Answer to Reviewer 1,2

This is a simple, clear and useful manuscript.
Implementation of the proposed quality flagging scheme when WPL correction is large when compared to the actual gas flux makes good sense, and will improve flux data quality.
I have several minor, a few medium, and one major comment. Minor editorial suggestions are comments # 1-3, 6-10, 13, 15 in the attached file.

We thank George Burba for his helpful comments and have modified or supplemented the paper accordingly.
We have adopted the minor comments given in the supplement, except for comment 9, so that we do not explicitly address them here.

The possible range of CO_2 concentrations is 400 – 1500 ppm, but the range for which factor 3 applies is only 1000 – 1500 ppm. Thus, we have not made any changes. But, we have added a "for".

Medium comments:

 # 4 – This is quite good but to brief. It may be helpful to explain in more detail.

See our comment to Rev. 3, line 52-55

#5 - The surface heating correction seems constant in Fig 1, but it is supposed to change with temperature. Is this a maximum range for coldest temperature on that day?

In the resolution of the ordinate, the surface heating correction appears constant, since the air temperature changed only insignificantly during the period shown during the polar night (268-270 K). We added the temperature range in the figure caption.

#11 - The sentence is perhaps a bit too broad. This would not hold over water surfaces.

We have added "land surfaces" as this is also the main application of flux measurements. The extension to water surfaces would require too much information on temperatures and stratification. Thanks for pointing this out, otherwise the sentence could be misunderstood.

#12 and #16 - It may be important to also add that relatively imperfections in both zero and slope of the sensor calibrations will affect open-path fluxes during periods with very small natural flux. Especially if calibrations are performed in the field, these calibrations related errors in small fluxes are quite frequent.

We agree and have added this.

#14 - Surface heating correction should not really be applied in warm periods. It is still there, but very small, and modeling it brings more harm than good.

We agree with the reviewer, but unfortunately the correction is sometimes still applied in warm periods, e.g. by Kittler et al. (2017). We have added a note.

#17 and #18 - I get nearly identical numbers for Table 1 in some cases but very-slightly different for others. It may be because I am using 50% humidity and constant Cp and lambda. It may be helpful to list what humidity, Cp, and lambda are used in this table.

The quantities cp and lambda are valid for 15 °C (standard atmospheric conditions), see our comment to Rev. 3, line 52-55. The humidity was assumed to be 100 %.
At lower humidity values, the correction factor is a few percent lower in the term of the sensible heat flow. We have added this to the table caption.

#19 - This sentence seems too categorical. Surely people gave special attention to WPL related uncertainties in the past. Tables 3,4,5 from Burba et al, 2018 (https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.14614) is just one example, but many others did similar calculations before that.

Thank you for pointing out your paper. We have reworded the sentence and cited your paper. Nevertheless, we generally have the feeling that although the original paper is very clearly presented (see line 142), the fluxes are calculated schematically without paying the necessary attention to the WPL correction.

What did not seem to have happened in the past is the QC scheme involving such uncertainties in relation to the flux itself. This is a great idea and seems novel.
By the way, something similar can also be achieved by simply assuming a WPL uncertainty error bar of 15%. When this error bar crosses zero, the flux should be flagged. But your proposed QC scheme looks much less arbitrary and more sophisticated.

The suggested control of the error bar in comparison to the zero line is certainly also a possibility. We are not sure whether this could really be applied by all users, as these values are not always implemented in the software. Our method - which is obviously also the opinion of the reviewer - seems to us to be generalisable here and easy to implement in common software packages. We have not made any additions in this regard.

Major concerns:

My only major concern is with how to use MAD in this case and avoid excluding perfectly good data when fluxes are highly variable (sun-shadow for CO2, ebullition for CH4, N2O episodic emissions, etc.). There certainly should be a way to use MAD but successful use would greatly depend on how exactly MAD is implemented.

The MAD test has been widely used in recent years in the analysis of flux data after its first application by Papale et al. (2006). The relevant equation for the MAD-test is

$$\langle d \rangle - \frac{q \cdot MAD}{0.6745} \leq d_i \leq \langle d \rangle + \frac{q \cdot MAD}{0.6745},$$

with the scaling parameter q
One can distinguish three time ranges in which the test has been applied:
- Detection of spikes in the time range < 1 s (Mauder et al., 2013), q=7
- Detection of individual periods with exceptional fluxes in the time range 5-60 min: short-term methane emissions (Schaller et al., 2019), q=6; Birch effect after forest fires (Oliveira et al., 2021), q=5, CO_2 fluxes during ice/snow (Jentzsch et al., 2021), q=4
- Time series of CO_2 fluxes, time range > 30 min (Papale et al., 2006), q=4.

The scaling of the MAD test (factor q) is adapted by all authors to the process under investigation. We take up the reviewer's hint that it may be necessary to adapt the MAD test when investigating special events in order to enable reliable detection.

References

Jentzsch, K., Schulz, A., Pirk, N., Foken, T., Crewell, S., and Boike, J.: High levels of CO2 exchange during synoptic-scale events introduce large uncertainty into the Arctic carbon budget, Geophys. Res. Letters, 48, e2020GL092256, doi: https://doi.org/10.1029/2020GL092256, 2021.

Kittler, F., Eugster, W., Foken, T., Heimann, M., Kolle, O., and Göckede, M.: High-quality eddy-covariance CO_2 budgets under cold climate conditions, J. Geophys. Res.: Biogeosci., 122, 2064-2084, doi: 10.1002/2017JG003830, 2017.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H. P., Schmidt, M., and Steinbrecher, R.: A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements, Agric. For. Meteorol., 169, 122-135, doi: 10.1016/j.agrformet.2012.09.006, 2013.

Oliveira, B. R. F., Schaller, C., Keizer, J. J., and Foken, T.: Estimating immediate post-fire carbon fluxes using the eddy-covariance technique, Biogeosci., 18, 285-302, doi: 10.5194/bg-18-285-2021, 2021.

Papale, D., Reichstein, M., Aubinet, M., Canfora, E., Bernhofer, C., Kutsch, W., Longdoz, B., Rambal, S., Valentini, R., Vesala, T., and Yakir, D.: Towards a standardized processing of Net Ecosystem Exchange measured with eddy covariance technique: algorithms and uncertainty estimation, Biogeoscience, 3, 571-583, doi: 10.5194/bg-3-571-2006, 2006.

Schaller, C., Kittler, F., Foken, T., and Göckede, M.: Characterisation of short-term extreme methane fluxes related to non-turbulent mixing above an Arctic permafrost ecosystem, Atmos. Chem. Phys., 19, 4041-4059, doi: 10.5194/acp-19-4041-2019, 2019.

Supplement
Importance of the WPL correction for the measurement of small CO_2 fluxes

Katharina Jentzsch[1], Julia Boike[1,2], Thomas Foken[3]

[1]Alfred Wegener Institute, Telegrafenberg A6, D-14473 Potsdam, Germany

[2] Geography Department, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany

[3] University of Bayreuth, Bayreuth Center of Ecology and Environmental Research (BayCEER), D-95440 Bayreuth, Germany

Correspondence to: Thomas Foken (thomas.foken@uni-bayreuth.de)

Temperature dependence of quantities in Eq. (1)

The WPL correction is given by

$$F_c = \overline{w'\rho_c'} + \mu \frac{\overline{\rho_c}}{\overline{\rho_d}} \overline{w'\rho_w'} + (1 + \mu\,\sigma)\overline{\rho_c} \frac{\overline{w'T'}}{\overline{T}}, \qquad \text{(S1)}$$

Most quantities in Eq. (S1) are temperature dependent. The relevant temperature-dependent quantities of the 2nd term of Eq. (1) are $\overline{\rho_c}/\overline{\rho_d}$ and in the 3rd term $(1 + \mu\,\sigma)\overline{\rho_c}/\overline{T}$ (essentially σ and $\overline{T}$). The numerical values are taken from a book chapter (Foken et al., 2021) with extensive tables based on the current ITS-90 (Preston-Thomas, 1990) and TEOS-10 (Feistel et al., 2010;Wright et al., 2010) standards. The book should have been published long ago but is now scheduled for December 2021.

Especially the third term is of interest since it has the more significant influence on the WPL correction according to the present study. The results for a constant assumed value of ρ_c= 0.00078 kg m^{-3} are given in Fig. S1. Note: The density of CO_2 is about a factor of 1.55 greater than that of dry air, and the factor is almost independent of temperature.

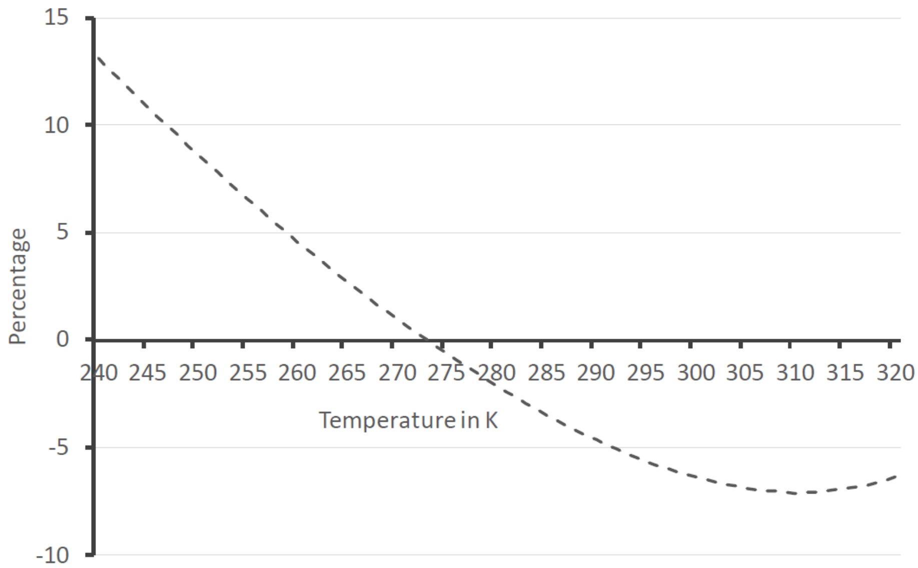

Figure S1: Percentage of the temperature dependent parts of the 3rd term in relation to the value at 273 K (constant density of carbon dioxide) for kinematic sensible heat flux

If the sensible heat fluxes are used in energetic units (correction with air density and specific heat at constant pressure), there is nearly no temperature dependency (Fig. S2).

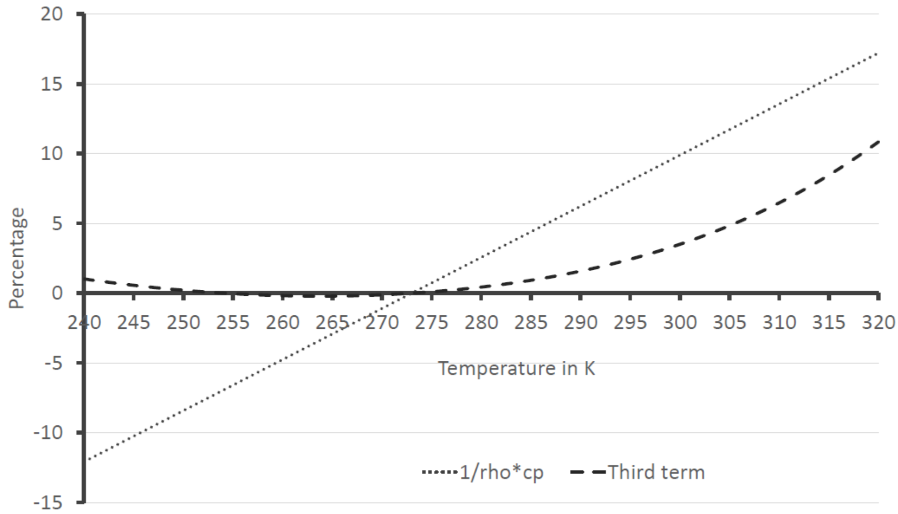

Figure S2: Percentage of the temperature dependent parts of the 3rd term in relation to the value at 273 K (constant density of carbon dioxide) for energetic sensible heat flux. Additionally, the percentage of the term $1/(\rho_d\, c_p)$ in relation to the value at 273 K is shown

References

Feistel, R., Wright, D. G., Kretzschmar, H. J., Hagen, E., Herrmann, S., and Span, R.: Thermodynamic properties of sea air, Ocean Sci., 6, 91-141, doi: 10.5194/os-6-91-2010, 2010.

Foken, T., Hellmuth, O., Huwe, B., and Sonntag, D.: Physical quantities, in: Handbook of Atmospheric Measurements, edited by: Foken, T., Springer Nature, Switzerland, 107-151, doi: 10.1007/978-3-030-51171-4_5, 2021.

Preston-Thomas, H.: The international temperature scale of 1990 (ITS-90), Metrologia, 27, 3-10, 1990.

Wright, D. G., Feistel, R., Reissmann, J. H., Miyagawa, K., Jackett, D. R., Wagner, W., Overhoff, U., Guder, C., Feistel, A., and Marion, G. M.: Numerical implementation and oceanographic application of the thermodynamic potentials of liquid water, water vapour, ice, seawater and humid air – Part 2: The library routines, Ocean Sci., 6, 695-718, doi: 10.5194/os-6-695-2010, 2010.