Tellus (1999), 51A, 387–399
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TELLUS
ISSN 0280–6495

Effective parameters for surface heat fluxes in heterogeneous terrain

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(Manuscript received 27 August 1998; in final form 1 February 1999)

ABSTRACT

The relations between most land-surface characteristics and surface heat fluxes are typically non-linear. Because the ground surface is heterogeneous at all scales, it is important to account for these non-linear relations. Effective parameters are often applied for that purpose. Steady-state simulations were used in this paper to thoroughly analyse the effective parameters impact under a broad range of atmospheric conditions. The effect of different types of aggregating functions on the accuracy of various effective parameters is also examined. The authors found that linear averaging of leaf area index and soil water content gives higher latent and lower sensible heat fluxes than the corresponding flux averaging over all surface types existing in one square grid. Linear averaging of roughness length under unstable conditions provides higher latent and lower sensible heat fluxes than flux averaging, whereas under stable conditions gives higher sensible and lower latent heat fluxes. Non-linear functions result to be more useful than linear functions to compute the effective value of those parameters which affect the surface heat fluxes independently of the atmospheric stability (e.g., leaf area index and soil water content, and unlike roughness length).

1. Introduction

The surface heat and momentum fluxes, which provide the coupling between the atmosphere and the earth surface, depend not only on atmospheric conditions but also on surface characteristics. The earth surface shows a high spatial variability at all scales, as can be readily appreciated by examining soil, vegetation and land-use maps. Consequently, the surface fluxes inherit such high spatial variability. The resolution of current atmospheric numerical models varies from a few km (in mesoscale models) up to about 500 km (in general circulation models). Therefore, it is necessary to integrate the effects of spatial variability to obtain representative surface fluxes at the grid resolution of the atmospheric models.

The effects of surface inhomogeneities on the atmosphere depend on the horizontal scale of landscape variation. Shuttleworth (1988) suggested that for length scales smaller than about 10 km, no apparent impact of the surface inhomogeneities can be observed in the atmosphere since turbulence is very efficient at mixing the boundary layer. Li and Avissar (1994) illustrated the impact of microscale variability of land characteristics (including soil water content) on the surface heat fluxes by comparing averaged surface fluxes computed from different distributions of land surface parameters with surface fluxes computed from the corresponding distribution means. They found that latent heat flux was the most sensitive to

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spatial variability, and that radiative flux emitted by the surface was the least sensitive. They emphasized the importance of considering the spatial variability of leaf area index, stomatal conductance, and, in bare land, soil-surface water content to calculate accurately the surface fluxes. They also found that the more positively skewed the distribution within the range of land-surface characteristics that is non-linearly related to the energy fluxes, the larger the difference between the energy fluxes computed with the distribution and the corresponding mean. Entekhabi and Eagleason (1989) also stressed the importance of spatial variability of soil moisture and precipitation for the parameterization of land-surface processes.

Giorgi (1997a, 1997b) represents the surface heterogeneity assuming that surface temperature and soil water content can be described by continuous analytical probability density functions (PDFs), and by integrating relevant non-linear terms over the appropriate PDF. His choice of linear symmetric PDFs allows analytical integrations which considerably reduce the computing time needed for this scheme. With the "statistical dynamical" approach (Avissar, 1992; Famiglietti and Wood, 1994; Sivapalan and Woods, 1995) surface inhomogeneities of vegetation and soil characteristics vary according to distributions that can be approximated by PDFs. Grid-scale average surface fluxes are explicitly calculated using numerical or analytical integration over appropriate PDFs. This approach, however, can be computationally demanding when several land characteristics need to be represented by PDFs.

Effective (or aggregated) parameters are parameters which account for the non-linear effects explicitly calculated with the statistical dynamical approach. A few averaging techniques have already been proposed to compute effective parameters for land processes of atmospheric numerical models (Noilhan and Lacarrere, 1995; Wood and Mason, 1991; Dolman and Blyth, 1997; Sellers et al., 1997; Noilhan et al., 1997; Kabat et al., 1997). For instance, an effective surface roughness has been considered by André and Blondin (1986), Wieringa (1986), Taylor (1987), Mason (1988) and Claussen (1990, 1991) and an effective stomatal resistance was proposed by Claussen (1990) and by Blyth et al. (1993). However, Blyth et al. (1993) pointed out that parameter aggregation fails to represent strongly varying conditions. This is due to the non-linearity of the relationship between turbulent fluxes and vertical mean profiles. For instance, the vertical gradient of potential temperature can be positive on average over a large area, while local fluxes can be in opposite direction due to a local negative gradient of temperature, as explained, e.g., by Stössel and Claussen (1993). The effects of soil moisture aggregation were estimated by Sellers et al. (1997) and Wood (1997). Finally, the impact of using effective land surface properties in atmospheric models at different scales has been studied among many others by Sellers et al. (1995) using the FIFE-89 data set, by Noilhan and Lacarrere (1995) using the HAPEX-MOBILHY-1986 data set and by Noilhan et al. (1997) using the EFEDA data set.

The so called "mosaic of tiles" approach circumvents these problems by coupling independently each land-use patch or "tile" of a grid element to the atmosphere of the model, and patches affect each other only through the atmosphere. The grid-average surface fluxes are obtained in this case by averaging the surface fluxes over each land-use weighted by their fractional area. This approach was introduced by Avissar and Pielke (1989), and adopted by Claussen (1991), Koster and Suarez (1992) and Decoudré et al. (1993).

At characteristic length scales of landscape variability larger than about 10 km, mesoscale circulations can be generated and affect the entire boundary layer (André, 1989; Avissar and Pielke, 1989; Bougeault et al., 1991; Mahfouf et al., 1987; Chen and Avissar, 1994a, 1994b; Avissar and Liu, 1996). At these scales the concept of effective parameters is no longer valid, because important dynamical processes (including clouds and precipitation) take place.

Because the dependence of surface fluxes on land characteristics is non-linear, estimates of the area averaged fluxes calculated with mean land characteristics do not yield the same results as those obtained by calculating the fluxes locally and then averaging them (Li and Avissar, 1994). Thus, the choice of effective land characteristics, such as leaf area index or soil water content, is not straightforward.

The objectives of the present study are: (i) to estimate the error in surface fluxes over heterogeneous terrain when they are computed from mean characteristics under different environmental conditions, assuming landscape scales smaller that the scale at which mesoscale circulations develop; and (ii) to propose some alternative non-linear aggregation algorithms for relevant characteristics.

In Section 2, an overview is presented of the treatment of heterogeneity by using effective parameters. Section 3 briefly describes the interaction soil biosphere atmosphere (ISBA) land-surface scheme (Noilhan and Planton, 1989) used to simulate the surface fluxes with fixed environmental conditions. The numerical experiments conducted with different PDFs and different algorithms for the computations of the effective parameters are presented in Section 4. Finally, results are discussed separately for fully vegetated and bare land cases in Section 5.

2. Parameter aggregation

Parameter aggregation is the averaging algorithm used to define effective parameters. Let define f^i as the relative area of one of the M land types within a grid element, Φ^i the corresponding flux from this land type, and $\bar{\Phi}$ the area-averaged flux. If we also define $\{\alpha_k^i, k=1, \ldots, N\}$ as the various parameters of a land type i (N being the total number of parameters), and $\{\alpha_{f_k}, k=1, \ldots, N\}$ as the effective parameters of the grid element, then for a given set of environmental conditions (Ω) and for each type of land, a flux can be expressed as

$$\Phi^i = F(\alpha_k^i, \Omega), \qquad i=1, \ldots, M, \tag{1}$$

and the grid-averaged as:

$$\bar{\Phi} = F(\alpha_{f_k}, \Omega) \tag{2}$$

where F is the same function relating parameters and fluxes in both expressions.

If, however, the area-averaged flux is assumed to be equal to the weighted average flux calculated from each land type, then it can also be expressed as:

$$\bar{\Phi} = \sum_{i=1}^{M} f^i \Phi^i. \tag{3}$$

If both expressions give the same results, then:

$$F(\alpha_{f_1}, \ldots, \alpha_{f_k}, \ldots, \alpha_{f_N}, \Omega) = \sum_{i=1}^{M} f^i F(\alpha_1^i, \ldots, \alpha_k^i, \ldots, \alpha_N^i, \Omega). \tag{4}$$

To estimate the effective parameters, we assume that all land parameters, except the one being aggregated, are identical in all patches of the grid element. If α is the parameter to aggregate, β_j are the other $N-1$ parameters and $\hat{F}$ the corresponding 1-dimensional function ($\hat{F}(\alpha_f) = F(\alpha_f; \beta_j, \Omega)$) then eq. (4) can be re-written

$$\hat{F}(\alpha_f) = \sum_{i=1}^{M} f^i \hat{F}(\alpha^i). \tag{5}$$

The effective parameter can be computed from eq. (5), assuming that $F(\alpha)$ is invertible. Formally,

$$\alpha_f = F^{-1}\left[\sum_{i=1}^{M} f^i \hat{F}(\alpha^i)\right]. \tag{6}$$

Thus, in summary, to calculate an effective parameter associated with a surface flux $\hat{F}$, the following procedure is used:

1. Compute the flux as a function of the parameter α;
2. Compute the inverse $\hat{F}^{-1}(\alpha)$;
3. Compute α_f from eq. (6).

Because $\hat{F}(\alpha)$ must be a monotonous function of the parameter to be aggregated, the above procedure is restricted to the ranges of values in the space of parameters in which its inverse, $\hat{F}^{-1}$, exists. The existence is locally assured if $\partial\hat{F}(\alpha)/\partial\alpha \neq 0$. If $\partial\hat{F}(\alpha)/\partial\alpha = 0$ in some interval of the parameter range, it implies that $\hat{F}$ does not depend on α and, therefore, the effective parameter is not relevant to this particular case. The functional dependency of the flux on the aggregating parameter must be explored to determine the range of validity of these previous assumptions. Likewise, this functional dependency should be considered under different environmental conditions, and under different β_j.

There is, in principle, one different aggregation algorithm for each surface flux (latent, sensible and radiative) but it is possible that one algorithm is applicable to two or all fluxes. If $\hat{F}$ is a linear function of α, then the effective parameter is simply $\alpha_f = \Sigma_{i=1}^{M} f^i \alpha^i$. If a sufficiently small range of values is selected for the parameters, then the linear approximation can generally be used. In fact, the entire range of values of the parameter can always be divided into small enough subranges, so that a linear approximation can be applied to calculate the effective parameter within these subranges.

The averaging algorithms for the land surface parameters should be defined according to the dependency of the surface heat fluxes on these parameters, as evident from eq. (6). This dependency, in principle, could change under different sets of environmental conditions and parameters. Aggregated parameters are well defined only when fluxes computed with them give the same results as fluxes obtained by averaging the contribution of the different patches in a grid element. If the concept of effective parameter is extended to all atmospheric conditions and to all parameters, then the properties of the surface fluxes computed from the effective parameters can be relaxed. Thus, the averaging algorithm can be selected to minimize the mean error in the calculation of the surface fluxes with effective parameters. Furthermore, the surface fluxes must be monotonously dependent on the parameter to aggregate. In fact, to obtain the surface heat fluxes, we need to find an interpolating function, $A(\alpha)$, to estimate the effective parameter, α_f, for each parameter α:

$$\alpha_f = A^{-1}\left[\int_{\alpha_{\min}}^{\alpha_{\max}} \rho(\alpha)A(\alpha)\,\mathrm{d}\alpha\right], \tag{7}$$

$$\int \rho(\alpha)\,\mathrm{d}\alpha = 1, \tag{8}$$

which results in a flux similar to that obtained when the real distribution of a land-surface parameter, $\rho(\alpha)$, is used explicitly, and such that the difference of surface heat fluxes:

$$\int_{\alpha_{\min}}^{\alpha_{\max}} \rho(\alpha)F(\alpha;\beta_j,\Omega)\,\mathrm{d}\alpha - F(\alpha_f;\beta_j,\Omega), \tag{9}$$

is minimized when averaged over as many environmental conditions and other land-surface parameters as possible. Since $A(\alpha)$ could vary with different distributions of land-surface parameters, several functions should be evaluated.

3. The model

The interaction soil–biosphere–atmosphere (ISBA) scheme is used in this study. It was developed by Noilhan and Planton (1989) and was modified by Bringfelt (1996) and by Giard and Bazile (1997) for its implementation in the HIRLAM and ARPEGE operational models, respectively.

This scheme is derived from the parameterization proposed by Deardorff (1978), expressing the coefficients for restoring and forcing terms as functions of soil water and soil texture. It has 5 prognostic variables: temperature and water content in a surface layer (about 10 cm deep), mean diurnal temperature, bulk soil water content in the entire soil (including the root zone), and the amount of liquid water retained in the canopy. There is no energy budget equation for the canopy.

The surface resistance is expressed by the product of a minimum resistance and a number of limiting factors (Jarvis, 1976; Dickinson, 1984; Jacquemin and Noilhan, 1989; Thompson, 1981) depending on environmental conditions (radiation, water stress, vapor pressure deficit and air temperature).

Since the scheme has been already described in several publications (Noilhan and Planton, 1989; Mahfouf and Jacquemin, 1989; Bougeault et al., 1991; Braud et al., 1993; Giordani, 1993; Manzi and Planton, 1994; Noilhan and Lacarrére, 1995), for brevity, it is not described again here.

4. Numerical experiment

The ISBA scheme was integrated until steady-state was reached. Mean temperature and bulk soil water content equations were kept constant with time and equal to a prescribed atmospheric temperature and an assigned soil water content, respectively.

The set of prescribed environmental conditions used here is summarized in Table 1. All possible combinations of maximum and minimum values of solar radiation, terrestrial radiation, wind speed, temperature and relative humidity were used. Thus, a total of $2^5 = 32$ possible combinations of conditions were selected.

Table 2 provides the range of the four most

Table 1. *Prescribed environmental variables used for the experiments*

Parameter	Units	Minimum	Maximum
wind speed	$\mathrm{m\,s^{-1}}$	1.0	6.0
relative humidity	%	20	100
air temperature	K	283	303
solar radiation	$\mathrm{W\,m^{-2}}$	200	1000
atmospheric radiation	$\mathrm{W\,m^{-2}}$	250	350

Table 2. *Land-surface parameters used in the ISBA scheme as input to the aggregation algorithm*

Parameter	Units	Minimum	Maximum	Average
% of sand (s)	%			50
% of clay (c)	%			50
surface soil water content (SWC_s)	$m^3\,m^{-3}$	0.0	field capacity	
total soil water content (SWC_d)	$m^3\,m^{-3}$	wilting point	field capacity	
roughness length (z_0)	m	0.01	2.0	
leaf area index (LAI)	$m^2\,m^{-2}$	0.5	6.0	
minimum stomatal resistance ($R_{s_{min}}$)	sm^{-1}			140
radiation transpiration factor (R_{st})	$W\,m^{-2}$			65
vapor transpiration factor (e_{st})				0.02
temperature transpiration factor (T_{st})	K			298
wetness transpiration factor (W_{st})				1.0
albedo (α)				0.15
emissivity (ε)				1.0

Maximum and minimum values are given to the most important parameters for land-surface processes. Averaged values are given to the parameters which have less impact on land-surface processes.

important land-surface characteristics considered in our analysis, namely, soil water content (SWC), roughness length (z_0), leaf area index (LAI) (in vegetated land) and soil texture (mainly in bare land) (Rodríguez-Camino and Avissar, 1998). Averages were used for the other (less important) parameters (see (Rodríguez-Camino and Avissar, 1998) for their explanation). SWC was assumed to vary between wilting point and field capacity. This is because vegetation typically develops within this interval of SWC.

Integrations were performed separately for vegetated terrain and bare land, as the parameters controlling the surface fluxes are different in these two cases. In vegetated land, latent and sensible heat flux mostly depend on LAI, SWC in the root zone and, when the atmospheric surface layer is stable, z_0. On the other hand, in bare land, SWC in the upper soil layer, soil texture and, also when the atmospheric surface layer is stable, z_0 are the most important parameters.

The parameter selected for aggregation takes 10 possible values, each with a different frequency. This can be compared to a grid element, which has 10 patches of different size, each one with a different fixed parameter. For the other unaggregated parameters, 4 equidistant values were taken between the maximum and minimum values. Therefore, for each parameter and each PDF, $2^5 \times 4^2 \times 10 = 5120$ integrations (assuming 2 other relevant parameters) were conducted for the computation by averaging fluxes, corresponding to 2^5 environmental conditions, 4^2 different values of the unaggregated parameters and 10 patches of the parameter to aggregate. With the aggregated parameters, $2^5 \times 4^2 = 512$ integrations were performed. Mean difference and standard deviation of latent, sensible, and net radiative surface fluxes were calculated between the two methods.

A variety of PDFs have been used in the past. Avissar (1992) uses a Gaussian distribution, Entekhabi and Eagleson (1989) and Famiglietti and Wood (1994) a gamma distribution, Avissar (1993) a lognormal function, and Sivapalan and Woods (1995) a polynomial PDF. Six different PDFs most likely to represent real field conditions were used in this study (Fig. 1): namely, two Gaussian centered in different parts of the parameter range (3 and 4), two bimodal (one produced by the addition of two Gaussians (6) and the other produced by the addition of Dirac's delta functions centered on the maximum and minimum parameter values (1)), an uniform (2), and one lognormal (5). The bimodal PDFs mimic the existence of two different types of vegetation or soil conditions. This type of bimodal PDF characterizes, e.g., the partioning of the HAPEX-MOBILHY area into pine forest and agricultural area (Noilhan et al., 1997). The Gaussian and lognormal PDFs simulate the subgrid-scale variability found in a single type of land surface.

The uniform distribution implies that all values attributed to a specific land-surface characteristic are given the same frequency (i.e., $p(x) = \text{constant}$).

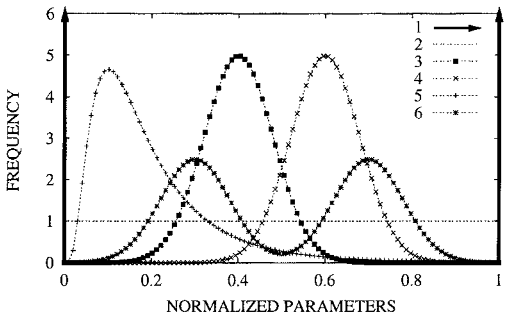

Fig. 1. Distributions used to represent spatial variability of the normalized land-surface parameters: (1) bimodal distribution obtained by adding two Dirac's delta distributions (represented by two arrows in the graphic) centered at 0 and 1; (2) uniform distribution; (3, 4) Gaussian distributions centered at 0.4 and 0.6, respectively; (5) lognormal distribution (constants a and b are 0.2 and 0.1, respectively. See Section 4 for their definition); and (6) bimodal distribution obtained by adding 2 Gaussian distributions centered at 0.3 and 0.7.

Thus, in a frequency graph, it appears as a straight line parallel to the horizontal axis.

The PDF for a normal distribution is given by:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right], \tag{10}$$

where μ and σ^2 are the mean and variance of the distribution. The mean values used for the four Gaussians distributions were $0.2(x_{max} - x_{min})$, $0.4(x_{max} - x_{min})$, $0.6(x_{max} - x_{min})$ and $0.8(x_{max} - x_{min})$, and their standard deviation was $0.1(x_{max} - x_{min})$.

The PDF of a lognormal distribution is given by:

$$p(x) = \frac{1}{s\sqrt{2\pi x}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - M}{s}\right)^2\right], \tag{11}$$

where M and s are the mean and standard deviation of the normally distributed "ln x" variable. Its mean is given by

$$e^{M+s^2/2} = x_{min} + a(x_{max} - x_{min}), \tag{12}$$

and its mode is defined as

$$e^{M-s^2} = x_{min} + b(x_{max} - x_{min}), \tag{13}$$

where a and b are empirical constants. The values (a, b) adopted for the lognormal distribution used here were (0.2, 0.1). This type of distribution proved to represent quite well the variability of stomatal conductance in agricultural fields (Naot et al., 1991; Avissar, 1993).

The PDF of a Dirac's delta distribution, $\delta(x-\mu)$, can be formally considered as a function which assigns zero values everywhere except at its center $(x=\mu)$ where it tends to infinity (Abramowitz and Stegun, 1972):

$$p(x) = \delta(x-\mu) = \begin{cases} 0 & \text{if } x \neq \mu \\ \infty & \text{if } x = \mu. \end{cases} \tag{14}$$

Different types of interpolating functions were used to minimized the surface heat flux error obtained as a result of the fitting procedure (see eq. (9)). They are given in Table 3.

Following Mason (1988), Claussen (1991) and Noilhan and Lacarrere (1995), the neutral-profile interpolating function was selected for the roughness length:

$$\frac{1}{\ln(z_b/z_0)^2}, \tag{15}$$

where the height of the first atmospheric model level, z_b, is used instead of the blending height, as originally proposed by Mason (1988). This is a reasonable approximation provided that z_b is sufficiently high. Furthermore, it appears that the system is not sensitive to this parameters, even when changed by one order of magnitude.

Fig. 2 represents some of the functions used here to interpolate LAI and SWC: trigonometric, parabolic and square root. Note, the parabolic and square root functions are fitted to minimize

Table 3. *Interpolating functions used for aggregating different land-surface parameters*

Aggregated parameter	Linear	Trigonometric	Parabolic	Square root	Logarithmic
roughness length (z_0)	x				$1/\ln(a/z_0)^2$
soil water content (SWC)	x	$sin(\frac{1}{2}\pi x)$	$-0.7x^2+1.7x$	$1.1\sqrt{x}-0.1x$	
leaf area index (LAI)	x	$\sin(\frac{1}{2}\pi x)$	$-x^2+2x$	$1.4\sqrt{x}-0.4x$	

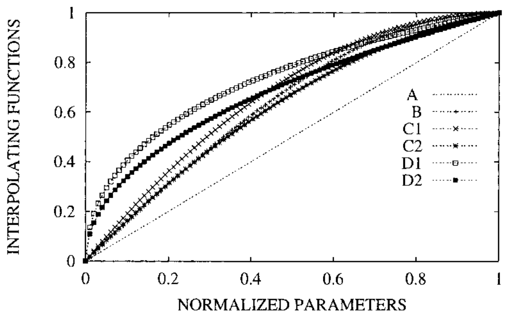

Fig. 2. Interpolating functions used to aggregate leaf area index (LAI) and soil water content: (A) linear [x]; (B) trigonometric [$\sin(\frac{1}{2}\pi x)$]; (C1) parabolic for LAI [$-x^2+2x$]; (C2) parabolic for soil water content [$-0.7x^2+1.7x$]; (D1) square root for LAI [$1.4\sqrt{x}-0.4x$]; (D2) square root for soil water content [$1.1\sqrt{x}-0.1x$].

the standard deviation of latent heat flux obtained from the ensemble of atmospheric conditions and the different values of the unaggregated parameters.

5. Results

5.1. Vegetated land

Table 4 presents the mean and standard deviation of differences between surface heat fluxes computed with the effective parameters and by regular flux averaging. Sign convention for fluxes is positive upward. A total of $2^5 \times 4^2 = 512$ different environmental conditions and values of the unaggregated parameters was used to calculate them. Linear interpolating functions were adopted to calculate the effective parameters. In general, the differences obtained for the radiative flux are clearly smaller than those obtained for the latent and sensible heat fluxes, as was already pointed out by Li and Avissar (1994). The differences of sensible heat flux are slightly more sensitive to roughness length than are the differences of latent heat flux. The opposite is found for LAI and SWC. It is interesting to note the sign of the mean differences. It is always negative for the latent heat flux calculated with the effective LAI and the effective SWC. Thus, fluxes computed with effective parameters are stronger than fluxes computed by averaging the contribution from different patches. This is due to the shape of the relation between latent heat flux and LAI or SWC, which presents a strong convexity (see, e.g., Fig. 1 in Li and Avissar (1994)). The opposite is obtained with the sensible heat flux, which shows a concave relation with these parameters. The same pattern is found with all the distributions considered in this study. Table 4 also shows that, in general, larger surface flux differences appear for distributions centered in lower regions of the parameter range. This is particularly remarkable for the lognormal distribution as compared with the Gaussians distributions.

Table 4. *Mean (μ) and standard deviation (σ) of differences between aggregated and averaged estimations of sensible heat fluxes (SHF), latent heat fluxes (LHF) and net radiative fluxes (RF) calculated with the different distributions of leaf area index (LAI), total soil water content (SWC_d) and roughness length (z_0)* illustrated in Fig. 1

PDF	μ^A_{LAI}	σ^A_{LAI}	$\mu^A_{SWC_d}$	$\sigma^A_{SWC_d}$	$\mu^A_{z_0}$	$\sigma^A_{z_0}$
SHF						
1	21.3	34.0	21.4	34.9	−36.6	43.0
2	8.2	13.3	8.3	13.8	−9.4	11.7
3	0.7	1.7	0.8	1.4	−0.3	2.2
4	0.5	1.9	0.6	1.7	−0.3	2.1
5	4.4	10.1	3.3	8.8	−2.6	3.2
6	4.1	6.8	4.2	7.3	−1.8	3.8
LHF						
1	−23.8	35.5	−24.0	37.6	20.2	31.5
2	−9.0	13.4	−9.3	14.3	5.3	8.6
3	−0.8	1.3	−0.9	1.5	0.2	1.3
4	−0.5	2.7	−0.6	1.4	0.2	1.4
5	−5.3	10.1	−3.7	8.9	1.5	2.8
6	−4.4	6.8	−4.6	7.0	1.1	2.6
RF						
1	2.6	5.0	2.4	6.2	16.2	16.8
2	1.0	2.0	0.9	2.3	4.1	4.5
3	0.2	0.7	0.1	0.2	0.1	1.3
4	0.0	1.0	0.0	0.5	0.1	0.8
5	0.7	2.5	0.2	3.0	1.1	1.1
6	0.4	1.3	0.4	1.1	0.7	1.6

Linear interpolating functions were used to compute the effective parameters. The ground was covered with vegetation. Units are W m^{-2}.

Fig. 3 provides the difference between the two methods of calculation of the fluxes as a function of latent heat flux and sensible heat flux for the double Dirac's delta distribution of z_0 (Fig. 3a), LAI (Fig. 3b) and SWC (Fig. 3c). Each point in

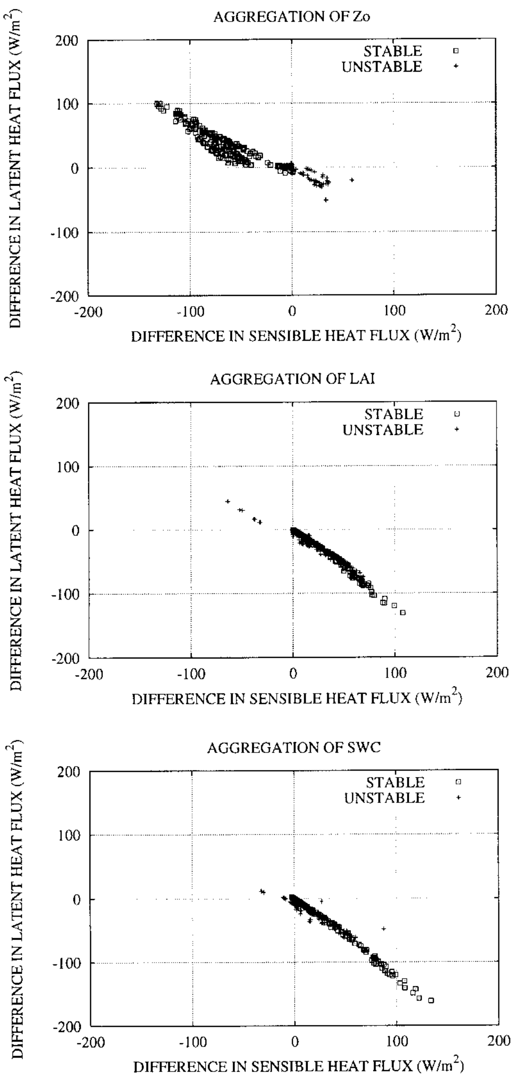

Fig. 3. Aggregated minus averaged difference of latent heat flux against aggregated minus averaged difference of sensible heat flux when fluxes are computed from (a) aggregated roughness length, z_0; (b) leaf area index, LAI; and aggregated soil water content, SWC. The ground was fully covered by vegetation. Each point represents a different set of environmental conditions (Table 1) and different values of the non-aggregated parameters (Table 2). Square (□) and plus (+) indicate stable and unstable conditions, respectively. PDF 1 was used for the three parameters.

this figure corresponds to one of the 512 sets of environmental conditions and unaggregated parameters.

Fig. 3a shows points mostly distributed in two quadrants. The points in the upper left quadrant (positive difference of latent heat flux and negative difference of sensible heat flux) reflect stable atmospheric conditions, and those in the lower right quadrant were obtained for unstable atmospheric conditions. The mean difference between aggregated and averaged sensible, latent, and radiative heat fluxes are -36.6, 20.2 and 16.2 W m^{-2}, respectively. Thus, on average, using an aggregated roughness length results in an enhancement of sensible heat flux and a reduction of latent heat and radiative fluxes. It should be stressed the non negligible impact of z_0 aggregation on radiative heat flux compared with the corresponding impact of LAI and SWC aggregations. This fact confirms that aggregation of z_0 not only affects the redistribution of surface heat fluxes but also the whole surface energy budget.

Fig. 3b presents a similar graph, but for the aggregation of LAI. Here, most points (including stable and unstable atmospheric conditions) are located in the lower right quadrant (negative difference of latent heat flux and positive difference of sensible heat flux). The aggregation method appears to enhance the latent heat flux (mean difference is -23.8 W m^{-2}) and reduce the sensible heat flux (mean difference is 21.3 W m^{-2}). However, the method has only a minor effect on the radiative flux (mean difference is 2.6 W m^{-2}). While the aggregation of LAI only affects directly the redistribution of surface heat fluxes, it has an indirect effect on the near-surface variables. Near-surface air temperature and relative humidity are significantly affected by the intensity of the sensible and latent heat fluxes, and, as a result, will be sensitive to the aggregation method.

Fig. 3c gives the corresponding graph for the aggregation of SWC. Results are generally quite similar to those obtained for the aggregation of LAI.

The other distributions considered in this study show a similar pattern but smaller differences (not shown).

Table 5 provides the mean and standard deviation of differences between surface heat fluxes computed with various interpolating functions for the effective LAI and by regular averaging. The

Table 5. *Mean (μ) and standard deviation (σ) of differences between aggregated and averaged estimations of sensible heat fluxes (SHF), latent heat fluxes (LHF) and radiative fluxes (RF) calculated with different distributions illustrated in Fig.1 and different interpolating functions (A — linear, B — trigonometric, C1 — parabolic, D1 — square root) for the leaf area index (LAI)*

	PDF	μ^{A}_{LAI}	σ^{A}_{LAI}	μ^{B}_{LAI}	σ^{B}_{LAI}	μ^{C1}_{LAI}	σ^{C1}_{LAI}	μ^{D1}_{LAI}	σ^{D1}_{LAI}
SHF	1	21.3	34.0	3.4	17.8	−0.7	16.5	−1.4	16.4
	2	8.2	13.3	1.0	7.0	−0.7	6.7	−0.1	6.8
	3	0.7	1.7	0.0	1.2	−0.1	1.2	0.1	1.2
	4	0.5	1.9	−0.5	2.1	−0.6	2.1	0.2	1.8
	5	4.4	10.1	2.7	8.5	1.6	7.7	−1.0	6.7
	6	4.1	6.8	−1.0	4.1	−1.9	4.3	0.5	4.0
LHF	1	−23.7	35.5	−4.3	18.5	0.3	17.2	1.0	17.5
	2	−9.0	13.4	−1.2	6.8	0.7	6.6	0.0	6.7
	3	−0.8	1.3	0.0	0.7	0.2	0.8	−0.1	0.7
	4	−0.5	2.7	0.6	2.2	0.7	2.2	−0.2	2.3
	5	−5.3	10.1	−3.4	8.2	−2.1	7.0	0.9	5.7
	6	−4.4	6.8	1.3	3.7	2.2	3.8	−0.5	3.5
RF	1	2.6	5.0	1.0	3.5	0.6	3.2	0.5	3.2
	2	1.0	2.0	0.2	1.5	0.6	1.6	0.2	1.5
	3	0.1	0.7	0.0	0.7	0.0	0.7	0.0	0.7
	4	0.0	1.0	−0.1	1.0	−0.1	1.0	0.0	1.0
	5	0.7	2.5	0.6	2.3	0.4	2.2	0.1	1.8
	6	0.4	1.3	−0.1	1.1	0.0	1.3	0.1	1.2

The ground was covered with vegetation. Units are W m^{-2}.

parabolic (C1) and square root (D1) functions were fitted to minimize the standard deviation of latent heat fluxes obtained with the uniform distribution (2). Although the adjustment was done with a single distribution for only one of the fluxes, improvement is remarkable for all fluxes and all distributions. Both mean and standard deviation are significantly reduced when the non-linear interpolation functions are used. But improvement is even more noticeable with the uniform and bimodal distributions (2, 1 and 6). It is interesting to note that fitting the interpolating function of the most variable heat flux (either latent or sensible), automatically improves the other. If any of the Gaussian (3 and 4) or the lognormal (5) distributions are used to characterized the parameters variability, interpolating functions B, C1 and D1 result also in a similar decrease of the mean and standard deviation of differences.

Table 6 shows that the results for the aggregation of SWC are very similar to those obtained for LAI. The parabolic (C2) and square root (D2) functions were also fitted here to minimize the standard deviation of latent heat fluxes obtained with the uniform distribution. All non-linear functions here used (B, C2 and D2) give again very similar results.

Table 7 gives the results for roughness length. Only two interpolation function were considered for this experiment, namely the linear and the logarithmic functions. The mean and standard deviation improve slightly when the logarithmic interpolating function was used. All three lognormal distributions show slight improvement when the logarithmic interpolating function is applied. No attempt was made to fit any other type of non-linear interpolating function because of the opposite sign of flux differences for stable and unstable atmospheric conditions (Fig. 3a). Fitting any function for results obtained with stable atmosphere deteriorates the results with unstable conditions, and vice-versa.

5.2. *Bare land*

The two most relevant parameters for this case are soil-surface water content, which is a pre-

Table 6. *Same as Table 5, but for total soil water content and with different interpolating functions (A — linear, B — trigonometric, C2 — parabolic, D2 — square root)*

	PDF	$\mu^{A}_{SWC_d}$	$\sigma^{A}_{SWC_d}$	$\mu^{B}_{SWC_d}$	$\sigma^{B}_{SWC_d}$	$\mu^{C2}_{SWC_d}$	$\sigma^{C2}_{SWC_d}$	$\mu^{D2}_{SWC_d}$	$\sigma^{D2}_{SWC_d}$
SHF	1	21.4	34.9	−1.9	21.4	0.4	21.7	−3.0	21.4
	2	8.3	13.8	−1.4	8.6	−0.3	8.6	−0.3	8.6
	3	0.8	1.4	−0.1	0.9	−0.0	0.9	0.1	0.9
	4	0.6	1.7	−0.7	1.7	−0.3	1.5	0.3	1.6
	5	3.2	7.8	2.2	8.0	1.5	7.6	−2.0	6.8
	6	4.2	7.3	−2.0	4.9	−0.8	4.6	0.6	4.8
LHF	1	−24.0	37.6	−1.9	23.8	−0.6	24.1	3.1	23.8
	2	−9.3	14.3	−1.4	9.1	0.2	9.1	0.3	9.1
	3	−0.9	1.5	0.1	0.9	0.0	0.9	−0.1	0.9
	4	−0.6	1.4	0.8	1.7	0.3	1.4	−0.3	1.4
	5	−3.7	8.9	−2.5	7.8	−1.7	7.2	2.3	5.5
	6	−4.6	7.0	2.3	4.7	1.0	4.3	−0.6	4.4
RF	1	2.4	6.2	0.2	4.4	0.4	4.6	0.1	4.4
	2	0.9	2.3	0.0	1.7	0.1	1.8	0.1	1.8
	3	0.1	0.2	0.0	0.1	0.0	0.1	0.0	0.1
	4	0.0	0.4	−0.1	0.4	−0.1	0.4	0.0	0.4
	5	0.2	3.0	0.1	2.9	0.0	2.8	−0.4	2.6
	6	0.4	1.1	−0.2	0.8	−0.1	0.8	0.1	0.9

scribed parameter here, and roughness length. Similar features are found for the flux differences when linear interpolation functions are used. SWC shows a very similar behaviour to the fully vegetated case, although the magnitude of the differences are slightly smaller. However, it should be noted that for roughness length, the mean difference of sensible and latent heat fluxes reverse their sign. Although differences under stable and unstable atmospheres behave as in the vegetated case, those obtained in unstable atmosphere weight more than those obtained in the stable one. The reason for such change comes probably from the enhancement of the non-linear dependency of heat fluxes on roughness length in case of unstability.

Additional tests were also conducted to estimate the error associated to the effective texture variables when linear interpolation functions are used. Differences in the case of the effective percentage of sand were almost negligible, whereas for the effective percentage of clay differences were around 20–30% of those found for z_0 and SWC.

In reality, soil-surface water content varies significantly with time, depicting essentially a diurnal cycle pattern. When there is no precipitation, this parameter is affected by evaporation and percolation, and it inherits the diurnal pattern of evaporation, which typically follows the solar radiation absorbed at the ground surface. Because of the frequent fluctuations of this parameter, no attempt was made to optimize its aggregation using non-linear interpolating functions.

6. Conclusions

Several studies have emphasized that the relation between most land-surface parameters and heat fluxes is non-linear (Avissar, 1992). Thus, not surprisingly, when a linear function is used to aggregate these parameters for the calculation of mean land-surface heat fluxes, a relatively large error can be generated. Fig. 3 show errors as large as $100\ \mathrm{W\ m^{-2}}$ for the extreme case of double Dirac's delta PDF. Errors as large as $40\ \mathrm{W\ m^{-2}}$ appear when the uniform PDF is used. Here, we showed that using non-linear functions for that purpose can, in most cases, significantly reduce this error. This is particularly true for those parameters which relate to the fluxes independently of the atmospheric stability, e.g., LAI and soil water content. However, finding a non-linear function for the roughness length, which has a different impact on the surface heat fluxes under stable and unstable atmospheric conditions, is more complicated.

Several authors (Noilhan and Lacarrere (1995)) have demonstrated, using field datasets, the validity of the effective parameters approach to compute surface heat fluxes. Such validations, however, are restricted to the particular conditions of the site under study. We have shown here that significant differences appear, however, in the academic case of the Dirac's delta distribution, which attempts to estimate the theoretical upper limit for differences between both computations. Some atmospheric conditions, represented by points in Fig. 3, result to be more sensitive than others to the procedure for computing surface heat fluxes.

While the type of aggregating function used for the various parameters is typically independent of the magnitude of the surface fluxes, it is nevertheless important to calibrate these functions under those environmental conditions resulting in strong heat fluxes (e.g., high solar radiation). This is because the non-linear effects then become more important.

It could be interesting to reproduce some of the experiments performed here with different soil–vegetation–atmosphere transfer (SVAT) schemes. Probably, SVAT schemes based on the same general concepts (namely, conservation of heat and water at the ground surface) would supply similar results to those here obtained. Details of the various parameterizations of the SVAT schemes processes, which make the difference between the various schemes (e.g., stomatal conductance, soil heat flux, etc.) seem not to have a direct impact on the aggregation process.

Further studies are intended for a follow-up work based on observational datasets (Cabauw, HAPEX-MOBILHY, etc.) to benefit from a self consistent atmospheric forcing. Long term runs would also allow to appreciate the integrated impact of aggregation on the water and energy budgets.

Finally, as general recommendations for the community of land-surface models, it can be stated: First, the process of linear aggregation of LAI and SWC enhances/decreases latent/sensible heat fluxes. Second, this is general for all PDFs studied in this work (more distributions not shown here confirm this point), being the upper limit for differences the extreme case of the double Dirac's delta distribution. Third, these systematic differences can be corrected using non-linear functions to aggregate parameters.

Table 7. *Mean (μ) and standard deviation (σ) of differences between aggregated and averaged estimations of sensible heat fluxes (SHF), latent heat fluxes (LHF) and radiative fluxes (RF) calculated with different distributions (1–6, Fig. 1) and different interpolating functions (A — linear, E — logarithmic) for roughness length*

	PDF	$\mu_{z_0}^{A}$	$\sigma_{z_0}^{A}$	$\mu_{z_0}^{E}$	$\sigma_{z_0}^{E}$
SHF	1	−36.6	43.0	−32.5	35.9
	2	−9.3	11.7	−8.2	9.8
	3	−0.3	2.2	−0.2	2.2
	4	−0.3	2.1	−0.2	2.1
	5	−2.6	3.2	−1.7	2.2
	6	−1.8	3.8	−1.5	3.4
LHF	1	20.2	31.5	17.7	25.6
	2	5.3	8.6	4.6	7.2
	3	0.2	1.3	0.1	1.2
	4	0.2	1.4	0.2	1.3
	5	1.5	2.8	1.0	2.8
	6	1.1	2.6	0.9	2.3
RF	1	16.2	16.8	14.6	14.6
	2	4.1	4.5	3.6	4.0
	3	0.1	1.3	0.1	1.2
	4	0.1	0.8	0.1	0.8
	5	1.1	1.1	0.7	0.7
	6	0.7	1.6	0.6	1.6

The ground was covered with vegetation. Units are $W\ m^{-2}$.

7. Acknowledgments

This study was performed while the first author was visiting the Department of Environmental Sciences at Rutgers University, supported by a Fulbright/Spanish Ministry of Development grant. Comments and suggestions by B. Bringfelt, C. J. M. Belandia, J. Ardao, J. A. Alonso and three anonymous reviewers significantly improved the manuscript.

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