Anonymous Referee #1

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This MS describes the new soil moisture monitoring network SOMOMOUNT launched in 2013 consisting of 6 soil moisture stations distributed along an altitudinal gradient between the Jura Mountains and the Swiss Alps.
Soil moisture monitoring in areas with low sensor density like Alpine regions is important e.g. for validation of global models and remote sensing products. Thus, it fits well to the scope of this journal.
The MS is mostly written in an understandable way. However part of the text is not well comprehensible and too speculative. Also, there are major issues regarding the methods and interpretations of the results (see comments below).

General comments:

Soil water content measurements: This study uses electromagnetic (EM) sensors to measure soil water content. It is very important to understand that this is an indirect measuring method and that EM sensors are only sensible to changes of the dielectric properties of the soil (i.e. the permittivity). To determine soil water content, EM sensors make use of the strong dependence of EM signal properties on volumetric water content that stems from the high permittivity of liquid water (_80) compared to mineral solids (2–9), and air (1), see e.g. Bogena et al., 2007. However, it is well known that the permittivity of pure ice is extremely lower compared to liquid water (_2-3) (e.g. Aragones et al., 2010). Therefore, during frozen soil conditions, the EM signal will decrease considerably, while the total soil water content stays the same. In addition, typically not all liquid water freezes at soil temperatures below 0_C, depending on the temperature, salinity, initial moisture, and soil texture (e.g. Zhang et al., 2003). Thus, the EM sensor determines the apparent permittivity of a mixture of liquid water, ice, mineral solids and air, with their respective permittivities. Consequently, the senor calibration determined for unfrozen soil is not valid any more (see e.g. Watanabe and Wake, 2009). From these theoretical considerations it becomes clear that the EM derived volumetric soil water content data shown in the EM during frozen soil conditions is not correct. This also means that the interpretations of the data are, at least partly, incorrect.

These problems are also very important with respect to publishing the data for validation purposes of global models. Clearly, a comparison of the erroneous volumetric soil water contents presented in this MS with model results will lead to deceptive deviations for frozen soil conditions.

Consequently, the authors either need to calculate the total soil water content, e.g. using the expanded dielectric mixing model presented by Watanabe and Wake (2009) or otherwise they would need to restrict their analysis to periods without soil freezing.

We are thankful to the reviewer for this important and detailed comment. While we are fully aware of the limitations of the electromagnetic methods in case of frozen conditions, we have failed to explain it accordingly in our manuscript. In this paper, we only consider the liquid water content given that both the TDR and the FDR technique are unable to measure the total water content in frozen conditions unless a dielectric mixing model is applied. At the moment we do not have all the parameters needed for the application of such models and we feel that it would constitute a study in itself.

We agree with the reviewer that liquid VWC measured at temperature below the freezing point should be handled with caution and identified as such. The calibration procedure and resulting sensor accuracy described in this manuscript is only valid for ground temperature above 0°C. Under frozen conditions, the accuracy of absolute measurement is difficult to assess. According to Watanabe and Wake (2009), for sands the application of Topp's empirical relationship in frozen

conditions shows only small deviations from the measured total VWC using NMR except for temperatures between 0 and -1°C.
However, from previous knowledge based on the continuous monitoring of ground electrical resistivity (based on Electrical Resistivity Tomography measurements) we are confident that the relative changes in liquid VWC are well captured. At Schilthorn, Hilbich et al. (2011) identified the same VWC (measured with similar FDR devices as in the present study) and temperature stages than the ones presented in this manuscript. These stages were compared to the measured apparent resistivity in the uppermost 50cm, which similarly to the electromagnetic technique is highly sensitive on the amount of unfrozen water content and is able to detect variations even at T <0°C (cf. Hauck 2002). This comparison showed that the timing of VWC increase measured with FDR sensors is consistent with resistivity decrease and the same stages (frozen, zero-curtain and unfrozen) were identified.

In order to fully answer this important comment in the manuscript we added an additional sub-section (3.1 *Technical considerations for frozen conditions)* after the calibration part:

"3.1 Technical considerations for frozen conditions

Given the high-elevation application of the FDR and TDR techniques at field sites which undergo freezing and thawing processes, some considerations are important to make. As mentioned above both techniques make use of the high permittivity of liquid water (~80) compared to the surrounding soil and air (2-9 and 1, respectively) to relate the recorded electromagnetic signal to the VWC. However, the permittivity of liquid water is sensitive to temperature variations and can increase from ~80 at 20°C up to ~88 at 0°C (e.g. Wraith and Or, 1999), thus introducing an additional uncertainty in the calibration for unfrozen conditions. Furthermore, under frozen conditions a part of this total water turns into ice, which has a much lower permittivity (~2-3, e.g. Aragones et al., 2010). Thus, upon freezing, the recorded signal and measured VWC strongly decreases although the total VWC stays constant. Given these limitations, the term VWC used hereafter is always referring to the liquid VWC.

Characteristically, at temperature below 0°C water and ice can coexist in the soil (e.g. Spaans and Baker, 1995). However, the calibration procedure presented was conducted at room temperature and thus does not account for the presence of ice in the soil mixture. The resulting sensor accuracy is therefore only valid for above 0°C ground temperature (unfrozen conditions). The use of standard empirical calibration in frozen conditions often yields overestimations of the liquid VWC (e.g. Spaans and Baker, 1995; Yoshikawa and Overduin, 2005). However, according to Watanbe and Wake (2009), for sand the calibration using Topp's empirical relationship in frozen conditions shows only small deviations from the measured total VWC using NMR except for temperatures between 0 and -1°C.

Although the absolute accuracy of measured liquid VWC under frozen conditions is difficult to assess, the relative changes are well captured. At SCH, Hilbich et al. (2011) showed that the soil apparent resistivity (using data from continuous ERT monitoring) and soil moisture (measured with similar FDR devices as in the present study) exhibit consistent variations under frozen and unfrozen conditions. Given the sandy composition of the ground at SCH and STO as well as the evidence from the coinciding resistivity measurements (cf. also Hauck 2002), we find the liquid VWC data to be consistent enough to be used here with the standard calibration described above. However, the VWC measurements carried out at temperatures below 0°C are clearly identified in all figures in the manuscript and have to be interpreted with care, especially regarding their absolute values."

Additionally, using the standard temperature quality flag (Dorigo et al., 2013), we clearly identified all VWC measurement made at temperature below 0°C in all the relevant figures of the revised version (new versions of Figures 5-9). We also clearly stated that whenever the term VWC is used in the manuscript it always refers to liquid VWC. The manuscript was entirely reviewed to clarify, wherever necessary, that only liquid water content is considered.

Finally, instead of showing the detailed evolution of the liquid VWC at Stockhorn, we show the liquid VWC, snow and temperature evolution at Schilthorn including the measured specific resistivities of the uppermost 1m of the ground in the revised version of figure 7(see below). Similarly to the observation of Hilbich et al. (2011), the relative changes of VWC are matching the evolution of the electrical resistivities. A corresponding paragraph was included in the text:

“Although, the accuracy of the soil moisture measurements during the frozen and zero-curtain periods is difficult to assess due to the presence of ice, the relative changes and thus the timing of each phase is well captured. The liquid VWC variations are coherent with the change of specific resistivity in the uppermost ~50 centimetres of the ground. Similar to dielectric permittivity, electrical resistivity is highly dependent on the amount of unfrozen water content in the ground (Hauck 2002). The frozen stage is thus characterized by high resistivities and a marked drop is observed during the zero-curtain period due to the thawing of the ground (see also Hilbich et al. 2011). Finally, the unfrozen stage exhibits the lowest resistivity values.”

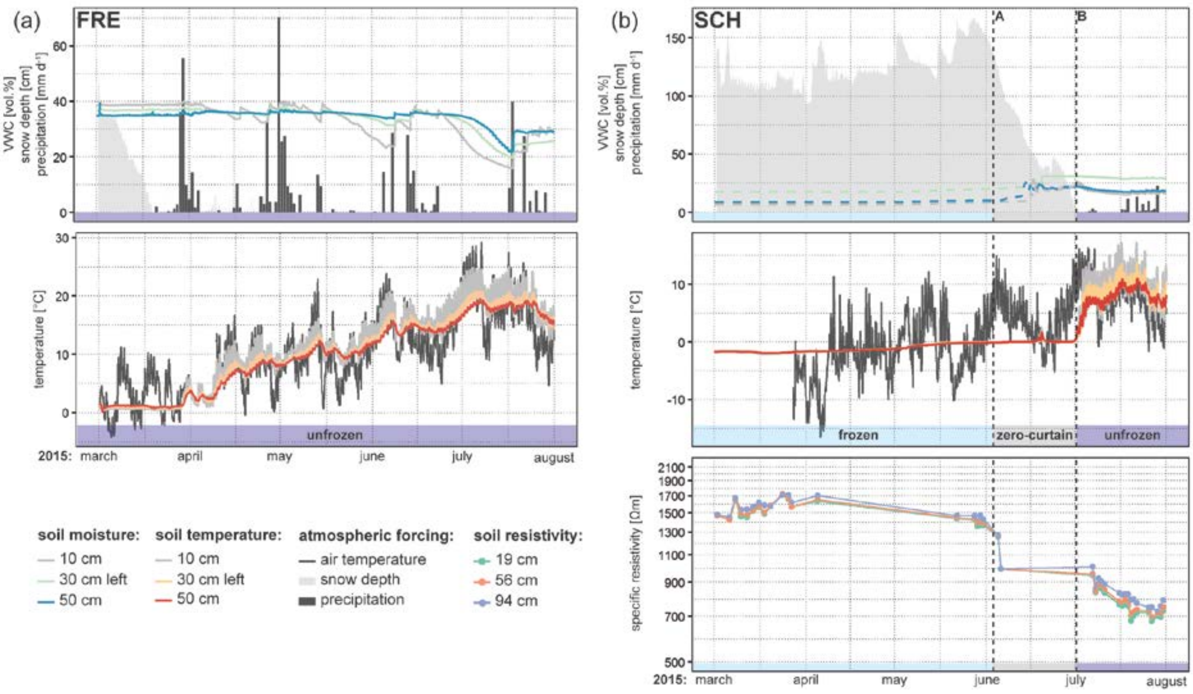

Fig. 7: Measured liquid VWC, ground temperature and soil resistivity at FRE (a) and SCH (b) from March to August 2015. In addition, daily air temperature, snow depth and precipitation sums are shown as well as the date of the transition between the different stages in the thermal evolution at SCH at 10cm (dashed lines A and B, see text for details). The dashed VWC lines represent the soil moisture measurements taken at ground temperature below 0°C.

Hauck, C.: Frozen ground monitoring using DC resistivity tomography. Geophysical Research Letters, 29 (21): 2016, doi: 10.1029/2002GL014995, 2002.
Hilbich, C., Fuss, C., Hauck, C.: Automated time-lapse ERT for improved process analysis and monitoring of frozen ground, Permafrost and Periglacial Processes 22(4), 306-319, DOI: 10.1002/ppp.732, 2011.

EM sensor calibration: The authors used TDR sensors as reference for the SMT100 sensors. However, they only used the empirical, soil unspecific function of Topp et al. (1980) to relate the permittivity measurements to soil water content. However, many studies showed that depending on the soil properties this can lead to uncertainties in the soil water content estimates (e.g. Robinson, 2004). Thus, the reference quality of the TDR data is questionable. The more advanced calibration approach presented by Rosenbaum et al. (2010) using the CRIM model would be more preferable to determine reference soil water content data.

We thank the reviewer for this pertinent comment. We are aware of the limitation of the soil unspecific calibration function of Topp et al. (1980). However, in this study the TDR sensors are only used for inter-network comparison with the SwissSMEX network but not for further analysis. Thus, for consistency we adopted the same approach as Mittelbach et al. (2011) and used the built in calibration of the TDR sensors. The text regarding the use of TDR as reference was clarified accordingly. As for the FDR sensors, the VWC measurement carried out at temperatures below 0°C are clearly identified in all the figures (5 and 6).

Original manuscript

"For the PICO64, the built-in calibration based on Topp's equation (Topp et al., 1980) was used and no additional material specific calibration was performed according to Mittelbach et al. (2011). In our study, the PICO64 is mainly used as reference sensor regarding future comparison of data between the SwissSMEX soil moisture network and the SOMOMOUNT network."

Revised version:

"For the PICO64, the built-in calibration based on Topp's equation (Topp et al., 1980) was used and no additional material specific calibration was performed. In this study the PICO64 sensors are only used for inter-network comparison with the SwissSMEX network but not for further analysis. Thus for consistency we adopted the same calibration approach as Mittelbach et al. (2011) (i.e. the built in calibration for generic soils)."

Interpretation of the data: The authors used so-called moisture orbits to analyse the soil water content data and to determine the dominate soil hydraulic processes. This is a quite appealing way to present the soil water content data and interesting pattern were shown. However, the interpretation of these patterns is at times very speculative and partly unrealistic if not completely wrong (see specific comments for examples).

We are thankful to the reviewer to point out the critical passages and for the input to our discussion of the results. We carefully reviewed our interpretations of the different moisture orbits and revised the manuscript according to the specific comments (see answers below).

Specific comments

P3 L20: This paper is not accessible. You should refer to the paper of Qu et al. (2013), which thoroughly described and tested the SPADE sensor, which is the successor of the SISOMOP sensor and precursor of the SMT100. All three sensor types are using exactly the same technique (ring oscillator) and only differ in their specific design (e.g. plastic material, sensor output etc.).

We are thankful to the reviewer for pointing out this fact and modified the reference accordingly.

P4 L4-7: I do not think that the technical description is fully correct. See Evett et al. (2006) for a detailed description of the Delta-T PR1/6 Profiler (precursor of the PR2/6).

We thank the reviewer for this comment and modified the technical description of the PR2/6 according to Verhoef et al. (2006). It now reads:
"Finally, the PR2/6 sensor is a 100cm long down-hole water content sensor measuring soil moisture at 6 different depths (10, 20, 30, 40, 60 and 100cm) using the capacitance technique (Fig. 2). Each measurement depth comprises a pair of stainless steel rings, which transmit the 100 MHz electromagnetic signal into the ground, and one detector, which records the returned signal. This technique relies on the fact that the emitted wave generates an electromagnetic field, which extends about 100mm into the surrounding soil and depending on its dielectric properties and thus on the VWC is partly reflected (Verhoef et al., 2006)."

P8 L14: Arithmetic mean?

We are thankful to the reviewer for this question and clarified this point in the text.

P9 L24-25: Different relationships might be due to specific soil properties. Since this is a purely empirical approach, I don't see the need for using the linear model for reasons of consistency. Instead the best model should be used to provide the best relationship between sensor output and soil water content.

We thank the reviewer for this comment. We agree with the reasoning and changed the sensor calibration accordingly. The sensor outputs were calibrated at DRE using the exponential fit and all relevant figures and text parts have been updated with the new calibrated values.

"Thus, the linear calibration is used for all sites since except at DRE, where the exponential one is preferred"

P10 L6-7: This is not plausible. Deviations are more likely due to small scale heterogeneities of the soil. Please remember that the SMT100 is only sensible to EM properties of the soil directly surrounding the sensor blade (just some mm to cm).

We thank the reviewer for this comment and clarified the sentence accordingly.

Original manuscript:
"Deviations from the one-to-one correspondence of the two sensors (black line) can be attributed to time delays in infiltration events and/or evaporation events."

Revised version:
"Deviations from the one-to-one correspondence of the two sensors (black line) can be attributed to small scale heterogeneities in the soil directly surrounding the sensors, which can result in differences of reaction time to the infiltration and/or evaporation events as well as wet or dry bias due to different soil properties"

P10 L10-14: Again not plausible. The deviations are due to the different soil properties, which directly influence the measurements.

We are thankful to the reviewer for pointing out this fact. The mentioned section was modified accordingly.

Original manuscript:
"At DRE (Fig. 4b) the right sensor shows consistently higher values (~5-10 vol.%) than the left sensor, but the relation between the measured VWC values is almost constant. This is due to the soil composition (sandy loam rich in organic matter and with a very low bulk density), which has a high

hydraulic conductivity leading to almost instantaneous increase in VWC following precipitation events."

Revised version:
"At DRE (Fig. 4b) the right sensor shows consistently higher values (~5-10 vol.%) than the left sensor, but the relation between the measured VWC values is almost constant, illustrating the effect of different soil properties."

P10 L14 (K instead of °C)

We modified the manuscript accordingly.

P10 L14-17: Unclear which physical processes you are referring to.

The text was modified by explicitly adding the physical processes we are referring to.

"DRE is also the site with the largest RMSE (0.566°K) between the measured temperatures at 30cm depth, indicating that specific physical processes ***such as the convective heat transport through air flow*** *(e.g. Wicky and Hauck 2016) may influence the two sensors in a different way (see Sect. 5.3)."*

Wicky, J., & Hauck, C.: Numerical modelling of convective heat transport by air flow in permafrost-affected talus slopes. The Cryosphere Discuss., 1–29, doi:10.5194/tc-2016-227, 2016.

P10 L28-29: Unclear why freezing and thawing should explain the differences. The wet bias could be explained by the unreliable TDR calibration using the Topp equation.

We thank the reviewer for this helpful comment. As seen in Fig.6 and mentioned in our above answer to the major comments, the largest changes in VWC at SCH and STO occur during the freezing/thawing of the ground. The observed relative VWC changes have been found to be consistent with ERT measurements and thus we believe them to be well captured. Due to soil heterogeneities and differential influence of the snow cover, the onset of freezing/thawing can differ significantly even at very small spatial scale, which creates easily strong deviations in determined unfrozen water content values at the sensor positions (e.g. Scherler et al. 2010, Hilbich et al. 2011, Pellet et al. 2016). The identification of the frozen and unfrozen period in the figure shows that the timing of the major deviations corresponds to the thawing period of the ground, further supporting our interpretation.

However concerning the wet bias at SCH we share the point of view of the reviewer and changed the text accordingly.

Original manuscript:
"At SCH and STO the differences between the sensors have a characteristic shape, but are centred on the one-to-one relation. It can be attributed to different onset of freezing and thawing processes at the two sensor locations (see also Fig. 6e-f). Additionally, a clear wet bias in the PICO64 measurements can be observed at SCH."

Revised version:
"At SCH and STO the differences between the sensors have a characteristic shape, but are centred on the one-to-one relation. It can be attributed to different onset of freezing and thawing processes at the two sensor locations marked by the grey dots (see also Fig. 6e-f). Additionally, clear wet and dry biases in the PICO64 measurements are observed at SCH and STO, respectively, which can be

explained by an unreliable calibration using Topp's equation for the high-mountain subsurface material present at SCH and STO (e.g. Robinson et al., 2004)."

P11 L12: Unreliable soil water content measurement due to frozen water.

The absolute values may be unreliable during freezing (see our answer to **general comments**), but the period of minimum values in winter is robust and not uncertain, as show the complementary data sets from electrical resistivity (inverse of conductivity) measurements. These were now included in the revised version of Figure 7.

P13 L20: What do you mean with "transfer"

The manuscript was modified in order to clarify this sentence.

Original manuscript:
"The shape of the resulting point cloud depends on the nature and speed of the water transfer processes, as well as on soil properties such as hydraulic conductivity, degree of saturation and porosity."

Revised version:
"The shape of the resulting point cloud depends on the nature and speed of the vertical transport of water through the soil layers, as well as on soil properties such as hydraulic conductivity, degree of saturation and porosity."

P13 L25-27: Which sensors were used? How did you derive the soil water contents for the profiles (simple arithmetic mean, weighted mean etc.)?

We thank the reviewer for this comment and specified in the text that only the SMT100 sensors have been used for the all moisture orbit analysis. The profile probe and the PICO64 were not considered.

Original manuscript:
"To investigate the seasonal dynamic of soil moisture, we used the moisture orbits between 10 and 50 cm depth for the year 2015 (Fig. 9)."

Revised version:
"To investigate the seasonal dynamic of soil moisture, we used the moisture orbits between the SMT100 sensors installed at 10 and 50 cm depth for the year 2015 at each site (Fig. 8)."

P14 L1-4: This is an indication for preferential flow processes. Dry top soils tend to bypass precipitation water (see e.g. Wiekenkamp et al., 2016).

We are thankful to the reviewer for this comment and changed the text accordingly.

Original manuscript:
"It indicates that at MLS the near surface VWC did not recover from the increased evaporation generated by the heat wave in July 2015 (cf. Fig. 6). "

Revised version:
"It indicates that at MLS the near surface VWC did not recover from the increased evaporation generated by the heat wave in July 2015 (cf. Fig. 6). The dry top soil conditions can generate a large water potential gradient with depth and thereby an increased infiltration capacity but also suitable

conditions for potential preferential flow processes which tend to induce bypass flow of precipitation water (e.g. Wiekenkamp et al., 2016).

P14 L5-6: Difference in precipitation sums is too small to explain this difference.
P14 L7-9: Not plausible. Evapotranspiration rates in this climate are mainly depending on meteorological forcing and vegetation characteristics.

We agree with the reviewer and carefully revised our interpretation of the effects of the July 2015 heat wave observed at FRE and MLS. Looking at the measured air temperature and incoming radiation, one can see that the meteorological anomaly during heat wave was of similar amplitude at both sites. Furthermore, according to MeteoSwiss the calculated potential evaporation for the three weeks period is in the same range (186mm at MLS and 203mm at FRE). Thus the larger VWC decrease observed at MLS can be attributed to a lower limitation of actual evaporation than at FRE due to higher initial VWC. The manuscript was modified as follow:

Original manuscript:
"On the contrary, at FRE the VWC returned to its original value. This can be explained by two main factors namely the precipitation regimes and the soil properties. MLS received less precipitation than FRE (1036 mm y^{-1} and 1254 mm y^{-1} respectively in 2015, MeteoSwiss), which hampered the full recovery of soil moisture conditions after the heat wave. Additionally, the absolute quantity of water lost at MLS was much larger due to stronger evaporation. The amount of water available for evaporation is dependent on the soil properties. At MLS the soil type is silty loam and is able to retain more water than the sandy loam (soil type at FRE)."

Revised version:
"On the contrary, at FRE the VWC returned to its original value. Comparatively, both sites received a similar amount of precipitation following the heat wave, from July to end of 2015 (443 mm and 534 mm respectively, MeteoSwiss). Furthermore, the atmospheric forcing (i.e. air temperature, radiation and calculated potential evaporation) was very similar at both sites (MeteoSwiss). Therefore, the larger and longer lasting impact of the 2015 heat wave at MLS is due to the higher initial VWC and thus lower potential evaporation limitation than at FRE. The amount of water available for evaporation is dependent on the soil properties. At MLS the soil type is silty loam and is able to retain more water than the sandy loam present at FRE.

P14 L13: This is counterintuitive. Why should melting start underground?

There are two processes that can cause the ground to start melting at larger depth: the preferential infiltration and refreezing of water at certain depths (e.g. by slope processes) or the influence of the heat penetration from the preceding summer. The heat from the summer penetrates in the ground and propagates by heat conduction to larger depths. Due to the time lag of this propagation to larger depths and depending on the strength of the winter freezing, the temperatures at depth can potentially be warmer than near the surface, and thus melting will start from below. This process is especially marked for permafrost temperature close to 0°C as it is the case at SCH. A description of this process can be found e.g. in Zenklusen Mutter and Phillips (2012). The manuscript was modified as follows:

Original manuscript:
"This is followed by a sharp increase at 50cm not seen at 10cm (1), followed by a strong increase at 10cm but not at 50cm (2) consistent with the melting of the ground from underneath, which takes place at different time at the two depths (spring zero-curtain)."

Revised version:

"This is followed by a sharp increase at 50cm not seen at 10cm (1), followed by a strong increase at 10cm but not at 50cm (2) consistent with the melting of the ground from underneath, which takes place at different time at the two depths (spring zero-curtain).The start of the thawing process at larger depth can be due to preferential water infiltration events or to the influence of warm temperatures from the preceding summer at depth (e.g. Zenklusen Mutter and Phillips, 2012). In the case of the latter, warmer ground temperatures in spring can be found at depth compared to the near surface due to the time-lag of heat propagation into the subsurface. The occurrence of this phenomenon depends on the thermal properties of the subsurface and the strength of the winter freezing. . Although the thawing process systematically starts at the surface in response to meteorological forcing, the warmer temperatures remaining at depth will also start the thawing from below. This process is especially marked for permafrost temperatures close to 0°C as it is the case at SCH."

P14 L28-29: Not plausible (see above).

The manuscript was adapted as follow.

Original manuscript:
"Furthermore, and in contrast to the soil type below, the organic rich material at the surface retains the water and lead to enhanced summer evaporation and winter freezing."

Revised version:
"Furthermore, and in contrast to the large blocks below, the organic rich material at the surface retains the water and has a large thermal conductivity (Beringer et al., 2001), thus favouring the summer evaporation and winter freezing."

P14 L30-31: Not plausible. There seems rather to be a constant groundwater influence at 50 cm depth.

After careful revision of the ancillary measurements at our disposal, we agree with the interpretation of reviewer1. The manuscript was adapted as follow:

Original manuscript:
"At GFU the presence of an organic rich layer in the uppermost 10cm of the soil causes the measured VWC at 10cm to be highly variable and higher than in the remaining soil column yielding an almost horizontal moisture orbit shape. "

Revised version:
"At GFU the presence of an organic rich layer in the uppermost 10cm of the soil causes the measured VWC at 10cm to be highly variable and higher than in the remaining soil column (see also Fig. 6d). At 50cm the measured VWC show near saturation conditions throughout the year indicating a potential influence of shallow ground water. This is confirmed by additional ERT measurements realized in summer from 2013 to 2015, which indicate extremely low specific resistivities (~250 Ωm) down to 2.5m (not shown). The combination of near saturated conditions at 50cm and highly variable VWC at 10cm yields an almost horizontal moisture orbit shape. "

P15 L1-2: This statement is too general (in structured soil Ks is not always lower in greater depths due to preferential flow).

This statement was relativized as follows:

Original manuscript:

"Furthermore the soil types at 30cm and 50cm have a lower hydraulic conductivity (Cosby et al., 1984), which also contributes to the lower soil moisture variability at these depths"

Revised version:
"Furthermore, at 30 and 50cm the soil is composed of loam and sandy loam with much larger bulk densities (Table 3), which are typically characterized by lower hydraulic conductivities if no preferential flow is occurring (Cosby et al., 1984). These soil properties also contribute to the observed lower soil moisture variability at these depths"

P15 L18: You need to mention that you are now showing the differentials.

We thank the reviewer for this remark and modified the text accordingly.

P15 L25-26: Not plausible. In that case, the sensor in 50 cm would show an increase.

We thank the reviewer for this comment and revised our interpretation as follow.

Original manuscript:
"At SCH the maximum VWC at 10cm is reached after two hours while no variation is recorded at 50cm. This pattern is typical for highly draining soils such as sand (found at SCH). "

Revised version:
"At SCH the maximum VWC at 10cm is reached after two hours while no variation is recorded at 50cm during that interval. The VWC starts increasing at 50cm once the VWC at 10cm is already decreasing. This pattern is consistent with the vertical succession of soil found at SCH: sandy loam at the surface, which retains water at the beginning of the event and sand at larger depth, which is more draining."

P15 L30: What is typical for this soil?

At DRE one has to keep in mind that the particular soil moisture behaviour is not really typical for one soil type but it is particular to the whole profile (including the coarse blocky talus slope below). The sentence was clarified as follow.

Original manuscript:
"It indicates a rapid transfer of water through the soil and no storage at 10cm typical for the particular soil composition found at DRE."

Revised version:
"It indicates a rapid transfer of water through the soil and little storage at 10cm, which is typical for the particular soil composition found at DRE (single organic rich layer with low bulk density underlain by coarse blocks with large interconnected pores). "

P16 L1-3: Not plausible. From basic soil physics is well known that the soil hydraulic conductivity decreases with decreasing soil water content. However, in structured soils preferential flow can be activated (see e.g. Wiekenkamp et al., 2016).

We thank the reviewer for this comment and changed the sentence accordingly.

Original manuscript:
"From Fig. 6c, it can be seen that, at the time of the precipitation event, the VWC at 10cm and 30cm depths were unusually low, enabling the water to pass through easily."

Revised version:
"From Fig. 6c, it can be seen that, at the time of the precipitation event, the VWC at 10cm and 30cm depths were unusually low, thus generating a larger gradient in pressure head from the surface to the lower soil layers as well as providing very suitable conditions for the activation of preferential flow (see e.g. Wiekenkamp et al., 2016). The degree of saturation of the soil layer is thus another key factor influencing the soil moisture dynamics."

P16 L7-9: Not plausible why these orbit patterns should indicate lateral processes.

Fig. 11e does not necessarily indicate lateral processes, but show the influence of snow melt processes. As water infiltration from snow melt is a spatially heterogeneous process on slopes, its potential influence is mentioned here. The paragraph was reformulated accordingly.

Original manuscript:
"An example of these lateral processes can be seen at STO, where the precipitation event shown in Fig. 11e did not yield a clear moisture orbit."

Revised version:
"The infiltration of snow melt water is a spatially very heterogeneous process on slopes, especially when the subsurface is characterized by large size particles and draining soil types. An example of the influence of snow melt processes can be seen at STO, where the precipitation event shown in Fig. 10e did not yield a clear moisture orbit."

P17 L28-34: Not plausible why these processes can produce lower soil temperatures, although the air temperature is relative high. Are you measuring air temperature farther away from the soil station?

The colder ground surface temperature at the bottom of the slope is due to the convective heat transport by air flow through the available pore space within the talus slope. In winter, the lower air temperature outside compared to inside the talus provokes the apparition of a pressure gradient and thus leads to ascending warm air in the talus compensated by cold air inflow at the bottom of the slope. During the summer (i.e. when the temperature of the air inside the talus is lower than outside), the circulation is reversed and gravitational cold air outflow is taking place at the bottom of the slope. This typical seasonally reversing air circulation was first described by Wakonigg (1996) and identified at DRE by Delaloye (2004) and Morard (2011). It was further confirmed through model studies (e.g. Wicky and Hauck 2016).

The paragraph relative to the cooling effect of the air circulation was reformulated as follows in order to clarify the process and to detail the location of the soil moisture and weather station.

Original manuscript:
"The low mean annual ground temperature results from a complex air circulation within the underlying talus slope (Delaloye, 2004; Morard, 2011), which is made possible by the large interconnected pore space between the coarse blocks of the talus. During winter, ascending warm air within the talus slope leads to cold air inflow at the bottom of the talus slope, where the soil moisture station is located. This process efficiently cools the ground even when the snow cover is present and has been observed at many similar talus slopes in low and high mountain regions (e.g. Delaloye and Lambiel 2005; Gude et al. 2003; Kneisel et al. 2000; Sawada et al. 2003; Wakonigg, 1996). In summer the reverse process takes place with outflow of cold air from the inside of the talus slope at the bottom by gravity. "

Revised version:

“The low mean annual ground temperature results from convective heat transport by a complex air circulation within the underlying talus slope (Delaloye, 2004; Morard, 2011), which is made possible by the large interconnected pore space between the coarse blocks of the talus. During winter, ascending warm air within the talus slope leads to cold air inflow at the bottom of the talus slope, where the soil moisture and weather stations are located. This process is able to efficiently cool the ground even when the snow cover is present. In summer the air circulation is reversed and a gravity-driven outflow of cold air from the inside of the talus slope takes place at the bottom, where soil moisture is measured. This process has been observed at many similar talus slopes in low and high elevation mountain regions (e.g. Delaloye and Lambiel 2005; Gude et al. 2003; Kneisel et al. 2000; Sawada et al. 2003; Wakonigg, 1996). Furthermore, the lower ground temperatures caused by the air circulation have been successfully reproduced using numerical modelling (Wicky and Hauck, 2016).”

P18 L5-7: Not plausible (see above)

See the answer to the previous comment

P18 L7-8: The soil seems not have been frozen during these phases (values are still relatively high)

During the winter 2014-2015 below 0°C temperatures have been measured at 10cm. At 30cm and 50cm as well as during the winter 2015-2016 the measured temperatures are slightly above 0°C at all depths but these values are still within the sensor accuracy (±0.2°C). Furthermore the observed liquid VWC decrease in winter is consistent with at least partial freezing of the ground. The text was rephrased accordingly.

Original manuscript:
“Thus two phases of minimal VWC values are observed in summer and winter (see Fig. 6b).”

Revised version:
“Thus two phases of minimal VWC values are observed: one during the summer due to evaporation and one in winter due to partial or complete freezing of the ground (see Fig. 6b). “

Revised figures and captions:

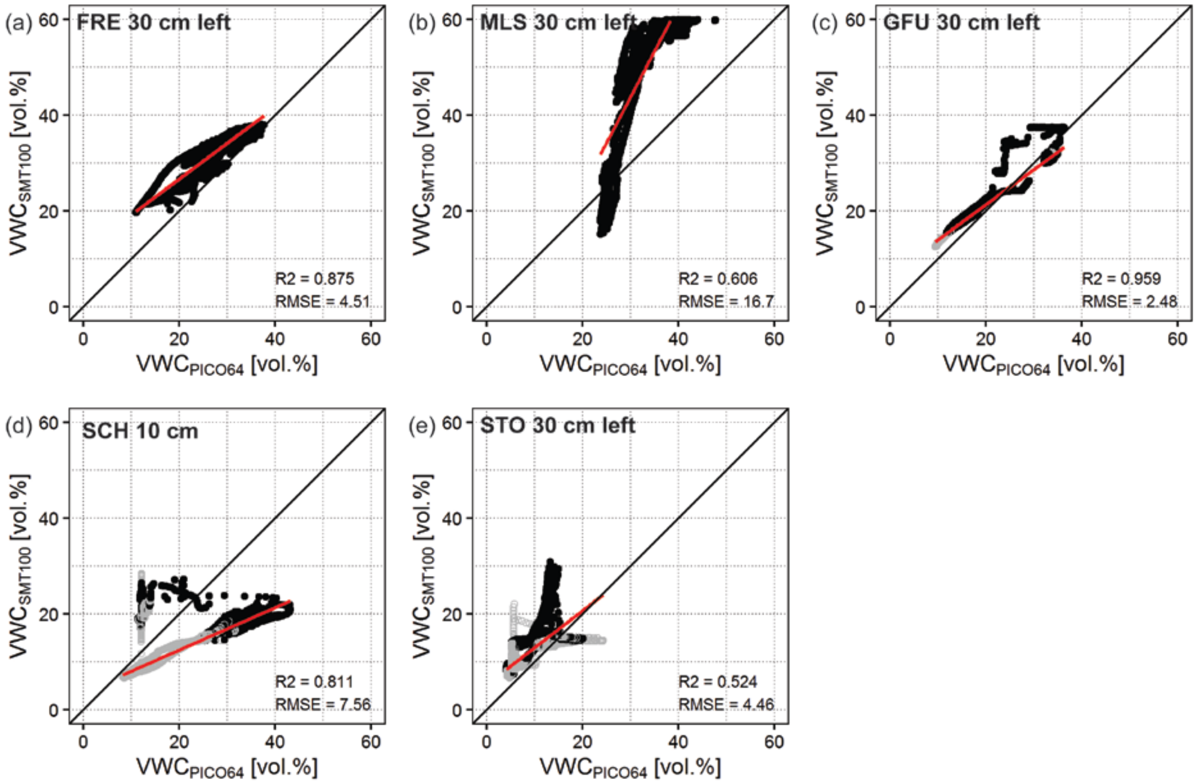

Fig. 5: Comparison between TDR- (x-axis) and FDR-measured liquid VWC (y-axis) at all sites. The linear relation is used for the FDR calibration. The hollow grey points at GFU, SCH and STO represent soil moisture measurements taken when the ground temperature was below 0°C.

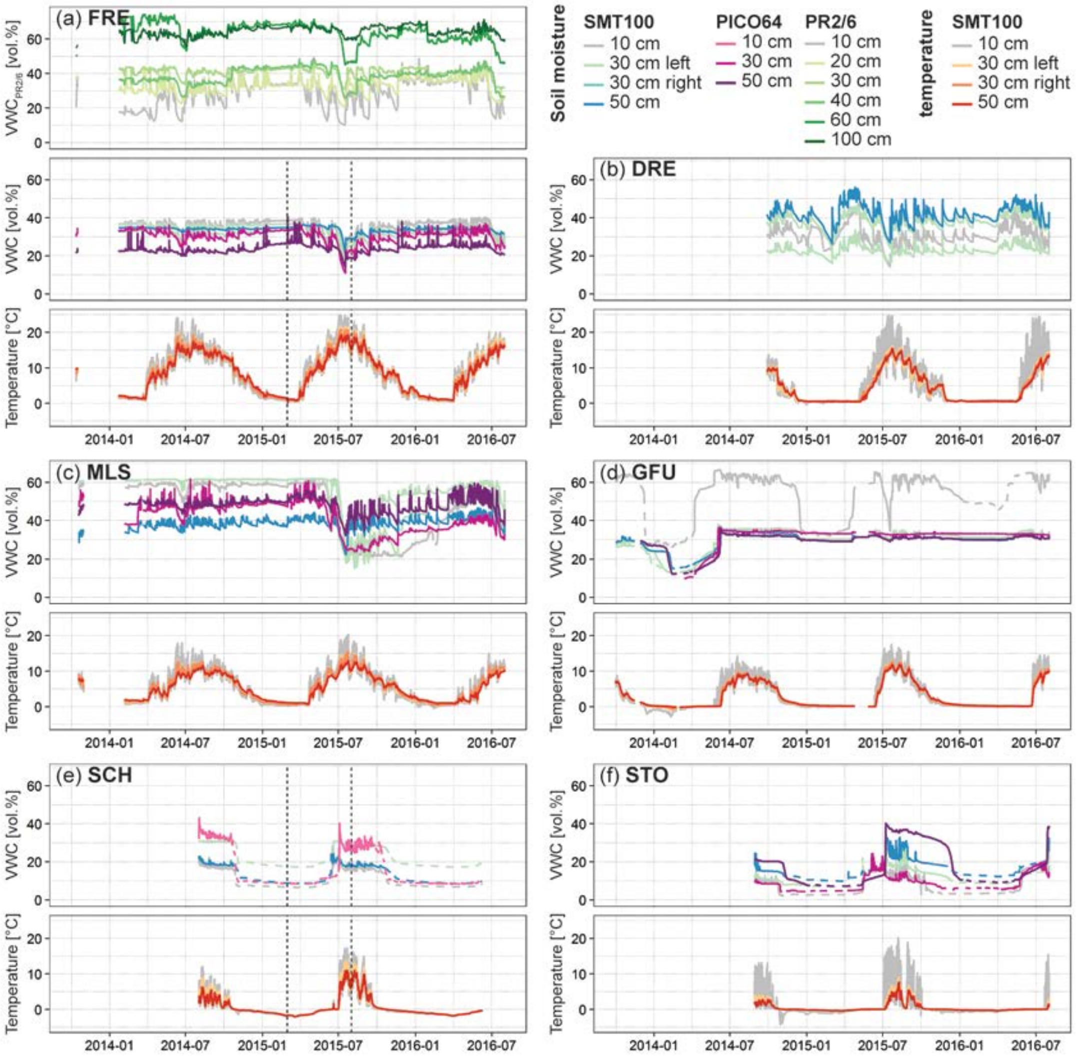

Fig. 6: Measured VWC (upper panel) and ground temperatures (lower panel) at each SOMOMOUNT station (a-f). At FRE the uppermost panel displays the PR2/6 measured liquid VWC. The vertical dotted lines at FRE and STO indicate the period analysed in Fig. 7. The dashed VWC lines represent the soil moisture measurements taken when the ground temperature was below 0°C.

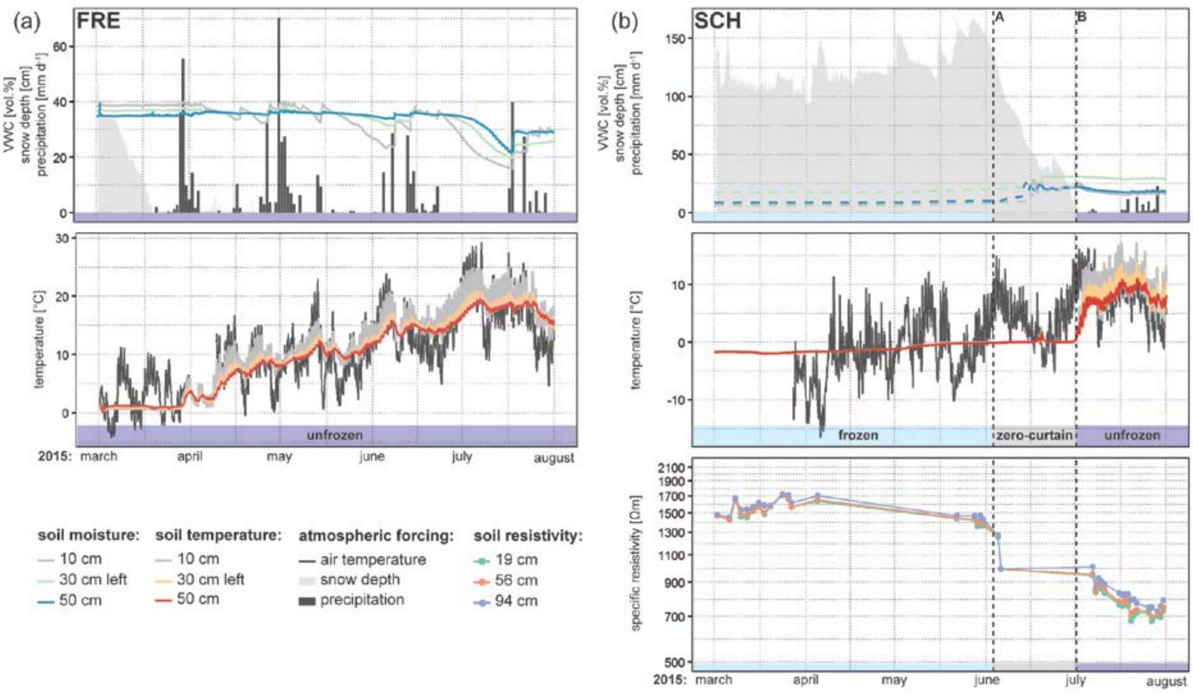

Fig. 7: Measured liquid VWC, ground temperature and soil resistivity at FRE (a) and SCH (b) from March to August 2015. In addition, daily air temperature, snow depth and precipitation sums are shown as well as the date of the transition between the different stages in the thermal evolution at SCH at 10cm (dashed lines A and B, see text for details). The dashed VWC lines represent the soil moisture measurements taken at ground temperature below 0°C.

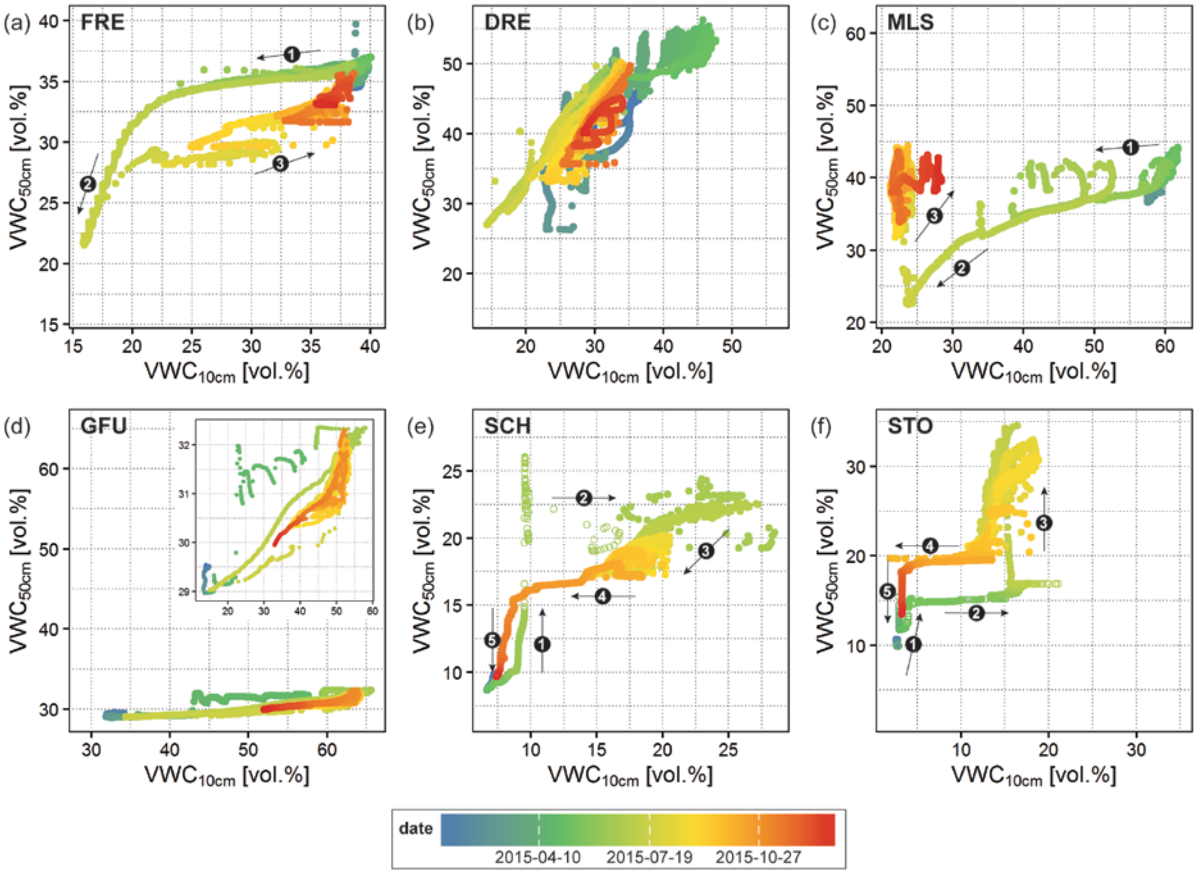

Fig. 8: Moisture orbit at each SOMOMOUNT station from the 1st January to the 31st December 2015. The numbered arrows indicate the most important stages at each station as well as the sense of the evolution. The hollow circles represent soil moisture measurements taken when the temperature was below 0°C at 50cm.

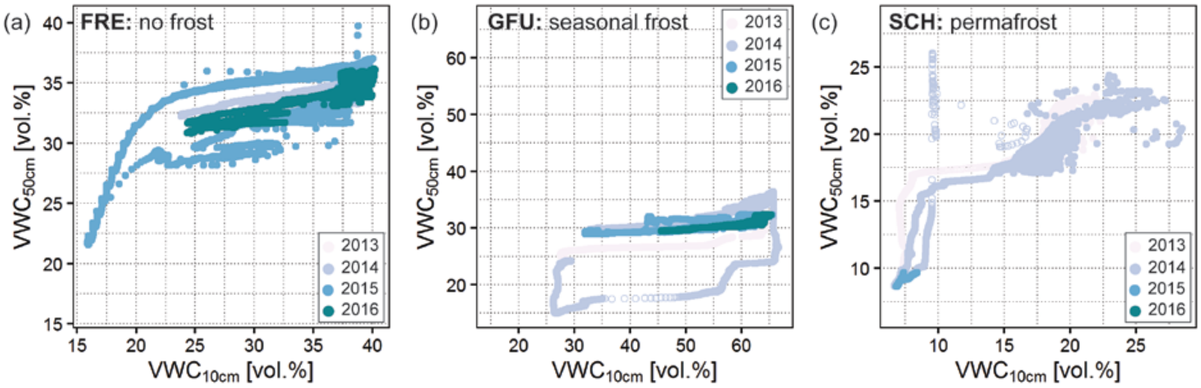

Fig. 9: Moisture orbits at FRE (a), GFU (b) and SCH (c) for the consecutive monitoring years (Jan. 2014-Aug. 2016 at FRE, Aug. 2013-Aug. 2016 at GFU and Aug. 2014-June 2016 at SCH). The hollow circles represent soil moisture measurements taken when the temperature was below 0°C at 50cm.

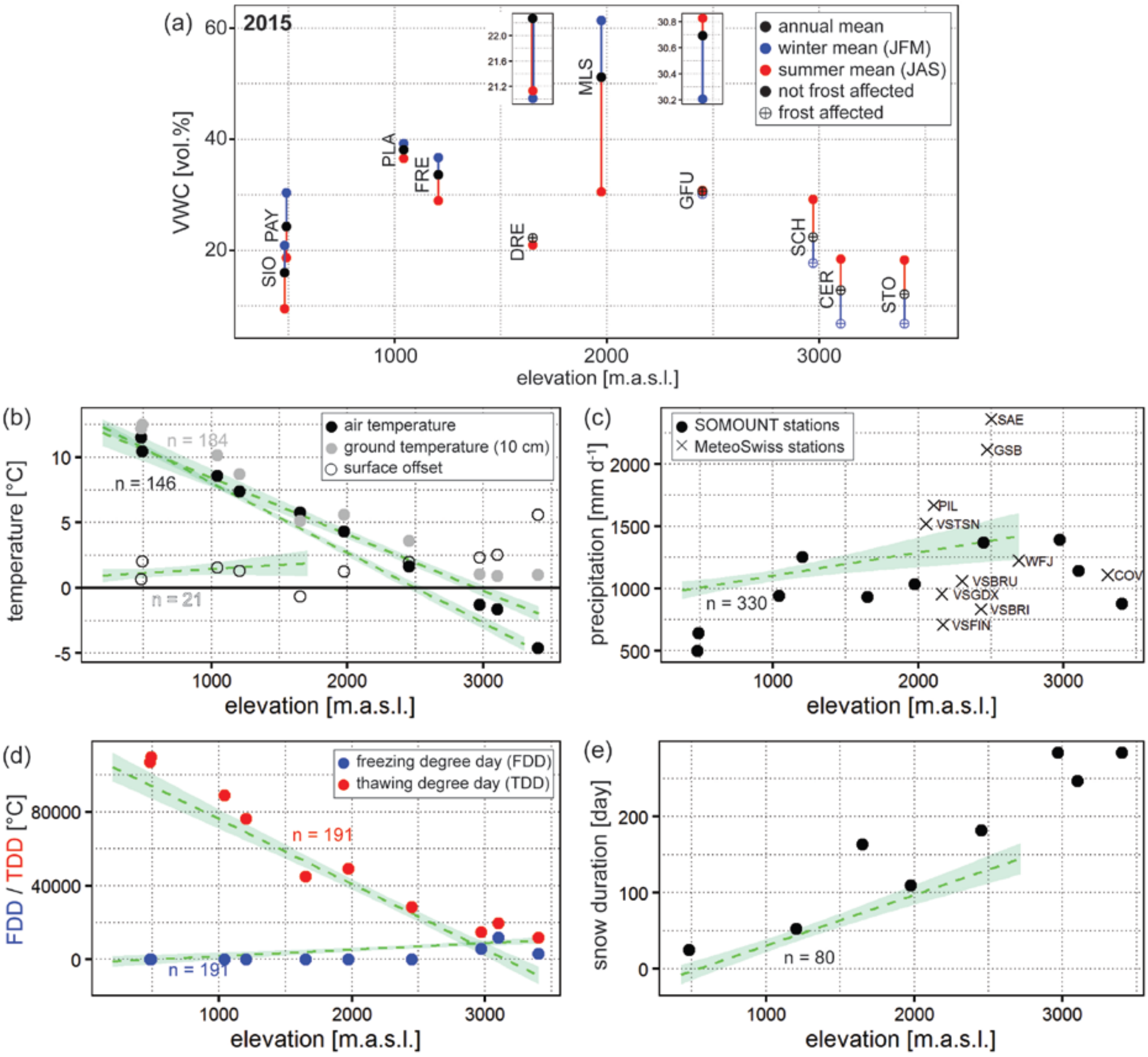

Fig. 12: Elevation dependency of the winter-, summer- and annual mean liquid VWC at 30cm depth (a), air-, ground temperature and surface offset (ground minus air temperature) at 10cm (b), annual precipitation sum including selected SwissMetNet stations for comparison (cf. Fig. 1) (c), freezing and thawing degree days (calculated from ground temperatures at 10cm) (d) and snow duration (calculated from ground temperature at 10cm using the method described in Staub and Delaloye (2016)) (e) during the year 2015. The VWC values for SIO, PAY and PLA are part of the SwissSMEX network (Mittelbach and Seneviratne, 2012). Due to missing data at 30cm the VWC shown for PAY and PLA was measured at 50cm and 20cm at CER. The dashed green lines illustrate the linear regression based on all available SwissMetNet, PERMOS and IMIS stations in Switzerland (the numbers of station with complete data series in 2015 are indicated) and the shaded areas represent the 99% confidence intervals. The length of each regression line corresponds to the maximum elevation of the available stations.

Anonymous Referee #2

Review of the Article hess-2016-474
Monitoring soil moisture from middle to high elevation in Switzerland: Set-up and first results from the SOMOMOUNT network
by C. Pellet and C. Hauck
This paper presents soil moisture observations collected along an altitudinal and climatic transect in Switzerland. The soil moisture dynamics is discussed (mostly qualitatively) with respect to elevation, soil properties and climate.

General comments:
I have mixed feelings about this paper.
On the one hand, it is a very nice paper to read. The soil moisture observations and the calibration procedures are well presented, in a didactic way. Observations are also interpreted in a clever way, the reasons of the differences among the stations clearly identified. At the end, the paper provides a good conceptual scheme to understand the role of elevation in controlling the yearly soil moisture cycle. I´m working with a similar soil moisture dataset collected in an Alpine region, and I recognize similar trends.
On the other hand, most of the results are based only on qualitative interpretations, and the paper does not add very new concepts on what is already known on the soil moisture behavior in cold/mountain climates.
I also share the doubts of the first reviewer on the unreliability of soil moisture observations when the soil is frozen. It is not so straightforward assuming that soil immediately freezes with negative soil temperatures. Soil could remain unfrozen in small pores also well below 0 C. Also assuming that TDR devices correctly detect low soil moisture when the soil is frozen it is also not so obvious. All the discussion is quite misleading on this point. You cannot consider the same situation having low liquid (but high total) water content due frozen soil and having a low total water content because the soil is dry. Those are completely different situations of low (liquid) water availability, and this should be clearly differentiated in the discussion.

We thank the reviewer for pointing out these facts. We fully agree that the discussion in the submitted manuscript was quite misleading concerning the distinction between total and liquid water content. As mentioned in our answer to reviewer 1's comment we carefully revised the manuscript and clearly stated that whenever we use the term VWC, liquid VWC is meant given the methods limitations.

We also thank both reviewers for sharing their concerns regarding the methods used here and their application in frozen conditions. On that topic a detailed answer was made to reviewer 1 and a whole new subsection was included after the calibration part. Similarly, all figures with VWC data during frozen conditions were revised in order to illustrate more clearly, where freezing occurred and uncertainties regarding the VWC calibration exist due to freezing. Furthermore, additional resistivity data have been included in figure 7 to illustrate our statement that the relative liquid VWC changes are well captured although the absolute values of liquid VWC is difficult to assess in frozen conditions.

Moreover, reading the introduction the paper seems here really focused on permafrost. Also the broad literature review on mountain SWC dynamics is biased toward permafrost. Then, later in the results and discussion sections, the topic permafrost is barely covered. I suggest a broader motivation. There are other important reasons to monitor mountain soil moisture, runoff production, climatic impacts, vegetation seasonality …

We are thankful to the reviewer for this comment. We modified the introduction and broadened the motivations for behind this study and downplayed the permafrost part. The text reads now as follows:

"In mountain environments, soil moisture is particularly crucial since it can control the initiation of convective precipitation (e.g. Barthlott et al., 2011; Hauck et al., 2011), the generation of runoff (e.g. Morbidelli et al., 2016; Zehe et al., 2010) and thereby the mitigation or intensification of flash floods (e.g. Borga et al., 2007). Soil moisture also significantly affects the vegetation growth and distribution (e.g. Paschalis et al., 2015; Porporato et al., 2004). In terrains affected by seasonal and permanently frozen conditions, its effect on the stability of slopes and the thermal and kinematic characteristics of periglacial landforms was highlighted in several observation and modelling studies (e.g. Boike et al., 2008; Hasler et al. 2011; Hinkel et al., 2001; Krautblatter et al. 2012; Scherler et al., 2010; Streletskiy et al. 2014; Westermann et al., 2009; Zhou et al. 2015). A general overview of the interactions between hydrological, mechanical and ecological processes in frozen grounds is given by Hayashi (2013)."

Nevertheless, I would recommend publication after a careful revision, since the paper could provide useful guidelines on how to interpret soil moisture observations in Alpine regions.

Specific comments:
Abstract
Please add more concrete results on which are the main soil moisture patterns.

The last paragraph of the abstract was modified as follow in order to include more detail about the observed soil moisture patterns.

Original manuscript:
"In this contribution we will present a detailed description of the SOMOMOUNT instrumentation and calibration procedures. Additionally, the data collected during the three first years of the project will be discussed in relation to their altitudinal distribution. Clear differences in soil moisture patterns are visible between sites with permanently and seasonally frozen as well as unfrozen ground conditions and can be related to several factors such as the subsurface composition (organic versus mineral), the elevation and the snow cover characteristics."

Revised version:
"In this contribution we present a detailed description of the SOMOMOUNT instrumentation and calibration procedures. Additionally, the data collected during the three first years of the project are discussed with regard to their soil type and climate dependency as well as their altitudinal distribution. The observed elevation dependency of soil moisture is found to be non-linear, with an increase of the mean annual values until ~2000m.a.s.l. followed by a decreasing trend towards higher elevations. This altitude threshold marks the change between precipitation/evaporation controlled soil moisture regime and frost affected ones. The former is characterized by high liquid VWC throughout the year and minimum values in summer, whereas the latter typically exhibits long lasting winter minimum liquid VWC values and high variability during the summer.

Introduction
Line 25-30. The paper seems really focusing on permafrost. Then, later in the results section, the topic permafrost is hardly covered. I suggest a broader motivation. There are other important reasons to monitor mountain soil moisture, from runoff production to climatic impacts to vegetation seasonality.

The relevant paragraph in the introduction speaking of the importance of soil moisture measurement in mountainous terrains was broadened. Furthermore, the reference to the ground thermal regime was removed from the description of the SOMOMOUNT.

"In mountain environments, soil moisture is particularly crucial since it can control the initiation of convective precipitation (e.g. Barthlott et al., 2011; Hauck et al., 2011), the generation of runoff (e.g. Morbidelli et al., 2016; Zehe et al., 2010) and thereby the mitigation or intensification of flash floods (e.g. Borga et al., 2007). Soil moisture also significantly affects the vegetation growth and distribution (e.g. Paschalis et al., 2015; Porporato et al., 2004). In terrains affected by seasonal and permanently frozen conditions, its effect on the stability of slopes and the thermal and kinematic characteristics of periglacial landforms was highlighted in several observation and modelling studies (e.g. Boike et al., 2008; Hasler et al. 2011; Hinkel et al., 2001; Krautblatter et al. 2012; Scherler et al., 2010; Streletskiy et al. 2014; Westermann et al., 2009; Zhou et al. 2015). A general overview of the interactions between hydrological, mechanical and ecological processes in frozen grounds is given by Hayashi (2013)."

"The project SOMOMOUNT (Soil moisture in mountainous terrain and its influence on the thermal regime in seasonal and permanently frozen terrains, see also Pellet et al., 2016), which started in 2013 and is funded by the Swiss National Science Foundation, has the main objective to fill this data gap. In collaboration with the Swiss permafrost monitoring network (PERMOS) and the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss), six automatic soil moisture monitoring stations have been established at different altitudes."

Instruments
This section is too long, with a long revision of the advantages and disadvantages of different measurement techniques and many details on the calibration procedures. This part could become shorter. However, I found this part useful. I learned something new.

The section was shortened accordingly, it now reads:

"Both FDR and TDR methods are indirect measurement techniques that use electromagnetic waves to estimate the dielectric permittivity of the ground and relate it to the soil volumetric water content (VWC). The SMT100 sensors are composed of a ring oscillator which feeds a 10cm long transmission line (Fig. 2). The sensors emit an electromagnetic wave at a fixed frequency and the recorded oscillation frequency can be related to the wave propagation velocity and thus the dielectric permittivity and VWC of the surrounding medium (Qu et al., 2003). The SMT100 sensors are the newest generation of the so-called SISOMOP sensors, which have been used to monitor soil moisture at Schilthorn (one of the high elevation permafrost sites, see section 2.3) since 2007 (Hilbich et al. 2011), demonstrating the sensors robustness and capability to measure in mountainous areas. Furthermore, laboratory experiments performed by Mittelbach et al. (2012) showed that the SISOMOP sensors have a similar absolute accuracy (±3 vol.%) compared to three other, more widely used, FDR sensors.
The PICO64 sensors are based on the standard TDR technique, which relates the travel time of an electromagnetic wave to the dielectric permittivity of the medium surrounding the sensors, which can in turn be related to the VWC of said medium. The PICO64 sensors emit an electromagnetic impulse at a frequency of 1 GHz along two 16cm long parallel rods separated by 40mm, yielding a measurement volume of ~1.25L (~10cm diameter around the rods). The recorded travel times are related to the VWC using a general calibration based on Topp's equation (Topp et al., 1980). This sensor was selected for its high absolute accuracy (±1 vol.%, IMKO, 2015) and because it corresponds to the new generation of TRIME-EZ sensors used by the SwissSMEX monitoring network (Mittelbach et al., 2011). Additionally, due to its large measurement volume, this sensor is particularly suitable for heterogeneous media (IMKO, 2015).

Finally, the PR2/6 sensor is a 100cm long down-hole water content sensor measuring soil moisture at 6 different depths (10, 20, 30, 40, 60 and 100cm) using the capacitance technique (Fig. 2). Each measurement depth comprises a pair of stainless steel rings, which transmit the 100 MHz electromagnetic signal into the ground, and one detector, which records the returned signal. This technique relies on the fact that the emitted wave generates an electromagnetic field, which extends about 100mm into the surrounding soil and depending on its dielectric properties and thus on the VWC is partly reflected (Verhoef et al., 2006). The sensor is lodged in an access polycarbonate tube of 25mm diameter and its measurement volume is ~10cm diameter with an absolute accuracy of ±6 vol.% (Delta-T Device, 2008). This sensor was selected for its measurement depth and its easy installation. However, it is not suited for heterogeneous subsurface or coarse grained material since a good contact between the access tube and the soil is necessary. Furthermore, at least 1m soil is needed for its installation, thus it was only used at Frétaz (Sect. 2.3)."

Network design
Line 25-30. This part could become shorter.

Part of the paragraph was deleted (see below) and a reference to Table 2 was included instead.

Original manuscript:
"The data are recorded using a CR1000 data logger (Campbell Scientific) and transmitted with wireless transfer to an ftp server. The measurement interval is depending on the electrical power capacity of each station. At Frétaz and Moléson, where direct connections to the power grid are available, a 10min interval was chosen to match the setup of the SwissSMEX network (Mittelbach et al., 2011). At all the remaining stations, solar panels are used for power consumption and thus a 30min measurement interval was selected, except at Dreveneuse were the shaded location requires an even longer interval (60min)."

Revised version:
The data are recorded using a CR1000 data logger (Campbell Scientific) and transmitted with wireless transfer to an ftp server. The measurement interval is depending on the electrical power capacity of each station (see Table 2).

Field sites
Pages 5-6-7 This part could also become shorter, moving more details to Table 3.

We thank the reviewer for this comment. The field site description was shortened, and the information relative to the site specific elevation, annual air temperature and precipitation sum have been integrated into table 3.

Soil moisture temporal evolution. This paragraph is very qualitative, but well written. However, I share here with Reviewer 1 some doubts on the methodology. It is not so straightforward assuming that soil freezes when soil temperatures are negative. Soil could remain unfrozen in small pores also below 0. Also assuming that a TDR device measures low soil moisture when the soil is frozen it is not so obvious. See the comments of the other reviewer on this point.

We are thankful to the reviewer for this comment. This issue was discussed in detail in the answer to the comments of reviewer 1 (see above).

Page 11, Line 34. "During the snow melt period only a small VWC increase is seen, which could be attributed to conditions close to saturation throughout the winter." Interesting observation, but it would be nice to quantify better the impact of snow melt on initial VWC in spring. It is a relevant research question in the context of climate change.

We thank the reviewer for this interesting comment. Unfortunately amongst our field sites only FRE, SCH and STO are equipped with snow sensors. Looking at the data from 2014 at FRE, the same observation can be made as for 2015. In both cases the VWC increase following the total snow melt was around +2 vol.%. This process is also seen at PLA (a SwissSMEX soil moisture station at 1000m elevation) but with slightly larger VWC increase (+ 5vol.%).
We agree that the quantification of the snow melt contribution to the VWC variation during the spring is an important topic, which would demand a detailed study and is beyond the scope of this paper.

Page 12, Line 5. Simply stating that VWC is minimum is not correct. The water is in the soil, but likely frozen. It is more correct to specify minimum liquid water content. Therefore, the whole the discussion is quite misleading. You cannot consider in the same way having low liquid (but high total) water content due frozen soil and having a low total water content because the soil is dry. Those are completely different ways to have low liquid water content.

We thank the reviewer for pointing out this fact – our argumentation was indeed misleading which was not our intention, as we focused throughout the manuscript on the LIQUID water content and not the total water content including ice. In the method section we included a new part that answers the major comments and concerns of the two reviewers concerning the reliability of VWC measurements in frozen conditions (see above). Within this part and throughout the text we now clearly state that whenever the tern VWC is used in the manuscript it always refers to liquid VWC.

Soil moisture spatial distribution. This paragraph is not very informative. It only informs us that there is (as expected) a large spatial variability, and where falls more rain is more wet. I suggest to skip or strongly reduce.

We are thankful to the reviewer for this comment. We agree with the reviewer and thus removed the whole section from the manuscript, including Figure 8. Mention of the spatially distributed sensors was added at the end of section 4.2. The main point about the large observed spatial variability is now summarized in the following sentence:

"These stages are also observed in the data collected by the spatially distributed SMT100 sensors installed at 30cm depth at SCH and STO, with marked differences in absolute VWC as well as variable onset and duration of the three stages even at close vicinity (not shown). "

Page 14, Line 28. How thick is the organic layer? What about organic soil in the other sites? Soil type dependency is not discussed for all the sites. Why?

The characteristics of the organic layer at DRE was clarified in the text as follows:

"At DRE the soil profile down to 50cm consists of one single organic rich sandy loam layer with a very low bulk density (Table 3), which is underlain by large sized boulders."

A new paragraph discusses the soil type dependency of the other field sites:

"At FRE and MLS, the soil type is relatively homogeneous within the uppermost 50cm of the ground, which results in similar VWC temporal evolution with only slight variations in timing and absolute values between the sensors. At MLS the soil type is silty loam and is thus able to retain more water than the sandy loam present at FRE. Finally at SCH and STO, the ground consists of sand or loamy sand, with a significant proportion of large size elements (at 10cm 25% of the soil particles are larger than 10mm at SCH and 45% at STO, see also Fig. 3e-f). Such soil composition is highly heterogeneous

even on small distance explaining the high variability between the sensors as well as the comparatively low VWC during unfrozen and snow free periods."

Page 15, Line 4. Do you mean Figure 10?

We are thankful for the comment, which helped to clarify the paragraph. Here we refer to the full dataset of soil moisture, which is shown in Figure 6. The inter-annual variations are then shown in detail in Fig. 10 using the moisture orbit representation. The text was modified to make this distinction more clear.

Original manuscript:
"As seen in Fig. 6, the annual soil moisture dynamics is strongly influenced by the variations in atmospheric conditions such as the extreme temperatures of July 2015."

Revised version:
"As seen in Fig. 6, the soil moisture temporal evolution is strongly influenced by the variations in atmospheric conditions such as the extreme temperatures of July 2015."

Page 16, Line 3 and line 20 "From Fig. 6c, it can be seen that, at the time of the precipitation event, the VWC at 10cm and 30cm depths were unusually low, enabling the water to pass through easily." "As for MLS above, the VWC is low at all depths enabling the precipitations to infiltrate quickly down to the deepest layers"
Those statements apparently contradict hydrologic theory. In fact, larger is the water content, larger is the soil hydraulic conductivity and therefore larger is the amount of water that can infiltrate. Please motivate your statements. Do you refer to the speed of the infiltration front or to the total amount of water infiltrated? (i.e. see Green – Ampt theory?). It is not only because if the soil is already wet you do not see a big change in soil moisture, but the infiltration amount is already significant?

We thank the reviewer for this comment which is of course correct and adapted our interpretation as follows (see also the answer to reviewer 1 above):

"From Fig. 6c, it can be seen that, at the time of the precipitation event, the VWC at 10cm and 30cm depths were unusually low, thus generating a larger gradient in pressure head from the surface to the lower soil layers as well as providing very suitable conditions for the activation of preferential flow (see e.g. Wiekenkamp et al., 2016). The degree of saturation of the soil layer is thus another key factor influencing the soil moisture dynamics."

"As for MLS above, the VWC is low at all depths creating suitable conditions for preferential flow as well as an increased infiltration capacity due to a high gradient of water potential. Both processes could explain the larger and faster increase of VWC observed at larger depth due to the bypass of the dry uppermost layer. The same indications for preferential flow are seen at DRE, where the second precipitation event is comparatively small (+10 mm d-1) but yields the strongest and fastest VWC increase at depth. Given the soil properties, the preferential flow interpretation is preferred to the enhanced infiltration capacity."

Page 16, Line 18. Do you mean Figure 10?

No, here we refer to the precipitation event of August 2015, which is shown in detail in Fig.11.No adaptation was made in the text.

Altitude dependency. This part of the paper is well written and informative, but very qualitative. This altitudinal dependency is already known in literature. Even if it is important to show how the new *data published in this paper follow or not follow what is known in literature, a more robust quantitative analysis would be beneficial for the paper.*

In order to assess the altitude dependency of all the selected parameters, we collected all available data from the MeteoSwiss, PERMOS and IMIS (Intercantonal Measurement and Information System, maintained by SLF) networks and performed linear regression of the mean annual (or annual sum) values in 2015 compared to elevation. The results have been included in the new version of Figure 13 and are discussed in the text (see below). Finally, the measured VWC at three additional stations (PAY, PLA and CER) have been added in Figure 13a. Unfortunately the limited number of soil moisture stations available for this study does not allow for more a quantitative analysis of the soil moisture trend with elevation. The new paragraph inserted reads as follows:

"For each variable, all available data from the monitoring networks of MeteoSwiss, PERMOS and IMIS (Intercantonal Measurement and Information System maintained by the SLF) were collected and a linear regression model was calculated based on the annual mean (resp. sum) of the year 2015. Globally, the same elevation dependency trends are observed using the single stations (dots) or the entire datasets (regression lines). "

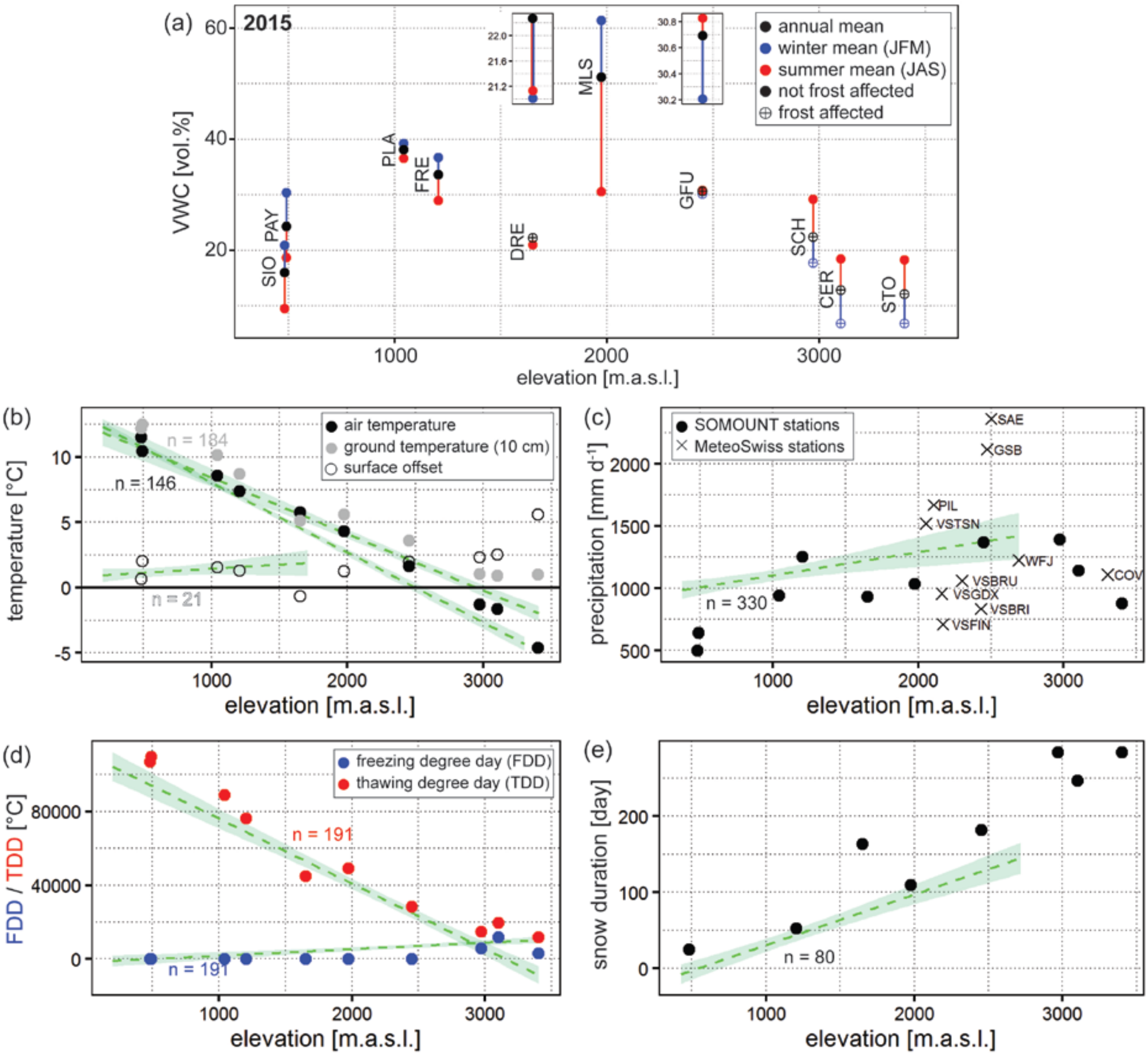

Fig. 12: Elevation dependency of the winter-, summer- and annual mean liquid VWC at 30cm depth (a), air-, ground temperature and surface offset (ground minus air temperature) at 10cm (b), annual precipitation sum including selected SwissMetNet stations for comparison (cf. Fig. 1) (c), freezing and thawing degree days (calculated from ground temperatures at 10cm) (d) and snow duration (calculated from ground temperature at 10cm using the method

described in Staub and Delaloye (2016)) (e) during the year 2015. The VWC values for SIO, PAY and PLA are part of the SwissSMEX network (Mittelbach and Seneviratne, 2012). Due to missing data at 30cm the VWC shown for PAY and PLA was measured at 50cm and 20cm at CER. The dashed green lines illustrate the linear regression based on all available SwissMetNet, PERMOS and IMIS stations in Switzerland (the numbers of station with complete data series in 2015 are indicated) and the shaded areas represent the 99% confidence intervals. The length of each regression line corresponds to the maximum elevation of the available stations.

Page 16, Line 28 . "Below 2000 m.a.s.l. the maximum VWC is recorded in winter and the minimum in summer, whereas above this threshold the inverse occurs (maximum VWC in summer and minimum in winter)."
This refers only to the liquid water content. The total (frozen + unfrozen) remains high all the winter even at high elevations. Please specify this better.

We thank the reviewer for pointing out this fact. In the method section we included a new part that answers the major comments and concerns of the two reviewers concerning the reliability of VWC measurements in frozen conditions (see above). Within this part we clearly state that whenever the term VWC is used in the manuscript it always refers to liquid VWC. Furthermore, in cases where confusion might arise, we specified that we are indeed referring to liquid VWC.

Page 17, Line 5-6 and following. Ok, such processes are somehow clear, but … what are the implications for SWC?

The implications of the presented elevation trends have been made clearer by modifying the text as follow:

Original manuscript:
"From Fig. 13 the following relationships can be determined: ground- and air temperature, as well as the thawing degree days (absolute sum of positive temperatures per year) all linearly decrease with elevation and conversely the freezing degree days (absolute sum of negative temperatures per year), surface offset and the snow cover duration increase with elevation. There is no clear trend in the precipitation distribution due to the strong microclimatic effects, however on larger spatial scale (continental) precipitation is known to increase with elevation (Smith, 1979)."

Revised version:
"From Fig. 12 the following relationships can be determined: ground- and air temperature, as well as the thawing degree days (absolute sum of positive temperatures per year) all linearly decrease with elevation, yielding a decreasing trend of evaporation and thus a theoretically increasing trend of liquid VWC. Conversely the freezing degree days (absolute sum of negative temperatures per year), surface offset and the snow cover duration increase with elevation, which results in longer lasting winter liquid VWC minimum and thus lower mean annual liquid VWC with increasing elevation. Finally, a slightly increasing trend in the precipitation distribution is observed with large site specific variations due to the strong microclimatic effects, however on larger spatial scale (continental) precipitation is known to increase with elevation (Smith, 1979). This combination of overall increasing precipitation and decreasing evaporation yields a trend of increasing soil moisture with elevation until the altitude threshold of about 2000m.a.s.l., where it is balanced by the increasingly important ground freezing and soil moisture starts decreasing with elevation."

Page 17, Line 18 "This is confirmed by the observed negative ground temperatures as well as the increasing freezing degree days. With increasing elevation, air and ground temperatures decrease yielding increasingly long duration of seasonally frozen ground and thus explaining the decreasing trend of VWC"

Could you qualitatively estimate a functional relationship? Which is the temperature threshold? (I have seen that later the paper partially answers to those questions …)

We thank the reviewer for this interesting question. However, given the all the uncertainties relative to the soil moisture measurements in frost affected soils raised by the reviewers and the limited amount of stations available it is not yet feasible to define a functional relationship. Particularly the lack of soil moisture data at the critical elevation (i.e. between 1600m and 2500m) prevents us from formulating any general relationship. We fully agree that this direction of research should be pursued in further work and we would be very interested for any additional soil moisture data available at these elevations.

Page 17, lines 30 and followings. Such "frost holes" are geological peculiarities well known in other places of the Alps (I.e. Kaltern, Italy; Lases, Italy). Their effect on SMC is interesting. May be there is more in the geological literature.

In answer to the comment of reviewer 1 regarding the cooling effect of the air circulation within the talus slope, we clarified the process and highlighted the relative location of our measurement setup. We also included a recent numerical modelling study which was able to reproduce the observed colder ground temperature. To the best of our knowledge none of the studies on this process so far include the effect on the water content.

Page 18, lines 25-32. Well written, but it could be shortened. Too many unnecessary details.

We thank the reviewer for this remark and shortened this passage accordingly. It now reads:

Original manuscript:
"From our field sites FRE appears to receive more precipitation than expected, whereas STO receives much less than predicted. Indeed, FRE is situated on top of the easternmost ridge of the Jura mountain chain, which is known to have a comparatively high annual precipitation sum, as is also shown by the neighbouring SwissMetNet stations of Chasseral (1599 m.a.s.l.) and Chaumont (1136 m.a.s.l.), which recorded annual precipitation sums of 1509 mm y^{-1} and 1240 mm y^{-1} respectively for the period 1961-1990 (MeteoSwiss). Precipitation maxima in middle mountain ranges are often found at the highest elevations, whereas the precipitation distribution in high mountain ranges is strongly influenced by the prevailing wind directions and found along the windward slopes, with smaller values on mountain tops and in the lee of the mountains (e.g. Smith 1979). In addition, STO is located in the central alpine region, which is very dry due to the wind shading effects from the surrounding mountain crests. This effect is also seen at the station of Findelen (VSFIN), which is located about 3km from STO and which is also much drier than the stations at comparable elevation (Fig. 13c)."

Revised version:
"From our field sites FRE appears to receive more precipitation than expected, whereas STO receives much less than predicted. Indeed, FRE is situated on top of the easternmost ridge of the Jura mountain chain, which is known to have a comparatively high annual precipitation sum, as is also shown by the neighbouring SwissMetNet stations of Chasseral (1599 m.a.s.l.) and Chaumont (1136 m.a.s.l.), which recorded annual precipitation sums of 1509 mm y^{-1} and 1240 mm y^{-1} respectively for the period 1961-1990 (MeteoSwiss). STO is located in the central alpine region, which is very dry due to the wind shading effects from the surrounding mountain crest (see e.g. Smith 1979). This effect is also seen at the station of Findelen (VSFIN), which is located about 3km from STO and which is also much drier than the stations at comparable elevation (Fig. 12c)."

Conclusions In general, I see here nothing on the implications on permafrost, which seems to be one of the major motivations of the paper. Either downplay this in the introduction, or develop more the permafrost topic in the discussion/conclusions sections.

We agree with the reviewer on that point and made the according changes in the introduction (see answer above for the specific modifications).

Page 19, lines 5-12. This part should be moved to the method section. It partially addresses the major objection of Reviewer 1. You say "Although the sensors are not specifically designed for freezing conditions, we found the measurements to be consistent, both regarding inter-sensor comparisons as well as in comparison with related variables such as ground temperature and precipitation". This should be better motivated in the method section.

In response to the major comment from reviewer 1 and 2, we added a new sub-section after the calibration part, which tackles the issues of VWC measurement in frozen conditions (see above). The selected passage was moved there and the conclusion was modified as follow.

Original manuscript:
"The use of two types of standard soil moisture sensors for application in coarse grained terrain undergoing freeze/thaw cycles at middle and high elevation was shown to be reliable. Although the sensors are not specifically designed for freezing conditions, we found the measurements to be consistent, both regarding inter-sensor comparisons as well as in comparison with related variables such as ground temperature and precipitation."

Revised version:
"The use of two types of standard soil moisture sensors for application in coarse grained terrain undergoing freeze/thaw cycles at middle and high elevation was shown to be reliable, both regarding inter-sensor comparisons as well as in comparison with related variables such as ground temperature and precipitation."

Page 19, lines 15-16. I suggest to add here more details on the result that it does exist a SWC "peak" at about 2000 m a.s.l. This is an interesting result that should be highlighted.

An additional sentence was added to the conclusion to highlight the observed 2000m threshold.

"This shift between the two distinct moisture regimes was found to take place at about 2000m.a.s.l., where the maximum annual VWC values were recorded."

Figure 11. I suggest to have the same x and y range in all the subplots.

We thank the reviewer for this remark. We agree that for the comparison homogeneous scales would be more appropriate. However, given the differential response of each field sites using one single scale makes the orbit too small in some cases (SCH, STO and GFU). Therefore we did not change the scales in figure 11.

Editor Prof. Roberto Greco
Received 13 December 2016

Dear Authors,
both the reviewers have made a thorough review of your manuscript, and both raised serious doubts about the correctness of volumetric water content data indirectly retrieved through dielectric permittivity measurements when part of the water is frozen, as well as about the discussion of the obtained results, in which no clear distinction between liquid and frozen water was made.
At the same time, both the reviewers recognize some merit in the manuscript, so my decision is to reconsider it after major revisions.
I have read your point-to-point answers, and I can see that you are going to address all the issues raised by the reviewers.
I add here a few comments of my own:

General comments:
Regarding the calibration of indirect measurements of soil water content based upon dielectric permittivity, you should consider that also the permittivity of liquid water is sensitive to temperature variations: the value of 80 which applies at 20°C grows up to 88 at 0°C. This implies that both the specific calibration of FDR and Topp's polynomial that you use for TDR have additional uncertainty when applied at low temperatures.

We thank Prof. Greco for the important additional considerations, regarding the validity of the presented calibration approaches at different temperatures. This is an important effect to be accounted for in the assessment of the sensor accuracy. An additional sentence in that regard was included within the subsection 3.1 technical considerations for frozen conditions (see below).

"Given the high-elevation application of the FDR and TDR techniques at field sites which undergo freezing and thawing processes, some considerations are important to make. As mentioned above both techniques make use of the high permittivity of liquid water (~80) compared to the surrounding soil and air (2-9 and 1, respectively) to relate the recorded electromagnetic signal to the VWC. However, the permittivity of liquid water is sensitive to temperature variations and can increase from ~80 at 20°C up to ~88 at 0°C (e.g. Wraith and Or, 1999), thus introducing an additional uncertainty in the calibration for unfrozen conditions. Furthermore, under frozen conditions a part of this total water turns into ice, which has a much lower permittivity (~2-3, e.g. Aragones et al., 2010). Thus, upon freezing, the recorded signal and measured VWC strongly decreases although the total VWC stays constant. Given these limitations, the term VWC used hereafter is always referring to the liquid VWC. "

I still find difficult to understand the supposed process of melting from below: although temperature variations in the soil are obviously more delayed at higher depths, it remains true that the amplitude of the variations decreases with depth. So, it is possible to have temperatures above melting point in depth and below freezing point in shallower layers, but only when the soil is refreezing after the summer season (the temperature is decreasing above, and is still high, or maybe even increasing, below). But the melting process in any case starts from above, and it should be clear in the discussion.

We are thankful to Prof. Greco for this comment. The manuscript as well as our response to the comment from reviewer #1 was carefully revised in order to explain this process more clearly and moderate its implications. Clearly the melting process starts from the surface and propagates downward. However, in case of very warm temperature during the preceding summer and/or mild winter temperatures, the warmer temperature at depth can persist throughout the summer and influence the melting process.

Original manuscript:
"This is followed by a sharp increase at 50cm not seen at 10cm (1), followed by a strong increase at 10cm but not at 50cm (2) consistent with the melting of the ground from underneath, which takes place at different time at the two depths (spring zero-curtain)."

Revised version:
"This is followed by a sharp increase at 50cm not seen at 10cm (1), followed by a strong increase at 10cm but not at 50cm (2) consistent with the melting of the ground from underneath, which takes place at different time at the two depths (spring zero-curtain).The start of the thawing process at larger depth can be due to preferential water infiltration events or to the influence of warm temperatures from the preceding summer at depth (e.g. Zenklusen Mutter and Phillips, 2012). In the case of the latter, warmer ground temperatures in spring can be found at depth compared to the near surface due to the time-lag of heat propagation into the subsurface. The occurrence of this phenomenon depends on the thermal properties of the subsurface and the strength of the winter freezing. . Although the thawing process systematically starts at the surface in response to meteorological forcing, the warmer temperatures remaining at depth will also start the thawing from below. This process is especially marked for permafrost temperatures close to 0°C as it is the case at SCH."

About your statement, criticized by both the reviewers, that under dry conditions you observed quicker infiltration, I would remind that the infiltration capacity of a soil is controlled not only by the unsaturated hydraulic conductivity (obviously smaller in drier conditions), but also on the vertical gradient of water potential, which can be very high downward when the soil is dry, so that usually the infiltration capacity is maximum when a soil is dry, and then reduces. So, before invoking preferential flows, often seen as the "miracle cure" to all problems, I would carefully check if the measurements (and the characteristics and even the visual observation of the topsoil) actually give evidence of the possible activation of by-pass flow. In other words, I would better motivate statements as "indicative for preferential flow processes", and similar.

We thank Prof. Greco for this important and helpful comment. Given that no specific infiltration experiment was performed before the installation of the sensors, which was realized in conditions without precipitation, we do not have exact field information about the potential preferential flow paths within the soil profiles. Based on the visual observations, preferential flow is likely to occur at DRE. However at FRE and MLS it is much more difficult to assess. Therefore we modified the manuscript and our answers to reviewer #1 and #2 accordingly:

Revised versions:
P.15, l.28-30: *"The dry top soil conditions can generate a large water potential gradient with depth and thereby an increased infiltration capacity but also suitable conditions for potential preferential flow processes which tend to induce bypass flow of precipitation water (e.g. Wiekenkamp et al., 2016)."*

P.18, l.21-25*: "From Fig. 6c, it can be seen that, at the time of the precipitation event, the VWC at 10cm and 30cm depths were unusually low, thus generating a larger gradient in pressure head from the surface to the lower soil layers as well as providing very suitable conditions for the activation of preferential flow (see e.g. Wiekenkamp et al., 2016). The degree of saturation of the soil layer is thus another key factor influencing the soil moisture dynamics."*

P.19, l.10-17: "*At FRE, the first and third events yield similar moisture orbit shapes with a larger amplitude for the larger precipitation event. However, the second event produces a diagonal moisture orbit with almost no VWC decrease. As for MLS above, the VWC is low at all depths creating suitable conditions for preferential flow as well as an increased infiltration capacity due to a high gradient of* *water potential. Both processes could explain the larger and faster increase of VWC observed at larger depth due to the bypass of the dry uppermost layer. The same indications for preferential flow are seen at DRE, where the second precipitation event is comparatively small (+10 mm d-1) but yields the strongest and fastest VWC increase at depth. Given the soil properties, the preferential flow interpretation is preferred to the enhanced infiltration capacity."*

Monitoring soil moisture from middle to high elevation in Switzerland: Set-up and first results from the SOMOMOUNT network

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Abstract. Besides its important role in the energy and water balance at the soil-atmosphere interface, soil moisture can be a particular important factor in mountain environments since it influences the amount of freezing and thawing in the subsurface and can affect the stability of slopes. ~~In permafrost areas, it is strongly linked to the ground ice content and by this modifies the characteristics and behaviour of periglacial landforms.~~

In spite of its importance, the technical challenges and its strong spatial variability usually prevents soil moisture from being measured operationally at high and/or middle altitudes. This study describes the new Swiss soil moisture monitoring network SOMOMOUNT launched in 2013 consisting in six entirely automated soil moisture stations distributed along an altitudinal gradient between the Jura Mountains and the Swiss Alps, ranging from 1205m to 3410m elevation. In addition to the standard instrumentation comprising Frequency Domain Reflectometry (FDR) and Time Domain Reflectometry (TDR) sensors along vertical profiles, soil probes and meteorological data are available at each station.

In this contribution we ~~will~~ present a detailed description of the SOMOMOUNT instrumentation and calibration procedures. Additionally, the data collected during the three first years of the project ~~will be~~are discussed ~~in relation~~with regard to their soil type and climate dependency as well as ~~to~~ their altitudinal distribution. The observed elevation dependency of soil moisture is found to be non-linear, with an increase of the mean annual values until ~2000m.a.s.l. followed by a decreasing trend towards higher elevations. This altitude threshold marks the change between precipitation/evaporation controlled soil moisture regime and frost affected ones. The former is characterized by high liquid VWC throughout the year and minimum values in summer, whereas the latter typically exhibits long lasting winter minimum liquid VWC values and high variability during the summer. ~~Clear differences in soil moisture patterns are visible between sites with permanently and seasonally frozen as well as unfrozen ground conditions and can be related to several factors such as the subsurface composition (organic versus mineral), the elevation and the snow cover characteristics.~~

Keywords: Soil moisture, monitoring network, TDR, FDR, mountain, elevation gradient, seasonal frost, permafrost

1 Introduction

Soil moisture is a key factor controlling the energy and water exchange processes at the soil-atmosphere interface as well as the physical properties of the subsurface such as heat capacity and thermal conductivity (for a review see e.g. Seneviratne et al., 2010). In 2010 soil moisture was classified as an Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) and has thus to be continuously and globally monitored. Even though the number of soil moisture networks is globally increasing, it is still far from being standardised, coordinated or spatially representative. Coordination efforts are however increasing with the International Soil Moisture Network being the largest soil moisture data source to date (Dorigo et al., 2011).

Existing soil moisture monitoring network have many different foci, such as the validation of remote sensing products (e.g. Bircher et al., 2012; Rautiainen et al., 2012), the investigation of hydrological processes at hillslope scale (e.g. Brocca et al., 2007; Martini et al., 2015) or catchment scale (e.g. Bogena et al., 2010) as well as the study of land-atmosphere interactions (e.g. Hauck et al., 2011; Krauss et al., 2010; Mittelbach et al., 2011). In the interest of representativeness for large scale studies and easy implementation most of the current monitoring networks are located at middle to low elevation. In Switzerland, the long term monitoring network SwissSMEX was initiated in 2008 and is composed of 16 stations distributed across the Swiss plateau and other low elevation regions (Mittelbach and Seneviratne, 2012).

In mountain environments, ~~where the ground is affected by seasonal and permanently frozen conditions, ~~soil moisture ~~and water flow can be~~is particularly crucial~~.~~ since it can control the initiation of convective precipitation (e.g. Barthlott et al., 2011; Hauck et al., 2011), the generation of runoff (e.g. Morbidelli et al., 2016; Zehe et al., 2010) and thereby the mitigation or intensification of flash floods (e.g. Borga et al., 2007). Soil moisture also significantly affects the vegetation growth and distribution (e.g. Paschalis et al., 2015; Porporato et al., 2004). In terrains affected by seasonal and permanently frozen conditions, its effect on the stability of slopes and the thermal and kinematic characteristics of periglacial landforms was highlighted in several observation and modelling studies (e.g. Boike et al., 2008; Hasler et al. 2011; Hinkel et al., 2001; Krautblatter et al. 2012; Scherler et al., 2010; Streletskiy et al. 2014; Westermann et al., 2009; Zhou et al. 2015). A general overview of the interactions between hydrological, mechanical and ecological processes in frozen grounds is given by Hayashi (2013).

However, soil moisture measurements in mountainous areas are technically challenging because of the often coarse blocky substrate, the temperatures below the freezing point and the remoteness of the sites, which also adds difficulties regarding energy supply and data transfer. They are therefore also more costly to implement. Furthermore, among the numerous well established in situ soil moisture monitoring devices (e.g. Hillel, 2004; Robinson et al., 2008; Vereecken et al., 2014), only few have been tested in such conditions (e.g. Pellet et al., 2016; Rist and Phillips, 2005, Zhou et al., 2015). Thus measurements in mountainous terrains are currently restricted to uncoordinated and project based installations (e.g. Hilbich et al., 2011; Rist and Phillips, 2005; Zhou et al., 2015). Furthermore the systematic investigation of soil moisture along a large elevation gradient reaching to Alpine permafrost conditions is non-existent so far.

The project SOMOMOUNT (Soil moisture in mountainous terrain and its influence on the thermal regime in seasonal and permanently frozen terrains, see also Pellet et al., 2016), which started in 2013 and is funded by the Swiss National Science Foundation, has the main objective to fill this data gap. ~~Combining resources from~~In collaboration with the Swiss permafrost monitoring network (PERMOS) and the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss), ~~this project also aims at quantifying the influence of soil moisture on the ground temperature regimes~~six automatic soil moisture monitoring stations have been established at different altitudes.

In this contribution we will present a detailed description of the SOMOMOUNT monitoring network's instrumentation, monitoring strategy and calibration procedure, and discuss the measurement accuracy. Additionally, the data collected during the three first years of the SOMOMOUNT project will be discussed regarding the importance of the different water related processes, which are dominant at the different elevation bands. Hereby the differential impact of a three-week lasting heat wave on the different sites during summer 2015 is highlighted.

2 Soil moisture network

The soil moisture network established within the framework of the SOMOMOUNT project is currently composed of six fully automatic soil moisture monitoring stations installed along an elevation gradient ranging from 1205 m.a.s.l. to 3410 m.a.s.l., which spans from the Jura Mountains to the western Swiss Alps (Fig. 1). It is designed to be compatible with the existing low elevation soil moisture monitoring network SwissSMEX (Mittelbach and Seneviratne, 2012) as well as the stations of the Swiss Permafrost Monitoring Network (PERMOS). Finally the high elevation soil moisture and permafrost monitoring station of Cervinia, Italian Alps, (Pellet et al., 2016; Pogliotti et al., 2015) is also included in the comparative analyses.

2.1 Instruments

Three different types of sensors are used within the SOMOMOUNT network: the SMT100 (TRUEBNER GmbH, Germany) based on the frequency domain reflectometry (FDR) technique, the TRIME-PICO64 (IMKO GmbH, Germany) based on the time domain reflectometry (TDR) technique and the PR2/6 (Delta-T Device Ltd, UK) based on the capacitance technique. Both the SMT100 and the PICO64 sensors are measuring simultaneously soil moisture and ground temperature. The sensor characteristics are listed in Table 1.

Both FDR and TDR methods are indirect measurement techniques that use electromagnetic waves to estimate the dielectric permittivity of the ground and relate it to the soil volumetric water content (VWC). The SMT100 sensors are composed of a ring oscillator which feeds a 10cm long transmission line (Fig. 2). The sensors emit an electromagnetic wave at a fixed frequency and the recorded oscillation frequency can be related to the wave propagation velocity and thus the dielectric permittivity and VWC of ~~along the line which interacts with~~ the surrounding medium ~~and, when buried in the ground, with the VWC: the higher the VWC, the higher the effective dielectric permittivity, leading to a lower wave propagation velocity~~

~~and thus to a lower oscillation frequency~~ (~~Schlaeger et al., 2005~~Qu et al., 2003). The SMT100 sensors are the newest generation of the so-called SISOMOP sensors, which have been used to monitor soil moisture at Schilthorn (one of the high elevation permafrost sites, see section 2.3) since 2007 (Hilbich et al. 2011), demonstrating the sensors robustness and capability to measure in mountainous areas. Furthermore, laboratory experiments performed by Mittelbach et al. (2012) showed that the SISOMOP sensors have a similar absolute accuracy (±3 vol.%) compared to three other, more widely used, FDR sensors.

The PICO64 sensors are based on the standard TDR technique, which relates the travel time of an electromagnetic wave to the dielectric permittivity of the medium surrounding the sensors, which can in turn be related to the VWC of said medium. The PICO64 sensors emit an electromagnetic impulse at a frequency of 1 GHz~~, which travels~~ along two 16cm long parallel rods separated by 40mm, yielding a measurement volume of ~1.25L (~10cm diameter around the rods)~~, is reflected at their ends and returns back to the sensor to be recorded~~. The recorded travel times are ~~then~~ related to the VWC using a general calibration based on Topp's equation (Topp et al., 1980).~~ The spacing between the two rods of the PICO64 is 40mm (Fig. 2), which results in a measurement volume of ~1.25L (~10cm diameter around the rods).~~ This sensor was selected for its high absolute accuracy (±1 vol.%, IMKO, 2015) and because it corresponds to the new generation of TRIME-EZ sensors used by the SwissSMEX monitoring network (Mittelbach et al., 2011). Additionally, due to its large measurement volume, this sensor is particularly suitable for heterogeneous media (IMKO, 2015).

Finally, the PR2/6 sensor is a 100cm long down-hole water content sensor measuring soil moisture at 6 different depths (10, 20, 30, 40, 60 and 100cm) using the capacitance technique (Fig. 2). ~~This technique relies on the fact that the charging time of an electromagnetic field depends on the capacitance of the soil, which in turn depends on the dielectric permittivity and thus can be related to the VWC of the surrounding soil.~~ Each measurement depth comprises a pair of stainless steel rings, which transmit the 100 MHz electromagnetic signal into the ground, and one detector, which records the returned signal. This technique relies on the fact that the emitted wave generates an electromagnetic field, which extends about 100mm into the surrounding soil and depending on its dielectric properties and thus on the VWC is partly reflected (Verhoef et al., 2006). The sensor is lodged in an access polycarbonate tube of 25mm diameter and its measurement volume is ~10cm diameter with an absolute accuracy of ±6 vol.% (Delta-T Device, 2008). This sensor was selected for its measurement depth and its easy installation. However, it is not suited for heterogeneous subsurface or coarse grained material since a good contact between the access tube and the soil is necessary. Furthermore, at least 1m soil is needed for its installation, thus it was only used at Frétaz (Sect. 2.3).

2.2 Network design

Each soil moisture station is equipped with 4 to 6 sensors along a vertical profile. The standard instrumentation consists of one SMT100 at 10cm, two at 30cm and one at 50cm as well as one PICO64 at 30cm and one at 50cm (Fig. 2). The doubled sensors at 30cm were installed to check for instrumental drift on the long term. Depending on the soil characteristics, the installation of the complete instrumentation at all depths was not possible at all sites. The site specific set-ups are summarized in Table 2.

The same sensor installation procedure was followed at all sites and is based on the criteria described in Krauss et al. (2010) and Mittelbach et al. (2011). While digging the pit for the sensor installation, each soil horizon was stored separately in order to preserve and restore the initial soil profile. At the depth of each sensor, up to two soil samples were collected at the side for granulometric analysis and water content determination. The sensors were then installed in the undisturbed soil with the blade in vertical position to avoid ponding (Fig. 2 and Fig. 3). Finally, the soil was refilled according to the original order of horizons and compacted to restore its original density. Additionally, larger samples of soils (about 8 L) were collected in the vicinity to perform material specific calibration of the sensors (Sect. 3).

The data are recorded using a CR1000 data logger (Campbell Scientific) and transmitted with wireless transfer to an ftp server. The measurement interval is depending on the electrical power capacity of each station (see Table 2). ~~At Frétaz and Moléson, where direct connections to the power grid are available, a 10min interval was chosen to match the setup of the SwissSMEX network (Mittelbach et al., 2011). At all the remaining stations, solar panels are used for power consumption and thus a 30min measurement interval was selected, except at Dreveneuse were the shaded location requires an even longer interval (60min).~~

2.3 Field sites

The site selection for the installation of the long term soil moisture monitoring stations within the SOMOMOUNT project was constrained by the following criteria:

i. high enough elevation, so that the ground thermal regime is affected by seasonally or permanently frozen conditions.
ii. equal distribution along an altitudinal gradient.
iii. availability of additional meteorological data and if possible ground temperature data.
iv. easy access on site and a minimum of 50cm of fine grained material, to guarantee the installation of the sensors.

The stations were installed in collaboration with the Swiss Federal Office for Meteorology and Climatology MeteoSwiss (cf. SwissMetNet, http://www.meteoswiss.admin.ch) for stations at middle elevation and the Swiss Permafrost Monitoring Network PERMOS (http://www.permos.ch) for stations at higher elevation (see Table 2). Located in the western part of Switzerland, the SOMOMOUNT network covers an elevation range from 1205 to 3410 m.a.s.l. with altitudinal differences between stations of 400-500m (Fig. 1). Detailed information about the climatic conditions and subsurface properties at each field site are summarized in Table 3.

2.3.1 Frétaz (FRE)

Frétaz is ~~the lowermost field site within the network with an altitude of 1205 m.a.s.l. It is~~ located in the western part of Switzerland on the first crest of the Jura Mountains at an altitude of 1205 m.a.s.l. ~~For the reference period 1981 to 2010 the~~

~~mean annual air temperature was 6°C and the annual sum of precipitations 1333 mm y^{-1} (MeteoSwiss).~~ The soil moisture monitoring station is installed within the perimeter of the weather station belonging to the MeteoSwiss automatic network SwissMetNet, where ground temperatures down to 1m depth were also measured until 2005.

~~During the monitoring period 2013-2016 no freezing of the ground was observed. However, during the period 1981-2005 several short occurrences of below freezing temperature were recorded at 5cm and 10cm (MeteoSwiss).~~ The surface cover consists of managed grass following the general directives from MeteoSwiss (grass cover maintained at all times at a few cm). The soil is composed of a unique layer of sandy loam down to 50cm (Table 3). According to geophysical surveys (Electrical Resistivity Tomography, ERT) the limestone bedrock is located at 5 to 10m depth underneath the station (see Pellet et al. 2016).

2.3.2 Dreveneuse (DRE)

The Dreveneuse field site is located at an altitude of 1650 m.a.s.l. in a small North orientated valley within the Swiss Pre-Alpine region, where the mean annual air temperature is around 5°C (Morard, 2011). The soil moisture station is installed on a vegetated talus slope near an automatic weather station, and ground temperatures are monitored in two boreholes down to 5 and 14m depth.

This site is situated below the lower altitudinal limit of permafrost occurrence in the Alps but is still affected by permafrost conditions due to complex air circulation within the talus slope (Delaloye, 2004). The coarse limestone blocks composing the talus slope are covered by a single layer of organic rich sandy loam (Table 3, Fig. 3b). The surface is covered by moss and spruces and according to repeated ERT soundings as well as drilling logs, the talus slope is approximatively 11m thick (Morard, 2011).

2.3.3 Moléson (MLS)

The Moléson soil moisture station is situated at 1974 m.a.s.l. on top of the eponym mountain in the Swiss Pre-Alpine region. For the reference period 1981 to 2010 the mean annual air temperature was 3°C and the annual sum of precipitations is 929 mm y^{-1} (MeteoSwiss). As for FRE, the soil moisture station is integrated within the perimeter of a SwissMetNet station, where the surface cover consists of managed grass.

~~The site is affected by seasonal freezing processes down to maximum 10cm for the monitoring period 2013-2016. As for FRE the surface cover consists of managed grass and n~~No apparent layering was found in the soil profile (homogeneous layer of silty loam down to 50cm, see Fig. 3 and Table 3) and~~.~~ According to ERT measurements and the construction journal of the weather station, the bedrock, which consists of limestone, is located at around 75cm depth underneath the station.

2.3.4 Gemmi (GFU)

The Gemmi soil moisture monitoring station is located at 2450 m.a.s.l. in a West-orientated valley within the main alpine ridge of Switzerland (Fig. 1). ~~The site receives between 1800 and 2500 mm y^{-1} of precipitations per year and has a mean~~

~~annual air temperature around 0°C (Krummenacher et al., 2008).~~ The monitoring station is installed on a solifluction lobe in the direct vicinity of a 1m deep temperature profile ~~installed in 1988 (Krummenacher and Budminger, 1992)~~ and a weather station ~~installed during summer 1999~~(Krummenacher and Budminger, 1992).

This site is situated just below the lower limit of permafrost occurrence in the Alps and therefore undergoes marked seasonal freezing processes down to at least 1m depth. The surface is covered by grass during the summer and the uppermost 10cm of the ground is composed of an organic rich silty loam layer (Table 3, Fig. 3). According to ERT measurements performed in 2014, the bedrock is located at around 5m depth underneath the station (Pellet et al., 2016).

2.3.5 Schilthorn (SCH)

The Schilthorn field site is situated at an elevation of 2900 m.a.s.l. on a small plateau in the North-facing slope of the Schilthorn summit in the northern Swiss Alps (Fig. 1). ~~The average annual sum of precipitation is around 2700 mm y^{-1} (Imhof et al., 2000) and the mean annual air temperature is about -3°C (PERMOS, unpubl.).~~ The soil moisture station is installed next to an automatic weather station and two boreholes, ~~(14m and 100m deep),~~ where ground temperatures have been monitored since 1998 (Harris et al., 2001).

Permafrost ~~was first discovered at Schilthorn in 1965 and has been extensively investigated since 1999. T~~is present at SCH and the depth of the seasonally unfrozen soil layer (the so-called active layer) can reach up to 10m (PERMOS, ~~2013~~2016). The surface cover is vegetation free and consists of a layer of fine grained debris with material ranging from loamy sand to sand (Table 3) which reach several meter thickness according to ERT measurements (Hilbich et al., 2008). SCH is the only station of the SOMOMOUNT network where soil moisture has already been monitored since end of August 2007 (Hilbich et al. 2011).

2.3.6 Stockhorn (STO)

The highest soil moisture monitoring station of the SOMOMOUNT network is located at an elevation of 3410 m.a.s.l. on the Stockhorn plateau in the Western Swiss Alps. ~~This East-West orientated mountain crest has a mean annual air temperature of about -5°C (PERMOS, unpubl.) and the annual precipitation sum is estimated to be around 1500 mm y^{-1} (King, 1990).~~ The soil moisture station is installed in the vicinity of an automatic weather station as well as two boreholes measuring ground temperatures since summer 2000 ~~down to 17 and 100m depth~~ (Harris et al., 2001).

The Stockhorn plateau is underlain by at least 100m deep permafrost~~, which is strongly affected by 3D topography effects of the site~~ (Gruber et al., 2004), where~~. T~~ the active layer thickness can reach up to 5m (PERMOS, ~~2013~~2016). The surface is free of vegetation and consists of a 1m deep layer of fine grained debris ranging from sand to loamy sand (Table 3) underlain by Albit-Muskovit schist bedrock (Gruber et al., 2004).

2.3.7 Additional stations

In addition to the SOMOMOUNT network we used the stations of Sion (SIO, Mittelbach and Seneviratne, 2012) and Cervinia (CER, Pellet et al., 2016; Pogliotti et al., 2015) for comparative analysis. The first one is part of the SwissSMEX network and is located in the Rhone valley at an elevation of 490 m.a.s.l. Since 2009, soil moisture is measured down to 80cm depth within the perimeter of the SwissMetNet station. Conversely, Cervinia is a high elevation (3100 m.a.s.l.) permafrost monitoring site managed by the regional environmental protection agency of Val d'Aosta (ARPA). Since 2006, the site is equipped with two boreholes (7m and 14m deep) as well as an automatic weather station and one soil moisture sensor at 20cm depth.

2.4 Data processing

To ensure the quality of the soil moisture and ground temperature data, two different automatic filters are applied: a technical filter and a temporal filter. The filters are based on guidelines from Dorigo et al. (2013).

The technical filter is designed to eliminate all unrealistic values due to technical issues. Firstly, a threshold method is applied to detect and remove measurements outside of the plausible ranges (<0% and >80% for VWC and <-20°C and > 30°C for ground temperature). The threshold for VWC used here was empirically determined based on the data from all SOMOMOUNT stations. It is slightly higher than the 60% proposed by Dorigo et al. (2013) for the International Soil Moisture Network. Secondly, the values collected with insufficient battery voltage (< 10 V) are removed, since too low power supply can disturb the measurements. For the SMT100 sensors, readings with a raw sensor output (given in so-called moisture counts, MC, see Truebner, 2016) outside of the range defined in the laboratory ($MC_{water} \approx 9000$ and $MC_{air} \approx 20000$) are also excluded. At all sites the technical filter eliminated less than 0.1% of the measured values except at GFU, where the PICO64 sensors had a default in wiring and thus 8.3% of the measured data were excluded.

The temporal filter is designed to eliminate any VWC value exhibiting unrealistically large temporal variability (random spikes). Three-day running means (r_{mean}) and standard deviations (r_{stdev}) are calculated for all sensors, and the values lying outside the range defined by $r_{mean} \pm x \cdot r_{stdev}$ are removed, where x is an empirically determined site specific tolerance factor (3 at FRE and GFU, 4 at DRE, SCH and STO and 5 at MLS). This filter is applied to soil moisture and ground temperature measurements with an elimination rate varying between 0% (DRE) and 0.3% (FRE and SCH) of the measured data.

Numerous data gaps occurred at the different SOMOMOUNT stations during the monitoring period 2013-2016 (see Fig. 6). They were mainly caused by problems related to power supply (large data gap for all the sensors at one station e.g. autumn 2013 at FRE and MLS), data logging (short gaps for all sensors of the station e.g. winter 2014 at GFU) or sensor malfunction (single sensors for variable time, e.g. PICO64 at 50cm end of summer 2016 at STO). Given the highly variable nature of soil moisture, no gap filling technique was applied.

2.5 Complementary analysis

All soil moisture datasets used in the following analysis were homogenised to hourly arithmetic mean values. For the elevation dependency investigation (Sect. 5.2), annual and seasonal means were calculated using the year 2015, since all stations except GFU have complete data series during that period. The data gaps at GFU (24.02-01.03.2015 and 24.04-25.05.2015) were filled for that analysis only by linear interpolation between the nearest available data points. Finally, for the analysis of the transport of moisture through the ground we used the so-called moisture orbits (see Sect. 5.1).

To analyse and understand in detail the temporal evolution of soil moisture, additional datasets such as weather and ground temperature data are needed. The stations of SIO, FRE and MLS are located next to SwissMetNet stations and thus data sets with good quality are available. This is not always the case at the high altitude/permafrost stations DRE, GFU, SCH and STO, where high altitude related logistical problems in maintenance may lead to data gaps and precipitation is not measured at all.

For the stations without explicit precipitation measurements, precipitation data were extracted from the 2km gridded dataset generated by MeteoSwiss (MeteoSwiss, 2014), which is based on 430 observation stations across Switzerland and available at daily resolution. The data gap of the measured in situ air temperature series were completed using the two step quantile mapping approach described in Rajczak et al. (2016). Finally the snow duration was extracted from the near surface ground surface temperature variability using the snow index method described in Staub and Delaloye (2016).

3 Calibration

In order to increase the accuracy of the absolute soil moisture measurements, the SMT100 sensors require a material specific calibration (Table 4). Using the large soil samples collected at each site, a material specific calibration was performed in the laboratory following the general procedure outlined by Starr and Paltineanu (2002).

In a first step, the entire soil sample was oven dried and packed into a plastic container at approximatively the field bulk density. A SMT100 sensor was then inserted in the sample and its raw outputs were continuously recorded. Finally, a soil sample was collected using a standard measurement cylinder. In a second step, 200ml of water were added to the calibration soil (increase VWC by about 3-5%) which was subsequently thoroughly mixed to get a homogenous repartition of the water. The SMT100 was then reinserted, its raw outputs recorded and a soil sample collected. This operation was repeated until saturation of the soil material was reached, yielding 9 to 12 calibration data points depending on the soil type.

The volumetric water content (VWC, θ_v) of the collected samples was determined following the standard gravimetric method. First the samples were weighted and oven dried at 105°C during 24 hours for the mineral soils and 60°C during 48 hours for organic soils. The dry samples were then weighted to determine the gravimetric water content (mass of water which evaporated θ_g) and to calculate the dry bulk density (ρ_b). Finally, θ_v was obtained using Eq. 1:

$$\theta_v = \rho_b \cdot \theta_g \tag{1}$$

The gravimetric method was also applied to the in situ soil samples collected during the sensor installation. The calculated VWC (θ_v) values obtained from both the laboratory and the in situ samples were then fitted to the SMT100 raw data (Moisture Counts, *MC*) using a linear (Eq. 2) and an exponential relation (Eq. 3).

$$\theta_v = a \cdot MC + b \tag{2}$$

$$\theta_v = c \cdot \mathrm{e}^{(MC \cdot d)} \tag{3}$$

Table 4 lists the value of the parameters *a*, *b*, *c* and *d* for each station as well as the number of samples considered and the goodness of the fit for both methods. At GFU, two different material specific calibrations for mineral and organic soil were realized due to the clear layering of the soil profile (Fig. 3). At all locations except DRE the linear relation yields higher r^2 and lower RMSE than the exponential one. ~~For consistency~~Thus, the linear calibration is used for all sites since ~~it yields the best fits in most cases and a still very satisfactory fit~~ except at DRE, where the exponential one is preferred.

For the PICO64, the built-in calibration based on Topp's equation (Topp et al., 1980) was used and no additional material specific calibration was performed~~ according to Mittelbach et al. (2011)~~. In this study the PICO64 sensors are only used for inter-network comparison with the SwissSMEX network but not for further analysis.~~In our study, the PICO64 is mainly used as reference sensor regarding future comparison of data between the SwissSMEX soil moisture network and the SOMOMOUNT network.~~ Thus for consistency we adopted the same calibration approach as Mittelbach et al. (2011) (i.e. the built in calibration for generic soils).

Similarly, the manufacturer's calibration was used for the PR2/6 sensor (Delta-T Device, 2008), which is mainly used for test purposes within the SOMOMOUNT network at the moment. Depending on the middle-term results further PR2/6 sensors might be added later to the network.

3.1 Technical considerations for frozen conditions

Given the high-elevation application of the FDR and TDR techniques at field sites which undergo freezing and thawing processes, some considerations are important to make. As mentioned above both techniques make use of the high permittivity of liquid water (~80) compared to the surrounding soil and air (2-9 and 1, respectively) to relate the recorded electromagnetic signal to the VWC. However, the permittivity of liquid water is sensitive to temperature variations and can increase from ~80 at 20°C up to ~88 at 0°C (e.g. Wraith and Or, 1999), thus introducing an additional uncertainty in the calibration for unfrozen conditions. Furthermore, under frozen conditions a part of this total water turns into ice, which has a much lower permittivity (~2-3, e.g. Aragones et al., 2010). Thus, upon freezing, the recorded signal and measured VWC strongly decreases although the total VWC stays constant. Given these limitations, the term VWC used hereafter is always referring to the liquid VWC.

Characteristically, at temperature below 0°C water and ice can coexist in the soil (e.g. Spaans and Baker, 1995). However, the calibration procedure presented was conducted at room temperature and thus does not account for the presence of ice in the soil mixture. The resulting sensor accuracy is therefore only valid for above 0°C ground temperature (unfrozen conditions). The use of standard empirical calibration in frozen conditions often yields overestimations of the liquid VWC (e.g. Spaans and Baker, 1995; Yoshikawa and Overduin, 2005). However, according to Watanbe and Wake (2009), for sand the calibration using Topp's empirical relationship in frozen conditions shows only small deviations from the measured total VWC using NMR except for temperatures between 0 and -1°C.

Although the absolute accuracy of measured liquid VWC under frozen conditions is difficult to assess, the relative changes are well captured. At SCH, Hilbich et al. (2011) showed that the soil apparent resistivity (using data from continuous ERT monitoring) and soil moisture (measured with similar FDR devices as in the present study) exhibit consistent variations under frozen and unfrozen conditions. Given the sandy composition of the ground at SCH and STO as well as the evidence from the coinciding resistivity measurements (cf. also Hauck 2002), we find the liquid VWC data to be consistent enough to be used here with the standard calibration described above. However, the VWC measurements carried out at temperatures below 0°C are clearly identified in all figures in the manuscript and have to be interpreted with care, especially regarding their absolute values.

4 Results

4.1 Sensor comparison and consistency

At 30cm depth two SMT100 sensors were installed in parallel in order to investigate potential instrumental drift over longer time periods. Comparing their outputs also allows us to assess the quality of the sensor installation, the reliability of the measurements and potential spatial heterogeneity.

At FRE, DRE, MLS and GFU the correlation between the VWC measured by the two sensors was found to be satisfactory (lowest correlation at MLS: r^2 = 0.~~766~~749, Fig. 4). Deviations from the one-to-one correspondence of the two sensors (black line) can be attributed to small scale heterogeneities in the soil directly surrounding the sensors, which can result in differences of reaction time ~~delays in~~to the infiltration ~~events~~ and/or evaporation events as well as wet or dry bias due to different soil properties. This is particularly visible at MLS, where the increase of VWC is systematically recorded first by the left sensor (y axis) and later by the right sensor (x axis).

At DRE (Fig. 4b) the right sensor shows consistently higher values (~5-10 vol.%) than the left sensor, but the relation between the measured VWC values is almost constant, illustrating the effect of different soil properties.

~~This is due to the soil composition (sandy loam rich in organic matter and with a very low bulk density), which has a high hydraulic conductivity leading to almost instantaneous increase in VWC following precipitation events.~~

DRE is also the site with the largest RMSE (0.~~566~~618°~~C~~K) between the measured temperatures at 30cm depth, indicating that ~~different~~ specific physical processes such as the convective heat transport through air flow (e.g. Wicky and Hauck 2016) may influence the two sensors in a different way (see Sect. 5.3). At FRE, MLS and GFU the measured temperatures correspond almost perfectly one-to-one showing no different physical processes. Therefore the VWC deviations are most likely due to soil heterogeneities.

Sensor comparison was only possible at four sites. At SCH the terrain prevented the installation of two sensors at 30 cm, whereas at STO two sensors were installed but only one gives reliable data. The second sensor at 30 cm depth at STO probably suffers from bad coupling with the soil (air pockets near the blade and thus bad contact with the soil) stemming from a faulty installation due to the blocky subsurface.

The TDR-based PICO64 sensors, which have a higher absolute accuracy (Mittelbach et al., 2012) are also, are installed at 30cm depth. Similar to Fig. 4, the comparison between FDR and TDR sensors at the same depth (Fig. 5) shows a generally good correlation (lowest r^2 = 0.~~541~~ 524 at STO) with some deviations from the one-to-one relation (black line). At FRE and GFU the comparison between PICO64 and SMT100 soil moisture measurements yield very similar results to the comparison of the two SMT100 sensors, with slightly higher RMSE values. MLS shows a larger dynamic range and mostly higher values for the SMT100 sensor, but a similar temporal variability. At SCH and STO the differences between the sensors have a characteristic shape, but are centred on the one-to-one relation. It can be attributed to different onset of freezing and thawing processes at the two sensor locations ~~(~~marked by the grey dots (see also Fig. 6e-f). Additionally,~~ a~~ clear wet and dry biases in the PICO64 measurements ~~can be~~are observed at SCH and STO, respectively, which can be explained by an unreliable calibration using Topp’s equation for the high-mountain subsurface material present at SCH and STO (e.g. Robinson et al., 2004).

Figure 5 only considers the sensors at 30cm (left) at all sites with the exception of SCH, where the 10cm sensor was used, since it is the depth of the only available PICO64. The same analysis was performed with the 30cm right and 50cm sensors (Table 5). The overall results are very similar regarding statistical fit (lowest fit at MLS and highest fit at GFU) and observed patterns (not shown).

4.2 Soil moisture temporal evolution

Figure 6 shows the evolution of the measured VWC and ground temperature at all SOMOMOUNT stations from July 2013 until August 2016 for all sensor types. The temperatures exhibit a typical seasonal pattern with maximum values during the summer and minimum values in winter. The amplitude of these seasonal variations is specific to each site. DRE, GFU, SCH and STO show a clear drop of temperatures below the freezing point during the winter, whereas no freezing was recorded at FRE. At MLS negative soil temperatures were only observed at 10cm depth during 10 days in early winter 2016.

On the other hand, the VWC differs strongly at each station and no common pattern is found. The sites can be divided into two categories of soil moisture dynamics: A low elevation pattern at FRE and MLS characterized by a summer minimum of short duration and high VWC values for the rest of the year. The second category, typical for high elevations (SCH and STO), is defined by a long lasting liquid VWC minimum in winter, and maximum absolute values accompanied by strong variability during the summer. GFU and DRE display features characteristic from both categories, namely a long winter minimum as well as VWC decrease during summer. At GFU the 10cm sensor is much more variable than the ones at 30 and 50cm and shows much higher values. This is due to the high organic content and high retention capacity of this particular soil layer (Fig.3d and Table 3).

Comparing the two summer seasons in 2014 and 2015 at FRE, MLS and GFU one can observed a stronger VWC decrease in 2015 at all sites. This marked soil moisture decrease is due to the exceptionally high air temperatures recorded in July 2015 (MeteoSwiss, 2016; Scherrer et al., 2016) leading to increased evaporation. However, the effect of this anomalous event on soil moisture is different at all sites. At MLS the effect is the most pronounced (44 vol.% VWC loss at 30cm) and the VWC in the uppermost layers still did not returned to their original values in May 2016. At FRE the effect is less marked (18% vol.% VWC loss at 30cm) and shorter but it can be observed down to 100cm. At DRE it is seen at all depths with a similar amplitude (12 vol.% VWC loss at 30cm), whereas at GFU the effect was strong but of short duration at 10cm (40 vol.% VWC loss) but almost not seen below. Finally, at the two highest stations (SCH and STO) no characteristic VWC decrease was observed.

To characterize the two patterns of soil moisture dynamics identified above in more detail and to analyse the processes controlling them, we focus on a 5 months period from spring to summer 2015 at the lowest and highest field sites, FRE and ~~STO~~ SCH (Fig. 7).

At FRE the minimum VWC is reached during the summer, when air temperatures are highest and thus evaporation is maximal. No clear VWC maximum can be identified throughout the year (Fig. 6a) but multiple maxima are observed following precipitation events. The snow cover, which disappeared mid-March in 2015, reduces the link between VWC variations and the atmospheric conditions. During the snow melt period only a small VWC increase is seen, which could be attributed to conditions close to saturation throughout the winter. After the disappearance of the snow cover the variability of VWC increases at all depths and is systematically related to precipitation events (VWC increase) and dry spells, both, with and without air temperature increases (VWC decrease). As expected, the uppermost layer (10cm) reacts stronger than the lower ones to atmospheric forcing, however, the response time is very fast and in some cases almost simultaneous at all depths.

At ~~STO~~ SCH the evolution is very different. Minimum liquid VWC values are recorded in winter, when the ground is entirely frozen and the maximum is reached in early summer due to the combined effect of snow melt and thawing of the ground (Fig. 6f and Fig. 7b). ~~The latter is more important, since the VWC increase is observed only once the ground is entirely unfrozen, which in 2015 happened several days after the total snow melt out. With~~ As long as ground temperatures are below the freezing point, the ~~snow~~ meltwater from the snow cover is either running off directly at the surface or refreezes at the top of the frozen layer (and releases latent heat which can contribute to further thawing, e.g. Scherler et al. 2010). In contrast to FRE (Fig. 7a) the evolution of liquid VWC at ~~STO~~ SCH is mainly driven by ground temperatures and the snow conditions and is less affected by liquid precipitation. Three main stages of liquid VWC evolution and ground thermal regime can be identified. The frozen stage is characterized by the lowest liquid VWC values due to the frozen state of the ground and the insulating snow cover. It is followed by the so-called zero-curtain period, defined by Outcalt et al., (1990) as extended period of time with near 0°C temperature induced by latent heat effects in a thawing or refreezing active layer. During this period liquid VWC increases/decreases slowly but remains decoupled from precipitation events. Punctual lateral inflow and/or snow meltwater infiltration are also possible. Finally, the unfrozen stage coincides with the snow-free period and is characterized by high liquid VWC variability coupled with the precipitation events. Although, the accuracy of the soil moisture measurements during the frozen and zero-curtain periods is difficult to assess due to the presence of ice, the relative changes and thus the timing of each phase is well captured. The liquid VWC variations are coherent with the change of specific resistivity in the uppermost ~50 centimetres of the ground. Similar to the dielectric permittivity, the electrical resistivity is highly dependent on the amount of unfrozen water content in the ground (Hauck 2002). The frozen stage is thus characterized by high resistivities and a marked drop is observed during the zero-curtain period due to the thawing of the ground (see also Hilbich et al., 2011). Finally, the unfrozen stage exhibits the lowest resistivity values. The same typical stages of liquid VWC evolution have been described for ~~different~~ other mountain permafrost sites (e.g. ~~Hilbich et al., 2011;~~ Pellet et al., 2016) and landforms (e.g. Zhou et al., 2015). These stages are also observed in the data collected by spatially distributed SMT100 sensors installed at 30cm depth at SCH and STO, with marked differences in absolute liquid VWC as well as variable onset and duration of the three stages even at close vicinity (not shown).

~~4.3 Soil moisture spatial distribution~~

~~In addition to its pronounced temporal variability, soil moisture is also spatially highly variable (Mittelbach et al., 2012). This is especially true in heterogeneous terrain with strong microtopographic differences (Brocca et al., 2007; Williams et al., 2009). At SCH and STO, where deep ground temperatures are recorded in two boreholes at close distance respectively, long-term monitoring shows significant ground temperature offsets within short distances (0.5K at SCH and 1K at STO even at 15m depth, PERMOS, 2013). These variations are partly due to spatial differences of VWC and ice content in the ground (Hilbich et al., 2011, Python, 2015). To analyse the effect of near-surface spatial soil moisture variability on the thermal regime at both sites, three additional spatially distributed SMT100 sensors were installed at 30cm depth within a radius of 20m around the standard SOMOMOUNT vertical profile. At both sites the standard SOMOMOUNT profile (“profile” in Fig. 8) is located in the direct vicinity of the shallower borehole (13m deep at SCH, 17m deep at STO) and the sensors named “bh100” in Fig. 8 were installed near the 100m deep boreholes.~~

~~Figure 8 shows that all sensors undergo the typical high altitude evolution of VWC described above for STO: (i) low variation and minimum values during the frozen winter period followed by (ii) a slow increase and punctual infiltration events during the zero-curtain period in late spring and finally (iii) high variability and maximum values in summer. The zero-curtain period occurs twice during year: in late spring associated with ground thawing and in autumn associated with ground freezing, and it exhibits different soil moisture behaviour depending on the season. The punctual infiltration events are only observed during the spring zero-curtain and can be explained by the occurrence of melt water infiltration through the snow cover (Scherler et al., 2010, Hilbich et al., 2011). These events are restricted to single sensors or to specific depths (Fig. 7b and Fig. 8) indicating a strong influence of the microtopography and the three-dimensional effects (slope, preferential flow paths, spatial snow melt patterns etc.) on the soil moisture regime.~~

~~Main differences between the spatially distributed sensors can be observed regarding the timing and duration of the three stages, but also regarding the measured absolute VWC values. At SCH the maximum spread of measured VWC during~~

~~summer is about 24 vol.% and about 17 vol.% during winter, whereas at STO the spread is clearly smaller (15 vol.% and 4 vol.%, during the respective seasons). At SCH the wettest sensor (“profile”) is the one of the standard SOMOMOUNT profile, which is located in the vicinity of the borehole which shows higher temperatures, whereas the driest sensor (“bh100”) is located near the borehole with the lower temperatures.~~

~~The timing of the different stages between the four sensors can vary up to 56 days at SCH and 35 days at STO. However, the duration of each stage is consistent within each field site. At STO, the zero-curtain lasts systematically longer, whereas at SCH the frozen stage is longer, indicating higher ice and water content in the near surface at STO. This is in good agreement with the measured temperatures, which are lower at STO than at SCH during the frozen stage.~~

5 Discussion

5.1 Dominant processes

To visualize how the moisture is transported through the ground we adapted the so-called thermal orbits (Beltrami, 1996) to soil moisture (moisture orbits). It consists of a scatter plot of simultaneously measured VWC at two different depths. The shape of the resulting point cloud depends on the nature and speed of the vertical transport of water ~~transfer processes~~through the soil layers, as well as on soil properties such as hydraulic conductivity, degree of saturation and porosity. Using moisture orbits of different time scales (annual, pluri-annual and daily), allows us to analyse the dominant processes playing a role in the temporal evolution of soil moisture.

5.1.1 Seasonal variations

To investigate the seasonal dynamic of soil moisture, we used the moisture orbits between the SMT100 sensors installed at 10 and 50 cm depth for the year 2015 at each site (Fig. 8~~9~~). Again, the field sites can be divided into two categories of soil moisture dynamics, controlled by different processes.

FRE and MLS exhibit similar moisture orbit shapes driven by precipitation events and evaporation. They are divided into three main stages. From January to May the VWC is maximal at both sensors, with some small variations due to snow melt and/or precipitation events. Starting in June, the summer evaporation causes the VWC to decrease strongly at 10cm and slightly at 50cm. Then VWC simultaneously decreases at both depths due to the increased evaporation generated by the July 2015 heat wave. Finally, VWC increases again, with different speed at each depth. The main difference between the two stations is that at MLS the orbit is not closed. At the end of 2015 there is about 30 vol.% VWC less than at the beginning of the year. It indicates that at MLS the near surface VWC did not recover from the increased evaporation generated by the heat wave in July 2015 (cf. Fig. 6). The dry top soil conditions can generate a large water potential gradient with depth and thereby an increased infiltration capacity but also suitable conditions for potential preferential flow processes which tend to induce bypass flow of precipitation water (e.g. Wiekenkamp et al., 2016). On the contrary, at FRE the VWC returned to its original value. ~~This can be explained by two main factors namely the precipitation regimes and the soil properties.~~

Comparatively, both sites received a similar amount of~~MLS received less~~ precipitation ~~than FRE~~ following the heat wave, from July to end of 2015 (~~1036~~ 443 mm ~~y^{-1}~~ and ~~1254~~534 mm ~~y^{-1}~~ respectively~~ in 2015~~, MeteoSwiss).~~, which hampered the full recovery of soil moisture conditions after the heat wave. Additionally, the absolute quantity of water lost at~~ Furthermore, the atmospheric forcing (i.e. air temperature, radiation and calculated potential evaporation) was very similar at both sites (MeteoSwiss). Therefore, the larger and longer lasting impact of the 2015 heat wave at MLS is due ~~was much larger due to stronger evaporation~~to the higher initial VWC and thus lower potential evaporation limitation than at FRE. The amount of water available for evaporation is dependent on the soil properties. At MLS the soil type is silty loam and is able to retain more water than the sandy loam present ~~(soil type~~ at FRE~~)~~.

At SCH and STO the shape of the moisture orbit is controlled by freezing/thawing processes. It can be divided into 5 stages consistent with the frozen, zero-curtain and unfrozen state of the ground. At the beginning of the year both sensors show their lowest value (frozen stage). This is followed by a sharp increase at 50cm not seen at 10cm (1), followed by a strong increase at 10cm but not at 50cm (2) consistent with the melting of the ground from underneath, which takes place at different time at the two depths (spring zero-curtain). The start of the thawing process at larger depth can be due to preferential water infiltration events or to the influence of warm temperatures from the preceding summer at depth (e.g. Zenklusen Mutter and Phillips, 2012). In the case of the latter, warmer ground temperatures in spring can be found at depth compared to the near surface due to the time-lag of heat propagation into the subsurface. The occurrence of this phenomenon depends on the thermal properties of the subsurface and the strength of the winter freezing. . Although the thawing process systematically starts at the surface in response to meteorological forcing, the warmer temperatures remaining at depth will also start the thawing from below. This process is especially marked for permafrost temperatures close to 0°C as it is the case at SCH. During the summer, the ground is unfrozen and strong variations are recorded at both depths (3). The orbit is finally closed by a succession of liquid VWC decrease at 10cm not seen at 50cm (4) and a strong decrease at 50cm but not 10cm (5), consistent with the downward propagation of the freezing front from the surface (autumn zero-curtain). The orbits are closed at both sites indicating no long-lasting perturbation during the year 2015 and similar winter conditions. These stages have been observed by e.g. Hilbich et al. (2011) and Zhou et al. (2015).

At DRE and GFU it is difficult to determine a clear temporal evolution of soil moisture. DRE exhibits a winter and summer minimum (see also Fig. 6b) corresponding to the freezing of the ground and the summer evaporation peak respectively. This double minimum is also found at GFU but less marked especially at the deeper layer.

5.1.2 Soil type dependency

At DRE the shape of the moisture is almost diagonal indicating very rapid transfer of water from the surface downward and little storage in the uppermost soil layer (wet anomaly at 50cm). This is due to the soil properties. At DRE the ~~complete~~ soil profile down to 50cm consists of one single organic rich sandy loam layer with a very low bulk density (Table 3), which is underlain by large sized boulders. This soil type is characteristically highly draining (Beringer et al., 2001) and the water is rapidly transported through. Additionally the boulders underneath do not retain the water, likely preventing the creation of any shallow water table. Furthermore, and in contrast to the ~~soil type~~large blocks below, the organic rich material at the surface retains the water and has a larger thermal conductivity (Beringer et al., 2001), thus favouring ~~lead to enhanced~~ summer evaporation and winter freezing.

At GFU the presence of an organic rich layer in the uppermost 10cm of the soil causes the measured VWC at 10cm to be highly variable and higher than in the remaining soil column (see also Fig. 6d). At 50cm the measured VWC show near saturation conditions throughout the year indicating a potential influence of shallow ground water. This is confirmed by additional ERT measurements realized in summer from 2013 to 2015, which indicate extremely low specific resistivities (~250 Ωm) down to 2.5m (not shown). The combination of near saturated conditions at 50cm and highly variable VWC at 10cm yields~~ing~~ an almost horizontal moisture orbit shape. ~~At 30 and 50cm the soil is composed of loam and sandy loam with much larger bulk densities (Table 3)~~. The organic rich layer has a lower thermal conductivity (Beringer et al., 2001) than the other soil types thus reducing the influence of air temperature (evaporation and/or freezing) at larger depth. Furthermore, at 30 and 50cm the soil is composed of loam and sandy loam with much larger bulk densities (Table 3), which are typically characterized by ~~the soil types at 30cm and 50cm have a~~ lower hydraulic ~~conductivity~~ conductivities if no preferential flow is occurring (Cosby et al., 1984).~~, which~~These soil properties also contribute~~s~~ to the observed lower soil moisture variability at these depths.

At FRE and MLS, the soil type is relatively homogeneous within the uppermost 50cm of the ground, which results in similar VWC temporal evolution with only slight variations in timing and absolute values between the sensors. At MLS the soil type is silty loam and is thus able to retain more water than the sandy loam present at FRE. Finally at SCH and STO, the ground consists of sand or loamy sand, with a significant proportion of large size elements (at 10cm 25% of the soil particles are larger than 10mm at SCH and 45% at STO, see also Fig. 3e-f). Such soil composition is highly heterogeneous even on small distance explaining the high variability between the sensors as well as the comparatively low liquid VWC during unfrozen and snow free periods.

5.1.3 Climate dependency

As seen in Fig. 6, the ~~annual~~ soil moisture temporal evolution ~~dynamics~~ is strongly influenced by the variations in atmospheric conditions such as the extreme temperatures of July 2015. Thus, the shapes of the moisture orbits can be different for each year even though the same processes are dominant (evaporation or freezing). Comparing all years where measurements are available (Fig. ~~10~~9), one can see that at low elevation (FRE), where the evolution of soil moisture is mainly controlled by evaporation and precipitation, the moisture orbits of the year 2014 and 2016 are very similar in shape and amplitude, whereas 2015 is marked by an exceptional decrease of VWC at both depths.

Conversely, at high elevation in permafrost terrain (SCH), 2015 is not particularly anomalous and the same patterns with comparable amplitudes are observed in all years available. This is to be expected since the freezing/thawing processes occur every year, with only slight variations regarding snow duration and timing.

Finally, at GFU, which is an intermediate site with similar characteristics to both FRE and SCH, two very different orbit shapes can be observed. In 2014, the ground froze down to 50cm producing a moisture orbit similar to SCH and STO characterized by large variations occurring at the two sensors. Conversely, in 2015 and 2016 only the 10cm layer froze, yielding horizontal shaped moisture orbits.

5.1.4 Infiltration events

Using differential ~~M~~moisture orbits one can also ~~be used to~~ characterize single infiltration events and investigate further the influence of the soil type on the short term soil moisture evolution. We selected one precipitation event recorded at all six stations and plotted the moisture orbits for a period of 5 days (Fig. 1~~1~~0). At all sites except STO, this precipitation event yields clear moisture orbits of different shapes and amplitudes. The slope of the orbits indicates at which depth the VWC is most affected by the precipitation event and the amplitude the amount of infiltrating water.

At FRE, GFU and SCH the orbits are horizontal (SCH) to slightly inclined (FRE and GFU), showing that the strongest variations of VWC are occurring at 10cm. The wetting and drying phases are faster and the perturbation larger at 10cm than at 50cm. At SCH the maximum VWC at 10cm is reached after two hours while no variation is recorded at 50cm during that interval. The VWC starts increasing at 50cm once the VWC at 10cm is already decreasing. This pattern is ~~typical~~consistent with the vertical succession of soil found at SCH: sandy loam at the surface, which retains water at the beginning of the event and sand at larger depth, which is more draining.~~ for highly draining soils such as sand (found at SCH).~~ At FRE and GFU the orbits correspond to soils with smaller hydraulic conductivity and higher retention capacity (sandy loam and loam-sandy loam respectively, Table 3).

At DRE the moisture orbit has ~~almost similar~~a large amplitude at both depths and the slope is about 45°. This is in good agreement with the annual moisture orbit described above. It indicates a rapid transfer of water through the soil and ~~no~~ little storage at 10cm, which is typical for the particular soil composition found at DRE (single organic rich layer with low bulk density underlain by coarse blocks with large interconnected pores).

At MLS the moisture orbit is almost vertical due to VWC increase/decrease at 50cm depth only, which indicates an instantaneous transfer of water through the uppermost layer. It is the station where the event was the smallest (+8 mm d^{-1}) but the resulting perturbation was the second highest (> +7 vol.%). From Fig. 6c, it can be seen that, at the time of the precipitation event, the VWC at 10cm and 30cm depths were unusually low, thus generating a larger gradient in pressure head from the surface to the lower soil layers as well as providing very suitable conditions for the activation of preferential flow (see e.g. Wiekenkamp et al., 2016)~~enabling the water to pass through easily~~. The degree of saturation of the soil layer is thus another key factor influencing the soil moisture dynamics.

Our interpretation of the moisture orbit shapes accounts only for vertical transfer of water in the soil. However, lateral flows can also play an important role. At DRE, MLS, SCH and STO the stations are located on slightly inclined slopes or at their bottom. Furthermore, permanent snow patches have been observed at SCH and STO on several occasions and may constitute a continuous water supply during summer (Python, 2015; Wicki, 2015). The infiltration of snow melt water is a spatially very heterogeneous process on slopes, especially when the subsurface is characterized by large size particles and draining soil types. An example of the~~se~~ influence of snow melt processes ~~lateral processes~~ can be seen at STO, where the precipitation event shown in Fig. ~~11e~~ 10e did not yield a clear moisture orbit. Its effect is lost in the daily moisture orbit patterns due to snow melt cycles. For each day shown in Fig. ~~11e~~10e, an oval shaped moisture orbit can be seen. These daily cycle orbits are very similar in amplitude and structure. The uppermost sensor reacts first (wetting and drying) and the maximum VWC increase happens at the same time at both depths.

As seen above for MLS, the influence of a single precipitation event on soil moisture not only depends on the soil properties but also on the moisture conditions prior to the event. To investigate this process we computed the moisture orbits of three selected precipitation events at FRE and DRE, which were preceded by different soil moisture conditions (Fig. 11~~2~~). The first event in mid-May is a combination of low precipitation amount preceded by comparatively high VWC . The second event is of very different amplitude at both sites (+39 mm d^{-1} at FRE and +10 mm d^{-1} at DRE) but it marked the end of the summer 2015 heat wave at both sites. The last event is the same as in Fig. ~~11~~10. It consists of a large amount of precipitation preceded by relatively high VWC.

At FRE, the first and third events yield similar moisture orbit shapes with a larger amplitude for the larger precipitation event. However, the second event produces a diagonal moisture orbit with almost no VWC decrease. As for MLS above, the VWC is low at all depths ~~enabling the~~ creating suitable conditions for preferential flow as well as an increased infiltration capacity due to a high gradient of water potential. Both processes could explain the larger and faster increase of VWC observed at larger depth due to the bypass of the dry uppermost layer.~~precipitations to infiltrate quickly down to the deepest layers.~~ The same indications for preferential flow ~~is~~are seen at DRE, where the second precipitation event is comparatively small (+10 mm d^{-1}) but yields the strongest and fastest VWC increase at depth. Given the soil properties, the preferential flow interpretation is preferred to the enhanced infiltration capacity.

5.2 Altitude dependency

As seen above four main processes are driving the annual soil moisture dynamics, namely evaporation/infiltration and freezing/thawing of the ground. The respective predominance of one of these processes is dependent on the station location and more specifically on its elevation. Using all SOMOMOUNT stations as well as the SwissSMEX station of Sion (SIO) we investigated the elevation dependency of mean annual and mean seasonal liquid VWC for the year 2015 (Fig. ~~13a~~12a).

The relation between soil moisture and elevation is clearly non-linear. Disregarding DRE (see Sect. 5.3), a distinct pattern emerges. The mean annual liquid VWC regularly increases with elevation until about 2000 m.a.s.l. and then decreases with increasing elevation. This tipping point corresponds also to a clear shift in the soil moisture regime. Below 2000 m.a.s.l. the maximum liquid VWC is recorded in winter and the minimum in summer, whereas above this threshold the inverse occurs (maximum liquid VWC in summer and minimum in winter).

This shift in soil moisture regime can be related to a series of variables, which are known to be important for mountain climates and which were also plotted against elevation (Fig. ~~13b~~12b-e). Air temperature (Fig. ~~13b~~12b), resulting from the radiation balance, controls the energy available for evaporation and freezing, whereas the precipitation amount (Fig. ~~13c~~12c) controls the water input at the surface. The snow cover duration (Fig. ~~13e~~12e) has several effects on the soil moisture dynamics: it insulates the ground from the cold winter temperatures (yielding positive surface offsets, Fig. ~~13b~~12b) and it acts as a water retention layer, which stores water throughout winter and liberates it in spring/early summer. For each variable, all available data from the monitoring networks of MeteoSwiss, PERMOS and IMIS (Intercantonal Measurement and Information System maintained by the SLF) were collected and a linear regression model was calculated based on the annual mean (resp. sum) of the year 2015. Globally, the same elevation dependency trends are observed using the single stations (dots) or the entire datasets (regression lines).

From Fig. ~~13~~ 12 the following relationships can be determined: ground- and air temperature, as well as the thawing degree days (absolute sum of positive temperatures per year) all linearly decrease with elevation, yielding a decreasing trend of evaporation and thus a theoretically increasing trend of liquid VWC. ~~and c~~Conversely the freezing degree days (absolute sum of negative temperatures per year), surface offset and the snow cover duration increase with elevation, which results in longer lasting winter liquid VWC minimum and thus lower mean annual liquid VWC with increasing elevation. Finally, a ~~There is no clear~~ slightly increasing trend in the precipitation distribution is observed with large site specific variations due to the strong microclimatic effects, however on larger spatial scale (continental) precipitation is known to increase with elevation (Smith, 1979). This combination of overall increasing precipitation and decreasing evaporation yields a trend of increasing soil moisture with elevation until the altitude threshold of about 2000m.a.s.l., where it is balanced by the increasingly important ground freezing and soil moisture starts decreasing with elevation.

At lower elevation (below 2000 m.a.s.l.), evaporation dominates the soil moisture regime, causing the summer liquid VWC minimum. With increasing elevation air temperature decreases, precipitation increases and the snow cover duration is prolonged, explaining the increase of mean annual liquid VWC.

At higher elevation (above 2000 m.a.s.l.), the ground thermal regime and more specifically the soil freezing process drives the soil moisture regime, causing the liquid VWC minimum to shift from summer to winter, when freezing occurs. This is confirmed by the observed negative ground temperatures as well as the increasing freezing degree days. With increasing elevation, air and ground temperatures decrease yielding increasingly long duration of seasonally frozen ground and thus explaining the decreasing trend of liquid VWC.

5.3 Special case: Dreveneuse

To summarise the findings from the SOMOMOUNT network presented above, a simple theoretical model of the evolution of soil moisture and its contributing factors with elevation can be visualised with the grey shading in Figure 14. Comparing the observations qualitatively with this model (circles in Fig. ~~14~~13), it can be seen that DRE does not fit the model. The recorded mean annual liquid VWC values are much lower than expected.

The case of DRE is particular not only for its soil moisture dynamics but also in terms of snow duration (longer than expected) and mean annual ground temperature (lower than expected). Both anomalies are due to site specific characteristics, which are independent from elevation.

The low mean annual ground temperature results from convective heat transport by a complex air circulation within the underlying talus slope (Delaloye, 2004; Morard, 2011), which is made possible by the large interconnected pore space between the coarse blocks of the talus. During winter, ascending warm air within the talus slope leads to cold air inflow at the bottom of the talus slope, where the soil moisture and weather stations are~~is~~ located. This process is able to efficiently cool~~s~~ the ground even when the snow cover is present. ~~and has been observed at many similar talus slopes in low and high mountain regions (e.g. Delaloye and Lambiel 2005; Gude et al. 2003; Kneisel et al. 2000; Sawada et al. 2003; Wakonigg, 1996).~~ In summer the air circulation is reversed~~ process~~ and ~~takes place with~~with gravity driven outflow of cold air from the inside of the talus slope takes place at the bottom, where soil moisture is measured~~ by gravity~~. This process has been observed at many similar talus slopes in low and high elevation mountain regions (e.g. Delaloye and Lambiel 2005; Gude et al. 2003; Kneisel et al. 2000; Sawada et al. 2003; Wakonigg, 1996). Furthermore, the lower ground temperatures caused by the air circulation have been successfully reproduced using numerical modelling (Wicky and Hauck, 2016). The longer snow duration is due to the spruces and low vegetation surrounding the station, which efficiently traps the snow for extended period of time. Additionally the cold ground temperatures help to conserve the snow cover for a longer period.

At DRE, the relatively low elevation of the station implies a high air temperature and thus more energy available for evapotranspiration. Additionally, the presence of vegetation at the surface induces water uptake. The reduced ground temperatures by the air circulation result in a negative surface offset (ground temperature lower than air temperature) and slightly positive freezing degree days, both indicating a seasonal freezing of the ground. Thus two phases of minimal liquid VWC values are observed: one during the~~in~~ summer due to evaporation and one in winter due to partial or complete freezing of the ground (see Fig. 6b). Additionally, the coarse grained soil type at DRE has low water retention properties and induces a fast transport of water to the deeper layers, affecting strongly the short term soil moisture dynamics.

Our elevation dependent model is an empirical model developed using seven stations. Although the stations are regularly distributed with elevation (~500m steps) the representativeness of these locations is hard to assess. Additional low elevation soil moisture monitoring stations are available within the SwissSMEX network and fit well in the presented model. Comparison with further low- to middle altitude stations in the Black Forest region (Southwest Germany) show also good agreement (Krauss et al. 2010). Finally, the high elevation monitoring station at Cervinia/Italy (3100 m.a.s.l., see Pellet et al., 2016) exhibits soil moisture dynamics comparable to STO and SCH and its mean annual liquid VWC for 2015 fits well in the elevation model presented above.

However, the example of DRE shows that some of the processes playing a role for the soil moisture dynamics do not have a trivial elevation dependency. Precipitation in mountainous areas is especially difficult to monitor and the elevation factor is hereby less important than topographic effects. As shown in Fig. ~~13c~~12c, the annual sum of precipitation at a given altitude can vary up to 2000 mm y^{-1} depending on the location. From our field sites FRE appears to receive more precipitation than expected, whereas STO receives much less than predicted. Indeed, FRE is situated on top of the easternmost ridge of the Jura mountain chain, which is known to have a comparatively high annual precipitation sum, as is also shown by the neighbouring SwissMetNet stations of Chasseral (1599 m.a.s.l.) and Chaumont (1136 m.a.s.l.), which recorded annual precipitation sums of 1509 mm y^{-1} and 1240 mm y^{-1} respectively for the period 1961-1990 (MeteoSwiss). ~~Precipitation maxima in middle mountain ranges are often found at the highest elevations, whereas the precipitation distribution in high mountain ranges is strongly influenced by the prevailing wind directions and found along the windward slopes, with smaller values on mountain tops and in the lee of the mountains (e.g. Smith 1979). In addition,~~ STO is located in the central alpine region, which is very dry due to the wind shading effects from the surrounding mountain crests (see e.g. Smith 1979)~~.~~. This effect is also seen at the station of Findelen (VSFIN), which is located about 3km from STO and which is also much drier than the stations at comparable elevation (Fig. ~~13c~~12c).

6 Conclusion

In this paper we presented a detailed description of the new soil moisture monitoring network for middle and high altitudes in Switzerland (SOMOMOUNT). Starting in summer 2013, six automatic stations have been set up along an elevation gradient ranging from 1205 to 3410 m.a.s.l.

The use of two types of standard soil moisture sensors for application in coarse grained terrain undergoing freeze/thaw cycles at middle and high elevation was shown to be reliable~~. Although the sensors are not specifically designed for freezing conditions, we found the measurements to be consistent~~, both regarding inter-sensor comparisons as well as in comparison with related variables such as ground temperature and precipitation. A standard calibration approach combining in situ and laboratory analysis was applied to improve the measurement accuracy. However the absolute value during the frozen period remains difficult to assess even though both the SMT100 and the PICO64 sensors yield similar absolute values (±3 vol.% range). The measurements also confirmed that unfrozen water content is present at temperatures below the freezing point and that it can be measured with the sensors.

The data collected during the first three years of the SOMOMOUNT network revealed very distinct soil moisture dynamics at the different sites, which could be summarized into a simple elevation dependent model. At middle and low elevation, annual soil moisture dynamics are controlled by evapotranspiration and precipitation events whereas at high elevation the freeze-thaw cycle is the main driving factor. This shift between the two distinct moisture regimes was found to take place at about 2000m.a.s.l., where the maximum annual liquid VWC values have been recorded.

Marked inter-annual variations have been observed. However, depending on the site-specific properties, the impacts have been more or less important. The exceptionally high air temperatures of July 2015 induced a stronger and longer lasting soil moisture decrease than 2014 or 2016, but only for low- and middle-altitude stations. At high elevation (>2900 m.a.s.l.) no effect of the 2015 heat wave was observed, since the soil moisture dynamics is predominantly controlled by the ground thermal regime.

Among the six soil moisture stations of SOMOMOUNT, and also in comparison with additional stations from other networks, the station of Dreveneuse is a clear exception to the elevation dependent theoretical model. This middle elevation site undergoes strong winter freezing as well as marked summer evaporation, the latter being due to the vegetation cover. Due to complex air circulation within the underlying talus slope the ground temperatures are unusually low for this elevation. In addition, the soil properties favoured rapid water transport through the ground. The soil properties were found to play an important role in the short term soil moisture variations as well as in the mitigation or intensification of the extreme events.

Competing interests

The authors declare that they have no conflict of interest.

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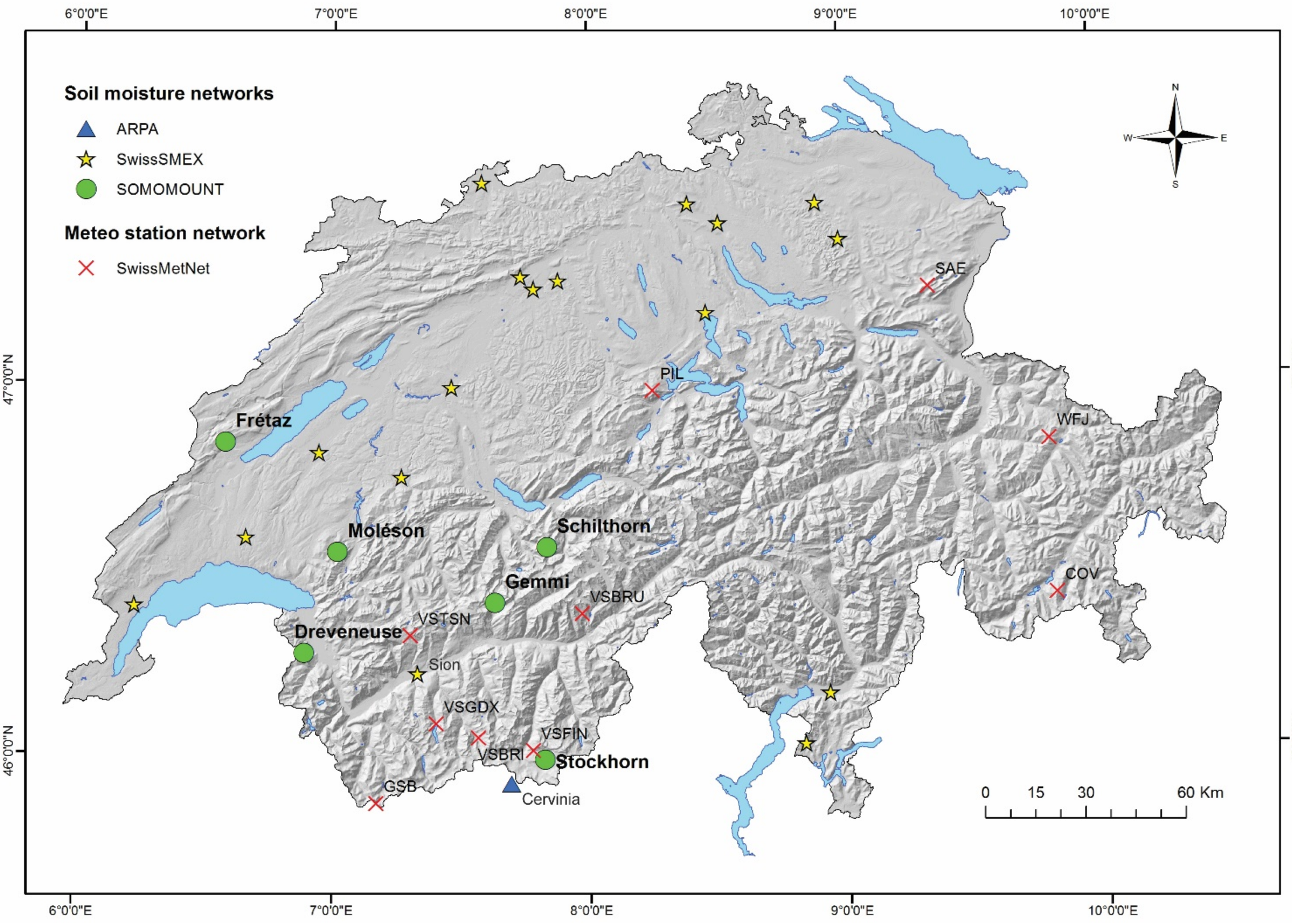


Fig. 1: Map of Switzerland showing the location of the soil moisture monitoring stations from the SOMOMOUNT and SwissSMEX project (Mittelbach and Seneviratne, 2012) as well as the ARPA monitoring station Cervinia (Pogliotti et al. 2015). Selected mountain weather stations form the SwissMetNet network used in Sect. 5.2 are also displayed.

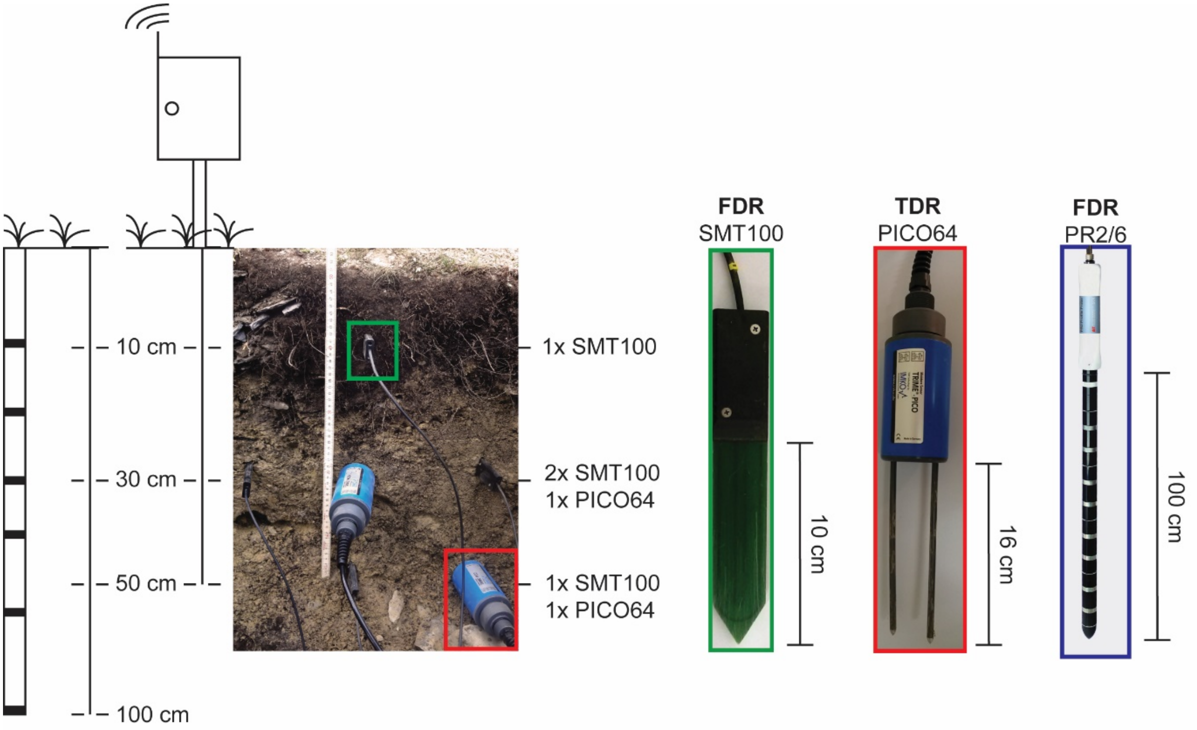


Fig. 2: Instrumentation of the standard SOMOMOUNT station.

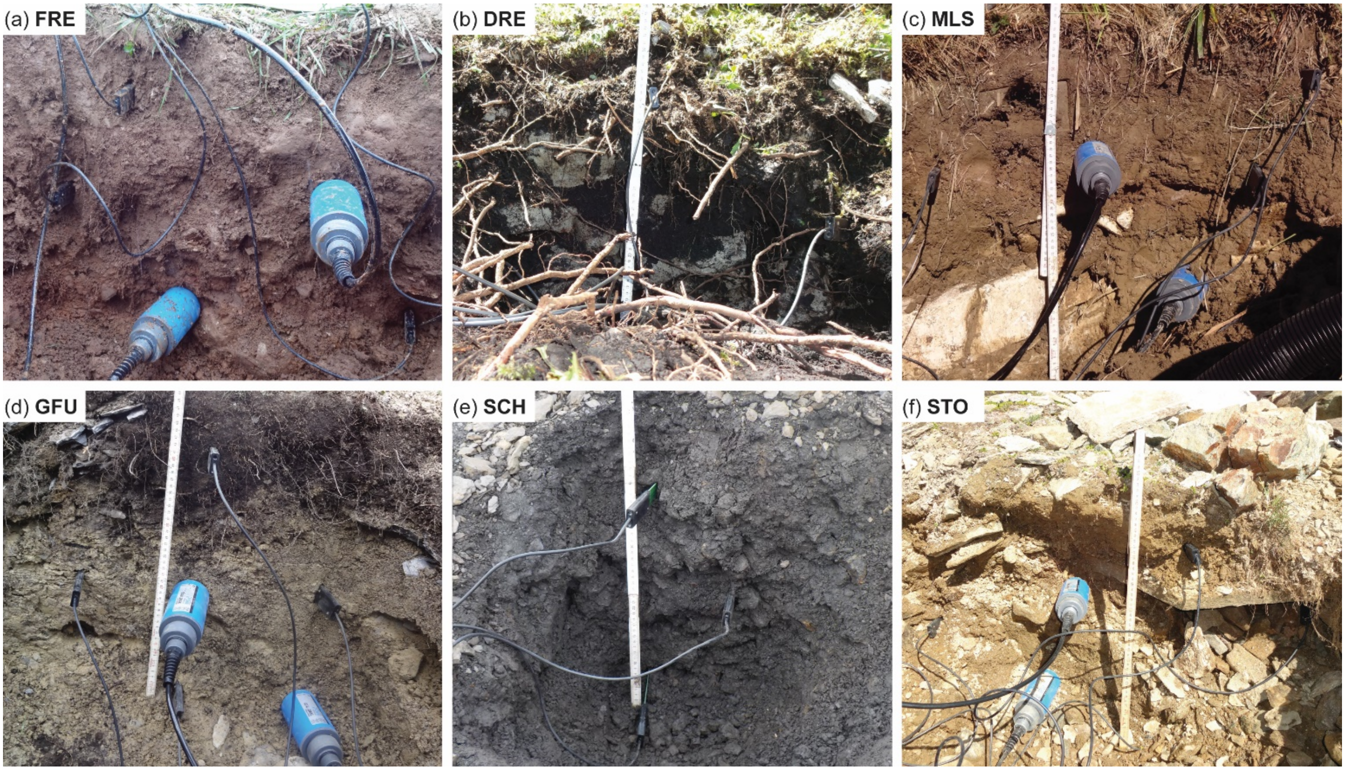


Fig. 3: Illustration of the soil characteristics and sensor installation for all SOMOMOUNT stations.

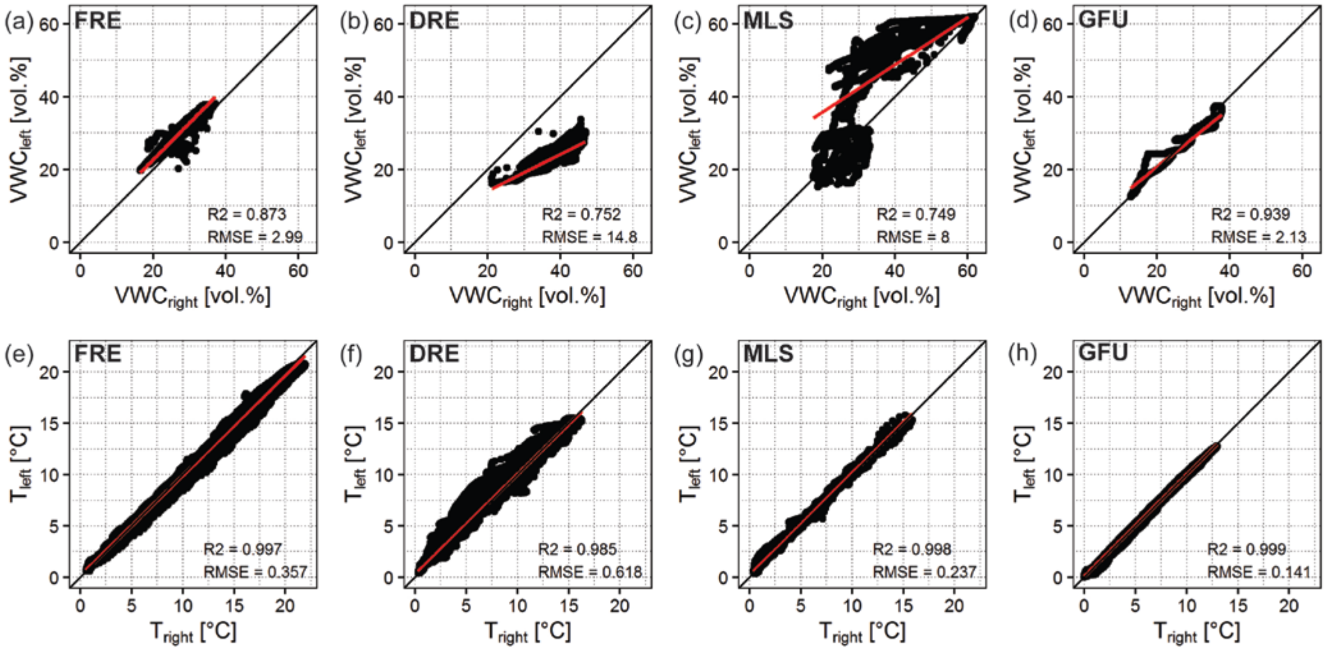
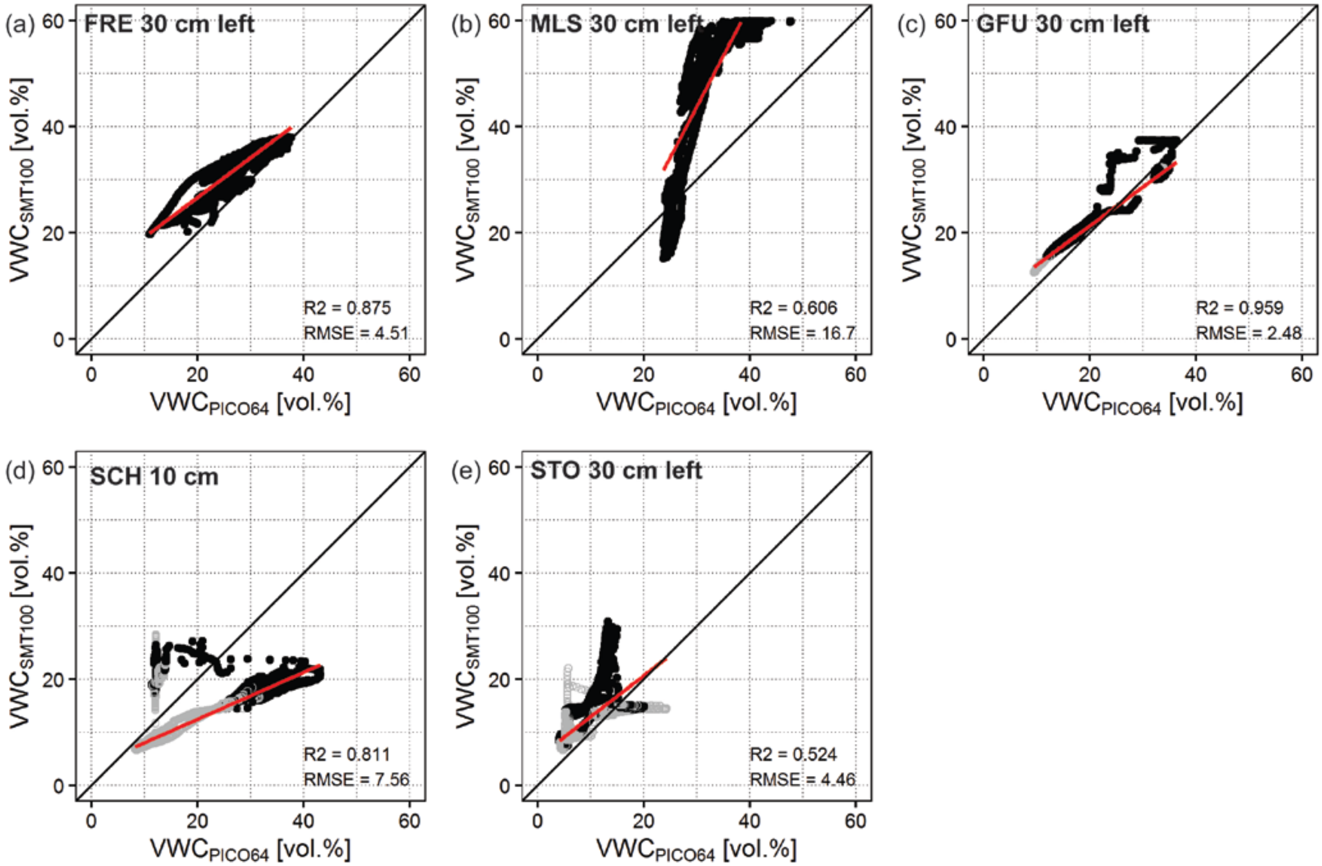


Fig. 4: Comparison of measured soil moisture (upper row) and ground temperature (lower row) from both FDR measurements at 30 cm depth using the linear calibration at FRE (a, e), DRE (b, f), MLS (c, g) and GFU (d, h).


(a) FRE 30 cm left
R2 = 0.875
RMSE = 4.51
(b) MLS 30 cm left
R2 = 0.606
RMSE = 16.7
(c) GFU 30 cm left
R2 = 0.959
RMSE = 2.48
(d) SCH 10 cm
R2 = 0.811
RMSE = 7.56
(e) STO 30 cm left
R2 = 0.524
RMSE = 4.46
VWC_{SMT100} [vol.%]
VWC_{PICO64} [vol.%]
0
20
40
60

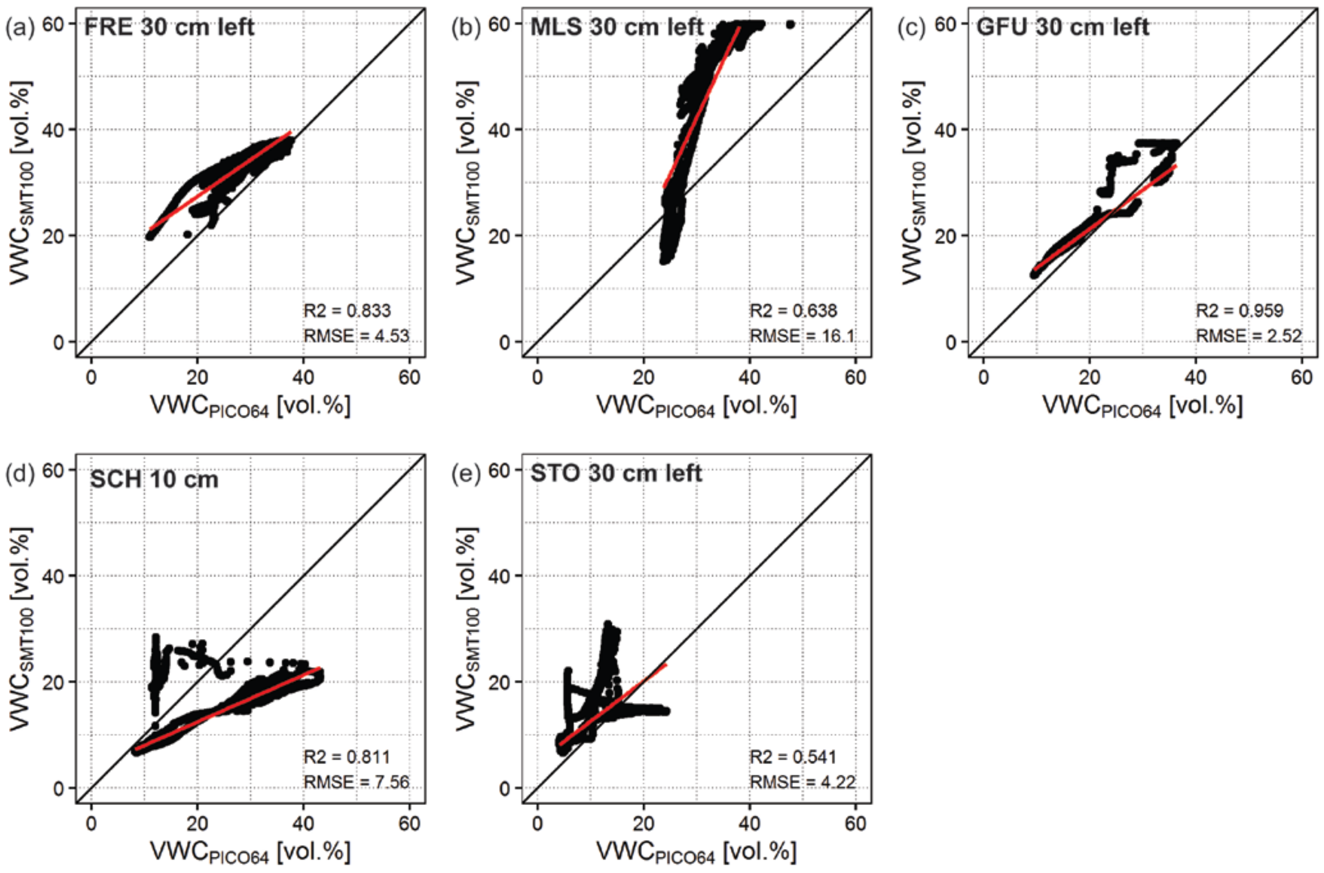
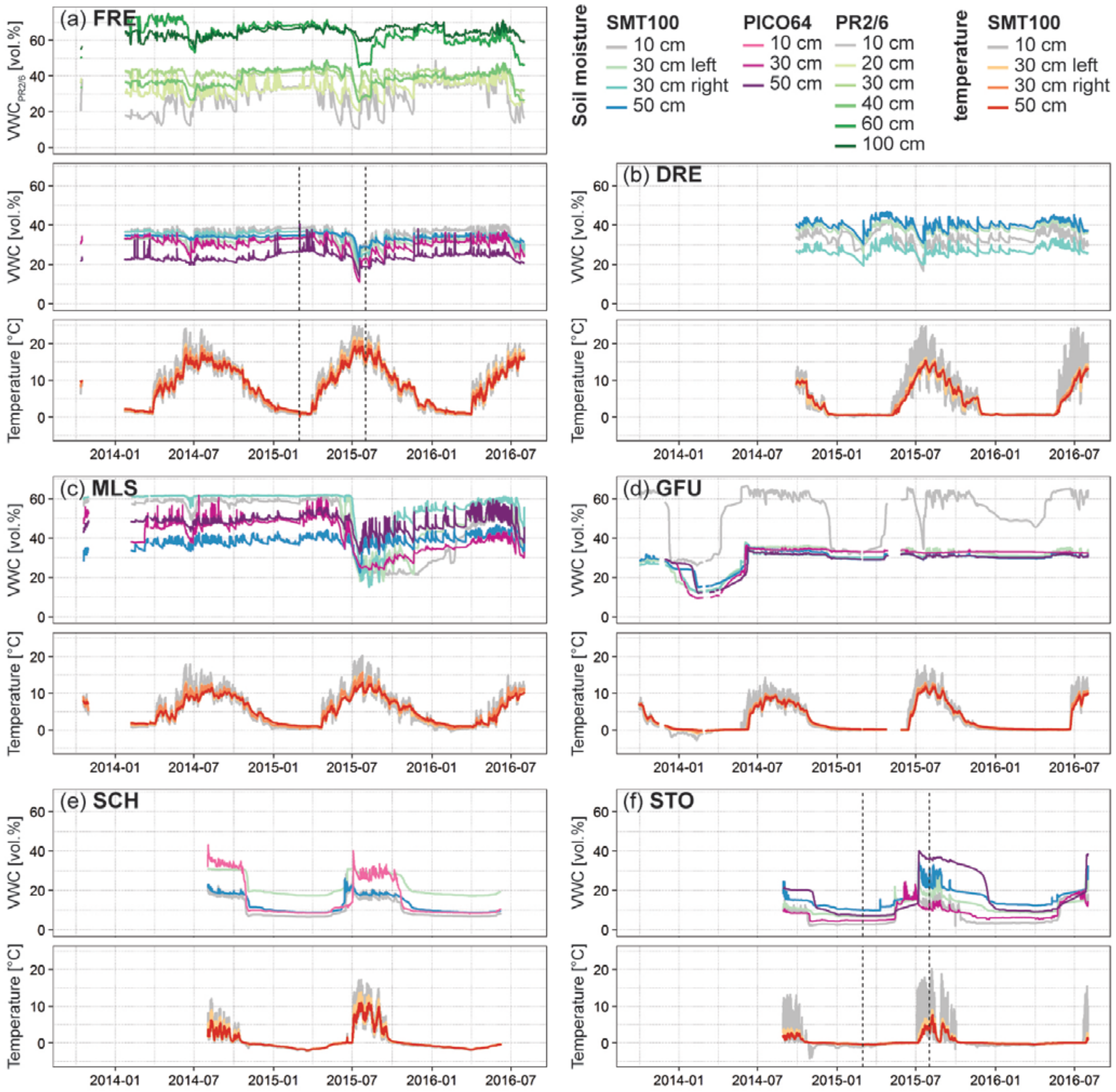


Fig. 5: Comparison between TDR- (x-axis) and FDR-measured liquid VWC (y-axis) at all sites. The linear relation is used for the FDR calibration. The hollow grey points at GFU, SCH and STO represent soil moisture measurements taken when the ground temperature was below 0°C.

5


(a) FRE
VWC_PR2/6 [vol.%]
Soil moisture
SMT100
10 cm
30 cm left
30 cm right
50 cm
PICO64
10 cm
30 cm
50 cm
PR2/6
10 cm
20 cm
30 cm
40 cm
60 cm
100 cm
temperature
SMT100
10 cm
30 cm left
30 cm right
50 cm
(b) DRE
(c) MLS
(d) GFU
(e) SCH
(f) STO
VWC [vol.%]
Temperature [°C]
0
10
20
40
60
2014-01
2014-07
2015-01
2015-07
2016-01
2016-07

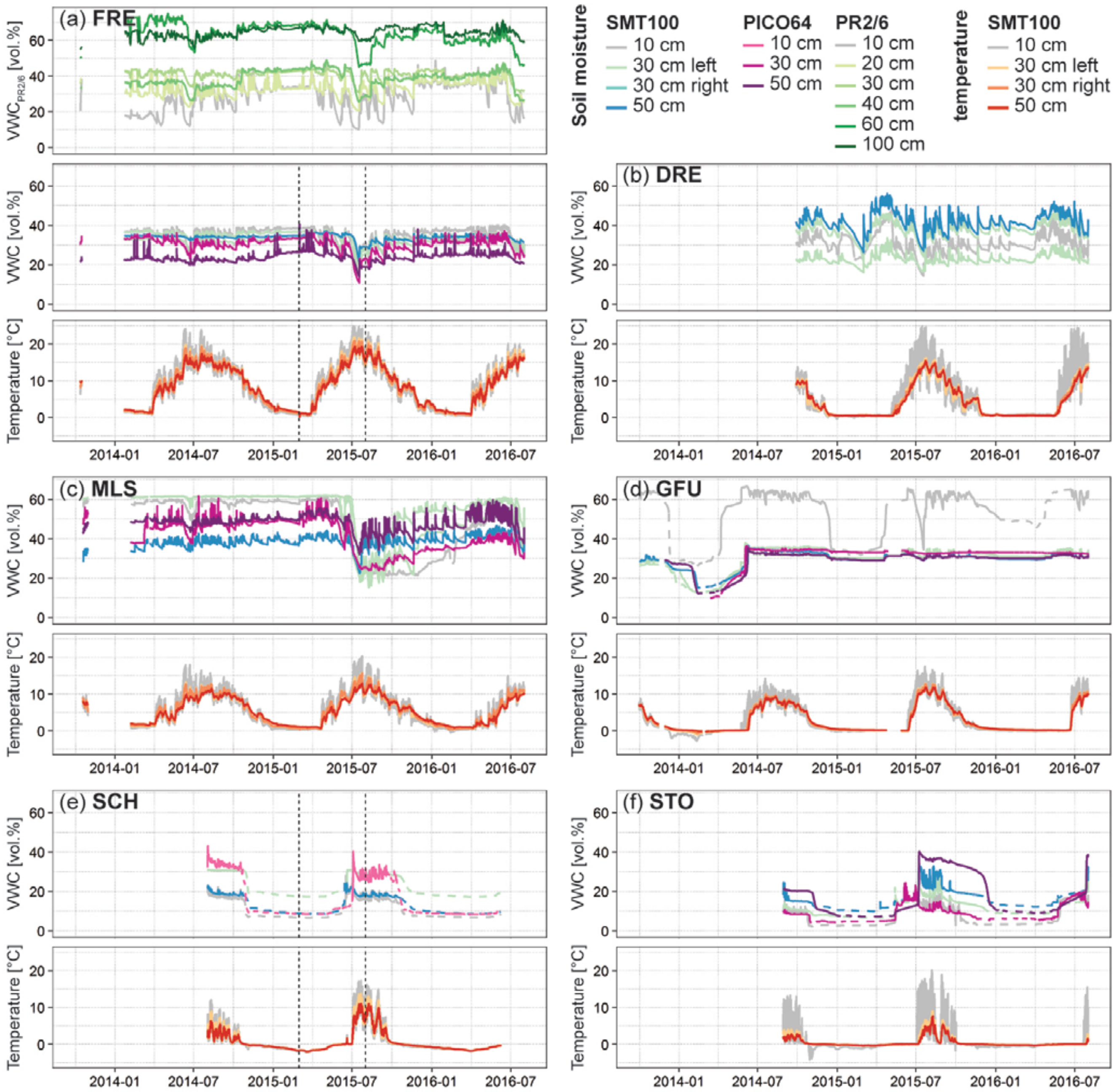
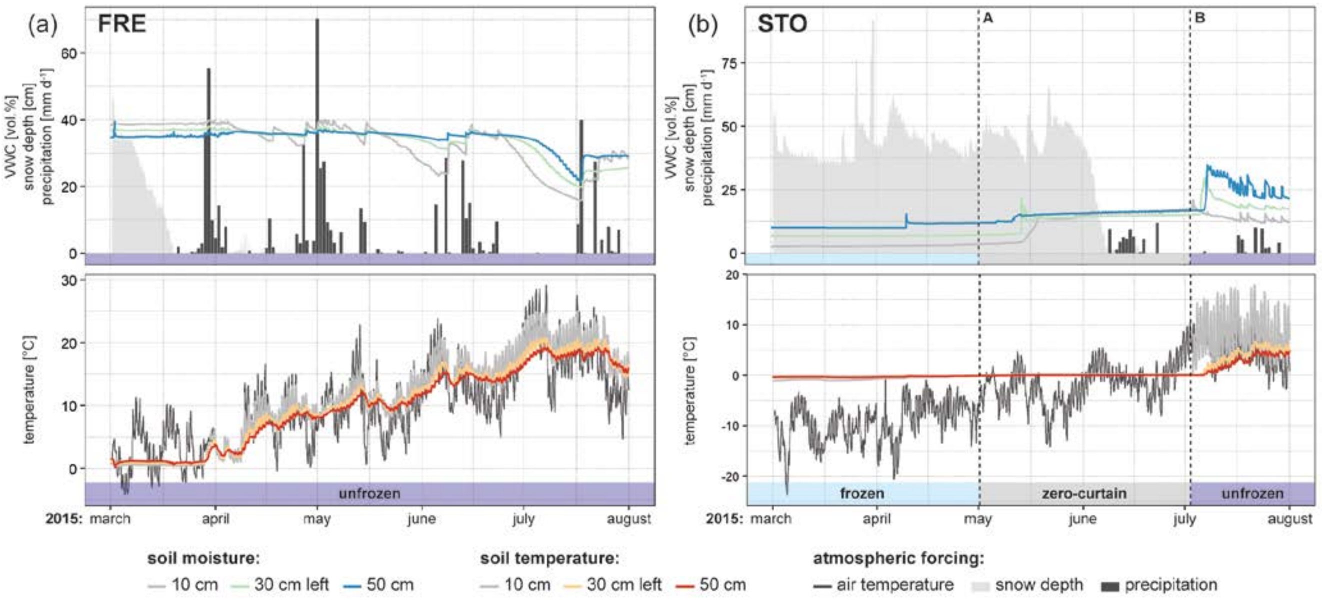


Fig. 6: Measured VWC (upper panel) and ground temperatures (lower panel) at each SOMOMOUNT station (a-f). At FRE the uppermost panel displays the PR2/6 measured liquid VWC. The vertical dotted lines at FRE and STO indicate the period analysed in Fig. 7. The dashed VWC lines represent the soil moisture measurements taken when the ground temperature was below 0°C.



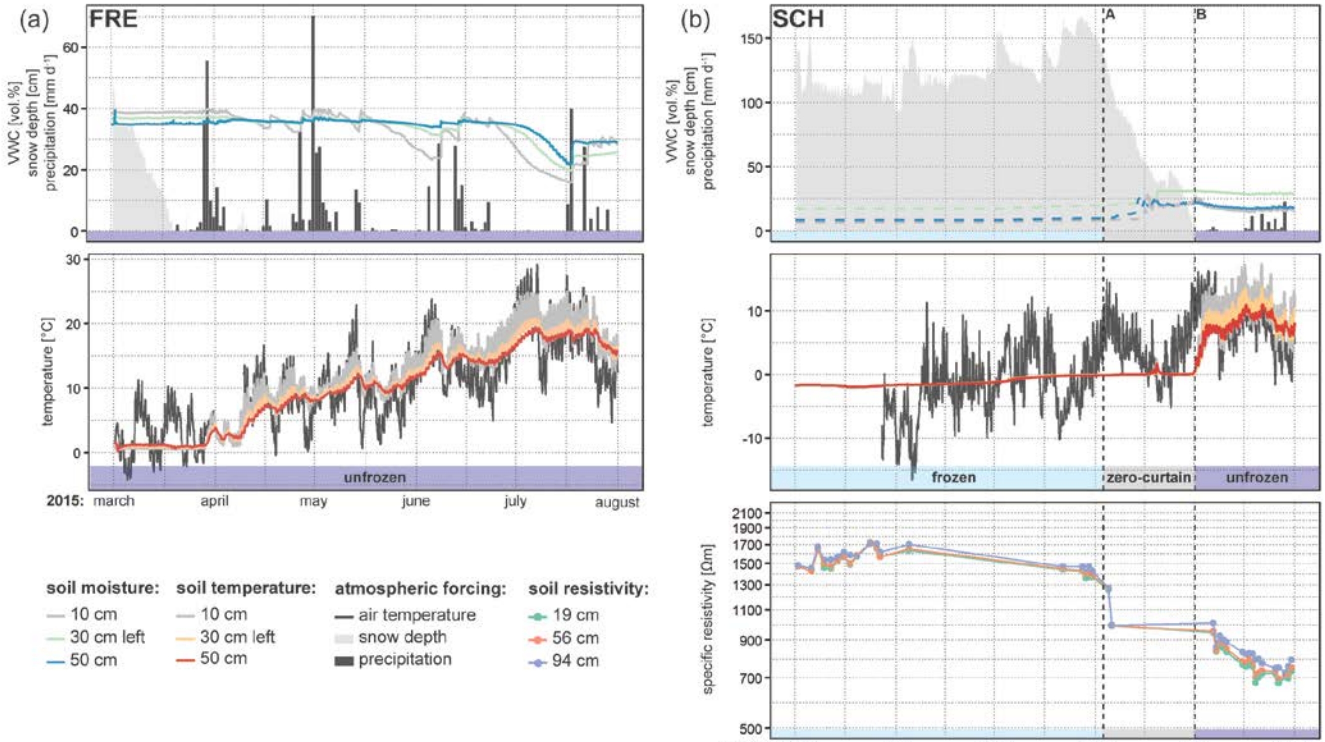
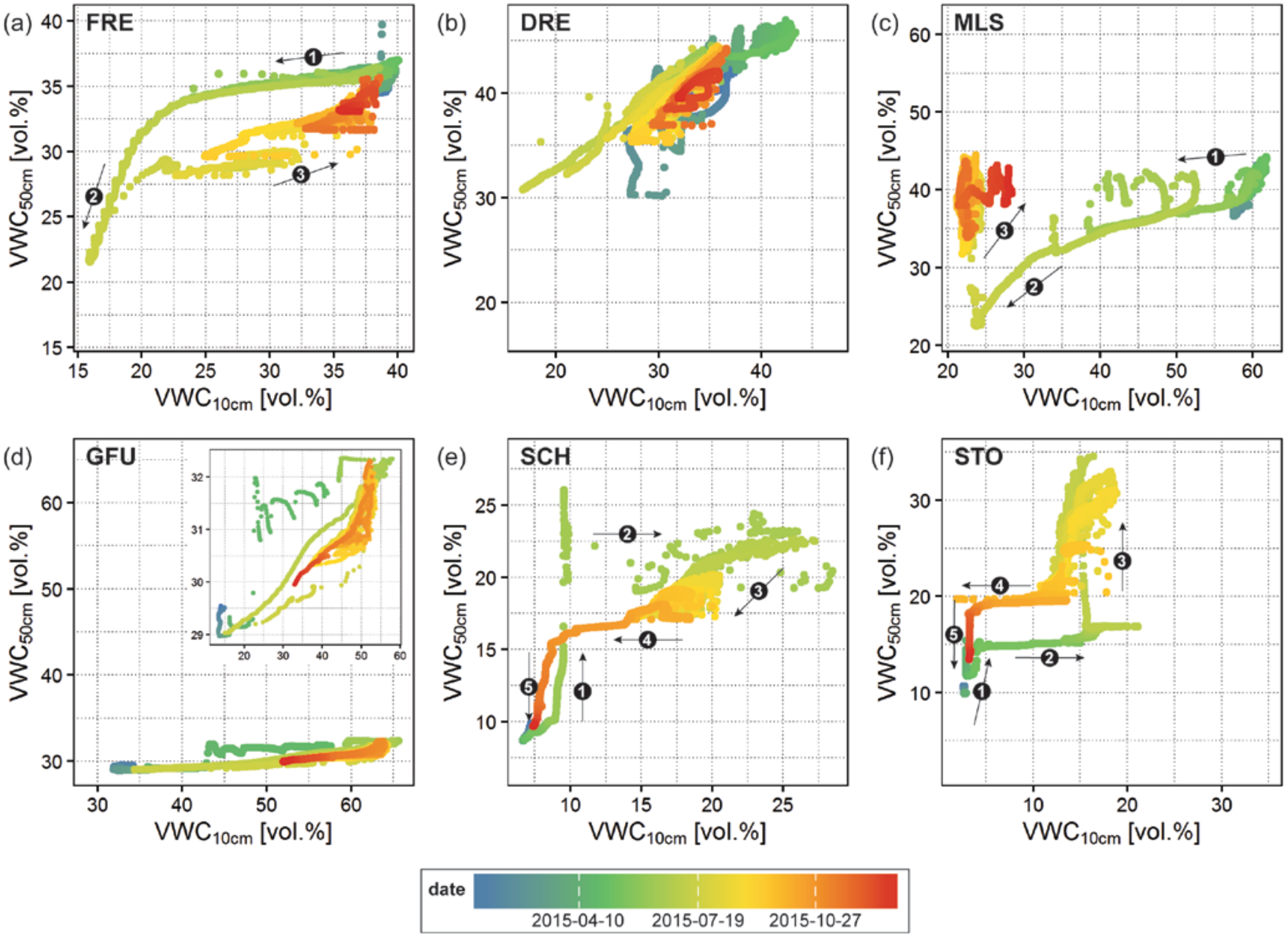


Fig. 7: Measured liquid VWC, ground temperature and soil resistivity at FRE (a) and SCH (b) from March to August 2015. In addition, daily air temperature, snow depth and precipitation sums are shown as well as the date of the transition between the different stages in the thermal evolution at SCH at 10cm (dashed lines A and B, see text for details). The dashed VWC lines represent the soil moisture measurements taken when the ground temperature was below 0°C.

~~**Fig. 7: Measured VWC and ground temperature at FRE (a) and STO (b) from March to August 2015. In addition, daily air temperature, snow depth and precipitation sums are shown as well as the date of the transition between the different stages in the thermal evolution at STO at 10cm (dashed lines A and B, see text for details).**~~


(a) FRE
(b) DRE
(c) MLS
(d) GFU
(e) SCH
(f) STO
VWC$_{50cm}$ [vol.%]
VWC$_{10cm}$ [vol.%]
❶
❷
❸
❹
❺
date
2015-04-10
2015-07-19
2015-10-27

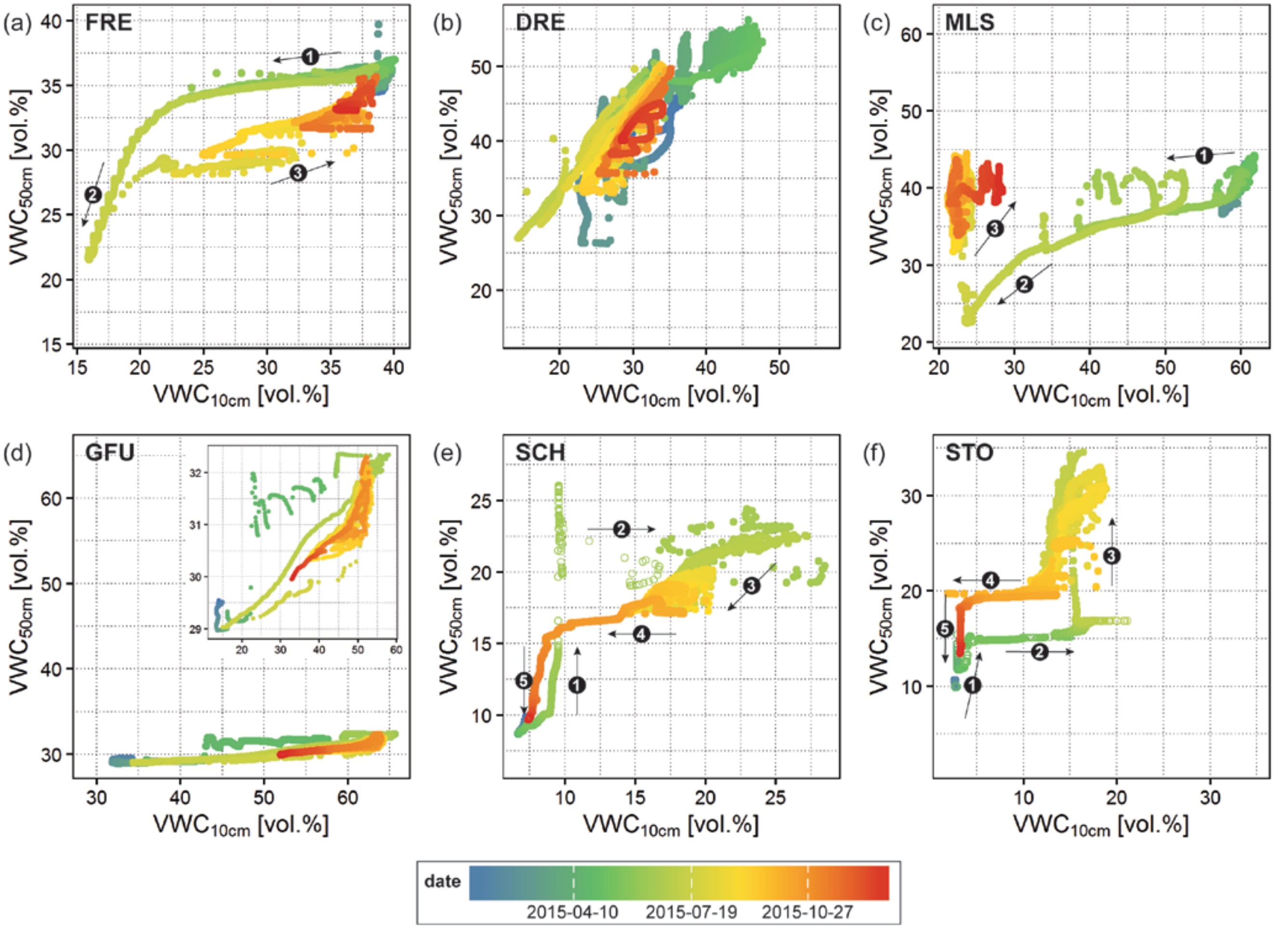


Fig. 8~~9~~: Moisture orbit at each SOMOMOUNT station from the 1st January to the 31st December 2015. The numbered arrows indicate the most important stages at each station as well as the sense of the evolution. The hollow circles represent soil moisture measurements taken when the temperature was below 0°C at 50cm.

5

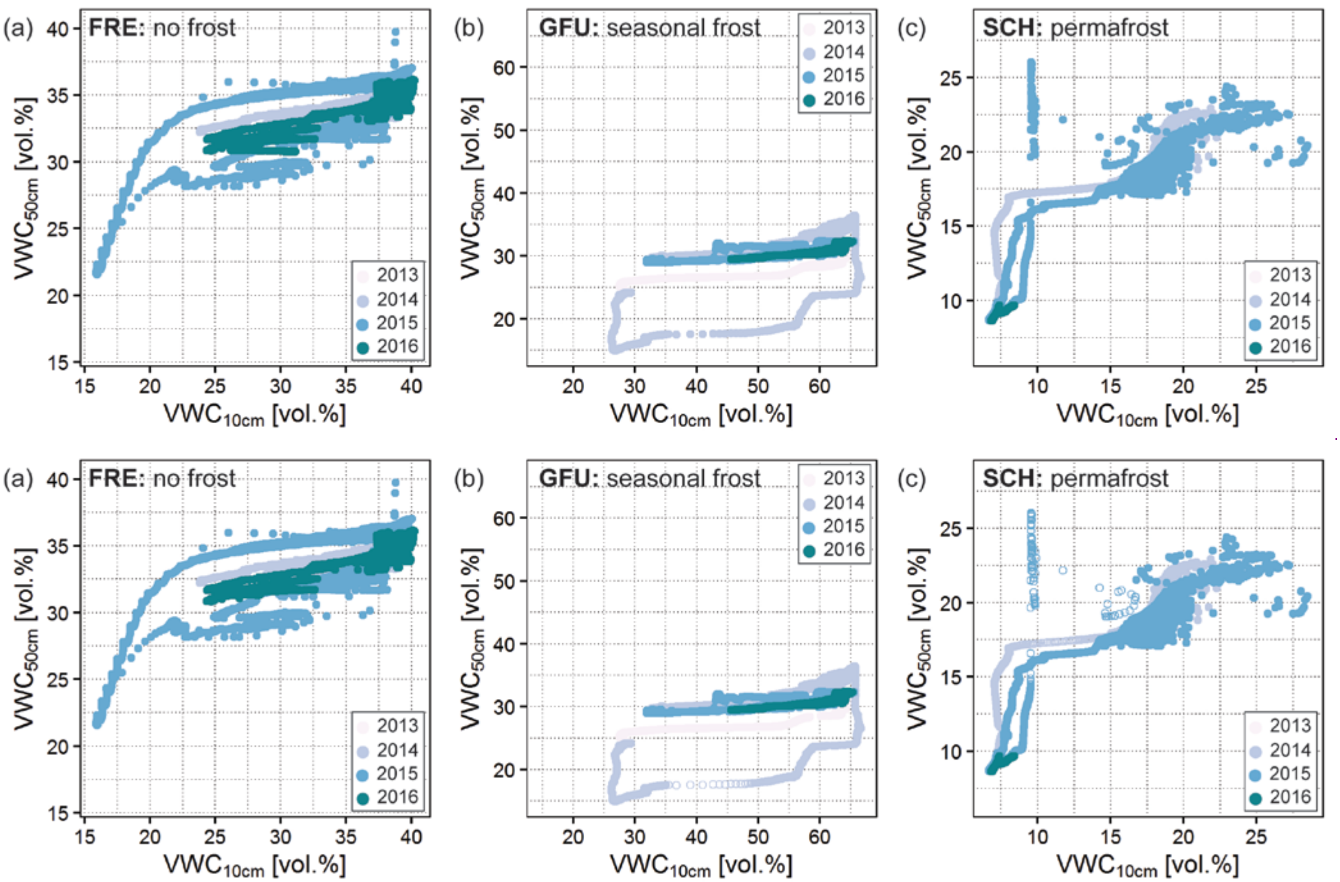


Fig. 9~~10~~: Moisture orbits at FRE (a), GFU (b) and SCH (c) for the consecutive monitoring years (Jan. 2014-Aug. 2016 at FRE, Aug. 2013-Aug. 2016 at GFU and Aug. 2014-June 2016 at SCH). The hollow circles represent soil moisture measurements taken when the temperature was below 0°C at 50cm.

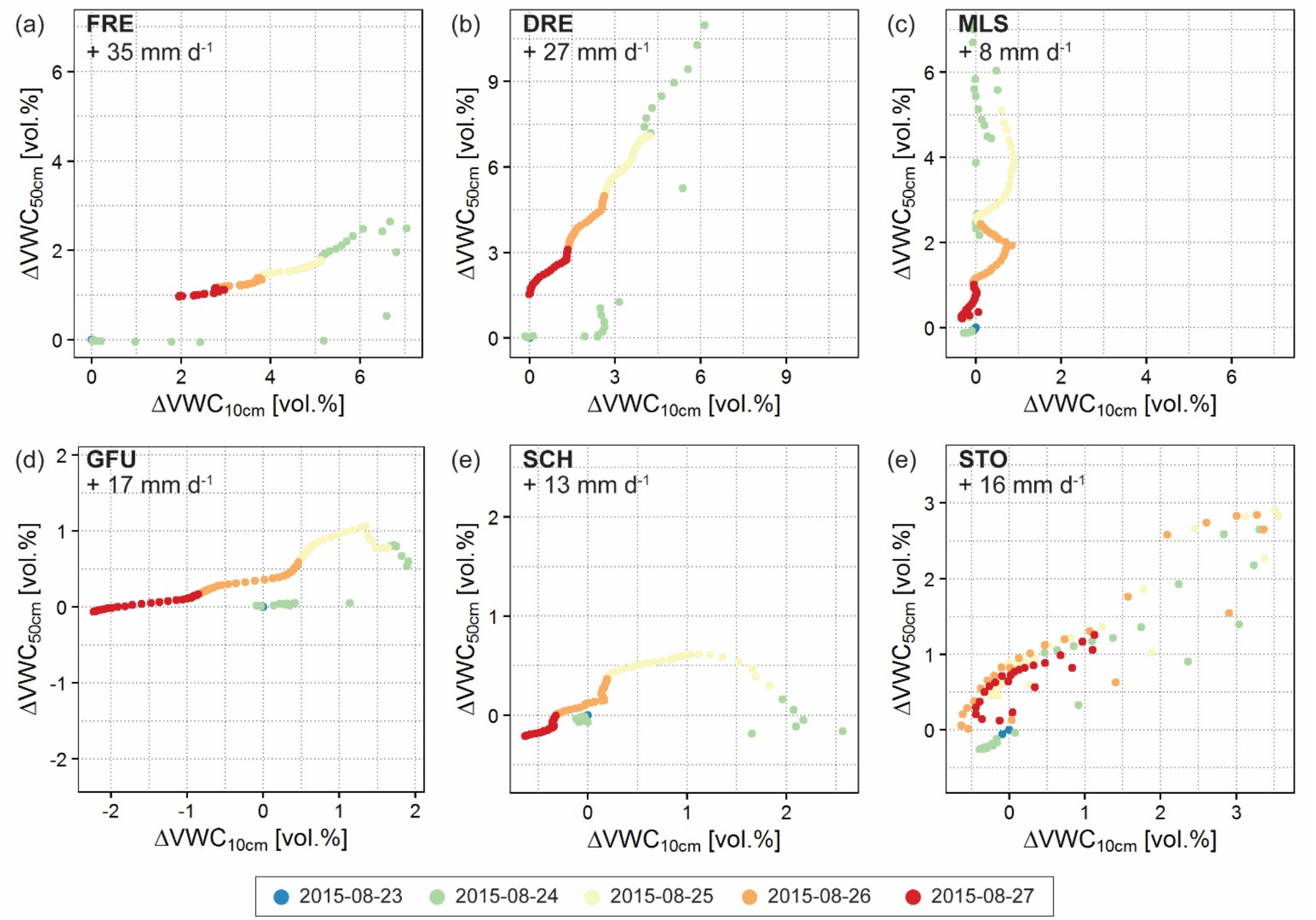


Fig. 10~~11~~: Moisture orbit at each SOMOMOUNT station for one precipitation event between the 23rd and the 27th August 2015. The VWC values are given as hourly mean and expressed as the change of absolute value compared to the first measurement (23rd August at 01:00). The daily precipitation sums recorded (FRE, DRE and MLS) and extrapolated (GFU, SCH and STO) for the 24th August are indicated.

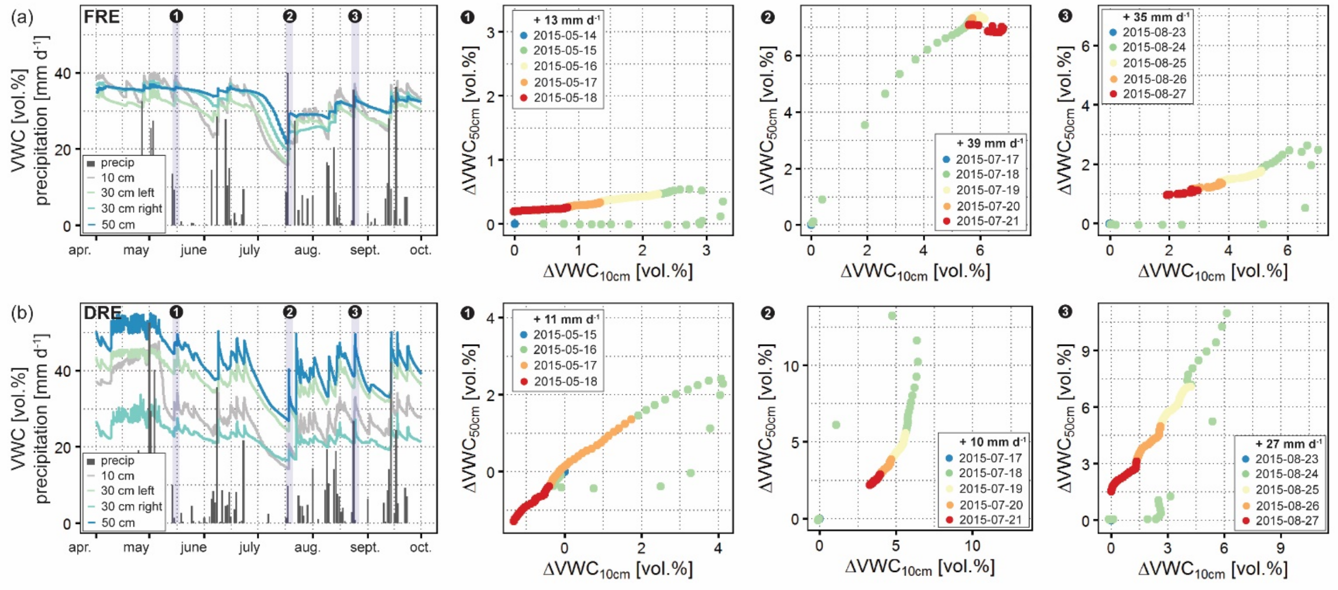
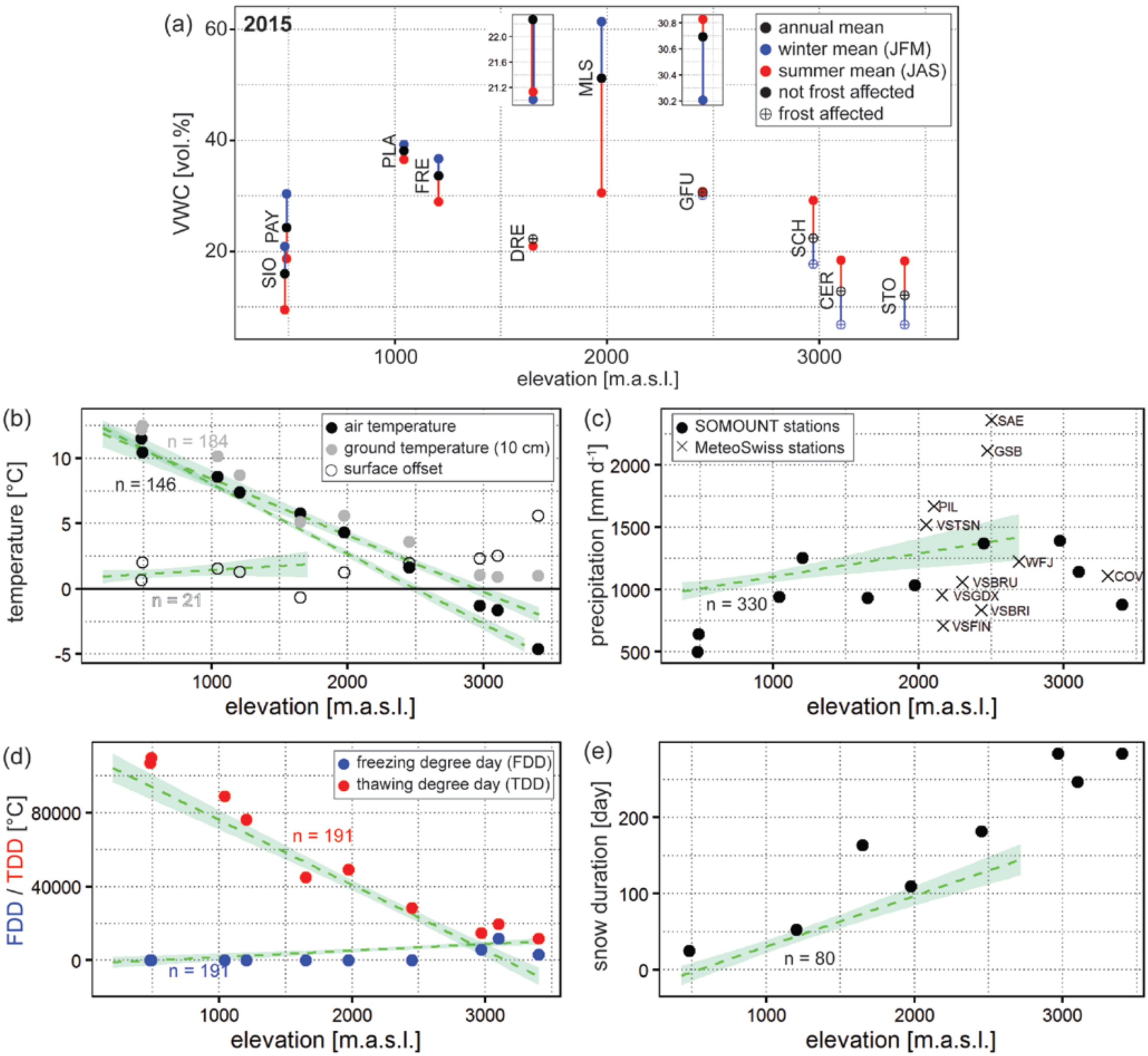


Fig. 11~~12~~: Moisture orbit at FRE (a) and DRE (b) for three precipitation events in 2015. The VWC values are hourly means and expressed as the change of absolute value compared to the first measurement (23rd August at 01:00). The daily precipitation sums recorded at the beginning of each event are indicated.


(a)
2015
VWC [vol.%]
60
40
20
elevation [m.a.s.l.]
1000
2000
3000
SIO
PAY
PLA
FRE
DRE
MLS
GFU
SCH
CER
STO
22.0
21.6
21.2
30.8
30.6
30.4
30.2
annual mean
winter mean (JFM)
summer mean (JAS)
not frost affected
frost affected
(b)
temperature [°C]
10
5
0
-5
n = 184
n = 146
n = 21
air temperature
ground temperature (10 cm)
surface offset
elevation [m.a.s.l.]
(c)
precipitation [mm d⁻¹]
2000
1500
1000
500
SOMOUNT stations
MeteoSwiss stations
SAE
GSB
PIL
VSTSN
WFJ
COV
VSBRU
VSGDX
VSBRI
VSFIN
n = 330
elevation [m.a.s.l.]
(d)
FDD / TDD [°C]
80000
40000
0
freezing degree day (FDD)
thawing degree day (TDD)
n = 191
n = 191
elevation [m.a.s.l.]
(e)
snow duration [day]
200
100
0
n = 80
elevation [m.a.s.l.]

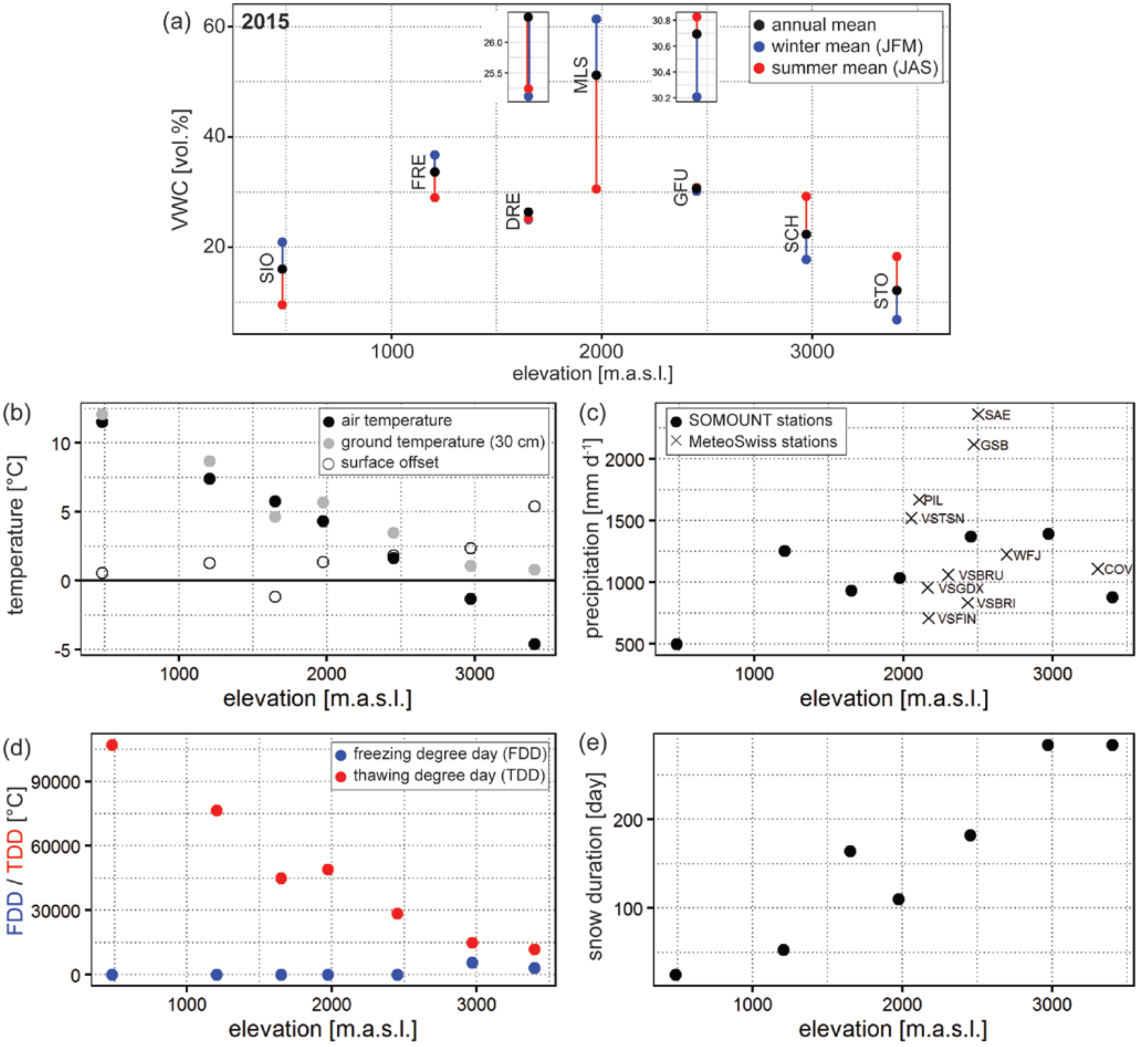


Fig. 12~~13~~: Elevation dependency of the winter-, summer- and annual mean liquid VWC at 30cm depth (a), air-, ground temperature and surface offset (ground minus air temperature) at 1~~3~~0cm (b), annual precipitation sum including selected SwissMetNet stations for comparison (cf. Fig. 1) (c), freezing and thawing degree days (calculated from ground temperatures at 10cm) (d) and snow duration (calculated from ground temperature at 10cm using the method described in Staub and Delaloye (2016)) (e) during the year 2015. The VWC values for SIO, PAY and PLA are part of the SwissSMEX network (Mittelbach and Seneviratne, 2012). Due to missing data at 30cm the VWC shown for PAY and PLA was measured at 50cm and 20cm at CER. The dashed green lines illustrate the linear regression based on all available SwissMetNet, PERMOS and IMIS stations in Switzerland (the numbers of station with complete data series in 2015 are indicated) and the shaded areas represent the 99% confidence intervals. The length of each regression line corresponds to the maximum elevation of the available stations.

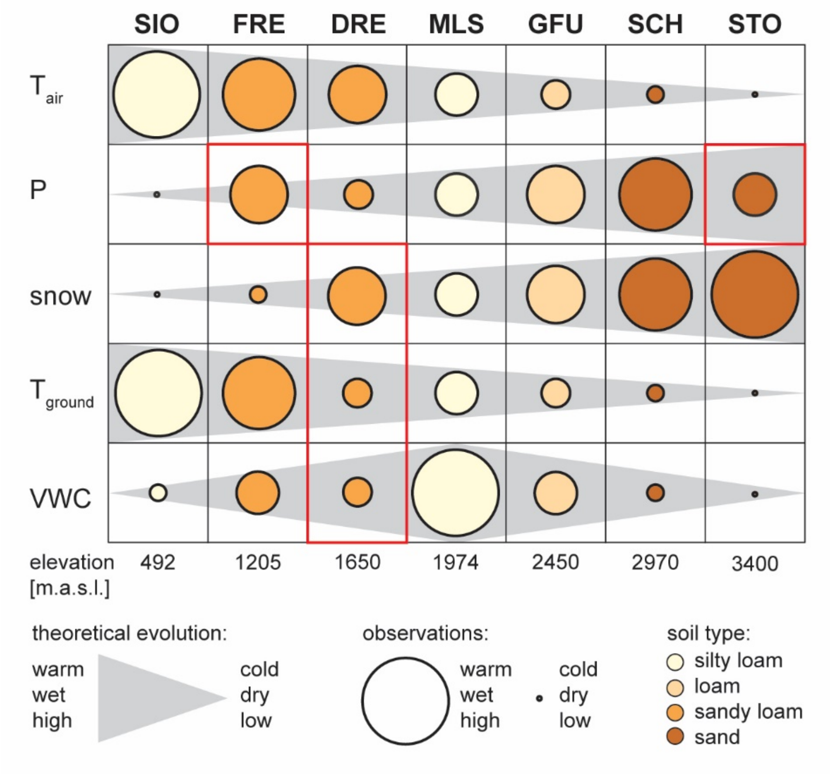


Fig. 134: Conceptual model of the evolution of air temperature, precipitation, snow duration, ground temperature and soil moisture with elevation. The circles represent the observations from 2015 (see Fig. 12), the grey area the expected theoretical evolution and the colour scale the soil type. The mismatches between model and observations are highlighted in red.

5

Sensors	Measurement technique	range of VWC	operating temperature	Accuracy
SMT100 (Truebner GmbH, Germany)	FDR	0 to 100 vol.% (60-100% limited accuracy)	-40° to 60°C	±3 vol.% for 0-50 vol.% ±1 vol.% using medium specific calibration
PICO64 (IMKO GmbH, Germany)	TDR	0 to 100 vol.%	-15° to 50°C	±1 vol.% for 0-40 vol.% ±2 vol.% for 40-70 vol.%
PR2/6 (Delta-T Devices Ltd, UK)	capacitance	0 to 100 vol.%	-20° to 60°C	±6 vol.% for 0-40 vol.% ±4 vol.% using medium specific calibration

Table 1: Characteristics of the three types of soil moisture sensors used in the SOMOMOUNT network. All values in the table are provided by the manufacturers (Delta-T Device, 2008; IMKO, 2015; Truebner, 2016).

Site	Elevation [m.a.s.l.]	Sensor depth [cm]			Measurement interval	Start date	Related networks
		SMT100	PICO64	PR2/6			
FRE	1205	10, 30, 30,50	30, 50	10,20,30, 40,60,100	10 min	11.10.2013	SwissMetNet
DRE	1650	10, 30, 30,50	-	-	60 min	26.09.2014	PERMOS
MLS	1974	10, 30, 30,50	30, 50	-	10 min	17.10.2013	SwissMetNet
GFU	2450	10, 30, 30,50	30, 50	-	30 min	17.07.2013	PERMOS
SCH	2970	10, 30, 50	10	-	30 min	31.07.2014	PERMOS
STO	3410	10, 30, 30,50	30, 50	-	30 min	27.08.2014	PERMOS

Table 2: Summary of the station instrumentation and characteristics at the field sites Frétaz (FRE), Dreveneuse (DRE), Moléson (MLS), Gemmi (GFU), Schilthorn (SCH) and Stockhorn (STO).

Site	Elevation [m.a.s.l.]	T_{air}^{a} [°C]	P^{a} [mm]	Depth [cm]	Particle size distribution [%]			Texture[b]	Bulk density	Organic Fraction [%]	Thermal regime
					Clay	Silt	Sand				
FRE	1205	6	1333	0-10	2.2	33.3	52.4	Sandy Loam	0.95	0.1	No frost
				10-30	2.5	36.1	39.3	Sandy Loam	1.06	-	
				30-50	3.0	30.8	53.7	Sandy Loam	1.01	-	
DRE	1650	5	936	0-50	0.6	24.4	71.3	Sandy Loam	0.12	7.7	Permafrost
MLS	1974	3	929	0-10	11.8	72.5	15.6	Silty Loam	0.58	0.15	Seasonal frost
				10-30	15.1	77.6	7.1	Silty Loam	0.71	-	
GFU	2450	0	1800-2500	0-10	2.0	63.3	34.2	Silty Loam	0.58	4.80	Seasonal frost
				10-30	2.1	39.7	27.8	Loam	1.52	-	
				30-50	2.6	46.5	39.8	Sandy Loam	1.39	-	
SCH	2970	-3	2700	0-10	1.0	14.5	60.0	Loamy Sand	1.53	-	Permafrost
				10-30	0.6	8.7	40.6	Sand	1.35	-	
STO	3400	-5	1500	0-10	0.3	6.4	48.7	Sand	1.42	-	Permafrost
				10-30	0.6	20.4	56.5	Loamy Sand	1.67	-	
				30-50	0.7	21.6	58.9	Loamy Sand	1.54	-	

[a] data source: MeteoSwiss at FRE and MLS; Morard (2011) at DRE; Krummenacher et al. (2008) at GFU; Imhof et al. (2000) and PERMOS at SCH; King (1990) and PERMOS at STO;

[b] according to the USDA classification

Table 3: Summary of the climatic conditions and ~~S~~soil properties ~~for~~ at each SOMOMOUNT station.

Site	linear fit				exponential fit				n
	a	*b*	r^2	RMSE [vol.%]	*c*	*d*	r^2	RMSE [vol.%]	
FRE	-0.005630	98.15	0.96	2.76	707.1	-0.0002680	0.93	3.66	16
DRE	-0.006361	114.7	0.89	5.71	1219	-0.0002889	0.96	3.51	12
MLS	-0.008108	139.2	0.97	3.59	741.7	-0.0002507	0.95	5.03	16
GFU_{min}	-0.005327	93.7	0.80	5.57	465.8	-0.0002336	0.75	6.18	13
GFU_{org}	-0.007819	140.2	0.95	3.93	534.2	-0.000209	0.93	4.83	14
SCH	-0.004301	77.55	0.81	4.47	899.2	-0.0002925	0.88	3.57	12
STO	-0.004851	85.71	0.84	4.02	457.9	-0.0002378	0.79	4.58	18

Table 4: Parameters and statistics of the linear and exponential calibration curve for each station.

Site	10 cm		30cm left		30cm right		50cm	
	r^2	RMSE [vol.%]	r^2	RMSE [vol.%]	r^2	RMSE [vol.%]	r^2	RMSE [vol.%]
FRE	-	-	0.833	4.53	0.934	2.12	0.504	10.4
MLS	-	-	0.638	16.1	0.848	12.1	0.553	10.1
GFU	-	-	0.959	2.52	0.89	2.37	0.91	1.78
SCH	0.811	7.56	-	-	-	-	-	-
STO	-	-	0.541	4.22	-	-	0.807	6.93

Table 5: Correlation (R^2) and RMSE between the TDR and FDR measured VWC at all sites.