Response to: Interactive comment on "A new perspective on the spatio-temporal variability of soil moisture: temporal dynamics versus time invariant contributions" by H. Mittelbach and S. I. Seneviratne

We are thankful for the positive, critical and constructive reviews on our manuscript that will help to improve the final version of the manuscript. In the following, the reviewer comments are in black text, the author responses are in green text.

Anonymous Referee #1

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Overview

The study investigates a new perspective for the analysis of soil moisture spatialtemporal variability that considers the variability of the soil moisture temporal anomalies instead of the absolute values. Results indicate that the time invariant term contributes for 94% of the spatial soil moisture variance whereas the contribution of the spatial variance of the temporal anomalies is quite limited. Moreover, by applying the classical temporal stability analysis to the absolute values and the temporal anomalies, the findings are quite different.

General Comments

The paper is well written, well structured and clear; the language is fluent and precise. The topic of the paper is of great interest for the HESS reader as the analysis of soil moisture spatial-temporal variability both in terms of absolute values and anomalies has significant effects for the effective use of soil moisture observations for many hydrological, meteorological or agricultural applications (to cite a few). Actually, from my working experience on the same issue, I found several times that the spatial variability of relative soil moisture data, obtained by normalizing the data to the range 0-1 (degree of saturation), can be quite different from the one of the absolute values. The paper clearly underlines this aspect and, hence, it represents a clear and welcome contribution on the analysis (and use) of soil moisture spatial-temporal variability. Despite the paper significant merits, I found some issues to be solved before its publication.

In the Methods section, the equation (4) could provide some inconsistencies for its application. In fact, while Stn and atn are two matrices, the term atn is a vector. Therefore, the summation of atn and mn is formally wrong. I suggest modifying this equation and, accordingly, also the following ones.

>> We agree. For consistence we include an additional equation and multiply the temporal mean of absolute soil moisture with a row vector with constant of one and size T.

Additionally, in equation (7) the second term should be without "cov", please correct.

>> We are thankful for this comment. This has been corrected.

Some parts of the description of the results should be revised. The analysis of Figure 4a contains a lot of symbols and numbers. It is not easy to follow the main findings that should be extracted from this analysis. Additionally, which is the reason of the analyses shown in Figure 5? Please specify.

>> Concerning Figure 4a we think to provide an overview by placing the variance of the overall soil moisture S above its single contributors. In addition, we will leave the sum of the single contributors in this figure but removed the Figure 4b.

The rationale for the analysis shown in Figure 5 is to show the relation between the single contributors. We implement the mean soil moisture within the scatter plots to indicate the different behavior of the variances and covariance for above or below mean soil spatial soil moisture values.

The main problem I found is in the temporal stability analysis. Why the relative and absolute differences are analyzed (Figures 6a and 6b)? The results are basically the same. Figure 6d seems to be wrong as I expected that the rank of the sites should be the same of the one reported in Figure 6c (see also page 830, lines 16-17). Please check. Again, the large number of symbols does not allow to easily derive the main outcomes of this analysis. I suggest showing the temporal stability analysis only for the relative (or absolute) differences of 1) the soil moisture original values, 2) the absolute value of the anomalies and 3) the temporal mean soil moisture values.

>> Thanks for drawing our attention to the wrong upper x-axis in Figure 6. As described in the text and mentioned by the reviewer, the respective rank of the sites has to be the same for the absolute and relative differences. The error was found in the formatting of the figure.

In this study, we are working with absolute values. Hence, we implement the absolute differences for the temporal stability analysis. We agree that the rank of absolute and relative differences are basically equivalent. Nevertheless, we include the relative values to link to the results to findings from other temporal stability studies (see manuscript p 830 L10 to 13). This is now more clearly specified in the manuscript.

I suggest smoothing out some of the conclusions of the paper. The authors are well aware (see page 833, lines 19-21) that the results are dependent on the investigated dataset.

>> We agree. The focus of the study is the introduction of a new perspective of the spatial variability. We used the SwissSMEX soil moisture network for a first application and illustration of the concept and are aware that results obtained with a single dataset cannot be generalized. We agree that the previous conclusions were written in a too general fashion and revised the text accordingly. We changed the first part of the conclusions (p 833 L 1 to 4) to: “From the analyses of the study, we conclude that frequently used frameworks assessing spatio-temporal characteristics of soil moisture networks need not generally apply to temporal soil moisture anomalies. Indeed, for the investigated data set…”.

Furthermore, we now also emphasize more clearly the need to apply the framework to other datasets before generalizing these results further (although such implementations would lie beyond the scope of the present study). We changed p 833 L 19 to 21 to: “We encourage the application of the present framework to further

long-term data sets. This would allow the assessment of the relative contributions of dynamic and static components to the spatial variability of soil moisture for different regions."

In fact, the climatic conditions, the spatial extension of the area, the soil texture and land use of the investigated sites and the layer depth are expected to have a significant influence on the obtained results as it occurs for the analysis of soil moisture absolute values. For instance, the authors only analysed grassland sites; this aspect may have a significant impact on the spatial distribution of soil moisture and also on the sampling requirements (e.g. Manfreda and Rodrìguez-Iturbe, 2006).

>> We agree that beside the considered heterogeneity in the sites characteristics also differences in land use will influence the obtained results. With the SwissSMEX soil moisture network we established a large-scale and long-term soil moisture network in Switzerland, which also includes forest sites. However, we did not include these forests sites in the analysis because (i) they are available over a shorter time period only, and we wanted to use continuous in-situ measurement over the possible longest time period, and (ii) the forest sites would introduce larger differences in topography. While the grassland sites have no slope, the forest sites have a slope of up to 68%, which would increase the room for interpretation/ uncertainties and would be beyond the scope of this study. Nevertheless, we are curious for results including different land use as well as the application to other data sets.

Specifically, by performing some preliminary analysis with two data sets at my disposal, I obtained quite different results (e.g. the contribution to spatial variance of the spatial variability of anomalies is found to be higher than the time invariant contribution). I also would like to see the proposed framework applied to the different soil moisture datasets that, nowadays, are widely (sometimes also freely) available

>> As discussed in comment No. 5, the focus of the paper is to introduce a new perspective on the spatio-temporal variability. We removed previous generalizations and clearly suggest to apply this perspective to further datasets to gain more insights for spatio-temporal variability of soil moisture and its dynamics.

On these bases, in my opinion, I find that the paper may become worthy of publication on HESS after a moderate revision.

Specific Comments/ Technical Corrections (P: page, L: line or lines)

P822, L5: See also Brocca et al. (2012) and Crow et al. (2012) who investigated the upscaling of soil moisture observations at different spatial scales.

>> Thanks for suggesting both interesting publications. They are included in the manuscript.

P827, L14: Why are the data "daily aggregated"? Are daily averages? This could have a non-negligible effect on soil moisture temporal variability thus influencing the overall findings of the paper. Please specify and discuss better this aspect.

>> Soil moisture is analyzed using daily averages. This is now specified in the revised manuscript.

P828, L1-2: Why is a minimum of the spatial variability of anomalies expected for values close to zero? With a different data set, I obtained a different pattern. Please specify.

>> This is a good point, and we agree that this would generally not be expected. This section will be revised.

P828, L13: What does "spatial P and Tair" mean? Spatially averaged values? Please specify.

>> Yes, we refer to the spatial average precipitation and 2-m air temperature. It is specified in the revised manuscript.

P829, L6-21: This part is not clear and it should be revised (see also General Comments).

>> We agree. The text is revised and cross-references to the respective figures are implemented.

Figure 3: This figure is quite small and hard to read.

>> The figure is now enlarged.

Figure 4b: This figure is not needed because it is simply a check of the correctness of the analysis.

>> We removed this figure in the revised manuscript as it does indeed not provide additional information.

Additional Reference

Brocca, L., Tullo, T., Melone, F., Moramarco, T., Morbidelli, R. (2012). Catchment scale soil moisture spatial-temporal variability. Journal of Hydrology, 422-423, 71-83, doi: 10.1016/j.jhydrol.2011.12.039.

Crow, W., A. A. Berg, M. H. Cosh, A. Loew, B. P. Mohanty, R. Panciera, P. de Rosnay, D. Ryu, and J. Walker (2012). Upscaling sparse ground-based soil moisture observations for the validation of coarse-resolution satellite soil moisture products. Reviews of Geophysics, in press, doi: 10.1029/2011RG000372.

Manfreda, S. and I. Rodrìguez-Iturbe (2006). On the spatial and temporal sampling of soil moisture fields. Water Resources Research, 42, W05409. Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 819, 2012.

Anonymous Referee #2

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Summary

The manuscript of Mittelbach et al. introduces a new framework for analysing the spatio-temporal variability of soil moisture. The main underlying idea is to decompose the spatial variance of absolute soil moisture over time in its time variant and time invariant contributions. The concept is applied to the soil moisture recordings from the SwissSMEX network. In their case study the authors conclude that the contribution of the time variant component is small compared to the time invariant spatial variance of the mean soil moisture at all sites. They further argue that commonly used frameworks do not apply to temporal soil moisture anomalies.

General comments

I found the manuscript of Mittelbach et al. both innovative and informative. The topic is relevant for the community of HESS and represents an interesting follow-up to previously published papers on the same subject. I have to admit that I read the revision that was published earlier and I agree with the

comments of the reviewer.

>> In cases of the same contents of the comments address by referee #1 we will refer to our answer to referee #1.

- It is necessary to correct the errors in the formulae 4-8.

>> The equations are changed. See comment #1 referee #1.

- It is necessary to correct the labels in Figure 6d.

>> Thanks for drawing our attention to the incorrect labels of Figure 6b. See also answer to comment #4 referee #1.

- Because of an extensive usage of symbolism it is at times hard to follow this manuscript. The manuscript would therefore benefit from being more concise. I know that there is no straightforward solution to this problem because of the nature of the study, but I believe that the previous reviewer gave some good recommendations in this respect.

>> For the current study the choice of the symbolism was not straightforward because we consider statistics in two dimensions (space and time). Hence we need to have separate notations for e.g. the spatial mean and temporal mean, as well as for the spatial variance and temporal variance. In this context, it is difficult to use a much simpler notation than the one currently employed.
However, we tried to improve the readability with the following revision: The variables are now presented using capital letters to indicate that they are matrices. Nonetheless, we would like to keep the rest of the notation. While other studies on the spatial and temporal variability often use the subscript ij (e.g. Brocca et al., 2009; Jacobs et al., 2004; Teuling et al 2006) we prefer the subscript tn to state the temporal and spatial dimension of the variables. Similar to other studies we are using \sigma to identify the variability. Using \mu for

the mean values is in our opinion more consistent with the \sigma than using an overbar. Using the “hat” over the n and t refers explicit to the averages in space and time respectively. Using the decomposed soil moisture results in using both \Delta and \delta with the respective variable (S, M, or A). This clearly leads to a high number of symbols, which shall, however, include consistence for the reader. To improve the readability we provide a list of notations at the end of the revised manuscript.

- In my opinion, some analyses are indeed rather trivial and could be removed from the manuscript (e.g. comparison between the temporal mean of differences and the corresponding absolute values, see e.g. Fig. 6a,c; comparison between absolute differences and relative differences, see e.g. Fig6a,b).

>> Please see answer to comment #4 of referee #1.

- It is necessary to be more precise concerning the data preparation (e.g. p.827 “aggregation” of soil moisture data).

>> Please see answer to specific comment #2 of referee #1.

- I recommend improving the readability of Fig. 3 (e.g. put the x-axis label only once, increase size of the subplots).

>> Figure 3 is enlarged.

- It is necessary to provide the units (or indicate [-]) on all plots.

>> This is revised.

- It is not necessary to “prove” that the contributions in Eq. 8 sum up to 1 (Fig. 3 & 4).

>> We removed the sum of the single contributors in Figure 3. Furthermore we removed Figure 4b. Nonetheless, we kept the sum in Figure 4a, given the very slight discrepancies induced by the lack of some sites for specific days.

- In general, it would be preferable to develop the interpretation of the findings of this study and to make a better link to underlying hydro-meteorological processes and area characteristics (p. 831 l.15). Did you observe systematic differences between the individual sites that could be related to differences in climatology, lithology, topography or land use? Moreover, it is important to bear in mind that the area covered by this study is 150 x 210 km. The contrasting climatologies may partly explain why the time invariant variance outweighs the time variant variance. However, there is only little information provided on this subject. Please provide more information on the spatio-temporal variability of precipitation in the area and how it may have affected the spatio-temporal variability of soil moisture. There is some information in Fig. 3a, but this is hardly readable.

>> We now provide two additional figures on this aspect in the revised manuscript.

The first figure displays the time series of each site as well as the spatial mean of (a) absolute soil moisture S, (b) temporal mean M, as well as (c) anomalies A. This figure displays that by removing the temporal mean the time series are getting more similar and the main difference in absolute values is given by the time invariant component.

The second figure is related to the comment of the referee on the potential impacts of the climatic region, soil texture, and topography for the findings. The land use over all the sites is managed grassland, thus cannot be distinguished (see answer to comment #6 of referee #1 why no additional land use is involved). Concerning the topography, all sites are flat but are located at different elevation ranging from about 200 m a.s.l. to about 1000 m. a.s.l. with most sites located between 400 and 600 m a.s.l. (the information about the elevation is implemented in the actual manuscript). The bar plots show the S, M, and A average and standard deviation for the each climatic region, soil texture type, and range of elevation. They indicate that for each characteristic the averaged values are within the standard deviation of the single categories. An exception are the mean values of A for the characteristic "climatic region". Here the average of A need not to be in the range of standard deviation of the single categories. This suggests that within the SwissSMEX data set the anomalies may be more influences by larger scale characteristics, such as meteorological forcing, and less by small scale characteristics, such as soil texture and topography. In contrast, contributing characteristic to the temporal mean of S were more difficult to indicate. However, we suppose that the soil texture will have a major influence on the overall ranges of its value.

It is important to relate the findings of this study to the particular characteristics of the study area and to refrain from jumping to general conclusions (e.g. p.833 l.1-3). In fact it is important to corroborate the findings of this study by applying the same evaluation framework to different data sets before any meaningful generalization can be envisaged.

>> We agree and removed generalizations. The purpose of the manuscript is the introduction of a new perspective and to provide case studies of different data sets (though the latter would be well suitable for a follow-up study). The SwissSMEX data set is used for a first application. However we emphasize the use of the framework for further networks as it promises to provide new insights for the spatio-temporal variability of soil moisture and its dynamics.

Overall, I think that this is an interesting addition to the existing body of published research on soil moisture analysis. I recommend publishing this manuscript in HESS, subject to some minor revisions.

Minor comments:

- p.828 l.2-4 why would the variability be minimal for moisture conditions close to the mean?

>> Please see answer to comment #10 of referee #1.

Please clarify - p.832 l.19 "sequence of the sites" please clarify the meaning of this sentence

>> With "sequence" we mean "rank". We changed the sentence to: "This implies that the rank of an individual site with respect to its mean status is not the same for its anomalies."