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Dual versus single source models for estimating surface temperature of African savannah

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Abstract

Predictions of average surface temperature of a sparsely vegetated West-African savannah by both single and dual source models of surface energy partitioning are compared. Within the single source model, the "excess resistance" to heat transfer away from the canopy (compared to momentum absorption) is characterised by parameter kB^{-1}, where k is the von Kármán constant and B is the Stanton number. Two values of this parameter are used; first $kB^{-1} = 2$ (a value often used within surface energy balance models but primarily applicable to permeable vegetation types) and then 12.4 (a value applicable to the savannah in question, which consists more of bluff roughness elements). As expected, the latter parameterisation generates better predictions of surface temperature.

To make accurate predictions of surface temperature using a dual source model, then that model's in-canopy aerodynamic resistance must be increased. Information on this increase is found through direct model intercomparison with the single source model parameterised with $kB^{-1} = 12.4$.

Keywords: Penman-Monteith equation; Surface temperature; Canopy resistance; Savannah; Dual-Source model

Introduction

The reliability of numerical weather models to predict climate change depends critically on the correct modelling of land surface-atmosphere interactions. Surface temperature is a sensitive diagnostic of the success of land surface energy partitioning models, since the surface temperature indicates how the modelled energy fluxes have been adjusted to the given conditions. So comparisons of the predictions of surface temperature by land surface-atmosphere transfer models against measurements is a very stringent test of the models.

There are numerous types of vegetation-atmosphere transfer models. For homogeneous land cover, a single source (big leaf) model (Monteith, 1965) is suitable. To represent more complex canopies, dual source models with an explicit upper canopy and an understorey composed of, for example, distinct plant types and bare soil have been developed (Shuttleworth and Wallace, 1985; Dolman, 1993; Huntingford *et al.*, 1995). Recently, the dual source approach has evolved to a multi-component approach (Verhoef and Allen, 2000).

Dual source models have two sets of aerodynamic resistances across which individual, local, single source models are applied and an in-canopy point where such resistances meet, allowing interaction between the soil/vegetation components. A single aerodynamic resistance connects the combined canopy with the free atmosphere. A single source model uses only one aerodynamic resistance and assumes that all the surfaces are at an identical temperature and humidity.

For complex vegetation communities a dual source model with its extra physical realism should replicate the overall surface energy balance with greater accuracy than a single source model. However, in spite of the over simplification of reality intrinsic to a single source model, many authors have found, after appropriate tuning of the model parameters, that it describes the overall surface energy balance of the complex vegetation satisfactorily. Analogous parameters require calibration within the dual source model. A simple but correctly calibrated single source model might well perform better than an ill-parameterised dual source model (Kustas, 1990).

The comprehensive data set available from the HAPEX-Sahel project provides an opportunity to assess the relative merits of single and dual source models for estimating the vegetation-atmosphere exchange for a spatially complex vegetation community – savannah consisting of shrubs (20%) with an understorey of sparse grasses and forbs.

The aim of this paper is to assess whether the greater physical realism of a dual source model for savannah vegetation provides improved estimates of the mean surface temperature. Initially, both models were run using the best estimates from the literature of their parameters for "general" vegetation and the estimates of the mean surface temperature compared. Then, the parameters of the models were changed individually to be appropriate for this particular location, before again comparing their outputs.

Theory

THE SINGLE SOURCE MODEL

The single source model (Monteith, 1965) is driven by values of windspeed, temperature and humidity at a reference height, and a prescribed available energy (net radiation minus soil heat flux), A (W m^{-2}). The model contains an aerodynamic resistance to momentum, r_a (s m^{-1}), and to heat transfer, r_{ah} (s m^{-1}). The difference between these two resistances satisfies

$$\frac{B^{-1}}{u^*} = r_{ah} - r_a \qquad (1)$$

where B is a nondimensional parameter (Stanton number) and u^* (m s^{-1}) is the friction velocity. For historical reasons, the difference is described by parameter kB^{-1} where $k = 0.41$ is the Von Kármán constant. For permeable rough surfaces such as grasses, Brutsaert (1982) and Garratt (1992) suggest $kB^{-1} \approx 2$. However, bluff rough surfaces such as the relatively rigid shrubs and bushes found in the Sahelian savannah have larger values of kB^{-1}; between 10 and 15 (see Garratt and Hicks, 1973; Stewart *et al.* 1994, Verhoef *et al.*, 1997).

THE DUAL SOURCE MODEL

The dual source model is based upon the aerodynamic resistance structure of Dolman (1993) and Huntingford *et al.* (1995), whereby such resistances influence the transfer of heat both within the canopy, and up into the atmosphere. Here the vegetation types are indexed (by i) as "1" for the canopy and "2" for the understorey. The canopy and understorey have heights h_i (m), stomatal resistances r_{ST_i} (s m^{-1}), local leaf area indices L_i and the vegetation is assumed to be clumped at heights $d_i + z_{0m_i}$ (m) where $d_i = 0.75\ h_i$ (m) and $z_{0m_i} = 0.1\ h_i$ (m). Vegetation "1" has a fractional coverage α of the ground, and vegetation "2" a fractional coverage of $1-\alpha$. The in-canopy resistance, r_{au} (s m^{-1}) is given by

$$r_{au} = \frac{\mu}{K(h_1)}$$

where μ (m) is a constant, but related to canopy and understorey heights and a decay coefficient for windspeed within the canopy. Variable $K(h_1)$ (m^{2}s^{-1}) is the eddy diffusivity of the atmosphere at canopy height (see Eqn. (15) of Huntingford *et al.*, 1995). The aerodynamic resistance from canopy to reference height and the boundary-layer resistances follow Eqns. (16) and (17) of Huntingford *et al.* (1995). Both vegetation surfaces receive an available energy, A_i.

LINKAGES BETWEEN THE SINGLE AND DUAL SOURCE MODELS

Predictions of surface temperature for the single source model, T_{SS} (°C) and the spatially averaged surface temperature of the dual source model T_{TS} (°C) are compared, where

$$T_{TS} = \alpha T_1 + (1 - \alpha) T_2 \qquad (2)$$

and T_i are individual surface temperatures as calculated by the dual source model. For the single source model, an available energy $A = \alpha A_1 + (1 - \alpha) A_2$ and stomatal resistance $r_{ST} = \alpha r_{ST_1}/L_1 + (1 - \alpha) r_{ST_2}/L_2$ are prescribed (see McNaughton, 1994, for example, for alternative aggregation schemes of stomatal resistance).

For the dual source model, variations within boundary-layer resistances and in-canopy aerodynamic resistance, r_{au} can perform a similar role to adjusting kB^{-1} within the single source model. However, the (thin laminar) boundary-layer resistances close to the leaves are well defined (see for example Jones, 1983). Variations to modelling heat transfer (and associated surface temperatures) within the dual source model are therefore placed within the less understood in-canopy aerodynamic resistance. Resistance r_{au} (Huntingford *et al.*, 1995) is replaced by fr_{au} whereby f may be adjusted.

The experimental data

The observations used to calculate values of the effective model parameters were made by the Department of Meteorology, Wageningen Agricultural University, The Netherlands as part of the HAPEX-Sahel experiment (Goutorbe *et al.*, 1994). The experimental location was at 13°32'N, 02°60'E which is within the Central West Supersite (Kabat *et al.*, 1996 and Gash *et al.*, 1997). The savannah consisted of 2–2.5 m high shrubs (*Guiera senegalensis*), with an undergrowth of sparse grasses and forbs. The shrubs covered about 20% of the ground area (hence $\alpha = 0.2$).

The data are from the period 16 September (Day 260) to 9 October, 1992 (Day 283). This corresponds to the start of the dry season and the last rainfall (0.5 mm) was observed on 20 September.

Windspeed, temperature and humidity were measured at a height of 4.5m using an anemometer and a psychrometer, respectively. The day to day variation of the microclimate is detailed in Verhoef *et al.* (1996b). Values for A_i were obtained from the difference between net radiation, R_{ni} (W m^{-2}) (obtained from two Funk radiometers, installed at a height of 10.2 and 1.6 m) and soil heat flux, G_i, ($i = 1,2$) (W m^{-2}) for both surface components. Here, G_1 is the average of nine thermopile flux plates that were installed under a shrub at an average depth of 0.04 m. Soil temperature measurements were used to correct G_1 for the heat storage in the soil layer overlying the plates. G_2 was found from the Calorimetric method using a soil temperature profile, measured with horizontally inserted PT-100 resistance thermometers and corresponding estimates of soil heat capacity (Verhoef *et al.*, 1996a).

The stomatal resistances are parameterised using Jarvis-Stewart type of equations (Jarvis, 1976, Stewart, 1988), where r_{ST} is dependent on environmental variables. The parameters for r_{ST_1} were derived from porometry (by Verhoef, 1995) whereas the parameters for the calculation of r_{ST_2} were taken from the inverse study by Huntingford *et al.* (1995) for a similar savannah site in the vicinity of the Central West Supersite. While r_{ST_1} represents the stomatal resistance of bushes, r_{ST_2} is meant to give an average surface resistance value of the total understorey, that is a combination of grasses, forbs and bare soil. A preliminary modelling exercise showed that the r_{ST_2} values calculated using parameters given in Huntingford *et al.*, (1995) are too low, although the diurnal course is described well. Therefore, the decision was made to double all values of r_{ST_2}; this was based upon the fact that the Central West Supersite savannah site was less densely vegetated than the savannah studied in Huntingford *et al.*, (1995), and had more bare soil thereby increasing surface resistance (see Verhoef, 1995). The analysis of the next Section provides a justification of this, and by default, highlights possible risks within such inverse methods.

The effective displacement and roughness length for the total surface were obtained from wind profile measurements as described by Verhoef (1995), giving the values $z_{0m} = 0.25$ m and $d = 1.14$ m. Estimates of L_1 and L_2 were taken from Hanan *et al.* (1997).

For model verification, continuous values of the canopy and understorey surface temperatures were obtained using two fixed infra-red thermometers, IRTs (Heimann KT15, Wiesbaden, Germany), with a field of view of 15 °, following the procedure described below (see also Verhoef *et al.*, 1997). One IRT was at a height of 1.60 m and was oriented vertically above the grass/soil surface between the shrubs. The other, with a horizontal inclination, was trained on the north-facing side of a bush. Furthermore, surface temperature has been measured by a hand-held IR sensor (Comet 8000, Mawi-therm, Monheim, Germany).

The fixed IRT representing the understorey appeared to overestimate the surface temperature because its vertical installation (90 °), caused the instrument to 'see' between the upright blades of grass (see also Malhi 1993). The readings for the total understorey, as recorded with this IRT, were very close to the surface temperatures of the bare patches of soil, whereas the values of T measured for the herb/grass layer (from a horizontal angle, using the hand-held IRT) were close to the bush temperatures. The hand-held instrument, operated at an angle of 45 °, indicated that understorey temperatures should be between these values measured for bare soil and the herb layer. Therefore, continuously measured surface temperatures were corrected with the help of the readings recorded with the hand-held Comet using a linear relationship developed by Verhoef (1995). Finally, the average surface temperature, was found using the relative coverage of both surface components: $T = 0.2T_1 + 0.8T_2$.

Applying the condition that incoming solar radiation is positive, 411 sets of data values for the environmental variables described above are available.

Results of model intercomparison

Three intercomparisons are made between the single and dual source models (Case 1 – Case 3). In each intercomparison, the two models are driven by a single set of environmental conditions (a single "control" driving data point) as presented in Table I. These data are time-averages of the 411 half-hourly data points, along with relevant vegetation parameters. This provides a first indication of model differences. Then the models are driven by the full set of savannah driving data, and with the diurnally varying stomatal resistances r_{ST_i} (see the Section above).

Case 1 sets $k\mathrm{B}^{-1} = 2.0$ within the single source model and uses the standard within-canopy aerodynamic resistance in the dual source model (i.e. $f = 1.0$). The difference between model predictions of surface temperature T_{SS} and T_{TS} for the "control" driving data point is small (Table II), suggesting that the dual source in-canopy aerodynamic resistance with $f = 1.0$ is similar to setting $k\mathrm{B}^{-1} = 2$ within the single source model. With these values of $k\mathrm{B}^{-1}$ and f, both the single source and dual source models are then driven by the complete set of environmental driving data. Predictions of surface temperature are compared against the half-hourly savannah measurements (Fig. 1a, closed circles for the single source model and Fig. 1b, closed circles for the dual source model). In both cases, there is little scatter, so each model is responding in a similar fashion to the driving data. However, there is a systematic under estimation of surface temperature, suggesting that both $k\mathrm{B}^{-1}$ and f are incorrect.

Case 2 is identical to Case 1 except that now $k\mathrm{B}^{-1} = 12.4$. This particular value was found for the savannah site by Verhoef *et al.*, 1997, and is towards the top of values for semiarid rangeland sites (Stewart *et al.*, 1994). From Fig. 1a (open circles), it is seen that this change results in far better predictions of surface temperature by the single source model, with the points generally clustered about the 1:1 line.

Case 3 adjusts parameter f so as to allow a similar improvement in the prediction of mean surface temperature by the dual source model. This is achieved with $f = 3.9$ where this value is such that the dual source model makes an identical prediction of mean surface temperature, for the

Table I. The mean of daytime meteorological variables, measured half-hourly and at 411 separate times, over Sahelian savannah (standard deviations in brackets). Also presented are model parameters applicable to the savannah vegetation.

Variable/parameter		Mean value	Standard deviation
Reference height windspeed	u_r (m s^{-1})	2.4	(0.7)
Reference height temperature	T_r (C)	30.6	(3.4)
Reference height humidity	e_r (kPa)	2.3	(0.13)
Canopy available energy	A_1 (W m^{-2})	380	(218)
Understorey available energy	A_2 (W m^{-2})	250	(105)
Canopy height	h_1 (m)	2.3	
Understorey height	h_2 (m)	0.5	
Fractional cover	α	0.2	
Canopy leaf area index	L_1	1.5	
Understorey leaf area index	L_2	1.1	
Canopy stomatal resistance	r_{ST_1} (s m^{-1})	128	(53.0)
Understorey stomatal resistance	r_{ST_2} (s m^{-1})	386	(122.0)
Roughness length for momentum	$z_{0\mathrm{m}}$ (m)	0.25	
Displacement height	d (m)	1.14	

"control" driving data, as that of the single source model with $k\mathrm{B}^{-1} = 12.4$ (see Table II). The new dual source model predictions of mean surface temperature, T_{TS} are compared against data in Fig. 1b (open circles). There exists a small tendency to overestimate at high temperatures and underestimate at low temperatures. However, the systematic bias has been almost eliminated when compared to Case 1 and Case 2 (filled circles, Fig. 1b).

Case 3 is considered to be a better parameterisation of the dual source model. Further evidence of this is the good performance, with $f = 3.9$, of the dual source model's predictions of bush and understorey temperatures (see Figs. 2a and 2b). By definition, the single source model cannot differentiate between such temperatures, but the earlier understanding of savannah behaviour through the use of the single source model has allowed a transfer of parameterisations such as to improve the more complicated dual source model's output.

The value of $k\mathrm{B}^{-1} = 12.4$ (Verhoef *et al.*, 1997) was derived using simultaneous measurements of surface temperature and sensible heat flux, and is therefore independent of model structure and parameterisation. The implicit adoption of this "correct" value within the dual source model (through the methodology of Case 3) isolates the influence of stomatal resistance upon surface temperature. With the aerodynamic resistances constrained, the accurate prediction of surface temperature in Case 3 suggests that the prescribed increase in understorey stomatal resistance is appropriate.

Table II. Values of parameters $k\mathrm{B}^{-1}$ (as required to evaluate the roughness length for heat within the single source model) and f (as used in the parameterisation of the in-canopy resistance of the dual source model) relevant to three model intercomparisons (Case 1 – Case 3). Also presented are predicted values of surface temperature for the single source model, T_{SS}, and spatially averaged surface temperature for the dual source model, T_{TS}, when driven by the "control" environmental data point (see Table I). By definition of the model intercomparisons, the surface temperatures are equal for Case 3.

Case	Coefficient		Surface temperature (°C)	
	$k\mathrm{B}^{-1}$	f	T_{SS}	T_{TS}
1	2.0	1.0	33.2	33.8
2	12.4	1.0	37.6	33.8
3	12.4	3.9	37.6	37.6

Discussion

This analysis shows that using either the single source or the dual source model with literature values appropriate to "average" vegetation gives poor results compared to the measured values of average surface temperature for the savannah site. In particular, the greater physical realism of the dual source model does not improve predictive ability. Work undertaken by others indicates that for the savannah, within the single source model, a parameter value of $k\mathrm{B}^{-1} = 12.4$ is appropriate. This greatly improves the performance of the single source model, although there is some underestimation of the surface temperature at low values and overestimation at higher surface temperatures.

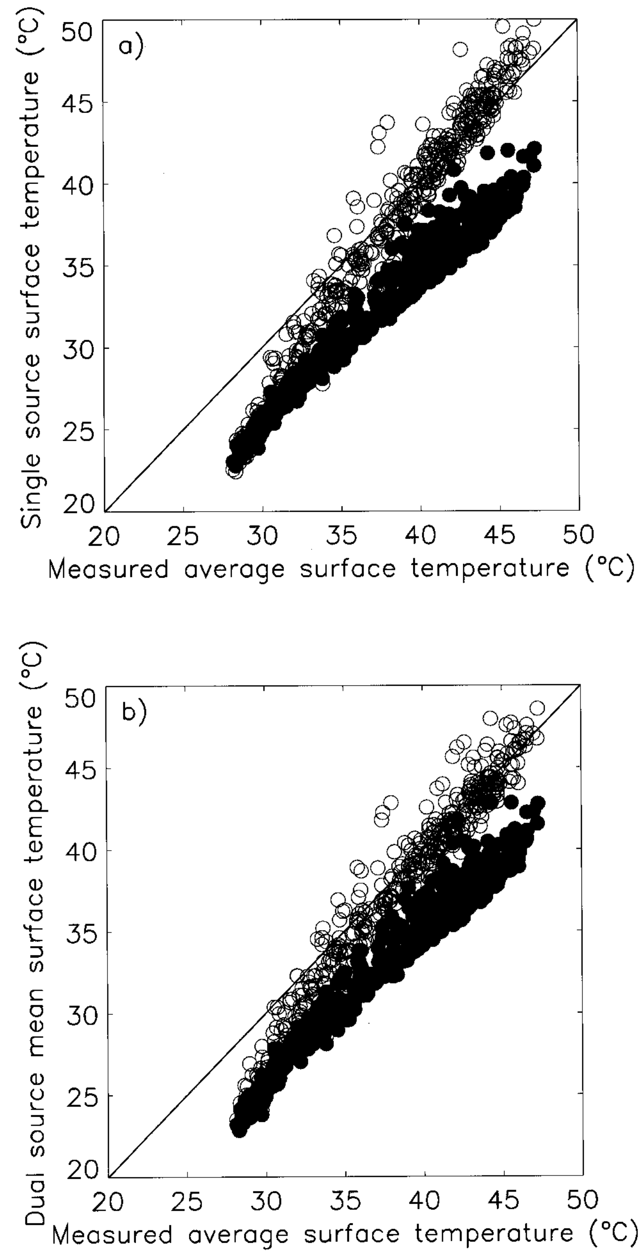

Fig. 1. *The relation between a) single source model predictions of surface temperature,* T_{SS}*, and savannah measurements and b) dual source model predictions of mean surface temperature,* T_{TS}*, and savannah measurements. In Fig. 1a), the closed circles correspond to Case 1 (*$kB^{-1} = 2$*) and the open circles correspond to Case 2 and Case 3 (*$kB^{-1} = 12.4$*). In Fig. 1b), the closed circles correspond to Case 1 and Case 2 (*$f = 1.0$*) and the open circles correspond to Case 3 (*$f = 3.9$*).*

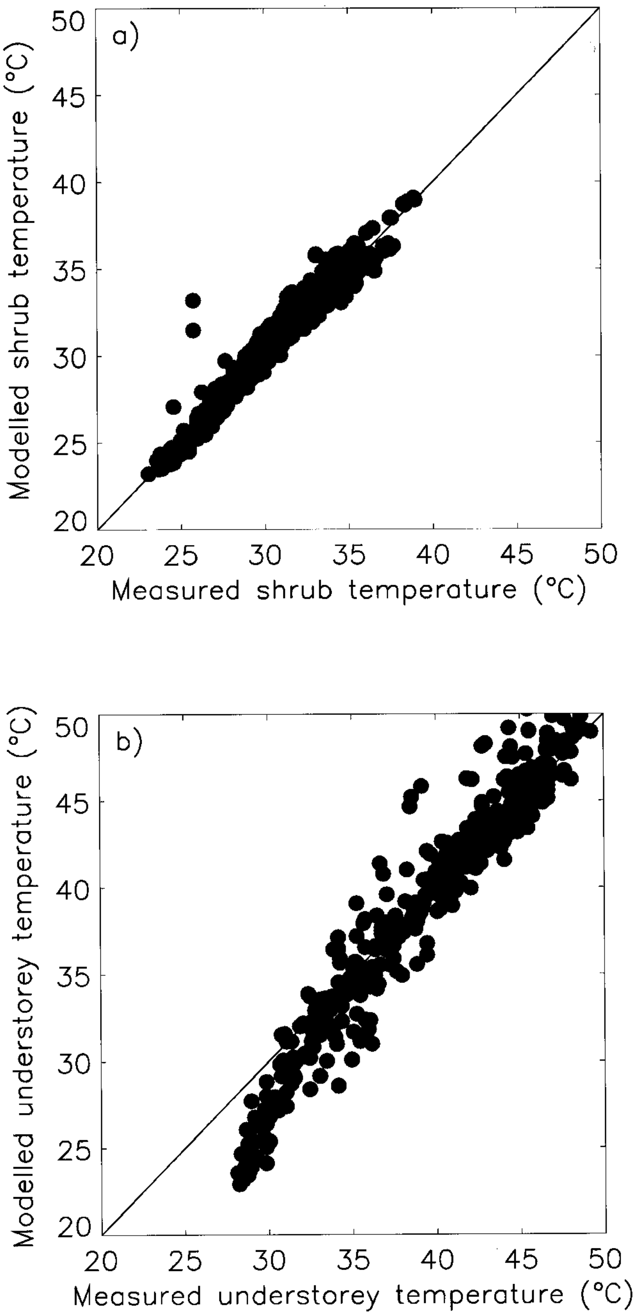

Fig. 2. *A plot of dual source model predictions (for Case 3) of a) the upper canopy temperature,* T_1 *and b) the understorey* T_2 *against measurements.*

(This latter effect may be caused by the fact that using a constant value of $k\mathrm{B}^{-1}$ does not acknowledge the full dynamic behaviour of the aerodynamic exchange processes near the vegetation, such as stability corrections and/or wind speed dependence. Unfortunately the exact course of diurnal variation of $k\mathrm{B}^{-1}$ and underlying processes causing it are highly unknown). Since surface temperature is a stringent check on the accuracy of any surface energy partitioning model, this implies that the single source model, using the new parameterisation for $k\mathrm{B}^{-1}$, can be expected to provide more reliable estimates of the fluxes of sensible and latent heat. This also confirms that an incorrectly calibrated dual source model may make predictions that are worse than those of a properly tuned but simpler single source model. In addition, inverting such a dual source model to derive parameters that are hereto unknown (such as those within the equation relating stomatal response to environmental variables) will inevitably map any incorrect prescribed model calibrations onto such new parameter derivations. This latter issue is likely to explain the need, within this paper, to increase the understorey stomatal resistance found from an earlier inverse study.

The dual source model can also be adjusted for savannah by varying the in-canopy aerodynamic resistance until the average surface temperature simulated agrees with that predicted by the single source model, the latter with the revised kB^{-1} value. Now the dual source model also performs well, giving the added benefit that temperatures of the two components of shrubs and understorey can be predicted explicitly. Comparison with measured surface temperatures of the individual components confirms that such predictions are accurate. The ability to differentiate between the different surface temperatures is of importance in designing agroforestry experiments, and may also influence vegetation-atmosphere exchanges of CO_2 (eg Huntingford *et al.*, 1998).

Conclusions

From this analysis it is concluded that the greater physical realism of the dual source model does no better at simulating the savannah surface temperature than the single source model when using parameters taken from the literature for "typical" vegetation – both models underestimate the surface temperature by about five degrees. However, the simulations of the single source model can be improved by using literature values of the parameters appropriate to the savannah vegetation. Similar improvements can then be obtained using the dual source model following calibration against the better parameterised single source model. The advantage of the adjusted dual source model is that it can provide good simulations of the surface temperatures of the two components.

Many studies of the surface energy balance reported in the literature use the single source model. This analysis has demonstrated that parameterisations found in such studies can be reused to calibrate more complex and more physically representative surface schemes such as the dual source model.

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