10 Canopy to region scale translation of surface fluxes

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INTRODUCTION

Since most of the relevant variables in hydrology, such as precipitation, evaporation, infiltration, runoff are both measured and modelled at a local scale, the canopy-region (or patch-region) scale translation has become an important issue, essential to comprehend, describe and model hydrological phenomena at regional scale. This issue has become very acute in relation to the parameterisation of land surface processes in large-scale atmospheric models. The topic discussed in this chapter is the areal averaging problem in land-atmosphere interaction, applicable to canopy-region scale translation. More precisely, it deals with convective fluxes of sensible and latent heat estimated by the Penman-Monteith formulae. The strategy used is based upon two basic principles: (1) matching of the model between scales, and (2) the scalar conservation, which implies that the spatially averaged flux of a given scalar (heat or water vapour) is simply the area-weighted mean of the flux contributions from each patch. The strategy used also involves the concept of «blending height», which has proved to be successful in calculating regionally averaged surface fluxes (Mason, 1988; Claussen, 1991; Blyth *et al.*, 1993). This concept stipulates that there exists a height at which the characteristics of the air flow (wind velocity, temperature, humidity) become approximately independent of horizontal position and can be extrapolated from one patch to another. Several aggregation schemes based upon this strategy have been recently published (Raupach, 1991; McNaughton, 1994; Lhomme *et al.*, 1994; Raupach, 1995; Braden, 1995). They apparently differ for reasons that have not been clearly explained. Here we examine these differences to show in what way they differ and why.

BASIC EQUATIONS AND GENERIC CONSTRAINTS

The convective flux of latent heat is expressed in the form of the Penman-Monteith equation

$$\lambda E = \frac{sA + \rho c_p D_a / r_a}{s + \gamma (r_v / r_a)} \qquad (1)$$

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where A is the available energy, D_a is the water vapour pressure deficit of the air in the well-mixed layer, ρ is the mean air density, c_p is the specific heat of air at constant pressure, γ is the psychrometric constant, *and* s is the rate of change of the saturated vapour pressure with temperature. r_a is the aerodynamic resistance to heat and water vapour transfer from the surface to the well-mixed layer. r_v is the total resistance to water vapour transfer expressed as $r_v=r_a+r_s$, where r_s is the surface resistance. The sensible heat flux is given by a similar equation

$$H=\frac{\gamma A-\rho c_p D_a/r_v}{\gamma+s(r_a/r_v)} \tag{2}$$

Both equations are based on a linearisation of the saturated vapour pressure curve between the surface temperature T_s and the air temperature in the well-mixed layer T_a. This linearisation is justified as a first approximation (Paw U and Gao, 1988). The available energy A is detailed as

$$A=R_n-G=(1-\alpha)R_s+\epsilon(R_l-\sigma T_s^4)-G \tag{3}$$

with α and ε the albedo and the emissivity of the surface, R_s and R_l the incoming short-wave and long-wave radiations, T_s the surface temperature, σ the Stefan-Boltzmann constant and G the soil heat flux.

We now aim to derive the aggregation procedures to be used to calculate the effective parameters of the energy balance at regional scale. At this scale they will be denoted by angle brackets. The air characteristics (T_a, D_a) in the well-mixed layer and the incoming radiations (R_s, R_l) are assumed to be constant over the whole area. Since surface emissivity (ε) does not vary markedly among the natural surfaces and much less than the other parameters, it is also assumed to be constant over the whole area. The strategy used consists in determining the effective parameters in such a way that the flux equations, valid at local scale, give the correct areal fluxes at grid-square scale. From the definition of a flux and the principle of scalar conservation, the spatially-averaged flux over a region or a grid-square is simply the area-weighted mean of the flux contributions from each patch. So, it is possible to write the following conservation equation

$$\langle\phi\rangle=\sum_i a_i\phi_i \qquad \textit{with} \qquad \phi=H,\lambda E,A \tag{4}$$

where a_i is the fractional area of patch i. It is worthwhile noting that the energy balance equation ($H+\lambda E=A$) is always closed at regional scale when each individual flux is preserved according to Equation 4, since the following equations hold

$$\langle\lambda E\rangle+\langle H\rangle=\sum_i a_i\lambda E_i+\sum_i a_i H_i=\sum_i a_i(\lambda E_i+H_i)=\sum_i a_i A_i=\langle A\rangle \tag{5}$$

Available energy can be preserved according to Equation 4 as an independent magnitude, irrespective of flux equations (H and λE). This preservation leads to

$$<A>=(1-<\alpha>)R_s+\epsilon(R_l-\sigma<T_s^4>)-<G>=\sum_i a_i[(1-\alpha_i)R_s+\epsilon(R_l-\sigma T_{s,i}^4)-G_i] \quad (6)$$

from which the following averaging procedures can be derived by matching term by term

$$<X>=\sum_i a_i X_i \qquad for \qquad X=\alpha, G, T_s^4 \quad (7)$$

Replacing T_s^4 by T_s in the averaging procedure above does not lead to a significant error. We can then say that all the parameters average linearly in the preservation of available energy.

FLUX-MATCHING AVERAGING PROCEDURES

LATENT HEAT FLUX

The Penman-Monteith equation is written with effective parameters as

$$<\lambda E>=\frac{s<r_a><A>+\rho c_p D_a}{s<r_a>+\gamma<r_v>} \quad (8)$$

since D_a is supposed not to change over the whole area. Using Equation 4, with $\phi=\lambda E$, and putting

$$\omega_i=\frac{1}{sr_{a,i}+\gamma r_{v,i}} \quad (9)$$

the areal latent heat flux also reads as

$$<\lambda E>=s\sum_i a_i\omega_i\, r_{a,i}\, A_i+\rho c_p D_a\sum_i a_i\omega_i \quad (10)$$

Matching Equations 8 and 10, term by term, gives two equations:

$$\frac{<r_a><A>}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i\, r_{a,i}\, A_i \quad (11)$$

and

$$\frac{1}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i \quad (12)$$

Assuming <A> is known and given by Equation 6, the following averaging procedure is obtained for the effective resistances (< r_a>, <r_v> and < r_s>)

$$<r_x>=\frac{\sum_i a_i\omega_i(A_i/<A>)r_{x,i}}{\sum_i a_i\omega_i} \qquad with \qquad x=a,v \text{ or } s \quad (13)$$

It is the solution given by Raupach (1991, 1995) and McNaughton (1994). In fact, Equation 12 is not quite the equation given by Raupach (1995) because he uses the «equilibrium departure» form of the combination equation and the isothermal net radiation, which leads to a slightly different algebraic expression, but the result is fundamentally the same.

Another solution can be obtained by replacing <A> in Equation 8 and A_i in Equation 10 by the detailed expression of available energy (Equation 3), before matching term by term (Lhomme *et al.*, 1994). This matching leads to the following set of equations

$$\frac{<r_a>}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i\, r_{a,i} \tag{14}$$

$$\frac{<r_a><\alpha>}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i\, r_{a,i}\alpha_i \tag{15}$$

$$\frac{<r_a><T_s>^4}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i\, r_{a,i}T_{s,i}^4 \tag{16}$$

$$\frac{<r_a><G>}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i\, r_{a,i}G_i \tag{17}$$

$$\frac{1}{s<r_a>+\gamma<r_v>}=\sum_i a_i\omega_i \tag{18}$$

This set of five equations with five unknowns (in angle brackets) has the following solution. For $<\alpha>$, $<G>$ and $<T_s>^4$, the averaging scheme is given by

$$<X>=\frac{\sum_i a_i\omega_i r_{a,i}\, X_i}{\sum_i a_i\omega_i r_{a,i}} \qquad with \qquad X=\alpha, G \text{ or } T_s^4 \tag{19}$$

and for $<r_a>$, $<r_v>$ and $<r_s>$, by

$$<r_x>=\frac{\sum_i a_i\omega_i\, r_{x,i}}{\sum_i a_i\omega_i} \qquad with \qquad x=a, v \text{ or } s \tag{20}$$

Calculating $<\alpha>$, $<G>$ and $<T_s>^4$ according to Equation 19 is strictly equivalent to calculating <A> in Equation 8 as

$$<A>_E=\frac{\sum_i a_i\omega_i r_{a,i}\, A_i}{\sum_i a_i\omega_i r_{a,i}} \tag{21}$$

The method developed by Braden (1995) is very similar to the one proposed by Lhomme *et al.* (1994), with the difference that the surface temperature (expressed as net radiation) is eliminated by linearisation. An additional term thus appears which is the radiative resistance (Monteith and Unsworth, 1990; Lhomme, 1992) in parallel with the convective resistance to heat transfer. It should also be pointed out that Braden (1995) does not develop the basic expressions to derive the effective values of the physical parameters.

SENSIBLE HEAT FLUX

The same procedure is used as for latent heat flux. It consists in matching term by term the equation written with effective parameters,

$$\langle H\rangle = \frac{\gamma\langle r_v\rangle\langle A\rangle - \rho c_p D_a}{s\langle r_a\rangle + \gamma\langle r_v\rangle} \tag{22}$$

and the equation obtained from the conservation principle,

$$\langle H\rangle = \gamma \sum_i a_i \omega_i \, r_{v,i} \, A_i - \rho c_p D_a \sum_i a_i \omega_i \tag{23}$$

with ω_i given by Equation 9. When $\langle A\rangle$ is not replaced by its expression (Equation 3), and assumed to be known, the solution for the effective resistances is the same as for latent heat, and is given by Equation 13. It is the solution proposed by Raupach (1991, 1995). When $\langle A\rangle$ is developed according to the procedure described for latent heat flux, the solution for the effective resistances is also the same as for latent heat, and is given by Equation 20. It is the solution proposed by Lhomme *et al.* (1994). The other parameters (a, G and T_s) are calculated as

$$\langle X\rangle = \frac{\sum_i a_i \omega_i r_{v,i} \, X_i}{\sum_i a_i \omega_i r_{v,i}} \qquad with \qquad X = \alpha, G, T_s^4 \tag{24}$$

which means, in this case, that $\langle A\rangle$ in Equation 22 must be replaced by $\langle A\rangle_H$ given by

$$\langle A\rangle_H = \frac{\sum_i a_i \omega_i r_{v,i} \, A_i}{\sum_i a_i \omega_i r_{v,i}} \tag{25}$$

Braden (1995) finds a similar result for sensible heat flux with the restriction stated concerning latent heat flux. The two methods developed above (Raupach's and Lhomme *et al.*'s) are summed up and compared in Table 1.

Table 1 Comparison of the two methods of calculating the effective parameters of the Penman-Monteith equations for sensible and latent heat flux.

	$\langle X\rangle=\langle\alpha\rangle$, $\langle G\rangle$ or $\langle T_s^4\rangle$	$\langle r_x\rangle$ ($x=a, v, s$)	$\langle A\rangle$ in $\langle H\rangle$ equation	$\langle A\rangle$in$\langle\lambda E\rangle$ equation
Raupach's method	a_iX_i	$a_i\omega_iA_ir_{xi}$ / $\langle A\rangle a_i\omega_i$	a_iA_i	a_iA_i
Lhomme *et al.*'s method	a_iX_i	$a_i\omega_i r_{xi}$ / $a_i\omega_i$	$a_i\omega_i r_{vi}A_i$ / $a_i\omega_i r_{vi}$	$a_i\omega_i r_{ai}A_i$/ $a_i\omega_i r_{ai}$

with $\omega_i=1/(s\,r_{ai}+\gamma r_{vi})$

DISCUSSION

COMPARISON OF THE TWO APPROACHES

A numerical simulation has been carried out to assess the performance of the two averaging procedures. A heterogeneous surface consisting of just two patches with the same area has been considered. Three cases, the same as in Lhomme *et al.* (1994), corresponding to three different combinations of two contrasted patches, have been analysed: crop-desert, forest-water, desert-water. The patch characteristics are given in Table 2. The aerodynamic resistance r_a is calculated between the surface and a reference height (z_m) within the well mixed layer by the following equation which assumes conditions of neutral atmospheric stability

$$r_a=\frac{\ln^2(z_m/z_0)}{k^2u_m} \tag{26}$$

z_0 is the roughness length, k is the von Karman constant (0.4), and u_m is the wind velocity at the reference height z_m set to 50 m. Soil heat flux is calculated as a given fraction of the isothermal net radiation $G=\zeta R_n^*$ (R_n^* being defined by Equation 3 in which T_s is replaced by T_a). This parameterisation is substantiated by the results from Clothier *et al.* (1986). For each component of the whole area, the albedo (α), the surface resistance (r_s), the roughness length (z_0) and the coefficient ζ are specified as input. The surface temperature of each patch is calculated by solving the energy balance equation.

The results of the simulations are presented in Table 3 which gives the three fluxes (H, λE and A) for each patch and for the whole area. For the whole area the

Table 2 Characteristics of the surfaces considered in the numerical simulations

Parameters	forest	crop	desert	water
α	0.1	0.2	0.3	0.05
ζ	0.01	0.05	0.3	0.6
z_0(m)	1.0	0.1	0.01	0.001
r_s(s m^{-1})	100	100	10000	0

α: albedo; $\zeta=G/R_n^*$; z_0: roughness length; r_s: surface resistance.

flux is obtained by areally averaging the component fluxes according to Equation 4. This value is considered as the true areal flux and is used as a reference, with which to compare the estimates. Three areal estimates are given. The first (a) is based upon a simple areal averaging of the surface parameters (albedo, soil heat flux, surface temperature and resistances). The second (b) is based on Raupach's averaging procedure. The third (c) uses Lhomme *et al.*'s averaging scheme. In each

Table 3 Comparison between the areal fluxes calculated by different means. The areal value is obtained from Equation 4. The areal estimates use three types of aggregation procedure: (a) simple areal averaging of the parameters, (b) averaging procedures according to Raupach's method, and (c) averaging procedures according to Lhomme *et al.*'s method. The climatic conditions used are : R_s=800 W m^{-2}, R_l=350 W m^{-2}, and at z_m=50 m, T_a=25 C, e_a=1500 Pa, u_m=5 m s^{-1}.

	Patch 1	Patch 2	Areal value	Areal estimates (a)	(b)	(c)
Case 1:	*crop*	*desert*				
λE (Wm^{-2})	334	8	171	18	171	171
H (Wm^{-2})	149	216	183	337	183	183
A (Wm^{-2})	483	224	354	355	354	354
r^* (%)	0	0	0	0	0	0
Case 2:	*forest*	*water*				
λE (Wm^{-2})	353	244	299	354	299	299
H (Wm^{-2})	242	12	127	72	127	27
A (Wm^{-2})	595	257	426	426	426	426
r (%)	0	0	0	0	0	0
Case 3:	*desert*	*water*				
λE (Wm^{-2})	8	244	126	19	126	126
H (Wm^{-2})	216	12	115	222	114	114
A (Wm^{-2})	224	257	241	242	241	241
r (%)	0	0	0	0	0	0

* $r=1-(H+\lambda E)/A$

case, the closure of the energy balance equation is tested by calculating the ratio $r=[A-(H+\lambda E)]/A$ expressed in percentage. The numerical simulations show that the simple areal averaging of the parameters (a) leads to a rather poor estimate of the areal fluxes of sensible and latent heat whereas methods (b) and (c) give perfect and equivalent results.

If the two methods are numerically equivalent for preserving the fluxes, they do not have the same characteristics and do not yield the same values for the effective resistances. In Raupach's scheme, the resistances are weighted not only by surface characteristics, as in Lhomme's scheme, but also by climatic conditions through available energy (which complicates the averaging procedure since the weighting coefficients depend upon the climatic inputs). Moreover, according to Raupach's averaging scheme, when all the patches have the same resistance r_x (x stands for a, v or s), the corresponding effective resistance $<r_x>$ is not necessarily this common value r_x, since $\Sigma a_i\, \omega_i\, A_i$ is not necessarily equal to $<A>\Sigma a_i \omega_i$. This result, a little surprisingly, is not produced by Lhomme *et al.*'s scheme.

In the averaging procedures obtained and summarized in Table 1, the effective surface temperature and the effective albedo are simple area-averages of component values, which intuitively conform to the physics of the measurements. Over a heterogeneous surface, the radiometer receives a radiative flux proportional to the relative area of each patch and to the fourth power of its absolute temperature and, considering constant emissivity, the measured temperature can be approximated by

$$<T_s>_{meas.} = \sum_i a_i T_{s,i} \tag{27}$$

As to the albedo, it is measured by the radiometer as an area-average of the component albedos, like temperature. So, for both parameters there is equivalence between satellite-measured and effective parameters.

SCHEMES NOT BASED UPON THE FLUX CONSERVATION PRINCIPLE

Lhomme (1992) proposed an averaging scheme based on the preservation of surface temperature expressed by developing the energy balance equation. $<T_s>$ is defined as the simple area-weighted temperature, such as would be measured by a remote infrared thermometer (Equation 27). Developing the energy balance and matching term by term leads to the following averaging scheme for the aerodynamic resistance

$$<r_a>^{*} = \frac{\sum_i a_i \omega_i' \, r_{v,i} \, r_{a,i}}{\sum_i a_i \omega_i' \, r_{v,i}} \tag{28}$$

and for the global resistance to water vapour transfer

$$<r_v>=\frac{\sum_i a_i\omega_i' r_{a,i} r_{v,i}}{\sum_i a_i\omega_i' r_{a,i}} \quad (29)$$

where ω'_i is defined as

$$\omega_i'=\frac{1}{sr_{a,i}+\gamma r_{v,i}(1+r_{a,i}/r_0)} \quad (30)$$

r_0 being the radiative resistance obtained by linearisation of T_s^4 (Monteith and Unsworth, 1990; Lhomme, 1992). When there is no radiative coupling ($T_s=T_a$ in the available energy formulation), r_0=infinity and $\omega'_i=\omega_i$. In this averaging procedure, available energy is no more the area-weighted mean of patch contributions. The weighting coefficients are more complex and given by $a_i\omega'_i r_{a,i} r_{v,i}$. Braden (1995) has shown that this method can lead to strong deviations with respect to the correct areal fluxes. Another procedure, based upon similar principles, was proposed by Chehbouni *et al.* (1995). The averaging scheme is based solely on the preservation of the energy balance equation and leads to a set of effective parameters, where $<\alpha>$, $<G>$, $1/<r_a>$, $1/<r_v>$ are direct area-weighted averages of the individual values, and the effective surface temperature is weighted by the component resistances in the following way:

$$<T_s>=\frac{\sum_i a_i T_{s,i} /(\omega_i' r_{a,i} r_{v,i})}{\sum_i a_i /(\omega_i' r_{a,i} r_{v,i})} \quad (31)$$

This aggregation scheme seems to perform better than the one proposed by Lhomme (1992), when fluxes are calculated by the basic diffusion equations (Chehbouni *et al.*, 1995). Nevertheless, this procedure does not preserve the fluxes when calculated by the Penman-Monteith equations.

CONCLUSION

When the Penman-Monteith equations are used to express sensible and latent heat fluxes, there are two different ways of calculating the effective parameters. The two methods, which are summarized in Table 1, are strictly equivalent from a flux conservation standpoint, yielding the same numerical results. In both schemes, the effective parameters for available energy (surface temperature, albedo and soil heat flux) are direct area averages of the component values, but the effective resistances are not calculated in the same way. In Lhomme *et al.*'s scheme they are weighted

only by surface characteristics (relative areas and component resistances), whereas in Raupach's procedure, the weighting factors are also a function of climatic conditions through available energy. This difference is compensated for by the fact that effective available energy in the Penman-Monteith equations is not expressed in the same way in the two schemes. With Raupach's scheme, $<A>$ is a simple area weighted mean of the component available energies, whereas in Lhomme *et al.*'s scheme the weighting factors also involve surface resistances as detailed in Table 1. It seems that the latter averaging scheme is sounder and more straightforward, firstly since it does not involve climatic conditions and secondly, because when the different patches of the regional mosaic have the same (surface or aerodynamic) resistances, it restores this common value as the effective resistance, while Raupach's scheme does not.

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Pole 5

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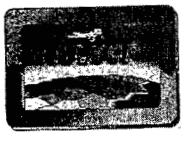

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