# Technical note: using Distributed Temperature Sensing for Bowen ratio evaporation measurements

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**Abstract.** Rapid improvements in the precision and spatial resolution of Distributed Temperature Sensing (DTS) technology now allow its use in hydrological and atmospheric sciences. Introduced by Euser [Hydrol. Earth Syst. Sci., 18, 2021-2032 (2014)] is the use of DTS for measuring the Bowen ratio (BR-DTS), to estimate the sensible and latent heat flux. The Bowen ratio is derived from DTS measured vertical profiles of the air temperature and wet-bulb temperature. However, in previous research the measured temperatures were not validated, and the cables were not shielded from solar radiation. Additionally, the BR-DTS method has not been tested above a forest before, where temperature gradients are small and energy storage in the air column becomes important.

In this paper the accuracy of the wet-bulb and air temperature measurements of the DTS are verified, and the resulting Bowen ratio and heat fluxes are compared to eddy covariance data. The performance of BR-DTS was tested on a 46 m high tower in a mixed forest in the centre of the Netherlands in August 2016. The average tree height is 26 to 30 m, and the temperatures are measured below, in, and above the canopy. Using the vertical temperature profiles the storage of latent and sensible heat in the air column was calculated.

We found a significant effect of solar radiation on the temperature measurements, leading to a deviation of up to 3 K. By installing screens, the error caused by sunlight is reduced to under 1 K. Wind speed seems to have a minimal effect on the measured wet-bulb temperature, both below and above the canopy. After a simple quality control, the Bowen ratio measured by DTS correlates well with eddy covariance (EC) estimates ($r^2 = 0.59$). The average energy balance closure between BR-DTS and EC is good, with a mean underestimation of 3.4 W m$^{-2}$ by the BR-DTS method. However, during daytime the BR-DTS method overestimates the available energy, and during night-time the BR-DTS method estimates the available energy to be more negative. This difference could be related to the biomass heat storage, which is neglected in this study.

The BR-DTS method overestimates the latent heat flux on average by 18.7 W m$^{-2}$, with RMSE $= 90$ W m$^{-2}$. The sensible heat flux is underestimated on average by 10.6 W m$^{-2}$, with RMSE $= 76$ W m$^{-2}$. Estimates of the BR-DTS can be improved once the uncertainties in the energy balance are reduced. However, applying e.g. Monin-Obukhov similarity theory could provide independent estimates for the sensible heat flux. This would make the determination of the highly uncertain and difficult to determine net available energy redundant.

# 1 Introduction

In recent years distributed temperature sensing (DTS) technology has quickly improved (Bao and Chen, 2012). The precision and spatial resolution now allow its widespread use in hydrological and atmospheric sciences (Selker et al., 2006; Thomas et al., 2012), from measuring groundwater flow (Blume et al., 2013) and seepage into streams (Westhoff et al., 2007), to soil moisture (Steele-Dunne et al., 2010), soil heat flux (Bense et al., 2016), and wind speed (Sayde et al., 2015). First introduced by Euser et al. (2014), DTS can also be used for measuring the Bowen ratio, to estimate the evaporation flux. A dry and wet stretch of the same fibre optic cable are installed vertically to obtain the so-called dry and web bulb temperature gradient, respectively. This method mitigates some problems of the conventional Bowen ratio, since usually at least two different sensors are used to measure the temperature and vapour pressure gradients, of which each has its own independent error (Angus and Watts, 1984; Fuchs and Tanner, 1970). The DTS based Bowen ratio does not suffer from this drawback, by having a large amount of data points over the height (up to 8 per meter) with only a single sensor. It also has a resolution of 0.06 K for 1 minute averages (Silixa machine calibration), and will be more accurate when measuring over a longer time period, allowing for very small temperature gradients to be measured.

In addition to estimating the latent and sensible heat flux, the measurements can also be used to get a better understanding of the processes taking place in complex ecosystems, such as forests. A vertical temperature and humidity profile is available in high resolution and precision, both above, inside, and under the canopy. DTS can also estimate different components of the energy balance, such as the heat storage in the air column, and the soil heat flux (Jansen et al., 2011). Finally, it can be used to increase our understanding of the energy exchange between the canopy and undergrowth layers by looking at the air temperature gradient under the canopy.

This paper elaborates on the method of Euser et al. (2014), by considering more energy balance components like the latent and sensible heat storage in the air column, including a data-quality system, and using the potential air temperature. The performance of the method is tested in a mixed forest in the Netherlands by looking at the accuracy of the DTS measured air temperature and wet-bulb temperature, compared to reference temperature and humidity sensors. It appears that solar radiation can have a significant influence on the cable temperature, which can be mitigated by providing artificial shadow. Lastly the fluxes resulting from the method are compared to an eddy covariance (EC) system, and the sources of differences between the methods are shown.

# 2 Materials and Methods

## 2.1 Theory

The Bowen ratio energy balance method (BREB) combines the energy balance with the Bowen ratio (Oliphant et al., 2004). The energy balance can be described by:

$$R_N + A = \rho \lambda E + H + G_S + \frac{\mathrm{d}Q}{\mathrm{d}t} \tag{1}$$

where $R_N$ is the net radiation (W m$^{-2}$), $\rho\lambda E$ the latent heat flux (W m$^{-2}$), $H$ the sensible heat flux (W m$^{-2}$), $G_S$ the soil heat flux (W m$^{-2}$), and $\frac{dQ}{dt}$ is the change of energy storage in the system (W m$^{-2}$). $A$ represents a net advection of energy into the system (W m$^{-2}$), but is assumed to be 0. The energy flux associated with photosynthesis ($G_P$) was not measured, and is therefore not included in the equation. The Bowen ratio ($\beta$) is the ratio of the sensible heat flux to the latent heat flux and can

5 be approximated using the air temperature gradient and the vapour pressure difference over the height (Bowen, 1926):

$$\beta = \frac{H}{\rho\lambda E} \approx \gamma \frac{\Delta T_a}{\Delta e_a} \tag{2}$$

where $\gamma$ is the psychrometric constant (kPa K$^{-1}$) (see Eq. 10), $\Delta T_a$ the difference in air temperature between two heights (K) and $\Delta e_a$ the difference in actual vapour pressure between the two heights (kPa). However, when gradients are very small, the adiabatic lapse rate can not be neglected (Barr et al., 1994). Therefore the potential temperature should be used instead:

10 $$\beta = \frac{H}{\rho\lambda E} = \frac{c_p}{\lambda} \frac{\partial\Theta/\partial z}{\partial q/\partial z} = \gamma \frac{\partial\Theta/\partial z}{\partial e_a/\partial z} \tag{3}$$

where $c_p$ is the specific heat of air (MJ kg$^{-1}$) (See Eq. 6), $\lambda$ the latent heat of vaporization (2.45 MJ kg$^{-1}$ K$^{-1}$), $\Theta$ the potential temperature (K), $q$ the specific humidity (kg kg$^{-1}$) (See Eq. 7) and $z$ the height above the ground (m). The potential temperature gradient can be approximated by the right-hand side of Eq. 4, as the ratio $\frac{\Theta}{T_a}$ is nearly 1 (Pal Arya, 1988).

$$\frac{\partial\Theta}{\partial z} = \frac{\Theta}{T_a}\left(\frac{\partial T_a}{\partial z} + \Gamma\right) \approx \frac{\partial T_a}{\partial z} + \Gamma \tag{4}$$

15 where $T_a$ is the air temperature (K), and $\Gamma$ is the adiabatic lapse rate (typically around 0.01 K m$^{-1}$). The numerical implementations of Eq. 3 & 4 are explained in section 3.2 Data Processing. Under dry and unsaturated conditions the lapse rate is equal to (Pal Arya, 1988):

$$\Gamma = \frac{g}{c_p} \tag{5}$$

where $g$ is the gravitational acceleration (9.81 m s$^{-2}$). The specific heat capacity of air is determined by (Stull, 2015):

20 $$c_p = 1.004 + 1.84q \tag{6}$$

And the specific humidity by (Pal Arya, 1988):

$$q = \varepsilon \frac{e_a}{P} \tag{7}$$

**3**

where $\varepsilon$ is the ratio of molecular mass of water vapour to dry air (0.622), and $P$ the atmospheric pressure (kPa). The actual vapour pressure is determined by (Allen et al., 1998):

$$e_a(T_a) = e_s(T_w) - \gamma(T_a - T_w) \tag{8}$$

where $T_w$ is the wet-bulb temperature (K), and $e_s$ the saturation vapour pressure (kPa) given by (Koutsoyiannis, 2012):

$$e_s(T_w) = 0.61 \cdot \exp\left(\frac{19.9 \cdot T_w}{273 + T_w}\right) \tag{9}$$

The psychrometer constant is related to the air pressure and ventilation of the psychrometer (Harrison and Wood, 2012; Allen et al., 1998). If sufficiently ventilated, the psychrometric constant is defined by (Allen et al., 1998):

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} \cdot P \tag{10}$$

As the air pressure also varies over height, the measurements have to be corrected for elevation using the following approximation (Stull, 2015, p. 8):

$$P(z) = P_0 \cdot \exp(-z/7290) \tag{11}$$

with $P_0$ being the pressure at sea-level (kPa). By combining the Bowen ratio (Eq. 3) with the energy balance (Eq. 1), the latent heat flux and sensible heat flux can be determined:

$$H = \frac{R_N - G_S - \frac{dQ}{dt}}{1 + \frac{1}{\beta}} \tag{12}$$

$$\rho\lambda E = \frac{R_N - G_S - \frac{dQ}{dt}}{1 + \beta} \tag{13}$$

The storage component in the energy balance has multiple parts, ranging from the storage of heat in the soil, to the storage of heat in the form of water vapour in the air column:

$$\frac{dQ}{dt} = \frac{dQ_H}{dt} + \frac{dQ_E}{dt} \tag{14}$$

The changes in storage of heat and water vapour in the air column below the height at which the energy fluxes ($R_N$, $H$ and $\rho\lambda E$) are measured are represented by $\frac{dQ_H}{dt}$ and $\frac{dQ_E}{dt}$ respectively (W m$^{-2}$). The change in biomass heat storage ($\frac{dQ_B}{dt}$) was not measured, and is therefore not included in this equation. $\frac{dQ_H}{dt}$ and $\frac{dQ_E}{dt}$ are defined as (Barr et al., 1994):

$$\frac{dQ_H}{dt} = \int_0^z \rho_a c_p \frac{dT_a}{dt} dz \tag{15}$$

$$\frac{\mathrm{d}Q_E}{\mathrm{d}t} = \int_0^z \rho_a \lambda \frac{\mathrm{d}q}{\mathrm{d}t} \mathrm{d}z \qquad (16)$$

## 3 Study Site

The measurements were carried out at the Speulderbos mixed forest (N: $52°15'4''$ - E: $5°41'24''$), on a tower located within a patch of Douglas Fir trees (*Pseudotsuga menziezii* (Mirb.) Franco) of 2.5 ha in Garderen, The Netherlands (Fig. 1). The surrounding area is characterized by the presence of broadleaved and coniferous tree species, distributed in blocks around the tower site (Bosveld and Bouten, 2001). Within a 500 m radius it is possible to find native tree species such as Beech (*Fagus sylvatica* L.), Pedunculate Oak (*Quercus robur* L.) and Scots Pine (*Pinus sylvestris* L.), as well as the introduced species Hemlock (*Tsuga heterophylla* (Rafinesque) Sargent) and Japanese Lark or Larch (*Larix kaempferi* (Lambert) Carriére) (Erisman et al., 1998; Raj et al., 2014; Su et al., 2009; Bosveld and Bouten, 2001; Tietema et al., 2002; Van Wijk et al., 2000; Weligepolage et al., 2013). Canopy heights differ between cover types depending on species and growing stage. Some coniferous canopies like the Douglas Fir have a canopy height between 26 m to 30 m, while the broadleaved stands can reach up to 30 m height for old growth Beech trees (Weligepolage et al., 2012; Wilkes et al., 2017), or heights under 10 m for smaller Pedunculate Oak trees.

The study site has a Oceanic Climate (Cfb) under the Köpen classification system, with a yearly average temperature of 9.8 °C and an average precipitation of 910 mm yr$^{-1}$ (Sluijter, 2011). The topography is slightly undulating with smooth height differences (Raj et al., 2014), a well-drained soil, and a groundwater table below 40 m depth (Tiktak and Bouten, 1994). The soil texture ranges from fine sand to sandy loam (Weligepolage et al., 2012; Tietema et al., 2002; Van Wijk et al., 2000).

### 3.1 Setup

The temperature of fibre optic cables is measured using the DTS technique (Selker et al., 2006). In the setup, two cables with different diameters were used. The first cable has a diameter of 6 mm and has both a dry and a wetted stretch. To wet the cable it was wrapped in cloth, and water was supplied to it continuously. A second cable with a diameter of 3 mm was used to study the effects of solar radiation, as a thinner cable will warm up less (De Jong et al., 2015). However, this method added additional uncertainties due to the required extrapolation and the 3 mm cable was not used in this study. (While correlation with reference sensors improved, the uncertainty of extrapolation caused extra noise in the Bowen ratio calculations). Both cables were connected to the same DTS machine (in single-ended mode) and calibrated in a calibration bath (see Fig. 2)

The DTS machine used was the Silixa Ultima (Silixa Ltd), which has a sampling resolution of 12.5 cm, measurement resolution of 35 cm, and a measurement standard deviation of 0.06 K at a 1 minute time resolution.
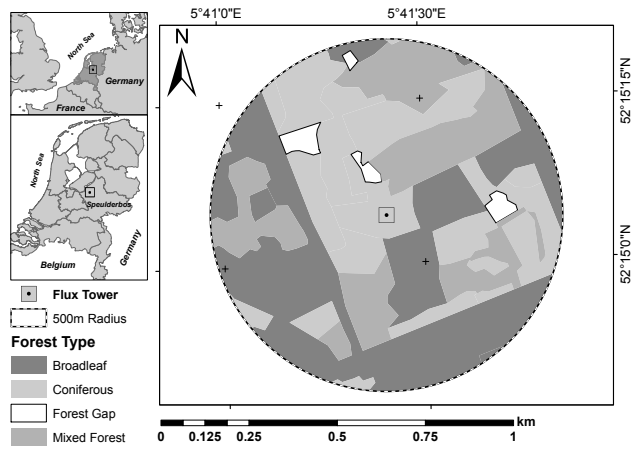
**Figure 1.** Forest type distribution within 500 m of the tower site at Speulderbos Forest, the Netherlands.
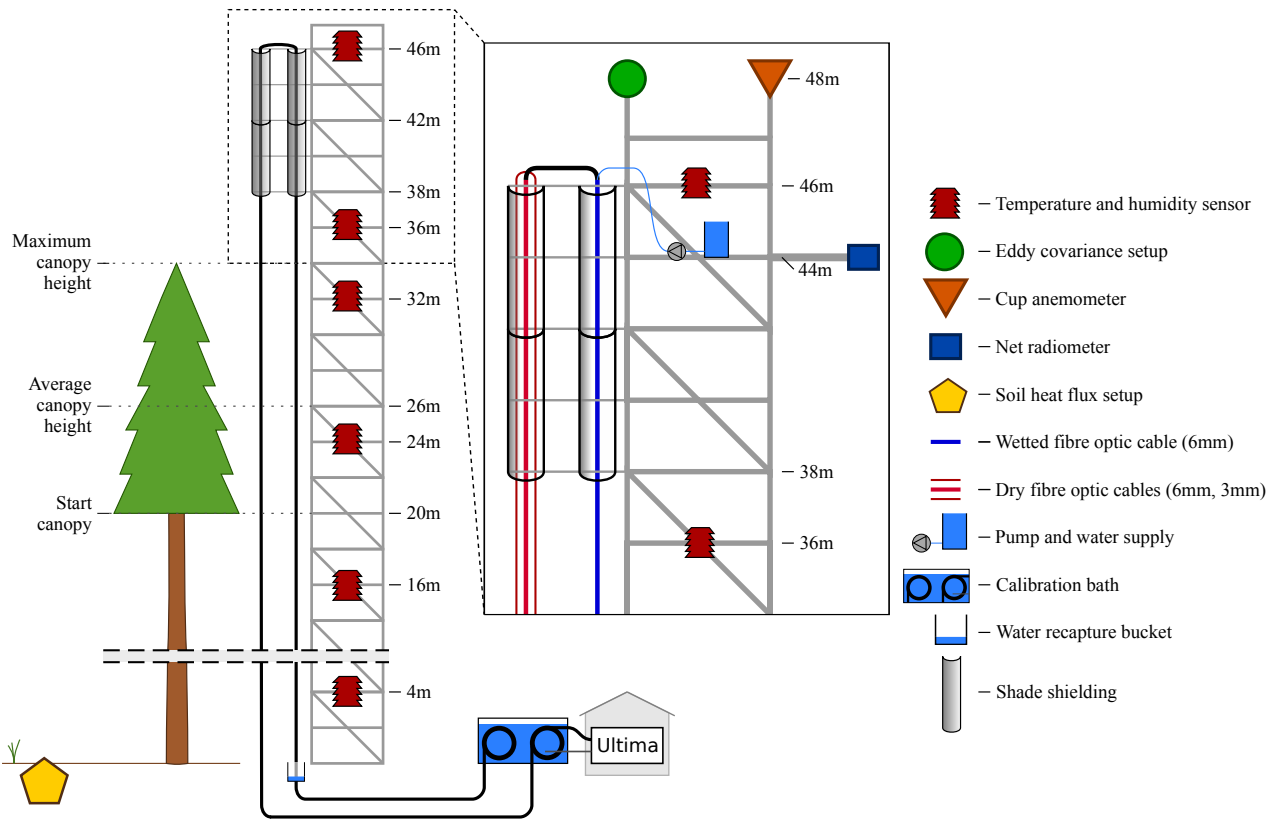


**Figure 2.** Schematic overview of the measurement setup at the tower.

The fibre optic cable with a diameter of 6 mm was secured at the top of the tower, with the dry stretch hanging 1.2 m away from the tower, and the wet stretch 0.25 m away. The cable with a diameter of 3 mm was secured next to the dry 6 mm cable. The response times of the cables are in the order of 2 - 3 minutes for the 6 mm cable, and 20 to 40 seconds for the 3 mm cable. The cables were secured at multiple locations distributed over the height (in and above the canopy, see Fig. 2), using loops

5 (with a diameter of 5 cm) to prevent direct contact with the support structure. For both cables a stretch of 10 m at both the start and end was placed in a calibration bath, an enclosed Styrofoam box filled with water, along with two Pt100 temperature probes that were connected to the DTS machine. An air bubbler was installed in the Styrofoam box to ensure a homogeneous temperature distribution. The cables were shielded from direct solar radiation using screen gauze secured onto PVC rings, see Fig. 3. Only the southern 180° of the cables was shielded, to allow for sufficient ventilation. The screen gauze had holes 1.5

10 mm wide, and the mesh material had a diameter of 0.3 mm. Two layers of the gauze were used. Each segment of shield was 2 m long, and was secured to the tower with a horizontal beam. Due to the angle of the incident sunlight the gauze was able to block most direct sunlight, except during the early morning. To supply the wet cable with water, a reservoir was installed near the top of the tower, along with a pump. The pump speed was set to 1500 ml h$^{-1}$ during sunny days without rainfall, and to 800 ml h$^{-1}$ on other days, which was enough to keep the cable wet over the entire height, while keeping the influence of

15 relatively warm water at the top of the cable at a minimum. As water supplied at the top has a higher temperature than the wet bulb temperature, the top two meters of wet cable data was excluded from the data analysis to allow the slowly flowing water to reach the wet bulb temperature.
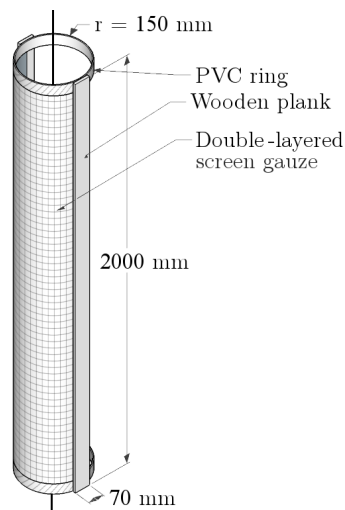


**Figure 3.** Schematic of one 2 m segment of the solar screen construction.

A net radiometer (Kipp & Zonen CNR4) was located on the top of the tower (48 m), measuring both incoming and outgoing short- and longwave radiation. One minute averages were logged. On the tower six humidity and temperature sensors were

20 located over the height, at 4, 16, 24, 32, 36 and 46 meters above ground level. The lower four were Rotronic HC2-S3C03

sensors (with active ventilation), and the top two were Campbell CS216 sensors with passive ventilation. The sensors were inter-calibrated to the sensor at 24 meters. The temperature and humidity was logged at one minute averages.

At the top of the tower an eddy covariance system was installed to measure the sensible and latent heat fluxes. It consisted of a Campbell CSAT3 sonic anemometer and a Li-Cor Biosciences LI7500 gas analyser connected to a CR5000 Campbell data
5　logger, to which the data was logged at 20 Hz.

Two cup anemometers (Onset S-WSB-M003) were used to measure the wind speed, one at the top of the tower (48 m), and one below the canopy (4 m). The data from the lower anemometer lacks the resolution to properly measure the low wind speeds below the canopy, which are at times too low to be registered. One minute average wind speeds, along with the maximum gust speeds were logged.

10　The biomass heat storage change and the photosynthesis energy flux were not measured. The biomass heat storage change is estimated to have a maximum of 45 W m$^{-2}$, and the photosynthesis energy flux is estimated to be in the order of 5 W m$^{-2}$ (Barr et al., 1994; Michiles and Gielow, 2008). For the soil heat flux, the soil temperature was measured at different depths (1, 3, 4, 8, 20, 50 cm). Soil moisture was measured using Campbell Sci. Inc. CS616 water content reflectometers. Thermal conductivity was fitted to soil heat flux measurements done at 8 cm. The soil heat flux was then determined using the harmonics method
15　(van der Tol, 2012).

## 3.2　Data Processing

The DTS machine was set to measure the cable temperature at one minute averaging intervals. For the comparison with reference temperature sensors, this one minute resolution data is used. To compare the wet-bulb temperature measured by the fibre optic cable to the reference sensors, the reference wet-bulb temperature is iteratively derived from the reference air
20　temperature and relative humidity. For the purpose of calculating the Bowen ratio, the temperature and actual vapour pressure are averaged over time for 15 minute time periods. For DTS Bowen ratio calculations, the temperatures between 38.5 m and 44 m are used. This area is shaded from the sun by the screen gauze, and at the top of the stretch the new water on the wet cable has reached the wet-bulb temperature.

When calculating the gradients for the Bowen ratio, the 15 minute average temperature and vapour pressure are fit to the
25　natural logarithm of the height, in the following form:

$$T_{a,\text{fit}} = a \cdot \ln(z) + b \qquad (17)$$

A logarithmic shape of the profiles was assumed based on Monin-Obukhov similarity theory. A linear fit was also looked at, but it resulted in a minimal difference in the resulting fit. From the fits the temperature difference over height is then calculated:

$$
\begin{aligned}
\frac{\partial \Theta}{\partial z} &\approx \frac{\partial T_a}{\partial z} + \Gamma(z) \approx \frac{\Delta T_{a,\text{fit}}}{\Delta z} + \Gamma(z) \\
&\approx \frac{T_{a,\text{fit}}(z=44) - T_{a,\text{fit}}(z=38.5)}{44 - 38.5} + \Gamma(\bar{z}=41.25)
\end{aligned}
\qquad (18)
$$

$$\frac{\partial e_a}{\partial z} \approx \frac{\Delta e_{a,\text{fit}}}{\Delta z} = \frac{e_{a,\text{fit}}(z=44) - e_{a,\text{fit}}(z=38.5)}{44 - 38.5} \tag{19}$$

Where $\Delta T_{a,fit}$ is the difference in air temperature (K) of the fitted temperature curve, between the top and bottom of the height range used for the Bowen ratio. $\Delta e_{a,fit}$ is the difference in vapour pressure (kPa) of the fitted vapour pressure curve between those heights. $\Delta z$ is the difference in height (m). The coefficients of determination of the regressions of the temperature and vapour pressure, $r_{T_a,z}$ and $r_{e_a,z}$, can be used for determining the goodness of fit. A high (positive or negative) regression means that the logarithmic slope (of the 15 minute average) is very well defined.

To calculate the air column storage terms $\frac{\mathrm{d}Q_H}{\mathrm{d}t}$ and $\frac{\mathrm{d}Q_E}{\mathrm{d}t}$ (Eq. 15 & 16), the DTS measured temperature and vapour pressure are used, except for the centre of the canopy where DTS data is not accurate due to the sunlight and lack of screens in the canopy. The temperature and specific humidity are integrated over the height from 0 to 41 m, up to the height of the Bowen ratio measurements.

As quality control scheme for the DTS-Bowen ratio, two flags are used. The first flag tests the correlation coefficient of the actual vapour pressure over height, for which we chose a lower limit of 0.20 (Eq. 20). We do not consider $r_{T_a,z}$ of the air temperature gradient as it is always higher than $r_{e_a,z}$ (as the uncertainty in $e_a$ is higher due to the propagation of errors in $T_a$ and $T_w$). The second flag is for the case where the Bowen ratio approaches -1, which causes the uncertainty in the BREB fluxes to be very high, as the denominator of Eq. 12 and Eq. 13 approaches 0 (Payero et al., 2003).

$$\text{Flag 1}: r_{e_a,z}^2 > 0.20 \tag{20}$$

$$\text{Flag 2}: \beta < -1.1 \text{ or } \beta > -0.9 \tag{21}$$

If flag 1 is true, the outcome of the Bowen ratio calculation is considered reliable. The other datapoints are removed from further analysis. If flag 2 is also true, then the Bowen ratio can be used for calculating the atmospheric heat fluxes.

After processing the eddy covariance data using LI-COR's EddyPro® software (LI-COR Inc., 2016), several quality flags are available. The quality flag system used is from Mauder and Foken (2006), ranging from 0 (best) to 2 (worst). The eddy covariance fluxes with a quality flag of 0 or 1 are used in this research.

To summarize, the method of this paper differs in a few points from Euser et al. (2014). The fit of the Bowen ratio temperature and vapour pressure profiles is done separately, to get the correct ratio, as $\frac{\partial T}{\partial z} / \frac{\partial e_a}{\partial z} \neq \frac{\partial T}{\partial e_a}$. More energy balance storage terms are taken into account, namely the latent and specific heat storage in the air column. The potential temperature is used instead of the air temperature, to correct for the lapse rate. The local air pressure is taken into account in the calculations, as it has an influence on the psychrometric constant, specific heat capacity and specific humidity. Lastly, a system for simple quality flags is introduced to allow for simple objective quality control.

# 4 Results and Discussion

## 4.1 Meteorological Conditions

For the comparison of the DTS temperature with the reference temperature data (Section 4.2), the days 10-22 August 2016 are used.

For a good comparison between DTS and EC, both devices should work properly. Due to several technical problems with data collection, only 11 days within the measurement campaign have both eddy covariance and DTS data available, namely 10, 12-14, 19-22, and 28-30 August 2016. On the other days data is missing in either the eddy covariance or the DTS. The meteorological conditions of these days are shown in Figure 4. All days were partially clouded, or completely clouded. The wind direction was mainly west and north-east. Above the canopy the wind speed varied between 2 and 6 m s$^{-1}$, while under the canopy the wind speed was often too low to be measured with the cup anemometer (under 0.4 m s$^{-1}$).
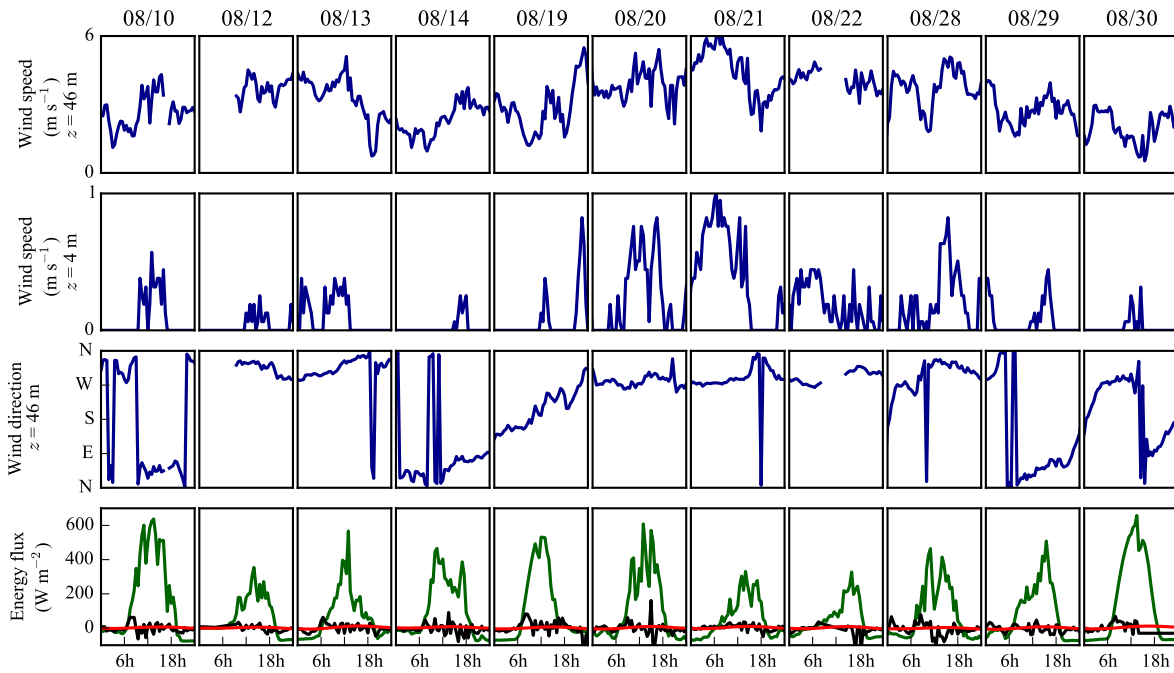


**Figure 4.** Meteorological conditions during the days that both DTS and eddy covariance data was available. From top to bottom: wind speed at the top of the tower, wind speed at the bottom of the tower, wind direction at the top of the tower, and the measured energy fluxes (green: net radiation, red: soil heat flux, black: energy storage change $\frac{dQ}{dt}$).

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## 4.2 Temperature validation

In Fig. 5 the comparison between the 6 mm DTS cable and the reference sensor is shown. For the above canopy comparison, the 46 m reference sensor is compared to the cable temperatures at 44 m height, as the temperatures at the top are unreliable due to influence from the sun and the warm water from the reservoir. Below the canopy the dry cable temperature correlates perfectly with the reference sensor temperature (Fig. 5e). In and above the canopy incoming solar radiation warms up the fibre optic cable (Fig. 5a, 5c), which causes an error at 34 m where no screen was installed. This error is a deviation of up to 3 K from the reference sensor temperature (for 1 minute temperature averages). The comparison at 34 m also has an offset, this is a constant error of about 1 K, due to the reference temperature sensor drift and inter-calibration problems. The addition of screens above the canopy largely reduces the error from solar radiation to under 1 K, leading to a very good agreement between the two sensor types (Fig. 5a).

Below the canopy the wet cable temperature is in good agreement with the reference wet-bulb temperature (Fig. 5f), even though wind speeds were often low. This shows that the wet cable gives a good estimate of the wet-bulb temperature. At 34 m, where no screens were placed, the error in the wet-bulb temperature is larger than the error in the air temperature. Deviations of up to 4 K occur in the measurement period. The shielded top part of the wet cable performs much better (Fig. 5b), and errors are small (under 1 K).
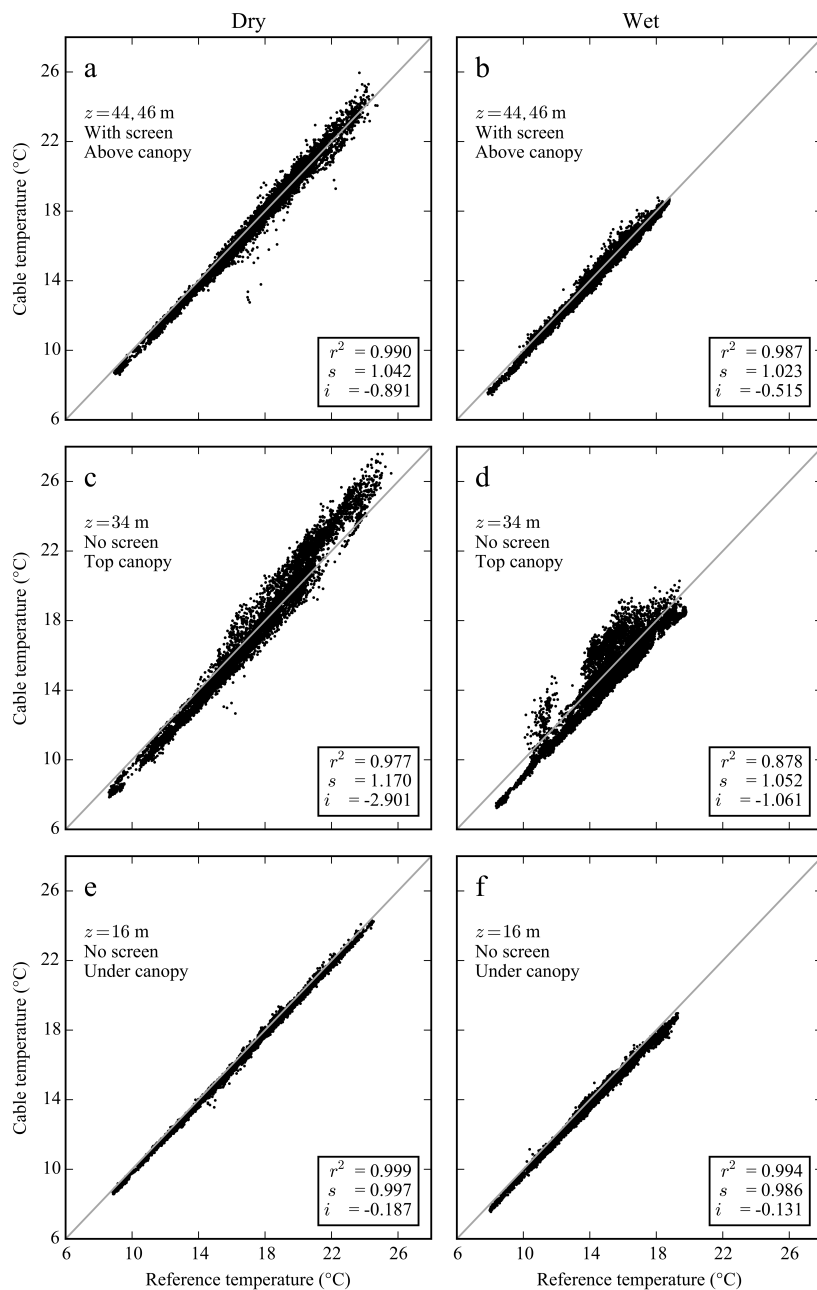
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**Figure 5.** Comparison between the 6 mm DTS cable and reference temperatures. Grey line shows 1:1 correlation. Data from 10-23 August 2016. **a**: Dry cable at 44 m and reference air temperature at 46 m, the cable is shielded by the screen. **b**: Wet cable at 44 m and reference wet-bulb temperature at 46 m, the cable is shielded by the screen. **c**: Dry cable and reference air temperature at 34 m, the cable is exposed to direct sunlight. **d**: Wet cable and reference wet-bulb temperature at 34 m, the fibre optic cable is exposed to direct sunlight. **e**: Dry cable and reference air temperature at 16 m, under the canopy so less direct sunlight hits the fibre optic cable. **f**: Wet cable and reference wet-bulb temperature at 16 m, under the canopy so less direct sunlight hits the fibre optic cable. Shown are the linear correlation coefficients; the coefficient of determination ($r^2$), the slope ($s$), and the intercept ($i$).

## 4.3 Bowen ratio verification

The Bowen ratio resulting from the BR-DTS method ($\beta_{DTS}$) is compared to the eddy covariance Bowen ratio ($\beta_{EC}$), at a 15 minute averaging interval. In Figure 6 the correlation between the eddy covariance Bowen ratio estimate and the BR-DTS is shown. It shows a grouping around the 1:1 line, and a good correlation ($r^2 = 0.59$). The eddy covariance Bowen ratio was only

5   calculated for fluxes with an absolute value larger than 10 W m$^{-2}$, as the uncertainty of the eddy covariance Bowen ratio is very high when the fluxes are small. Even the negative (night-time) values seemed to be accurate, since they passed the quality control flags. However, both eddy covariance and BR-DTS have problems measuring the night-time Bowen ratio. For eddy covariance this is due to the lower friction velocity at night (Wilson, 2002), while for the BR-DTS method the gradients are very small due to the small fluxes.
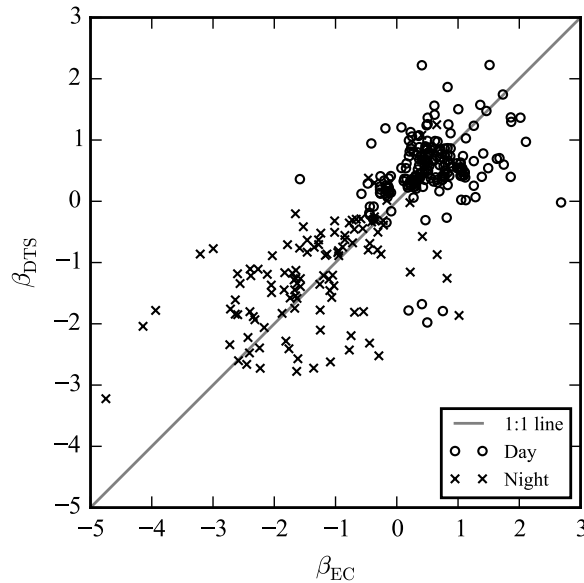


**Figure 6.** Correlation between the DTS measured ($\beta_{DTS}$) and eddy covariance measured ($\beta_{EC}$) Bowen ratios. Daytime data is between 7:00 and 18:00. Data from 10, 12-14, 19-22, and 28-30 August. R$^2$=0.59. RMSE=0.81. $n = 319$ data points.

10   One drawback of the DTS based Bowen ratio, is the assumption that the eddy diffusivity of heat and water vapour are the same. In reality these eddy diffusivities can be dissimilar (Irmak et al., 2014). This can cause an error (both a bias and extra noise) in the Bowen ratio as measured by the temperature and vapour pressure gradients compared to the eddy covariance Bowen ratio. Another source of differences between $\beta_{DTS}$ and $\beta_{EC}$, is that the two are measured at different heights.

During the measurement period the 80% fetch of the EC system was between 200 and 300 m. By applying the findings of

15   Stannard (1997), the Bowen ratio 80% equilibrium ratio would be reached at a fetch to height ratio of 20 to 40. This corresponds to a distance of 350 to 700 m. The fetch of the Bowen ratio will therefore not be equal to the eddy covariance fetch, which could cause some differences in measured fluxes.

**13**

## 4.4 Energy balance closure

A known problem in measuring fluxes is that the energy balance often does not close well. This is caused by differences in fetch between the used devices, device inaccuracies, and possibly problems with the eddy covariance method (Wilson, 2002). Part of the difference between the BR-DTS method and the eddy covariance method may be explained by this energy balance closure problem. Eddy covariance measurements have a fetch, which does not include the area close to the flux tower. The available energy in the BR-DTS method depends on measurements of net radiation, ground heat flux and heat storage change ($\frac{dQ}{dt}$) close to the tower. Heterogeneity in the fetch may cause differences between the two methods. In addition, the biomass heat storage change ($\frac{dQ_B}{dt}$) was not measured for the BR-DTS method, and assumed to be 0 W m$^{-2}$. The photosynthesis energy flux ($G_P$) was also assumed to be 0 W m$^{-2}$.

To investigate the energy balance closure for the two methods, we summed up the available fluxes in the following equations, where $\frac{dQ}{dt}$ is the storage term from Eq. 14:

$$B_{\text{DTS}} = R_N - G_S - \frac{dQ}{dt} \tag{22}$$

$$B_{\text{EC}} = H_{\text{EC}} + \rho\lambda E_{\text{EC}} \tag{23}$$

where $B_{\text{DTS}}$ is the energy available for heat fluxes in the BR-DTS method (W m$^{-2}$) and $B_{\text{EC}}$ is the sum of the eddy covariance measured heat fluxes (W m$^{-2}$).

To compare the two measurement methods, a Tukey mean-difference (or Bland-Altman) plot was made (Fig. 7) (Altman and Bland, 1983). The mean of the two measurement methods is plotted against the difference between them. The mean difference ($\mu$) between $B_{\text{DTS}}$ and $B_{\text{EC}}$ is a 3.4 W m$^{-2}$ underestimation by the BR-DTS method. At low fluxes (below 100 W m$^{-2}$), the BR-DTS method measures less energy available for fluxes compared to eddy covariance. At high fluxes (over 400 W m$^{-2}$) the opposite is visible. One possible reason for this is that the biomass heat flux ($\frac{dQ_B}{dt}$) was not measured, which causes an underestimation of the available energy in $B_{\text{DTS}}$ during the night, and an overestimation during the day.
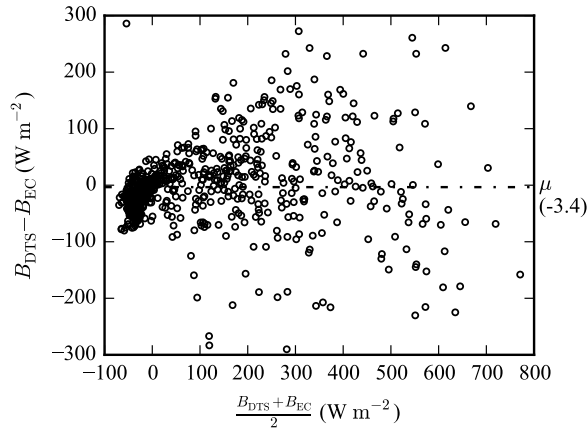
**Figure 7.** Tukey mean-difference plot comparing $B_{\text{DTS}}$ and $B_{\text{EC}}$. With $\mu = -3.4$ W m$^{-2}$, RMSE $= 76$ W m$^{-2}$, $n = 741$ data points. (15 minute averages). Data from 10, 12-14, 19-22, and 28-30 August 2016.

## 4.5 Energy fluxes

Figures 8 and 9 show the mean difference plots comparing the latent and sensible heat fluxes of the eddy covariance method to the BR-DTS method. The BR-DTS fluxes are calculated above the canopy, using only temperature data from the shielded cables. The Tukey mean-difference plot for the latent heat flux shows no large bias when comparing the BR-DTS method to eddy covariance, with the mean difference being a 18.7 W m$^{-2}$ overestimation by the BR-DTS method (Fig. 8).
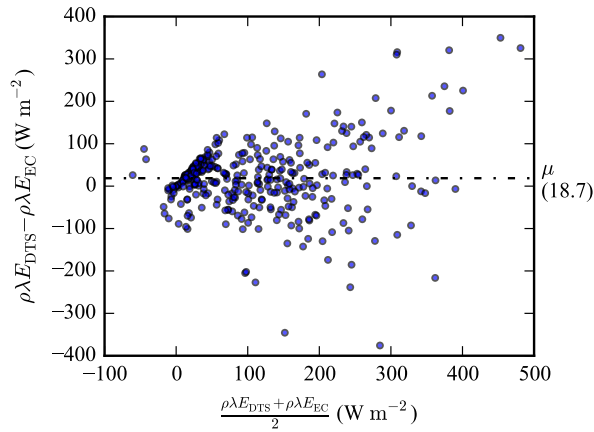


**Figure 8.** Tukey mean-difference plot comparing $\rho\lambda E_{\text{EC}}$ and $\rho\lambda E_{\text{DTS}}$. With $\mu = 18.7$ W m$^{-2}$, RMSE $= 90$ W m$^{-2}$. (15 minute averages). Data from 10, 12-14, 19-22, and 28-30 August 2016.

The Tukey mean-difference plot comparing the sensible heat flux (Fig. 9) shows a strong negative bias for negative fluxes, resulting from the negative bias in the energy balance comparison (Fig. 7). At positive fluxes there seems to be a positive bias ($H_{\text{DTS}} > H_{\text{EC}}$). The mean difference is small, being a 10.6 W m$^{-2}$ underestimation by the BR-DTS method.
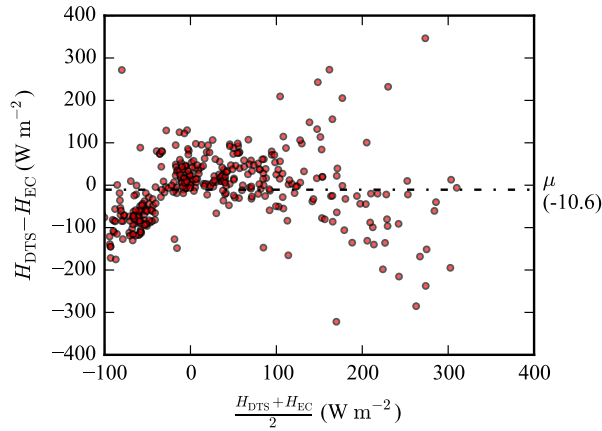
**Figure 9.** Tukey mean-difference plot comparing $H_{EC}$ and $H_{DTS}$. With $\mu = -10.6$ W m$^{-2}$, RMSE $= 82$ W m$^{-2}$. (15 minute averages). Data from 10, 12-14, 19-22, and 28-30 August 2016.

Figure 10 shows the time series of the BR-DTS and EC measured heat fluxes. The daytime flux estimates correspond well, and follow the same trends. The night-time BR-DTS estimates of the sensible heat flux are more negative than the EC estimates, one possible reason being the energy balance differences discussed before. On many days, during the early morning and start of the evening, the BR-DTS has missing values, which is mainly due to the inversion of the gradient, as the temperature gradients

5    changes from negative (stable conditions) to positive (unstable conditions) and vice versa. This inversion causes uncertainty, which is filtered out by the quality control flags.
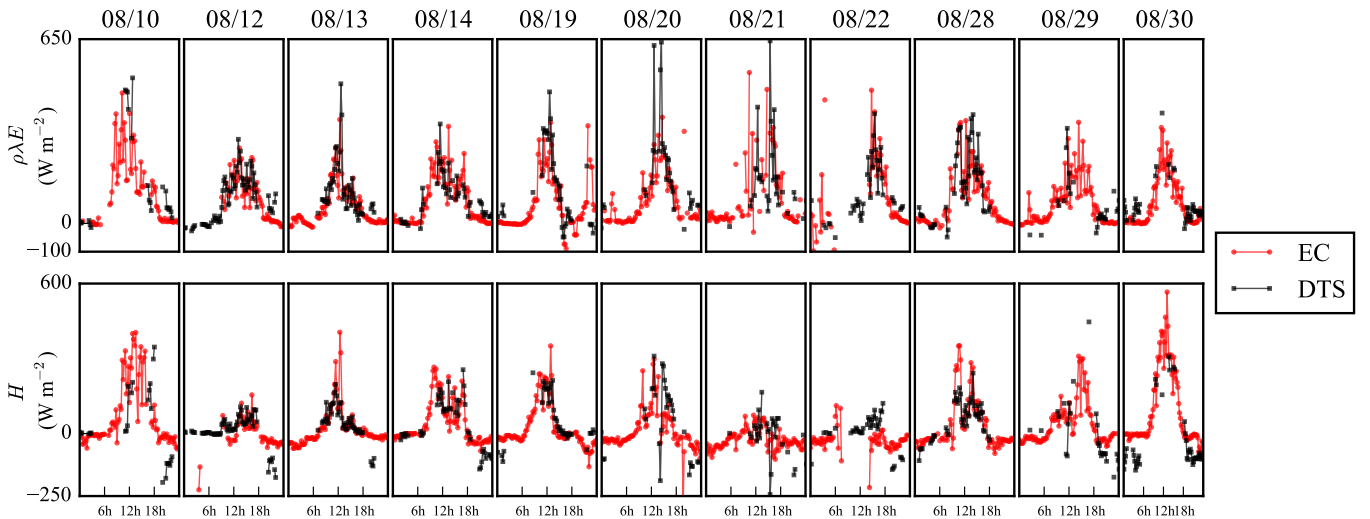


**Figure 10.** Plot comparing the BR-DTS and EC measured sensible ($H$) and latent ($\rho\lambda E$) heat fluxes over time. (15 minute averages). Data from 10, 12-14, 19-22, and 28-30 August 2016.

## 5 Conclusions and recommendations

This technical note investigates the use of the BR-DTS method above a forest canopy, and introduces a number of improvements on the method as presented by Euser et al. (2014). The performance is investigated by comparing the measured DTS cable temperatures to reference sensors, looking at energy balance closure, and comparing the measured Bowen ratio, sensible heat flux, and latent heat flux to eddy covariance measurements.

When comparing the fibre optic cable temperature to reference sensors, it shows that the wet-bulb and air temperatures can be well represented. Under the canopy, where the cables are shaded from direct sunlight, the DTS cable and reference sensors are in near perfect agreement. However, above the canopy direct sunlight may cause a large error, up to 3 K. This error can be largely mitigated by placing screens to block the sunlight, reducing the error to less than 1 K. Hence screens are effective and should also be placed in the canopy.

The Bowen ratio measured by DTS correlates well with eddy covariance estimates ($r^2 = 0.59$). A simple quality control method, using the goodness of fit of the vapour pressure gradient, also works well, and filters out most outliers and errors. The small gradients above the forest canopy are hard to measure accurately, which increases the uncertainty during days where fluxes (and thus gradients) are small. The Bowen ratio assumption that the eddy diffusivities of heat and vapour are equal was not studied, but can be a source of differences between the BR-DTS and eddy covariance methods. The difference in fetch for the two methods can also be a cause for differences.

The energy balance closure between the BR-DTS method and eddy covariance is in good agreement, with the mean difference being a 3.4 W m$^{-2}$ underestimation by the BR-DTS method, and an uncertainty of RMSE = 76 W m$^{-2}$. However, the BR-DTS method estimates a more negative amount of available energy during night-time, and a more positive amount during daytime compared to eddy covariance. One cause could be the lack of biomass heat storage change measurements, which is in the order of 45 W m$^{-2}$. Another source for the difference is that the energy balance components of the BR-DTS method are generally point measurements, while eddy covariance and the Bowen ratio both have a large fetch. As a result, heterogeneity can cause large differences in the available energy for latent and sensible heat fluxes.

When comparing the latent heat flux of the two methods, they are in agreement, although the uncertainty is high (RMSE = 90 W m$^{-2}$). The BR-DTS method slightly overestimates the latent heat flux, with a mean difference of 18.7 W m$^{-2}$. The results for the sensible heat flux are similar, with an uncertainty of RMSE = 82 W m$^{-2}$, and the BR-DTS method underestimating the sensible heat flux by 10.6 W m$^{-2}$. However, the underestimation mainly takes place during night-time, which can be caused by differences in available energy.

While the average profiles can be useful and valuable, extra information could be gained by opting for a smaller diameter fibre optic cable, and measuring at a high frequency (1 Hz). This could give new insights into surface interactions and could show convective cells transporting heat upwards.

A way to improve the performance of the BR-DTS method is to find an independent estimate for the sensible heat flux ($H$), to avoid the uncertainties in the energy balance components ($R_N$, $\frac{\mathrm{d}Q}{\mathrm{d}t}$). Through the universal functions of the Monin-Obukhov similarity theory estimates of the sensible heat flux can be made. This could be done either by measuring the wind speed over

height (Stricker and Brutsaert, 1978) using DTS (Sayde et al., 2015), or by applying the Flux-Variance method (Katul et al., 1995). The Bowen ratio can then be used to calculate the latent heat flux.

## 6 Data availability

The data used in this study is available online on the 4TU data repository (Schilperoort et al., 2017).

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# Reply to referee 1

Dear referee,

Thank you for your detailed look at our manuscript. With your comments we can hopefully solve the present inconsistencies and ambiguities and improve the quality of this submission.

> *The paper validated temperature measurements in BR-DTS method and introduced the use of screens in reducing the impact of solar radiation on temperature measurements in an experiment over a forest. Sensible and latent storage are also considered in energy balance in this paper. The aim to better represent sensible and latent heat flux is within the scope of HESS and the usage of screens is new. However, there are some inconsistencies and ambiguous demonstrations in this paper.*

> *Page 1 Line 2, "now allows its use in hydrological", should be "allow" rather than "allows".*

We will change this in the revised manuscript.

> *Page 2 Line 1, "distributed temperature sensing technology (DTS)", DTS is the abbreviation for "distributed temperature sensing" rather than "distributed temperature sensing technology".*

We will change this in the revised manuscript to *"distributed temperature sensing (DTS) technology"*.

> *Line 1-2, "The precision and spatial resolution now allows its. . ." should be "allow" rather than "allows".*

We will change this in the revised manuscript.

> *Line 11-12, "It also has a resolution of 0.014 K for 15 minute averages, allowing for very small temperature gradients to be measured", please give reference for this sentence.*

This is based on the Silixa provided machine calibration sheet. The calibration gives the resolution as 0.06 K for 1 minute averages at a measurement range of 500 m. This value was extrapolated to the 15 minute averages, based on personal communication with Silixa about the sources of noise[1]. As these numbers are not further investigated in this manuscript, adding the whole analysis would distract from the rest of the manuscript and would have a negative effect on the readability, we will change this to *"It also has a resolution of 0.06 K for 1 minute averages (Silixa machine calibration), and will be more accurate when measuring over a longer time period, allowing for very small temperature gradients to be measured"* in the revised manuscript.

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[1] The main sources of noise in the measurements are Johnson-Nyquist thermal electronic noise and optical shot noise (which are both white noise). As the noise is white noise, every doubling of data points (in space and in time) will lead to a reduction in the uncertainty by a factor $\sqrt{2}$. Of course this will have a limit as other types of noise/errors will become dominant over longer time periods. The exact temperature resolution also depends on the device used, different ULTIMA-S devices can be set to different acquisition distances which will influence accuracy.

*Page 5 Line 23-24, "second cable with a diameter of 3 mm was used to study the effects of solar radiation", however, the 3 mm diameter fiber temperature is not shown in this paper. What is the temperature difference between the thicker and thinner fiber?*

Without the radiation shield, the difference between the cables was in the order of 1 K. The original goal of the installation of the 3 mm cable was to use the solar radiation correction from de Jong, Slingerland, and van de Giesen (2015). However, this method added additional uncertainties due to the required extrapolation. While comparison with reference sensors improved, the uncertainty of extrapolation caused a lot of noise in the Bowen ratio calculations. We will add this explanation to the revised manuscript to explain the lack of the use of the 3 mm diameter cable.

*Page 7 Line 5, "The cables were shielded from direct solar radiation using screen gauze secured onto PVC rings", please describe more about screens, e.g. materials, size and manufacturers. These are quite important as different screen gauzes may lead to different shielding effects.*

We should indeed have included more information about the screens, and will do so in the revised manuscript. Below is a schematic drawing of one section of screen. The screen gauze we used has coated fibreglass as material, with square holes with a width of 1.5 mm and a gauze material width of 0.3 mm. We used two layers on top of each other to achieve a higher reduction in solar radiation.
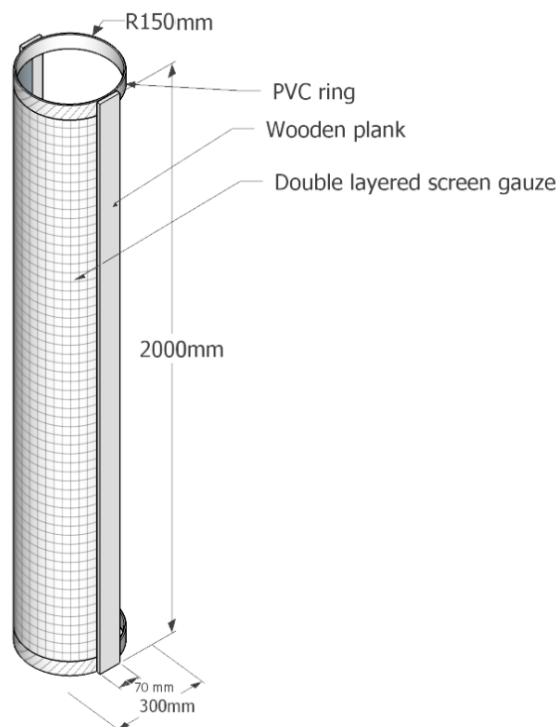


*Line 23, "The biomass heat storage change and the photosynthesis energy flux were not measured", so GP in equation (1) and dQB/dt in equation (14) should be removed as they are not considered here.*

Good point. We will change this in the revised manuscript.

*Page 8 Equation (18) is inconsistent with equation (4), which one has been used? In equation (18) and (19), how many vertical points have been used in calculating Bowen ratio? In Euser*

*et al 2014, it was shown that multiple measurements will lead to better results than two data points.*

The difference between Eq. 4 and Eq. 18 are that in Eq. 4 the partial derivative $(\frac{\partial T}{\partial z})$ was used, which is the average gradient at a point. In Eq. 18 we use the numerical approximation $(\frac{\Delta T}{\Delta z})$. We will clarify this in Eq. 18 by rewriting the first part to;

$$\frac{\partial \Theta}{\partial z} \approx \frac{\partial T_a}{\partial z} - \Gamma \approx \frac{\Delta T_{a,\text{fit}}}{\Delta z} - \Gamma(z) \approx \cdots$$

In the air temperature cable fit, we used all data points from 38.5 to 44 m height. As there are 8 data points per meter this means 44 data points.

*Line 14-15, "the DTS measured temperature and vapour pressure is used", "are" rather than "is" should be used.*

We will change this in the revised manuscript.

*Page 10 Line 3-4, "the 46 m reference sensor is compared to the cable temperatures at 44 m height", there will be some difference between the temperature at 44 m and 46 m since a log profile used here. One way to address this issue may be extrapolating the 46-meter-high temperature of DTS using the 44-meter-high temperature and log profile.*

That could indeed be a way to address the issue, although this would add extra uncertainties. Because of the uncertainties and additional assumptions related to extrapolating the fitted log profile, I believe it is best to make the comparison to the sensor in this way.

*Line 6-7, "This error is a deviation of up to 3 K from the reference sensor temperature", what is the time of averaging in calculating this deviation?*

The data is for 1 minute averages. This will be included in the text of the revised manuscript.

*Page 12 Figure 5. The correlation between Bowen ratios measured by DTS and EC is shown here. It may also help to show the correlation between sensible heat fluxes measured by DTS and EC to compare with figure 8 in Euser et al 2014.*

We chose for Tukey mean-difference plots instead of correlation plots because this will make visual comparisons easier (Bland and Altman, 1983). It is also less sensitive to outliers and high values than correlation plots, as it is focussed around the mean error. The visual comparison is improved by clearly showing around which ranges it deviates from the mean; in our case in Fig. 6, it is easily visible that the low values are underestimated while the higher values are overestimated.

*Page 14 The RMSEs in Figure 6 and 7 are large. What would be the RMSEs if the time average is 30 minutes?*

The RMSEs of the comparison between the EC and BR-DTS heat fluxes is indeed large, but is for a large part a propagation of the difference in available energy (Page 14 - Fig. 6). The RMSEs are shown in the table below. There are no large differences between 15 minute and 30 minute time averages.

| | RMSE 15 min (W m$^{-2}$) | RMSE 30 min (W m$^{-2}$) |
|---|---|---|
| $B_{DTS}$, $B_{EC}$ | 76 | 82 |
| $\rho\lambda E_{DTS}$, $\rho\lambda E_{EC}$ | 90 | 93 |
| $H_{DTS}$, $H_{EC}$ | 82 | 78 |

*Page 19 Line 15, journal name should be added to the citation.*

Well spotted. We will add it in the revised manuscript.

# Reply to referee 2

Dear referee,

Thank you for the critical review. We are happy to hear you feel that the vertical profile measurements using DTS could be very useful to improve flux measurements. We hope that we can improve the manuscript and clarify some points using your comments.

*General comments:*

> *The idea of vertically-resolved temperature and humidity measurements using DTS is very nice, and with some technical and conceptual adjustments such an approach is likely to improve near-surface flux measurements. However, I find that the present study falls short in bringing to bear the main advantages that full profiles could offer and at the end, the measurements are reduced to invoking the standard logarithmic profiles followed by extensive averaging to remove "noise" that, in fact, could offer the most interesting new insights into the fluxes of interest... I found the comparison with EC measurements a bit weak and contributing to the ambiguity in the value of the new method (e.g., the comparisons made by Euser et al. 2014 including Surface layer scintillometer were somewhat more definitive). In order for such a new method to gain traction, it is imperative (in my view) that the method is tested over as simple surfaces as possible such as water surfaces or a flat land surface after irrigation and follow drying, etc. to remove as much as possible confounding effects of canopy and other aerodynamic masking effects. Alternatively, the authors should convincingly show how this new DTS profiler performs better than simple two point measurements routinely done by standard BR stations.*

We understand the concerns you have, and agree that DTS measured profiles could have more information in them. The main goal of this manuscript however, is to improve on the previously published research done by Euser et al. (2014) on a few points, and to take care of unanswered questions that arose from that publication. It is part of ongoing improvements and an exploration of the possibilities of DTS. In this case we chose for measuring in the forest due to the increased complexity and difficulty that can arise from such a measurement site, while flat land surface could have shown more conclusive results. Additionally, while measured profiles could have more information in them, we only studied the Bowen ratio above the canopy, and used fibre optic cables with a diameter of 6 mm. This large diameter causes them to respond slowly to temperature changes, which averages out events with timescales smaller than 2 to 3 minutes.

*Specific comments:*

> *p 3 l 5: it is unclear how eqs. 2 and 3 were implemented with the continuous temperature and vapor pressure profiles (unlike the standard 2 points of classical BR)?*

The gradients of temperature and vapour pressure were calculated from the measured DTS profiles by fitting a logarithmic profile to them. From this fitted profile the gradient was calculated. The exact implementation of equations 2 and 3 is explained in section 3.2: Data Processing.

We supplied the water at the top of the cable. As this water is warmer than the wet bulb temperature, we removed the top two meters of the wet cable from the analysis. In these top two meters the water have reached the wet bulb temperature while slowly flowing down. We will explain this more clearly in the revised manuscript.

We used 15 minute average data for the Bowen ratio to have stable profiles, as the DTS measurements have an inherent noise in them. We did not calculate the averages to measure out "noise" in the air temperature itself. The Bowen ratio was only calculated above the canopy (38.5 to 44 m height, as it is not valid in the canopy, and there are questions about its validity under the canopy). The rest of the profile was used to study the storage of heat and water vapour  in the air column.

To measure events in the temperature profiles (such as convective bubbles) we would need to use a much thinner fibre optic cable, and measure at 1 Hz (the machine limit). At this scale, the DTS measurement noise would have a standard deviation of 0.34 K. However, as we measured using 6 mm fibre optic cables, all the small fluctuations are averaged out.

The basis of the logarithmic profile is indeed MOST. As we looked at averages over 15 minutes, the measured profiles approached this logarithmic shape. Due to the DTS measurement noise and the very small gradients, fitting the profile to many points over the heights gives a more accurate estimate of the Bowen ratio.

As for quality flag 1; the reason we assumed the logarithmic profile is to account for changing conditions. If during the 15 minute averaged period the conditions changed (gradient changed due to the switch from unstable to stable boundary layer, rainfall started, the wind direction shifted significantly), the Bowen ratio is not valid over that averaging period. We will add this explanation to the improved manuscript.

During our measurements the EC system had a 80% footprint of 200 to 300 m. If we use the findings of Stannard (1997), the Bowen ratio 80% equilibration ratio after a large step change

would be reached at a fetch to height ratio of 20 to 40, this corresponds to 350 to 700 m. However, there is no (large) step change in available energy or Bowen ratio near to our measurement site (as it is mixed forest in all directions, for at least 1100 m), which could make the 80% equilibrium ratio distance much smaller.

As for the energy balance closure; on average during our entire measurement period the difference in available energy between EC and BR is around 3.4 W m$^{-2}$ (p. 14 – Fig 6). This could indicate that while the net radiation is representative for the EC fetch, the storage terms are not fully accounted for. As the biomass heat flux was not measured, it could account for over half of the current error.

> *A few general technical comments:*
>
> *- I also wonder about the fundamentals of the measurement itself: (1) the boundary conditions for the wet bulb mass exchange (summarized in the psychrometric constant in eq. 10) are different at 0 and 40 m (the boundary layer around the wet and dry DTS cables due to different wind speed and other factors). This is somewhat related to the comment in page 12 line 10 but not only for the turbulent transfer of the two quantities heat and vapor in the air, but also for the inferences made at the two locations say 0 and 40 m regarding the wet bulb temperature (it is a bit subtle, I admit. . .). It is possible that the psychrometric "constant" which we take for granted as being constant, is different at the two elevations, because the evaporative cooling behaves differently (I am not even entering into the question if the resistance to vapor transport from cloth is important or not). Hence, separating the Bowen ratio estimate to two independent profiles for vapor and temperature may not necessarily be a good idea. . . (I don't know for sure, I simple raise a possible issue that you have listed as an "advantage")*

The Bowen ratio was only applied above the canopy. The profiles themselves can indeed suffer from an error due to different ventilation above, in, and under the canopy, but the effect of this on the results would be subtle (seeing as the differences between the wet cable and the reference sensor under the canopy where small (Fig. 4f)).

The psychrometric "constant" itself is mainly dependent on the air pressure (assuming the resistance to vapour transport from the cloth is insignificant), and influenced by the wind speed if the ventilation of the wet sock is insufficient. For the evaporation of the water from the cloth, the transport regime will change depending on the wind speed (either dominated by forced convection or a combination of forced convection and natural convection). Harrison and Wood (2012) studied the effects of wind speed on the psychrometric "constant", and found that it scales exponentially with low wind speed.

> *- I think that you need to resolve the issue of water input energy to the system – for example, by applying a pulse of water during which you don't measure and then, after liquid and energy relaxation, you may measure with confidence the entire profile without the water supply "holes" you now have*

The water input was located only at the top of the cable; as such there are no 'holes' in the data, just the top 2 m of wet temperature data (44 – 46 m) is affected. We will mention this

more clearly in the setup section. The main gap in the profile is the canopy, where the cable heats up significantly due to solar radiation, but where no radiation shielding was located during the measurement period. Applying water in pulses would be possible, but we chose for continuously supplying the water as that is easier to set up and maintain in the field, and makes data processing much simpler.

> *- An important and potentially interesting feature of the proposed method is to capitalize on the observed profiles and deduce how fluxes and near surface interactions actually work*

Thank you for the suggestion. We are indeed working on capitalizing on the complete observed profiles, and using them to study other processes in the forest ecosystem. An animation of some of the profiles is available on https://www.youtube.com/watch?v=7Iw4L0fFXjc.  Due to the slow response of the 6mm cables we used in this publication short timescale processes were not visible. We also plan to use additional thin fibre optic cables to study processes which happen on smaller timescales.