Temperature vs. potential temperature in CABLE

Ian Harman, 9th July 2018

Introduction and background

The CABLE land-surface model (Kowalcyzk et al. 2006) evolved from the Soil-Canopy-Atmosphere-Model of Raupach et al. (1997) in combination with the Wang and Leuning (1998) single-layer model for the coupled radiation-energy balance of a canopy. Simple, and more complex, representations of the carbon cycle subsequently have been included within CABLE.

The representation of the sensible heat flux in both the Raupach et al. and Wang and Leuning components utilises bulk aerodynamic representations, i.e.

$$H \propto \rho c_p \delta T \tag{1}$$

with the proportionality constant dependent on canopy architecture, height above ground, reference level height, wind speed, and diabatic stability etc. A chain of such relationships is established between the soil, canopy and air temperatures. In some parts of CABLE's algorithms (1) is used to evaluate H given the temperatures; in others it is used to evaluate the temperature given H. Other components of CABLE (radiation, latent heat, ground heat) similarly depend on temperature and differences in temperature.

In contrast JULES, the native land-surface model of the UK Met Office (Best et al. 2011, Essery et al. 2001), represents the sensible heat flux as

$$H \propto \rho c_p \left(T_s - T_a - \frac{g}{c_p} \left[z_r + z_{0m} - z_{0h} \right] \right) \tag{2}$$

with T_s the surface (skin) temperature, T_a the air temperature and z_r the reference level height (2) is similar to (1), except that the sensible heat flux is now set by differences in potential temperature[1]. Fundamentally the use of potential temperatures is correct – and CABLE's implementation incorrect – when evaluating the sensible heat flux. However, other components of CABLE (in particular the vapour pressure deficit and radiative exchange) should remain determined by temperature.

One (unfortunate and under-appreciated) element of ACCESS1.3 reflected this difference between the CABLE and JULES representation of the sensible heat flux (see Ticket #197). When operating within ACCESS1.3, CABLE takes the lowest model level temperature, T_L, as its forcing air temperature. However, in parallel to JULES, CABLE-in-ACCESS1.3 incremented T_L by an amount set by the lowest model layer height when used

[1](2) The height adjustment also depends on the roughness lengths for momentum, z_{0m}, and heat, z_{0h}. For the purpose of this note, these are of minor importance both quantitatively and qualitatively

within the energy balance part of CABLE but T_L in the radiation component i.e.

$$\%T_k = T_L + \frac{g}{c_p}(z_r + 0.9 z_{0m}) \quad (3a)$$

$$\%T_{vrad} = T_L \quad (3b)$$

noting that, in CABLE for this purpose, $z_{0h} = 0.1 z_{0m}$. This implementation was unfortunate twofold:

- The usage of $\%T_k$ and $\%T_{vrad}$ was incomplete leading to a lack of energy closure
- The incorrect, now potential, temperature $\%T_k$ propagated into parts of the energy balance where the temperature should have be used.

In effect CABLE-in-ACCESS operated with a undiagnosed energy source/sink of approximate magnitude $2\mathrm{Wm}^{-2}$ and as if the atmosphere was 0.2K warmer than it actually was.

In ACCESS-CM2 the increment has been removed which solves the energy balance issue and moves the configuration of CABLE utilised within ACCESS closure to that used in offline, surface-only, studies. CABLE now simply takes the lowest model level temperature as the air temperature $\%T_k$; no distinction is made between temperature and potential temperature[2].

However this leaves the underlying weakness of CABLE (the dependence of the sensible heat flux on temperature not potential temperature) unresolved. This note explores this issue further and makes a recommendation which would resolve the issue. The recommendation impacts both coupled and offline modes of CABLE.

Existing formulation of the coupled soil and canopy energy balances and the within_canopy algorithm

This section provides a brief overview of pertinent material in §3 of Raupach et al. (1997), with a particular focus on the implementation within CABLE.

The sources of latent and sensible heat from a single canopy layer are

$$f_{E1} = \frac{\varepsilon r_{b1} f_{A1} + \rho\lambda D_1}{(\varepsilon + 1) r_{b1} + r_{s1}} \quad (4a)$$

$$f_{H1} = f_{A1} - f_{E1} \quad (4b)$$

where f_{A1} is the available energy for the layer, D_1 is the saturation deficit of the air, r_{b1} and r_{s1} are the boundary-layer and stomatal resistances respectively, and $\varepsilon = (\lambda/c_p)\,\mathrm{d}Q_{sat}/\mathrm{d}T$ is the dimensionless gradient of the

[2]for legacy purposes the $\%T_k$ and $\%T_{vrad}$ are retained but set equal. Minor code changes are implemented so that if $\%T_k \neq \%T_{vrad}$ then energy closure is maintained

saturation specific humidity with respect to temperature. In CABLE f_{A1} is a net radiation, though can be extended to permit the change in energy stored by the canopy fabric.

The sources of latent and sensible heat from the soil underneath the canopy layer are given by

$$f_{E0} = \rho\lambda\beta\frac{Q_{sat}(T_s) - Q_1}{r_{b0}} \tag{5a}$$

$$f_{H0} = \rho c_p\frac{T_s - T_1}{r_{b0}} \tag{5b}$$

where T_s is the temperature of the soil, T_1 and Q_1 are the temperature and humidity in the canopy air, r_{b0} the boundary layer resistance for the soil and β is a soil-moisture multiplier[3].

The fluxes out of the canopy are then

$$\hat{f}_{E1} = f_{E0} + f_{E1} = \rho\lambda\frac{Q_1 - Q_r}{r_{t1}} \tag{6a}$$

$$\hat{f}_{H1} = f_{H0} + f_{H1} = \rho c_p\frac{T_1 - T_r}{r_{t1}} \tag{6b}$$

where T_r and Q_r are the reference level temperature and humidity and r_{t1} is the aerodynamic resistance between the canopy air and the reference level. $\hat{f}_{E1}$ and $\hat{f}_{H1}$ are the total[4] turbulent fluxes passed to the atmospheric model on each time step.

The equation set is solved each time step, iteratively as

i Soil and canopy layer fluxes evaluated given $T_1 = T_r$, $Q_1 = Q_r$ and the available energy.

ii T_1 and Q_1 evaluated given the soil and canopy fluxes and the resistance network (within_canopy).

iii Soil and canopy layer fluxes re-evaluated given the updated T_1 and Q_1 and the available energy.

iv Parts [i]–[iii] occur each time within a more general iteration with respect to diabatic stability, as quantified by the CABLE variable zetar.

The within_canopy algorithm

Part ii) of the approach requires some further manipulation and linearisation of the system of equations. Specifically - the canopy air temperature, humidity and all source fluxes are partitioned into 'reference' and increments,

[3]the α representation of soil evaporation is also noted in Raupach et al. (1997) but not supported in CABLE or ACCESS-CM2; CABLE supports a Penman-Monteith (PM) approach to soil evaporation however this is not currently supported by the within_canopy algorithm.

[4]but not quite finalised values

where 'reference' refers to the value taken if $T_1 = T_r$ and $Q_1 = Q_r$ (as evaluated in step i), i.e

$$
\begin{aligned}
T_1 &= T_r + T_1' && \text{(7a)}\\
Q_1 &= Q_r + Q_1' && \text{(7b)}\\
f_{Ej} &= f_{Ej,r} + f_{Ej}' && \text{(7c)}\\
f_{Hj} &= f_{Hj,r} + f_{Hj}' && \text{(7d)}
\end{aligned}
$$

for $j = 0, 1$. Next the perturbation source fluxes are linearised in terms of the perturbation temperatures and humidities i.e.

$$
\begin{aligned}
f_{Hj} &= f_{Hj,r} + \rho c_p \left(a_{Hj} T_1' + b_{Hj} Q_1'\right) && \text{(8a)}\\
f_{Ej} &= f_{Ej,r} + \rho \lambda \left(a_{Ej} T_1' + b_{Ej} Q_1'\right) && \text{(8b)}
\end{aligned}
$$

Manipulations given in Raupach et al. (1997) show that

$$
\begin{aligned}
a_{H1} &= -\frac{\varepsilon}{(\varepsilon+1) r_{b1} + r_{s1}} = -\frac{\varepsilon}{r_{d1}} && \text{(9a)}\\
b_{H1} &= \frac{\lambda}{c_p r_{d1}} && \text{(9b)}\\
a_{E1} &= \frac{\varepsilon c_p}{\lambda r_{d1}} && \text{(9c)}\\
b_{E1} &= -\frac{1}{r_{d1}} && \text{(9d)}\\
a_{H0} &= -\frac{1}{r_{b0}} && \text{(9e)}\\
b_{E0} &= -\frac{\beta}{r_{b0}} && \text{(9f)}\\
a_{E0} = b_{H0} &= 0 && \text{(9g)}
\end{aligned}
$$

and finally a matrix equation for T_1' and Q_1' is formed where

$$
\begin{aligned}
A_H T_1' + B_H Q_1' &= C_H && \text{(10a)}\\
A_E T_1' + B_E Q_1' &= C_E && \text{(10b)}
\end{aligned}
$$

where

$$
\begin{aligned}
A_H &= 1 - r_{t1} \left(a_{H0} + a_{H1}\right) && \text{(11a)}\\
B_H &= -r_{t1} \left(b_{H0} + b_{H1}\right) && \text{(11b)}\\
A_E &= -r_{t1} \left(a_{E0} + a_{E1}\right) && \text{(11c)}\\
B_E &= 1 - r_{t1} \left(b_{E0} + b_{E1}\right) && \text{(11d)}\\
C_H &= r_{t1} \left(f_{H0,r} + f_{H1,r}\right) / \rho c_p && \text{(11e)}\\
C_E &= r_{t1} \left(f_{E0,r} + f_{E1,r}\right) / \rho \lambda && \text{(11f)}
\end{aligned}
$$

Given T_1' and Q_1' the full sources and fluxes can be re-evaluated.

Note that the within_canopy algorithm in CABLE evaluates $r_{d1}A_H/r_{b1}r_{s1}$ in place of A_H etc. Note that Eq (3.39) in Raupach et al. (1997) is incorrect; the equation set above and the code are in agreement. Extensions have been applied to within_canopy to account for alternate forms for soil evaporation and/or litter. [5]

Adjustments to account for potential temperature

The outline solution stays as previously but is extended to include the same linear lapse rate in temperature as JULES to accommodate the difference between temperature and potential temperature. We note/formalise two additional assumptions that (to date) have not been overly critical to this component of CABLE:

1. The nominal height of the within-canopy air is the displacement height, d.
2. The lowest model height/reference level, z_r, is specified relative to the displacement height.

Given these two assumptions we can accommodate the lapse rate as follows: The sensible heat flux from the soil and from the canopy are changed to

$$f_{H0} = \rho c_p \frac{T_s - T_1 - gd/c_p}{r_{b0}} \tag{12a}$$

$$\hat{f}_{H1} = f_{H0} + f_{H1} = \rho c_p \frac{T_1 - T_r - gz_r/c_p}{r_{t1}} \tag{12b}$$

Now, as the lapse rate terms are independent of the reference level values, the lapse rate term appears as i) a re-evaluated $f_{H0,r}$ and ii) and extra term in the equation for T_1'. The revised system remains (10) but where now

$$A_H = 1 - r_{t1}\left(a_{H0} + a_{H1}\right) \tag{13a}$$

$$B_H = -r_{t1}\left(b_{H0} + b_{H1}\right) \tag{13b}$$

$$A_E = -r_{t1}\left(a_{E0} + a_{E1}\right) \tag{13c}$$

$$B_E = 1 - r_{t1}\left(b_{E0} + b_{E1}\right) \tag{13d}$$

$$C_H = r_{t1}\left(f^{\star}_{H0,r} + f_{H1,r}\right)/\rho c_p + gz_r/c_p \tag{13e}$$

$$C_E = r_{t1}\left(f_{E0,r} + f_{E1,r}\right)/\rho\lambda \tag{13f}$$

where

$$f^{\star}_{H0,r} = \rho c_p \frac{T_s - T_r - gd/c_p}{r_{b0}} \tag{14}$$

[5] To fully incorporate the PM formulation for the soil energy balance into CABLE would require the re-evaluation of the soil sensible heat flux to be the PM form and the cross coupling of coefficients a_{E0} and b_{H0}.

Implementation

There are three steps to the implementation:

1. Adjusting the equation for the soil sensible heat flux due to the lapse rate term wherever this occurs (2 instances, complicated by the litter and pore-scale resistances).
2. Adjusting the C_H term in the within_canopy algorithm
3. Formally removing the option of the ACCESS1.3 implementation and the possibility of different $\%T_k$ and $\%T_{vrad}$.

The sensitivity terms in the soil energy balance and the associated correction terms to the energy balance are not impacted by this suggested change.

Magnitude of impact

In the absence of trial simulations it is difficult to assess the magnitude and character of any impact. This issue will affect both offline (surface-only) and coupled simulations. In both cases the direct effect would to be require the land surface to be warmer (by approximately gz_r/c_p, i.e. 0.2°C for a 20m reference level height) so as to provide the same difference in potential temperature as would have been established as a temperature difference without the change. Indirect effects would emerge firstly as a repartitioning of energy into (more) latent and (more outgoing) longwave radiation, with subtle changes in the diurnal cycle. Secondly, changes in the energy balance trigger feedbacks through the atmosphere (coupled simulations) and soil moisture, leading to differences in the surface state.

Qualitatively these impacts are similar to those from the former ACCESS1.3 implementation. In both cases, it is likely that the quantitative impacts are difficult to discern against background climate variability, especially in the situation where parameter value re-optimisation occurs.

References

Best et al. (2011) The joint UK Land Environment Simulator (JULES), model description - Part 1: energy and water fluxes. *Geosci. Model Dev.*, 4:677–699

Essery et al. (2001) MOSES 2.2 Technical Documentation. Hadley Centre Technical Note 30, August 2001

Kowalcyzk et al. (2006) The CSIRO Atmosphere Biosphere Land Exchange (CABLE) model for use in climate models and as an offline model. CSIRO Marine and Atmospheric Research paper 013, November 2006.

Raupach et al. (1997) SCAM: Soil-Canopy-Atmosphere-Model: Description and comparisons with field data. CSIRO, Centre for Environmental Mechanics, Technical Report 132, January 1997.

Wang and Leuning (1998) A two-leaf model for canopy conductance, photosynthesis and partitioning of available energy I: model description and comparison with a multi-layer model. *Ag. For. Meteorol.*, 91:89–111