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

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Abstract. The WPL (***W**ebb*, ***P**earman*, and ***L**euning*) correction is fully accepted to correct trace gas fluxes like CO_2 for density fluctuations due to water vapor and temperature fluctuations for open-path gas analysers. It is known that this additive correction can be on the order of magnitude of the actual flux. However, this is hardly ever included in the analysis of data quality. An example from the Arctic shows the problems, because the size of the correction is a multiple of the actual flux. As a general result, we examined and tabulated the magnitude of the WPL correction for carbon dioxide flux as a function of sensible and latent heat flux. Furthermore, we propose a parameter to better estimate possible deficits in data quality and recommend integrating the quality flag derived with this parameter into the general study of small carbon dioxide fluxes.

1 Introduction

The WPL (***W**ebb*, ***P**earman*, and ***L**euning*) correction (Webb et al., 1980) has been fully accepted in the international scientific community for many years. After initial discussions on the derivation of the correction up to the beginning of the 2000s, no further discussions took place after the clarification by Leuning (2007, 2004). The correction is used in the textbook literature (Aubinet et al., 2012) and integrated in a similar form in all software packages for the calculation of eddy-covariance measurements and must be applied predominantly for open-path devices when the input variables are not measured as mixing ratios. The correction is necessary because fluctuations in temperature and humidity cause fluctuations in trace gas concentrations and that can simulate a flux, for instance of CO_2, or modify its size.

The size of the WPL correction on the CO_2 flux is generally assumed to be a few 10 %, and on the latent heat flux only about 1 % (Liebethal and Foken, 2003, 2004), but for Bowen ratios $Bo \gg 1$, it can be up to 10 % (Foken, 1989) of the raw flux data. The absolute value of the correction is in the range from –2.5 to +10 µmol m^{-2} s^{-1} depending on the magnitude of the sensible and latent heat flux. This correction to the measured flux can be large, i.e. the additive correction may significantly change the CO_2 flux calculated using the covariance of vertical velocity and partial density (Mauder et al., 2021). However, there is a lack of investigations under which circumstances the application of the WPL correction is uncritical and under which conditions it might produce physically impossible effects on the fluxes. However, it is obvious that CO_2 fluxes on the order of 1 µmol m^{-2} s^{-1} can be significantly altered by the WPL-correction.

In a recently published article on CO_2 fluxes under Arctic conditions (Jentzsch et al., 2021), events with strong CO_2 uptake and emission were investigated, which were also found by other authors (e.g., Lüers et al., 2014). It was found that these events may be artifacts due to the WPL correction because the CO_2 fluxes during the events are very strongly correlated with the sensible heat flux. These investigations were the reason to investigate the WPL correction under conditions of small CO_2 fluxes in more detail.

Such low fluxes occur, for example, over burned areas (Oliveira et al., 2021) or over sandy deserts (Su et al., 2013). This paper uses an example from the Arctic (Jentzsch et al., 2021) to show that the WPL correction may well lead to misjudgements of water vapour and carbon dioxide measurements with an open path gas analyser. The conditions under which the WPL correction has a considerable influence on the CO_2 flux are shown with possible consequences. Errors in CO_2 flux measurements in cold climate conditions have often been associated with the Burba correction (Burba et al., 2008;Kittler et al., 2017). This correction is relevant when convective processes occur at heated windows of the gas analyser. Because of the application of a low window temperature and an inclined position of the gas analyser this correction was not applied in the following study.

The WPL correction is relevant for the measurement of the partial density, e.g. of CO_2, with open path gas analyzers and the basic equations are (Foken et al., 2012)

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

with the corrected flux of scalar quantity (CO_2) F_c, the mass density of a scalar (CO_2) quantity ρ_c, the mass density of dry air ρ_d, the density of water vapor ρ_w, the measured trace gas (CO_2) flux $\overline{w'\rho_c{}'}$, the water vapor flux $\overline{w'\rho_w{}'}$, the sensible heat flux $\overline{w'T'}$, the mean temperature $\bar{T}$, and

$$\mu = \frac{m_d}{m_w} = 1.61\,;\ \sigma = \frac{\overline{\rho_w}}{\overline{\rho_d}}, \tag{2}$$

with the molar masses of dry air m_d and of water vapor m_w. Equation (1) can be simplified for the correction of H_2O-flux (latent heat flux)

$$F_w = (1+\mu\,\sigma)\left(\overline{w'\rho_w'} + \overline{\rho_w}\,\frac{\overline{w'T'}}{\bar{T}}\right). \tag{3}$$

In (1) and (3), ρ_w' and T' represent fluctuations of water vapor and temperature inside the measurement volume of the open path gas analyzer.

Most quantities in Eq. (1) are temperature dependent. It is obvious to investigate whether there is a temperature dependence of the WPL correction. The relevant temperature-dependent quantities of the 2nd term of Eq. (1) are $\overline{\rho_c}/\overline{\rho_d}$ and in the 3rd term $(1+\mu\,\sigma)\overline{\rho_c}/\bar{T}$ (essentially σ and $\bar{T}$), see Foken et al. (2021). Temperature effects in the terms partially compensate each other.

For the sensible and latent heat flux in kinematic units there is no temperature dependence for temperatures > 0 °C. For negative temperatures, there is a dependence that provides up to 15% higher correction at approx. –30 °C. If the heat fluxes are used in energetic units (correction with air density), there is no temperature dependency, only a few percent at temperatures above 20–30 °C. For more details see Supplement.

2 Material and carbon dioxide fluxes under Artic conditions

The measurements shown are from the Bayelva site located at 78°55'N and 11°50'E in the European high Arctic, about 2 km south west of the research settlement of Ny Ålesund, in the north west of the Svalbard archipelago. The eddy-covariance instruments relevant for this study are an ultrasonic anemometer CSAT3 (Campbell Sci.) and an open-path gas analyser 7500A (Licor Biosciences). The data were calculated with the software package EddyPro (Licor Biosciences, 2017, Version 7.0.6). For more details on the site, instrumentation, and data analysis, see Jentzsch et al. (2021). The measurements of this site were published e. g. by Westermann et al. (2009) and Lüers et al. (2014).

Figure 1 shows a measurement example for short-term CO_2 emission (positive flux) on 06 December 2015 (polar night). In comparison, the magnitude of the WPL correction is shown. Also, the Burba correction (Burba et al., 2008) is shown and is well below 50% of the corrected flux. During the short period around 9 am, the sensible heat flux was about –70 W m^{-2} and the latent heat flux 35 W m^{-2}. Evaporation/sublimation was also confirmed by gradient measurements (data not shown). The necessary energy for evaporation was supplied in the polar night by the downward directed sensible heat flux.

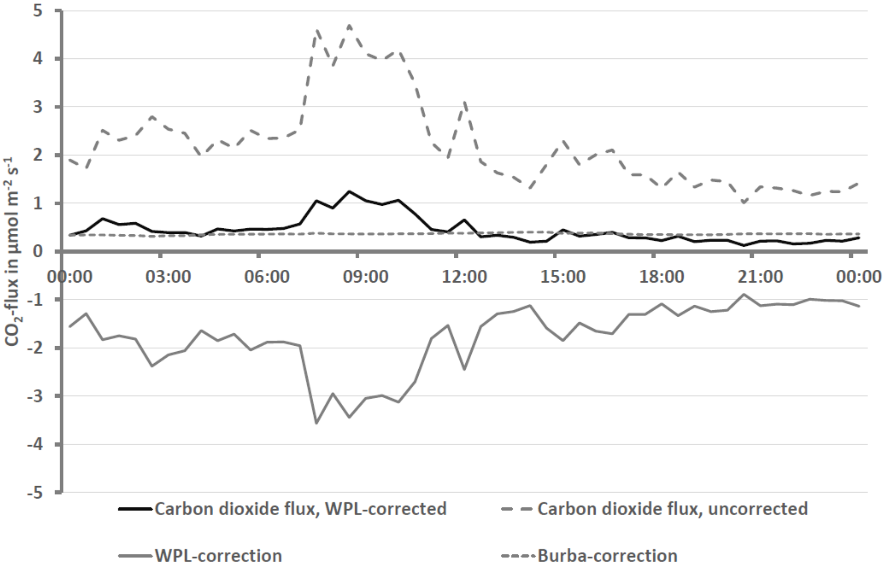

Figure 1: Comparison of WPL-corrected and uncorrected CO_2-flux together with the size of the WPL- and Burba-correction on 06 December 2015 at the Bayelva site calculated with EddyPro, temperature range 268–270 K

In Fig. 2, both terms were explicitly calculated with the measured data and not by EddyPro with identical results. It is shown that temperature fluctuations have a much stronger influence on the size of the WPL correction.

In the case of a CO_2 uptake (negative flux) with negative sensible heat flux, the absolute value of the flux would be even larger. In the case of positive sensible heat flux, the 3rd term in Eq. (1) is also positive and an uptake would be reduced, while emissions would be increased.

The influence of the WPL correction on the latent heat flow is not shown. It is known to be relatively small, and in the present case for the period from 08:00 to 11:00 am it was about 3%, at all other times 1–2%. This is below the typical flux measurement error (Foken et al., 2012) for most of the fluxes of about 10%.

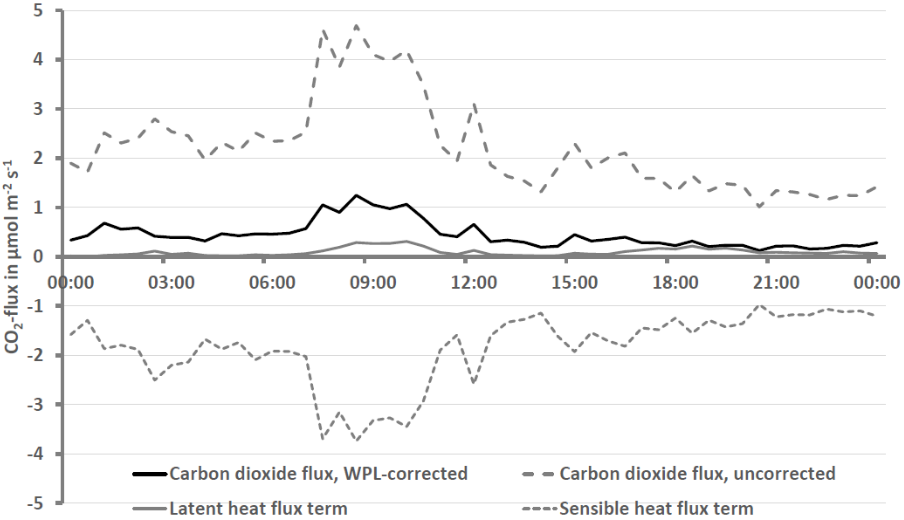

Figure 2: Comparison of WPL-corrected and uncorrected CO_2-flux together with the size of humidity fluctuations term (2nd term on the righthand side of Eq. (1) and temperature fluctuations term (3rd term) for the data set shown in Fig. 1

3 Results and Discussion

3.1 Size of the WPL correction

A variable CO_2 density has a linear influence on the WPL correction, since it is part in both terms. This can lead to an increase of the correction up to about a factor 3 (for 1000 to1500 ppm CO_2 concentration) over strongly respiring surfaces under stable stratification. With strong assimilation, on the other hand, the concentration can go only slightly below the global average.

Table 1 shows for standard atmospheric conditions (1013 hPa, 15 °C) and a CO_2-concentration of 415 ppm the WPL correction as a function of the size of the sensible and latent heat flow. The table hardly differs from Fig. 1 in Webb et al. (1980), who have already pointed out the considerable size of the correction in kg m^{-2} s^{-1}.

For small CO_2 fluxes, the WPL correction is sometimes a multiple of the actual flux. Especially for fluxes < 5 µmol m^{-2} s^{-1} the interpretation of extraordinary events is very questionable. In the present case (Fig. 1), an absolute value of the sensible heat flux increased by 20 W m^{-2}, which is still within the error range, would no longer show a clear emission event. Since the event cannot be plausibly explained physically, it should be marked as faulty and excluded by a MAD test (absolute deviation from the median, Papale et al., 2006), which must be adapted to the respective process to be investigated.

Small errors could have a large impact on cumulative fluxes, especially if the errors have a bias. Therefore, the interpretation of such fluxes has to be done very carefully. However, in the case of a carbon uptake and positive sensible heat fluxes, these fluxes would be reduced and, as the above example has shown, emissions with negative sensible heat fluxes would also be reduced. This could compensate the errors, but this would have to be shown in each individual case.

Furthermore, small CO_2 fluxes often occur in connection with negative sensible heat fluxes. This is the case when evaporation takes place, but the energy required for this must be provided at least partially by a downwardly directed sensible heat flux. This is known as the so-called oasis effect (Foken, 2017;Stull, 1988), which occurs relatively often in the late afternoon. The case discussed here during the polar night can also be described as an oasis effect. Furthermore, a strong cooling of the surface by long-wave radiation causes a compensation by a downward directed sensible heat flux. This is particularly typical in the first half of the night, when the stratification is stable. Over land surfaces small CO_2 fluxes can always be considered reliable when the sensible heat flux is close to zero.

Table 1: WPL correction in µmol m^{-2}s^{-1}, 2nd and 3rd term of Eq. (1), as a function of sensible and latent heat flux for standard atmospheric conditions (1013 hPa, 15 °C) and a CO$_2$-concentration of 415 ppm and 100 % relative humidity (At lower humidity values, the correction factor is a few percent lower in the term of the sensible heat flux)

Sensible heat flux in W m^{-2}	Latent heat flux in W m^{-2}							
	0	10	20	30	50	75	100	200
-50	-2.5	-2.5	-2.4	-2.3	-2.1	-1.9	-1.7	-0.9
-30	-1.5	-1.4	-1.4	-1.3	-1.1	-0.9	-0.7	0.1
-20	-1.0	-0.9	-0.8	-0.8	-0.6	-0.4	-0.2	0.7
-10	-0.5	-0.4	-0.3	-0.3	-0.1	0.1	0.3	1.2
0	0.0	0.1	0.2	0.3	0.4	0.6	0.8	1.7
10	0.5	0.6	0.7	0.8	0.9	1.1	1.3	2.2
20	1.0	1.1	1.2	1.3	1.4	1.6	1.9	2.7
50	2.5	2.6	2.7	2.8	3.0	3.2	3.4	4.2
75	3.8	3.9	4.0	4.1	4.2	4.4	4.6	5.5
100	5.1	5.2	5.3	5.3	5.5	5.7	5.9	6.8
200	10.2	10.3	10.3	10.4	10.6	10.8	11.0	11.8

3.2 Quality flagging of the WPL correction

Since the specificity of possible errors in WPL-correction is not taken into account by usual error analyses of eddy-covariance data (e. g. Mauder et al., 2013), measurement data with very large WPL corrections should be marked. A possible parameter could be the ratio of WPL correction and corrected CO$_2$ flux:

$$QF_{WPL} = \frac{\mu \frac{\overline{\rho_c}}{\overline{\rho_d}} \overline{w'\rho_w'} + (1+\mu\,\sigma)\overline{\rho_c}\,\frac{\overline{w'T'}}{\overline{T}}}{\overline{w'\rho_c'} + \mu \frac{\overline{\rho_c}}{\overline{\rho_d}} \overline{w'\rho_w'} + (1+\mu\,\sigma)\overline{\rho_c}\,\frac{\overline{w'T'}}{\overline{T}}} \qquad (4)$$

Similar parameters could be defined separately for the term of humidity fluctuations QF$_w$

$$QF_w = \frac{\mu \frac{\overline{\rho_c}}{\overline{\rho_d}} \overline{w'\rho_w'}}{\overline{w'\rho_c'} + \mu \frac{\overline{\rho_c}}{\overline{\rho_d}} \overline{w'\rho_w'}} \qquad (5)$$

and temperature fluctuations QF$_T$

$$QF_T = \frac{(1+\mu\,\sigma)\overline{\rho_c}\,\frac{\overline{w'T'}}{\overline{T}}}{\overline{w'\rho_c'} + (1+\mu\,\sigma)\overline{\rho_c}\,\frac{\overline{w'T'}}{\overline{T}}}\,. \qquad (6)$$

Fig. 3 shows these parameters for the example given in Fig. 1. Here QF$_w$ is < 1 and therefore has only little influence on the correction, which is essentially determined by QF$_T$. The parameter QF$_{WPL}$ should be sufficient for the quality identification of WPL corrected CO$_2$ flux. Following common systems with quality flags (Foken and Wichura, 1996;Foken et al., 2012), $|QF_{WPL}| \leq 0.5$ could be classified as very good, $0.5 < |QF_{WPL}| \leq 1$ as good and all values $|QF_{WPL}| > 1$ should be specially checked. It is useful to define maximum limit values for the WPL-corrected CO_2 flux if the flux is below the detection limit, because then the absolute $|QF_{WPL}|$ values can be significantly higher than 5 (see Fig. 1 and 3 after 18:00).

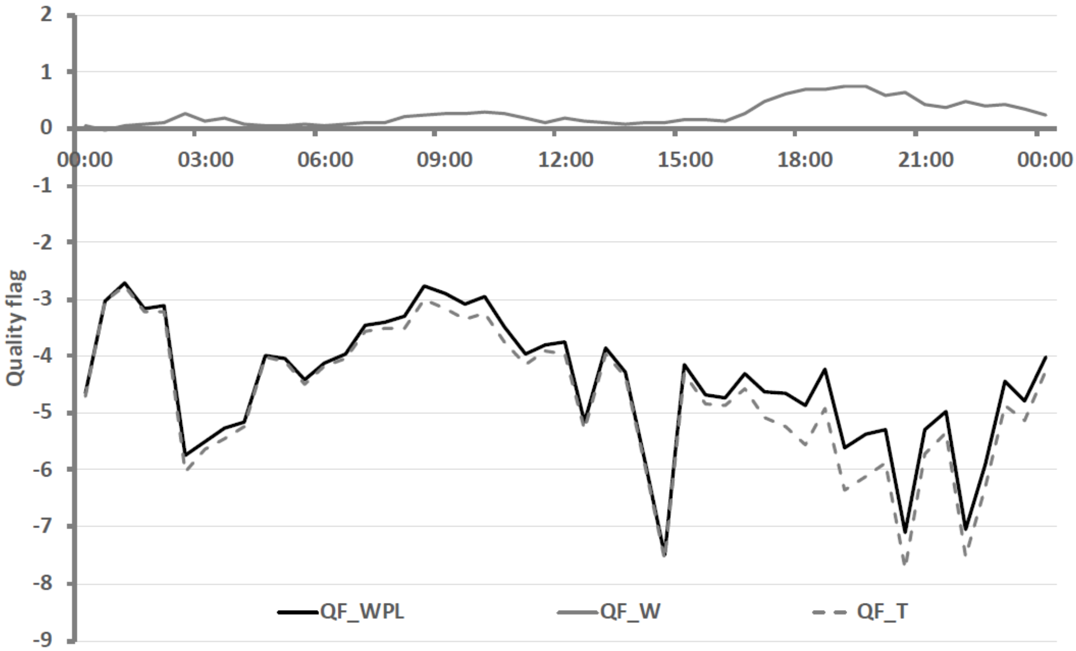

Figure 3: Quality flags of the WPL correction according to Eq. (4) for the example given in Figure 1

Due to the significant problems with the additive WPL correction, other possible influencing factors, such as spectral cross-sensitivities between CO_2 and water vapor (Kondo et al., 2014) and imperfect sensor calibrations are excluded from the discussion. Furthermore, the Burba correction (Burba et al., 2008), which is a modified WPL correction, should be re-examined under these conditions. This might explain Burba corrections in the summer half year that are difficult to interpret (Kittler et al., 2017). However, the correction should generally not be applied in the warm season.

4 Conclusion

According to the original work on the WPL correction (Webb et al., 1980), it should be known that in some conditions the correction is expected to be in the same order of magnitude as the flux. This fact has only been given the necessary attention in a few works on the error analysis of CO_2 fluxes or other trace gas fluxes (Burba et al., 2019), to which the above statements apply analogously, measured with open-path gas analysers. From the investigation of individual events of CO_2-fluxes presented in this study, we have formulated the following conclusions:

(i) We strongly suggest that the WPL correction should be subjected to a special quality analysis. For this purpose, the quality flag of the correction expressed in Eq. (4) or/and (Eq. (6) could, for example, be explicitly output for all eddy-covariance software packages. At least for small fluxes it would have to be included in the quality considerations.

(ii) We propose that special events in time series of trace gas fluxes should only be interpreted if the WPL quality flag is below a maximum limit values and they can be clearly assigned to physical processes, qualitatively and quantitatively. Otherwise, these data should be identified with a MAD analysis and interpolated if necessary.

(iii) We suggest that respiration data for the derivation of the gap-filling algorithm (Lloyd and Taylor, 1994) should be obtained at times when the sensible heat flux is near 0 W m^{-2}, i.e. if possible in the second half of the night and not at sunset because of the relatively large negative sensible heat fluxes. The quality criterion should be applied to these data.

(iv) If CO_2 fluxes < 5 µmol m^{-2} s^{-1} are expected at a site, we recommend the use of a closed-path gas analyser instead of an open-path gas analyser. However, it must be guaranteed that complete isothermal conditions are achieved in the measurement volume of the closed path sensor, otherwise the same problems as described above will occur.

(v) In addition to the WPL correction we recommend that all corrections used in the eddy-covariance method, which are made by adding correction terms to the measured flux, should be critically reviewed. This applies, for example, to the Burba correction for open-path gas analysers and the various corrections for closed-path devices. It may also be necessary to investigate whether errors in the application of the WPL correction and the above-mentioned corrections lead to a bias in accumulated fluxes, for which appropriate simulations will probably have to be performed.

(vi) These remarks suggest that a discussion on alternative measurement methods and minor imperfections in field calibrations should be continued. This includes the direct measurement of the mixing ratio (Kowalski and Serrano-Ortiz, 2007), as realized in closed-path instruments, when complete isothermal condition is guaranteed in the measurement volume. But also a density averaged measurement of CO_2 fluctuations (Kramm et al., 1995) according to the Hesselberg averaging (Hesselberg, 1926) should be reconsidered.

Author contributions KJ made first investigations of the WPL term under Arctic conditions, guided by JB. These first analyses were extended by TF to the present paper. After the discussion of the results, KJ, JB, and TF completed the paper.

Competing interests. The authors declare that they have no conflict of interest.

Data availability. The eddy-flux data are openly available under CC-BY-4.0 in the FLUXNET data base (http://www.europe-fluxdata.eu/;ID:Sj-Blv).

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