Response to Nilda Sánchez's Comments

I perused this manuscript with great interest. First, I know the previous work of the authors in which the current methodology was proposed and refined. Second, the re- search was developed in the REMEDHUS network, which our team has owned since 1999 and where a good number of studies have been done related to remotely sensed soil moisture products. I found this manuscript very interesting, well written and structured, and the objective (a downscaling approach of soil moisture products) is a must nowadays for the remote sensing community. However, I would like to propose and discuss several aspects with the authors.

Response: We thank you very much for all the effort that you invested in this manuscript. And thank you for the positive comments. In the following, we provide an item-by-item response to your specific comments. Your comments are written in italic black color; our responses are shown in upright font blue color.

GENERAL COMMENTS

I would like to suggest enlarging the period of study. I am aware that the reason for choosing this interval was to coincide with other similar studies to be compared. This comparison can be preserved but the robustness of the analysis would be improved with more years of testing.

Response: Thank you for the suggestion. We fully agree that the increase of sample data would make the analysis more robust. However, we decide to keep using the current time period in this study for the following reasons: Firstly, the aim of this study is to evaluate the accuracy of the developed downscaling scheme. It has been found that the accuracy of the proposed scheme highly depends on the original CCI soil moisture. From the results of evaluation of CCI against REMEDHUS in-situ measurements, it can bee seen that the CCI accuracy level is quite similar to the results reported by Dorigo et al. (2015), who validated the CCI soil moisture around the world with in-situ measurements from 28 historical and active monitoring networks. Therefore, the results are not expected to change a lot if we would enlarge the study period here. In addition, as we indicated in the manuscript, the same time period as other similar studies will make the cross comparison more feasible and fair. And the results from different time periods (time period for inter-comparison with published studies, time period for validation) will make the paper a bit confusing. We will consider your suggestion in following studies, where we will explore the accuracy of passive/active CCI according to your suggestion below.

I find the use of SEVIRI very promising owing its detailed temporal resolution. Indeed, I myself proposed the integration of SEVIRI data with SMOS in another downscaling scheme. You proposed the use of SEVIRI for the LST alternative and MODIS for the vegetation. I wonder why you discarded the SEVIRI FVC (or LAI alternatively). Actually, the FVC is the parameter originally proposed by Carlson in the Universal Triangle and, furthermore, this product has a much better temporal resolution and, thus, higher free- cloud cover potential. I would appreciate some discussion about this.

Response: It is really a good point. We actually have tested the use of SEVIRI LAI. And the results are quite similar to the use of MODIS LAI. The decision of using MODIS LAI rather than SEVIRI LAI is to avoid the use of products from too many different sources. Besides, the surface temperature is more sensitive to soil moisture than the LAI. The use of MODIS LAI also makes it more reasonable to compare the difference between MODIS NDVI/EVI/FPAR and MODIS LAI.

Other analysis I would have liked to see in this paper was the spatial correlation for each date of study, i.e., a correlation for each day using all possible ground measurements on that given day. I am aware that for the current remotely sensed soil moisture (especially passive-derived products, e.g., SMOS) it is difficult to reproduce the spatial variability at point scale owing to the (low) spatial resolution of the radiometric measurements. But after a downscaling model like yours, a test of the spatial patterns makes sense at the improved resolution, and it would be a valuable and challenging analysis. It could be interesting to test if your downscaling approach is able to reproduce the spatial variability of soil moisture. In your paper, this issue is neither addressed nor discussed.

Response: Thanks, it is really a good point. It is important and interesting to investigate if the downscaled soil moisture can represent the real spatial variability of soil moisture. The problem is the lack of proper reference (spatial map of in-situ soil moisture) dataset. We actually have tried to get this reference data through interpolating of the REMEDHUS in-situ measurements. But we found that the interpolation scheme itself would incur uncertainties, as different interpolation schemes lead to different results. In another study in China (Peng et al., 2016), we compared the spatial pattern of the downscaled soil moisture with high spatial resolution land cover maps, and found that the downscaled soil moisture corresponds well with the land cover map. Nevertheless, we fully agree with you, and we think the best solution for validating the spatial pattern of downscaled soil moisture is the availability of proper reference data. This could only be achieved through intensive measurement campaigns using comprehensive in situ as well as airborne data to fill the scale gap between the SMOS pixels and in situ data. We would aim to further investigate this approach using data collected during the SMOS validation campaigns in the Upper Danube catchment.

Finally, the overestimation found for both the original CCI SM and the downscaled soil moisture in this area deserves further analysis, perhaps not in this research study but in future comparisons. After our experience with passive-based soil moisture estimations in REMEDHUS, the retrieved values generally underestimated those observed, despite the semi-arid climate and low soil moisture content. It would be interesting to analyze the overestimation in light of the passive/active inputs of this product separately.

Response: Thanks a lot for the suggestions. It is good to know that the passive-based soil moisture tends to underestimate soil moisture from your experience. The CCI SM used here is the active/passive-merged product. It is indeed a good idea to analyze the performance of passive and active soil moisture respectively. We will carry out the investigation in a follow on study.

SPECIFIC COMMENTS

In Section 3.2 about MODIS products, explain in more detail the Aqua/Terra source of the products and justify their choice (Aqua/Terra).

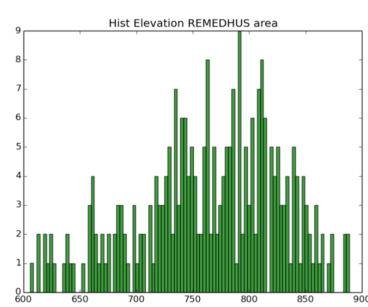
Response: The following texts have been added in the manuscript to clarify the reasons of using both Terra and Aqua. In addition, more information can be found in section 4.1—*surface temperature paragraph*.

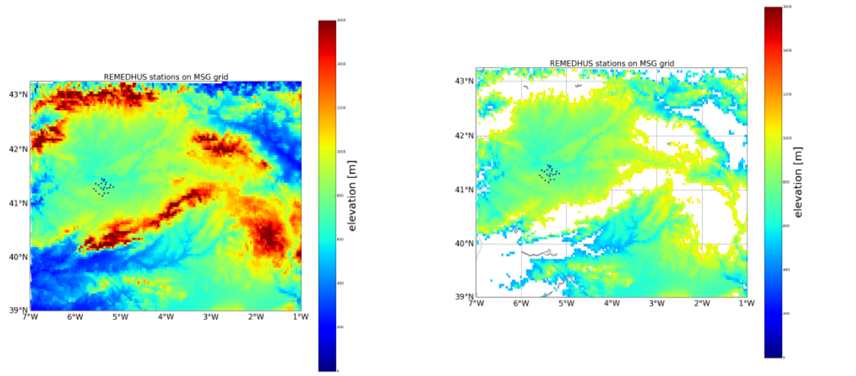
"The surface temperature normally has strong diurnal variation. Therefore, the surface temperature products provided by Terra and Aqua have different values due to different overpass time of Terra and Aqua. Since surface temperature is one of the most important inputs in downscaling methods, both MODIS/Terra and MODIS/Aqua are used to downscale soil moisture in this study."

The study of the topography seemed contradictory to me with the downscaling approach, and wrongly focused. First, since the area of study is selected, among other reasons, based on its flatness (lines 12–13 p.8510, according to the Triangle method assumption), I do not see how the topography would be worth considering. Second, you chose a criterion based on 'removing the areas with 300 m higher or lower elevation than the average REMEDHUS elevation'. Given the REMEDHUS average of 777 m, there are almost no areas below the range you chose, and only a few beyond. I enclose the Figure 1 to illustrate this reasoning. Thus, the poor influence of the topography showed in the sensitivity analysis is not surprising, as you recognize on p.8520 and in Figure 5.

Figure 1. Digital Elevation Model of Castilla y León

Response: Thank you for the comments. You are right, the triangle method requires that the study area is relatively flat. The variation of elevation can incur the variation of surface temperature, while the surface temperature in triangle method is assumed to be caused by evaporative cooling effect rather than elevation. Therefore, the areas with very high and low elevation should be masked out before applying triangle method. It then raised the question: How sensitive is the triangle method to elevation? What is relatively flat? In other words, which range of elevations should be masked out? The LSA SAF elevation data was used to characterize the topography of the study area. The average elevation calculated from LSA SAF is 765m (see figure below), which is similar to 777m that calculated from your DEM. From the DEM of the study area, it can be seen that dark blue and red color areas have elevations out of the range of REMEDHUS elevations. The figure also shows the study area after removing the areas with 300m higher or lower elevations than average REMEDHUS elevation. Therefore, it is worth to investigate the influence of topography on triangle method.





(a) LSA SAF elevation for study area.

(b) LSA SAF elevation for study area. Only values between 465 and 1065m are shown.

Similar to the previous comment, I find the analysis of the 'land cover heterogeneity' meaningless and contradictory here. As you stated, 'the study area also needs to be homogeneous' (L3 p. 8518). Actually, the area is distinctly homogeneous, with 80% of the area corresponding to rain-fed areas and almost 90% to 'cropland areas', the category you chose to separate from the 'full land cover'.

Response: We agree with you that 'land cover heterogeneity' and 'homogeneous study area' is contradictory. That is actually the motivation of doing this analysis. On one hand, the triangle method requires a wide range of soil moisture and vegetation cover conditions to generate the triangular shape. On the other hand, it also requires the vegetation type and surface roughness to be homogeneous (Moran et al., 1994, Carlson et al., 1990). In practice, it is hard to meet the two requirements at the same time. Then, which requirement is more important? The current study found that having a wide range of soil moisture is more important than keeping vegetation type and surface roughness homogeneous.

In the sensitivity analysis, you justify the better performance of the LAI over the NDVI because of the NDVI saturation at dense vegetation levels. My experience in this area with very different kinds of image datasets and field radiometric measurements is that the NDVI never saturates here owing to the type of vegetation canopies (herbaceous crops, sparse vineyards or trees, grassland/pasture, etc.). Perhaps this better performance should be attributed to other causes?

Response: Thank you very much for sharing your experience and findings with us. Our conclusions are based on the theoretical differences between NDVI and LAI. Based on your suggestions, the texts have been revised to:

"It is because NDVI is only an indicator of surface greenness due to its sensitivity to effect of soil background. The other indexes are physical parameters and can better represent the reality of vegetation density, which leads to better performance of VTCI."

It is unclear if the analysis in 5.2, and consequently Figure 4, compute the station average or another kind of spatial average. Also, in this section it is stated that 'the VTCI, combining the *information from both LAI and surface temperature, agrees well with soil moisture with R of 0.37/0.52'. A correlation coefficient in such a range does not seem to 'agree well' to me.*

Response: Thanks for pointing this out. The analysis in 5.2 is based on station-averaged values. The corresponding descriptions have been improved. Yes, the word 'well' is a bit subjective, since there is no standard range for quantifying 'good' or 'bad'. The 'well' used here comes from the published studies such as Patel et al., (2008) and Sun et al.,(2012), which compared TVDI against in-situ soil moisture and got similar R values as we found here.

In 5.4. Section of validation, you show the results of R in terms of 'mean R'. These results are a bit confusing. I assume that you mean an average of each station correlation. But those values differ from those in Table 4 of your current study. Do the results in Table 4 come from a correlation of the comparison from the soil moisture average of all stations? Please, clarify.

Response: Thanks for the comments. Yes, you are right. The 'mean R' value in section is the average of each station correlation. That is why it is in the form of R±std (0.51±0.16). The values of Table 4 are from the station averaged-values comparisons, which can be found in Fig 8. The following sentence has been added in caption of Table 4.

"The statistics of the current study are from the comparison of station averaged soil moisture."

It would be interesting, in Figures 5 f and g, to add the soil moisture records of each point as a colour ramp, to see if the theoretical distribution in Figure 2 was verified. In our experience, the supposed distribution in the Universal Triangle of the wet/dry edges does not always work as expected, depending on several conditions. It would be good to know your results with the original and derived products.

Response: Thanks for the suggestion. It is a good idea. However, it is hard to carry out due to the non-availability of reference soil moisture data. Because the triangle shapes that shown in Figure 5 f and g are based on high spatial resolution data. Similar to your comment above about validation of spatial pattern of downscaled soil moisture. The point here is the missing of high resolution soil moisture (reference dataset). Therefore, the production of spatial distributed soil moisture product ('truth dataset') is urgent.

FORMAL/TYPO

L4, p. 8506: 'prediction', I guess.

Response: Corrected, thanks.

L13, p. 8510: 'central' is meaningless.

Response: The central area means the middle plot that is shown in Figure 1. In the current study, this area rather than the whole Spain was used to generate the triangle space to calculate VTCI.

L16, p. 8510: 'most of the area is larger than 450 m'. This is not correct. The mean elevation in the Castilla y León region is 800 mm. Plus, the citation of Zhang et al. is inadequate here.

Response: The description of "larger than 450 m" is a bit ambiguous. From our statistics, the mean elevation of the study area (middle figure in Fig 1.) is about 650 m. The description in the manuscript has been changed to "the mean elevation of the area is about 650 m above sea level"

L18, p. 8510: For a description of this area, a more appropriate citation could come from our own research there, which we have developed since 1999. I suggest: Antonio Ceballos, José MartÄś ́ÌĄ nez-Fernández, Miguel Ángel Luengo-Ugidos, Analysis of rainfall trends and dry periods on a pluviometric gradient representative of Mediterranean climate in the Duero Basin, Spain, Journal of Arid Environments, Volume 58, Issue 2, July 2004, 215-233, ISSN 0140-1963.

Response: Thanks for the reference. We have cited it in the manuscript.

L23, p. 8518: I guess you use the form 'satellite minus in situ' for BIAS. Please, indicate.

Response: Yes, you are right. The reference below has been added, where the detailed equation of each variable is shown.

"Entekhabi, D., Reichle, R. H., Koster, R. D., & Crow, W. T. (2010). Performance metrics for soil moisture retrievals and application requirements. Journal of Hydrometeorology, 11(3), 832-840."

L20, p. 8525: 'Evaluation'.

Response: Corrected, thanks.

L12-13, p. 8519: I do not see the meaning of this explanation: 'It might be caused by the use of high quality surface temperature products in this study'.

Response: What we would like to state are the followed sentences. If the surface temperature has high accuracy, then the temperature difference method performs similar to instantaneous temperature method. To avoid confusion, this sentence has been removed from the manuscript.

L13-14, p. 8520: The 85% of the cloud mask category cannot be seen in Figure 3.

Response: It is the last third column "LAI_A_DN_cf85" for MODIS, and "LAI_tmintmax_cf85" for MSG.

Please, be careful with the citations of the Spanish accent marks in Sánchez, Fernández and so on, as there are lots of mistakes.

Response: Thank your for point this out. We have double checked the names, and corrected them.

Table 1: J14 is rainfed.

Response: Thanks a lot. We have integrated this info into Table 1 and Figure 10.

Table 3 and Figure 3: Abbreviations for products must be indicated.

Response: Good comment. During the writing of the manuscript, we were bothered about how to explain the label of x-axis in Figure 3. Then we had the idea of Table 3, whose aim it to explain the meaning of each label in Figure 3. And in the caption of Figure 3, the reference to Table 3 is also noted.

Table 4: Is the field 'soil' actually 'soil moisture'?

Response: Yes, corrected, thanks.

Figure 4: Clarify if the series you show come from a spatial average.

Response: Yes, they are spatial averaged values. The descriptions in Figure 4 and section 5.2 have been changed.

References:

Dorigo, W. A., Gruber, A., De Jeu, R. A. M., Wagner, W., Stacke, T., Loew, A., Albergel, C., Brocca, L., Chung, D., Parinussa, R. M., and Kidd, R. (2015). Evaluation of the ESA CCI soil moisture product using ground-based observations. Remote Sensing of Environment, 162:380–395.

Moran, M. S., Clarke, T. R., Inoue, Y., and Vidal, A.: Estimating crop water deficit using the relation between surface-air temperature and spectral vegetation index, Remote Sensing of Environment, 49, 246-263, 1994.

Carlson, T. N., Perry, E. M., and Schmugge, T. J.: Remote estimation of soil moisture availability and fractional vegetation cover for agricultural fields, Agricultural and Forest Meteorology, 52, 45-69, 1990.

Patel, N. R., Anapashsha, R., Kumar, S., Saha, S. K., & Dadhwal, V. K. (2009). Assessing potential of MODIS derived temperature/vegetation condition index (TVDI) to infer soil moisture status. International Journal of Remote Sensing, 30(1), 23-39.

Sun, Liang, et al. "Monitoring surface soil moisture status based on remotely sensed surface temperature and vegetation index information." Agricultural and forest meteorology 166 (2012): 175-187.

Peng, J., Loew, A., Zhang, S., Wang, J., and Niesel, J.: Spatial Downscaling of Satellite Soil Moisture Data Using a Vegetation Temperature Condition Index, IEEE Transactions on Geoscience and Remote Sensing, 54, 558-566, 2016.