Research paper


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Natural temperature gradient (NTG) can be a significant problem in thermal sap flow measurements, particularly in dry environments with sparse vegetation. To resolve this problem, we propose a novel correction method called cyclic heat dissipation (CHD) in its thermal dissipation probe (TDP) application. The CHD method is based on cyclic, switching ON/OFF power schema measurements and a three-exponential model, extrapolating measured signal to steady state thermal equilibrium. The extrapolated signal OFF represents NTG, whereas the extrapolated signal ON represents standard TDP signal, biased by NTG. Therefore, subtraction of the OFF signal from the ON signal allows defining the unbiased TDP signal, finally processed according to standard Granier calibration. The in vivo Kalahari measurements were carried out in three steps on four different tree species, first as NTG, then as standard TDP and finally in CHD mode, each step for ~1–2 days. Afterwards, each tree was separated from its stem following modified Roberts’ (1977) procedure, and CHD verification was applied. The typical NTG varying from ~0.5 °C during night-time to ~1 °C during day-time, after CHD correction, resulted in significant reduction of sap flux densities (Jp) as compared with the standard TDP, particularly distinct for low Jp. The verification of the CHD method indicated ~20% agreement with the reference method, largely dependent on the sapwood area estimate. The proposed CHD method offers the following advantages: (i) in contrast to any other NTG correction method, it removes NTG bias from the measured signal by using in situ, extrapolated to thermal equilibrium signal; (ii) it does not need any specific calibration making use of the standard Granier calibration; (iii) it provides a physical background to the proposed NTG correction; (iv) it allows for power savings; (v) it is not tied to TDP, and so can be adapted to other thermal methods. In its current state, the CHD data processing is not yet fully automated.

**Keywords:** cyclic heat dissipation, natural thermal gradient, sap flow, signal extrapolation to steady state, thermal dissipation probe.

Introduction

Thermal methods of tree sap flow measurements (Swanson 1994, Smith and Allen 1996, Köstner et al. 1998, Čermák et al. 2004) are effective solutions in determining the whole plant water use and/or plant transpiration (Wullschleger et al. 1998, Lu et al. 2002, Dzikiti et al. 2007). Three different thermal principles are typically used: heat pulse velocity (HPV), heat balance (HB) and heat dissipation (HD) methods. In HPV methods, a heat pulse is applied by a linear heater in the sapwood. By measuring the temperature change with time for one or more probes located upward and/or downward of the heater probe, an assessment of sap velocity can be made. Three main implementations of the HPV method are typically used: the compensation heat pulse method (Edwards et al. 1996), the T-max method (Cohen et al. 1981) and the heat ratio method.
(Burgess et al. 2001). In HB methods, sap flow is derived from the general HB equation. Two main implementations of the HB method are typically used: trunk segment heat balance and stem heat balance methods, both well described in the review paper by Smith and Allen (1996). In HD methods, heat is continuously supplied to the sapwood by a linear heater. Sap flux density is then estimated from the changes of the heat field around the heater because of the heat-carrying (convection) sap. Two main implementations of the HD method are mostly used: the thermal dissipation probe (TDP) (Granier 1985, 1987) and the heat field deformation (HFD) method (Nadezhdina et al. 1998). This study proposes and explains the novel NTG correction method in its implementation into the TDP method.

The TDP method has been widely applied in tree sap flow measurements because of its low cost, practical installation and simplicity. It uses two probes assembled according to the Granier (1985) design, i.e., one constantly heated at 0.2 W positioned downstream of the sap flow and the other unheated, positioned upstream of the sap flow. The two probes have active lengths of 20 mm each, are inserted parallel in the sapwood at a vertical separation of ~10 cm and are equipped with copper-constantan thermocouples to measure their temperature difference (ΔT). Under conditions of thermal stability in the heating element, in the wood structure and in the sap, the constant heat input is equal to the heat dissipated by convection and conduction at the wall of the probe (Granier 1985, Lu et al. 2004). When there is no sap flow, heat is not dissipated by convection but only by conduction, hence the measured temperature difference reaches its maximum (ΔT_max). When sap flow increases, ΔT reduces proportionally to the increase of the convective heat dissipation. This proportionality was described by Granier (1985) in his empirical formula that defines sap flux density (Jp) as

\[ J_p = 0.0119K^{1.231}\times3600 = 42.84K^{1.231} \text{ [cm}^3\text{ cm}^{-2}\text{ h}^{-1}] \]  

(1)

where \( K \) is a flow index defined as

\[ K = \frac{\Delta T_{\text{max}} - \Delta T}{\Delta T} = \frac{\Delta T_{\text{max}}}{\Delta T} - 1 \]  

(2)

No-flow conditions are expected to occur during night-time; therefore, \( \Delta T_{\text{max}} \) is typically assigned as the largest temperature of the preceding night, even though it has been shown that transpiration often continues during the night (Daley and Phillips 2006, Dawson et al. 2007, Fisher et al. 2007). The standard TDP method cannot guarantee zero night flow but such conditions are expected when the vapor pressure deficit is <0.1 kPa (Kavanagh et al. 2007) and when the night-time ΔT pattern is stable and flat (Ewers and Oren 2000, Lu et al. 2004). Many validation tests proved Eqs. (1) and (2) as being independent of the sapwood characteristics. However, Bush et al. (2010), who carried out TDP laboratory calibration tests, found out that for the diffuse-porous species indeed Eqs. (1) and (2) are appropriate but for the ring-porous species they may be associated with substantial error. This observation was confirmed by TDP heat transfer modeling carried out by Wullschleger et al. (2011), which also indicated \( K \) dependence on thermal conductivity, radial \( J_p \) variability and xylem disruption near the probe.

The TDP method assumes that the combination wood–sap is in thermal equilibrium, i.e., that it has uniform heat field without natural (ambient) temperature gradient along the tree trunk, so the only cause of temperature gradient between the two TDP thermocouples is the externally applied, constant 0.2 W heat. However, in standard TDP field condition, this assumption is often violated due to the presence of natural temperature gradient (NTG). An NTG is a spatio-temporally variable temperature gradient in tree trunks occurring due to the natural, environmental forcing. It biases the TDP measurements in a way that is not detectable applying a standard TDP setup (Granier 1985). The NTG depends on (Čermák and Kučera 1981): climatic conditions of an area investigated including seasonal solar incidence, wind speed and direction, latitude, cloud cover, density of vegetation, species type, biometric properties, the height of the measuring point above the ground, thickness of the bark, azimuthal positioning at the perimeter of a stem, positioning with respect to adjacent trees, growth irregularities of the tree trunk, soil type, canopy shielding and possibly other unknown factors still not mentioned. The exact reasons of NTG and the contributions of different factors enhancing NTG are not fully described in the literature. It is observed by experiments that the impact of NTG upon measured sap flow is the most significant in sparse savannah vegetation well exposed to the sun, in conditions of large diurnal temperature variations (Čermák and Kučera 1981, Do and Rocheteau 2002a) and on trees with low sap flows (Reyes-Acosta et al. 2012). In such circumstances, the NTG may be \( >+1 \text{ °C} \) during a night and \( <-2 \text{ °C} \) during a day (NTG > 0 means that the unpowered upper probe has higher temperature than the lower and NTG < 0 otherwise). If not taken into account, such NTG can overestimate \( J_p \) by >100% (Lundblad et al. 2001, Do and Rocheteau 2002a, 2002b, Lu et al. 2004, Chavarro-Rincon 2009). However, there are also areas where the NTG bias is less important. For example, in dense, shaded forests of moderate climates, the NTG is typically low and does not exceed ~0.2 °C, which corresponds to ~10% of \( J_p \) considered by Do and Rocheteau (2002a) as negligible bias of high sap flows.

Handling NTG has always been a challenge. There are two strategies in that respect, either minimizing NTG impact or removing NTG from the measured signal. Following Lu et al. (2004), minimizing the NTG impact can be done by: (i) extending tree insulation to the ground surface; (ii) shading exposed
roots; and (iii) installing probes sufficiently high above the ground. Implementation of these NTG precautions is cumbersome and often difficult in practice. For example, when stems are short it is not possible to install probes high. The other strategy is to remove the NTG bias from the measured signal. The NTG bias can be monitored in situ by unpowered Granier probes but there is a fundamental problem in using such measurements simultaneously with standard, powered TDP measurements to correct the latter because: (i) the powered TDP systems can influence unpowered NTG measurements; (ii) the NTG is spatio-temporally variable, varying not only between different trees but also between different sensor installations in the same tree. A solution combining powered and unpowered sensors to remove NTG bias was proposed by Goulden and Field (1994) and later improved by Lu et al. (2004) who integrated an extra pair of thermocouples installed in the same tree on the opposite side to the Granier system, all included in one TDP electrical circuit, attempting to offset automatically the NTG. However, as stated by the authors, the use of such a system for NTG correction is limited because it requires that the NTG variability around the trunk is negligible which is rare in practice, and that the powering of the TDP heater does not affect the NTG measuring thermocouples, which means that the method is restricted to large trees only. Another, different approach was proposed by Köstner et al. (1998), who monitored NTG between days of sap flow measurements with similar climatic conditions and proposed posterior NTG correction. This solution was debated by Do and Rocheteau (2002a), who pointed out that such an approach requires repeated sacrifices of measurement days and assumes that NTGs of the consecutive days are equivalent, which is rarely the case because of possible changes in pedo-climatic conditions and sap flows. To minimize this difficulty, Cabibel and Do (1991b) used a correlation between NTG for each probe and climatic data. This method, however, also proved to be complicated and unwieldy as stated by Braun and Schmid (1999) and besides the correlations were often imprecise (Do and Rocheteau 2002a). It is difficult to state who was the first to introduce the original idea of using a cyclic power schema (CPS) of data acquisition to remove NTG from the TDP measurements. Two such attempts from the late 1990s are reported, first by Köstner et al. (1998) and second by Do et al. (2008). Köstner et al. (1998) quoted unpublished work of Granier who used a logger to switch ON and OFF power every 30 min to reach thermal equilibrium in every ON and OFF measurement interval. In such a way the original Granier (1985) calibration could be used but the 30 min intervals did not guarantee the thermal equilibrium, particularly when low flows were measured. Do et al. (2008) quoted their CPS measurements in 1996–99 from Senegal, involving 15 min power ON and 45 min power OFF, processed according to the transient thermal dissipation (TTD) method explained by Do and Rocheteau (2002a, 2002b). In contrast to Granier's principle based on processing a thermally equilibrated signal, the TTD method accepts that at the ends of the power ON/OFF intervals, the measured signals do not reproduce thermal steady state, therefore proposing a new empirical calibration of \( I_p \), different than the one proposed by Granier (Eqs. (1) and (2)). The TTD method was tested with respect to different durations of the power ON and OFF. Do and Rocheteau (2002a, 2002b) recommended 15 min ON and 15 min OFF that was also followed by Chapotin et al. (2006) and Abid Karray et al. (2008). Recently, another calibration for the TTD method was introduced by Isaranrkoool Na Ayutthaya et al. (2010) who stated that their new calibration is species independent and also recommended different powering schema, i.e., 10 min ON and 20 min OFF. The TTD method was recently debated by Nourtier et al. (2011) who indicated that their time needed to reach the stationary regime is determined by the heat exchanges between probes, wood and xylem sap. Therefore, the TTD sap flow estimates depend on the thermal properties of tree species, the magnitude of the actual sap flow in the investigated tree and the trunk diameters, which means that it has to be calibrated for each length of on and OFF transients and also for each species investigated. They also showed, in the example of silver fir trees (Abies alba Mill.) with low sap flux densities (maximum of 0.68 l dm\(^{-2}\) h\(^{-1}\)), that the TTD calibrations based on non-extrapolated to steady state data may lead to significant errors. As a solution, they proposed to use CPS schema next to an additional continuously heated TDP correction system, providing a stationary TDP signal with similar temporal behavior as the cyclic one. In practice, their additional system was installed either on the same tree but on a different side of the stem or on another adjacent tree of the same species and similar in size. However, in environments with large NTG, also this proposal seems to be prone to errors because it uses different TDP installations that can be differently affected by NTG and also because the additional continuously heated TDP used for the NTG correction can itself be affected by NTG in a different temporal manner than the cyclic one. Besides, the proposed correction procedure is cumbersome because it requires time-consuming confirmation of similarity in temporal behavior between cyclic and constant power installations which is not always certain for the selected trees. Finally, the correction proposed by Nourtier et al. (2011) was applied on one species at one location so as the authors admit ‘it is not certain whether it is suitable for fir trees with higher growth rates or different trunk diameters or for other tree species’.

The proposed cyclic heat dissipation (CHD) method offers a solution to the above-specified problems and does not require an extra sensor, thanks to the extrapolation of the CPS signal to thermal steady state. Because of this principle, it also provides a better opportunity of understanding the mechanism of the NTG bias and its removal from the CPS signal. The presented work uses the data acquired by the authors of this
Novel CHD method for the correction of natural temperature gradients in sap flow measurements: part 1

C. Rocheteau

The thermal system across which heat transfer takes place is characterized by two relevant thermal parameters: thermal capacitance \( C_w \) and thermal resistance \( R_w \). The thermal capacitance \( C_w \) is the ratio between the amount of heat \( h_c \) needed to bring the initially thermally homogeneous system to the steady state temperature difference \( \Delta T \):

\[
C_w = \frac{h_c}{\Delta T} \tag{3}
\]

The thermal resistance \( R_w \) is the ratio between the temperature difference \( \Delta T \) at the steady state and heat flow \( h_c \) needed to maintain that temperature difference \( (H = 0.2 \text{ W during power ON}) \):

\[
R_w = \frac{\Delta T}{h_c} \tag{4}
\]

Defining \( t \) as instantaneous time and \( \Delta T \) as the temperature above or below the temperature at the initial (starting) condition, the total impulse response of the system can be evaluated as

\[
H = h_c + h_{Rw} = 0.2 \text{ W} \tag{5}
\]

where \( h_c \) and \( h_{Rw} \) are the instantaneous heat flows consumed by the heat capacity and heat conduction components, respectively, and \( H \) is a sensor’s heat source power which is equal to 0.2 W when power is ON and 0 when power is OFF. With the same \( \Delta T \) across \( R_w \) and \( C_w \) in Eqs. (3) and (4), and integrating over \( dt \):

\[
R_{w}h_{Rw} = \int_0^t \frac{h_c}{C_w} \, dt \tag{6}
\]

Multiplying both sides of Eq. (5) by \( R_w \) and inserting Eq. (6) into (5):

\[
R_{w}H = \int_0^t \frac{h_c}{C_w} \, dt + h_cR_w \tag{7}
\]

which results in

\[
R_{w}H = \frac{h_c}{C_w} t + h_cR_w \tag{8}
\]

Solving for \( h_{Rw} \):

\[
h_{Rw} = H \frac{R_wC_w}{t + R_wC_w} = He^{(-t/(R_wC_w))} \tag{9}
\]

Replacing (9) in (5) and solving for \( h_{Rw} \):

\[
h_{Rw} = H(1 - e^{(-t/(R_wC_w))}) \tag{10}
\]

Equation (10) can be introduced into Eq. (4) to evaluate steady state \( \Delta T \):

\[
\Delta T = HR_{w}(1 - e^{(-t/(R_wC_w))}) \tag{11}
\]
where the $R_wC_w = T_w$ is a thermal time constant of the sapwood cylinder under investigation and $HR_w = A_w$ is the peak amplitude of a $\Delta T$ signal.

For the cases when the power is ON Eq. (11) is

$$\Delta T = A_w(1 - e^{-t/T_i})$$

(12)

while when the power is OFF the Eq. (11) is

$$\Delta T = -A_w(1 - e^{-t/T_i}) = A_w(e^{-t/T_i} - 1)$$

(13)

The solutions of Eqs. (12) and (13) determine the fitting parameters $T_w$ and $A_w$ as if the thermal process took place in a single, homogeneous material. In fact, however, the TDP set-up is clearly a heterogeneous system and therefore, at the conceptual level, Eqs. (12) and (13) are split into three different thermal components roughly distinguished as follows: (i) the heater filament and all the components wrapped by this filament (i.e., isolation layer and thermocouple assembly) represented by parameters $A_i$ and $T_i$; (ii) the assembly of aluminum tube and conductive silicone compound applied to improve thermal contact between the heating filament and aluminum tube, represented by parameters $A_2$ and $T_2$; and (iii) the portion of sapwood in contact with the heating probe represented by parameters $A_3$ and $T_3$. The actual physical boundaries between the three thermal components are not necessarily as clear-cut as their conceptual descriptions. Following these assumptions Eq. (12) for cycle intervals with power ON takes a third-order exponential form as

$$\Delta T = A_1(1 - e^{-t/T_1}) + A_2(1 - e^{-t/T_2}) + A_3(1 - e^{-t/T_3})$$

(14)

while Eq. (13) for cycle intervals with power OFF takes a third-order exponential form as

$$\Delta T = -A_1(1 - e^{-t/T_1}) - A_2(1 - e^{-t/T_2}) - A_3(1 - e^{-t/T_3})$$

(15)

where $A_1$, $A_2$, $A_3$ are the signal amplitudes and $T_1$, $T_2$ and $T_3$ are the time constants for the three thermal components in consideration. Note, that for $t \to \infty$ the extrapolated to steady state asymptotes of Eqs. (14) and (15) for the cycles with power ON and OFF are expressed as $A_{ON} = A_1 + A_2 + A_3$ and $A_{OFF} = -A_1 - A_2 - A_3$, respectively.

**Model implementation—CHD method**

The $\Delta T$ signal of CPS consists of cycles, where each cycle consists of two transients, a signal rising part corresponding to the power ON called ‘ON transient’ and a signal declining part corresponding to the power OFF called ‘OFF transient’, each transient marked by subscript $i$. Figure 1 shows a sample of field CPS data consisting of 15 min-long ON transient extrapolated to steady state and two adjacent OFF transients, each with 15 min length and each also extrapolated to steady state. Considering that the extrapolated to steady state signal ON ($\Delta T_{ON}^{E}$) represents the sum of an unknown, unbiased signal and NTG, while the extrapolated to steady state signal OFF represents the NTG only, the corrected unbiased signal ON ($\Delta T_{ON}^{E}$) can be defined as

$$\Delta T_{ON}^{E} = \Delta T_{ON}^{E} - \Delta T_{NTG}^{E}$$

(16)

where $\Delta T_{ON}^{E}$ is the extrapolated (marked with index E) to steady state signal ON for the $i$-th transient while $\Delta T_{NTG}^{E}$ is the extrapolated to steady state signal OFF (NTG) for the $i$-th transient, calculated as an average of the extrapolated OFF signals of the preceding and subsequent OFF transients (Figure 1).

$$\Delta T_{NTG}^{E} = 0.5(\Delta T_{OFF_{i-1}}^{E} + \Delta T_{OFF_{i+1}}^{E})$$

(17)

The $\Delta T_{ON}^{E}$ in Eq. (16) is calculated as

$$\Delta T_{ON}^{E} = \Delta T_{OFF_{i-1}}^{E} + A_i(1 - e^{-t/T_i}) + A_2(1 - e^{-t/T_2}) + A_3(1 - e^{-t/T_3})$$

(18)

where $\Delta T_{OFF_{i-1}}^{E}$ is the measured temperature difference at the end of the preceding OFF transient and $A_1$, $A_2$, $A_3$ and $T_1$, $T_2$, $T_3$ are the fitted parameters.

The $\Delta T_{OFF_{i-1}}^{E}$ and $\Delta T_{OFF_{i+1}}^{E}$ in the Eq. (17) are calculated as

$$\Delta T_{OFF_{i-1}}^{E} = \Delta T_{ON}^{E} - [A_i(1 - e^{-t/T_i}) + A_2(1 - e^{-t/T_2}) + A_3(1 - e^{-t/T_3})]$$

(19)

$$\Delta T_{OFF_{i+1}}^{E} = \Delta T_{ON}^{E} - [A_i(1 - e^{-t/T_i}) + A_2(1 - e^{-t/T_2}) + A_3(1 - e^{-t/T_3})]$$

(20)

where $\Delta T_{ON}$ and $\Delta T_{OFF_{i-1}}$ are the signals at the end of the ON transients preceding the calculated $\Delta T_{OFF}$ and $A_1$, $A_2$, $A_3$ and $T_1$, $T_2$, $T_3$ are the fitting parameters of Eqs. (18)–(20).

**Field application of the CHD method**

The sap flow measurements of this study were carried out in the semi-arid Kalahari savannah type of desert (S 22°17′, E 26°25′) in Botswana on four trees of four different species (local names are in brackets): *Boscia albitrunca* (W. Burchell) (motopi), *Dischrostachys cinerea* (Wight & Arn.) (mosoletsele), *Acacia fleckii* (H. Schinz) (mohahu) and *Acacia luederitzii* (H. Schinz) (mokha). The diameters at breast height of the investigated trees, their estimated sapwood areas and the timing of different steps of the experiment are listed in Table 1. The experiment was carried out during clear sky days in May.
2005, i.e., at the end of wet season, when soil moisture was at its full retention capacity, peak short-wave solar incoming radiation was of the order of 800 W m\(^{-2}\) and temperature differences between day and night were > 10 °C, typically from ~25 °C in the nights to 35 °C during days. The sap flow measuring system consisted of: (i) three pairs of standard TDP sensors (UP GmbH, Ibbenbüren, Germany) identified as Sap1, Sap2 and Sap3; (ii) multi-channel data logger (DataHog2, Llandridod Wells, Powys, Skye Instruments Ltd, UK) programmed for data acquisition at 30 s sampling interval; (iii) power supply; (iv) custom-made sequencer to force power into ON and OFF cycle transients. The measurements were carried out by moving the sap flow measuring system from one tree to another. In each tree, the three TDP sensors were installed at three different azimuths, ~120° from each other but at the same height, as far as possible from the ground, normally at 70–100 cm height below the first tree ramifications. The TDP probes were installed in aluminum tubes following standard UP GmbH procedure. Each drilling of a tube-hole was carried out slowly to control whether wood fines originate from sapwood and not heartwood—coring of the trees was impossible due to the extreme hardness of the wood. The probe installations were carefully isolated from direct solar radiation by protection shields made of a combination of styrofoam (thermal conduction protection) and aluminum foil (radiation shielding). The schedule of measurements

Table 1. Main tree parameters and schema of the three-step in vivo measurements. DBH, diameter at breast height in cm; Axd, sapwood area in cm\(^2\); NTG, natural thermal gradient; CTD, constant thermal dissipation (standard, constant power TDP); CHD, cyclic heat dissipation.

<table>
<thead>
<tr>
<th>Species</th>
<th>DBH</th>
<th>Axd</th>
<th>Step #1—NTG</th>
<th>Step #2—CTD</th>
<th>Step #3—CHD</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Boscia albitrunca</em></td>
<td>13</td>
<td>45</td>
<td>11/5/13:00–12/5/14:30</td>
<td>12/5/14:30–13/5/16:00</td>
<td>13/5/16:00–15/5/13:30</td>
</tr>
<tr>
<td><em>Acacia fleckii</em></td>
<td>12</td>
<td>81</td>
<td>24/5/11:00–25/5/11:00</td>
<td>25/5/11:00–26/5/11:00</td>
<td>26/5/11:00–29/5/11:00</td>
</tr>
<tr>
<td><em>Acacia luederitzii</em></td>
<td>19</td>
<td>205</td>
<td>26/5/18:00–28/5/18:00</td>
<td>28/5/18:00–30/5/18:30</td>
<td>30/5/18:30–31/5/14:30</td>
</tr>
</tbody>
</table>
was designed in three steps after Do and Rocheteau (2002a). Each step lasted 24–48 h (Table 1) and followed one after another without reinstallation: Step #1: acquisition of NTG data by measuring $\Delta T$ using a standard TDP system, but unpow- ered; Step #2: collection of standard TDP $\Delta T$; Step #3: data acquisition according to CPS with 15 min power ON and 15 min power OFF for the application of the CHD method. The data of Step #2 acquired according to the standard TDP method were processed with Eqs. 1 and 2. The CPS data of Step #3 were fitted with the CHD model (Eqs. (16)–(20)) applying the least squares optimization method. The ON transients were extrapolated to steady state equilibrium according to Eq. (18). The OFF transients were extrapolated with Eqs. (19) and (20) and the averages of the two were calculated according to Eq. (17) afterwards. Finally the true, unbiased signals ($\Delta T_{\text{true}}$) were calculated according to Eq. (16) and processed applying standard TDP Eqs. (1) and (2).

Field verification of the CHD method

To verify the CHD method, cut-tree experiments were conducted on each of the four trees investigated, essentially according to the procedure presented by Roberts (1977) with minor modifications. After completing the three-step measurements as described above, the sap flow sensors were removed from the stems (aluminum tubes remained), the trees were severed from their stems and immediately after immersed in a container with water. Next, a fresh cut was made under-water, a few centimeters above, with a specially designed chain-saw to avoid air-induced embolism in the sapwood. A plastic bag filled with water was then wrapped under-water around the bottom of each tree while it was still in the water container, taking care not to expose the cut sapwood to air. Immediately after, the tree was placed in a transparent cylinder, slightly larger than the stem diameter and filled with water and the plastic bag was removed. Next, the ensemble of the severed tree in the cylinder was lifted by the combination of a mast and a pulley and finally removed. Next, the ensemble of the severed tree in the cylinder was placed under convection. The NTG differences between measurements at different trees (Figure 3) and its relative value as compared with thermal diffusivity of the soil particularly at the contrasting interface near the ground surface. This is because bodies with lower $D$ (i.e., with larger thermal capacity and lower thermal conductivity) are able to accumulate a large amount of heat during a day and delay its return during a night, thus enhancing NTG. The NTG differences between different sensor installations within a given tree are due to various factors including different sun exposures as a function of sensor azimuth, heterogeneous distribution of $D$ etc. For all the trees investigated in this study,
Figure 2. An example of raw \( \Delta T \) for: (a) B. albitrunca (Sap 1); (b) D. cinerea (Sap 3); (c) A. fleckii (Sap 1); and (d) A. luederitzii (Sap 2). All the measurements are acquired in three steps: Step #1—measurement of NTG; Step #2—standard TDP (CTD) measurement; Step #3—CPS measurement with 15/15 min transients.
positive or nearly zero night-time NTGs and negative day-time NTGs were observed, although the temporal patterns differed between species, as indicated by the boxplot in Figure 3. Also the Kruskal–Wallis test of difference confirmed that not only averages per species, but also all individual sensors in the four investigated trees were statistically different. The NTGs for B. albitrunca, A. fleckii and A. luederitzii (Figure 2a,c,d, Table 2) were typically between approx. −1 °C during day-time and < +0.5 °C during night-time, and were relatively consistent among the three sensors in each investigated tree (Chavarro-Rincon 2009). The NTG of D. cinerea (Figure 2b, Table 2) differed between the three sensors and was generally larger than in the other three species investigated.

### Table 2. The NTG (Step #1) normalized with respect to daily cycle. S ↓ max and S ↓ avg are short-wave incoming radiations, maximum of the day and average of the day, respectively, in (W m⁻²); Tmin and Tmax are minimum and maximum daily air temperatures at 2 m height in (°C); NTG in (deg).

<table>
<thead>
<tr>
<th>Species</th>
<th>Date</th>
<th>S ↓ max</th>
<th>S ↓ avg</th>
<th>Tmin</th>
<th>Tmax</th>
<th>Sap no.</th>
<th>NTG Min</th>
<th>NTG Max</th>
<th>NTG Mean</th>
<th>NTG Std. Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boscia albitrunca</td>
<td>11/12 May 2005</td>
<td>790.20</td>
<td>25.65</td>
<td>−0.93</td>
<td>+0.14</td>
<td>Sap 1</td>
<td>−0.37</td>
<td>0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>225.15</td>
<td>36.76</td>
<td>−1.18</td>
<td>−0.03</td>
<td>Sap 2</td>
<td>−0.38</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−0.85</td>
<td>+0.14</td>
<td>Sap 3</td>
<td>−0.02</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichrostachys cinerea</td>
<td>18/19 May 2005</td>
<td>759.80</td>
<td>24.32</td>
<td>−5.20</td>
<td>+0.11</td>
<td>Sap 1</td>
<td>−1.44</td>
<td>1.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>209.72</td>
<td>38.25</td>
<td>−0.61</td>
<td>+0.43</td>
<td>Sap 2</td>
<td>−0.14</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−2.26</td>
<td>+0.97</td>
<td>Sap 3</td>
<td>1.02</td>
<td>0.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acacia fleckii</td>
<td>24/25 May 2005</td>
<td>749.02</td>
<td>26.06</td>
<td>−1.60</td>
<td>+0.98</td>
<td>Sap 1</td>
<td>−0.11</td>
<td>0.46</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>196.44</td>
<td>37.12</td>
<td>−1.01</td>
<td>+0.46</td>
<td>Sap 2</td>
<td>−0.09</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−1.65</td>
<td>+0.44</td>
<td>Sap 3</td>
<td>−0.01</td>
<td>0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acacia luederitzii</td>
<td>27/28 May 2005</td>
<td>744.12</td>
<td>24.68</td>
<td>−1.69</td>
<td>+0.68</td>
<td>Sap 1</td>
<td>−0.13</td>
<td>0.76</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>205.90</td>
<td>38.04</td>
<td>−0.98</td>
<td>+0.38</td>
<td>Sap 2</td>
<td>−0.15</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−0.86</td>
<td>+0.63</td>
<td>Sap 3</td>
<td>+0.05</td>
<td>0.50</td>
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</tr>
</tbody>
</table>

Figure 3. Boxplot presenting NTG statistics of the four trees each integrated over the three TDP systems installed at the same height but in three different azimuthal directions.

### Constant power signal versus CPS signal ON

The standard, constant power TDP signal of Step #2 (Figure 2), also known as constant thermal dissipation (CTD) signal (Do et al. 2008) and the interrupted after 15 min CPS ON signal of the Step #3 (upper part) are both constrained by the same type of external temperature gradient originated from the constant power source of heat of 0.2 W (Granier 1985). In the real, field condition, on top of that gradient there is also NTG. The extrapolated condition equivalent to the CTD signal obtained from the constantly powered Granier system affected by NTG. Such a signal represents the sum of the unbiased TDP signal and the NTG. In Figure 2, the expected similarity between patterns of the CTD signal of Step #2 and the raw (non-extrapolated) 15 min CPS signal ON of Step #3 (upper part) can be observed. The small differences between the two signal patterns are because: (i) Step #3 ON not reaching steady state; (ii) possible differences between sap flow rates in consecutive days of data acquisition, first as the CTD signal (Step #2) and then as CPS ON signal (Step #3); (iii) temporal variability of the NTG during consecutive days differently affecting the measurements in consecutive days.

### CHD model fitting and parameterization

The proposed three-exponential CHD model fitting is based on Eq. (11). In the thermal system the three identified thermal components of that system were modeled by three different exponentials (Eqs. (14) and (15)) jointly simulating CPS signal ON and OFF extrapolation to steady state thermal equilibrium. In practice, the fitting of the model into the field-acquired CPS data was carried out by least-squares fitting of the parameters $A_i$ and $T_j$ (i: 1–3) to every 15 min ON and 15 min OFF transients as per Eqs. (18)–(20). After preliminary sensitivity analysis, the first two thermal time constants $T_1$ and $T_2$ representing two system components...
components such as the heater filament and the assembly of the aluminum tube with conductive silicone compound, were shown to be insensitive and were fixed as $T_1 = 12$ s and $T_2 = 80$ s, respectively. The other four fitting parameters, i.e., $A_1$, $A_2$, $A_3$ and $T_3$, were optimized in each ON and OFF transient using the least-squares parameter optimization routine. The results of the optimization for the four investigated trees, three TDP sensors per tree, is presented in Table 3. The $A_1$ amplitude was generally very stable (low variations while fitting to different transients) through all ON and OFF and for day- and night-time transients but different for different sensor installations. Such insensitivity of $A_1$ and its largest amplitude value was expected because it represents a thermally stable component of the heater filament, i.e., minimally affected by convective heat transport. The mean amplitude $A_2$ representing the thermal system component of an aluminum tube was also thermally stable but slightly less than $A_1$, as showed by larger standard deviations relatively to the mean of $A_2$. The mean amplitude $A_3$ representing the response of a conductive sapwood component was different than the $A_1$ and $A_2$. The mean $A_3$ was quite similar for transients ON and OFF but significantly different between nights and days. This difference was due to the sensitivity of $A_3$ to the day-time sap flow heat convection lowering the day-time amplitude as compared with night-time amplitude. The larger day-time standard deviation of $A_1$ was resulted by temporal variability of the sap flow and related heat convection variability. Such variability implied signal drift (convection-based variation of the $\Delta T$ signal) affecting mainly end parts of day-time cycles, more OFF

Table 3. Parameters of the CHD models normalized with respect to a full day-time for the four investigated tree species, each monitored by three sap flow sensors (Sap 1–3). $A_1$, $A_2$, $A_3$ are signal amplitudes and $T_1$, $T_2$, $T_3$ are thermal time constants.

<table>
<thead>
<tr>
<th>Species</th>
<th>$T_1$ (s)</th>
<th>$A_1$ (°C)</th>
<th>$A_2$ (°C)</th>
<th>$A_3$ (°C)</th>
<th>$T_3$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Day</td>
<td></td>
<td>Night</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ON</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
</tr>
<tr>
<td>Boscia albitrunca</td>
<td>12</td>
<td>8.162</td>
<td>1.859</td>
<td>0.604</td>
<td>0.706</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dichrostachys cinerea</td>
<td>10.527</td>
<td>1.750</td>
<td>2.060</td>
<td>2.248</td>
<td>2.237</td>
</tr>
<tr>
<td></td>
<td>10.053</td>
<td>1.827</td>
<td>1.925</td>
<td>1.938</td>
<td>1.938</td>
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<td>9.761</td>
<td>1.684</td>
<td>1.506</td>
<td>2.015</td>
<td>1.938</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>Acacia fleckii</td>
<td>7.585</td>
<td>1.672</td>
<td>0.744</td>
<td>0.755</td>
<td>2.098</td>
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<td></td>
<td>3.636</td>
<td>1.605</td>
<td>1.848</td>
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<td>2.586</td>
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<td></td>
<td>8.058</td>
<td>1.507</td>
<td>0.315</td>
<td>0.340</td>
<td>1.974</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>Acacia luedentzi</td>
<td>8.450</td>
<td>1.909</td>
<td>1.176</td>
<td>1.263</td>
<td>1.708</td>
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<td></td>
<td>8.805</td>
<td>1.763</td>
<td>1.349</td>
<td>1.428</td>
<td>1.755</td>
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<tr>
<td></td>
<td>9.222</td>
<td>1.747</td>
<td>1.298</td>
<td>1.313</td>
<td>1.751</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.107</td>
<td>0.196</td>
<td>0.267</td>
<td>0.248</td>
<td>0.060</td>
</tr>
<tr>
<td></td>
<td>0.050</td>
<td>0.098</td>
<td>0.177</td>
<td>0.140</td>
<td>0.026</td>
</tr>
<tr>
<td></td>
<td>0.047</td>
<td>0.126</td>
<td>0.274</td>
<td>0.187</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Tree Physiology Online at http://www.treephys.oxfordjournals.org
than ON transients, when the signal was less determined by the external 0.2 W gradient. The optimized thermal time constant parameter $T_3$, also representing the response of the sapwood system, was sensitive to convective heat influence too. However, as compared with $A_3$, the $T_3$ differed more between ON and OFF transients and less between day and night transients. Like in the case of $A_3$, the standard deviation of $T_3$ reflecting signal variability was significantly larger during day-time than during night-time, pointing to the influence of temporally variable heat convection signal drift particularly distinct during day-time OFF transients when temporal changes of sap flow were the largest and the measured signal was the least determined by external 0.2 W gradient.

The variability of the fitting parameters of the proposed three-exponential model is an interesting problem that warrants further consideration. Our experience hitherto (also acquired from other study areas and from laboratory experiments) indicates that: (i) $T_1$ and $T_2$ are essentially independent of the conditions of sensor installations and monitoring so can be assigned as constants for the particular equipment used regardless of species investigated and environmental conditions; for example, the same $T_1$ and $T_2$ parameters were also successfully used in parameterization of the CHD method applied to sap flow measurements in oak trees in Spain (Reyes-Acosta and Lubczynski 2012, in revision) acquired with the same equipment as used in this Kalahari study; (ii) $A_1$ and $A_2$ depend on sensor installation but do not differ significantly between ON and OFF transients and between day and night; (iii) $A_3$ depends on sensor installation and vary between day- and night-time measurements but does not differ significantly between ON and OFF transients; (iv) $T_3$ differs between sensor installations, between day and night and between ON and OFF transients. If these observations are confirmed on more sap flow installations, then general optimization rules following the presented observations can be established in forthcoming research.

**Accuracy of the CHD model fitting**

The patterns of sap flow cycle transients differ between: (i) day-time transients when sap flow convection is typically significant and night-time transients when sap flow convection is typically negligible and (ii) between ON transients, when an external 0.2 W constant power gradient is applied enforcing conductive heat dissipation and OFF transients when the external gradient rapidly declines after power shut-off. The examples of four different but typical patterns of cycle transients are presented in Figure 4a–d. The heat conduction due to the external 0.2 W constant power gradient in ON transients and the heat convection due to the day-time sap flow, both enhance heat transfer between two TDP probes inserted in sapwood both stimulating reduction of the time necessary for the $\Delta T$ signal to reach thermal steady state and reduction of the signal amplitude reflected by extrapolated to steady state $\Delta T = \Delta T_e$. Therefore, the day ON transients typically reach steady state the fastest—in the case presented in Figure 4a, already after 1 min the $\Delta T$ signal flattened and after 15 min was close to steady state, having the lowest $SR = 0.002 \degree C$ and also the lowest $\Delta T_e = 9.249 \degree C$. In contrast, during night OFF transients (Figure 4d), after 1 min, the $\Delta T$ signal was still far from flattening, approaching steady

![Figure 4. An example of multi-exponential $\Delta T$ signal fitting and extrapolation of CPS data acquired on 14 May 2005 (DOY 134) during: (a) day-time ON; (b) day-time OFF; (c) night-time ON; and (d) night-time OFF. Data from B. albitrunca, Sap 1. SR, signal residual; $\Delta T_e$, extrapolated to steady state $\Delta T$; MISFIT, relative root mean squared error.](https://academic.oup.com/treephys/article-abstract/32/7/894/1643874)
state in the slowest manner—in the case presented in Figure 4d after 15 min, the $\Delta T$ signal was still quite far from steady state, having the largest $SR = 0.276 \, ^\circ C$. It is important to be aware that the sap flow heat convection not only shortens the time of the signal’s arrival at steady state but may also increase $SR$, particularly during day OFF transients (this was not the case for Figure 4b) when external constant power gradient declines and natural variability of sap flow convection, for example, due to the cloud effect or wind speed variability, becomes comparable with conduction resulting in signal drift. Such signal drift was the main reason for the misfit (root mean square relative error) between the measurements and the fitted multi-exponential model. An example of the misfit in the CHD modeling of the three $B. \, \text{albitrunca}$ sensors is presented in Table 4. Indeed, the largest misfit is observed during day-time OFF transients when sap flow changes are the largest and the signal is the least constrained by the external, constant power gradient and the smallest during night-time ON transients when eventual sap flow-related heat convection changes are the smallest and the signal is largely constrained by the external, constant power gradient. The signal drift was tree specific and the most distinct in the morning OFF transients when plants were the most active and temporal changes of sap flow were the largest. The signal drift can be considered as noise in the CHD modeling which

Table 4. Example of the misfit (relative root mean squared error) of the CHD models fitted into the 15 min ON/15 min OFF transients of the three sap flow sensors (Sap1–3) installed in Boscia albitrunca tree for the period from 16:00 on 13/5/2005 till 13:30 on 15/5/2005. No. is a number of transients analyzed.

<table>
<thead>
<tr>
<th>Sap no.</th>
<th>Day_ON</th>
<th>Day_OFF</th>
<th>Night_ON</th>
<th>Night_OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Misfit $\times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sap 1</td>
<td>2.00</td>
<td>62.40</td>
<td>0.27</td>
<td>3.49</td>
</tr>
<tr>
<td>Sap 2</td>
<td>1.61</td>
<td>39.04</td>
<td>0.65</td>
<td>4.75</td>
</tr>
<tr>
<td>Sap 3</td>
<td>2.67</td>
<td>76.53</td>
<td>0.23</td>
<td>5.62</td>
</tr>
<tr>
<td>No.</td>
<td>30</td>
<td>30</td>
<td>58</td>
<td>58</td>
</tr>
</tbody>
</table>

Figure 5. An example of measured, extrapolated and CHD corrected $\Delta T$. Data from $B. \, \text{albitrunca}$, Sap 1.
affects mainly the end parts of transients when heat is carried mostly by convection rather than conduction. Therefore, signal drift can be considered as a constraint in extending the lengths of the OFF transients in future CHD optimization. Even though the presented three-exponential model might still be improved and the proposed data acquisition schema optimized in forthcoming research, the very good fit between the model and the measured signal (Figure 4 and Table 4) confirms that the proposed CHD method is suitable to accurately represent tree thermal steady state equilibrium, compromising influences of heat conduction and convection.

CHD correction

Figure 5 shows an example of NTG signal correction applying the CHD method. At the bottom part, the OFF transients representing signals measured after 15 min are presented next to the corresponding extrapolated to steady state OFF transients reproducing NTG. The difference between the two represents SR for the OFF transients. In the upper part of Figure 5, the ON transients representing signals measured after 15 min are presented next to the extrapolated to steady state ON transient signals reproducing the CTD signal. The difference between the two represents SR for the ON transients.

It can be observed in Figure 5 that during night-time, when sap flow convection is not present or negligible, the SR is larger than during day-time when sap flow convection is active. Besides, the night SR is smaller for ON (upper part of Figure 4) than for OFF transients, thanks to the influence of external 0.2 W constant power gradient. During day-time, the SR of the ON and OFF transients are generally low. The very low day-time SR of the ON transients is thanks to the joint effect of the external constant power gradient and the convective heat dissipation of the flowing sap. The slightly larger SR of the day-time OFF transients is because of the decline of the external constant power gradient toward the ends of transients when heat dissipation is mainly dependent on the convection sometimes affected by signal drift. In the upper part of Figure 5 there is also ΔT corrected by the CHD method, i.e., obtained by subtracting the extrapolated signal OFF (NTG) from the extrapolated signal ON (CTD) as per Eq. (16). In practice, following Do and Rocheteau (2002b), we correct each signal ON by averaging the two adjacent signals OFF as per Eq. (17), neither to favor preceding nor subsequent NTG conditions. The corrected by CHD method ΔT signal has a pattern typical for sap flow measurements, consisting of large and flat night ΔT and parabolic day-time ΔT drop. Thanks to the applied CHD method and removal of the NTG bias, the corrected signal also became smoother and more stable during the two consecutive nights (nearly horizontal ΔT lines and nearly the same ΔTmax). In contrast, the measured and extrapolated signals ON, corresponding to the non-corrected CTD signal, show distinct temporal variability likely due to the presence of NTG in the measured signal that, if not corrected, affects the Jp calculation particularly biasing ΔTmax. The signal variability observed in Figure 5 likely resulted due to temporal variability of atmospheric influences, also in the night-time when the signal was likely affected by wind influence. The proposed CHD method indeed filters out the NTG bias extracting the corrected, unbiased signal. In all sensor installations, after the CHD correction, the shape of the corrected ΔT (so also Jp) became smoother, stabilizing in the night-time, eliminating ‘morning peak’ (Lu et al. 2004) and better resembling the daily limb of solar radiation than the CTD signal.

From ΔT to Jp—importance for ΔTmax estimates

The CHD method proposes novel NTG-correction method of cleaning the ΔT signal from NTG noise. In the TDP application, such signal is used, in the calculation of Jp according to the widely tested and validated Granier (1985) formula (Eq. (1)). The Granier flow index K (Eq. (2)) depends on ΔT and on ΔTmax. Obviously, the NTG bias affects both ΔT and ΔTmax. That bias is typically positive during nights and negative during days (Do and Rocheteau 2002a, 2002b, Chavarro-Rincon 2009) although exceptionally can also have an opposite pattern particularly in the roots (Cabibel and Do 1991a, Lu et al. 2004). Let us then analyze how the typical NTG combination of night-positive and day-negative NTG affects CTD estimates of Jp. The presence of the positive night-time NTG in the extrapolated as per Eq. (18) signal ON implies overestimation of any extrapolated night-time ΔT signal, and also the overestimation of ΔTmax. The CHD correction of NTG as per Eq. (16) then reduces the ΔTmax and also decreases K in Eq. (2) and Jp in Eq. (1).

Not only positive night-time but also negative day-time NTG contributes to overestimating K (Eq. (2)) and Jp (Eq. (1)) while using CTD. Let us introduce negative, day-time NTG to K of Eq. (2).

\[
K = \frac{\Delta T_{\text{max}} - [\Delta T + (-\text{NTG})]}{\Delta T + (-\text{NTG})}
\] (21)

The presence of the negative day-time NTG increases the numerator and reduces the denominator of Eq. (21) while ΔTmax is fixed through the no-flow assumption typically obtained as maximum of the night-time measurement. As a result of such day-time negative NTG, K increases implying also overestimation of Jp. For example, for the B. albitrunca ΔT measurements of Sap 1 presented in Figure 5, where the night-time NTG was positive and close to 0 °C and the day-time NTG was negative and close to −1 °C, the CHD correction reduced Jp nearly threefold from 7.84 cm^3 cm⁻² h⁻¹ as estimated by CTD to 2.77 cm^3 cm⁻² h⁻¹ after the CHD correction (see also Table 5 and Figure 6).

CTD Jp versus Jp corrected by CHD

To illustrate graphically the Jp overestimates when using the CTD method in NTG-prone environments, an example of comparison of constant power ΔT measurements of three TDP
systems installed in *B. albitrunca* tree (Step #2) with subsequent CPS measurements corrected with the CHD method (Step #3) is presented in Figure 6. Despite nearly the same weather conditions in the monitoring days 133 and 134 (see the solar radiation record at the top of the Figure 5), after switching from CTD (DOY 133, Step #2) to CPS mode of data acquisition processed with CHD method (DOY 134, Step #3), all the three sensors showed substantially lower \( J_p \) in DOY 134. The \( J_p \) reduction was also observed in all other sensors installed in other three tree species (Table 5), all indicating positive night-time NTG and negative day-time NTG. Analyzing Table 5, it can be noted that the most distinct \( J_p \) reductions, and so the largest NTG impacts, were observed in the cases of *D. cinerea* and *A. luederitzii*, as indicated by the CTD/CHD correction factor presented in the last column of Table 5, i.e., in trees with the lowest \( J_p \). This observation is in agreement with the outcomes of the laboratory CHD verification experiment presented in the companion paper by Reyes-Acosta et al. (2012) showing that the impact of NTG declines with increasing \( J_p \). This is because larger \( J_p \) provides better heat exchange conditions, so with

![Figure 6. An example of sap flux densities of the three sensors (Sap 1–3) installed in a *B. albitrunca* tree, first in CTD mode (Step #2) and afterwards corrected with the CHD method (Step #3).](image-url)
larger \( J_p \) the relative contribution of the NTG-related bias is less. The importance of CHD correction in estimating any tree \( J_p \) depends on the magnitude and sign of NTG that for given climatic conditions vary per species, setting and installation, i.e., mainly on the wood properties and on species-dependent and the phenologically constrained \( J_p \) rate. Our Kalahari sap flow measurements, as most of the measurements carried out in arid and semi-arid countries, were characterized by large NTG and low \( (J_p < 10 \text{ cm}^3 \text{cm}^{-2} \text{h}^{-1}, B. albitrunca \) and A. fleckii) or very low \( J_p \) \( (J_p < 1 \text{ cm}^3 \text{cm}^{-2} \text{h}^{-1} \) in D. cinerea and A. luederitzii), so without NTG-correction were particularly vulnerable to miscalculation.

**Observations related to optimal selection of the ON/OFF transients**

The optimal selection of the length of the ON and OFF transients is an important issue in the CHD method because it: (i) influences the accuracy of the method; (ii) constrains temporal resolution of valid output data and (iii) determines power savings as compared with the standard TDP (CTD) method. The accuracy of the CHD method depends on how well the CHD model based on the available data reproduces the steady state equilibrium. Therefore in general the longer the cycle transients are, the better the model constrain and the confidence in it, but not always; too long OFF transients can be undesirably affected by signal drift particularly distinct at the ends of transients during day-time, when the external constant power gradient declines to minimum but sap flow-related heat convection is active and variable in time. The temporal resolution of the valid output data is determined by the sum of the ON and OFF transients. For example, with 15/15 min cycle (15 min ON transient/15 min OFF transient) the output \( J_p \) time resolution will be 0.5 h; shorter cycles allow depicting better short-time variability of sap flow and for more accurate \( \Delta T \) selection. Power saving is an important issue in sap flow monitoring studies, particularly in remote areas where the measurements are dependent on battery type of the power supply. The proportion of the length of the OFF transient as compared with the ON transient determines the power saving relatively to the CTD method. Despite us using uniform 15 min ON and 15 min OFF after Do and Rocheteau (2002b), the experience gained from this Kalahari study and other studies in other areas we carried out indicate that the optimal length of transients is likely to be different for ON and OFF transients. Even quick visual assessment of Figure 4 indicates that ON transients, which are better thermally determined, thanks to their external constant power gradient, reach steady state equilibrium faster. It means they need shorter time than OFF transients to reach thermal steady state. If no specific CPS optimization is carried out we recommend twice shorter ON than OFF transients which is also in agreement with Isarangkool Na Ayutthaya et al. (2010) who used a 10/20 min cycle.

The quantitative optimization of the length of transients should focus toward the best accuracy, the highest possible temporal cycle resolution (min ON + OFF) and the lowest power consumption (min ON). In defining the optimal lengths of transients the most important are the following two constraints: (i) minimum length of ON and OFF transients allowing for appropriate extrapolation of the measured signal to steady state; and (ii) impact of the signal drift limiting the length of the transients. The minimum length of ON and OFF transients necessary for appropriate extrapolation of the measured signal to steady state is dependent on the property of the wood investigated. Species characterized by low thermal resistance \( (R_w) \) and low thermal heat capacitance \( (C_w) \) can dissipate heat faster so need relatively shorter time to reach steady state (Eq. (11)). Combination of low \( R_w \) (high thermal conductivity) and low \( C_w \) reflects high thermal diffusivity \( \times \) density product \( (D \times p) \), which means that species with large \( D \times p \) require shorter ON/OFF cycle transients than otherwise.

In practice, it is possible to get a first idea about the thermal property of the wood, by preliminary \( \Delta T \) sapwood measurement in the standard, powered TDP mode at no-flow conditions. Such no-flow conditions often can be met during nights when sap flow ceases but also can be forced by severing part of the tree sapwood either in situ by making \( \sim 2 \text{ cm} \) deep fractures above and below the two TDP probes similar to Williams et al. (2004) who drilled holes and filled them with silicone, or by cutting out pieces of sapwood (Burgess et al. 2000, Nadezhdina et al. 2006) for the proposed measurements. Following Eq. (11), for the no sap flow condition the stabilized \( \Delta T \) achieved for \( t \rightarrow \infty \) is as follows:

\[
\Delta T = HR_w
\]

where \( H = 0.2 \text{ W} \) is the Granier constant so the sapwood \( R_w \) for no sap flow condition can be estimated as \( R_w = \Delta T/H \). Once \( R_w \) is known, the \( C_w \) can be estimated from any pair of \( (t; \Delta T) \) inserted in Eq. (11) solved for \( C_w \). Species with lower \( R_w \times C_w \), i.e., with larger \( D \times p \), can be fitted with shorter ON and OFF transients than otherwise. These observations need to be further investigated.

The signal drift, if present, limits the extension of the ON and OFF transients. It originates from temporal variability of sap flow within the time scale of a transient so affects the most the end parts of the OFF transients when the signal is the least determined during largest \( J_p \) changes such as the morning \( J_p \) rise. In practice, to optimize the length of ON and OFF transients, we recommend preliminary data acquisition for \( \sim 1 \text{ day} \). The night-time ON transients approach slower the steady state equilibrium than day-time ON transients so they can be used to define the minimum length of the ON transients that would guarantee a good fit of the model to the experimental data. Certainly, the longest time to reach steady state is required by
night-time OFF transients when signal is the least determined and the convective heat dissipation is the lowest due to the low or absent sap flow. Therefore, the night-time OFF signal can be optimally used to define the minimum length of the OFF transients that will guarantee a good fit of the model to the data while the day-time OFF signal drift may restrict the increase of that length. A separate issue, also influencing CHD modeling accuracy, is the sampling frequency; in Kalahari experiments, we successfully used a 30 s sampling interval; the lower sampling frequency does not provide a sufficient amount of data for model fitting while the larger frequency, although provides better model constrain, it also forces loggers and modelers to handle large data files in post-processing. The above-presented observations related to the optimal selection of the ON and OFF transients in CPS data acquisition are based on our experience hitherto; however, a structured optimization of the CHD method requires further research effort.

**Sap flow verification**

The objective of our sap flow verification experiments was not to retrieve realistic, in vivo conditions of Kalahari tree transpiration but to test the agreement between volumetric CHD sap flow estimate and the digital pump estimate. With such a defined objective, the verification tests were carried out on trees severed from their stems as per the modified Roberts (1977) procedure. However, the extreme heat conditions of the Kalahari Desert negatively affected the digital pump performance through an intermittent overheating problem. As a consequence some individual pump filling events were not identified in real time being postponed but the cumulative sap consumption volumes were properly recorded (also with the totalizer register) and are presented in Figure 7 and Table 6 as valid, accumulated volumetric sap flow estimates. To establish correspondence between the CHD $J_p$ measurements and digital pump measurements, an assumption of the sapwood area was required to process the CHD data. The sapwood areas (Axo) for the four investigated Kalahari trees (Table 1) were defined experimentally by Chavarro-Rincon (2009) using a combination of visual assessment, staining and X-ray tomography. Considering the unavoidable uncertainty in sapwood area definition and radial $J_p$ variability, particularly relevant for sapwoods thicker than the 2 cm of the TDP length, we also derived optimized by the least-squares method, sapwood areas (Axo) using digital pump accumulated sap volumes, additionally constrained by totalizer data. The verification experiment showed good, i.e., within 20% accuracy agreement between volumetric CHD estimates based on pre-defined Axo and the volumetric pump estimates. This is quite an achievement considering that the verification was carried out in the NTG-prone Kalahari conditions under large NTGs and low or very low $J_p$, so conditions particularly vulnerable to NTG-related measurement errors. Relatively the largest overestimation error of 29% was observed in the *A. luederitzii* experiment. This was likely due to the largest size of the sapwood depth among the four species (~5.5 cm), significantly exceeding the 2 cm length of the TDP probes possibly affected by not accounted in standard TDP equipment, radial decline of $J_p$, with depth. An interesting observation is that for the two tree species *B. albitrunca* and *A. fleckii* with relatively larger in vivo $J_p > 1$ cm$^2$ cm$^{-2}$ h$^{-1}$ than the other two (Step #3, Table 5), after tree cutting, i.e., in the verification experiment, their $J_p$ declined (Table 6) whereas the ‘thirsty’ species *D. cinerea* and *A. luederitzii* with very low in vivo $J_p < 1$ cm$^2$ cm$^{-2}$ h$^{-1}$ (Step #3, Table 5), under the infinite water availability during verification experiment, increased their $J_p$ (Table 6).

The CHD verification experiment showed that even with the obstacle of pump overheating problems, the proposed schema was suitable for the field verification under very low $J_p$ (Table 6) in extremely difficult Kalahari conditions. We found that the critical difficulty of such a verification experiment that may even condition the success of the TDP verification experiment, is not the pump setup but the reliable assessment of the sapwood area and of the $J_p$ along its entire sapwood depth.

Table 6. Results of the field volumetric verification experiment—comparison of the cumulated sap flow estimated by the CHD method and a digital pump controlled by a totalizer. DBH, diameter at breast height; Axo, sapwood area experimentally defined (Chavarro 2009); Axo, sapwood area optimized; Time, total time of each verification experiment; $V_{CHD}$, volume obtained by integrating CHD $J_p$ over the Axo; $V_{pump}$, total volume obtained from the pump confirmed by totalizer; RMS(Axo), root mean squared difference between accumulated volumes of CHD method while using Axo and the pump; RMS(Axo), root mean squared difference between accumulated volumes of the CHD method while using Axo and the pump; APE, absolute percentage error ($|V_{CHD} - V_{pump}|/V_{pump}$ 100%); $Q_{pump}$, average flow rate estimated using $Q_{pump}$ and Axo.

<table>
<thead>
<tr>
<th>Species</th>
<th>DBH (cm$^2$)</th>
<th>Axo (cm$^2$)</th>
<th>Axo (cm$^2$)</th>
<th>Time (min)</th>
<th>$V_{CHD}$ (ml)</th>
<th>$V_{pump}$ (ml)</th>
<th>RMS (Axo)</th>
<th>RMS (Axo)</th>
<th>APE (%)</th>
<th>$Q_{CHD}$ (ml min$^{-1}$)</th>
<th>$Q_{pump}$ (ml min$^{-1}$)</th>
<th>$J_p$ (cm$^2$ cm$^{-2}$ h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Bosica albitrunca</em></td>
<td>13</td>
<td>45</td>
<td>39</td>
<td>2203</td>
<td>851</td>
<td>750</td>
<td>126</td>
<td>74</td>
<td>13</td>
<td>0.386</td>
<td>0.340</td>
<td>0.524</td>
</tr>
<tr>
<td><em>Dichrost. cinerea</em></td>
<td>15</td>
<td>41</td>
<td>53</td>
<td>2020</td>
<td>847</td>
<td>1064</td>
<td>183</td>
<td>57</td>
<td>20</td>
<td>0.419</td>
<td>0.527</td>
<td>0.596</td>
</tr>
<tr>
<td><em>Acacia fleckii</em></td>
<td>12</td>
<td>81</td>
<td>89</td>
<td>1520</td>
<td>1516</td>
<td>1675</td>
<td>199</td>
<td>150</td>
<td>9</td>
<td>0.997</td>
<td>1.102</td>
<td>0.743</td>
</tr>
<tr>
<td><em>Acacia luederitzii</em></td>
<td>19</td>
<td>205</td>
<td>159</td>
<td>1352</td>
<td>5595</td>
<td>4344</td>
<td>1169</td>
<td>450</td>
<td>29</td>
<td>4.138</td>
<td>3.213</td>
<td>1.212</td>
</tr>
</tbody>
</table>
Therefore, when verifying TDP measurements, the most accurate are the verification schemas involving a minimum of three sensors installed at the same height but at different azimuthal directions, in trees with sapwood depth of ~2 cm or only slightly larger, otherwise, sensors penetrating larger depth should also be installed. In the case of our four verification experiments we attribute the TDP-CHD uncertainty to the difficulty in the sapwood area estimates and unknown radial variability of \( J_p \) beyond the 2 cm TDP length. A laboratory-controlled verification experiment under artificially created NTGs additionally verifying the CHD method is presented in the companion paper by Reyes-Acosta et al. (2012).

**Conclusions**

The NTG is a serious bias that affects TDP sap flow measurements in dry, sparsely vegetated areas. The proposed CHD method has the following advantages: (i) provides unique, reliable and accurate solution of removing NTG bias from the \( \Delta T \) and from \( \Delta T_{\text{max}} \) based on signal extrapolation to thermal steady state equilibrium; (ii) does not need any specific calibration because it makes use of the well-tested and species-independent Granier calibration; (iii) provides a physical explanation of the principle of NTG correction while using CPS data acquisition; (iv) allows for power savings; (v) is universal so can be implemented to other methods such as HFD or e.g., HB methods. The CHD method in its current state of implementation is not yet optimized with respect to variety of species in various environmental conditions and its data processing is also not fully automated yet. The optimization of the method requires significant research effort but the improvement of efficiency of data processing can be easily done by development of the CHD-user-friendly data processing software that can make the CHD method efficient and widely available. Thanks to the physical background, the proposed CHD method can be considered as a step forward toward the development of the 3D thermodynamic model simulating sap flow-related heat convection/conduction processes (e.g., Wullschleger et al. 2011) biased by NTG. Such a model would improve the accuracy of not only the TDP method but also the knowledge related to the convective and conductive heat transfer in trees under the forced heating (in TDP it is 0.2 W) and environmental heat influence in the form of NTG.

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Conflict of interest

None declared.

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