Referee #2

Several studies have indicated the great potential of VOD for characterising land surface dynamics. To my knowledge, this study is the first one to report on a large-scale assimilation of VOD retrieved from various satellite sensors into a land surface model with dynamic vegetation. Therefore, I recommend publishing it after addressing several concerns and clarifications.

Thank you for the constructive comments. We have made significant changes to the manuscript to address your concerns. Please see below for our specific responses.

My major issues:

The study refers to VOD as an estimate of above-ground biomass, which it is not. Although relationships between the two quantities exist, which depend also on the microwave frequency, it is not the same thing -> Rephrase throughout the manuscript.

We have corrected these references to say that VOD is an ‘analog’ of above-ground biomass, instead of an ‘estimate’ of biomass.

To my knowledge, VOD (tau) retrievals from SMAP L2 are not independent of optical observations but a function of (MODIS) NDVI. Thus, it is not allowed to correlate VOD with (MODIS) LAI or assess its assimilation against that of assimilating LAI. In principle, an indicator of vegetation productivity is assimilated.

The SMAP L2 VOD observations are, in fact, independent of optical (MODIS) NDVI/LAI observations. We have explicitly stated with appropriate references in section 2.1 as:

“The SMAP satellite launched in January 2015 is a mission dedicated to measuring soil moisture and freeze/thaw states, employing a passive microwave radiometer to collect measurements of vertical and horizontal polarizations of L-band brightness temperature data at an incident angle of 40°. The retrievals from SMAP are also developed using the τ-ω model. The soil moisture retrievals are made using a single channel algorithm using the vertical polarizations (Chan et al. (2018)) whereas the VOD retrievals employ both polarized brightness temperature observations (Chaubell et al. (2020)). Though the sampling resolution of the SMAP radiometer is approximately 36 km, 150 oversampling of the antenna overpasses is used to enhance the spatial resolution to 9 km. This 9km, level 2 SMAP dataset (SPL2SMP−E) is used in this study. “

The impact of the retrieval algorithm on the results is unclear. For a robust comparison of the performance of the different frequencies, I strongly recommend using the same retrieval algorithm for all frequencies.

We agree that the study is not structured to compare and contrast the retrieval algorithm performance, as we simply use the available products. Developing VOD retrieval products with the same algorithm and comparing them within a data assimilation framework is beyond the scope of this study. We have added the following caveat to acknowledge this limitation in the Summary section (pages 18 and 19).

“The study is conducted in the NLDAS-2 configuration over the Continental U.S. A suite of publicly available VOD retrievals from X-, C- and L-band instruments is assimilated in Noah-MP using a 1d ensemble Kalman filter algorithm. The X-and C-and retrievals from the Land Parameter Retrieval Model, whereas the L-band retrievals of VOD are from SMAP.”

“It must be stressed that as the retrieval algorithms used to develop these VOD products are different, this particular study is not structured to assess the relative merits of each algorithm.”

It is unclear which VOD data are exactly assimilated. VODCA provides merged C-, X, and Ku-band products based on multiple sensors. Apart from the AMSR sensors mentioned, VODCA C- and X-band products alo use TRMM TMI and Windsat observations.

The reviewer is correct that VOCA also uses data from WindSat, TMI, and GMI. We have updated the text as follows:

The text on pages 3 and 4 reads:

“As described in detail in Konings et al. (2017), a number of approaches have been used to retrieve VOD from microwave sensors. Here we employ VOD retrievals primarily from two approaches for data assimilation. The Land Parameter Retrieval Model (LPRM; Owe et al. (2008)) uses single frequency, polarized brightness temperature in the range of 1-20 GHz to retrieve both soil moisture and VOD. In this study, we use the C-band (6.9 GHz) and X-band (10.7 GHz) based VOD retrievals from LPRM. The C- and X-band measurements are less sensitive to cloud water content and more sensitive to soil moisture and vegetation canopy, which are also prone to Radio Frequency Interference (RFI). NASA’s SMAP mission operates in a protected L-band over the U.S., which minimizes the impact of RFI contamination. The sensitivity of L-band to cloud water content is lower compared to C- and X-band. In addition, the L-band measurements provide more sensitivity to deeper soil moisture and canopy layers.”

Pages 3 and 4 include the following description:

“In this study, we employ the VOD retrievals from LPRM version 6 (Van der Schalie et al. (2018)), available from the VOD climate archive (VODCA; Moesinger et al. (2019)). VODCA provides products from multiple sensors, including the Advanced Microwave Scanning Radiometer - Earth observing system (AMSR-E) aboard NASA’s Aqua satellite, the AMSR2 instrument onboard the Global Change Observation Mission-Water (GCOM-W), WindSat microwave radiometer aboard the joint DoD/Navy Coriolis platform, the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) and the Global Precipitation Measurement (GPM) Microwave Imager (GMI). The C-band VOD retrievals rely on AMSR-E, AMSR2, and WindSat, whereas the X-band VOD retrievals include data from AMSR-E, AMSR2, WindSat, TMI, and GMI."

Line 397ff: it is surprising that the assimilation of L-band VOD gives results similar to those of X-band VOD, particularly because, as mentioned earlier, L-band is less sensitive to vegetation. Is this because you are assimilating NDVI rather than VOD (see my comment above)? Also provide quantitative results in addition to pattern descriptions.

As noted in the manuscript, the X-band and L-band evaluation results are presented for different time periods (X-band integrations cover a time period of 2000-2018 whereas L-band runs are only for 2015-2019). Since evaluation time periods also differ for X- and L-band VOD runs, the results for X- and L-band are not directly comparable. As noted in our earlier response, the assimilation of NDVI is not a factor in the SMAP VOD retrievals.

Section 3.5: soil moisture and VOD are both derived from SMAP, which makes them strongly dependent. Do your assimilation operator account for these covariances? I recommend using soil moisture from SMAP and VOD from one of the other frequencies instead. In addition, for comaprability, can you show difference maps of the univariate and multivariate assimilation?

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. We also consider obtaining fresh retrievals from select frequencies to be outside the scope of this paper.

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."

Some smaller issues:

line 8, line 21: do you really mean vegetation indices (i.e. spectral band ratio like NDVI) or vegetation variables (e.g LAI, GPP, biomass etc.)?

‘Vegetation indices’ is used to mean both estimates such as NDVI, LAI, GPP, and biomass.

correct water limited -> water-limited, energy limited -> energy-limited, etc. when used as adjective.

Thanks for the suggestion. All such instances have been corrected in the manuscript.

line 31; for vegetation monitoring 70-100 ,m resolution is not considered high-resolution

‘high resolution’ has been changed to ‘fine resolution’

line 37: Although the benefits of passive MW are clearly acknowledged, it is also has disadvantages in terms of temporal resolution. -> add to manuscript

line 62: why do passive MW observations provide the opportunity to extend the spatial and temporal coverage when solar-reflective observations have been available globally for almost 50 years?

In the above two comments, we assume that the reviewer is referring to the diurnal coverage afforded by GEO-based optical/IR measurements in cloud free days. The following changes are made to the manuscript.

“Gap-filling strategies, such as using the nearest clear-day observation, are often used to improve the cloud- related gaps in spatio-temporal coverage from optical/TIR instruments (Hall et al. (2010)).”

“As the use of all-weather VOD measurements from microwave sensors provides the opportunity to extend the spatial and temporal coverage of vegetation observations into overcast and clouded conditions, here we examine the influence of assimilating VOD retrievals from microwave radiometry.”

line 70: guranteed (typo)

Corrected.

The work of Teubner et al., 2018, 2019 [1,2] should be acknowledged wrt the relationship VOD-GPP.

Thank you for suggesting these relevant references. They have been included in the discussion about prior studies examining VOD as an analog for vegetation conditions on page 2.

Line 143: reference to the SMAP mission and the product used in this study shall be given.

The reference to the SMAP mission (Entekhabi et al. 2010) is provided earlier in the text, at the first mention.

Line 210: reference to Vreugdenhil et al. [3,4], who developed the ASCAT VOD product shall be provided

Thanks for the reference. It has been included in the manuscript on page 8.

Line 223: This is not surprising as the 6.9 GHz C-band channel in the eastern US is strongly affected by RFI, whereas with SMAP you indirectly assimilate MODIS NDVI.

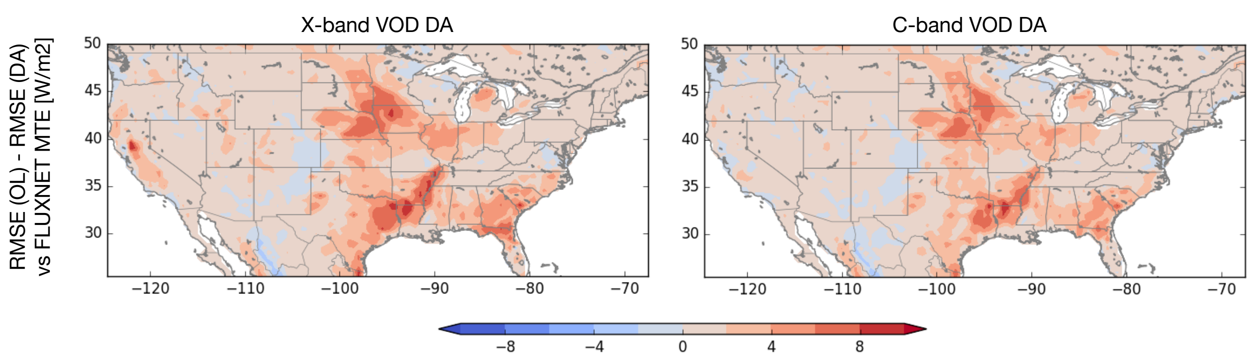
The SMAP VOD retrievals are not dependent on MODIS NDVI. The VOD retrievals are based on using both polarizations (V and H pol) to estimate soil moisture and VOD.

Line 228: Why does the rescaling not work in the southwestern US?

The correlation between LAI and VOD is weaker in the southwest US because the vegetation is sparse (Figure 1). As noted in the text the correlations are strong in areas with high vegetation density. The assimilation results also show a near neutral impact over the southwest from VOD assimilation.

Line 278: I recommend using the more recent FLUXCOM product (Tramontana, 2016)

Thank you for the suggestion. We computed the impact of X-band and C-band VOD DA using the FLUXCOM energy fluxes from 2001-2015. The improvements in RMSE from this comparison is shown below (X-band DA on the left, C-band DA on the right). The results are qualitatively similar to the FLUXNET MTE comparison shown in the paper. Given that the paper discusses comparisons to the optical sensor based LAI-DA results (which are already published with FLUXNET MTE data) and because the conclusions about the impact of DA remain unchanged, we have not included this updated comparison in the manuscript.



Line 319: In terms of radiative transfer mechanisms this is a very strong generalisation. Can you provide the statistics for each category separately?

The actual vegetation type used in the model simulations include 13 categories (Figure 1). As noted in the text, grouped categorization is used here for simplicity. The statistics for each category is provided in Figure 5.

Line 329: phrased a bit unclear -> rephrase

This statement on page 11 has been modified to:

"Over bare soil and urban areas, the impact of VOD assimilation is very small, due to the lack of vegetation influence on ET and GPP."

Line 340: In the terms and conditions of the ISMN (https://ismn.geo.tuwien.ac.at/en/terms-and-conditions/) it is stated that reference (incl. citations) shall be given to all networks used -> please add

Thanks for pointing out this detail. On page 11, we have updated the references to include additional as suggested on the 'terms and conditions' page (Note that the link to the "Networks" is not working at the moment, we included all the references that are available in the Readme.txt that comes with the data).

Line 342: which depths were used?

We used data up to 1 m of the root zone. This has been clarified in the text on page 11 as:

"The surface and root zone soil moisture values are defined as the soil moisture content of the top 10 cm and 1 meter of the soil column, respectively. These are computed from the layer soil moisture values as suitably weighted vertical averages based on the thickness of the soil layers."

Lines 348-363: Since these results are not shown, I suggest moving these analyses to a supplement

Though additional figures are not included to describe these results, we think it is important to include them in the main manuscript, partly because the following sections (that contrast soil moisture and VOD DA) do include more detailed evaluations of these variables.

Line 385: Most LAI products are also derived from LEO orbits

We have rephrased the description on page 13 as:

“Note that the spatial resolution of passive microwave retrievals is typically coarser than those from the optical/IR sensors. In addition, passive microwave measurements are only available from low earth orbits (LEO) due to the antenna size requirements, so they can't provide the diurnal view as available for optical/IR instruments from geostationary satellites.”

Line 421: Isn’t this more a bias correction?

As noted in the text, the corrections are more to the phase of the vegetation seasonality from assimilation. Note that in the non-peak months, the changes to LAI from DA is small, which suggests that the main impact of assimilation is not a systematic bias correction. Yes, there are bias changes in the peak vegetation months, but those are important for fixing the seasonality, demonstrated in the evaluation of ET, GPP and other variables.

[1] Teubner, I.E., Forkel, M., Jung, M., Liu, Y.Y., Miralles, D.G., Parinussa, R., van der Schalie, R., Vreugdenhil, M., Schwalm, C.R., Tramontana, G., Camps-Valls, G., Dorigo, W., 2018. Assessing the relationship between microwave vegetation optical depth and gross primary production. International Journal of Applied Earth Observa- tion and Geoinformation 65, 79–91. https://doi.org/10.1016/j.jag.2017.10.006

[2] Teubner, I.E., Forkel, M., Camps-Valls, G., Jung, M., Miralles, D.G., Tra- montana, G., van der Schalie, R., Vreugdenhil, M., Mösinger, L., Dorigo, W.A., 2019. A carbon sink-driven approach to estimate gross primary production from microwave satellite observations. Remote Sensing of Environment 229, 100–113. https://doi.org/10.1016/j.rse.2019.04.022

[3] Vreugdenhil, M., Dorigo, W., Wagner, W., de Jeu, R., Hahn, S., van Marle, M., 2016. Analysing the vegetation parameterisation in the TU-Wien ASCAT Soil Moisture Retrieval. IEEE Transactions on Geoscience and Remote Sensing 54 (6), 3513-3531. doi: 10.1109/TGRS.2016.2519842

[4] Vreugdenhil, M., Hahn, S., Melzer, T., Bauer-Marschallinger, B., Reimer, C., Dorigo, W., Wagner, W., 2017. Characteristing vegetation dynamics over Australia with ASCAT. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 10 (5), 2240-2248, doi: 10.1109/JSTARS.2016.2618838