Referee #3

This paper presents results of VOD data assimilation in the Noah-MP land surface model and its impact on soil moisture GPP, ET and streamflow. VOD products from AMSR-2 at X-Band and C-band are used, and SMAP VOD is assimilated separately and jointly with SMAP soil moisture products. The topic is highly relevant for to land surface scientific community. The paper is very well written, results are clearly presented and validated against a large range of observation types, and the analysis of the results is very thorough. I suggest the paper to be published in HESS after the suggestions below are considered.

Thanks you for the supportive and helpful comments. Please see below for our responses and the details of the changes made to the manuscript.

Specific comments:

Abstract, lines 11-13: “The results also indicate that the independent information on moisture and vegetation states from SMAP can be simultaneously exploited through the joint assimilation of surface soil moisture and VOD.”: I don’t agree with “independent information” as moisture and vegetation states are from the same sensor. Also, this sentence repeats line 9 and do not provide additional information. I suggest removing this sentence.

Thanks you for the comment. The ‘independent’ qualifier mainly applies over locations where vegetation is thick, since soil moisture is excluded from assimilation over those regions (whereas VOD is not). In any case, based on your suggestion, we have removed the ‘independent’ qualifier in the text, to avoid any confusion.

Line 70: It would be worth mentioning the Copernicus CIMR candidate mission (http://www.cimr.eu/). It will include all these frequencies. Although its primary objectives are related to sea ice and SST, it will be very relevant for VOD.

Thank you for the suggestion. We have added CIMR to the list of mentioned missions on page 3.

Lines 96-97: “. NASA’s Soil Moisture Active Passive (SMAP; Entekhabi et al. (2010)) mission operates in a protected L-band, which minimizes the impact of RFI contamination.” You should specify “ over the US” because, unfortunately, L-band is much affected by RFI sources in many other regions.

We have added this additional clarification to the text on page 4.

Page 7 top paragraph (lines 194-205): As clearly explained in this section, X-band, C-band and L-band VODs are CDF matched to the GLASS LAI data so that they can be assimilated. However, it is not clear why GLASS LAI CDFs are computed (last sentence). Please clarify.

Thanks for the comment. The GLASS LAI CDFs are employed here based on the findings from the previous study assimilating GLASS LAI (Kumar et al., JHM 2019). The transformation of VOD into the LAI space, provides a quick way to enable the assimilation of VOD. To acknowledge this issue further, we have modified the description on page 7 as follows:

“Note that the rescaling strategy used here also relies on the fact that the systematic errors between the GLASS LAI data and the NoahMP LAI are small, as demonstrated in Kumar et al. (2019b). In this prior study when GLASS LAI retrievals were assimilated within NoahMP, the demonstrated improvements were primarily from the adjustment of vegetation/crop seasonality, rather than from the correction of systematic errors. In addition, the positive impacts from the use of this strategy shown in the following sections, further confirm that this rescaling approach is reasonable.”

Page 7: Is there any quality control applied to the VOD data set before assimilation?

Yes, a number of QC flags are applied to the VOD data. Retrievals are excluded near water bodies, for being at the edge of the swath and when soil is frozen/covered by snow. The description in the text on pages 8 and 9 has been modified to say :

“Similar to the strategy used in prior studies, soil moisture retrievals are excluded near water bodies, for being at the edge of the swath, when soil is frozen/covered by snow, and when the vegetation cover is thick (Kumar et al. (2019a)), to account for the known limitations of passive microwave-based soil moisture retrievals. Similar flags except for thick vegetation are also applied to screen out VOD retrievals.”

Page 8, lines 261-262: are SMAP VOD and soil moisture correlated observation errors accounted? The authors should clarify, and comment and justify the choice made in this study.

When SMAP VOD and soil moisture estimates are assimilated jointly, we simply combine two separate sequential assimilation instances (the observation vector does not consist of both VOD and soil moisture, and therefore the explicit consideration of the covariances is not needed). In addition, the state vector used in these sequential assimilation instances are different. The soil moisture assimilation employs model soil moisture states whereas LAI is updated in the VOD assimilation instances. The manuscript has been updated with the following clarification on page 17:

“As the results in the previous section indicate that assimilation of soil moisture and VOD can provide mutually exclusive information, an assimilation configuration that employs these retrievals simultaneously is developed. Note that in this joint configuration, rather than augmenting the observation vector to encompass both VOD and soil moisture retrievals, we simply combine the two separate sequential univariate assimilation instances within a single integration. Similar to the univariate configurations, in this multivariate configuration, soil moisture retrievals are used to update the surface soil moisture state, whereas VOD retrievals are used to update the prognostic LAI variable within the LSM."

Page 10, lines 333-334: I find it confusing to give domain improvements in RMSE (in addition to R) for the comparison against ALEXI in these two sentences. The figures only present R statistics against ALEXI as explained on the previous page.

The percentage improvements in RMSE are given in the text to allow the comparisons presented in Table 1 (since the LAI-DA results in Kumar et al. 2019 were only provided for RMSE).

Page 11, line 340: "The impact of VOD assimilation on other land surface states such as soil moisture, terrestrial water storage, and streamflow is also evaluated using a number of reference products." Soil moisture and TWS validation results for the OL and the VOD DA experiments are discussed but results of streamflow validation are not given in this sub-section. There are streamflow validation results in the next subsection but not comparing VOD DA with the OL. So, it would be interesting in section 3.1 to give streamflow validation results for C-band and X-band VOD DA compared to the open-loop.

Thank you for pointing out this omission. We have updated Section 3.1 with the following additional paragraph.

"The impact of VOD assimilation on streamflow is evaluated by comparing to the U.S. Geological Survey (USGS) daily gauge measurements at locations minimally impacted by reservoir operations (Kumar et al. (2014, 2019b)). The impact of DA is quantified using the Normalized Information Contribution (NIC) metric on Nash Sutcliffe Efficiency (NSE) of streamflow (Kumar et al. (2014)), with positive and negative NIC values indicating benefit and degradation from assimilation, respectively. Overall, there is a small, but beneficial impact from VOD assimilation on streamflow. The domain averaged NIC improvements from X-band and C-band VOD DA is 0.03 and 0.02, respectively, with larger improvements noticed over the agricultural areas of the Midwest U.S."

Pages 11, lines 371-371 and Table 1: LAI DA has no impact on soil moisture. In this paragraph, the authors should comment on why.

Thank you for pointing this out. Upon examining the % changes from the Kumar et al. (2019) LAI-DA study, we discovered that the 0% improvements reported for soil moisture were incorrect. The table has now been updated with the correct values, which report 0.6% and 2.3% improvements in surface and root zone soil moisture from LAI-DA.

Page 14, lines 453-455, Figure 8: the authors claim that the figure shows an overall improvement of soil moisture in the Western US. However, the figure shows a patchy impact in the Western US, with dominating blueish colours, which are related to degradation. It is perhaps an artefact of the figure which need to be made clearer.

The reviewer is correct that there is some patchiness (with degradations mixed in) in the western U.S. of Figure 8. However, the average changes in anomaly R west of 100W shows that the DA has a slightly more positive impact. For example, the domain averaged percentage improvements in surface and root zone from soil moisture DA over the western domain are 2.50% and 1.45%, respectively (compared to 2.14% and 1.30% for the whole domain). Similarly, for the assimilation of VOD, the domain averaged percentage improvements in surface and root zone soil moisture for the western domain are 0.28% and 0.7% (compared to 0.31% and 0.5%). Given that these domain improvements are small, we have changed the description on page 15 to acknowledge these facts, as:

"Figures 8 to 10 show the impacts of separately assimilating SMAP soil moisture and VOD retrievals on various land surface water and carbon states. Using the in-situ soil moisture measurements from ISMN as the reference, Figure 8 shows the changes in anomaly R of surface and root zone soil moisture from soil moisture and VOD assimilation. Overall, soil moisture DA has a positive impact on the simulation of surface soil moisture, particularly in the Western U.S. and Highplains. Approximately 2.1% improvement in domain averaged anomaly R is obtained from SMAP soil moisture assimilation. The impact of soil moisture DA over the Eastern U.S. is small, as these regions of high vegetation density are generally excluded from soil moisture DA. Comparatively, VOD assimilation has little impact on surface soil moisture, as the changes in anomaly R are not statistically significant in most locations. Both soil moisture and VOD assimilation also impact root zone soil moisture estimates, with varying levels of improvements and degradations across the domain. The assimilation of SMAP soil moisture improves the root zone estimates over the lower Mississippi and parts of the Western U.S. including California, Nevada, and Colorado. The patterns of improvements and degradations in root zone soil moisture are more mixed in the VOD assimilation results, over these same areas."

Page 14, line 450 indicates that Figures 8 to 10 show results of SMOS soil moisture and VOD DA. It should be clarified that they show results in the univariate configurations. Also, the caption of Figure 9 has typos (see technical corrections).

Thanks for the comment. We have modified the line on page 15 to say : "Figures 8 to 10 show the impacts of separately assimilating SMAP soil moisture and VOD retrievals on various land surface water and carbon states."

The caption of Figure 9 has been updated as well.

Page 15, line 510-515, and abstract line 11: the results presented in this paper clearly support the conclusion that soil moisture assimilation has more impact over water-limited areas. They also show that VOD assimilation has more impact in the eastern US and time series at location D shown in Figure 11 illustrate the impact very well. However, it is not convincing to conclude that VOD has an impact in energy-limited areas as patterns shown in eastern US and point D are not particularly energy limited, with point D is at latitude ~33 degrees North. The way it is formulated in the general conclusion line 597-599 is more correct (beneficial in areas with high vegetation and no water limitation). So, the abstract and the discussion page 15 should be updated accordingly.

Thank you for the comment and we agree. The following changes are made to the manuscript:

Abstract now reads:

"The utility of soil moisture assimilation for improving ET is more significant over water-limited regions, whereas VOD DA is more impactful over areas where soil moisture is not the primary controlling factor on ET."

The corresponding discussion in the text on page 16 has been modified to say:

"Over areas with high vegetation and little water limitation, vegetation growth and stomatal control, more than surface moisture conditions, influence the ET evolution."

Technical corrections
Line 110: 'independent reference datasets' is too vague. Please clarify.

We have modified the text on page 4 to say:

"These questions are addressed by examining the impact of assimilation with the use of a large suite of independent reference datasets of soil moisture, evapotranspiration, gross primary productivity (GPP), streamflow and terrestrial water storage (TWS)."

Line 327: (Reichle and Koster (2004))

Corrected

Line 328: over bare soil and urban areas

Corrected
Line 332: "4.6 % and 6.8 %"

Corrected
Figure 9 caption: 'of and VOD' -> 'of SMAP soil moisture and VOD'

Corrected