sensor for measurement of soil moisture has a wide-area horizontal footprint of several hectometers. At the Copenhagen COSMOS Workshop in 2016, we asked whether it would be possible to reduce this footprint in order to enable measurements of soil moisture at higher spatial resolutions. Four years after Copenhagen the answer to this question is "yes" and here we present the development of the downward-looking, or local-area, cosmogenic neutron sensor.

The downward-looking sensor comprises the standard moderated COSMOS sensor with added plastic shields on all sides except the bottom. These shields reduce the contribution of neutrons coming from above and from the sides, but the absence of the shield at the bottom allows the neutrons that come from below to enter the detector. Field experiments and modeling with URANOS have yielded the following results. The depth of measurement is similar to that of the standard COSMOS sensor, from one decimeter when the soil is wet to a few decimeters when it is dry. But the horizontal footprint is different than that of the standard COSMOS sensor. It ranges from approximately one meter when the sensor is on the ground surface, to several meters when it is above it. The calibration function, which relates neutron count rate to soil moisture, is similar to that for the standard COSMOS sensor. These findings suggest that the two sensors, standard COSMOS and downward-looking, can be used as complementary devices for measuring soil moisture at various horizontal scales.

CRNS Networks III — Chair: S. Oswald

17:20

Establishing a new soil moisture monitoring network for the UK

D. Boorman

UK Centre for Ecology and Hydrology, Wallingford, Oxfordshire, OX10 8BB, UK.

The cosmic-ray neutron sensor (CRNS) method has revolutionised the measurement of soil moisture, as is no doubt described in other presentations at this workshop. This paper describes how the technique has been adopted in the UK to develop a new Cosmic-ray soil moisture monitoring network: COSMOS-UK.

COSMOS-UK was established to provide a wide range of soil and meteorological parameters to the support both operational and research activities, rather than to undertake research into the CRNS method itself. It was, perhaps naively, thought that technique had reached a level of maturity at least in terms of standard implementation.

This presentation will describe the challenges faced in establishing COSMOS-UK in terms of securing sites, data management and delivery, resourcing, and putting in place an operational service. It will also mention some of the methodological developments that have been necessary to achieve this outcome.

COSMOS-UK has now been operational since 2013 and currently there are 49 sites from across the UK, and representing a variety of land uses, soil types and the range of UK climates.

Data have been provided for a wide variety of purposes. These include some that were recognised at the outset relating to hydrology, ecology and agriculture. However, the data have also been used for some rather unexpected purposes which will also be described.

Monte Carlo I

Chair: S. Oswald

17:50

Moisture and humidity dependence of the above-ground cosmic-ray neutron intensity

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Investigations of neutron transport through air and soil by Monte Carlo simulations led to major advancements towards a precise interpretation of measurements, especially they improved the understanding of the cosmic-ray neutron footprint. Up to now, the conversion of soil moisture to a detectable neutron count rate relies mainly on the equation presented by Desilets et al. (2010). While in general a hyperbolic expression can be derived from theoretical considerations, their empiric parameterisation needs to be revised for two reasons. Firstly, a rigorous mathematical treatment reveals that the values of the four parameters are ambiguous because their values are not independent. We find a 3-parameter equation with unambiguous values of the parameters which is equivalent in any other respect to the 4-parameter equation. Secondly, high-resolution Monte-Carlo simulations revealed a systematic deviation of the count rate to soil moisture relation especially for extremely dry conditions as well as very humid conditions. That is a hint, that a smaller contribution to the intensity was forgotten or not adequately treated by the conventional approach. Investigating the above-ground neutron flux by a broadly based Monte-Carlo simulation campaign revealed a more detailed understanding of different contributions to this signal, especially targeting air humidity corrections. The packages MCNP and URANOS were used to derive a function able to describe the respective dependencies including the effect of different hydrogen pools and the detector-specific response function. The new relationship has been tested at exemplary sites and its remarkable performance allows for a promising prospect of more comprehensive data quality in the future.

18:10

Eight fathoms under the SWE: Venturing into deep water with a cosmic ray neutron sensor

D. Desilets

Hydroinnova LLC, Albuquerque, NM, USA

Depth measurements of neutron intensity provide valuable information including the calibration function for snow water equivalent (SWE) sensors and the intrinsic detector background for soil moisture devices. I will discuss measurements from a reservoir in New Mexico taken from the surface to 14 m (about 8 fathoms). As far as I know this is the first high resolution study over this range. I will compare my results to my own simulations with MCNP and also a handful of simulations from others, with particular focus on the attenuation length in water for the energetic (neutron generating) component of cosmic rays.

Snow Water **Chair: M. Schrön**

9:00

Continuous and autonomous snow water equivalent measurements by a cosmic ray sensor on a Swiss glacier

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The annual amount of snow accumulation in high mountain regions is a key parameter in various research fields such as glaciology, hydrology and/or agriculture. Additionally, it is of great importance in view of coping with climate change impacts, risks and adaptation. Reliable and temporally continuous snow water equivalent (SWE) measurements are therefore essentially needed. However, such measurements are challenging in high mountain regions because of the harsh environment with cold and windy conditions, the remoteness and the complex topography.

The cosmic ray sensor (CRS, SnowFox provided by Hydroinnova LLC) is a device that estimates SWE continuously through cosmic ray neutron fluxes. We placed this sensor directly on the glacier surface (below the snow pack) of the Glacier de la Plaine Morte (Switzerland) where it has been measuring since October 2016. To validate the CRS estimates of SWE, we use 15 manual field measurements (snow pits, snow probings) obtained during three winter seasons (2016-2019). On average, the CRS overestimates the manual measurements by +2%±11%. A sonic ranging sensor installed next to the CRS provides continuous snow depth (SD) measurements. These are on average -1%±5% lower than manual measurements. From daily SD and SWE observations, we calculate the daily bulk snow density which overestimates manual observations by +1%±8% on average.

Based on our three years of continuous SWE measurements validated with numerous field measurements, we conclude that the CRS is a reliable device for temporally continuous observation of snow accumulation in high mountain regions. The advantage of the CRS is that it withstands the harsh environmental conditions, requires no flat surface, no signal reception from satellites or a fixed location as many other similar and promising devices do.

9:20

Estimating snow water equivalent using cosmic-ray neutron sensors from the COSMOS-UK network

J. Wallbank, S. Cole, R. Moor, S. Wells, S. Anderson, E. Mellor, Cosmos-Uk Team

UK Centre for Ecology & Hydrology, Wallingford, Oxfordshire OX10 8BB, UK

The COSMOS-UK sensor network has the potential to provide new insights into snowfall and snowmelt events in the UK, and to improve the modelling of snowmelt floods. Although the Cosmic Ray Neutron Sensors (CRNSs) in this network are currently only used to produce estimates of soil moisture, they are also sensitive to water held in a snowpack. Here, COSMOS-UK data across five winters are used to produce Snow Water Equivalent (SWE) estimates for 913 snow days from 263 separate events at 46 sites (Wallbank et al. 2020). Moreover, the large (hundreds of metres) footprint of the CRNS potentially allows representative measurements of SWE even for inhomogeneous snowpacks. A number of COSMOS-UK sites additionally include a buried "SnowFox" neutron sensor, and an ultrasonic snow depth sensor.

For each site in the network, periods of snow cover are identified automatically using a measured albedo. CRNS and SnowFox SWE estimates are calculated using the reduction of their neutron count rates during these periods, while optionally attempting to correct for changes in the underlying soil moisture using data from point probes. CRNS and SnowFox SWE estimates are compared to independent estimates based on either snow-depth sensor measurements or a snowmelt model. Application of the triple colocation method suggests typical uncertainties of less than around 4 mm for the CRNS and SnowFox SWE estimates which, while small, are still considerable compared to the typically shallow SWE depths experienced in the UK. The analysis also suggests that variation in the soil moisture over the snow period is the largest source of uncertainty, and that the typically high soil moisture exacerbates this uncertainty. Nevertheless, CRNS and SnowFox SWE estimates were found to be more accurate than the depth-based and snowmelt model alternatives, and can prove useful even for the challenging ephemeral and shallow snow conditions encountered in the UK.

REFERENCE

Wallbank, J.R., Cole, S.J., Moore, R.J., Anderson, S.R., Mellor, E.J. (2020). Snow water equivalent estimates using cosmic-ray neutron sensors in the United Kingdom (2014-2019). NERC Environmental Information Data Centre (Dataset). https://doi.org/10.5285/e1fa6897-0f09-4472-adab-5d0d7bbc2548

9:40

Cosmic-ray neutron sensing based monitoring of snowpack dynamics: A comparison of four conversion methods

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Snow monitoring instruments like snow pillows are influenced by disturbances such as energy transport into the snowpack, influences from wind fields or varying snow properties within the snowpack (e.g. ice layers). The intensity of epithermal neutrons that are produced in the soil by cosmic radiation and measured above the ground surface is sensitive to soil moisture in the upper decimetres of the ground within a radius of hectometres. Recently, it has been shown that aboveground cosmic ray neutron sensors (CRNS) are also a promising technique to monitor snow pack development thanks to the larger support that they provide and to the lower need for maintenance compared to conventional sensor systems. The basic principle is that snow water moderates neutron intensity in the footprint of the CRNS probe. The epithermal neutrons originating from the soil become increasingly attenuated with increasing depth of the snow cover,so that the neutron intensity measured by the CRN probe above the snow cover is directly related to the snow water equivalent.

In this contribution, we use long-term CRNS measurements in the Pinios Hydrologic Observatory, Greece, to test different methods for the conversion from neutron count rates to snow pack characteristics, namely: i) linear regression, ii) the standard N_0-calibration function, iii) a physically-based calibration approach and iv) the thermal to epithermal neutron ratio. The latter was also tested for its reliability in determining the start and end of snowpack development, respectively. The CRNS-derived snow pack dynamics are compared with snow depth measurements by a sonic sensor located near the CRNS probe. In the presentation, we will discuss the accuracy of the four conversion methods and provide recommendations for the application of CRNS-based snow pack measurements.

10:00

Sensing Area-Average Snow Water Equivalent with Cosmic Ray Neutrons in Alpine Terrain

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In contrast to preliminary studies focusing on shallow snow conditions (SWE $<$ 130 mm), more recently the Cosmic Ray Neutron Sensing (CRNS) was shown experimentally to be sensitive also to deeper snowpacks providing the basis for its use at mountain experimental sites. However, hysteretic neutron response has been observed for complex snow cover including patchy snow-free areas. A comprehensive modelling approach was therefore used to understand and support the experimental findings. Several simulations have been set up in order to disentangle the effect on the signal of different land surface characteristics and to reproduce multiple observations during periods of snow melt and accumulation. To represent the actual land surface heterogeneity and the complex snow cover, the model used data from terrestrial laser scanning. The results show that the model was able to accurately reproduce the CRNS signal and particularly the hysteresis effect during accumulation and melting periods. Moreover, the sensor footprint was found to be anisotropic and affected by the spatial distribution of liquid water and snow as well as by the topography of the nearby mountains. Under fully snow-covered conditions the CRNS is able to accurately estimate SWE without prior knowledge about snow density profiles or other spatial anomalies. These results provide new insights into the characteristics of the detected neutron signal in complex terrain and support the use of CRNS for long-term snow monitoring in high elevated mountain environments. Further improvements of the method are expected by increasing of signal-to-noise ratio in snow covered conditions and by quantifying the increase of the neutron count rates due to snow-free patches in different conditions.

CRNS Networks IV

Chair: H. Kunstmann

10:40

Space-time soil moisture retrieval at the catchment scale using a dense network of cosmic-ray neutron sensors

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Over the past decade, cosmic-ray neutron sensing (CRNS) has emerged as a powerful technique to retrieve volume-integrated soil moisture estimates. These estimates are considered as representative for a horizontal footprint of hundreds of meters (the ”plot scale”) and a vertical footprint of tens of centimeters (”the root zone”). This study investigates the potential of the CRNS technique to obtain spatio-temporal patterns of soil moisture beyond the volume-integrated averages of isolated CRNS footprints. To that end, the Cosmic Sense research consortium carried out an observational campaign in a pre-alpine catchment from May to July 2019. In an area of just 1 km2 that exhibits pronounced soil moisture gradients, the campaign featured a dense network of more than 20 cosmic-ray neutron sensors with partly overlapping footprints. The present study is the first attempt to combine these observations in order to capture soil moisture heterogeneity inside and in-between CRNS footprints. In order to homogenize the observed neutron count rates in space and time, we account for the static effects of sensor sensitivity, vegetation biomass, soil organic carbon and lattice water, as well as the dynamic effects of barometric pressure, humidity, and the incoming neutron flux. Based on these homogenized neutron count rates, we investigate how robustly a spatially uniform N_0 value can be estimated across the study area. Using such a uniform N_0, we compute time series of soil moisture for each CRNS sensor location separately. Finally, we compare different approaches in order to obtain continuous space-time representations of soil moisture: as a benchmark, we simply interpolate the CRNS-derived soil moisture estimates in space; in a second step, we suggest a heuristic approach that complements the concept of spatial interpolation by the idea of a geophysical inversion: we define a geostatistical model of the spatial soil moisture variation in the study area, and then optimize the parameters of that model so that the error of forward-simulated neutron count rates is minimized. In order to make the optimization problem computationally feasible, we use a ”pragmatic” forward operator that is based on the horizontal sensitivity pattern of the CRNS sensor. The performance of both interpolation techniques is evaluated by using independent measurements from a SoilNet cluster in the north-eastern part of the study area.

11:00

Harmonizing the international environmental research infrastructure landscape – a chance for Cosmic-Ray Neutron Sensing

S. Zacharias [1], M. Schrön [1], H. W. Loescher [2], M. Mirtl [1]

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In recent years and decades, several "continental"-scale infrastructures for long-term environmental research have been established worldwide or are currently under construction. More recently, increased international efforts have been made to achieve better networking of these infrastructures, with particular attention also being paid to harmonizing methods of environmental monitoring.
The collection and provision of representative data on soil moisture dynamics on a continental or global scale is one of the major challenges of environmental monitoring. Corresponding data are essential for the further development and validation of effective forecasting systems and a multitude of other applications from remote sensing to environmental modeling. Cosmic-ray neutron sensing (CRNS) is currently one of the most promising methods to provide such data with reasonable effort for management-relevant scales and in high temporal resolution. Consequently, the method is also of great importance in the current discussions on international standardization and harmonization of environmental monitoring.
The contribution gives an overview of the state of the debate on standardization of environmental monitoring both in Europe and on a global scale and presents eLTER RI (integrated European Long-Term Ecosystem, critical zone and socio-ecological systems Research Infrastructure) and GERI (Global Ecosystem Research Infrastructure), two of the most important European and global initiatives respectively. At the same time, the contribution should be seen as a strong plea for the international CRNS community to become actively involved in the discussion on harmonizing environmental monitoring.

11:20

From Sensor to Real-Time Forecasts: Setup of a Cosmic-Ray Neutron Sensor Network for Data Assimilation and Optimization of High-Resolution Real-Time Predictions of Soil Moisture

P. Ney, A. Belleflamme, M. Iakunin, N. Wagner, B. Schilling, A. Weuthen, K. Görgen, H. Bogena

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The current long-lasting dry weather conditions in central Europe and projected regional climate change, with accompanying impacts such as droughts, pose an increasing problem for agriculture. Within the framework of the projects ADAPTER (ADAPT TERrestrial systems) and DG-RR (Digital Geosystem Rhinland Region), we are aiming to support the agricultural sector with novel soil condition and weather forecasting products that provide the basis for an increased resilience to short-term changing weather patterns and extremes as well as to long-term, regional climate change.
These products are realized using a prototypical monitoring and real-time forecasting system. In a data synthesis approach, a measurement network of soil moisture sensors is established, in a first step in collaboration with the forecast users.The measurement network consists of novel Cosmic Ray Neutron Sensor (Styx Neutronica), SoilNet sensors (soil moisture, temperature and matrix potential measured in three depths) and a combi-sensor to measure common meteorological parameters (ATMOS-41, METER Environment) such as air temperature, humidity, pressure, solar irradiance, wind speed and precipitation. In real time, the measured data are transmitted and stored to a cloud server via the cellular solution NBIoT (Narrow Band Internet of Things). After data post-processing the data is assimilated into the fully coupled, multi-physics TSMP (Terrestrial Systems Modelling Platform, www.terrsysmp.org) numerical model system at Forschungszentrum Jülich. One of the implementations uses the ParFlow hydrological model (www.parflow.org) in combination with the Common Land Model to predict hourly, high-resolution (near plot-level) information on soil moisture or other soil and meteorological parameters for the next 10 days.
Both the measured data and the forecasting products are made gradually available in near real-time on the digital product platform at www.adapter-projekt.de. This allows the users to access relevant information that can be used as basis for decision-making in the management of current farming activities (irrigation and fertilization requirements, sowing and harvesting times, trafficability and workability). Furthermore, the data and findings may also contribute to improve the prediction of soil hydrology or to validate hydrogeophysical measurements.

CRNS Method I

Chair: H. Kunstmann

12:00

Accuracy and precision of the cosmic-ray neutron sensor at three English sites

J. Iwema [1,2], M. Schrön [3], R. Rosolem [1]

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The accuracy and precision of the Cosmic-Ray Neutron Sensor (CRNS) counting rates and soil moisture estimate are usually affected by different mitigating factors. Moreover, whereas the accuracy can be improved by correcting for different hydrogen pools, the precision can only be improved by improving the detector efficiency or by increasing its integration time. To date, the effects of different neutron mitigating factors on CRNS accuracy and precision are not yet completely understood. We used data from three agricultural and low biomass sites located within a few kilometres distance from each other in South England, each comprising of different land use, biomass, and soil characteristics. We have extended the COsmic-ray Soil Moisture Interaction Code (COSMIC) to explicitly include the effects of relevant mitigating factors on the neutron counts (i.e., organic matter, plant roots, litter layer, ponding, above ground biomass, intercepted water, animals). Employing a model calibration strategy and a sensitivity analysis approach, we assessed which neutron mitigating factors were most influential on both the measured neutron counts and on the estimated soil moisture. We found atmospheric pressure and soil moisture content to be most influential on neutron count accuracy and precision. However, of the newly added variables, above-ground biomass was most influential and not accounting for it would yield limited soil moisture accuracy of up to 0.07 cm3/cm3. The precision of the soil moisture estimate however, was ten times more sensitive to soil moisture than other factors and was therefore mostly a function of soil moisture content itself.

12:20

Data-driven scaling approaches for soil moisture sensing with cosmic ray neutron probes

R. Baatz [1], Y. Zhang [2], S. Oswald [3], H. Bogena [1], H. Vereecken [1], M. Zreda [4]

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Cosmic ray neutron probe observations are used globally for in-situ soil moisture measurement and prediction. The increasing number of cosmic ray neutron probes around the globe sparks the need for accurate site specific neutron scaling models or correction functions. The current site-specific scaling models can account for variations in air pressure, air humidity, incoming cosmic ray intensity and for some sites for aboveground biomass variation. Importantly, these scaling models rely on a range of local and global models such as energy spectra, sensor specific dimensions, geomagnetic inclination, shielding effects of the geomagnetic field.
To overcome limiting assumptions in these observation derived scaling models, we propose a novel data-driven site-specific and sensor-specific correction method using generalized relationships of the above and observations. A feedforward neural network is applied on multi-year cosmic ray neutron probe observations to derive site specific data-driven scaling models for the three variables air pressure, incoming cosmic ray intensity and air humidity. The transferability to other sites is tested and compared to known corrections from literature. The henceforth corrected neutron flux is used to compare soil moisture estimates using traditional correction methods with the data-drive correction methods.

12:40

Uncertainty quantification of soil moisture predictions

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The agricultural drought, which represents one of the most impactful consequences of the climate change, is typically characterized by soil moisture values. However, direct measurements of soil moisture are very costly. Indeed, we have only very sparse soil moisture measurements obtained by Cosmic-Ray Neutron Sensing within the MOSES project at UFZ at our disposal. While classic regionalization methods (e.g. kriging and its variants) provide reasonable predictions for interpolation problems when the available data is uniformly distributed accross the area under consideration, they are of little practical use in the present project since we deal with extremely sparse and non-uniformly distributed data. That's why we use more sophisticated methods from machine learning and predict soil moisture from other quantities (for instance aspect, bulk density, elevation, precipitation, soil type), which are easier to measure. One of the key aspects of our project is that we quantify the prediction uncertainty. This is crucial for measuring the reliability and robustness of our model. To this end we need to know the uncertainties of the training data and investigate how they propagate through the model and get mixed with the model uncertainty.

CRNS Method and Hydrology I   Chair: H. Bogena

14:00

Mobile Platforms for Soil and Snow Water Mapping Across Scales with Cosmic-Ray Neutrons

M. Schrön [1], M. Kasner [1], C. Zengerle [1], L. Bannehr [2], M. Köhli [3], U. Koedel [1], C. Schütze [1], S. Oswald [4], S. Zacharias [1], P. Dietrich [1], S. Attinger [5]

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Cosmic-ray neutron sensing (CRNS) is a modern technology that can be used to non-invasively measure the average water content in the environment. The CRNS footprint encompasses an area of 10-15 hectares and extends tens of decimeters deep into the soil. The method might have the potential to bridge the scale gap between conventional in-situ sensors and remote-sensing data in both, the horizontal and the vertical domain.

Mobile CRNS platforms can be used for on-demand mapping of snow and soil water from the field to country scale. In the presentation we will explore novel opportunities to measure these spatial patterns of water content with CRNS. We will discuss ongoing research activities that are aimed at improving the operationality, frequency, and spatial extend of CRNS measurements. New strategies that will be discussed are, for example, event-based campaigns using cars; the potential of CRNS on trains; and airborne surveys using gyrocopters.

The data can be particularly useful to study the spatial extend of hydrological extreme events, heat-waves, droughts and snow cover. Future CRNS observations could provide a valuable contribution to the multi-sensor approach, e.g. to help tracking and characterizing surface water movement, to map regional-scale soil moisture patterns, or to calibrate and evaluate hydrological models and satellite data.

14:20

Application-driven developments of cosmic-ray neutron sensing open the path to wider and new uses: the cases of agricultural water management and pipe leakages.

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Cosmic ray neutron sensing (CRNS) emerged as a new method to estimate soil moisture non-invasively at the intermediate scale. From the seminal paper in 2008, intensive research activities have been conducted by several interdisciplinary research groups of physicists and hydrologists all around the World. These technology-driven studies improved our understanding of the detected signal and its interaction of the different hydrogen pools at the land surface and they showed that the CRNS can be a promising method for many applications.

Despite that, nowadays, integration of CRNS with existing monitoring networks and with agro-hydrological models for supporting water management and planning are still very limited. The reason can be two-fold. From the one hand, CRNS is considered a high entry-level method due to some complexities in the analysis of the signal and the relative high costs of the detectors. On the other hand, applications are not fully exploited and the added value of the method in comparison to current alternatives is not well identified and quantified.

This contribution presents and discusses some activities specifically conducted to address these issues. First, a commercial sensor based on scintillators optimized for agro-hydrological applications is presented. The added value of CRNS method is then discussed based on two examples in the context of agriculture and urban environment, respectively. In the first case, it is shown that farmers are highly constrained in the water management while marginal improvements can be achieved at the district level. For this reason, field measurements at high temporal resolution are not necessary while only a dense and well-connected CRNS network would provide support for improving water management and assessment. In the second case, it is shown that neutron measurements can be an efficient monitoring system for detecting leakage in urban water pipes. In both cases, the added value of CRNS is beyond the perfect understanding of the footprint, of the effect of the different hydrogen pools and on the calibration functions.

Overall, it is underlined that further improvements of CRNS method are relevant, but they should not overwhelm its current potentialities. In contrast, application-driven studies should be performed to provide the necessary technical requirements and to fully exploit the added value of the CRNS method in contrast to current practices.

14:40

Cosmic Ray Neutron Sensing: Improved field-scale soil moisture estimation by assimilation in land surface model

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The present study evaluates the added value of field-scale soil moisture estimates from Cosmic Ray Neutron Sensing (CRNS) by assimilation into Noah-MP land surface model. For this purpose, the spatially distributed Noah-MP model was set up to simulate the land surface variables at 1 km horizontal resolution in the Rott and Ammer catchments in southern Germany. For model development, we updated the soil parameterization in Noah-MP to allow the usage of EU soil data along with Mualem-van Genuchten soil hydraulic parameters. Dual state and parameter estimation experiments were conducted by assimilation of observed neutron counts from five CRNS stations within the study area. For validation, we used independent observations from extensive soil moisture sensor network (SoilNet) within the vicinity of the CRNS sensor at TERENO-preAlpine observatory. The evaluation has been carried out to understand the effect of assimilation on spatio-temporal changes in updated root zone soil moisture and its implications on the energy balance component of Noah-MP. The analysis showed that the RMSE for assimilated root zone soil moisture was reduced from 15.5 vol. % to 5.8 vol. %. Also, the Kling-Gupta efficiency of assimilated soil moisture in upper soil layers improved from -0.62 to 0.46. Overall, the field scale soil moisture information from CRNS network can be effectively utilized to improve the water and energy budget computations in land surface modelling.

15:00

Foreseen potential of CRNS for better understanding of catchment runoff dynamic

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The runoff formation on small catchments very often exhibits threshold behavior, independently, whether the most of the runoff takes place on the surface, in a shallow subsurface or via an artificial drainage system. Based on the measured rainfall-runoff data on an experimental catchment Nucice, we have identified rather scattered rainfall-runoff relationship with a strong dependence of the runoff on the actual topsoil saturation. It seems, that once the soil moisture conditions are bellow a certain threshold value, the rainfall totals are not correlated to the magnitude of the stormflow. Nucice catchment is situated in a moderately hilly region in Central Bohemia in the Czech Republic. The catchment area is 0.5 km^2, slopes reach up to 11 %, there is a very homogeneous landuse with more than 95 % of arable land. Soil is tilled to approximately 12 cm, bellow the tilled topsoil there is a compacted plough pan with very low hydraulic permeability. Therefore, the shallow topsoil and its water holding capacity play significant role in the runoff formation. Once the topsoil gets saturated on the large part of the catchment, water is quickly routed via surface (especially through the compacted wheel tracks in the slope wise direction) and shallow subsurface runoff towards the drainage channel. The catchment is equipped with instrumentation for monitoring of basic meteorological and hydrological variables, since autumn 2020 two cosmic rays neutron sensors have been installed. The foreseen utilization of the CRNS data is monitoring of the actual topsoil water saturation on a representatively large area, which will help us to identify the threshold values of the catchment saturation. It is very complicated to measure representative topsoil water content on the arable fields with the standard soil moisture probes as the agricultural activities and growing crops make the long term installations of the individual sensors nearly impossible. The soil moisture data will be also used for calibration and validation of numerical models (e.g. MIKE SHE, SWAT) which are further used for catchment water balance and rainfall-runoff simulations with the overall goal to understand the hydrological behavior of the agricultural catchment.

15:20

Opportunities and challenges in obtaining catchment-scale representative soil storage estimates from Cosmic Ray Neutron Sensors and their use in rainfall-runoff modelling

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Here we present one of the first applications of CRNS data in conceptual rainfall-runoff modelling and explore this potential in the context of a humid mixed-agricultural landscape in Scotland. For that, we deployed and calibrated a CRNS with a heterogeneous but landscape representative soil and land use footprint over a ∼3-year period. We used CRNS-derived, as well as single point-scale estimates, of near-surface soil storage (S_{NS}) to explore their characterisation of storage dynamics at the catchment-scale. Inter-comparison using linear regression showed that S_{NS} related well to catchment-scale storage dynamics. However, this relationship was stronger for CRNS (R^2=0.91) compared to point-scale derived estimates (R^2=0.76). Based on this, we evaluated the effect of using the CRNS and point scale derived S_{NS} data to constrain storage estimates controlling runoff generation in a common rainfall-runoff model (HBV-light). Including CRNS or point-scale field S_{NS} data alone in model calibration was especially useful for characterising intermediate and wet periods. A combined model calibration using discharge and either S_{NS} storage estimates provided a better representation of catchment internal dynamics, additionally reducing uncertainty during low flows. Furthermore, we evaluated the additional information of areal-weighted average S_{NS} information from portable CRNS data, as compared to S_{NS} form the static CRNS, for the combined model calibration. For this, a portable CRNS was used to obtain spatially variable near-surface soil storage timeseries for key soil and land use units in the catchment. However, differences between simulated discharge and storage using the static or spatially variable CRNS data were marginal and model efficiencies similar. This suggested that static CRNS data from a landscape-representative location could suffice to inform rainfall-runoff modelling at the catchment scale, although this may depend on model structure and the degree to which storage dynamics vary within the landscape. At least in the context of humid mixed-agricultural landscapes, this study showed the potential of using CRNS over point scale data (in terms of representativeness for single point data and practicality for point sensor networks) to characterise the catchment storage-discharge relationship and inform hydrological modelling, which can aid agricultural, flood and other management decisions.

15:40

COSMOS-UK: Near real time soil and hydrometeorology data

H. Cooper, S. Stanley

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The COSMOS-UK network delivers near real time soil moisture along with a variety of hydrometeorological observations across the UK. Data from each site's meteorological and soil sensors provide greater insight into local land surface processes and conditions. These observations can also be used to derive additional variables and help validate data.
Measurements such as precipitation and point or profile soil moisture can be used to assess the accuracy of the CRNS (cosmic-ray neutron sensor) soil moisture data by exploring local soil moisture dynamics in response to rain events. Snow and radiation sensors, plus an on-site camera, also provide further information about the data, by indicating when CRNS soil moisture may have been impacted by snow cover.
CRNS soil moisture has been used to validate land surface models and ground-truth remote sensing products; in such research the additional in situ measurements can be used as model driving data or for further data validation to improve soil moisture datasets. These observations can therefore help in producing improved soil moisture products at a greater spatial resolution.
In situ measurements also make it possible to derive additional data such as potential and actual evaporation across the UK. These variables can prove critical in understanding the role of soil moisture in land-atmosphere processes and interactions, for example during extreme climate events.
This presentation will describe the additional variables delivered by the COSMOS-UK network and provide examples of how these data can be used to increase the value of the CRNS soil moisture product. This presentation will also explain how the data can be accessed via in The Environmental Information Data Centre (EIDC).

16:00

Evaluation of Soil Moisture from Temperate and Semiarid Environments Using Cosmic-Ray Neutron Sensors and Sentinel-1 Data

H. Said Ahmed [1], *L. Heng* [2], *M. Mbaye* [3], *E. Fulajtar* [2], *G. Weltin* [1], *T. Franz* [4], *G. Dercon* [1], *P. Strauss* [5], *G. Rab* [5]

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Climate change has a major impact on the availability of water in agriculture. Sustainable agricultural productivity to ensure food security requires good agricultural water management.
Soil moisture is an important variable in irrigation management, hydrological modelling, ground water recharge, flood, and drought forecasting. Many different techniques have been used to provide soil moisture estimation at different scales from point to landscape scales.
The Cosmic-Ray Neutron Sensor (CRNS) has been used to estimate soil moisture at field scale of 20 ha and has demonstrated its ability to support agricultural water management, hydrology studies and land surface modelling. However, measurement of soil moisture on a global or regional scale can only be achieved from satellite remote sensing.
Recently, active microwave remote sensing Synthetic Aperture Radar (SAR) imaging has emerged as an effective tool to estimate surface soil moisture. The Sentinel-1 (SAR) satellite shows great potential for high spatial resolution soil moisture monitoring. The satellite imagery can be the basis for producing soil moisture maps. However, these maps can be only used after calibration. Such calibration can be done through traditional, point soil moisture sampling or measurement, which is time-consuming and costly. CRNS technology can be used for more rapid calibration, at field and areawide level.
In this study we built, calibrated and validated a simple conversion model to retrieve soil moisture from Sentinel-1 (SAR) data using CRNS data from temperate and semiarid environments.
This study is a major step in the monitoring of soil moisture at high spatial and temporal resolution by combining remote sensing and the CRNS nuclear technology. The preliminary results show the great potential of using nuclear technology such as CRNS for remote sensing calibration of Sentinel-1 (SAR).

CRNS Method and Hydrology II — Chair: H. Bogena

17:00

Opportunities and challenges towards integration of hydrogeophysical sensors in agriculture

T. Franz

University of Nebraska-Lincoln, Lincoln, USA

A vast number of companies offer access to hydrogeophysical sensor data to improve agricultural management practices: including increased crop yield, decreased water and fertilizer use, and increased profitability. However, bridging the gap between applied research and operational use remains challenging given the needs of any technology to be deployable, scalable, and profitable. In this work, I will summarize the opportunities and challenges of integrating various hydrogeophysical sensors in large scale commercial agriculture from examples in the Midwestern USA. Specifically, results from fine-resolution (10 m) datasets for eight 64 ha agricultural field sites, spanning a range of climatic, topographic, and soil conditions across Nebraska will be presented. Lastly, I will discuss some opportunities for use of hydrogeophysical sensors beyond large scale commercial agriculture including smallholders, high-value crops, and plant breeding.

Posters

Chair: M. Zreda

17:30

On the possibilities of CR-39 and LR-115 nuclear track detectors as soil moisture sensors using isotopic neutron sources

B. O. Vega Cabrera, D. F. Palacios Fernández

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In Peru, agriculture represents the second economic sector after mining. Hence, the measurements of soil moisture levels are of vital importance allowing farmers to save water, to fulfill an irrigation schedule and to adapt to global change. The cosmic-ray probe is an innovate technique that provides spatial estimates of surface soil moisture replacing networks of conventional in-situ instruments. To carry out these estimations using isotopic neutron sources and cosmogenic neutrons, the possibilities of CR-39 and LR-115 nuclear track detectors (NTDs) as neutron gauge sensor have been studied. For their atomic compositions, low cost, response effectiveness, among other advantages, the NTDs coupled to appropriate converters could become a complementary alternative to estimate soil moisture. Presence of hydrogen in the elemental composition of NTDs and polyethylene radiator favors the scattering process (n, p), while ^{10}B of converter causes the transmutation process (n, α). Both charged particles can be registered by NTDs that will permit to correlate with the soil moisture. As first approximation to realize these estimations using NTDs, an isotopic neutron source of ^{241}Am-Be was simulated using MCNPX code considering this energy spectrum (from ISO-8529). In addition, the elemental dry soil composition (from Evaluated Nuclear Data File library: ENDF-VI), cylindrical soil geometry (250cm high and 150cm radius), and soil water content from 25% up to 100% were taken into account. The NTDs, some coupled to ^{10}B and others to polyethylene (5 x 5 cm^2), were placed at different soil depths (up to 250 cm with steps of 25 cm) and above the soil surface (up to 150 cm in air with steps of 25 cm). For each location, the correlation curve between θ_v (cm^3.cm^{-3}), Φ (n.cm^{-2}.s^{-1}), and number of Q reactions (reactions.cm^{-3}.s^{-1}) were obtained. The ambient dose equivalent H*(10) (mSv.h^{-1}) was also estimated. Preliminary results are presented in this work.

17:35

How cosmogenic neutron derived soil moisture can be used to estimate dynamic groundwater recharge rates at the field scale

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Cosmic-ray neutron sensing (CRNS) delivers an integral soil moisture over a support volume covering the field scale as a state variable. It overcomes limitations of point measurements regarding small scale heterogeneity and could also be a promising basis for the evaluation of water fluxes such as groundwater recharge.
Estimation of groundwater recharge with the help of unsaturated soil hydrological models requires knowledge about soil hydraulic properties (SHPs). Effective SHPs for the field scale can be inversely estimated with the help of CRNS data. For this purpose, also soil column models, like HYDRUS 1D can be utilized, as they are representative for the field scale due to the spatial coverage of CRNS derived soil moisture as input data. Some previous studies have successfully estimated effective SHPs with the help of HYDRUS 1D and the externally coupled COSMIC operator, developed for data assimilation purposes, that utilizes the measured neutron counts instead of the CRNS derived soil moisture.
Within our study we want to test several options of how best to implement CRNS derived soil moisture within soil hydrological models, estimate SHPs and derive groundwater recharge. The integrated groundwater recharge flux using CRNS derived soil moisture is compared to established methods using point scale estimates from a distributed sensor network and the variability observed for single sensor network nodes.
CRNS derived soil moisture is, because of the sensitivity of the sensor, inherently weighted and this behavior should be explicitly considered. Using the COSMIC operator and directly comparing neutron count rates from simulated soil moisture to measured count rates, avoids the inherent weighting in the soil moisture product and is one option to deal with the sensitivity of the sensor. As a second approach we want to implement within the model a corrected CRNS soil moisture, which is deprived of its inherent weighting, with the help of soil moisture profiles measured additionally to CRNS. As a third approach, instead of directly using the integrated CRNS soil moisture, we distribute it to depth specific soil moisture with the help of such profile measurements and the information on the depth-dependent distribution of water in the field. The approaches are assessed with respect to their ability to estimate natural groundwater recharge rates.

17:40

Soil moisture observations: CRNS vs TDR-profile in a flooded agriculture regime at the Yaqui Valley

Z. Sanchez-Mejia [1], *E. Yepez* [1], *F. Gaxiola* [1], *O. Peñuelas-Rubio* [2], *J. R. Torres-Velázquez* [2], *J. C. Alvarez-Yepiz* [1], *J. Garatuza-Payan* [1]

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Soil moisture is an essential measurement to manage water and improve crop production. However, agricultural research in the Yaqui Valley (in northwestern Mexico) with extensive wheat fields (*Triticum sp.*) have focused on other monitoring schemes (e.g. remote sensing) with less attention to soil moisture. Most of this cultivated soil contains up to $\sim$ 50% clay, which results in changes to soil properties from wet to dry conditions and challenges in the implementation of in-situ measurements of soil moisture. For this research, we selected a 1-ha wheat field in the Yaqui Valley representative of a typical flood irrigation system. We measured meteorological variables (ClimaVUE50), and soil moisture for the winter crop-cycle from December 2019 to Abril 2020. Volumetric water content (VWC) was recorded from 5 to 50 cm using two TDR (SoilVUE10), one located in the bottom of the furrow under bare conditions, and the other on the top under the vegetated condition for further integration and comparison. A Cosmic Ray Neutron Sensor (CRNS) was located alongside the meteorological sensor. An analysis using the CRNS and the TDR single depth, as well as, integrated values at different depths TDR was performed. While both technologies respond to water inputs, the CRNS is a more reliable measurement during the dry-down periods when the high-clay soil cracks to the extent of 40 cm where the soil is exposed to air. During this driest period, recorded VWC at 50 cm was, on average, 0.25 $m^3\ m^{-3}$, while measurements with the CRNS was on average, 0.16 $m^3\ m^{-3}$.

17:45

Applicability of machine learning-based approaches to predict CRNS Roving-derived soil moisture estimates on the catchment scale

E. Nixdorf, M. Schrön, M. Hannemann, T. Kalbacher

Helmholtz Centre for Environmental Research - UFZ, Permoserstraße 15, 04318 Leipzig, Germany

In this study we aim to characterize the trends of soil moisture distribution in the 209 km^2 large Mueglitz River Basin by learning from a huge dataset of more than 120 000 vehicle-mounted CRNS rover readings measured over different regions of Germany within the last 5 years. Two different sets of soil moisture estimates have been processed using either on-board meteorological sensors or interpolated data substitutes from the German weather service network. To each data record we assigned 31 independent dynamic and stationary features derived from public databases. Subsequently, three different supervised machine learning algorithms (MLR, RF and ANN) were trained to predict both, raw neutron records and derived soil moisture estimates on the catchment scale.
Testing these three approaches, the Random Forest algorithms gave the best prediction with R2= $\sim$0.8 for neutron counts and R2=$\sim$ 0.7 for soil moisture estimates. All applied algorithms predict raw neutron counts better than soil moisture estimates. Moreover, the replacement of on-board meteorological sensor data by data from the German Weather service does not significantly influence model performance.
The comparison of the machine learning results with soil moisture estimates from a distributed hydrological model demonstrates that an improved description and prediction of the soil water dynamics across heterogeneous terrain may be achieved by combining CRNS monitoring and processing workflows with machine learning. The modeling approach and the variable importance and relationships assessed in this study are further beneficial for management and environmental modeling tasks where spatially explicit soil moisture information is important.

17:50

How to correct near-surface neutron measurements for incoming cosmic-ray fluxes?

M. Schrön [1], J. Weimar [2], K. Herbst [4], M. Köhli [2,3], K. Shah [5], T. Sato [6], M. Zreda [7], R. Bütikofer [8], C. Steigies [4], R. Baatz [9], P. Schattan [10], B. Heber [4], S. Zacharias [1]

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The method of cosmic-ray neutron sensing (CRNS) relates measured low-energy neutron intensity to soil water content. A critical factor for the reliability of such data is the knowledge of the dynamics of incoming cosmic-ray neutrons from the atmosphere. Conventionally, independent data from Neutron Monitor stations (NM) are consulted to serve as a reference for the correction of the local detectors. Neutron monitor measurements are usually used to track the dynamics of the cosmic ray flux near Earth, but outside the Earth‘s magnetic field and therefore also outside the Earth‘s atmosphere. It is assumed that the local environmental conditions only marginally influence the characteristics of energetic neutron intensity and therefore the NM measurements.

The correction approach assumes a proportional relationship between the local low-energy flux at the measurement location and the high-energy flux measured at a distant neutron monitor location. Unfortunately, sometimes NM data from different stations appear to be inconsistent, and the performance of the simple correction approach is often not satisfactory, particularly during solar events. Reasons could be that the measurement locations of CRNS and NM are far apart in terms of spatial distance, cut-off rigidity, and altitude, and that different types of detectors are used.

The presentation explores different approaches to deal with this problem, such as modified correction methods that depend on the cutoff-rigidity, geomagnetic simulations that predict the cosmic-ray flux anywhere on Earth, or local mini-NMs close to the CRNS site. We also discuss experiments to estimate the correction parameters, e.g. with a CRNS detector in a buoy on a lake.

As the demand for accurate observations and predictions of environmental states and fluxes is globally increasing, the correction for incoming radiation and meteorological effects should become a key challenge in the research field of terrestrial cosmic-ray neutron sensing.

17:55

Establishing a European COSMOS network in the light of continental drought events

H. Bogena [1], *M. Schrön* [2], *P. Ney* [1], *J. Jakobi* [1], *S. Zacharias* [2], *D. Boorman* [3], *H. Vereecken* [1]

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An extraordinary heatwave struck northern Europe in the summer of 2018, with record-breaking daily temperatures and critical plant water stress on agricultural fields and forests. The summers of 2003, 2010, 2015, and 2018 are considered as the most notable years of the 21st century in Europe in terms of drought but also witnessed numerous heat-related deaths and extensive forest fires. The events stimulated a debate on how changes in the occurrence and characteristics of droughts are related to climate variability.
In order to improve the predictions and future response to climate change, it is important to monitor air humidity, temperature, precipitation and soil moisture levels across the European continent. The establishment of a long-term database of these essential variables could help to boost research on heatwaves and hydrological droughts, and to understand the causes, development, and impact of future events.
The Cosmic-Ray Soil Moisture Observing System (COSMOS) is a stationary monitoring instrument that could provide continuous data of hectare-scale root-zone soil moisture and snowpack, together with instruments for air humidity and precipitation. Of the more than 200 stations globally, more than 100 are located on the European continent. The COSMOS stations were installed in the course of the last 10 years and are often operated as regional networks, such as TERENO or COSMOS-UK, to complement measurements in hydrological observatories.
We propose to collect and process data from the past 10 years from all European COSMOS stations to generate a continental view on European drought conditions of the preceding decade. We believe that a sound and harmonized processing of the data could facilitate and advance the application and interpretation of soil moisture droughts in the European continent and substantially support hydrological and climate models that aim for near-real-time predictions of future heatwaves and droughts in Europe. We invite all research institutes in Europe to contribute to this data base and to the unparalleled effort of lifting COSMOS to the next level of large-scale hydrological monitoring.

18:00

Examining the relationship between CRNP soil moisture data and GLDAS based Noah LSM Evapotranspiration product

M. B. Duygu, Z. Akyurek

Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

Soil moisture and evapotranspiration are the two key elements of hydrological studies having their own dynamics in relation with the water and energy exchanges between different stages of the hydrological cycle. Understanding the behaviour of terrestrial evaporation and soil water is crucial in all fields of soil water studies including agriculture. However, being the most difficult variable to measure in the field makes our knowledge on evaporation highly limited when compared to the knowledge on other elements of the cycle. In addition to that, acquiring reliable information about soil moisture content on large areas may require intensive effort due to the heterogeneous nature of the soil. In this study, we identify the relation between soil moisture and modelled evapotranspiration. Soil moisture data have been obtained fromexisting Cosmic Ray Neutron Probe (CRNP) stations of the COSMOS database and a CRNP station that was installed in October 2016 in Çakıt basin, which is in the south part of Turkey. Actual Evapotranspiration (ETa) data have been retrieved from global land surface model Global Land Data Assimilation System (GLDAS) dataset.The time interval of the analyses is between October 1, 2016 and September 30, 2018. For Çakıt basin, we also introduced actual evapotranspiration output of the uncoupled Noah LSM. Since soil moisture and evaporation data are defined in different units, all data are normalized. Coefficient of determination (r2) and root mean square error (RMSE) are used as the statistical measures. For Çakıt station, the GLDAS based Noah LSM ET products have much higher correlation than local Noah model products with CRNP soil moisture data. For Çakıt Basin, relation between soil moisture data obtained from CRNP and ETa values are further investigated by both comparing them directly and analysing the similarities between the cumulative distribution functions (cdf). Two different sources of evapotranspiration information are taken into account for the analyses. First one is based on Eddy covariance system data and the second one is the Noah LSM output The results of Noah LSM show that ETa obtained from Noah LSM has more similar distribution with the soil moisture data obtained from the CRNP than the Eddy based ETa. It is observed that the relationship between soil moisture and evaporation is stronger in the drier months.

18:05

Event identification electronics for neutron proportional counters

B. Brauneis [1], *J. Weimar* [1], *M. Köhli* [1,2], *U. Schmidt* [1]

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Neutron proportional counters in low-count rate environments such as monitoring cosmic-ray induced environmental radiation require large instruments in order to provide substantially good statistics. This makes gaseous detectors susceptible to background like protons, (Compton) electrons, gammas, muons and nuclear fragments which are emitted from the wall material. Furthermore, due to the helium-3 crisis the baseline technology shifted towards boron-lined detectors, which have an energy spectrum continuously extended downwards to 0 eV. An event from a neutron conversion, however, can be distinguished from non-signal events by the drift time characteristics of the ionization track in the gas. Within the COSMIC Sense collaboration we are developing readout electronics for large-scale neutron detectors based on microcontrollers which act as digitizers as well as a triggered data acquisition. The frontend features a pulse-shape analysis for signal height and time over threshold including rise time discrimination using the built-in 10-bit analog-to-digital converter. We present the current status of the frontend electronics DAQ and measurements of the separation efficiency for this readout.

18:10

Large-Scale Boron-Lined Neutron Detection Systems as a cost-efficient solution for Cosmic-Ray Neutron Sensing

M. Janke, M. Köhli, J. Weimar

StyX Neutronica GmbH, Wilhelmstraße 35, 69221 Dossenheim, Germany

The above-ground intensity of epithermal to fast cosmic-ray neutrons with energies from 300 meV to 30 keV is a suitable proxy for environmental hydrogen content within a footprint of several hectares. Low systematic and statistical errors of the neutron intensity measurements increase the signal-to-noise ratio and are the essential requirement for a precise soil moisture retrieval.
We present a novel large-area and modular detection system composed of several boron-lined neutron counters. The large sensor volume results in a high overall neutron flux penetrating the detection system leading to high count rates which reduce the statistical error in a given time frame. The system's modularity allows for individual energy resolution of the different segments within the detector featuring the capability of gaining spectral information about the detected neutrons. This opens the possibility for active signal correction, especially useful when applied to mobile measurements, where the influence of constantly changing near-field to the overall signal should be corrected.
The read-out electronics uses pulse shape analysis to differentiate between neutrons and other radiation types with a single-event resolution of milliseconds. An optional thermal shield with a strong absorber prevents contamination of thermal neutrons and thereby increases the signal-to-noise ratio. The data logging unit provides real time information via a display and uploads data using either MQTT, UDP or FTP via GSM, LTE or NB-IOT. GNSS functionality enables positioning in case of mobile applications and may also update the real-time clock to guarantee stable timing over long periods. Environmental temperature, relative air humidity and atmospheric pressure are also recorded, while further sensors may be connected using SDI-12, UART or I2C connectivity.
Lastly, the price per count rate could be reduced to a large extent by replacing scarce and expensive ^{3}He by solid ^{10}B as a neutron converter. This novel detector therefore combines highly selective counting electronics with large-scale instrumentation technology tailored to the needs of an affordable cosmic-ray probe.

Tools

Chair: U. Schmidt

10:00

URANOS - modeling cosmic-ray neutron transport

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The precise interpretation of CRNS measurements was based on the fundamental understanding of neutron transport by Monte Carlo simulations. URANOS (**U**ltra **Ra**pid **N**eutron-**O**nly **S**imulation) is a free software package, which has been developed in the last years in a cooperation of Particle Physics and Environmental Sciences, specifically for the purposes of cosmic ray neutron sensing. Its directly accessible user interface and input/output scheme tailored for the CRNS method offers hydrologists straightforward first steps in setting up their model and directly performing advanced neutron transport calculations. A URANOS user models the geometry by a set of png images in which the colors stand for different predefined materials - allowing to construct objects on the basis of pixel graphics without a 3D editor. It furthermore features predefined cosmic-ray spectra and detector configurations, which allow for example a replication of an instrument site - from a small pond to the catchment scale. The simulation thereby gives precise answers to questions like: From which location do neutrons originate? How do they propagate to the sensor? How does the neutron flux change for specific environmental parameters? URANOS has been successfully applied to calculate the cosmic-ray neutron footprint, signals in complex geometries like mobile applications on roads, urban environments and snow patterns. In this contribution we present an overview about the features of this versatile tool for researchers.

10:20

Cornish Pasdy – COsmic-Ray Neutron flavored Processing and Analysis of Sensor Data in pYthon

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In this presentation we would like to promote the idea of a general and easy-to-use python package for data processing and discuss various approaches to get there.
Processing sensor data often follows the same steps and procedures every time: from downloading the data, applying temporal and spatial corrections, calculating a derivative and propagating errors, to drawing plots and maps and exporting harmonized tabular files. Pasdy has been developed to run through all those repeating workflows without requiring more than a gentle click on a button.
Pasdy is currently specialized on COsmic-Ray Neutron data, that‘s why it has a subtle CORNish flavour. The concept of Pasdy is to allow for various ways of usage depending on the level of detail and interaction required by individual users. It can be used either in the console, by double click, in jupyter notebooks, imported as a package, and even in a GUI interface. In any case, all of the calculation steps in the tabular output can be used later on for further analysis. This way, cosmic-ray neutron data becomes accessible for everyone: users without deeper knowledge of the science behind it, and for scientists alike.

10:40

Cosmic-Ray Sensor Python tool (crspy): a python tool for harmonized processing of CRS data for global analysis

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Networks of Cosmic-Ray Sensors (CRS) have been set up around the world including in the USA, Australia, the UK, and Germany. As these networks have grown so has the literature surrounding best practices for calibration and correction of the sensor signals. However, due to a lack of a harmonized data processing steps across different networks, there is less opportunity to undertake a global big data analysis using the CRS technology.
To provide an easily accessible platform for multi-site comparison worldwide, we developed the Cosmic Ray Sensor Python tool (crspy). crspy (pronounced 'crispy') is an open-source Python tool which is designed to process CRS data from global networks in a uniform and harmonized way. The tool easily implements the most up to date correction factors and calibration processes to any CRS site globally. It is designed to collect relevant metadata for each site from several publicly available global datasets that will allow additional environmental and hydrological analysis. The structure of this package allows for an easy and quick implementation across many sites from the collections of publicly available data whether the site comes from an established network or it has been independently deployed by the user. Here, we present the crspy tool in details highlighting its features as well as showing example of applications for a selected number of sites.

11:00

Features of PARMA: PHITS-based Analytical Radiation Model in the Atmosphere

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The evaluation of the temporal and locational variations of cosmic-ray fluxes in the atmosphere is essential for various research fields such as the radiological protection of human and semi-conductor devices, the Earth science and geochronology using cosmogenic nuclide yields, and CRNS. We therefore developed an analytical model for calculating the cosmic-ray fluxes nearly anytime and anywhere in the atmosphere by fitting the results of airshower simulations performed by the Particle and Heavy Ion Transport code System PHITS (http://phits.jaea.go.jp). The model was named PARMA: PHITS-based Analytical Radiation Model in the Atmosphere.

The important features of PARMA to be utilized in CRNS are: (1) it is capable of calculating the angular differential fluxes of neutrons at ground level, considering the water density in soil, (2) it is freely available as EXCEL, Fortran, and C++ programs from the website of EXPACS (http://phits.jaea.go.jp/expacs), (3) the solar modulation potential used in the model is automatically evaluated from the count rates of several neutron monitors every day (https://wasavies.nict.go.jp/FFPday.txt). These features will be discussed in detail at the meeting.

Monte Carlo II

Chair: M. Schrön

12:00

MCNP6 and its galactic cosmic-ray source: A study about the production and propagation of cosmic ray neutrons in the Earth's atmosphere and what we may infer with respect to cosmic ray neutron sensing.

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Cosmic ray neutrons are produced as secondary particles in air showers when galactic cosmic rays penetrate the earth's atmosphere. These showers include a large variety of particle species. In particular, charged pions, protons and muons, which play an important role for the production and annihilation processes of cosmic-ray neutrons. The primary proton flux induces neutron production but protons also act as an intermediate production agent just like muons and pions. These are formed as secondary particles and may also induce neutron production via further showers or excitation of nuclei. The production of cosmic-ray neutrons, therefore, not only depends on the incoming flux of primary galactic cosmic rays but also on the specific propagation characteristics of these particles in the atmosphere.

Hence, the relationship between above-ground neutron intensities and environmental conditions such as atmospheric pressure or humidity content is coupled to the properties of all involved particle species. MCNP6 with its built-in galactic cosmic-ray source is capable of simulating these particles and therefore offers an elusive tool to emulate the complete history of a cosmic-ray neutron from creation to annihilation. Above-ground cosmic-ray neutron intensities strongly depend on the amount of air the neutrons and their precursor particles have to pass through. This varying influence may be corrected for by monitoring the atmospheric pressure, which is the major correction factor when neutron intensities are interpreted for soil moisture sensing. After experimental observations in the Alps created doubts about the accuracy of the currently used correction factors, MCNP6 is now applied to revise these by simulating a multitude of different atmospheric and magnetic field conditions. These Monte-Carlo simulations compared to several field observations at different pressure levels may hint to a potential revision of the atmospheric pressure correction.

12:20

Assessment of secondary neutron characteristics from galactic cosmic rays at mountain altitudes with Geant4 simulations and ground-based measurements of neutron energy spectra

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In this study, the Geant4 Monte Carlo toolkit was used to simulate secondary cosmic radiation, starting with primary cosmic ray particles hitting the atmosphere at 100 km a.s.l. and calculating the transport through the atmosphere down to ground level. The resulting neutron fluence as a function of atmospheric depth were determined.

Energy spectra of neutrons from secondary cosmic radiation were calculated at mountain altitudes for the Environmental Research Station "Schneefernerhaus" at the Zugspitze mountain, Germany (2,660 m a.s.l.) and for Sphinx astronomical observatory at the Jungfraujoch, Switzerland (3,585 a.s.l). The resulting neutron fluxes were compared with the measurements that had been performed at both locations by means of an Extended-Range Bonner Sphere Spectrometer. Measurement conditions were quite different for both locations – at Schneefernerhaus the measurements had been performed on the flank of a hill in March 2015 with much snow, while at Jungfrauchjoch the measurements had been performed on top of a steep rocky summit in September 2018 with much less snow. Despite these differences, agreement between measurement and simulation was reasonable at both locations, especially at neutron energies greater than 20 MeV where the hydrogen content of the environment (e.g., snow cover, soil moisture) has only a marginal effect on the neutron fluence. The results from the simulations were 11-35% higher than those from the measurements for the Schneefernerhaus, and were within $\pm$ 5-6% for Jungfraujoch, depending on the intra-nuclear cascade model used in the simulations.

The influence of snow height was simulated in a simplified geometry of a flat limestone ground at 2660 m a.s.l. with a layer of water from 0 to 50 cm on top. For a water layer thicker than 15-20 cm the neutron energy spectra do not change any more.

We would like to thank the staff of the UFS "Schneefernerhaus" for their long-term support in the ERBSS measurements, the staff of the High-Altitude Research Station Jungfraujoch, and the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat for free use of the infrastructure required for the measurements. This research received funding from the Bavarian State Ministry of the Environment and Consumer Protection, within the research project "Virtual Alpine Observatory" under contract number "71-1d-U8729-2013/193-5".