

Manuscript: Title: Suitability of fiber-optic distributed temperature sensing to reveal mixing processes and higher-order moments at the forest-air interface

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Review round 2

We thank both the editor and the referee for the comments on the revised version of the manuscript. Please find below point-by-point responses to the presented critique. Editor and referee comments are in **bold**, responses with **red** and changes to the manuscript with **blue**.

## EDITOR COMMENTS

**1) In the previous review, referee#3 placed the following comment:**

**"My only broader comment is in relation to the connection between the flow and the temperature variability; the connection between these two values needs to be better supported; there are places where it appears that the two variables are used interchangeably and it can lead to a little confusion for the reader."**

**This comment has not been addressed in the author's reponse. Please do so now.**

**(One exemple for the issue is on page 17, line 10)**

**RESPONSE:** We are sorry for missing this comment during the previous round and will answer to it now. While it is true that air movement cannot be directly derived from scalar- temporal and spatial variability, there is a large body of studies showing that particularly for forest canopy flows with well-developed coherent structures (CS) the signals between vectorial components and scalars are very systematic. This is why CS are considered part of the organized turbulence, and not part of the stochastic inertial subrange turbulence. Due to the mediating effect of the 3-D turbulent pressure field, structures observed in time series of vectorial components are not as sharp as those of scalars, this is also well documented (see e.g. Fig. 2 in (Thomas and Foken, 2005) or Fig.2 in (Thomas and Foken, 2007)). Hence, particularly for larger and longer-lived organized motions a direct inference between vector and scalar components seems justified. We will add a short note about this in the manuscript, but also emphasise that the analysis relies on temperature variability only.

**CHANGES TO THE MANUSCRIPT:** Modified Sect. 3.5 header as "Examples of organised patterns observed with the DTS system across vertical coupling regimes". Added "temperature" between "spatial" and "patterns" on page17line10. Added the following sentence to page17line11: "During well-developed turbulence these patterns are interlinked with large scale organised turbulent air motions (see e.g. Fig. 3 in Gao et al., 1989)." Modified the sentence on page17lines11-12 as "Large coherent eddies dominated the flow (Fig. 8b) and their signatures on vertical temperature profiles were captured with the DTS measurements." Changed the sentence on page18lines1-2 to "By relying on Taylor's frozen turbulence hypothesis, two dimensional spatial details of the large temperature patterns can be delineated from the vertical DTS measurements." Added "related to" before "downward" on page18line2. Replaced "turbulent motions" with "turbulence" on page18line19.

Added the following sentence on page20line2: "Note however, that these two examples relied only on temperature observations, for similar observations of wind vectors, actively heated fibre optics would be needed (Sayde et al., 2015)."

**2) page 2, line 9: omit "respectively"; change "it is recognised" to "it has been recognised"**

CHANGES TO THE MANUSCRIPT: Modified as suggested.

**3) page 6, line 18: clarify to "...time series for both parameters."**

CHANGES TO THE MANUSCRIPT: Modified as suggested.

**4) page 12, line 18: change to "The bulk of ..."**

**page 12, line 19: change to "...and the DTS system..."**

CHANGES TO THE MANUSCRIPT: Modified as suggested.

**5) page 16, line 3: omit "For comparison". (It is misleading here).**

**page 16, line 6: change to "As shown above, DTS and 3D sonic temperature measurements showed ..."**

CHANGES TO THE MANUSCRIPT: Modified as suggested.

**6) page 18, line 1: change to "two-dimensional"**

CHANGES TO THE MANUSCRIPT: Modified as suggested.

**Anonymous Referee #2**

**General: check the whole text for the use of articles, they are missing regularly.**

**RESPONSE: We will try to improve the text in this respect.**

**Abstract, line 12: put a comma before and after "however"**

CHANGES TO THE MANUSCRIPT: Added

**Abstract line 16: replace "discern" with "be discerned"**

CHANGES TO THE MANUSCRIPT: Modified as the referee suggests.

**Page 2line 9: ...respectively. Yet, it is...**

CHANGES TO THE MANUSCRIPT: Modified as the referee suggests.

**Page 2line 16: information on**

CHANGES TO THE MANUSCRIPT: Modified as the referee suggests.

**Page 2line 26: why is Traeumer in capital letters?**

**RESPONSE:** Due to issues related to the software used to manage references.

**CHANGES TO THE MANUSCRIPT:** Fixed.

**Page 2line 27: put a comma after yet?**

**CHANGES TO THE MANUSCRIPT:** Modified as the referee suggests.

**Page 2line 29: replace yet with but. Split sentence in two: ".....(e.g. at measurement towers). Consequently, spatial details..."**

**CHANGES TO THE MANUSCRIPT:** Modified as the referee suggests.

**Page 2line 30: Hence,...**

**CHANGES TO THE MANUSCRIPT:** Modified as the referee suggests.

**Page 3, line 16: what is meant with transition periods?**

**RESPONSE:** Transition periods mean in these two studies sunrise in the morning (Higgins et al., 2018) and beginning and end of total solar eclipse (Higgins et al., 2019).

**Page 3, line 20: systems**

**CHANGES TO THE MANUSCRIPT:** Modified as the referee suggests.

**Page 3, line 30: split sentence. ".....to boundary layer top. Consequently, the DTS system bridges...."**

**CHANGES TO THE MANUSCRIPT:** Modified as the referee suggests.

**Page4line 10: remove "the" before north-south direction. Write North and South in capital letters. question for my interest: why do you have three different sonic types along the tower?**

**RESPONSE:** The different sonic types along the tower stem simply from the fact that the site has been running since 1996 and different sonic types have been purchased along the years. Furthermore, ICOS measurement protocols demand the usage of Gill HS-50 for EC measurements, whereas based on our own experiences METEK USA-1 sonic anemometers are maybe more suitable for northern conditions.

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page4line 27: name the range of the lidar**

**CHANGES TO THE MANUSCRIPT:** Added the following sentence: "The Doppler lidar provides data from 75 m to 9585 m in range and the clearest signal typically originates from the boundary layer where the aerosol loading is the highest."

**Page5line 12: reformulate "This setup enabled reference measurements at both...."**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page5line 13: ".., and provided"**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page5line 20: shouldn't the mean be constant for each time averaging interval to ensure a proper application of this composition...?**

**RESPONSE:** In theory yes. For instance, air temperature (T) has a distinct diel course and hence T time series contain a low-frequency component which is not related to turbulence. This contamination of T' signal by non-turbulent motions can be counterbalanced by limiting the averaging period length or alternatively by using e.g. running mean filters (McMillen, 1988) to separate the turbulent signal from measurements. However, these approaches cause an underestimation of the turbulent variability at low-frequencies (Rannik and Vesala, 1999). Commonly accepted compromise is to use 30-min averaging period and block-averaging (Sabbatini et al., 2018).

**Page6line 6: "This value" refers to  $u^*$  or the  $T^*$ ?**

**CHANGES TO THE MANUSCRIPT:** Replaced "This value" with " $T^*$ "

**Page6line 10: "as a function..."**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page6line 22: one bracket missing after the numbers**

**CHANGES TO THE MANUSCRIPT:** Fixed.

**Page6line 30: "...be approximated by"**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page7lines 1-3: "An estimate for the attenuation of the DTS-derived temperature variance due to imperfect high frequency response and lower sampling frequency can be derived by"**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page7line 28: comma after "Similarly"**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page8line 20: the experimental setup**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page8line 21: comma after hence?**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page8line 25: split sentence; "...outer cable (sheath, protection). These are...."**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page8line 27: estimate**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page8line 28: due to the fibre-optic cable**

**CHANGES TO THE MANUSCRIPT:** Modified the text as the referee suggests

**Page9line 9: "showed" instead of "did show"**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page11line 5: ...can be considered independent...**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page11line 8: you use "dependence" at several other places in the manuscript, here you use "dependency". Be consistent.**

CHANGES TO THE MANUSCRIPT: Replaced "dependency" with "dependence"

**Page11line 9:...can be considered constant...**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page12table 1 heading: ...derived via...**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page12line 1: comma after hence**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page12line 3: comma after hence**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page12line 4: ...a fixed value...**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page12line 7: replace "did cause" with "caused"**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page13line 1: comma before "suggesting"?**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Figure 5: write  $wT$  in the figure with overbar and apostrophes, as it is standard to describe the turbulent fluxes**

CHANGES TO THE MANUSCRIPT: Modified the text as the referee suggests

**Page14line 2: the sensor separation between DTS and sonic was the same above and below canopy, right...? if so, it cannot be used as argument here.**

**RESPONSE:** We disagree with the referee and argue that the sensor separation can be used as an argument to explain the disagreement between below-canopy heat fluxes calculated using  $T$  either from DTS or 3D sonic anemometer measurements. Turbulence in the subcanopy is much more short-lived than above-canopy turbulence, and turbulence spectra can be multi-modal because of motions generated by waving branches, short-circuiting, von Karman vortices shed by tree trunks etc, see e.g. Fig.2 ( lower row at 4m in comparison with 16m and above-canopy level) in (Vickers and Thomas, 2014). Because of this short-lived nature at around 2 Hz and the weak winds, from Taylor's hypotheses one can infer that spatial scales are also small (assume time scale at peak of 2 Hz:  $t=0.5s$ ;  $u=1m/s$ ;  $l=u*t=0.5m$ ) and hence sensor separation around these scales may have a significant impact on fluxes. Therefore, the flux (but not variance) related to these small eddies is damped due to large horizontal sensor separation.

**Page14lines 7 - 10: split this sentence in two.**

CHANGES TO THE MANUSCRIPT: Split the sentence in two: “This is supported by the finding that the in-canopy temperature variance was captured accurately, while the heat flux was not. The temperature fluctuations related to the large eddies sweeping into the in-canopy were captured accurately yet their signal was decorrelated with respect to the vertical wind speed (i.e. vertical turbulent flux) by the canopy elements and large horizontal sensor separation”

**Page14line 18 - page 15 (line 2): split this sentence in two.**

CHANGES TO THE MANUSCRIPT: Split the sentence in two: “Imposing a DTS SNR threshold of 0.5 still left 54 % of all DTS data measured during the campaign and 63 % of DTS data measured below 50 m height available for generating third-order statistics. Hence, we conclude that this DTS system can still be used after SNR filtering to monitor higher-order statistics and the non-Gaussian character of the flow despite the higher noise floor of this instrument relative to the older 2 km variant used in Thomas et al. (2012).”

**Page15first paragraph: this is a quite big difference in the temperature profiles between DTS and reference. I wonder if the authors want to say a sentence about strategies to improve DTS in this regard. Without considering the radiation errors DTS seems useless with regards to T profiles.**

RESPONSE: We partly agree with the referee, radiation errors significantly decrease the usability of mean temperature (T) measurements with DTS. However, please note that in this section of the manuscript we are analyzing T gradients, not mean values. The influence of radiation errors on gradients disappear if the errors are the same across the cable. However, this is not true when comparing above- and below-canopy data due to canopy shading and hence T gradients derived from DTS data were biased. However, we argue that the found biases in T gradients were not extremely large (0.07 K and 0.04 K at night and day, respectively) and hence do not fully invalidate the usage of these gradients in research, as the referee suggests. Given the very uniform longwave radiative environment in the subcanopy and the small shortwave mostly diffuse radiative fluxes (see e.g. Fig.2 in (Thomas, 2011)), the expected radiation errors in the below-canopy air space are on the order of a few tenth of K despite the weak flows. Sun flecks caused by direct-beam radiation do cause spatial variability, but magnitudes – again – are on the order of a few tenth of K for this specific fibre-optic (FO) cable. See more on the radiation errors for this specific FO cable type in (Sigmund et al., 2017). One should note that the radiation shielded Pt100 thermistors often used for air temperature measurements are not free from biases either (Huwald et al., 2009).

CHANGES TO THE MANUSCRIPT: Added the following sentence to page16line5: “Radiation shields around the cable could have presumably decreased these biases in gradients (Schilperoort et al., 2018), however the usage of screens would have invalidated the estimation of turbulent fluctuations from the DTS data since they disturb the turbulent air flow.”

**Page16line 17: site (it's only one)**

CHANGES TO THE MANUSCRIPT: Fixed.

**Page16line 18: ...a previous study...**

CHANGES TO THE MANUSCRIPT: Fixed.

**Page16line 18 - line 21: split sentence and reformulate.**

CHANGES TO THE MANUSCRIPT: Modified as “This is in line with a previous study at this site (Rannik, 1998) and others, where estimates for the roughness sublayer height typically range between  $2h_c$  to  $5h_c$  ( $3h_c$  being the most common estimate) (Garratt, 1980; Coppin et al., 1986; Mölder et al., 1999; Poggi et al., 2004; Thomas et al., 2006).”

**Page16line 22 - 24: not sure if everyone will understand what you try to say with this sentence**

CHANGES TO THE MANUSCRIPT: We reformulated the sentence as “In near-neutral situations the scaled temperature variability ( $\sigma_T/|T_*|$ ) exceeded the predictions made with M-O scaling, since the heat fluxes (and hence also  $|T_*|$ ) decreased with  $\zeta$  yet the temperature variability ( $\sigma_T$ ) did not decrease at the same rate. In other words, heat transfer efficiency approached zero at the neutral limit (e.g. Rannik, 1998).”

**Page16line 27: in which regard are they in line with previous studies...?**

RESPONSE: Similarly as in here, Pahlow et al. (2001) showed that in strongly stable situations height is not a governing variable for  $\sigma_T/|T_*|$  variability.

**Page16line 30: fluxes are constant with height only in the surface layer, and this surface layer is not very big...; furthermore, here we are in and above a forest which modifies the atmospheric stratification schemes.**

RESPONSE: Yes, vertical turbulent fluxes can be conjectured to be constant with height in the surface layer only, we refer to this with the “bottom part of the ABL” in the text. As the referee suggest, air flows above canopies differ significantly from boundary layer flows, but vertical turbulent fluxes can still be conjectured to be constant with height above canopies (Patton et al., 2015).

**Page17line 15: ...the vertical what? Feels like here is a noun missing.**

CHANGES TO THE MANUSCRIPT: Added “column” at the end of the sentence.

**Page18line 18: replace "do demonstrate" with "demonstrate"**

CHANGES TO THE MANUSCRIPT: Fixed.

**Page18line 22: to which surface are you referring here? soil surface? canopy top?**

RESPONSE: Surface here refers to the Earth’s surface below the instrument. This includes mostly canopy but also those parts of the forest floor that are not covered by the canopy.

CHANGES TO THE MANUSCRIPT: Replaced “surface” with “forest”

**Page19line 1: comma after "in principle"**

CHANGES TO THE MANUSCRIPT: Fixed.

**Page20fig. 9: it might be useful to indicate in this fig. that blue is standing for the unstable stratification example and pink for the stable stratification example. Maybe switch colours as blue is often used intuitively for stable stratification.**

CHANGES TO THE MANUSCRIPT: Colors were switched based on the referee suggestion.

**Page21fig. 11: it would help the reader to name directly in this fig. that you are referring here to the stable stratification nighttime example. Also, it would help to indicate how gradients were calculated (upper height - lower height, I guess).**

**RESPONSE:** The method used to calculate the gradients is already described in the caption.

**CHANGES TO THE MANUSCRIPT:** Modified the first sentence of the Fig. 11 caption to “Evolution of potential temperature gradient ( $d\theta/dz$ ) (subplot a) for the nighttime period shown in Fig. 10 and concurrent wind speed timeseries from two heights (subplot b).”

**Page21line 5: in line with what from Thomas et al. (2012)? And what in Thomas et al. (2012) is complemented? Readers will not have the content of Thomas et al. (2012) in mind. Reformulate: "...these results are in line with their findings and complement them."**

**RESPONSE:** We opt not to give a detailed summary of the findings of Thomas et al. (2012) here. The agreement between the findings in this study and in Thomas et al. (2012) is already summarized in the first part of Sect. 4

**CHANGES TO THE MANUSCRIPT:** changed the sentence on page21lines5-6 to “Despite the fact that these results were obtained with a different DTS machine compared to Thomas et al. (2012) and that different cable suspension techniques were used, these results are in line with their findings on DTS capturing second-order moments of air temperature variability and complement them.”

**Page21line 14: in the current study...**

**CHANGES TO THE MANUSCRIPT:** Replaced “In this study” with “In the current study”

**Page22line 9: ...help to separate...**

**CHANGES TO THE MANUSCRIPT:** Fixed

**line 10: ...since the measurements allow the tracking of the temperature...**

**CHANGES TO THE MANUSCRIPT:** Fixed

**line 16: place a comma after "ultimately"**

**CHANGES TO THE MANUSCRIPT:** Fixed

**Generally to the conclusions and outlook: can the authors briefly acknowledge the shortcomings of DTS which got obvious in this study and give information on how these can be overcome? I have e.g. in mind the topic radiation error which appears to be quite substantial. And which makes the use of derived absolute temperatures questionable. Give a brief overview please on the current limitations of DTS and how they will be tackled in the future.**

**RESPONSE:** The main shortcomings of the DTS measurement technique are 1) the high noise floor, 2) lower high frequency response compared to the 3D sonic anemometers and 3) the biases in absolute temperatures caused by radiation. The first two are already briefly mentioned in the first part of the Sect. 4 but radiation error is not mentioned. We will add a short sentence on this as well. There is not much to be done with the first two, since they are largely dictated by the DTS instrument specifications and the used fibre-optic cable. Radiation error on the other hand could be minimized by using radiation shields around the cable. However, like mentioned above, this would inhibit the estimation of turbulence from DTS measurements since the shields would strongly disturb the turbulent flow. We would like to emphasise that absolute temperatures ( $T$ ) are rarely of great interest when studying mixing processes in the atmosphere (the topic of this manuscript). More important are  $T$  gradients and  $T$  variability as they are related to the controls on the turbulent mixing in the air. Furthermore, the influence of radiation errors on cross-canopy  $T$  gradients were not found



to be extremely large, especially when recognizing that traditional thermometers can be biased as well (Huwald et al., 2009).

CHANGES TO THE MANUSCRIPT: Added the following sentences to page21line9: “Cross-canopy temperature gradients were found to be biased due to radiation induced errors, especially during morning and evening. These biases could be reduced with radiation shields around the DTS cable, however such shields would severely disrupt the air flow and hence inhibit the estimation of turbulence from DTS measurements. Other approaches have been proposed as well (de Jong et al., 2015; Sigmund et al., 2017).”. Modified also the sentence starting on page21line9 as: “Despite these shortcomings DTS measurements can provide the missing spatial details of atmospheric mixing close to the surface which cannot be acquired with conventional in-situ or remote sensing methods.”

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