Reply on RC1

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Author comment on "The soil heat flux sensor functioning checks, imbalances' origins, and forgotten energies" by Bartosz M. Zawilski, Geosci. Instrum. Method. Data Syst. Discuss., https://doi.org/10.5194/gi-2021-34-AC3, 2022

Answer to the referees.

I am sincerely grateful to Leonardo Montagnani, designated hereafter as "RC1", and particularly to the second referee designated as "RC2", for the comments, criticism, and enriching suggestions that helped me to improve this paper.

I would like to answer, point by point, the first referee RC1 including the answer that I have alredy posted during the interactive discussion.

RC1: « The paper is relevant since it poses a basic question related to G measurements. In the end, what is the uncertainty related to G measurements? Should we add other heat flux plates, since there is a problem of spatial heterogeneity, or the overall accuracy and precision are too low, so G measurements are nearly useless, and it would be better to concentrate the efforts on multiple net radiation instruments instead? An answer to this question would be relevant in the flux community. »

The uncertainty of the G measurement is very site-dependent. Depending on the soil properties, water table depth, vegetation cover, pluviosity, and so on. The main uncertainty is not coming from measurements errors but rather from technique limitations and, more particularly, from *conductive* heat exchanges versus *convective* heat exchanges. To my knowledge, there is no sensor able to measure soil *convective* heat fluxes. Then, we cannot just measure, we have to assess the unmeasured heat fluxes and correct them, if possible.

I am stating L181-:" On can expect to overcome imbalances due to surface soil inhomogeneities using numerous flux plates judiciously placed." Adding more sensors to overcome spatial variability is always desirable, but not always feasible. The practical aspect needs to be considered too. All sensors need to be purchased, installed, interfaced, maintained, frequently checked, and so on. Unfortunately, it is not just about making a probability calculation.

The overall precision of the soil heat flux measurement, in my mind, is not a disqualifying problem, and G measurements are necessary. The "errors" are not exactly what I would call "measurement errors," but rather what I would call "technical errors." This means that

the used technique inevitably represents only a very *local coductive* heat flux and does *not measure overall* heat flux. Consequently, I would rather talk about the *leak* of measurements and *omissions.* Namely, when we are measuring soil heat flux using the heat flux plates, we are measuring local, one-dimensional, *conduction* heat flux neglecting local *convection* heat flux and horizontal deviations. This means that even if the conduction heat flux is spatially representative and exempt from any calibration error the convection heat flux is ignored. And the corresponding unbalance is not negligible on FR-Lam. Also, the target is to measure the overall heat flux as the eddy covariance footprint is much larger. SHFP measuring surface is very small making its measurement very vulnerable to local inhomogeneities influence. Assuming SHFP measurements are representative, we have to assume that the local inhomogeneities are correctly measured, which means on both sides of each inhomogeneity.

On the other hand, concerning the surface energy balance, not only solar radiation and geothermal energy have to be considered but all the energies brought to the soil surface such as rainfall. Snowfall and hailfall energy apports are more difficult to assess since there is also heat absorption during later liquefaction. This point was not raised in my paper since snowfall and hail-fall are extremely rare on FR-Lam but the corresponding sentences mentioning also mist, fog, marine breeze, and dew, as suggested by the second referee, are added to the revised version.

RC1: "One problem quite evident is the language. I am not a native English speaker, but I notice several basic errors (like a singular verbal form after a plural subject) that should be corrected."

Although I agree that my English writing is not my strongest point in this paper, I plan to have a native speaker correct it.

RC1: "A second weakness is about a possible synthesis, which is lacking in my view. I propose to organize the different topics into groups based on the fact they are producing random errors (so the error tends to zero in the long term) or systematic or selective-systematic errors. See Moncrieff et al. 1996. »

I reorganized the revised version. Moncief et al. describe errors in carbon dioxide flux measurements by the Eddy Covariance technique. Measurements errors arise from non-respect for eddy covariance requirements, spatial inhomogeneities, and eddy covariance technique uncertainty. Eddy Covariance technique is complex, requiring special aerodynamic conditions which is not the case with heat flux plates. In my paper, I am pointing out the fact that spatial inhomogeneity causes positive or negative deviations which could be checked by annual integration for each plate because we are usually using several plates when eddy covariance setup is rarely duplicated on a site. I am pointing out also *conductive* soil heat fluxes resulting from evapotranspiration (vegetation respiration and soil evaporation) mainly giving rise to positive G^C imbalance, and from rainfall water infiltration giving rise to negative or positive G^C imbalance. On FR-Lam the sum of rainfall water infiltration contributions is close to zero but I'll hardly call it "random error". I am also pointing out soil surface energy apports that are neglected such as rainfall. Resulting errors are not caused by instrumental imprecision but by used techniques limitations or by measurement leaks such as convective fluxes measurement. Unfortunately, we do not

have yet specific sensors installed on FR-Lam to complete the necessary measurements and I can only roughly assess by minimizing each contribution which seems to be all the same not negligible. These complementary instruments are not commonly used or even do not exist yet. In other words, as I said, I would rather talk about technical errors, which means measurements leak, rather than measurement errors. Some of these measurement leaks are important for short-time integrations such as rainfall water infiltration but not for long-time integration (on FR-Lam). Others, on the contrary, are important for long-time integrations but not for short time such as evapotranspiration. Others for both, short-time and long-time integration such as rainfall energy apport. Anyway, in my mind, the only *random error* I can see is the SHFP emplacement near an inhomogeneity without another SHFP installed at a "symmetrical" emplacement counterbalancing its deviated measurements. These random errors are minimized by multiplying the SHFP and by avoiding obvious artificial inhomogeneities where a "symmetrical" SHFP emplacement is not even always possible. The SHFP number is then the minimizing error factor, not the time. Some of the measurements are not relevant for a longtime integration on FR-Lam, because of the specificity of the local climate but may be necessary for another location. This statement is added to the revised version.

This paper presents three main problematics:

1) Soil inhomogeneities and possible measured G^C unbalances. By placing multiple SHFPs away from artificial inhomogeneities, inhomogeneities imbalances can be overcome. An a posteriori check for obvious discrepancies can be used to eliminate SHFPs for a representative overall conductive soil heat flux calculation.

2) Convective flux assessment. Subtraction of geothermal heat flux and yearly integration followed by convective flux assessment (such as evaporation, evapotranspiration, rainfall water penetration). Convective heat fluxes are real and not sensed by SHFP which is a measurement leak and should be assessed and added if possible. Beneath SFHP evaporation is sensed by eddy covariance giving rise to a "double counting" which is an error and should be corrected if possible.

3) Neglected energies and their importance assessment. To bring the SEB equation into balance, these energies must be included.

RC1: "Another point on which I disagree is the use of the annual sum of G as a benchmark if is close to zero. This leads for example, to the suggestion of the removal of geothermal energy. In my view, all the soil heat flux plates located in the footprint of an eddy covariance tower should be representative of the actual energy flow and not corrected. I would place the sensors on the shade, in the partial shade and in full sun since the scope of the measurement is to assess the average value of the selected variable and its standard deviation »

I do agree with the point that all the plates *should* be representative of the actual energy

flow. Unfortunately, they are not because they cannot be. Eddy covariance footprint is much larger than the SHFP area then, in a case of not-perfectly homogeneous soil, only one SHFP cannot represent overall soil heat flux for the eddy covariance measurements but, in the best case, the overall measured soil heat flux when SHFPs are located in the eddy covariance footprint which is far to be always the case. I think that one of the crucial points was not clearly expressed in my original paper. Indeed, all inhomogeneities are causing non-vertical heat fluxes which give rise to the SHFP measurements imbalances *only on the boundary* of these inhomogeneities and the *real operturbation is nil*. We can see it as energy conservation. In other words, any inhomogeneity may perturb the local SHFP measured heat flux balance bat not the overall heat flux balance in the area containing this inhomogeneity if correctly measured with numerous enough plates. Depending on which side of the boundary of the inhomogeneity is placed the SHFP, its measurement *balance* will be positively or negatively influenced. In my mind, "adequately measured inhomogeneity" is then an inhomogeneity with SHFP placed on each side of the boundary giving overall measurement exempt from the inhomogeneity boundary influence because the real, overall heat flux is not imbalanced. Theatrically speaking it is possible to "adequately measure" all inhomogeneities with numerous SHFP but in piratic it is not evident to know where are the boundaries. Using numerous randomly placed SHFPs, the *probabvility* of valid representability is rising but this point is not guaranteed in any way and has to be checked. With only one-dimensional measurements, it is difficult, if not impossible, to correct any SHFP measurements concerning the non-representability of the overall measurement. The only way that I can see is to discard one or more implicated SHFPs if their imbalances are too far from the overall measurement imbalance. It would be possible to investigate closer SHFP measurements with 3D fluxes measurements but it is not yet the case. With vertical and non-vertical heat fluxes measurements inhomogeneities influence could be better delimited. This statement was added to the text. With the new overall measurement calculated using only approved SHFPs, a missing soil heat flux, see next point, can be assessed. Please, note also that we are placing the SHFP horizontally, assuming a one-dimensional flow, which means that only the vertical heat flow is measured. This assumption is no more valid in the case of shallow non-vertical heat exchanges, it means in the case of shallow inhomogeneity boundary presence. In this case, the SHFP measurement is no more representative of the actual overall energy flow. What is representative is the overall SHFPs' measurement with SHPS placed on both sides of the inhomogeneity boundary and this has to be checked. For example, using my scheme of three plates with one under a tree shade (Fig. 3): supposing that the plates are measuring the real heat flux. If plate C (under shadow) is placed symmetrically to plate B, it means that its imbalance is opposite to the plate B imbalance, then the overall heat flux imbalance is nil, as it should be because the imbalance of the real, overall heat flux present on the considered surface is nil. Now, supposing that we have only two plates, not three plates, installed on the same surface. If it is plate A and plate B, then the overall heat flux imbalance will be positive. If it is plate A and plate C, the overall heat flux imbalance will be negative and, if it is plate B and plate C; the overall heat flux imbalance will be nil. Using annual integration, we can see immediately that plate A does not have any inhomogeneity boundary in the vicinity and that plate B and plate C are "symmetric". In the case where only two plates are used, by individual integration we can see if the inhomogeneity boundary is present and was correctly compensated by placing as many plates on one side as on the other side. Of course, the reality is a bit more complicated since not only one inhomogeneity may be present, and not only inhomogeneities causing imbalances.

Second point: SHFP can only measure the conductive heat exchanges, and the resulting heat flux measurement does not represent the total, *real* heat flux. The geothermal heat flux G_{Th} is sensed by the plates (G), and corresponding subtractions are suggested for an unbalance check by annual integration ($G^c = G - G_{Th}$). Integration of SHFP's measurements allows us to compare their behavior more precisely. When all SHFPs, as they do on FR-Lam and FR-Aur, exhibit roughly the same G^c imbalance, we can assume that the special

variability is not to blame. In this situation, the possible corrections do not concern natural inhomogeneities but rather missing measurements. For a better explanation, I am adding an appendix with a simple scheme of a soil column along with a short comment. Please see the posted pdf for the corresponding scheme and formulas.

RC1: Line (L) 11: "'latent heat conversion…' into liquid water?"

Mainly by evaporation (into water vapor then), but condensation is also causing integrated G^c imbalance when the condensing water vapor is coming from the atmosphere, not from the deeper soil. This may happen with the crack presence. If the condensing water vapor is coming from the deeper soil, before becoming water vapor it was liquid water, before a condensation, we have evaporation. In this case, condensation counterbalances the evaporation effect. The solid (ice) melting into the liquid water gives rise to energy absorption too.

 RC1: L26" Many process->many processes (I report a few examples only of grammar errors)."

Grammar and spelling corrected.

RC1: L46 "the plates are not a technique"

Indeed, the plate *uses* a technique of sensing the temperature difference between two faces of a well-known material crossed by a heat flux. To my knowledge, all the plates use the same technique. The corresponding sentence is reformulated.

RC1: L65 "'de Beeck'-> Op de Beeck."

Done. I apologize to Maarten Op de Beeck.

RC1: L49" 'biased by inhomogeneities'. As mentioned above, I believe that all inhomogeneities should be adequately measured in proportion to their contribution to the overall flux."

This point is effectively similar to the previous one raised at the beginning of RC1 comments. Again, the inhomogeneities are not influencing the overall measurement *imbalance* but only influencing the local measurements imbalance close to the inhomogeneities boundaries installed SHFP. The target is not to correct the concerned measurements but to check that we have as many positively influenced SHFP as negatively influenced SHFP and to discard if any, obviously biased SHFP for overall heat flux calculation. This is suitable for later assessment of missing soil heat fluxes.

As mentioned previously, with a preserved soil temperature profile and preserved specific heat profile after one year, the overall flux integration, once geothermal energy is subtracted, should be nil, by definition. But it is true if, and only if, the plates' emplacements are representative. It means if all SHFPs are placed to counterbalance inhomogeneities deviations since each inhomogeneity gives rise to a positive imbalance in one emplacement and a negative imbalance in an adjoining emplacement the sum being nil by energy conservation. If not, the annual integration of the overall measurement is not nil and the main problem is then the measurement *representativity*. We cannot talk

anymore about adequately measured inhomogeneities. Furthermore, we never know in advance if plates are adequately measuring each inhomogeneity in proportion to their contribution to the overall flux (which is nil). Statistically, the more SHFP we are placing, the better is the chance to get representative measurement but it is not guaranteed. For these reasons also an annual integration of each SHFP measurement and the overall measurement gives us a quick idea about each SHFP representability and overall missing heat flux measurements.

RC1: "…11.2% sand, 2.8% organic matter. Here, granulometry and chemical composition are mixed up."

Absolutely, this soil classification is realized according to Malterre H. and M. Alabert (1963), Nouvelles observations au sujet d'un mode rationnel de classement des textures des sols et des roches meubles - pratique de l'interprétation des analyses physiques. Bulletin de l'AFES 2. pp. 76-84. Corresponding reference added into the text.

RC1: "L91-92: This sentence is explained in the following paragraph only."

Indeed, the corresponding indication is added to the concerned sentence for more clarity.

RC1: L97"'glocalization': geographical location?"

Mistyping, the correct word is "geolocalization" or Geo-localization.

RC1: "Around L 165 (Figure 3)., but why not use the data coming from partial shade? In a savanna, should all the trees be avoided? If we perform a stratified sampling, all the strata should be sampled. If we use random sampling, why not measure at specific, randomly selected, locations? I believe that this reasoning introduces a bias, not the contrary."

In this paragraph, I am discussing possible positive and negative biases. I am not trying to discourage anyone from installing the plates under partial or total shade. On the contrary, I stated L150- "Of course, if the plate B is placed at "symmetrical" emplacement of the plate C, the positive daily imbalance of plate B is then opposite of C plate imbalance, averaging these two plates will recover the accurate measurements. This is one of the reasons to have numerous plates installed." Based on my personal experience I am just noticing that "naturally" we tend to avoid shadowed surfaces. I am not cautioning it. That said, in the case of *obvious singular* inhomogeneity, I think that this position should be avoided. In a savanna, the trees' shadow is not a *singular* inhomogeneity.

RC1: "L200: 'the deep roots absorbed water has a lower temperature than the soil surface temperature.' Not always, in winter the contrary happens."

Absolutely, in the winter. However, during cold seasons, vegetation water use is much lower than it is in the hotter seasons. I calculated the amount of water used by winter wheat during one year, and winter wheat water usage during the cold seasons is relatively small. However, I nuanced this sentence. Please note that this calculation does not imply any relative temperature assumptions.

RC1: "L231: Rainfall has always a negative effect or it could be positive, for instance when the rain is liquid and the soil is frozen?"

Of course, this is a possibility. I did not record any corresponding occurrence on FR-Lam but this is a possibility. Please note again that for corresponding calculations no assumption on relative temperatures (rain temperature versus soil surface temperature) is needed.

RC1: "L270: I cannot understand why the geothermal flux should be added or removed from the measured flux."

I agree that this point was not clearly described and can be developed in the revised version. If for the SEB equation we are using overall SHFP measured G flux with subtracted geothermal flux $G^c = G - G_{Th}$, then we have to add to the SEB equation (please note that is negative). If it was subtracted from SHFP measured thermal flux only for missing convective soil heat flux assessing purpose but in the SEB equations we are using the raw SHFP measurement G then do not have to be added to the SEB equation.

RC1: "Figure 10: Could you place more intuitive units along the X-axis? 2.5 *10^7 s is about 289 days."

I have changed the units from seconds to days. The reason to use seconds rather than days or any other units is that a linear fit of J/m² versus seconds provides directly a slope in w/m².

RC1: "L293: I am getting lost here. I do not see any graph, Figure 6 was earlier, depicting the rainfall effect."

An error in the figure number in the text. It should be mentioned "10", not "6".

RC1: "L306: 'It is important to carefully chose the installation place and check the possible imbalance by a yearly integration.' Besides 'chose' (choose), I disagree with the concept expressed. I would prefer a fully random selection of the location places or stratified sampling, but always avoiding subjective 'expert selection'."

Effectively my sentences can be misinterpreted. Rather than privileging "emplacement designations" I am privileging "emplacement exclusions" such as near the pit for soil water

content probes or instrument enclosures. These pits or enclosures are not natural inhomogeneities but results from our (scientific) activities, are invasive and do not represent natural inhomogeneities existing on the studied plot. Random placement or other protocols are not discussed here and are beyond the scope of this paper. I would suggest "choosing" the way to place the plates (randomly or another way) at *natural* locations and *check* "a posteriori" if it was a "judicious choice" as even randomly placed plates may not equally represent heat fluxes affected by the inhomogeneities boundaries or be biased by SHFP malfunctions (SHFP cables can be deteriorated by animals causing intermittent malfunctions and so on).

RC1: "L327: The possible role of water table temperature is not discussed in the text."

Water table temperature was used to assess the G^c imbalance caused by evapotranspiration (l214-).