Responses to Reviewer 1

We thank the reviewer for the insightful comments. Below is a point-by-point response to their review.

All new major modifications are highlighted in yellow here and in the main manuscript.

General comments

This manuscript aims to evaluate the performance of different scalar flux quantification methods that can be applied to measurements at one height, especially when only slow-response sensors are available that do not suffice for direct eddy covariance (EC); these methods are disjunct eddy covariance (DEC), relaxed eddy covariance (REA) and the mixing length model of A22. They are tested for two real-world data sets of high-frequency turbulence measurements that are artificially deteriorated or filtered. The paper is generally well written and clearly structured, but I have one main concern, which is that the authors do not apply the DEC and REA method as is it usually applied in other studies, thereby potentially giving the false impression that these methods create a systematic bias in flux estimates. This should not be the case if everything is done properly. Normally, only the random uncertainty or the scatter should increase. At least from this manuscript, I cannot rule that the authors have a fundamental misconception about the DEC method. It still requires a fast sampling, even if a slow-response sensor is applied, and the sampled air can then be analysed for a while before the next fast (instantaneous) grab sample is taken. Hence there is no low-pass filtering involved. Only the number of samples per averaging period is decreased, which usually leads to a larger random error but no systematic error (Karl et al. 2002, Rinne et al. 2001, 2008). Similarly, it should be clear to any micrometeorological practitioner that the REA method requires fast switching valves that can change the air flow in less than 0.1 s. However, the authors apply filtering time scales of several seconds. This is not how REA is done in reality. Because of this shortcoming, I can only recommend a major revision of this manuscript.

Response:

We thank the reviewer for bringing up these important points and the shared references which were instrumental for the revised version. To address the reviewer's concern here, we are recapping below the original flow of the paper and showing the modifications we made.

The main purpose of the paper was to evaluate the performance of different models in estimating the scalar turbulent fluxes under **stable** conditions across two contrasting sites (Q1). The second motivation was to test these models under scenarios for which fast sensors are not available or where slow/medium response sensors are technically and/or economically the only viable option (Q2). To that end, we revised the paper, adjusted the approach, and incorporated the necessary modifications to address these questions/motivations in a clearer way. (Q1)'s approach stays the same. In addressing (Q2), we are explicitly considering scenarios where only slow-response sensors are deployed. Our original text may have been confusing since we indeed agree that REA apparatuses can be fast and give results comparable to our REA results with fast sensors; this is now made clearer though the caveat of this need for speed is underlined. DEC grabs instantaneous samples fast but at large intervals, and while this does indeed miss contributions from a range of small scales, it does not give identical fluxes to a filtered signal, so we have removed any analyses of DEC directly.

But we still aim to examine the application of an REA approach that does not require a mechanical apparatus, as now explained and motivated more clearly. Hence, we give our proposed model another name when we apply filtering (**VEA**: Virtual Eddy Accumulation instead of **REA**), i.e., when using the slow-response scalar signal and when a mechanical experimental apparatus to separate the flows is not involved. VEA **recovers** an REA system when filtering is not applied.

The **observed filtered** fluxes with the slow sensors are now referred to as **LEC** fluxes (LEC: Large eddy-covariance), instead of **DEC**. Hence, the DEC is no longer referred to as a benchmark to compare to in the analysis, and REA is only used and referred to when dealing with the **high-frequency** signal sampled in a way that mimics a fast, flawless mechanical flow separation device..

As such, the **main** elements that have changed in the paper are listed below:

1. Abstract:

   Conventional and recently developed approaches for estimating turbulent scalar fluxes under stable atmospheric conditions are evaluated, with a focus on gases for which fast sensors are not readily available. First, the relaxed eddy accumulation (REA) classical approach and a recently-proposed mixing length parameterization, labelled A22, are tested against eddy covariance computations. Using high-frequency measurements collected from two contrasting sites (the frozen tundra near Utqiagvik, Alaska and a sparsely vegetated grassland in Wendell, Idaho during winter), it is shown that the REA and A22 models outperform the conventional Monin-Obukhov Similarity Theory (MOST) utilized widely to infer fluxes from mean gradients. Second, scenarios where slow trace gas sensors are the only viable option in field measurements are investigated using digital filtering applied to fast-response sensors to simulate their slow-response counterparts. With a filtered scalar signal, the observed filtered eddy-covariance fluxes are here referred to as large eddy-covariance (LEC) fluxes. A virtual eddy accumulation (VEA) approach, akin to the REA model but not requiring a mechanical apparatus to separate the gas flows, is also formulated and tested. A22 outperforms VEA and LEC in predicting the observed unfiltered (total) eddy-covariance (EC) fluxes; however, VEA can still capture the LEC fluxes well. This finding motivates introducing a sensor response time correction into the VEA formulation to offset the effect of sensor filtering on the underestimated net averaged fluxes. The only needed parameter for this correction is the mean velocity at the instrument height, a surrogate of the advective timescale. The VEA approach is very suitable and simple to use with gas sensors of intermediate speed ($\sim$ 0.5 to 1 Hz), and with conventional open or closed path setups.

2. Introduction:

Highlighted in the paper.

3. Subsection 2.5: VEA: Virtual eddy accumulation flux model

   New Subsection Highlighted in the paper.

4. Subsection 2.6: LEC: Large eddy covariance model

   New Subsection Highlighted in the paper.

5. Subsection 4.2: Simulating a slow scalar sensor for model testing

   Highlighted in the paper.

6. Subsection 4.3: LEC, VEA and A22 model evaluation using simulated slow sensor data

   Highlighted in the paper.

7. Subsection 4.4: A sensor-response correction for the optimal VEA coefficient β_v

   Highlighted in the paper.

8. Conclusions:

   Highlighted in the paper.

The correction factor in the new model (**VEA**) is now referred to β_v instead of β_s

All relevant figures were **updated** to reflect these modifications.

Specific comments

L4: The abstract is rather short, I would welcome one or two more sentences describing the two field experiments.

Response:

Thanks for the suggestion. Please refer to point 1 above which shows the revised and more detailed abstract.

We added a brief description to the two field experiments.

L8-9: I am not sure what you try to say with this sentence, be more specific. Under which circumstances?

Response:

The new sentence in the revised abstract is below:

A22 outperforms VEA and LEC in predicting the observed unfiltered (total) eddy-covariance (EC) fluxes; however, VEA can still capture the LEC fluxes well.

No special circumstances, all periods are under stable conditions.

L120-125: Any references for the DEC method?

Response:

Added in the **new** subsection 2.5: VEA: Virtual eddy accumulation flux model

L167: What sonic anemometer model was used?

Response:

Thanks for pointing this out. The below lines are added there:

The lowest anemometer (model TR90-AH, Kaijo Denki, Japan) had a 5-cm pathlength and provided data at a frequency of 20 Hz, while the other three sonic anemometers (model CSAT3, Campbell Scientific Inc., Logan, Utah) each had a 10-cm pathlength, and provided data at a frequency of 10 Hz.

L187-193: I am not sure about the purpose of this paragraph here. It is not really suited as an overarching introduction to section 4, but rather belongs to only to section 4.1, since it does not mention DEC, which is treated in section 4.2 and 4.3

Response:

Corrected to account for all the proposed models (A22, REA, LEC, and VEA).
Note that the DEC model is not an element in the paper anymore.

L205-210: Based on this text passage I have the impression the authors have a misconception about the DEC method, since normally only grab samples are analyses but now low-pass filtering is applied.

Response:

Removed. The DEC model is not an element in the paper anymore.

L239: As the authors rightfully state, REA with fast-switching valves will lead to a good agreement with EC, and that is the only way REA should be applied in the first place. The authors should make sure to avoid the impression that this strong bias shown in Fig. 2 is the result of the REA method itself, while it is actually an effect of the strong (artificial) low-pass filtering.

Response:

Corrected. REA and VEA concepts are clearly differentiated now. However, we still caution on this need for a fast switching REA apparatus under stable conditions, which as we show is much less problematic under unstable conditions.

Figure 2: The results for DEC are confusing since such a systematic bias is not to be expected based on the literature on DEC. If DEC is applied properly, only the time interval between grab samples should be altered, and any low-pass filtering should be avoided. The REA results are also misleading, since they imply that slow-switching valves are used or some other form of low-pass filtering is applied. This is not how REA is or should be done in practice.

Response:

Removed. The DEC model is not an element in the paper anymore.

Karl TG, Spirig C, Rinne J, et al. (2002) Virtual disjunct eddy covariance measurements of organic compound fluxes from a subalpine forest using proton transfer reaction mass spectrometry. Atmos Chem Phys 2:279–291. https://doi.org/10.5194/acp-2-279-2002

Rinne HJI, Guenther AB, Warneke C, Gouw JA De (2001) Disjunct eddy covariance technique for trace gas flux measurements. Geophys Res Lett 28:3139–3142

Rinne J, Douffet T, Prigent Y, Durand P (2008) Field comparison of disjunct and conventional eddy covariance techniques for trace gas flux measurements. Environ Pollut 152:630–635