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Discussions

Interactive comment on "Global Downscaling of Remotely-Sensed Soil Moisture using Neural Networks" *by* Seyed Hamed Alemohammad et al.

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We thank Referee #2 for their comments. Here, we respond to the general comments and specific points.

General Comments:

> The authors have downscaled global satellite-based soil moisture observations to 2.25km spatial resolution using neural networks. The manuscript is well written, and the methodology is sound. The high-resolution products will be useful for global hydro- logical and climate studies. However, there are a few issues in this manuscript, hence I suggest some major revisions.
>
> My major concerns are:

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1. The training and retrieval in the NN algorithm are based on the hypothesis that it shares the same "relationship" between inputs and outputs to downscale soil moisture from 36km to 9km and to downscale soil moisture from 9km to 2.25km. The author should provide more information about how the SPL3SMP_E product is enhanced from the SPL3SMP product. As the author mentioned, the native resolution of SPL3SMP_E is actually about 33km. So what is the relationship among 36km, 33km, and 9km?

Response/Action: *In this study, we made the assumption that the scaling relationship from the 36km product to the 9km product can be used to estimate soil moisture at 2.25km. We have independently validated the soil moisture values at the 2.25km scale; therefore, we believe this is a valid assumption.*

We agree with the difference between native resolution and grid spacing of the SPM3SMP_E product. The 9km product applies the Backus-Gilbert (BG) optimal interpolation technique to the oversampled radiometer measurements to estimate brightness temperature (TB) at each point, which is the center of each 9km pixel. Meanwhile, the native resolution of the data which is the spatial extent projected on earth surface by the 3-dB beamwidth of the radiometer is very close to the 36km product.

Contrary to this approach, the SMAP 36km product uses the antenna pattern information to estimate TB from the original radiometer measurements, and does not take into account the oversampling effect. This results in a coarser grid resolution data.

2. It is a little confusing to add standard deviation of NDVI in the downscale scheme. All the schemes have included NDVI at the higher resolution (9 km for training and 2.25km for retrieval). What additional improvement will the standard deviation of NDVI provide? As the author stated, "This estimate provides a proxy of the heterogeneity within the coarse scale grid". Hasn't the higher-resolution NDVI already provided information about "sub-pixel heterogeneity"? This makes

the conclusions somehow self-contradictory. The key of the downscaling algorithm is the higher-resolution NDVI "as an ancillary data to quantify sub-pixel heterogeneity of soil moisture". However, the similar performance of the four schemes suggests that "variability of NDVI within the coarse scale pixel does not provide additional useful information on the spatial heterogeneity of soil moisture for the downscaling".

Response/Action: *We would like to highlight that the final algorithm (scheme R1) which is used to retrieve soil moisture at the downscaled 2.25km scale does not include standard deviation of NDVI (NDVI_std). The reason we included NDVI_std in schemes R2 and R4 was to check if an explicit input of the variability of the NDVI (reflecting within watershed variations) within each coarse scale pixel (36km during training and 9km during estimation) would increase the accuracy of the soil moisture retrieval at the finer scale. NN algorithms apply a combination of linear operations to the inputs, but not necessarily power operations that might inform the network of the variance/std of the inputs. So we made an assumption, added this variability as an input, tested the results, and reported that it does not improve the accuracy of estimation. Therefore, to reduce complexity of the model we did not include NDVI_std (or TI for the same reason) in the final algorithm. We believe reporting this analysis is informative for the readers who might be interested in expanding our approach and building new downscaling algorithms, especially to account for watershed variations in soil moisture.*

Specific Comments:

- P2, L29: "Our final product is soil moisture estimates at 2.25km spatial resolution with full global coverage every 2-3 days ... " Is it possible to explain why the final product is downscaled at 2.25km spatial resolution here?

  Response/Action: *We will add the following sentence in this paragraph to explain the reason for the choice of 2.25km data:*

"The 2.25km spatial resolution is chosen since we use SMAP 36km and 9km soil moisture products for training and developing the scaling relationship. This is used to estimate soil moisture at the finer 2.25km resolution which is $\frac{1}{4}$ of 9km."

- P4, L8: What are the temporal resolution of the in situ soil moisture observations?

  Response/Action: *They are hourly measurements, but we have only used the measurement at 6am local time which is concurrent with SMAP measurement.*

- P4, L13: 20 measurements at one station?

  Response/Action: *We apologize for the confusion, we meant 20 measurements in time at each station. We have excluded any station that has less than 20 measurements during the study period because temporal statistics won't be meaningful. We will revise the sentence in the revised manuscript.*

- P4, L14: What is the resolution of the "pixel" here? Does one pixel only contain one station?

  Response/Action: *We apologize for the mistake. We meant stations and not pixels. The numbers for each network refer to the number of stations used from each. We will correct this in the revised manuscript.*

- P7, Table 1: Are they inputs only for training? It would be better to include the information about retrieval.

  Response/Action: *The information for training and retrieval are the same but their spatial resolution differ. We will change the table in the revised manuscript to reflect the specifications of the input data for retrieval.*

- P9, L8: The maps look pretty similar, can you tell any difference between them, or which one is better?

Response/Action: *We expect them to be similar at this scale. However, there are differences in regions such as the Sahara and regions with high soil moisture gradient (near Congo basin, and the Amazon). Other differences are in the latitudinal averages and pixels that do not have soil moisture estimate (such as major rivers). Due to the suggestion of referee 1, we will include soil moisture maps from focus regions in the revised manuscript that will depict differences between the products.*

- P9, L12-13: "...at higher spatial resolutions there is more spatial heterogeneity. The latitudinal average for the 36 km product is much smoother than the 2.25 km one." What is the purpose of this? Does more spatial heterogeneity indicate better quality?

  Response/Action: *It is a measure of quality relative to the spatial resolution. Soil moisture at higher spatial resolution is more informative for applications at small scale. This comparison shows that the soil moisture estimate at 2.25km has indeed more variability, and is not just an interpolated version of the coarser resolution product.*

- P11, Figure 7: Any explanation for the dry bias over the arid area?

  Response/Action: *We had briefly noted this in the conclusion section (P13, L19-22):*

  "Use of NDVI as an ancillary measurement to disaggregate soil moisture builds on the assumption that there is a moderate vegetation cover in the pixel of interest. Therefore, this lowers the quality of the downscaling algorithm in bare soil or sparsely vegetated regions. Moreover, NDVI estimates tend to saturate in highly dense vegetated regions such as the tropical forests which results in limited ability of the downscaling algorithm to resolve the heterogeneity of the soil moisture in those regions."

We will revise this paragraph as following:

"Use of NDVI as an ancillary measurement to disaggregate soil moisture builds on the assumption that there is a moderate vegetation cover in the pixel of interest. Therefore, this lowers the quality of the downscaling algorithm in bare soil or sparsely vegetated regions. Figure 7 shows a dry bias in arid regions which is an indication of lack of NDVI – soil moisture relationship. Moreover, NDVI estimates tend to saturate in highly dense vegetated regions such as the tropical forests which results in limited ability of the downscaling algorithm to resolve the heterogeneity of the soil moisture in those regions."

- P12, L2: How are the metrics calculated? calculate correlation temporally, then average among the pixels/stations? About the error bars on Figure 8, are they standard deviation among pixels or anything else?

  Response/Action: *For each pixel that has in situ observations one set of metrics is calculated. If more than one station from a network fall within a pixel, their observations are averaged before calculating the metrics. Finally, metrics from each network are summarized in Figure 8 with mean and standard deviation among pixels.*

- P12, L4: For Figure S6, It would be better to show the 10 networks with different colors or symbols on the map... Also, this map should have been mentioned in section 2.4.

  Response/Action: *We will change the figure as requested by the referee and reference it in Section 2.4.*

- P12, Figure 8: It is really hard to tell from the figure if there is any better performance of the downscaled products than the 9km SMAP product.

  Response/Action: *This figure summarizes the performance of different products with respect to temporal dynamics metrics. Since the downscaled product is*

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derived from the 9km product, we do not expect to see significant improvement in temporal dynamics of soil moisture estimates. Rather we check to verify that the increased spatial resolution in the downscaled product does not decrease the temporal performance.

- P12, Figure 8: Any idea why there is poor performance over some network (e.g., SNOTEL) but good performance over some other networks (e.g. SOILSCAPE). Why does SMAP 36km have the best agreement with iRON?

  Response/Action: *While this assessment is beyond the scope of this manuscript, we would like to note that while iRON has the best agreement with SMAP data with respect to ubRMSE it does not have the best correlation. While SOILSCAPE has the best correlation, it has an average ubRMSE metric. More detailed assessment of SMAP retrievals across different ground truth stations is provided in:*

  Chan, S. K. et al. (2016) 'Assessment of the SMAP Passive Soil Moisture Product', IEEE Transactions on Geoscience and Remote Sensing, 54(8), pp. 4994–5007. doi: 10.1109/TGRS.2016.2561938.

- P13, L7-9: This conclusion might only be true among the different NN downscaling schemes.

  Response/Action: *We agree with the referee, and will revise this statement as following in the revised manuscript:*

  "Our investigation shows that topographic index and variability of NDVI within the coarse scale pixel do not provide additional useful information on the spatial heterogeneity of soil moisture for the downscaling using our proposed NN technique and are thus omitted in the final product."

- P13, L20: "...this lowers the quality of the downscaling algorithm in bare soil or sparsely vegetated." Do any of the results support this statement? According to Figure 4, there is very high correlation coefficient over those regions.

Response/Action: *Lower quality is with respect to both correlation and bias. Figure 4 shows that those regions have high correlation, but Figure 7 shows the same regions have a negative bias in soil moisture estimates. We will revise the sentence as following:*

"Therefore, this lowers the quality of the downscaling algorithm in bare soil or sparsely vegetated regions as indicated by negative bias in arid regions in Figure 7.

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