Soil moisture measurements
Climatological and hydrological field work - FS2019

1 Introduction

Soil moisture is a key variable in the climate system. By controlling evapotranspiration, soil moisture impacts the partitioning of incoming radiation into sensible and latent heat flux. Furthermore, it represents an important water and energy storage component of the regional climate system. Regional simulations of recent and future climate conditions indicate that a projected increase in summer temperature variability and the occurrence of heatwaves in Central and Eastern Europe is mainly due to soil moisture-atmosphere interactions (Seneviratne et al., 2006).

During the field work we will explore how soil moisture varies in space and get a feeling for measurement uncertainty. For the analysis, we will have more data available (e.g. continuous in-situ measurements) in order to investigate the temporal variability of soil moisture. You will quickly find that in-situ measurements are sparse both in time and space when you want to study soil moisture-atmosphere interactions at a larger scale. You will then need to turn to alternative techniques such as satellite measurements or land surface model based soil moisture. As you will find out, these data products have their own specific properties and limitations compared to the in-situ measurements.

2 Data

The following data will be available or you will need to collect it:

1. **Vertical and temporal** i.e. the variation of soil moisture with depth and time
   (a) *At the point scale:*
      - In-situ soil moisture measurements at Büel at six depths.
   (b) *At the grid cell scale:*
      - Land surface model based soil moisture from ERA5 at four levels.

2. **Horizontal** i.e. the variation of soil moisture in space (near surface)
   (a) *At the point scale:*
      - Measurement strategy to be defined (discussion on site).
      - Take measurements with a hand-held sensor.
      - Documentation of the measurements and associated information.
   (b) *At the grid cell scale:*
      - Remotely sensed soil moisture at 0.25°resolution.
      - Land surface model based soil moisture from ERA5 0.25°resolution.
3. Additional data

- All data that is measured at the Rietholzbach station is available and may be used for the analysis (e.g. precipitation measurements).

3 Definitions

The volumetric soil moisture content (or simply soil moisture content) of a soil ($\theta$) is defined as the volume of water $V_w$ that can be removed from a volume of soil $V_s$ by drying the soil at 105°C:

$$\theta = \frac{V_w}{V_s} [m^3/m^3].$$

(1)

Often, $\theta$ is expressed as a percentage rather than a fraction (i.e., by multiplying by 100%). The porosity of the soil (the relative volume of pores in a soil sample) represents the maximum soil moisture content. Another often used quantity, although poorly defined, is the field capacity (FK in Figure 1). A practical definition of field capacity is the soil moisture content that cannot easily be removed by gravitational forces, and is defined as the volumetric water content at a suction head (negative pressure) of 63 to 330 hPa (1.8 to 2.5 pF). It is often associated with the soil moisture that remains after 2-3 days since the last major rainfall.

![Diagram of soil moisture tension vs. volumetric water content for different soil types](image)

Figure 1: Relation between suction head and volumetric water content for different soil types (adapted from Scheffer, 2002).

The permanent wilting point (PWP in Figure 1) is the soil moisture content below which plant roots can no longer extract water from the soil matrix. It is often defined as the volumetric moisture content at a suction head of 15000 hPa (4.2 pF). The water
which is available for the plants is within the field capacity and the permanent wilt-
ing point. Figure 1 illustrate the relation between suction head and volumetric water
content for different soil types.

In water balance calculations, the total amount of water $S_i$ stored in a particular soil
(or model) layer per unit area is important. This quantity is obtained by multiplication
of the fraction of water (volumetric soil moisture content) in layer $i$ ($\theta_i$) by the depth of
the layer $z_i$:

$$S_i = \theta_i z_i.$$  \hspace{1cm} (2)

4 In-situ soil moisture measurements

Although the moisture content of a soil can be determined by weighing and drying of
soil samples (the so-called gravimetric method), this method is destructive and hence
not very practical for continuous monitoring, or when a large number of measurements
is required. Most of the alternative methods to measure soil moisture are based on the
high relative permittivity $\epsilon$ of water ($\sim 80$) in comparison to air ($\sim 1$) or stone ($\sim 4-6$).

One technique that utilizes the soil moisture content dependency on $\epsilon$ is referred to
as Time Domain Reflectometry (TDR). Due to the relative permittivity of materials (in
our case soil), an electromagnetic wave traveling through it will experience a charac-
teristic velocity $v$:

$$v = \frac{c}{\sqrt{\epsilon \mu}} \quad \text{and} \quad \epsilon = \left(\frac{c t}{2L}\right)^2,$$  \hspace{1cm} (3)

where $c$ is the speed of light, $\mu$ the relative magnetic permeability of the soil ($\sim 1$), $t$
the travel time of the TDR pulse, and $2L$ the travel path of the wave. Since the travel
time of electromagnetic waves through soil is a function of the effective $\epsilon$, and the rela-
tive contribution of water to $\epsilon$ is a factor 20 larger than all other (in)organic soil parts,
the travel time is mainly a function of the water content.

At the measurement site in Büel, soil moisture is measured continuously (at 10 min
resolution) with 4 different soil moisture sensors at 6 depths (range -5 to -110 cm) since
May 2009. Additionally, soil moisture is measured continuously (with hourly resolu-
tion) in two profiles since 1994. These data will be available to you.

During the field course, you will conduct your own measurements with a TRIME
1GHz TDR system (see Figure 2). This system is supplied with different sensors types,
i.e. for measurements in a tube (for the vertical profiles) or with rods (for the horizontal
profile). The TRIME has a built-in relation between $\epsilon$ and $\theta$ based on Topp et al. (1980),
and outputs volumetric soil moisture content directly.

5 Satellite-derived soil moisture

Like the in-situ soil moisture method, remotely sensed soil moisture also relies on the
high relative permittivity $\epsilon$ of water in comparison to air or stone. However, the total
signal (as received by the satellite) is not just dependent on soil moisture conditions but
is also influenced by e.g. the vegetation canopy and the atmosphere. Information from
the ESA-CCI soil moisture project (Dorigo et al. 2017) will be available to you. This
product is a 40-year long (1979–2018) soil moisture data set that has been generated
by combining multi-satellite active C-band scatterometer data (ERS-1/2 scatterome-
ter, METOP Advanced Scatterometer) and multi-frequency radiometer data (SMMR,
SSM/I, TMI, AMSR-E, Windsat, AMSR2). Spatial coverage is global and the resolution is 0.25°(about 27km).

6 Reanalysis soil moisture

Reanalysis data products combine models with observations by correcting the model solution towards available observations. In the reanalysis data set ERA5, most of the assimilated observations concern atmospheric variables. However, satellite derived soil moisture measurements from active remote sensing scatterometers are ingested as well. In ERA5, the land surface model H-TESSEL (Balsamo et al. 2009) is used to obtain soil moisture. In this discretized model, subsurface water fluxes are computed with Darcy’s law in four vertical layers (individual layer depths are: 7 cm, 21 cm, 72 cm, 189 cm). The top boundary condition is determined by infiltration and surface evaporation. At the bottom, free drainage is assumed. Each layer has an additional sink of water in the form of root extraction. This soil moisture product is a 40 years long (1979 – 2018). The spatial coverage is global and the resolution is 0.25°(about 27km).

7 To Do in the field

In the field work you will survey the spatial variability of soil moisture around the Büel experimental site. First, you will be given a short introduction to the role of soil moisture in the climate system and the TRIME 1GHz TDR hand-held soil moisture sensor. Then, we propose you conduct the two following experiments. Additional ideas are encouraged.

1. Uncertainty of soil moisture measurements

In this experiment, your objective is to discuss and quantify the uncertainty of your measurements.
Question 1 What are the different sources of uncertainty which could affect your measurement at one location?

Question 2 How would you quantify these different sources of uncertainty?

Question 3 What could you do to reduce these uncertainties?

Question 4 What level of uncertainty do you consider acceptable? What are the consequences for your planned work?

2. Spatial variability of soil moisture
   In this experiment, your objective is to gather some information on the spatial variability of soil moisture around the main experimental site.

   Question 1 What landscape characteristics would you expect to influence the spatial variability of soil moisture?

   Question 2 Where do you want to make your measurements? Points to consider could be a sufficiently large and dense spatial coverage of the feature of soil moisture variability which you are interested in.

   Question 3 What information needs to be recorded (time, coordinates, weather...)?

   Question 4 What about soil information, is it important? how would you determine the soil texture and porosity?

   Question 5 Try to think about how you will analyze and present the collected information. What type of figure or table would you want to show as a main result?

8 References


Appendix A  Defining an appropriate sample size

1. Theoretical background

The central limit theorem (CLT) states that as the number of independent observations becomes large, their arithmetic mean will be approximately normally distributed, regardless of the underlying distribution (Wilks, 2011).

Given \( \{x_1, ..., x_n\} \), a random sample of size \( n \), the distribution of the sample mean \( \bar{x} \) will tend to a gaussian distribution as \( n \to \infty \):

\[
\bar{x} \sim \mathcal{N} \left( \mu, \frac{\sigma}{\sqrt{n}} \right)
\]  

(4)

With uncertainty confidence intervals given by

\[
P \left( \bar{x} - z_{\alpha/2} \frac{\sigma}{\sqrt{n}} < \bar{x} < \bar{x} + z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \right) = 1 - \alpha
\]

(5)

Where \( z_{\alpha/2} \) is the critical value at which \( P(Z > z_{\alpha/2}) = \alpha/2 \) for the standard normal distribution \( Z \sim \mathcal{N}(0,1) \). However, this theorem will not hold for small sample sizes (\( n < 30 \)). If we assume that the underlying random variable is normally distributed, then the Student distribution is appropriate:

\[
P \left( \bar{x} - t(n-1)_{\alpha/2} \frac{\sigma}{\sqrt{n}} < \bar{x} < \bar{x} + t(n-1)_{\alpha/2} \frac{\sigma}{\sqrt{n}} \right) = 1 - \alpha
\]

(6)

Where \( t(n-1)_{\alpha/2} \) is the critical value at which \( P(T > t_{\alpha/2}) = \alpha/2 \) for a Student distribution with \( n - 1 \) degrees of freedom (d.o.f).

2. In practice...

Step 1 Choose a given location and take \( n = 10 \) independent measurements.

Step 2 Compute the sample mean \( \bar{x} \) and standard deviation \( \sigma \).

Step 3 Choose a confidence level (e.g. 90%) and get \( t(n-1)_{\alpha/2} \) from Table 1.

Step 4 Compute the confidence interval using equation 6.

Step 5 Repeat steps 3-4 for smaller values of \( n \) and look at how the confidence interval becomes larger when using smaller sample sizes.

Appendix B  How to determine soil texture
Table 1: Table of critical values for Student’s $t$ distribution

<table>
<thead>
<tr>
<th>$d.o.f \ \alpha/2$</th>
<th>0.1</th>
<th>0.05</th>
<th>0.025</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>3.078</td>
<td>6.314</td>
<td>12.706</td>
</tr>
<tr>
<td>2</td>
<td>1.886</td>
<td>2.920</td>
<td>4.303</td>
</tr>
<tr>
<td>3</td>
<td>1.638</td>
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<tr>
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<td>1.533</td>
<td>2.132</td>
<td>2.776</td>
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<td>1.476</td>
<td>2.015</td>
<td>2.571</td>
</tr>
<tr>
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<td>1.833</td>
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<tr>
<td>10</td>
<td>1.372</td>
<td>1.812</td>
<td>2.228</td>
</tr>
</tbody>
</table>

Figure 3: Soil Texture Triangle (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054311).
Figure 4: Manual for soil texture determination (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054311).