

Answer to reviewer #1 comments.

We kindly thank the reviewer for his useful comments and suggestions. Particularly, we want to point out that it greatly helped to learn about the last outcomes about flow distortion issues in sonic anemometers and we were aware of the simplicity of our previous approach. By analyzing the reviewer's proposed literature, we have been able to strengthen our analysis of the related errors. We provide a full answer to this particular point in this document and inside the manuscript.

Answer to all general, specific, and editorial comments can be found below. References to changes in the main text have been introduced when necessary. We provide an edited version of the manuscript, and a final version. Pages and lines numbers refer to those of the final version of the manuscript. Added text related to reviewer #1 comments is shown in red in the edited version, and in blue for answers related to reviewer #2 comments.

Aim of the paper and how it advances science

We understand the concern of the reviewer regarding the focus of the paper. The paper is strongly motivated by previous publications concerning the same dataset (Sicart et al., 2014, Litt et al., 2015) and other energy balance studies conducted on mountain glaciers. Uncertainty assessment is crucial to test the sensibility of distributed energy balance models dedicated to the calculation of glacier melt using meteorological variables (Conway and Cullen, 2013). Energy balance studies on glaciers generally correctly assess the radiation fluxes, and their related errors, but turbulent fluxes and associated errors remain poorly understood. There are only a few studies dealing with error assessment on turbulent fluxes measurements on mountain glaciers, and this one is probably the most comprehensive on tropical glaciers. Following the reviewer's remark we updated the introduction with all these comments in order to clarify the scope of the paper.

Specifically concerning the motivation of this paper, (as stated in the text on pages 3-4 at lines 27-30 and 1-3), the study of Litt et al. (2015) showed that larger flux magnitudes were found using the EC method than when using the bulk method. Considering the EC method as a reference, Litt et al. (2015) stated that the underestimation of the bulk method was probably due to non-stationarity of the flow and to a non-equilibrium surface layer. Nevertheless we felt that a thorough error analysis was necessary to confirm that other measurement biases were not responsible for this discrepancy.

Changes in the text:

Section Introduction, page 3 lines 4-8,

“Uncertainty assessment is necessary for sensibility studies in distributed energy balance models dedicated to glacier melt estimation from meteorological variables (Conway and Cullen, 2013). Generally, energy balance studies precisely assess the radiation components of the balance, and the related errors, but turbulent fluxes and associated errors remain poorly understood.”

Section Introduction, page 5, line 8-9,

“This study is one of few concerning error assessment of turbulent fluxes measurements on glaciers (e.g., Box and Steffen, 2001; Conway and Cullen, 2013; Sicart et al., 2014a).”

(1) Energy Balance Closure

The reviewer underscores that reporting on the degree of energy balance (EB) closure at our site would enhance the paper. We totally agree, and would have liked to be able to conduct such a study: EB closure would provide another independent estimation of the turbulent fluxes, since they can be inferred from melt measurements if the radiative fluxes (measured during the campaign) and conductive fluxes below the surface are known. Unfortunately, the glacier surface conditions and the experimental set-up during the campaign did not allow for measurements of the subsurface conductive fluxes.

The glacier surface temperature constantly changes between nights and day. The surface was generally at 0°C (melting) during the day while during the night large radiative losses lead the surface temperature to strongly negative values of around -8°C (see Fig. 8). It results in a non-negligible conduction flux below the surface. During the day, significant heat is transferred from the surface to the ice or snow to compensate for the nocturnal heat losses. Since temperature measurements below the ice or snow surface are challenging due to solar radiation heating of the sensors inside the ice or snow and since the surface height continuously changed due to snow compaction, snowfalls or snow and ice melt, measurements of the conductive fluxes were not made during the campaign. This prevents us from calculating the EB closure at this site.

Following the reviewer’s comment, we added a statement at the very end of the conclusion.

Changes in the text:

Section 5 Conclusion, page 28, lines 5-20,

“An estimation of the turbulent fluxes could be obtained from the estimation of melt rates and of all other energy balance terms. Such an independent estimation may help understanding the origin of biases evidenced herein. Since ice or snow temperature measurements are challenging due to solar radiation contamination heating of the sensors below the surface (Helgason and Pomeroy, 2012), the potentially large conduction flux below the surface remained unknown during the 2007 campaign on Zongo glacier. This prevented us from conducting an energy balance closure check. Energy balance closure studies should be conducted on temperate glaciers when the surface is constantly melting, the temperature profile below the surface is isothermal at 0°C and conduction fluxes are zero. Such studies may improve the estimation of measurement errors on turbulent heat fluxes.”

(2) Transducer shadowing

We carefully read the proposed literature and had a contact also with J. Frank from USDA Forest Service, Colorado. We received comments and a copy of the suggested talks presented at AGU in 2014. Following the reviewer’s comments, we applied the method of Horst et al.

(2015) to correct our CSAT data for transducer shadowing and compared corrected and uncorrected covariances for given events, representative of each of the three wind regimes. Unfortunately Frank's paper is still unavailable at this time so we couldn't use his method. With Horst's method we obtain a more precise estimation for the flux underestimation due to transducer shadowing. Underestimations are lower than what was inferred previously: we obtained 6% (in agreement with the findings of Horst et al., 2015) as a maximum underestimation against the 16% that we obtained in the first calculations. We removed references to the Gash and Dolman method that we used previously to analyse the contributions to fluxes at different attack angles. We changed Figure 4 for a new figure which presents the relative difference in the covariance estimations obtained with and without correction. The text in methods, results and conclusion sections and the caption in Figure 4 have been updated according to these new findings.

Changes in the text:

Section 3.2.2, Potential systematic errors on eddy-covariance fluxes, page 12, lines 5-12,

"To evaluate the degree to which this error could affect our measurements, we selected runs during specific events for which wind conditions were representative of the three main wind regimes. For each event we compared the covariances of w with θ and q , obtained without correction related to the attack angle, and covariances obtained after correcting the wind components for transducer shadowing following the method proposed by Horst et al. (2015). The relative difference between these covariances, plotted against ω , the attack angle relative to the u - v plane of the instrument, helps us to evaluate the degree of flux underestimation under each wind regime. and calculated which portion of flux, Φ_{ω} , was exchanged at a given attack angle ω . The angles of attack were binned in intervals of 2.5° denoted by the γ indice. We have (Gash and Dolman, 2003):

Equation suppressed

where β is the number of angles of attack ω lying in the γ^{th} bin, N is the total number of samples in the run, and $x = \theta$ or q .

Section 4.1.2, Estimates of systematic errors, page 19, lines 16-26,

"Relative difference between covariances Flux contributions corrected with the Horst et al. (2015) method and uncorrected covariances at different attack angles for one of the EC systems are shown in Fig. 4, for selected cases whose characteristics were representative of the three wind regime subsets. The difference is shown for different attack angles. Slightly higher flux was found at large attack angles in "upslope" and "downslope" cases than in the "katabatic" case, probably because the flow was gustier under strong winds in "upslope" and "downslope" cases. We found that, at most, around 30% (19% plus 11%; red dotted lines in Fig. 4) of sensible heat flux was exchanged at attack angles greater than 15° . Regarding latent heat, 21% (19% + 2%) of the flux was exchanged at attack angles greater than 15° . We assumed that the relation between attack angles and flux underestimation was the same for H and LE , that the fluxes exchanged at $\omega < 15^{\circ}$ were underestimated by 10%, following Frank et al. (2013), and

~~that for $w > 15$ the underestimation was 20% (slightly higher than the 15% found by Kochendorfer et al., 2012a, for the R.M. Young Sonic Anemometer (Kochendorfer et al., 2012). For most attack angles, corrected fluxes are between 3 and 6% larger than the uncorrected fluxes, in agreement with findings from Horst et al. (2015). Corrections larger than 6% are found only for the “pure-katabatic” case, for both H and LE between -10° and 0° attack angles, and for LE in “downslope” cases above 25° attack angles. On average over all attack angles, the correction remains small, it is 5.6%, 3.7% and 3.6% for H in the “pure-katabatic”, “upslope” and “downslope” cases, respectively, and 5.7%, 3.9% and 2.6% for LE, respectively. Consequently, we assume that roughly, both sensible heat and latent heat fluxes were underestimated by about 46%, as an upper boundary.”~~

Section 4.1.2, Estimates of systematic errors, page 20, lines 22-26,

~~The main source of underestimation was probably related to potential underestimates of w in non-orthogonal sonic-anemometers ($\sim 46\%$, Fig. 4). Putting aside flux divergence between the surface and the sensors and including the high-frequency spectral losses ($\sim 4\%$, Table 3), underestimates from the EC method could be as large as 2010%. The large flux bias resulting from the w bias must be considered with caution, since this issue has only been recently studied, is not well documented, remains controversial (e.g. Mauder, 2013; Kochendorfer et al., 2012b), and since large potential biases were considered in our study.~~

Section 5 Conclusion, pages 26-27, lines 25-26 and 1-2,

~~Biases could lead to underestimating flux magnitude by around 2010% using the EC method. The largest bias was potential underestimation of vertical wind speed by the non-orthogonal anemometers, which could lead to underestimating fluxes magnitudes by about 46%. Such a large bias must be considered with caution, since we intentionally used large estimates. Furthermore, this issue is not well documented and remains controversial. High-frequency losses remained small, at most $\sim 4\%$.~~

Figure 4 caption, page 46,

~~Relative difference between uncorrected covariances (w_x , $x = \theta, q$) and covariances corrected for transducer shadowing ($w_{x,c}$) for different attack angles and selected events inside each of the main wind regime subsets. Results for (a) w_θ and (b) w_q during “pure-katabatic” (black), “downslope” (blue) and “upslope” (red) events are shown. Cumulative contribution to fluxes H and LE (%) from different attack angles, calculated over selected events inside each of the main wind regime subsets. Flux contributions are aggregated from higher attack angles to lower attack angles. The height of the curve at a given attack angle indicates the total flux contribution at angles higher than the given angle. Cumulative contribution to (a) H fluxes and (b) LE fluxes during “pure-katabatic” (black), “downslope” (blue) and “upslope” (red) events. Red dotted lines indicate the 15 deg threshold and the corresponding percentage of flux.~~

Specific comments.

(3) Page 1063, Equation (2) – I believe that the ‘Wpl’ should be all upper case, i.e., ‘WPL’.

we agree, changed

(4) Page 1074, lines 10-11 – The authors claim that “relative random errors derived from the ML method canceled out to a mean of 12%”. Their statement is at the very least not clear and at worst contradicts their Section 3.3.1 and Equations (15) and (16). According to these last two equations random errors are estimated as positive definite quantities. As such they cannot cancel each other out; they can only add to an ever increasing estimate.

We simply follow error analysis theory, the error on the mean \bar{F} of n values of the flux F , each one affected by an error δF , is given by:

$$\delta \bar{F} = \frac{\delta F}{\sqrt{n}}$$

So that by increasing the number of measurements, this reduces the random error on the mean. That is why our random error decreases on the mean flux over the campaign compared to that on the individual 1-h measurements.

(5) Page 1081, paragraph defined by lines 5-9 – The authors suggest that the BA method severely underestimates the magnitude of the net turbulent fluxes due to its inability to account for the flux induced by katabatic oscillations or outside-layer interactions with the surface layer. This is certainly plausible, but I also think that it is also one aspect of the larger failure of the similarity and non-stationarity assumptions upon which the BA method is based. I think the authors should also include this point in their discussion.

This problem is discussed in Section 4.2.2, “Estimates of systematic errors”, on page 23, lines 18-27, but the statement in the discussion section was not so clear, we agree. We added a sentence to clarify.

Changes in the text:

Section 4.3 Net turbulent fluxes and wind regimes, page 25 lines 24-26,

“These influences lead to nonstationarity of the flow and flux divergence above the ground and thus to divergence from the required conditions for similarity to hold, which may explain the observed flux underestimations.”