Referee 1

This study evaluates the impact of integrating satellite-derived land cover and vegetation characteristics into the HTESSEL land surface model. By incorporating inter-annually varying land cover, leaf area index, and effective vegetation cover parameterization, the model's representation of evaporation and soil moisture is significantly improved, particularly in regions with changing land cover and during dry seasons. It is an interesting study, making good use of the satellite products available - it is very thorough with a lot of figures and quantitative analysis. Nevertheless, I have a few comments that must be addressed before the manuscript can be published.

We would like to thank the referee for the comments. We appreciate the time and effort taken to read our manuscript in detail and to provide us the very useful and interesting thoughts on our research. We will take the comments into account when revising the manuscript.

We have separated the different comments (shown in *italic*) and have written our replies below. Text in the original manuscript is shown in '*italic*' and revised text in '***bold***'. Unless differently stated, line numbers mentioned in our reply refer to the original manuscript version.

Introduction

Comment 1.1

The introduction needs to be expanded. The authors mention that the LSMs do not adequately represent the variability of vegetation, but which models and what do they do instead? The authors also talk about how satellite data has been used to derive ancillary maps, improve parameterisation and evaluate models but don't really talk about how these data are used in data assimilation, which is similar to what is done here. There are a number of studies assimilating LAI (e.g., direct insertion, Kalman filter etc) as well as other satellite products to constrain phenology. I think the study not only benefit from an expanded literature review but also discussing the results in context of other studies. Few examples below:

Albergel, C., Calvet, J.-C., Mahfouf, J.-F., Rüdiger, C., Barbu, A. L., Lafont, S., et al. (2010). Monitoring of water and carbon fluxes using a land data assimilation system: A case study for southwestern France. Hydrol. Earth Syst. Sci. Discuss. 14, 1109–1124. doi:10.5194/hess-14-1109-2010

Kumar, S. V., Mocko, D. M., Wang, S., Peters-Lidard, C. D., & Borak, J. (2019). Assimilation of remotely sensed leaf area index into the Noah-MP land surface model: Impacts on water and carbon fluxes and states over the continental United States. Journal of Hydrometeorology, 20(7), 1359-1377.

MacBean, N., Maignan, F., Peylin, P., Bacour, C., Bréon, F.-M., and Ciais, P.: Using satellite data to improve the leaf phenology of a global terrestrial biosphere model, Biogeosciences, 12, 7185-7208, doi: 10.5194/bg-12-7185-2015

Rahman, A., Zhang, X., Houser, P., Sauer, T., & Maggioni, V. (2022). Global Assimilation of Remotely Sensed Leaf Area Index: The Impact of Updating More State Variables Within a Land Surface Model. Frontiers in Water, 3, 200.

Rahman, A., Zhang, X., Xue, Y., Houser, P., Sauer, T., Kumar, S., et al. (2020). A synthetic experiment to investigate the potential of assimilating LAI through direct insertion in a land surface model. J. Hydrol. X 9:100063. doi: 10.1016/j.hydroa.2020.100063

We expanded the introduction with (the suggested, and other) literature on data assimilation of vegetation properties in other land surface models than HTESSEL.

We modified line 31-36 as follows:

"To improve the representation of land surface-atmosphere dynamics, satellite remote sensing data based products have been widely used in LSMs. Global satellite derived maps of land cover and albedo have been directly used as boundary conditions (Faroux et al., 2013; Alessandri et al., 2017; Boussetta et al., 2021). In addition, Leaf Area Index (LAI) derived from satellite remote sensing has been assimilated in several LSMs for different spatial scales, generally leading to improved water, energy and carbon fluxes (Kumar et al., 2019; Ling et al., 2019; Rahman et al., 2020, 2022). Albergel et al. (2017, 2018) also combined LAI assimilation with the assimilation of remote sensing based surface soil moisture in the LSM called ISBA (Interactions between Soil, Biosphere and Atmosphere). This resulted in reduced errors of modeled soil moisture, evaporation, river discharges, and gross primary production with respect to observations. *Furthermore, satellite products have been used to improve model parameterizations of for example* ***leaf phenology****, surface roughness, soil characteristics, and subsurface water storage (Lo et al., 2010; Trigo et al., 2015;* ***MacBean et al., 2015****; Yang et al., 2016; Orth et al., 2017). Moreover, LSMs have been evaluated …"*

Additionally, we included a more detailed discussion of our results in relation to other studies in Sect. 4.1 L349:

"Recent studies also applied data assimilation methods to integrate satellite-based LAI in LSMs. For example, Rahman et al. (2022) found improved anomaly correlations of transpiration in many areas when integrating satellite based LAI in the LSM called Noah-MP (Noah Multi-Parameterization), with largest effects in the regions where E and SM_s anomaly correlations consistently improved in our results (Fig. 9). However, this study also found limited sensitivity of model surface and root zone soil moisture when only LAI assimilation was applied (Rahman et al., 2022). Similarly, Albergel et al. (2017) concluded that LAI assimilation only affected deeper SM. In contrast, our results showed considerable changes of near-surface soil moisture when integrating CGLS LAI, which can be explained by the interplay between LAI, effective vegetation cover, soil evaporation and near-surface soil moisture schematized in Fig. 17, which apparently differs from the interplay in Noah-MP (Rahman et al., 2020, 2022) and ISBA (Albergel et al., 2017)."

Additional references:

Albergel, C., Munier, S., Jennifer Leroux, D., Dewaele, H., Fairbairn, D., Lavinia Barbu, A., Gelati, E., Dorigo, W., Faroux, S., Meurey, C., Le Moigne, P., Decharme, B., Mahfouf, J. F., and Calvet, J. C.: Sequential assimilation of satellite-derived vegetation and soil moisture products using SURFEX-v8.0: LDAS-Monde assessment over the Euro-Mediterranean area, Geoscientific Model Development, 10, 3889–3912, https://doi.org/10.5194/gmd-10-3889-2017, 2017

Albergel, C., Munier, S., Bocher, A., Bonan, B., Zheng, Y., Draper, C., Leroux, D. J., and Calvet, J.-C.: LDAS-Monde Sequential Assimilation of Satellite Derived Observations Applied to the Contiguous US: An ERA-5 Driven Reanalysis of the Land Surface Variables, Remote Sensing, 10, https://doi.org/10.3390/rs10101627, 2018

Ling, X. L., Fu, C. B., Guo, W. D., and Yang, Z. L.: Assimilation of Remotely Sensed LAI Into CLM4CN Using DART, Journal of Advances in Modeling Earth Systems, 11, 2768–2786, https://doi.org/10.1029/2019MS001634, 2019

About ESA-CCI SM

Note that the ESA-CCI SM combined product uses the GLDAS-Noah model to rescale the different retrievals prior to merging. In theory, this preserves the dynamics and trends of the SSM retrievals but imposes on the combined product the absolute values and dynamic range of GLDAS-Noah (Lui et al., 2012). However, there are also some cases where the dynamics are also impacted (e.g., Raoult et al., 2022). As such, the authors need to be more mindful when discussing the product in the text:

Comment 1.2

L231: It is not just the difference in representative soil layers which is an issue, but the construction of the product itself. The merging process uses the climatology and soil depth (10cm) of the GLDAS-Noah model, changing the absolute values.

We integrated the information of this comment in L212 as follows:

"Model near-surface soil moisture (SM_S) (0-7 cm) was compared to the ***combined active-passive*** *ESA-CCI soil moisture product (ESA-CCI SM* ***v06.1****),* ***which is generated from satellite-based active and passive microwave products that are combined using the absolute values and dynamic range of the modeled soil moisture of the top 10 cm soil layer from the Global Land Data Assimilation System (GLDAS)-Noah LSM (Liu et al., 2012;*** *Dorigo et al., 2017; Gruber et al., 2019).*

and in L229-L231 as follows:

Model SM_S and reference ESA-CCI SM cannot be compared directly in absolute terms due to the different representative soil layers and ***the imposed dynamic range from the GLDAS-Noah model (Liu et al., 2012), and so potentially*** *resulting in different temporal variability (Sect. 2.5.2).*

Liu, Y. Y., Dorigo, W. A., Parinussa, R. M., de Jeu, R. A., Wagner, W., McCabe, M. F., ... & Van Dijk, A. I. J. M. (2012). Trend-preserving blending of passive and active microwave soil moisture retrievals. *Remote Sensing of Environment*, *123*, 280-297.

Comment 1.3

L414: This needs to be rephrased since it is not strictly true. Although the ESA CCI SM combined product is only made up of remote sensing retrievals, the fact that it does use a land-surface model means that the end product contains information inherited from GLDAS-Noah. Calling it the "most trustworthy" is quite strong. It is a very good global product but deserves more caveating. In fact, I think more text about its limitations is needed in this paragraph.

We included the additional information on the ESA-CCI SM generation using GLDAS-Noah model in L212 and L231 (see comment 1.2). Furthermore, we rephrased L411-L414 as follows:

"Evaluation of the modeled near-surface soil moisture was limited by missing data due to dense forests or snow cover, and the lack of information of the representative soil depth. ***While the ESA-CCI combined active/passive SM product was generated using the absolute values and the dynamic range of GLDAS-Noah soil moisture, preserving the dynamics and trends of the original retrievals (Liu et al., 2012), it is important to note that during drydowns the soil moisture dynamics can also be impacted to some extent, as highlighted by Raoult et al. (2022).*** *However, we still find the ESA-CCI SM* ***the best suited globally available reference data for our study,*** *because it is a direct product of remote sensing observations, without* ***directly blending land surface model dynamics*** *as done for DOLCEv3."*

About *k*

Comment 1.4

More discussion about k would be interesting. I realise the values are listed in Figure 10, but maybe a table of the different values for each vegetation in the supplementary materials could be referenced on L180.

To clarify the k-results, we included a table in the supplementary materials (Table S3) and a reference to this table in L277 and the caption of Fig. 10.

Comment 1.5

L276: Do these values of k make sense? Do we expect it to be lower for high vegetation than low vegetation? If is why?

Yes, the values make sense are in line with our expectations (Chen, 2021). The value of *k* represents the amount of vegetation clumping, indicating how much the leaf structure deviates from a random distribution. Low vegetation has more leaves side by side, and, therefore, a larger *k*. For high vegetation, leaves are found more on top of each other, and are, therefore, more clumped and have lower k (Chen, 2005).

We will add the following lines after L276:

"These findings are in line with our expectations, as leaf organization of low vegetation is more regular (larger k) than leaf organization of high vegetation, where leaves are found more on top of each other (smaller k) (Chen, 2005; Chen 2021)."

Chen, J. M., Menges, C. H., & Leblanc, S. G. (2005). Global mapping of foliage clumping index using multi-angular satellite data. Remote Sensing of Environment, 97(4), 447-457.

Chen, B., Lu, X., Wang, S., Chen, J. M., Liu, Y., Fang, H., ... & Wang, X. (2021). Evaluation of clumping effects on the estimation of global terrestrial evapotranspiration. Remote Sensing, 13(20), 4075.

General

Comment 1.6

Figures 2-4 and their discussion belong in the results selection. For example, Figure 4 is first introduced on L161 but with no supporting analysis. Maybe it could be moved to when it is discussed later in the text.

We agree that Figures 2-4 could have also fitted in the results section. However, we specifically aimed for a clear distinction between preliminary work (i.e., data preparation), and our main contributions (i.e., effective cover parameterization and model evaluation). Therefore, we strongly prefer to keep the structure of the method and results as it is.

To clarify the structure, we will add the following line in L161:

"Figure 4 shows the LAI inter-annual variability as integrated here in HTESSEL, quantified with the standard deviation. ***The effects of this added variability are presented in Sect. 3.2."***

Comment 1.7

L149: this is not shown anywhere, should Fig 2c be changed to show this? Maybe a stacked bar chart to show the different contributions of vegetation type replacing each vegetation?

Figure 2c visualizes these findings, with hatched bars showing low/high vegetation types replacing other low/high vegetation types. For example, crops and short grass have a relatively large hatched bar, compared to the other low vegetation types, indicating crops and short grass were often replacing other low vegetation types.

To clarify this case, we will rephrase L149 as follows:

“.. The figure shows that crops and short grass were relatively often replacing other low vegetation types (relatively large hatched bars), while evergreen needleleaf (EN) and deciduous broadleaf (DB) trees were relatively often replaced by other high vegetation types (relatively large plain bars).”

Moreover we will add which vegetation types are ‘low types’ and which are ‘high types’ in Figure 2c.

Comment 1.8

Figure 5 would benefit from an extra panel for DOLCEv3 E since it discussed in Section 3.1

A figure showing the differences of mean E in the experiments CTR and IALC with respect to DOLCEv3 E is now included in the supplement (Figure S1), with reference to this figure in the caption of Fig. 5 and Sect. 3.1 (L272 in the revised manuscript).

Minor

Comment 1.9 - *I would personally avoid using the word “observations” when referring to retrievals but acknowledge that “observations” is widely used.*

We agree with this comment. We re-read the text and we will change the terms ‘observations’ in the following lines:

L402: change observations to reference data.

L426: change observations to reference data.

L435: change observations to retrievals.

Title: change satellite observations to remote sensing data (see also comment 2.1).

Comment 1.10

The “jet” colour scheme is also no longer recommended for figures

We will change the colour schemes.

Comment 1.11 - *Section 2: add punctuation to the end of equations 10, 11*

We will change this.

Comment 1.12 - *Section 2.1: rename since doesn’t include evaluation sets which are still EO products*

We will change the name to ‘***Land cover and vegetation data***’.

Comment 1.13 - *L61 : add citations*

We will add citations.

Comment 1.14 - *L80: I believe Earth System Model could be capitalized*

We will change this according to the suggestion.

Comment 1.15 - *L100: I believe it should be 7-189*

We discovered a mistake in line 98 where ‘100’ should be ‘72’. The fourth layer has a depth of 189, but the total depth of the four layers is 289 cm (layer 1 + 2 + 3 = 100 cm). To avoid this confusion we will clarify this description in lines 98-100 as follows:

“The subsurface in HTESSEL consists of 4 soil layers ***with thicknesses of 7, 21, 72 and 189 cm****. In this study we differentiate between near-surface soil moisture (SM_s) in the top layer (0-7 cm), and the subsurface soil moisture (SM_{sb}) in the three deeper layers (7-289 cm).”*

Comment 1.16 - *L113: formatting issue*

We will change this.

Comment 1.17- *L212: please put the version number of ESA-CCI SM product used*

We will include the version number in the text (v06.1).

Comment 1.18 - *L215: remind the reader what the model resolution is*

We will change this.

Comment 1.19 - *L233: what models? Do you mean experiments?*

We meant experiments, so we will change this accordingly.

Comment 1.20 - *L435: not sure that “obviously” is very sciency*

Agree, we will remove the word ‘obviously’.