Response to comments by Dr. David Chaparro

Dear Dr. David Chaparro,

We sincerely thank you for your quality review of our manuscript. Your constructive comments and suggestions are very useful to improve the quality of the paper. Please find below our point-to-point responses to your comments as well as the corresponding changes in the manuscript.

Sincerely,

Hong Zhao, Yijian Zeng, Jan G. Hofste, Ting Duan, Jun Wen, Zhongbo Su

Referee comments are written in normal font; author's responses are written in blue font; and proposed changes are highlighted in green font.

Review of "Modelling of Multi-Frequency Microwave Backscatter and Emission of Land Surface by a Community Land Active Passive Microwave Radiative Transfer Modelling Platform (CLAP), by Zhao et al.

Reviewer: David Chaparro

This paper presents a multifrequency active-passive transfer modelling, named CLAP, for simulating backscatter and emission signals of a vegetated (herbaceous) surface in the Maqu area in Tibet. Results are compared with ground-based radiometer and scatterometer measurements, and with AMSR2 data. The authors explore how simulations using different frequencies (L-, S-, C- and X-bands), vegetation configurations (cylinders vs. discs), seasons (winter vs. summer) and soil moisture sources (in situ vs modelled) track radiometer and scatterometer observations. With this, they aim at enhancing our understanding of vegetation, soil, and temperature impacts on daily variations in emission and backscatter.

The paper is well written and encompasses a wide range of characteristics influencing model outputs, thus being complete research. The work improves previous papers estimating microwave emissions by including the backscatter component in the outputs. Overall, it is research with good potential, but I have relevant major concerns that must be thoroughly addressed through the manuscript, especially regarding that: (i) the metrics used in the results should be extended,

Response: Thanks a lot. The metrics including the correlation coefficient R and unbiased root mean square ubRMSE have been added in Tables 3, 4, 5, 6 and 7 and Tables S2 and S3 in the supplementary materials. As the model parameter calibration is not our main concern in this manuscript, you may notice that the obtained statistics shown in Tables 3, 4, 5, 6 and 7 and Tables S2 and S3 are worsened than those shown in the previous studies (Dente et al., 2014; Zheng et al., 2021). While the similar poor statistic value (e.g., 3.91 dB) is also reported by Vermunt et al. (2021), which used the coupled IME-TVG with the support of ground-based L-band radar backscatter measured for corn in Florida. We expect to do the model parameter optimization using for instance a simple data assimilation framework, but this is currently beyond the scope of this manuscript. We added section 4.4 to discuss the 'Limitations in this study' in the revised manuscript.

(ii) it is needed an extended discussion based on literature previously mentioned by the authors in the introduction,

Response: Thank you. As described in Introduction, the previous studies, for instance, Dente et al. (2014) and Zheng et al. (2021) used the coupled IEM with TVG models (IEM-TVG) and focused on calibrating model parameters based on either in situ or satellite observations. Using calibrated parameters, the calculated statistics shown in their studies are good enough for forward signal modelling and SM retrieval.

However, our focus in this study is to go through CLAP, namely the coupled ATS-AIEM-TVG model with a more physically-based consideration than the coupled IEM-TVG. As described in Introduction, the dielectric roughness parameterized in the ATS model is related to wavelength information and the surface status modulated by hydrometeorological conditions (Equations 4,5,6 in (Zhao et al., 2021)). Additionally, it is known that the employed AIEM in this study uses a more complete expression of the single scattering terms than IEM does to keep the acceptable energy conservation for calculating bistatic scattering and further emission.

Specifically, we focused on using CLAP—a uniform active and passive multi-frequency observation operator, to investigate all factors and possible physical processes that influence the dynamics of the observed multi-frequency microwave signals. In particular, we investigated the impacts of different soil moisture and temperature profiles, vegetation structure and dynamics of vegetation water and temperature on the signal simulation, as you saw in the manuscript, which was not investigated in the previous studies (Dente et al., 2014; Zheng et al., 2021).

Accordingly, we did revisions in the introduction:

Lines 120-129: "It models dynamic dielectric roughness related to surface status modulated by hydrometeorological conditions, additionally, the modelled dielectric roughness scales with wavelength with maintaining physical consistency (Zhao et al., 2021). The ATS model integrated with the AIEM was further coupled with the TVG model for simultaneously modelling L-band scattering and emission of the overall vegetation-soil medium, and the simulated signals were closer to the observations and exhibit more dynamics than those simulated by the model without considering the ATS model (Zhao et al., 2021). As such, the coupled ATS-AIEM-TVG model has a more physically-based consideration with the improved ability in modelling signal dynamics than the fundamental IEM-TVG model."

Lines 143-147: "Despite the above advancement, it is noted that the previous studies (Dente et al., 2014; Zheng et al., 2021) assumed the grass leaf to be parameterized with a disc shape and be calibrated with the constant VWC. The role vegetation (e.g., its different shapes and diurnal changes in water content and temperature) plays in mechanistic microwave scattering and emission processes reflected in these (in situ) microwave observations has not been explored yet."

Lines 166-169: "However, the variation in dielectric properties of both the soil and vegetation due to the temperature effect, and how the signal diurnal variation (affected by these factors) differs in terms of frequencies and surface conditions are not fully investigated in the previous studies (Dente et al., 2014; Zheng et al., 2021)".

(iii) the paper needs putting the results obtained in the context of the current and future missions and retrievals (e.g., which could be the impact of the reported RMSE and Biases in SM retrievals?). The third point is especially important, as the authors emphasize the applicability of the model stating that it can mimic observations and that it could be applied to global scales. None of these are fully justified if the reader cannot understand how CLAP could be applied: how can it be transferred to global scale? Which could be the impact of model errors if it was to be applied in moisture estimates?

Response: Thank you. We focused on understanding the impacts of vegetation water content and temperature and soil moisture and temperature profiles on forward simulations of dynamics in emission and backscatter. We presented in this manuscript what we achieved and pointed out the direction in which we should put efforts in the next step. We have not stepped into the retrieval (of SM or vegetation parameter). Based on the investigation results shown in this manuscript, the mismatch still exists between the dynamics of modelled signals and the observations, especially during the soil freeze-thaw processes. This may indicate that some fundamentals, for instance, the abrupt phase change of topsoil water during the winter period that leads to big differences in dielectric property values and the resulting signal dynamics as reported by Lv et al. (2022) are not expressed with explicit physical formulations in CLAP. In future work, we will consider this and improve the current ATS setup with THE two-layer model considering soil conditions both in the surface layer and penetration layer. Moreover, the differences of the normalized τ at multi-frequency exist in this case and the physical reason needs to be investigated. As such, we still need to make clear what is observed at multi-frequency and how to use it in a consistent way. These are directions for future efforts but beyond scope of this study.

Regarding applying CLAP on a large scale up to a global scale, we have ideas and are working on it. However, we agree with you that saying CLAP applied on the global scale is too advanced in this paper, and this manuscript is long enough. We delete the phase involving the ‘global’ word in the relevant sentence to eliminate such meaning.

We added section 4.4 to discuss the ‘Limitations in this study’. We went through the Results and Conclusions and did corresponding revisions.

“Section 4.4

As investigation results shown in section 3, by considering dynamics (i.e., diurnal cycles) of vegetation water content and temperature as well as soil moisture and temperature, the dynamics of the ground-based observed microwave signals are interpreted and modelled to some extent. However, there are limitations in this study that lead to mismatches between modelled signals and the observations as shown in some results with less good performance metric values. Because there are no continuous measurements of VWC in this study, a sinusoidal function is assumed to estimate daily VWC. The assumed phase shift (ϕ in Equation (1)) influences the phase characteristic of the modelled signals. In situ vegetation temperature data is also not available, and the value of vegetation temperature is assumed to be the same as that of air temperature. While it is known that vegetation temperature and air temperature are not equal, because vegetation cools off through evaporation and warms up through irradiance. The value of vegetation temperature should be in between that of air temperature and surface temperature, and it is noted that the phase shift exists between air temperature and surface temperature (see Fig. 2b and Fig. 7b). Thus, the vegetation temperature surrogate in this study also accounts for mismatches (in both magnitude and phase) between modelled signals and the observations especially at higher frequencies. Additionally, the investigation results show that the vegetation orientation influences the variation of cross-polarization signals at high frequencies (see section 4.1), while the grass morphology during the growth period is not considered in this study.

Regarding the soil part, the investigation results shown in section 3.3 (e.g., Figure 12b (i.e., σ_{VV}^{0} at C-band estimated based on in situ SM at 2.5 cm and SM at 1 mm simulated by STEMMUS process model) indicate the necessity of considering the topsoil moisture information in modelling dynamics of the observed signals, and the accuracy of topsoil moisture information influences the adequate simulation of signal dynamics. While the deviation exists between the process modelled soil moisture and in situ measurement (see Figures S1 and S2), accurate topsoil moisture information is still difficult to obtain (either by a process model or in situ measurement). Moreover, as discussed in section 4.2, the explicit physical formulations that can parameterize the abrupt change in dielectric properties due to the soil-water-ice phase change are not yet considered. Furthermore, surface roughness is another important factor influencing soil scattering and emission. The used values of the surface roughness parameter during the summer period in this study are calibrated values based on satellite observations. On the other hand, surface roughness during the winter period may exhibit slight changes due to the soil freeze-thaw processes, such as frozen soil water causing volume expansion and melted surface water smoothing the surface. These kinds of effects that influence the observed signal dynamics are also not considered in this study.

As the model parameter calibration is not our main concern in this paper, the obtained statistics (see Tables 3, 4, 5, 6 and 7 and Tables S2 and S3) are less satisfactory than those shown in the previous studies (Dente et al., 2014; Zheng et al., 2021). The similar poor performance of IEM-TVG simulation results (e.g., RMSE of 3.91 dB) is also reported by Vermunt et al. (2021), when compared with the ground-based L-band radar backscatter measured for corn in Florida. The model parameter optimization using for instance a simple data assimilation framework, is expected to help improve performance."

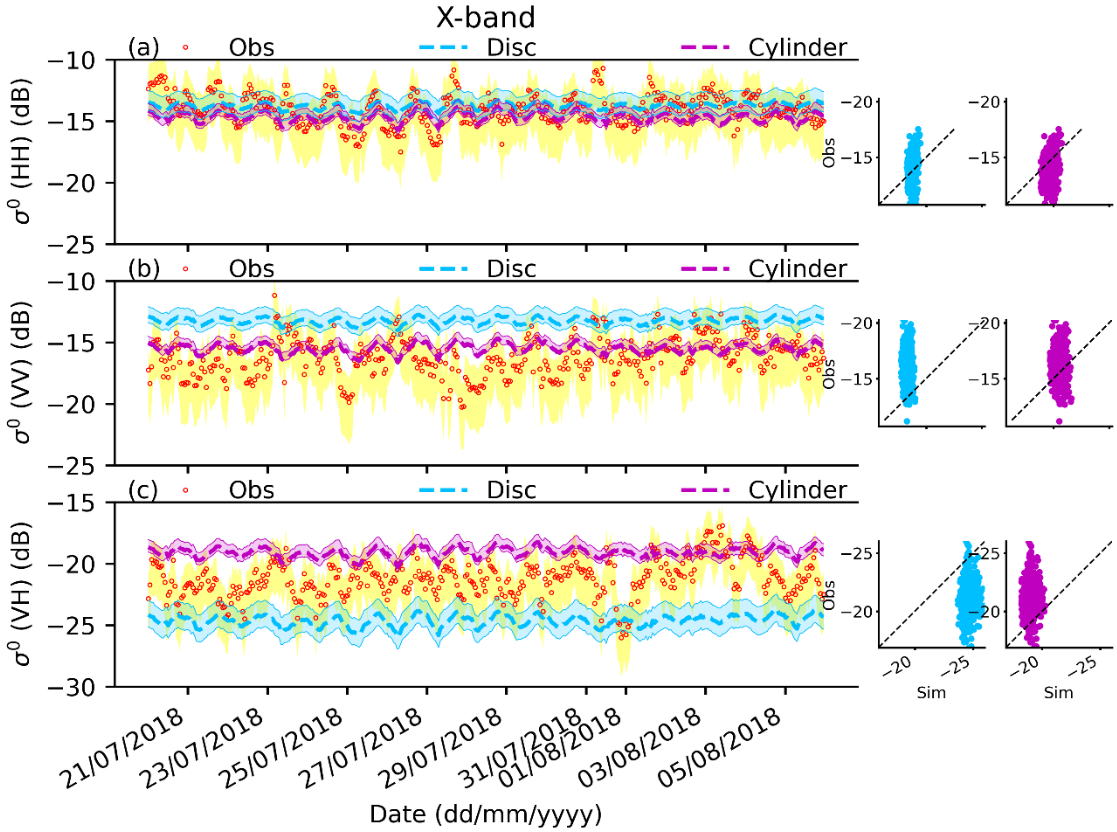
Lines 716-717: "Nevertheless, using microwave signals to probe leaf water potential can help understand plant water use regulation and the associated drought vulnerability at a regional scale."

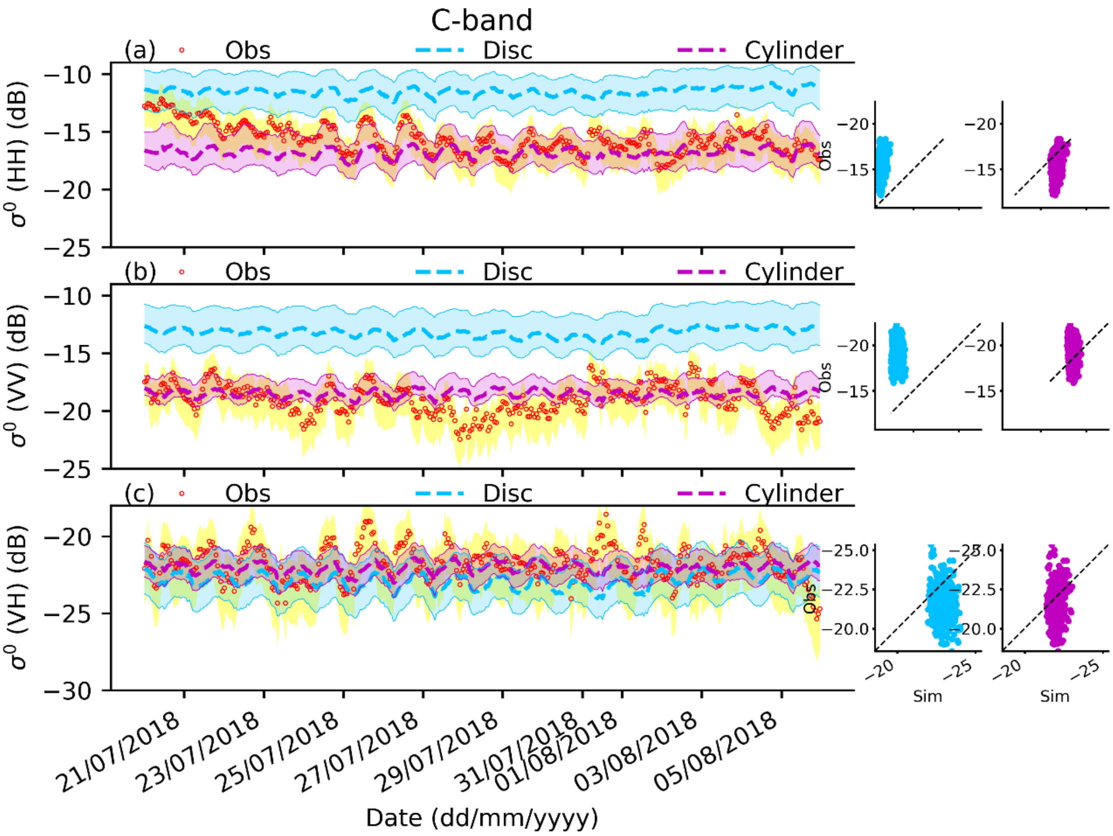
Lines 829-833: "CLAP will be extended as a full-spectrum (from optical, thermal infrared, to microwave) observation operator by adding SCOPE modelling canopy radiative, photochemical, and physiological processes and STEMMUS modelling soil water, heat and vapor transfer processes. As such, CLAP has the potential to synergistically utilize available and future satellite resources for monitoring (e.g., vegetation and soil) variables of interest."

I detail my comments hereafter. Major comments

- The results presented are based on RMSE and Bias metrics between the estimates and the in situ, as well as on time-series plots. However, as the authors focus on the study of the daily variability, correlation metrics are needed. Also, optionally, scatters between in situ and estimates can be plotted next to the time-series (instead of in separate figures; note that the number of figures in the paper is very large and should not be increased).

Response: Thanks a lot. We've added R values in Tables 3, 4, 5, 6 and 7 and previous Tables S2 and S3 in the supplementary materials. As we mentioned in the previous reply, the limitations described in section 4.4 in this study lead to some poor statistic values between simulated signals and the collected detailed ground-based observations, although in contrast, better statistical values (e.g., much higher R values) are obtained when compared to the satellite AMSR2 observations (see Tables 3, 4, 5 and 6). Our major focus in this manuscript is to investigate the dynamics of VWC and vegetation temperature and soil moisture and temperature on the modelled signals. We did not add scatter plots because we think they do not provide extra useful information in terms of current time series plots and statistic values. We anyhow attached the plotted scatter plots for your reference.




C-band
(a)
Obs
Disc
Cylinder
σ0 (HH) (dB)
(b)
σ0 (VV) (dB)
(c)
σ0 (VH) (dB)
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Sim
21/07/2018
23/07/2018
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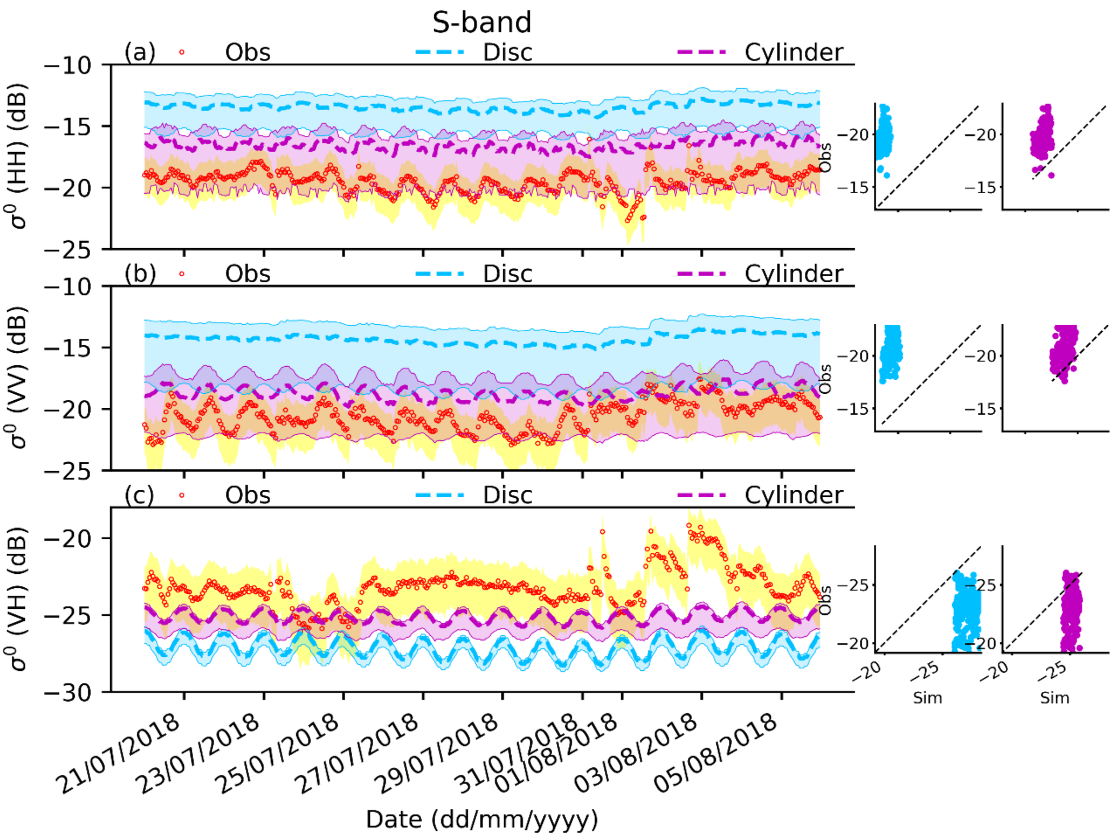
S-band
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σ0 (HH) (dB)
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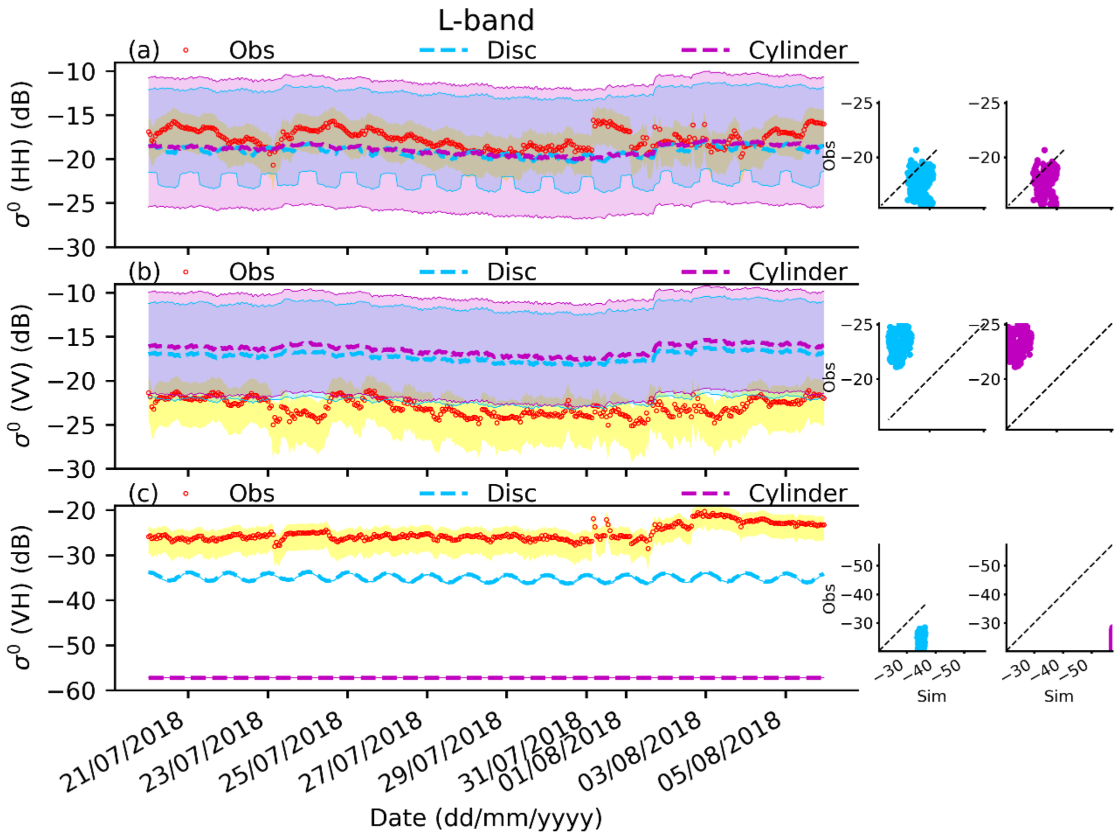

• Lines 120-132, and 142-145, in p. 5, provide an interesting state of the art which is used as the basis for this paper. The manuscript will improve a lot if the authors extend the discussion explaining how the current manuscript improves previous literature. For instance (among others) the authors could address the question: "which are the improvements if compared to Zheng et al. (2021) and Dente et al. (2014)?"

Response: Thanks a lot. Please refer to our reply to your second major concern (ii).

• The authors conclude that the model is able to track well the observations in many cases (especially for cylinders and in summer). Still, the results show some differences between estimates and observations. In that sense:

o In Figures 2 to 5 and Table 3, even in the best cases (cylinders and X to S frequencies) the errors reach RMSEs between 1 and 4. As the authors are presenting this model as potentially applicable for future missions, how would an error like this impact soil moisture and optical depth retrievals? Based on either literature or observations, the authors should discuss which is the impact of this error and if it is small enough to allow the applicability of the algorithm.

Response: Many thanks for spotting this. Please refer to our response to your first major comment. We added section 4.4 to describe the limitations of this study that lead to low values of R and high values of RMSEs and Biases and future directions.

o Table 4: similar to above. RMSE minimum values are 5.9 and 2.4 at H and V polarizations. Which would be the impact in soil moisture simulations? Is the conclusion of CLAP "mimicking the observations" consistent according to these results? Why? Maybe, the problem is that affirming that the model reproduces well the observations is subjective if there is no reference for what is "good" and what is “bad” (in terms of amount of error). Can the authors provide reference or thresholds of errors to justify why their affirmation of CLAP mimicking the observations is true enough to allow the model applicability?

Response: Thanks a lot for your comments. We have added metric values as references for good and poor performances described in the manuscript. We went through the Results and Conclusions and did corresponding revisions.

Lines 428-432: “Figure 6 shows that T_B^H simulated with the disc parameterization is closer to ELBARA-III observed T_B^H at L-band (RMSEs of 12.7 vs 30.4 K in Table 4) than those with the cylinder parameterization, despite slightly higher R values obtained by cylinder parameterization (R of 0.27 vs 0.16). While the disc parameterization performs similarly as the cylinder parameterization does in the good simulation of T_B^V (Fig. 6, and R over 0.8 and RMSEs of 6.5 K and 5.6 K in Table 4)”.

Lines 487-493: “Figure S19 shows that using STEMMUS simulated soil moisture and temperature as the input in CLAP does not outperform using the in situ measured soil moisture and temperature in reproducing the observed σ_{pq}^0 at X-band, and both lead to the heavy overestimation of σ_{HH}^0 at X-band with poor performance metric values (e.g., Biases of 10.9 dB and RMSE of 11.0 in Table 5 for in situ case). However, using STEMMUS simulated soil moisture and temperature outperforms in reproducing the observed σ_{pq}^0 at C-band (Fig. 8) with good performance metric values of Bias of 1.6 dB and RMSE of 1.9 dB (Table 6).”

Lines 531-534: “Figure 9 also shows that the model can capture the observed diurnal variations (with R of 0.65 and 0.73 for H and V polarization respectively, Table 7), but the large systematic underpredictions of T_B^p are observed in comparison to the ELBARA-III observations (RMSEs of 26.3 K under V polarization and 48.9 K under H polarization in Table 7).”

Lines 636-639: “Figure 12 shows that the Case1_surface_moisture_shallow_boundary can capture the observed diurnal variation of T_B^p signals but present a systematic overprediction (RMSEs of 15.0 K at V polarization and 16.5 K at H polarization in Table S4) of T_B^p, which is opposite to the heavy underprediction by Case0_surface_moisture_deep_boundary (RMSEs over 26 K in Table 7).”

Lines 648-652: “In contrast, the Case2_penetration_depth_moisture_shallow_boundary captures the magnitude of the observed T_B^H (RMSE of 5 K in Table S4) and σ_{VV}^0 (RMSE of 0.9 dB in Table S5), the Case3_penetration_depth_moisture_boundary simulates the magnitude of the observed T_B^V (RMSE of 5 K in Table S4) and σ_{HH}^0 (RMSE of 3.3 dB in Table S5), although the diurnal changes simulated by both cases are flat.”

In Conclusions: “In comparison to the in situ and available satellite AMSR2 X- and C-bands microwave emission observations during the summer period, CLAP using the cylinder parameterization of vegetation representation can mimic multi-frequency σ_{pq}^0 better than the disc parameterization does (e.g., mean RMSEs of 2.1 vs 3.7 dB, with L-band σ_{VH}^0 data excluded), and it performs similarly well as the disc parameterization does in the simulation of L-band T_B^V (e.g., with RMSEs around 5.6 K and R over 0.8), although the latter case performs better in the simulation of T_B^H (e.g., with RMSEs of 12.7 K)……

The comparison results show that CLAP using the cylinder parameterization and either the in situ measurements or the process model outputs can mimic the observed C-band co-polarization σ^0 of grassland especially at VV polarization (e.g., with RMSE of 1.9 dB) and its diurnal variations during the winter period. However, the current platform cannot reproduce σ^0 and T_B^p dynamics at other bands during this period."

o Similar problems arise in Figures 7 to 14, but in this case they are well justified in the discussion.

Response: Thanks a lot.

o Similarly, the following sentence would need justification answering the question: "why are the errors low enough to affirm that the CLAP is reproducing or close enough to observations?": ▪ P. 29, l. 508-509: "In short, the observed co-polar σ_{pq}^0 and its diurnal variations especially at VV polarization during the winter period can be reproduced…".

Response: We have rewritten section 3.3 and the summary at the end.

Lines 512-522: "In short, the observed co-polar σ_{pq}^0 at C-band and its diurnal variations especially at VV polarization during the winter period can be reproduced by CLAP using the process model simulated soil moisture and temperature as the input (i.e., the STEMMUS model in this case). Further investigations need to be done for improving CLAP simulations of the co-polar σ_{pq}^0 at other bands. By investigating the impact of different soil moisture and temperature profiles on the simulated signals, the previously described results, to some degree, imply the different sensing depths for soil moisture at the different frequencies. Thus, obtaining precise dynamic surface soil (moisture) information and further investigating the foregoing sensing depth play a significant role in reproducing the observed diurnal microwave signal especially at high frequencies. Moreover, it is necessary to figure out the contribution from the surface soil and the soil at the deeper depth (e.g., soil temperature penetration depth in this case) to elaborate simulations of signals at low frequencies, but this is beyond the scope of this paper".

o L. 515-516: Figure 15 shows differences between disc/cylinder and observations of around 50K in H and 25K in V. Based on this, at L-band, the affirmation that the model is reproducing the observations is not true. Please review the sentence and derived conclusions through the paper.

Response: Thank you. We replaced 'reproduce' with 'simulate' and revised the conclusion. Although our final goal is to make CLAP reproduce the observed signals, some aforementioned pivotal issues we discussed in this paper need to be resolved first. We went through the Results and Conclusions and did corresponding revisions.

• In some sentences, the authors derive conclusions or potential applicability at global scale, which is not demonstrated by the results. These sentences should be rephrased: o L. 686-687: even if it is shown in the results that combination of frequencies is not enough for constructing a homogeneous time-series of , it cannot be concluded that this would happen globally. It could be said that this is the case for the study area and maybe in other grasslands.

Response: Thanks a lot for your comments. We agree with your point. We have revised the sentence and relevant descriptions in the Abstract as

"As such, in this case and maybe in other grasslands, the retrieved τ at different frequencies (e.g., X-band and L-band) cannot be simply combined for constructing the long-term microwave-based vegetation product".

o L. 760-761: suggesting that CLAP can be applied at a global scale is maybe premature. The model has potential, but I suggest saying that larger scales (up to global) should be studied in the future. Let it open as a future work rather than an affirmation.

Response: Thank you. We revised the sentence into

Lines 888-837: "Furthermore, CLAP will be extended as a full-spectrum (from optical, thermal infrared, to microwave) observation operator by adding SCOPE modelling canopy radiative, photochemical, and physiological processes and STEMMUS modelling soil water, heat and vapor transfer processes. As such, CLAP has the potential to synergistically utilize available and future satellite resources for monitoring (e.g., vegetation and soil) variables of interest".

Minor comments

• Title: can you explain briefly in the introduction why the word "Community" is used as part of the name of the algorithm?

Response: Thank you. We added the explanation in

Line 128: "Being a unified multi-frequency scattering and emission observation operator, the coupled ATS-AIEM-TVG model forms the prototype of a Community Land Active Passive Microwave Radiative Transfer Modelling Platform (CLAP), which can be used for integrated modelling, interpretation and application of multi-frequency emission and backscattering signals of land surface".

• L. 26: "simulate both ground-based and space-borne". This sentence may lead the reader to think that two different simulations (one for ground-based and the other for space-borne) are built. I think that the differentiation in these two types is more appropriate when you talk about the sensors used for validation.

Response: Thanks a lot for spotting this. Yes, as you pointed out, we did one type of simulations for ground-based measurements and used both ground-based and space-borne observations for validation. We have revised the sentence as:
"The CLAP was used to simulate multi-frequency microwave measurements collected at the Maqu grassland observatory on the eastern Tibetan plateau, and the simulation results were compared to ground-based and space-borne observations for validation".

• Abstract & introduction: I suggest being specific from the beginning of the paper stating that this analysis is conducted in soils covered by herbaceous vegetation.

Response: Thanks a lot. We have added 'grassland' information in the Abstract and Introduction.

Lines 20-24: "We present here a prototype of a unified multi-frequency scattering and emission simulator named the Community Land Active Passive Microwave Radiative Transfer Modelling platform (CLAP), to simulate the in situ scatterometer measured X-, C-, S- and L-band σ_{pq}^{0} and

ELBARA-III L-band radiometer meauserd T_B^p of grassland at the Maqu site on the Eastern Tibetan Plateau.".

Lines 29-32: "this paper investigated the impacts of different grass properties (i.e., structure, water and temperature dynamics) and soil conditions (i.e., different moisture and temperature profiles) on the microwave signals to understand factors that account for diurnal variations of the observed signals of natural grassland."

Lines 36-37: "The model derived optical depth τ of natural grassland in this case varies with frequencies and different model parameterizations"

• L. 45 – 47: following my major comments, reevaluate if this conclusion can be driven from the results. It should be further justified.

Response: Thank you. CLAP is a unified physically based multi-frequency scattering and emission observation operator and can be utilized to improve our capability for understanding and applying current and future multi-frequency space-borne microwave systems for land monitoring.

As the replies to your main comments, the used ground-based microwave active and passive signals with fine temporal resolution observed the fixed scene (of grassland) for a year-long period. CLAP was developed to simulate the observed signals due to the surface condition change, which is mainly related to the vegetation growth process and soil freeze-thaw processes mainly in this study. The investigation results demonstrate different roles of VWC, vegetation temperature dynamics and soil moisture and temperature profiles in affecting the dynamics of signals at different frequencies. This is helpful for us to interpret and further utilize the existing and future observed signals in a consistent way for dynamic land monitoring.

We have revised the sentence as
Lines 45-50: "Overall, the results show the potential of CLAP in advancing the interpretations and assuring modelling capability to mimic microwave signal dynamics observed at the Maqu grassland as a case. The limitations discussed in this paper are necessary to be mitigated in future efforts. Nevertheless, CLAP is expected to improve our capability for understanding and applying current and future multi-frequency space-borne microwave systems (e.g. those from ROSE-L and CIMR) for vegetation monitoring".

• L. 55: instrument → instruments

Response: Thanks a lot. Done.

• L. 59-60: maybe add the soil texture here?

Response: Done

• L. 75-77: in addition to the Steele-Dunne paper maybe you want to add further references referring specifically to agriculture. Some suggestions: Patton & Hornbuckle (2012), Hornbuckle et al. (2016), Chaparro et al. (2018), Mateo-Sanchís et al. (2019); Weiss et al. (2020).

Response: Thank a lot for suggestions. We added those references.

• L. 87-89: with some exceptions, such as the Multi-temporal Dual Channel Algorithm (MT-DCA).

Response: Thank you. We revised the sentence

Lines 91-95: "Except directly retrieved using for instance the Multi-temporal Dual Channel Algorithm (MT-DCA) (O'Neill et al., 2018), the parameterized VOD at nadir (τNAD) is generally linked with vegetation indices (e.g., Leaf Area Index (LAI), Normalized Difference Vegetation Index (NDVI) and vegetation water content (VWC)) through empirical equations for low vegetation covers."

• L. 94-95: I cannot understand clearly what you mean with the first sentence of the paragraph. Please rephrase or remove.

Response: Thank you. We deleted the sentence to remove the ambiguity.

• L. 141: after "Wang, 1987), a comma should follow instead of a full stop.

Response: Thanks a lot. Done.

• L. 153: "temprature" → "temperature".

Response: Done.

• L. 216: temperature → VWC

Response: Thanks. Done.

• L. 225-226: "the simulated data during the winter period is focused, as we assume…". Review the structure of the sentence.

Response: Thanks. We revised the sentence into

Line 240: "The simulated data during the winter period is utilized, and we assume that vegetation is in dormancy in this period and the ground surface conditions (i.e., in moisture and temperature) are the main driving factors of the signal variation".

• L. 226-227 & Fig. S2: at 2 cm, the simulated soil moisture fluctuates much more than the observed SM. Even if we do not have 1 mm observations, it is reasonable to think that the same "excess of fluctuations" could happen at the skin layer. How can this impact the results?

Response: Thank you. Yes, SM at the skin layer should undergo manifested fluctuations and these changes should act on the dynamics of the observed signals. But as we mentioned in Introduction, it is hard to obtain in situ measured SM at the skin layer. We tried using the process model simulated SM and the investigation results demonstrate the necessity of considering the topsoil moisture in modelling signals especially at high frequencies. Moreover, the current dielectric consideration of abrupt soil-water-ice phase change during the winter period needs to be improved, which will be our future studies.

Please see the added section 4.4 about the 'Limitations in this study'.

• Fig. 1: do you mean "Rayleigh-Jeans" instead of "Ryleigh-Gans"?

Response: Here it refers to "Rayleigh-Gans approximation". The Rayleigh-Gans approximation is used to compute scattering coefficients of randomly-oriented disk-like particles. We corrected misspelling in Figure 1, revised the sentence and added the reference.

Lines 254-258: "After defining the shape of discrete scatters, the corresponding electromagnetic approximations (i.e., Rayleigh-Gans (Eom & Fung, 1984; Schiffer & Thielheim, 1979), physical optics (LeVine et al., 1983) and infinite length (Karam & Fung, 1988; Wait & Maxwell, 1988)) are adopted in respect of selected geometry and frequency (Fig. 1) to calculate vegetation bistatic scattering and extinction (absorption plus scattering) cross-sections."

• Fig. 2b: the dashed line is not in the legend.

Response: We modified Figure 2b with showing the dashed line in the legend.

• Fig. 4b: the high variability of the observations between 31-7-18 and 5-8-18 is not captured by the model, which in general (also in other figures) shows a very regular, sinusoidal behavior, not capturing extreme deviations such as these ones. Could you discuss why this happens and its implications, please?

Response: The high variability of the observations are due to rainfall events. There might be intercepted water and surface water accumulated on the ground (in terms of infiltration capability) that account for these observed variations. As there is no in situ measurement of interception water in this study, the current model setup cannot capture the foregoing phenomenon. We have described these in line at the end of section 4.2.

Lines 681-687: "The impact of heavy rainfall (> 6.0 mm/hour, Fig. 2a) on the observed signal is pronounced at the X- and C-bands at full polarizations, at S-band at cross-polarization, and at L-band at HH- and cross-polarizations (see Figs. 2-5). This finding is consistent with those reported by Vermunt et al. (2021) and Khabbazan et al. (2022), in which the radar backscatter of corn fields at L-band is found to exhibit diurnal variations partially due to the intercepted water. As there is no *in situ* measurement of interception water in this study, the current setup cannot capture the foregoing phenomenon".

• L. 457: Fig. 8 → Fig. 9

Response: Thanks a lot for spotting this. Done.

• L. 458: Fig. 13 → Fig. 10.

Response: Done.

• L. 458: "simulated those" → "those simulated"

Response: Thanks. Done.

• L. 480 and 482: Table 5 → Table 6.

Response: Thanks a lot for spotting this. Done.

• L. 540: for further comparison of the albedo values, Baur et al. (2021) could be an interesting reference.

Response: Thank you for recommending this paper. As the grassland is not selected as one of areas of interest, no available values can be used for our case, but we will consider it (e.g., Table 2 in Baur et al. (2021)) in our future work.

• L. 545: "suppressed". Instead, I would say "reduced".

Response: Thanks. Done.

• Figure 16: for readers who are used to see VOD satellite retrievals which are not polarization dependent, values of up to 5 for a grassland are absolutely out of the expected range. Is this expected in the vertical polarization? Why?

Response: Thanks a lot for your comments. We do not have measured VOD to validate the model estimated VOD. However, as CLAP with cylinder parameterization outperforms that with disc parameterization in simulating signals at high frequencies, the corresponding estimated VOD is assumed to be reasonable. Furthermore, the maximum bound of VOD at L-band was set 3 in Baur et al. (2021), we'd say that the estimated VOD at X-band (higher frequency than L-band) exhibits values up to 5 seems possible.

• L. 670: wavelenth → wavelength

Response: Thanks. Done.

• L. 689-690: is this sentence incomplete?

Response: Thank you. To make it clear, we revised the sentence into

Line 713: "Instead, the radiative transfer modelling approach needs to be considered for combination, but the physical factor resulting in differences in τ at multi-frequency should be investigated first".

• L. 694-695: you could add the reference Jagdhuber et al. (2022) as an example, optionally.

Response: Thank you so much. We added the reference.

• L. 702: in line with my major comments, affirming that CLAP has been proven as a key tool for understanding is too much if no impact of the errors in the potential retrievals is assessed.
Response: Thank you. Please see the added section 4.4 about the 'Limitations in this study'.

• L. 706-708 and 758: SCOPE has not been presented or explained before in the paper. I suggest removing it or explaining previously.

Response: Thanks. We added the full name of SCOPE. The sentence was revised into

Line 774: "in which the Soil Canopy Observation of Photosynthesis and Energy fluxes (SCOPE) (Van der Tol et al., 2009) model simulating canopy radiative and photochemical processes provides vegetation information, and STEMMUS model (Yu, 2022; Yu et al., 2018; Zeng et al., 2011) provides information of profile soil moisture and temperature".

• L. 717-725: review specifically this paragraph according to the major comments.

Response: Thank you. We keep this paragraph as an outlook in this manuscript.

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