Response to reviewer #3

**General comment:**

In this study, SMAP 9km soil moisture and MODIS LAI are assimilated with the Noah-MP land surface model, and the improvement in the simulation of the ET and carbon fluxes alongside the root zone soil moisture-based drought index is examined over the MENA region. As irrigation contributes significantly to the seasonal ET and carbon flux, the model performance in simulating the parameter mentioned above after activating the irrigation module is also investigated. The paper is interesting, thorough, and well written. In my opinion, the authors have addressed the objectives of the study. However, there are a few concerns regarding the choice of the satellite soil moisture product for assimilation and the evaluation datasets that are listed below. Addressing these concerns, I recommend acceptance.

**Response:** We thank the reviewer for the positive feedback to our study. Please see our responses in more detail below.

**Major comments:**

1- L110) Most of the agricultural areas around the world are smaller than 0.5 km2; thus, it is possible that the coarse resolution soil moisture product such as SMAP enhanced 9km can not capture the irrigation signal. Thus, assimilating the soil moisture data might not improve the irrigation simulation, leading to underestimation of ET over cropland area. My question is why the authors did not consider using a higher resolution soil moisture product such as SMAP - Sentinel1 1km soil moisture product that is proven to contain the irrigation signal over the irrigated cropland area (Jalilvand et al., 2021). I see that in conclusion, it is mentioned that SMAP-Sentinel1 1km soil moisture data can be used in the future study, but a justification for why you have chosen to work with the 9km product in this study is needed here.

**Response:** We thank the reviewer for this comment. Selecting the SMAP product for this research is mainly inspired by the following aspects: 1) the product has been proved to have higher information content compared to other products such as ASCAT and SMOS [*Kumar et al.,* 2018], 2) it has capability of detecting irrigation signal especially for semi-arid regions with Mediterranean climate [*Lawston et al.,* 2017], and 3) it has the capability to constrain and improve irrigation simulation in LSMs [*Felfelani et al.,* 2018]. A justification statement is added in Lines 115-116 as follows:

*"The product has also been proved to have higher information content with capability in detecting irrigation signals and improving irrigation simulations in large-scale LSMs (Kumar et al., 2018; Lawston et al., 2017; Felfelani et al., 2018)."*

We agree with the reviewer that utilizing soil moisture product at a higher spatial resolution such as SMAP-Sentinel1 datasets may provide more benefits in capturing the irrigation signal and its impact on surface conditions and we look forward to incorporating and testing these products within LIS in future projects.

2- L250: In contrast with what is mentioned here, a study by Javadian et al., 2019, over a basin in Iran (which is located in the MENA region), showed that WaPOR is systematically underestimated the ET over the irrigated cropland area while having more accurate estimates over rainfed agriculture and bare soil. This can significantly impact the results reported in this study as the WaPOR is used as the evaluation dataset for E, T, ET, and NPP. Please comment on this.

**Response:** We thank the reviewer for providing this information. Generally, it is safe to assume that there is no state-of-art ET product that can accurately represent the ET magnitudes. Therefore, our analyses for ET and its components are more focused on evaluating their seasonal to interannual variabilities. We acknowledge that the comparison associated with the magnitude of ET such as RMSE and BIAS should be interpreted carefully along with evidence of consistency on other variables such as GPP. The comparison on ET magnitude is discussed by acknowledging the uncertainties from both WaPOR dataset and the model output, which are noted in Line 327-329, and 371-373 as follows:

*Lines 327-329: "We note that both FAO WaPOR and FLUXSAT data sets are remote-sensing model data-driven products and are thus subject to uncertainties. However, the consistent results obtained by comparing the carbon fluxes against the two independent data sources highlight the benefit of assimilating LAI into the system."*

*Lines 371-373: "This may stem from different ET partitioning algorithm between Noah-MP and WaPOR as well as their associated uncertainties. The different impact on E and T due to LAI assimilation results in overall small difference in terms of correlation while general improvements in terms of RMSD for ET."*

Noah-MP OL simulation show overall positive BIAS in ET during the growing seasons across all three land cover types. LAI assimilation reduces the magnitude of BIAS, but the sign is still positive. WaPOR is regarded as one reasonable reference dataset rather than an approximation to the ground truth. A thorough investigation on the ET magnitude accuracy could not be achieved without integrating multi-source measurements, which is limited for the region and is beyond the scope of our study.

3- Figure 3b) Following the first comment, one important difference between the LAI and SMAP datasets is that the native MODIS LAI resolution is 500 m, upscaled to 0.05 degrees, while the SMAP enhanced product native resolution is coarser than 9 km resampled to the 0.05 degree.

Thus, the LAI data may contain the subpixel information while SMAP does not. This is especially important over cropland areas where land cover and soil moisture constantly change due to a different land and water management at the plot scale. This might be another explanation for the greater impact of LAI-DA on improving the T simulation relative to the SSM-DA. Please comment on this.

**Response:** We thank the reviewer for this comment. We agree that the spatial resolution of SMAP is one of the important factors that limits the improvement in transpiration simulation. Besides, the representation of soil moisture and ET coupling is known to have issues in land surface models that an improved soil moisture condition may not be effectively converted to improved ET [*Crow et al.,* 2020] and the contribution of assimilating soil moisture on improving ET may also depend on region and climate [*Kumar et al.,* 2020]. We now elaborated this discussion in Section 3.1.2, lines 344-349 as follows:

*"The impact of SSM-DA on ET components is limited. On the one hand, this may be resulted from the coarse spatial resolution of the SMAP dataset as it cannot provide information for finer scale soil moisture variability. On the other hand, it could also be possible that improved soil moisture condition in SSM-DA is not effectively converted to improved ET because of the weakness in model representation of ET and soil moisture coupling. This is an known issue for many land surface models (Crow et al., 2020). Moreover, the impact of soil moisture assimilation on ET can also heavily depend on region and climate (Kumar et al., 2020)."*

4- L368) According to Figure 5, LAI-DA significantly increases the RMSD relative to the OL run. If I understand correctly, you attribute this to using different ET algorithm. The only difference between the LAI-DA and OL run is the assimilation of LAI and not the difference in the ET algorithm. Can you explain why assimilation of LAI resulted in much larger RMSD?

**Response:** We apologize for the ambiguity here. We meant to say that Noah-MP and WaPOR have different ET algorithms, resulting in different partitioning of E and T. Assimilating LAI affects the greenness fraction in Noah-MP, which is one of the most sensitive parameters that controls the partition of E and T. Assimilating LAI reduces the LAI magnitude as compared to OL for all three land cover types (Figure 4), leading to increased fractional area for bare soil as well as increased evaporation. This is the main reason for increased RMSD for E in LAI-DA shown in Figure 5. To avoid ambiguity, we now rephrase the sentence in Line 371-373 in the revised manuscript as follows:

*"This may stem from different ET partitioning algorithm between Noah-MP and WaPOR as well as their associated uncertainties. The different impact on E and T due to LAI assimilation*

*results in overall small difference in terms of correlation while general improvements in terms of RMSD."*

**Moderate comments:**

1. L195) Please summarize all the experiments information in one table. As I understand, you have 6 different experiments that can be shown in this table.

**Response:** We thank the reviewer for the suggestion. A table summarizing the simulations is now added to the revised manuscript.

2. L260: Is there any flux tower site in northern Morocco? If not, please explain why the FLUXCOM data is reliable over the study region.

**Response:** We thank the reviewer for bringing up this point. Unfortunately, FLUXCOM does not have sites over northern Morocco. This reference dataset is included in our analyses, along with FLUXSAT GPP and GOME SIF to provide multiple views regarding how the simulated carbon flux compared to available remote sensing data sets. As shown in Figure 6, the comparison with FLUXCOM GPP yields similar results as compared to FLUXSAT and GOME SIF data sets. We now modify Lines 263-264 in section 2.5.2 to note this issue:

*"As there is no flux tower site over the study domain and FLUXCOM products do not cover the SMAP period, we also utilize the recently developed FLUXSAT GPP estimates, which are available from 2000-2020."*

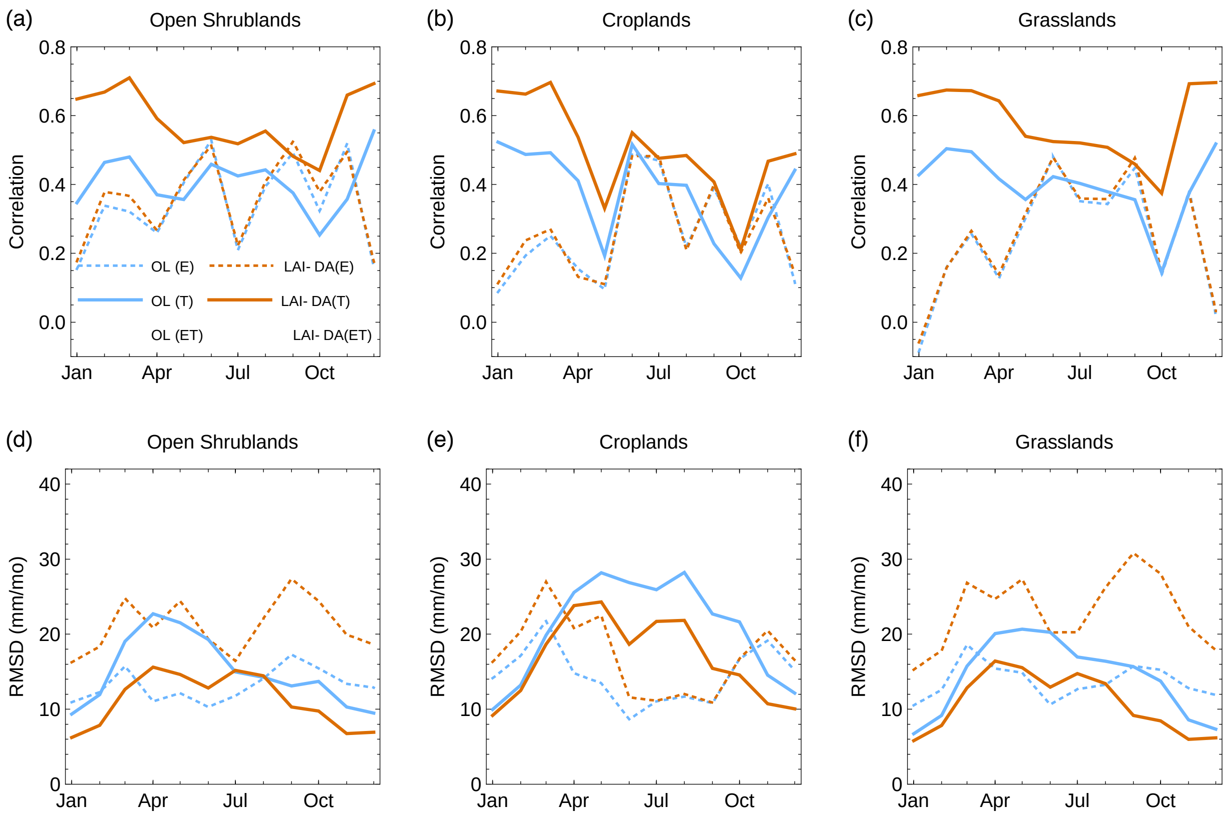
3. Figure 5) add the median to either y-axis label or the figure caption, so the readers know these are the median of the metrics shown for each month, as explained in L361.

**Response:** Caption of Figure 5 is modified as suggested.

4. Figure 5) I like to see the same plot for ET to see how the good and bad performance of LAI-DA in simulating T and E respectively cancel out each other on a monthly basis. Can you add this plot to the supplementary material?

**Response:** We thank the reviewer for the suggestion. The figure below includes the comparison for ET. In general, LAI-DA impact on the ET correlations are small while it leads to overall reduced RMSD especially during the growing seasons. We now update Figure 5 in the main text by including the ET correlation and RMSD and report the findings in Lines 372-373 as follows:

*"The different impact on E and T due to LAI assimilation results in overall small difference in terms of correlation while general improvements in terms of RMSD for ET."*



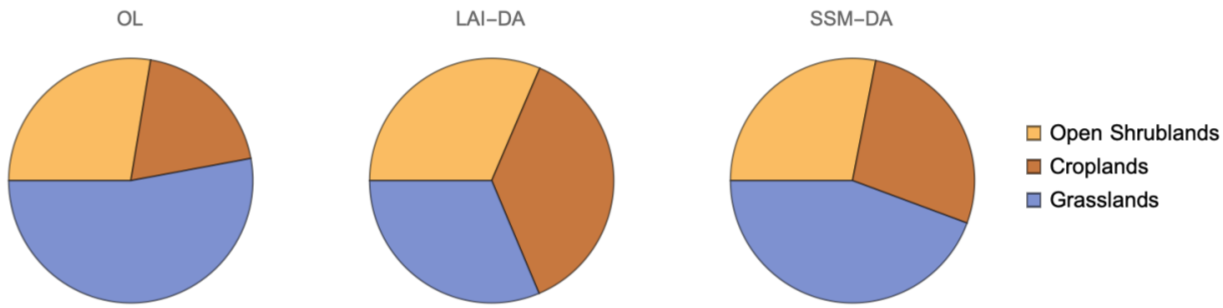

5. L364) Transpiration RMSD during the summertime and over cropland area is high. Can you explain why LAI-DA does not significantly improve the vegetation seasonality?

**Response:** We thank the reviewer for the comments. LAI-DA did improve the seasonality (Figure 3b) and interannual variability (Figure 5b) for transpiration. The high RMSD for croplands is more associated with the magnitude difference between Noah-MP and WaPOR, which may stem from different E/T partitioning algorithm between the two, different forcing inputs (Noah-MP driven by GDAS+IMERG vs. WaPOR driven by MERRA), and other associated uncertainties respectively.

6. L466) Based on figure 8, almost the same pattern is observed using OL run (stronger drought over cropland region and weaker over other landcover types), so I do not think this is an artifact of assimilating LAI.

**Response:** We agree that this pattern is not clearly shown in Figure 8. Here we provide the following figure showing the distribution of percentage area under >D3 drought during the 2018-2019 event for each land cover type. Here it can be seen that with LAI-

DA, the percent area under drought for croplands occupies a greater amount than in OL or SSM-DA.




7. L479) Based on Figure 9 it seems that the area under extreme drought (D3) is almost similar for both LAI-DA and SSM-DA over all the land cover types and the difference is limited to the exceptional drought category (D4).

**Response:** We thank the reviewer for pointing this out. We agree that this opposite tendency is more shown for D4 category, and we have revised the text accordingly in Lines 482-485 as follows:

*"More differences are seen in categorizing the moderate to extreme drought events (D1-D3) and there is no clear pattern associating with the differences. When it comes to the exceptional drought (D4), LAI-DA and SSM-DA show the opposite tendency as compared to OL for open shrublands and grasslands, in that LAI-DA tends to limit the spatial extent of the extreme and exceptional drought while SSM-DA is more likely to expand the impact of higher level of drought extremes."*

References:

Javadian, M.; Behrangi, A.; Gholizadeh, M.; Tajrishy, M. METRIC and WaPOR Estimates of Evapotranspiration over the Lake Urmia Basin: Comparative Analysis and Composite Assessment. Water 2019, 11, 1647. https://doi.org/10.3390/w11081647

E. Jalilvand, R. Abolafia-Rosenzweig, M. Tajrishy and N. N. Das, "Evaluation of SMAP/Sentinel 1 High-Resolution Soil Moisture Data to Detect Irrigation Over Agricultural Domain," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 14, pp. 10733-10747, 2021, doi: 10.1109/JSTARS.2021.3119228.

**References:**

Crow, W. T., C. A. Gomez, J. M. Sabater, T. Holmes, C. R. Hain, F. Lei, J. Dong, J. G. Alfieri, and M. C. Anderson (2020), Soil Moisture–Evapotranspiration Overcoupling and L-Band Brightness Temperature Assimilation: Sources and Forecast Implications, *Journal of Hydrometeorology*, *21*(10), 2359–2374, doi:10.1175/JHM-D-20-0088.1.

Felfelani, F., Y. Pokhrel, K. Guan, and D. M. Lawrence (2018), Utilizing SMAP soil moisture data to constrain irrigation in the Community Land Model, *Geophys. Res. Lett.*, *45*(23), 12–892–12–902.

Kumar, S. V., P. A. Dirmeyer, C. D. Peters-Lidard, R. Bindlish, and J. Bolten (2018), Information theoretic evaluation of satellite soil moisture retrievals, *Remote Sensing of Environment*, *204*, 392–400.

Kumar, S. V., T. R. Holmes, R. Bindlish, R. de Jeu, and C. Peters-Lidard (2020), Assimilation of vegetation optical depth retrievals from passive microwave radiometry, *Hydrology and Earth System Sciences Discussions*, *24*(7), 3431–3450.

Lawston, P. M., J. A. Santanello Jr, and S. V. Kumar (2017), Irrigation signals detected from SMAP soil moisture retrievals, *Geophys. Res. Lett.*, *44*(23), 11–860–11–867.