Biophysical homoeostasis of leaf temperature: a neglected process for vegetation and land-surface modelling

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In steady state, net radiation ($R_n$) is balanced by the combined sensible and latent heat fluxes:

$$R_n - c_p g_b \Delta T - \lambda E = 0$$

leading (via the Penman linearization) to the classical energy balance equation:

$$\Delta T = \frac{(R_n - \lambda g \cdot D)}{c_p (g_b + \varepsilon g \cdot)}$$

Leaves have a small heat capacity, so they track the steady state (time scale ≈1 min)
Theory

• A simple approximation:

\[ \lambda E = (1 + \omega) \left[ \frac{s}{s + \gamma} \right] R_n \]  \hspace{1cm} (3)

leads to a simplified equation:

\[ \Delta T = \frac{R_n \left\{ 1 - (1 + \omega) \left[ \frac{s}{s + \gamma} \right] \right\}}{c_p g_b} \]  \hspace{1cm} (4)

• \( \Delta T \) decreases with increasing temperature

• \( \Delta T < 0 \) above \( \approx 30^\circ C \) (‘crossover temperature’)
Background

- Transpirational cooling
- Crossover temperature
More observations of $\Delta T$

Figure 2. Empirical Support for the Leaf Homeothermy Hypothesis. Leaf temperatures estimated using two independent approaches support leaf homeothermy across large air temperature gradients. (A) Leaf temperature and (B) leaf temperature excess ($T_l - T_a$) from short-term point measurements of 68 individual leaves from over 62 species. Figures redrawn from [1]. For leaf temperature, the fitted slope of $0.670 (r^2 = 0.822)$ is greater than 0 ($P < 2.2 \times 10^{-16}$) and less than 1 ($P = 2.286 \times 10^{-12}$). For leaf temperature excess, the fitted slope of $0.330 (r^2 = 0.528)$ is less than 0 ($P < 2.2 \times 10^{-16}$) and greater than 1 ($P = 2.2 \times 10^{-12}$). (C) Leaf temperature and (D) leaf temperature excess ($T_l - T_a$) from long-term photosynthetically-weighted estimates from cellulosic $\delta^{18}O$ from over 38 species of trees. Figures redrawn from [11]. For $\delta^{18}O$ leaf temperature, the fitted slope of $0.062 (r^2 = 0.010)$ is not different from 0 ($P = 0.404$) and is less than 1 ($P < 2.2 \times 10^{-16}$). For leaf temperature excess, the fitted slope of $0.938 (r^2 = 0.706)$ is less than 0 ($P < 2.2 \times 10^{-16}$) and not different from 1 ($P = 0.404$). Black [7] unbroken lines are ordinary least squares regressions, black [8] broken lines indicate leaf-air temperature equivalence ($T_l = T_a$), blue [8] broken lines indicate a $21.72°C$ homeothermy, and red [8] broken lines indicate a $34.83°C$ homeothermy (homeothermy isolines are leaf–air equivalence temperatures of point and $\delta^{18}O$ temperature data, respectively).
Crossover observed at leaf level

N Dong et al., in revision
Crossover observed by canopy monitoring

N Dong et al., in revision
Global pattern of $\Delta T$ using MODIS LST

Monthly average $\Delta T$ in July 2013

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Crossover observed in MODIS LST

Figure 6: SMA regression of $\Delta T$ against $T_a$ in different forest types. Tropical Broadleaf Forests (TroBF) showed a significantly more negative slope than other forest types.

Figure 7: SMA regression of $\Delta T$ against $T_a$ in Tropical Broadleaf Forests. The slope is near to $-1$ indicating a near constant maintenance of canopy temperature at the crossover temperature.
Prediction of $\Delta T$ with the simple model (temperate deciduous forest)

Figure 10: Blue line shows the 1:1 relationship. $\Delta T$ is best predicted in Temperate Deciduous Broadleaf Forests ($R^2 = 0.5817$), see Table 4 for coefficients.

Figure 11: Blue line shows the 1:1 relationship. $\Delta T$ is worst predicted in Boreal Evergreen Needleleaf Forests ($R^2 = 0.1234$). See Table 4 for coefficients.

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Prediction of $\Delta T$ with the simple model (boreal forest)

Observed vs Predicted $\Delta T$ in Boreal Evergreen Needleleaf Forests using $R_{nl}$ and $T_a$

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Key quantities can be inferred

- Crossover temperature: $\text{Cr}$, $\alpha_0 = 1 + \omega$, and $g_b$,

$k = c_pg_b$ inferred from MODIS LST and WFDEI data

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<th>Forest type</th>
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<th>Observed Cr temp. (°C)</th>
<th>Observed $\alpha_0$</th>
<th>Observed $k$</th>
<th>Inferred $g_H$</th>
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$\bullet$ Crossover temperature: $\text{Cr}$, $\alpha_0 = 1 + \omega$, and $g_b$,

$k = c_pg_b$ inferred from MODIS LST and WFDEI data
Can JULES simulate this phenomenon? Yes, but..

Diurnal time course of JULES-simulated and observed leaf temperatures in a tropical dry woodland

N Dong et al., in revision
Canopy T from future simulations by HadGEM2

N Dong, B Stocker, unpublished
Issues and future developments

- Why does the simple model work?
- How can leaves maintain a negative sensible heat flux (especially in a closed forest)?
- $\Delta T$ as a potential benchmark for $g_s$ responses to temperature and vpd
- In-canopy measurements needed to assess influence of leaf size, leaf form, wind speed on $\Delta T$
Conclusions

• Biophysical homoeostasis keeps leaves within a narrower temperature range than the air.

• This phenomenon is important for maintaining optimal leaf function.

• The mechanisms are only partly understood.

• Heat-stress vulnerability of tropical forests: need to model canopy T (well) – otherwise we may overestimate vulnerability.