Revision of Manuscript: "Soil dielectric characterization during freeze-thaw transitions using L-band coaxial probe and soil moisture probes" by Alex Mavrovic *et al.*

In blue: Reviewer's comments.
[ ] = Numbering (coherent with the first round of reviewer's comments), R= Reviewer; P = Page; L = Line as they appear in the Original manuscript version
G= General comment followed by numbering

In black: Answers to referees.
P=Page; L=Line; Track change version
In black and italic: Modification added to text.

Comments from the Reviewers:

Reviewer #1:

Synopsis:

Comments reviewer 1 (Jan Hofste) on revised manuscript: "Soil dielectric characterization during freeze-thaw transitions using L-band coaxial probe and soil moisture probes", Alex Mavrovic, Renota Pardo Lara, Aaron Berg, François Demontoux, Alain Royer, and Alexandre Roy, HESS, 2020

We made improvement to the manuscript by adding details on the experimental setup, the accuracy/precision of the OECP and our experimental setup, and the similarities between the OECP and HP measurements, along with clarifications where the reviewer's comments suggested doing so.

Specific comments:

[2] R1, G1: General remark on the samples and measurement setup. With the OBS sample HP measurements were taken at three positions. As Figure 5 shows the measured responses at these three positions varies. Why were there not also measurements at multiple positions for the OECP with the OBS sample? And why were the other 3 samples not also measured with the HP (and the OECP) at multiple positions? Was this because the OBS sample was expected to be less homogeneous due to the organic content? And why only one sample per soil type was measured? The choices the authors made in this regard should be explained in the text, even if simply for practical reasons.

The OECP is a promising instrument currently developed by the Université de Trois-Rivières and Université de Sherbrooke. Only one OECP was available for the experiment. Logistics is the primary reason for the difference in setup between the OBS soil samples and the others, the soil sample collections were not made in the same type of container for all sites. Even if the cylinder samples are smaller in size, the probed were properly positioned to ensure reliable measurements (see previous response to comment R1[1]). The repeatability of the measurements gives us confidence that the experimental protocol is robust. The explanation for the two distinct setups was added.

P7, L216-218: *The Fig. 3a and 3b setup discrepancies only reflect the two distinct containers used for soil collection at different sites, both configurations ensured sufficient spacing for undisturbed measurements.*

Author reply clear, but revision in manuscript not yet sufficient. Mention in text that OECP measurements were only performed at one position of OBS sample because only one OECP was available (applies to OBS sample). Mention also that the other three samples were too small to allow for measuring at multiple positions (at same depth of course), doing so would disturb the samples because they would then have holes in them. (As author explains in response to comment [4].) The low number of OECP sampling positions is, unfortunately, a shortcoming of the experiment. The authors should be honest about this.

Revisions in the manuscript were added to reflect more clearly the author reply to the reviewer's comment.

P7, L218-222: The Fig. 3a and 3b setup discrepancies only reflect the two distinct containers used for soil collection at different sites, both configurations ensured sufficient spacing for undisturbed measurements. *OECP measurements were performed at only one position in each experiment because only one OECP was available. The setup of Fig. 3b only includes one HP position because of containers' size limitation.*

Finally, I disagree with the sentence "The repeatability of the measurements gives us confidence that the experimental protocol is robust." Measurements at same positions are indeed alike, and thus are repeatable (albeit there is still some variation..) but this does not have to mean that the retrieved epsilon values are accurate.

It was clarified that the cited previous work already provides estimates on the OECP accuracy and precision with quantified uncertainties. The repeatability of the measurements gives us a certain confidence that the experimental setup is suitable to obtain reliable soil permittivity measurements during freeze/thaw transitions.

P9, L285-291: *Previous work already shown that the OECP is a reliable instrument to measure a medium's permittivity such as tree trunks (Mavrovic et al., 2018), leaves (Holtzman et al., accepted) and snow (Mavrovic et al., 2020). The OECP displays uncertainties under 3.3% and 2.5% for real and imaginary permittivity respectively when tested on reference materials (Mavrovic et al., 2018). In this study,* the repeatability of the OECP measurements *through several freeze/thaw cycles* can also be seen as an indicator of the reliability of the *experimental setup to measure soil permittivity during freeze/thaw transitions with the OECP and HP.*

P14, L518-521: *Holtzman, N., Anderegg, L., Kraatz, S., Mavrovic, A., Sonnentag, O., Pappas, C., Cosh, M., Langlois, A., Lakhankar, T., Tesser, D., Steiner, N., Colliander, A., Roy, A., Konings, A.: L-band vegetation optical depth as an indicator of plant water potential in a temperate deciduous forest stand, Biogeosciences, doi: 10.5194/bg-2020-373, accepted.*

[3] R1, P7, L243: The amplification of the hysteresis -effect by the setup, is it possible to explain this in the text with a few sentences? You refer to this hysteresis amplification later on, it would be better if the reader could find an explanation for this effect in this manuscript rather than somewhere else (the reference). You can of course leave the reference.

Further explanations and reference were added.

P8-9, L286-291: Hysteresis effects can be observed between the freezing and thawing cycles in Figs. 5 through 8*, i.e. a different behavior of permittivity variation depending on whether the ground freezes or thaws*. Although hysteresis *is reported in soil freezing studies, this effect was amplified by the temperature transition speed and differences in the sensing volume for temperature and permittivity observations (Pardo Lara et al., 2020)*. Fig. 11 shows a slow freeze/thaw transition displaying a hysteresis effect of diminished amplitude, but still noticeable.

P9-10, L321-323: Even if amplified by the experimental setup, the hysteresis effect between the freezing and thawing cycles is not simulated by any model since *they do not include the evolution of soil properties in time*.

I mis the sentence found in the original manuscript (line 244) explaining the hysteresis: "hysteresis should be expected because of the latent heat of fusion of water". Line 287 of new manuscript not necessary: you don't need to give the definition of hysteresis. The hysteresis-amplification is explained better now.

The unnecessary hysteresis definition was removed. The hysteresis amplification explanation based on the difference in permittivity and temperature sensing volume replaced the latent heat explanation because it was deemed more plausible.

P9, L295-298: Hysteresis effects can be observed between the freezing and thawing cycles in Figs. 5 through 8. Although hysteresis is reported in soil freezing studies, this effect was amplified by the temperature transition speed and differences in the sensing volume for temperature and permittivity observations (Pardo Lara et al., 2020 *and in review*).

P16, L629-631: Pardo Lara, R., Berg, A., Warland, J., Parkin, G.: Implications of measurement metrics on soil freezing curves: A simulation of freeze-thaw hysteresis, Hydrol. Process., doi:10.22541/au.160466100.02966301/v1, in review.

[6] R1, P8, L270-272: Based on the Figures 5 - 8 I find the freeze/thaw transitions not similar. Can the differences of the OECP and HP measurements be explained by the difference in probing volume? Also you mention that the main difference between the OECP and HP measurements are the epsilon values at the end of the cycle, at the "stable plateaus" as you call it. But isn't the hysteresis just as important? Perhaps if a found calibration equation for a given soil is applied to the HP results the freeze/thaw hysteresis is more like that of the OECP?

It is correct that the difference in freeze/thaw transition steepness could be explained by the difference in probing volume. The authors share the same point of view that this is probably the main explanation and it is put forward in the Experimental Results section (4.1).

The fully frozen/thawed values comparison between measurements and models consist of the strongest differences observed in this study. The hysteresis is of equal importance, but the trends are similar between the permittivity measurements. This is to say that the hysteresis effect occurs at very similar temperatures.

It is typical to use soil specific calibration equation to produce soil moisture estimates from HP raw permittivity measurements. However, the HP instrument does not allow for customized calibration equation to compute permittivity from raw reflection coefficients. We clarify few points in the manuscript:

P9, L 310-315: It can also be observed that the freeze/thaw transition measurements are *steeper* with the *OECP* than the HP. This is probably due to the HP's larger probed volume. Since the instruments measure an average permittivity for the whole probed volume, a larger probed volume will record a *more extended* freeze/thaw transition because of the longer time required for the freezing/thawing fronts to penetrate the depth of volume probed. *Since the freezing/thawing front is mostly vertically oriented, it is the difference in probes' sensing diameter that causes the difference in transition steepness.*

Author reply and corresponding manuscript revision not yet sufficient. You mention in the explanation and in the manuscript (line 335) the (hysteresis) trends are similar between the permittivity measurements. This statement should be more specific and quantified. Are measurements similar between thaw/freeze cycles?, or between HP positions?, or between different soil samples? Based on the theoretical curve in figure 10 you can define quantities such as ΔT, $\Delta \varepsilon'$, maximum steepness of the slope, and the positions where the slopes are steepest. These quantities you then apply to the various measurements. Based on that you can then also make statements on for example the repeatability (see also comment [27]).

Similarities between permittivities were detailed and quantified.

P10, L343-347: *The soil temperature offsets from water freezing point are consistent between the OECP and HP measurements for both the freezing and thawing transitions. The difference is ranging from -1.00 to +0.83 °C when evaluating the soil temperature* *offset at maximum transition rate (Tables S1 and S2).* The main difference between the permittivity measured at microwave and MHz frequencies appears to be *a permittivity* offset *and the temperature span of the freeze/transition* dependent on the soil type.

Tables S1 and S2: Added in supplementary material.

[8] R1, P9, L300: What hypothesis do the authors refer to?

The hypothesis referred is the one proposed in the previous paragraph about the correlation between the hysteresis effect and the temperature transition speed. It was clarified to avoid further confusion.

P11, L368-369: *We further tested the hypothesis that the hysteresis effect is correlated with the temperature transition speed* using an OBS soil sample using a slower freeze/thaw transition rate.

Author reply and corresponding manuscript revision not yet sufficient. Don't you mean hysteresis amplification -effect? Because the hysteresis itself is known to be present regardless of any probing volume.

It was clarified that the hysteresis amplification is specifically referred in the sentence.

P11, L373-374: We further tested the hypothesis that the hysteresis *amplitude* is correlated with the temperature transition speed using an OBS soil sample *with* a slower freeze/thaw transition rate.

[18] R1, P4, L116: "The penetration depth of the… " This sentence is too vague for my taste. I propose something like: "The sensing depth of the OECP is the maximum depth at which the medium is polarized due to the incident electric field, and as such contributes to the reflection of the EM wave backwards into the coax."

Sentence reworked.

P4, L120-127: The *sensing* depth of the OECP *is* defined as the maximal depth at which a medium is *polarized due to the incident electric field, and as such contributes to the electromagnetic wave reflection*. *The sensing depth is proportional to the medium's permittivity and the magnitude of the electric field generated by the reflectometer*, which *displays a constant power output of 10 dBm* (Fig. 1b). The OECP typical *sensing* depth approaches 1 cm under dry soil conditions and the cylindrical probed volume is about 3.5 cm wide in diameter (Figure 2). Under wet soil conditions, the *sensing* depth shrinks down to 0.4 cm.

Author reply and corresponding manuscript revision not yet sufficient. Line 122 should be: "The sensing depth is inversely proportional to the medium's permittivity and proportional to the magnitude of the electric field generated by the reflectometer, which provides a constant power output of 10 dBm (Fig. 1b). ". This is also what is shown in Figure 2.

Clarifications added.

P4, L122-124: The sensing depth is *inversely* proportional to the medium's permittivity and *proportional to* the magnitude of the electric field generated by the reflectometer, which displays a constant power output of 10 dBm (Fig. 1b).

[19] R1, P4, L118: "The magnitude of this effective electric… " the effective electric field has not been defined or explained previously. I assume you refer the resulting electric field in the medium? Which is the sum of the original electric field coming from the coax E0, which polarizes (rotates and or translates) the molecules and the electric field produced by the rotated or displaced molecules themselves Ed. Latter counters E0, which counters Ed, which counters E0 etc. You end up with a resulting electric field E, which is actually lower in magnitude for a higher epsilon.

The effective electrical field refers here to the extent of the electrical field influencing the reflection coefficient measurements. The use of this term here seems confusing and not necessary. Therefore, it was removed and the sensing depth was directly referenced.

P4, L122-124: *The sensing depth is proportional to the medium's permittivity and the magnitude of the electric field generated by the reflectometer*, which *displays a constant power output of 10 dBm* (Fig. 1b).

See comments [18].

See response to comment R1[18].

[25] R1, P7, L243 – 246. Authors state that trends of OECP and HP are "very similar" and the fully frozen/thawed epsilon values are "also similar". I disagree with this description. Judging from Figures 5 - 8 there are significant differences. These differences and explanations for their causes are discussed further down in the text.

The similarity mentioned here was meant to point at the closer similarities between OECP and HP measurements than the model estimates. Since the model results are discussed in the next section, the sentence was reformulated to remove this mention.

P9, L296-299: The HP measurements show trends *in agreement with* the OECP measurements during freeze/thaw transitions, especially for the real permittivity*, although the fully* frozen and thawed permittivity values *display soil type dependent offsets* between the OECP and HP measurements (Tables 2 and 3).

See comment [6]

See response to comment R1[6].

[27] R1, P10, L325 - 327: The question whether the OECP correctly measures the epsilon in not shown in this manuscript. It is implied by your earlier work, see also comment [10].

The reliability of OECP measurements are not thoughtfully investigated in this study, although confidence in the reliability of the measurements can be inferred from the repeatability through freeze/thaw cycles. The conclusion was adapted to shift focus from OECP reliability to soil permittivity results and a hint to OECP measurements repeatability was added in the Results section.

P8, L281-282: *The repeatability of the OECP measurements can also be seen as an indicator of the reliability of the measurements.*

P11, L387-392: *This study presents soil microwave permittivity measurements during freeze/thaw transitions in* the same frequency range as the SMAP and SMOS satellites, as well as future L-band satellite missions. *The permittivity measurements were taken using a novel open-ended coaxial probe (OECP).* It is shown that lower frequency (MHz) soil permittivity probes can be used to estimate microwave permittivity given proper calibration relative to an L-band probe*, which holds significant potential considering the already widespread operational networks of low frequency soil permittivity probes deployed to measure soil moisture.*

Author reply and corresponding manuscript revision not yet sufficient. I disagree with added lines " The repeatability of the OECP measurements can also be seen as an indicator of the reliability of the measurements" (281-283) in revised manuscript. Measurements can have a high repeatability, yet be inaccurate at the same time. You can make quantitative statements on the repeatability, but you assume the epsilon values you measure are accurate based on the calibration of your probe and on whether the sample containers or sample edges don't influence the measurement.

See response to comment R1[2].

Reviewer #2:

Synopsis:

Thank the authors a lot for their dedicated revisions, elaborating the potential measurement uncertainties and adding more explanations about the experiment, used models, and results, which addressed most of my concerns. I only have some minor comments for consideration.

We made improvement to the manuscript by adding clarifications where the reviewer suggested doing so, namely on the Zhang's model ice fraction estimation and on the slow freeze/thaw transition experiment.

Specific comments:

[30] R1, P7, L246: Please check the appropriate use of “experiment”?

A more suitable formulation replaced ‘‘experiment’’.

P7, L249-250: The objective of this experimental setup was to *undergo* a slow freeze/thaw transition.

[31] R1, P7, L249: “Permittivity measurements were taken only when the soil temperature equilibrated with the cold chamber air temperature (± 0.1°C).” Please explain more about the cold chamber air temperature. The cold chamber air temperature is measured by sensors or the temperature settings of the cold chamber. If for the later option, what is the range of the temperature fluctuations when you set the cold chamber to a specific temperature value?

The cold chamber temperature was measured by the Climats EXCAL 1411-HE cold chamber temperature sensors and permittivity measurements were taken when the cold chamber air temperature stabilized and the fluctuations between the cold chamber air temperature and the soil sample temperature were under ± 0.1°C. It was clarified in the manuscript.

P8, L252-254: Permittivity measurements were taken only when *the cold chamber air temperature measurements stabilized and the fluctuations between the air and soil temperature were under* ± 0.1°C.

[32] R1, P5, Sect. 2.2.1 and P10-11, L357-359 and P11, L380: The treatment of ice fraction in Zhang’s model is still not mathematically clear to me.

In its original form (Equations 1 &2), the liquid water fraction is calculated as the exponential function of soil temperature. Then how is the ice fraction calculated?
In the updated Zhang’s model with consideration of the hysteresis effect, the ice fraction is added as an exponential function ($\frac{e^x}{e^x+1}$). What is “x” represented for? How the ice fraction is differed for the freezing and thawing cycles?

Precisions were added on the ice fraction calculation for the original Zhang’s model. It was also specified that the ‘‘x’’ in the exponential function refers to soil temperature and that a temperature offset was used to reproduce the hysteresis effect.

P5, L170-172: An empirical exponential decay function ($f_w = A \cdot |T_{soil}|^{-B}$) is used to estimate the liquid water *fraction in the freezing soils, the ice fraction is determined from the liquid water fraction and the total amount of water in the soil.*

P11, L369-370: This ice fraction was prescribed following an exponential function ($\frac{e^{T_{sol}}}{e^{T_{sol}+1}}$) around the freezing point *with a ±0.5°C temperature offset for the freezing and thawing cycles*.

The definition of ice fraction as "this ice fraction should not be interpreted as actual ice at temperature below freezing point but rather as an aggregate of the heterogeneous soil temperature" is only for the thawing cycle or for both the freezing and thawing cycles?

The correct wording should have been ''liquid water'', it was corrected.

P12, L365-367: The classic Zhang's model only takes into account ice fraction below 0°C, *the resulting liquid water* fraction should not be interpreted as actual *liquid water* at temperatures below freezing point but rather as an aggregate of the heterogeneous soil temperature.

The cases where "this definition of ice fraction" is used should be clearly indicated. The concept "freezing/thawing temperature offset" needs more explanation (Line 380).

Explanations were added on the temperature offset proposition.

P11-12, L391-394: This empirical approach would require determining *independently for each transition type the freezing/thawing hysteresis amplitude as a temperature offset between the state transition and 0°C. This* would depend on liquid water content, textural composition, solute concentration, and the pore pressure of the soil (Daanen et al., 2011).

[33] R1, P5, Sect. 2.2.1 and P5, Eq. 1-2 and P24, Table 1: Although the symbols are well defined, I think it is better to keep the symbols (θ_V, θ_G, ρ_d) in Table 1 consistent with Equations 1&2.

The symbols were standardized through the manuscript based on the symbol defined in Eq. 1 and 2.

P24, L809, Table 1: $f_i(V)$ and $f_i(G)$ stands for volumetric and gravimetric liquid water content, respectively.

P24, Table 1: Updated in manuscript.