Development of a Non-Linear Measurement Operator for Cosmic Ray Soil Moisture Measurements in a Land Surface Model

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Introduction

Land surface models provide lower boundary conditions for a range of meteorological and climate models. Key state variables of land surface models are surface soil moisture and temperature, and water and energy fluxes between atmosphere and soil. Improvements in modeling these fluxes can be facilitated through a better representation of saturated and unsaturated flow processes in the aquifer and root zone domain. An approach to improve model state variables is data assimilation (DA) which implies the assimilation of soil moisture observations. Cosmic ray (CR) soil moisture measurements could represent a means to measure soil moisture on a model consistent resolution. CR probes bridge the gap between point scale and airborne soil moisture measurements. Effective absorption of neutrons by hydrogen nuclei in the soil yields a non-linear negative correlation between neutron flux density and soil moisture content. CR probes measure these neutron fluxes close to the earth surface.

In this study we installed ten CR probes in the Rur catchment (Germany). The performance of CR probes against a distributed soil moisture measurement network under humid conditions is tested. Knowledge of uncertainties and measurement principles will be used in the setup of a DA framework for a regional land surface model.

The motivation of this study is to improve soil moisture state variables and model parameters of a regional land surface model. The results may give some indication on how to improve current weather forecast and climate models on regional and global scale.

The objective of this study is to develop a non-linear measurement operator for DA and evaluate the benefits of CR soil moisture measurements in a DA framework.

Study Area and Model

Rur catchment: Area of 2360 km²; annual precipitation: 600-1300mm/year; elevation ranges between 16 and 690 m.a.s.l.; annual average temperature: 7-10 °C. The land use type is mainly agricultural in the flat Northern part, while coniferous and decidious forests dominate the hilly Southern part (Eifel).

A CLM 4 model was build for the Rur catchment:

- Spatial resolution 1 x 1 km, temporal resolution 1 hour
- Land use: Data product of ASTER / ATKIS (15 x 15 m; year: 2009)
- Precipitation: Station-corrected radar data (1 x 1km; hourly)
- Temperature, wind speed, air pressure, humidity, solar radiation from reanalysis data (German Weather Service)
- Soil parameters from German soil map BK50 (1:50 000)
- LAI time series from MODIS (1 x 1 km resolution)

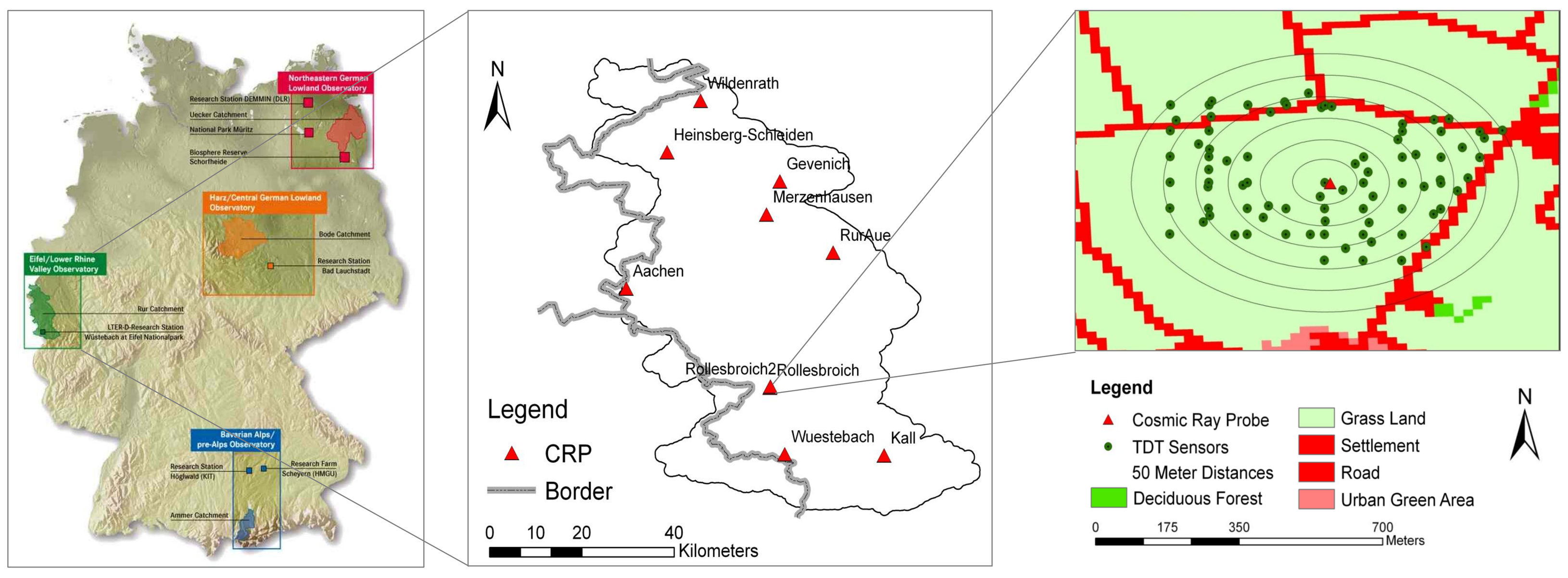

Fig. 1: Locations of the TERENO Observatories in Germany (left); location of the Rur catchment and ten installed cosmic ray probes (middle); detail of Rollesbroich cosmic ray validation site with land use and TDT sensors (right).

Cosmic Ray Validation Site (Rollesbroich)

- Managed grass land, pre-dominant soil type: Loam
- Over 504 time domain transmissivity (TDT) sensors installed in 5, 20 and 50 cm depth; measurements of air pressure, -humidity, -temperature, precipitation
- One cosmic ray probe measures since May 20th, 2011 until now
- Correction of raw neutron counts for overall incoming radiation, air pressure and water vapor at 2m above ground (Fig. 3 + 4 + 6)
- Use of eq. 1 (Desilets et al., 2010) to fit N_0 to vertically weighted TDT soil water content
- Derivation of vertical weighting function through best-fit of eq. 2 to the depth z_i at 86% cumulative fraction of counts (Fig. 2)
- The derived vertical weighting function eq. 4 is applied on the horizontally weighted soil water content measurements in three depths of the soil moisture sensor network

$$\theta_{vol} = \frac{a_0}{(N_{corr} / N_0) - a_1} - a_2 \qquad \text{Equation 1}$$

$$z_i = \alpha \cdot \ln(1 - CFoC) \qquad \text{Equation 2}$$

$$\alpha = \frac{-5.8}{\ln(0.14) \cdot (\theta + 0.0829)} \qquad \text{Equation 3}$$

$$w_z = 1 - e^{\left(-\frac{z}{\alpha}\right)} \qquad \text{Equation 4}$$

Θ_{vol} – volumetric soil water content
a_0 - a_2 – fitting parameters
N_{corr} – corrected neutron counts / hour
N_0 – Neutron source calibration parameter
z_i – depth i [cm]
$CFoC$ – Cumulative fraction of counts
α – fitting parameter for vert. weighting
w_z – weight of soil water content in depth z

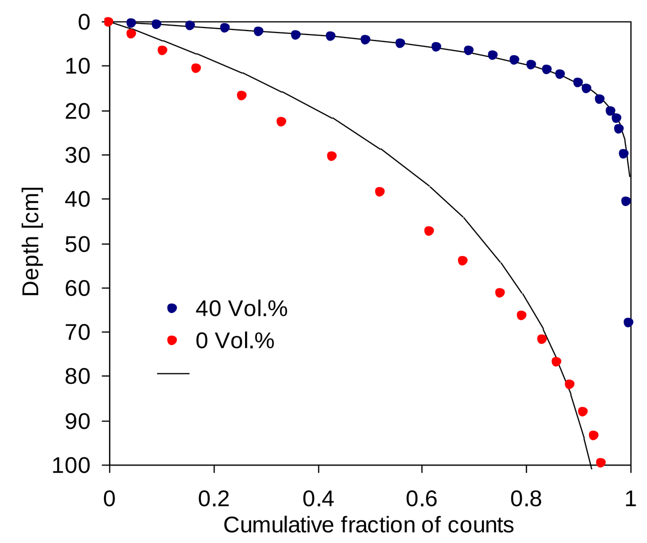

Fig. 2: Cumulative weighting function indicating the contribution of different soil layers to the total neutron count, for 0% soil water content and 40% soil water content, calculated with idealized monte carlo neutron particle modeling (Zreda et al., 2008).

Results

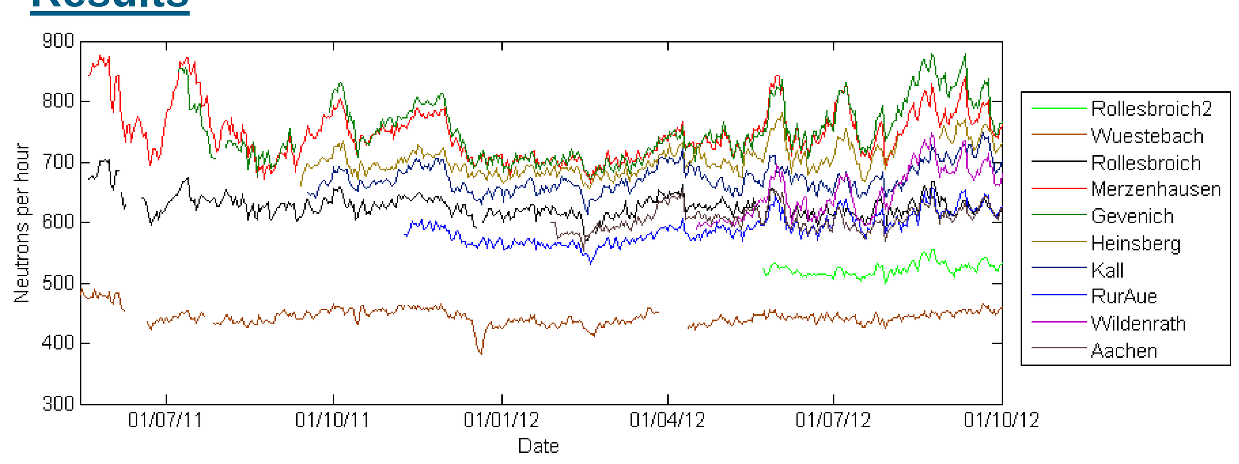

Fig. 3: Daily averaged neutron counts per hour corrected for pressure, incoming radiation and partially for absolute water vapor at ten locations in the Rur catchment normalised to sea level pressure (1013.25 hPa).

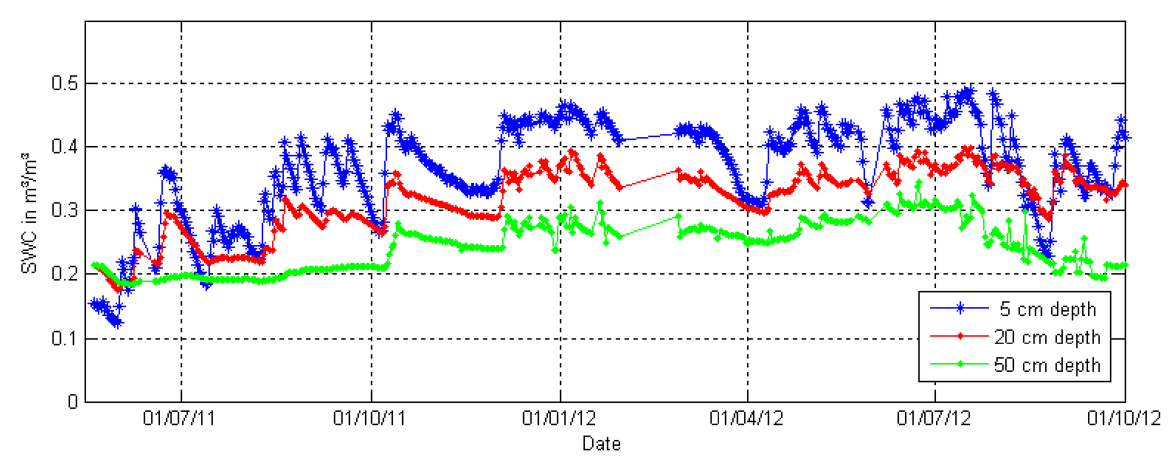

Fig. 5: Daily averaged horizontally weighted soil water content in three depths at the field site Rollesbroich measured by TDT-sensors.

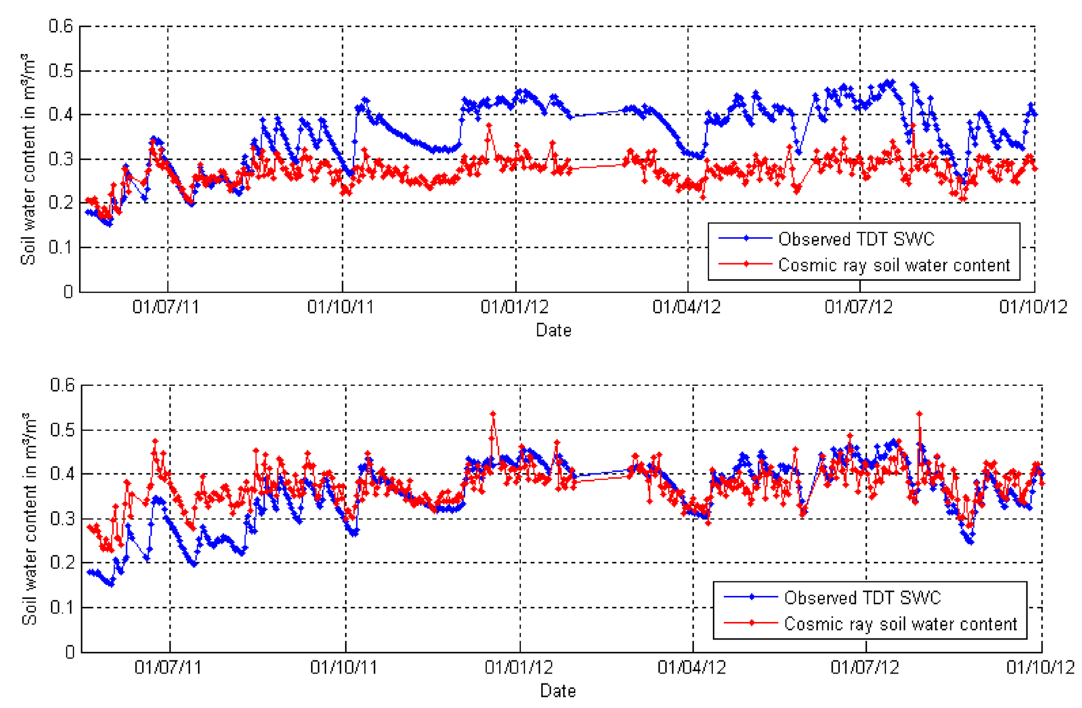

Fig. 7: Estimated soil water content and horizontally weighted soil water content of the TDT sensor network at the field site Rollesbroich for two shorter calibration periods: **(B)** 20th May – 20th Sept. 2011; **(C)** 20th Sep. 2011 – 7th Oct. 2012; R² and RMSE are for the calibration period respectively in as in table 1.

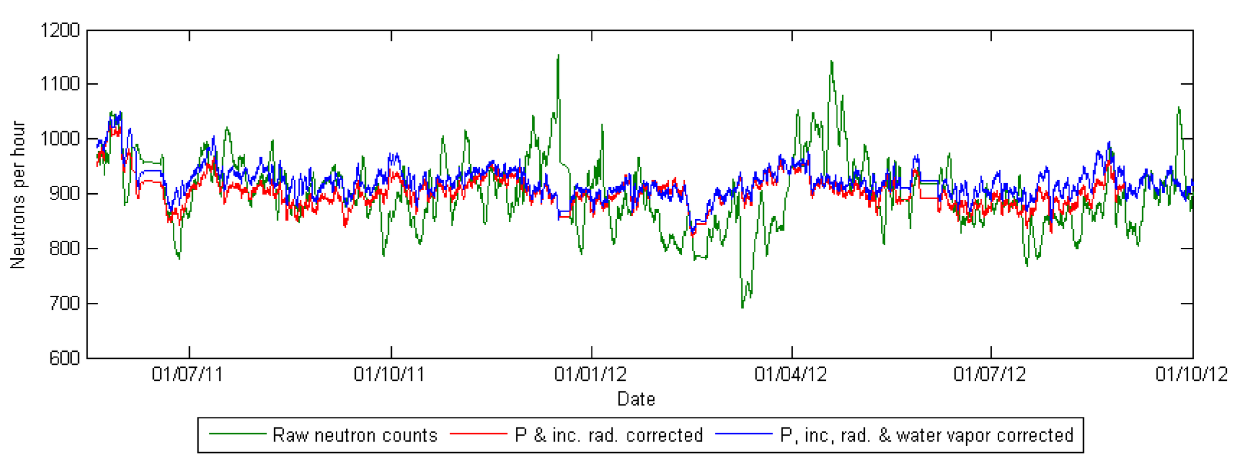

Fig. 4: 24 hour running mean neutron counts monitored by the cosmic ray probe in Rollesbroich: Raw counts, counts corrected for air pressure fluctations and incoming radiation; counts corrected for air pressure, incoming radiation and water vapor in 2m height.

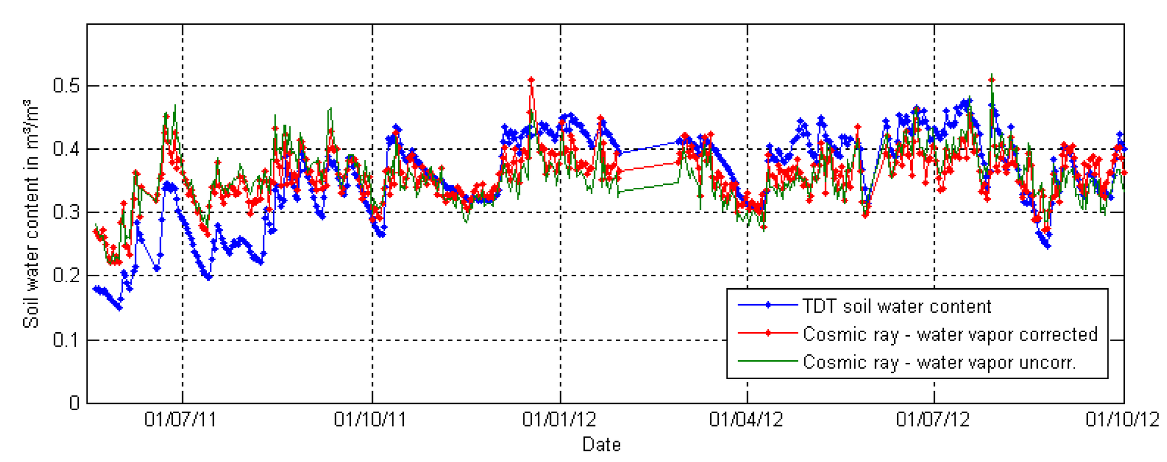

Fig. 6: Cosmic ray based soil water content and horizontally weighted soil water content of the TDT sensor network at the field site Rollesbroich for the whole measurement period. Visualisation of the benefits of water vapor correction by **A(1)** compared to no correction **A(2)** with RMSE and R² as in table 1.

Tab. 1: N_0 calibration results for the identifiers as in Fig. 6 & 7.

	N_0	R²	RMSE
A(1)	1696	0.561	0.049
A(2)	1662	0.369	0.058
B	1586	0.812	0.026
C	1714	0.518	0.035

Conclusions & Outlook

- Corrections for fluctuating incoming total cosmic rays, air pressure and water vapor improve soil moisture estimates significantly.
- Additional corrections for the relation between neutron counts and soil moisture content are investigated: corrections for variations in biomass and improvement of the correction of the temperature dependence of TDT sensors.
- Linear and non-linear weighting of the vertical soil moisture content distribution is subject of study.
- The cosmic ray based soil moisture data will be assimilated with Local Ensemble Transform Kalman Filter (LETKF); soil texture and vegetation parameters will also be updated. The relative value of the cosmic ray data will be explored.

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