APPROACHES FOR AGGREGATING HETEROGENEOUS SURFACE PARAMETERS AND FLUXES FOR MESOSCALE AND CLIMATE MODELS

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Abstract. Land surface and climate processes possess dynamics and heterogeneities across a wide range of scales. This study explores the utility of, and procedures for, using local scale measurements to obtain large-scale information. An aggregation scheme is proposed to bridge the scale gap between the scale of measurements including remote sensors and climate and mesoscale models. The proposed scheme derives a set of effective parameters which obeys the energy balance equation exactly and partitions the surface fluxes accurately at different scales. It produces a unique set of aggregated land surface parameters that are easily measurable through remote sensing and have sound mathematical and physical basis. It is shown that aggregated ground heat flux, emissivity and albedo may be obtained by simple areally weighted averaging while temperature, aerodynamic and surface resistances require more involved aggregation operators. The effective surface temperature, although it requires a complicated operator involving subgrid-scale temperature and surface emissivity, is easily measurable through remote sensing. The proposed scheme was compared and contrasted with existing effective parameter approaches. It was shown that several effective parameters of the previous schemes can be easily derived from the proposed scheme by introducing additional assumptions and simplifications.

Keywords: Aggregation and disaggregation, Surface fluxes, Surface heterogeneity.

1. Introduction

Adequate representation of land surface processes is critical for understanding and modeling regional weather and climate. Several recent numerical studies have shown that the modelled climate is very sensitive to the representation of the land surface (Manabe, 1969; Walker and Rowntree, 1977; Rind, 1988; Delworth and Manabe, 1993). Several land surface models, ranging from a simple bucket type model (Manabe, 1969) to very detailed soil-vegetation-atmosphere transfer (SVAT) schemes (Dickinson et al., 1993; Sellers et al., 1996), were developed for use in atmospheric models. Many of these models require a few dozen land surface parameters as well as initial and boundary conditions that cannot be reliably obtained over large areas by conventional measurement technology.

Recently, advances in remote sensing technology have shown promising results to obtain land surface parameters over large areas by using satellite or airborne

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remote sensors. One outstanding problem, however, is that large-scale general circulation models (GCMs) or numerical weather prediction models that use remotely sensed land surface parameters do not require them at the same spatial resolution at which the remote sensing measurements are obtained. Recent studies have shown, in general, that surface parameter heterogeneity has a significant impact on the estimation of the surface fluxes. In particular, use of areally weighted land surface parameters has produced significant error in grid level fluxes and in the partitioning of surface moisture and energy fluxes (Lhomme, 1992; Bonan et al., 1994; Hu and Islam, 1997a and references therein). Thus, several recent studies have focused on the development of an aggregation scheme that can use existing land surface representations over large areas (e.g., Finnigan and Raupach, 1987; Raupach, 1991; Lhomme, 1992; Lhomme et al., 1994; McNaughton, 1994; Braden, 1995; Chehbouni et al., 1995; Raupach and Finnigan, 1995). In this so-called effective parameter approach, land surface models that are developed and tested over small homogeneous areas are now used at larger scales by redefining the model parameters.

Several aggregation schemes were proposed to obtain effective land surface parameters from small-scale land surface parameter values (Raupach, 1991; Lhomme, 1992; Braden, 1995; Chehbouni et al., 1995). These studies show that it is possible to obtain effective parameters from small-scale land surface parameter values. However, many of these aggregation schemes cannot obtain reliable partitioning of surface fluxes by using effective land surface parameters. In addition, some of these effective parameters have no physical meaning (Braden, 1995). A common approach, often referred to as term-by-term matching, to obtain effective land surface parameters is to (i) write an energy balance equation for the grid as a whole, then (ii) rewrite the same equation for each component surface element (i.e., subgrid) and take an area-weighted sum of individual terms over all the elements of the grid, and (iii) match equation (i) and (ii) term by term to obtain a set of relationships between grid scale and subgrid-scale parameters.

Linearizations of the Stefan–Boltzmann equation and dependence of saturation vapour pressure on temperature are also widely used. Use of these linearizations in the surface energy balance equation leads to a partitioning problem among surface radiation, sensible and latent heat fluxes, because surface radiation and latent heat flux are expressed in terms of a surface-air temperature difference and then combined with sensible heat flux in the term-by-term matching methodology. It appears that results obtained by using term-by-term matching methodology are applicable for some rather special cases and cannot be generalized. Furthermore, incautious use of this methodology could lead to some awkward aggregation schemes. For example, Lhomme et al. (1994) found that three different aggregated surface temperatures are possible depending on whether sensible heat flux, latent heat flux, or available energy (e.g., net radiation minus ground heat flux) is preserved. Braden (1995) found that effective surface parameters obtained by satisfying certain ad-hoc aggregation equation often led to parameters with no physical meaning.

Our main objective in this paper is to obtain a unique set of effective surface parameters such that each flux in the energy balance equation, and the partitioning of radiation into surface fluxes, are preserved. We plan to show that resulting effective surface parameters have physical meaning and that the aggregation scheme has a physical and mathematical basis. Problems with previous aggregation schemes, especially the term-by-term matching approach, will also be discussed. The organization of this paper is as follows. In the following section, some comments on the existing aggregation schemes are provided. In Section 3, we present our proposed aggregation scheme and its simplifications for specific applications. In Section 4, we compare and contrast results of our schemes with those from an existing scheme using numerical simulations. Concluding remarks are given in Section 5.

2. Brief Review of Existing Parameter Aggregation Approaches

Several existing aggregation schemes use the so-called term-by-term matching approach to obtain aggregated land surface parameters (Finnigan and Raupach, 1987; Raupach, 1991; Lhomme, 1992; Lhomme et al., 1994; McNaughton, 1994; Braden, 1995; Chehbouni et al., 1995; Raupach and Finnigan, 1995). Lhomme (1992) assumed that effective surface temperatures can be estimated by using areally weighted average temperature. Using linearized saturated vapour pressure in the latent heat flux and the surface temperature raised to fourth power in the surface radiation flux, he derived an equation for the land surface temperature from the surface energy balance equation. Based on the simulated scenarios, he found that by using the effective parameter values from his aggregation scheme to estimate the sensible and latent heat flux, the error could be up to 30%. This error is much smaller than that obtained using the traditional areally weighted average land surface parameter values, in which case the error could be as large as 186%. The error introduced in Lhomme's (1992) approach may come from term-by-term matching, linearization of latent heat flux and surface radiation equations, and the assumption that the effective surface temperature is an areally weighted average temperature.

Lhomme et al. (1994) explored the problems of the term-by-term matching approach from latent and sensible heat flux equations and surface available energy (net radiation minus ground heat flux) equations. Using the term-by-term matching approach to each equation, three effective surface temperatures are derived. Thus, in order to scale up and conserve the energy balance equation, one needs to calculate three different effective surface temperatures. Their main finding is that the effective value of a given parameter is not unique, but differs according to the magnitude being conserved and the equation used to express this magnitude (Lhomme et al., 1994). A similar conclusion was obtained by McNaughton (1994) by comparing averaging schemes of Raupach (1991) and Lhomme (1992). Both approaches used term-by-term matching method. Braden (1995) presented an aggregation scheme based on the Penman–Monteith equation, and has shown some advantages over the method proposed by Lhomme (1992). Braden (1995) also used the term-by-term matching method and noted that the effective parameters obtained by using his method satisfied certain constraints without much physical meaning.

Recently, Chehbouni et al. (1995) relaxed the assumption in Lhomme (1992) that effective surface temperature can be estimated by using the areally weighted average temperature. By matching term-by-term in the surface energy balance equation, they obtained another aggregation scheme. Based on simulated scenarios, Chehbouni et al. (1995) have shown that the effective temperature could be 4 K lower than that of the areally weighted average temperature and the sensible and latent heat flux from this scheme produce less than 10% error compared to the corresponding distributed estimates.

Hu and Islam (1997a) developed a framework to analyze and parameterize the effect of surface heterogeneity on estimations of grid-level surface fluxes. They found that there are two conditions that will lead to the scale invariant land surface flux parameterization: a linear model or homogeneous land surface parameters. The scale invariant land surface flux parameterization is defined such that the difference between the lumped model estimation with areally weighted land surface parameters and the distributed model estimation is zero. For the distributed model estimation, for each subgrid, a land surface model is used to get the subgrid flux and then the grid level flux is aggregated by using the areally weighted average. For the lumped model estimation, areally weighted average parameters are used as model parameters to obtain the grid-level flux. They found that reflected surface shortwave radiation is scale invariant and longwave radiation from the surface is quasi-scale invariant. For the latent and sensible heat fluxes, second order correction terms involving the variance and covariance of the land surface parameters ought to be included to account for the effect of surface heterogeneity, if the grid-level surface parameters are estimated by using areally weighted averages. In summary, Hu and Islam (1997a) call for modifying existing land surface parameterizations in order to account for the effect of surface heterogeneity on the estimation of grid-level sensible and latent heat fluxes. This approach does not need subgrid-scale information and could form the basis for parameterizing the effect of the surface heterogeneity without the knowledge of detailed surface parameter values (Hu and Islam, 1997b, 1998). For the ground heat flux and longwave radiation to and from the surface, results of Hu and Islam (1997a) are similar to existing effective parameter approaches. For sensible and latent heat fluxes, however, simple areally weighted average aerodynamic and surface resistances are not adequate. Thus, we have to seek an alternative way to obtain grid-level sensible and latent heat flux estimates. The effective parameter approach presented in this paper is a step toward that direction.

3. Proposed Approach

The objective of the effective parameter approach is to derive a set of land surface parameters such that land surface parameterizations that were developed over a small or local scale can be used at a larger scale or even at the GCM grid scale. One common assumption is that at some height (e.g., a blending height) the atmosphere behaves as if the air flows over a homogeneous land surface (Shuttleworth, 1988; Raupach, 1991). One implication of this assumption is that land surface heterogeneity is disorganized rather than organized. Otherwise, due to mesoscale circulations induced by the land surface heterogeneity, the atmospheric boundary layer will behave differently. After making this assumption, we can consider atmospheric variables to be homogeneous. We also assume that the effect of advection is relatively weak and the classical resistance formulations for the sensible and latent heat fluxes are valid for each relative homogeneous sub unit. Now, sensible and latent heat fluxes can be expressed as:

$$H = \rho c_p (T_s - T_a)/r_a \tag{1}$$

$$E = (\rho c_p/\gamma)[e^*(T_s) - e_a]/(r_a + r_s), \tag{2}$$

where H and E are the sensible and latent heat fluxes from the surface respectively, ρ is the air density at the reference level, c_p is the specific heat of air at constant pressure, T_s is the surface temperature and T_a the air temperature at the reference level height, r_a is the aerodynamic resistance from surface to the mixed layer and is related to surface roughness and wind velocity, γ is the psychrometric constant, $e^*(T_s)$ is the surface saturated vapour pressure at the surface temperature T_s and e_a is the vapour pressure at the reference level height, r_s is the surface resistance for the vapor to move from the soil to the air and can be used to describe evaporation from bare soil and transpiration from the canopy.

Assuming the surface to be a very thin layer, we can neglect the heat storage, then the net radiation to the surface R_n is partitioned into three components: sensible heat flux H, latent heat flux E and ground heat flux G. The energy balance equation for the surface is:

$$R_n = H + E + G. \tag{3}$$

where net radiation can be written as follows:

$$R_a = (1 - \alpha)R_s + \epsilon_s(R_l - \sigma T_s^4). \tag{4}$$

This formulation for the net radiation takes into account the reflectance of the longwave radiation of the surface by using the surface emissivity ϵ_s. R_s is the shortwave radiation at the surface and is taken to be homogeneous over the domain under consideration, and α is the surface albedo, $R_l = \epsilon_a \sigma T_a^4$ is the longwave radiation from the air and is homogeneous over the domain under consideration; and σ is the Stefan–Boltzmann constant.

Let us assume that the domain under consideration can be subdivided into finite homogeneous categories and each with a relative area of a_i. Then the distributed fluxes and the energy balance can be expressed as:

$$H^D = \sum_i a_i \rho c_p (T_{s,i} - T_a)/r_{a,i} \tag{5a}$$

$$E^D = \sum_i a_i (\rho c_p/\gamma)[e^*(T_{s,i}) - e_a]/(r_{a,i} + r_{s,i}) \tag{5b}$$

$$G^D = \sum_i a_i G_i \tag{5c}$$

$$R_s^D = \sum_i a_i (1 - \alpha_i) R_s \tag{5d}$$

$$R_{\text{down}}^D = \sum_i a_i \epsilon_{s,i} R_l \tag{5e}$$

$$R_{\text{up}}^D = \sum_i a_i \epsilon_{s,i} \sigma T_{s,j}^4 \tag{5f}$$

$$H^D + E^d = R_s^D + R_{\text{down}}^d - R_{\text{up}}^D, \tag{5g}$$

where superscript 'D' indicates the flux is from the distributed calculation. R_s^D is the total shortwave radiation that is absorbed by the surface from the distributed calculation. R_{down}^D is the total downward longwave radiation that is absorbed by the surface from the distributed calculation, R_{up}^D is total upward longwave radiation from the distributed calculation.

From the effective parameter approach, if we can find the corresponding set of land surface parameters such that the parameterization schemes developed over small scale can be used at larger scale, then at the grid (i.e., larger) scale level, we have:

$$H^L = \rho c_p (T_s - T_a)/r_a \tag{6a}$$

$$E^L = (\rho c_p/\gamma)[e^*(T_s) - e_a]/(r_a + r_s) \tag{6b}$$

$$G^L = G \tag{6c}$$

$$R_s^L = (1 - \alpha) R_s \tag{6d}$$

$$R^L_{\text{down}} = \epsilon_s R_l \tag{6e}$$

$$R^L_{\text{up}} = \epsilon_s \sigma T_s^4. \tag{6f}$$

The energy balance equation should also be valid over the grid, thus:

$$H^L + E^L + G^L = R^L_s + R^L_{\text{down}} - R^L_{\text{up}}, \tag{6g}$$

where superscript ‘L’ indicates that the total flux is from the lumped model calculation. T_s, r_a, r_s, G, α, ϵ_s are the six effective land surface parameters that need to be determined in order to use the lumped models (6a)–(6f). We would like to find a set of land surface parameters that would not only conserve the energy flux at the surface but also partition the fluxes with reasonable accuracy, and we minimize the following objective function to obtain the parameters:

$$\begin{aligned} M \; = \; & (H^L - H^D)^2 + (E^L - E^D)^2 + (G - G^D)^2 \\ & + (R^L_s - R^D_s)^2 + (R^L_{\text{down}} - R^D_{\text{down}})^2 + (R^L_{\text{up}} - R^D_{\text{up}})^2. \end{aligned} \tag{19}$$

In order to minimize M, we take the derivative of M with respective to G, α, r_s, r_a, T_s, ϵ_s respectively and set these derivatives to zero. This leads to

$$G^L = G^D \tag{8a}$$

$$R^L_s = R^D_s \tag{8b}$$

$$E^L = E^D \tag{8c}$$

$$H^L = H^D \tag{8d}$$

$$R^L_{\text{up}} = R^D_{\text{up}} \tag{8e}$$

$$R^L_{\text{down}} = R^D_{\text{down}}. \tag{8f}$$

The objective function M is zero when (8a)–(8f) are satisfied. (8a)–(8f) also indicate that each flux component is conserved by using the effective parameter (lumped approach). From (5a)–(5f), (6a)–(6f) and (8a)–(8f), we have

$$(T_s - T_a)/r_a = \sum_i a_i (T_{s,i} - T_a)/r_{a,i} \tag{9a}$$

$$[e^*(T_s) - e_a]/(r_a + r_s) = \sum_i a_i [e^*(T_{s,i}) - e_a]/(r_{a,i} + r_{s,i}) \tag{9b}$$

$$G = \sum_i a_i G_i \tag{9c}$$

$$\alpha = \sum_i a_i \alpha_i \tag{9d}$$

$$\epsilon_s = \sum_i a_i \epsilon_{s,i} \tag{9e}$$

$$\epsilon_s T_s^4 = \sum_i a_i \epsilon_{s,i} T_{s,i}^4. \tag{9f}$$

The three effective land surface parameters (e.g., ground heat flux G, surface albedo α, and surface emissivity ϵ_s) can be estimated by using the areally weighted arithmetic averages. This result is consistent with that of Hu and Islam (1997a).

From (9e) and (9f), an effective surface temperature can be estimated as:

$$T_s = \left[\frac{\sum_i a_i \epsilon_{s,i} T_{s,i}^4}{\sum_i a_i \epsilon_{s,i}} \right]^{1/4}. \tag{10}$$

The effective surface temperature is also a weighted arithmetic average based on the surface radiation budget equation including the effect of surface emissivity heterogeneity. The aggregation scheme for surface temperature (10) is similar to the observational mechanism for satellite and airborne sensors. Remote sensors measure radiation energy from the surface. If the surface is heterogeneous, then the remote sensor measures the total energy from the heterogeneous surface rather than the temperature itself. In order to derive an equivalent temperature for heterogeneous terrain, the Stefan–Boltzmann equation is used to invert the surface temperature (Cracknell and Hayes, 1991). Thus, the aggregation scheme for surface temperature (10) is physically sound and this aggregated surface temperature can be measured by remote sensors over heterogeneous terrain.

Intuitively, one can argue that we should be able to obtain surface temperature by using an areally weighted arithmetic average directly without resorting to the radiation equation. It is commonly assumed that the following approximation for surface temperature is applicable:

$$T_s^4 = T_a^4 + 4T_a^3 (T_s - T_a), \tag{11}$$

since $|T_s - T_a| \ll T_a$. Using this approximation in (9f) and assuming that surface emissivity is homogeneous, we have

$$T_s = \sum_i a_i T_{s,i}. \tag{12}$$

We denote this temperature as AT, the *A*really weighted *T*emperature,

$$\mathrm{AT} = \sum_i a_i T_{s,i}. \tag{13}$$

Assuming surface emissivity to be homogeneous, from (10), we have ET: *E*nergy equation based areally weighted *T*emperature:

$$\mathrm{ET} = \left[\sum_i a_i T_{s,i}^4\right]^{1/4}. \tag{14}$$

The difference between these two schemes is found to be small and a detailed discussion will be give in Section 4.1. Thus, use of areally weighted surface emissivity and surface temperature with the lumped model would produce a reasonably accurate estimate of surface radiation over the heterogeneous surface. This result is also consistent with that of Hu and Islam (1997a).

Substituting (10) into (9a), we have effective aerodynamic resistance as:

$$r_a = \frac{\left[\frac{\sum_i a_i \epsilon_{s,i} T_{s,i}^4}{\sum_i a_i \epsilon_{s,i}}\right]^{1/4} - T_a}{\sum_i a_i (T_{s,i} - T_a)/r_{a,i}}, \tag{15a}$$

which is a weighted harmonic average. From (9b), (10) and (15a), the effective surface resistance is:

$$r_s = \frac{e^*\left(\left[\frac{\sum_i a_i \epsilon_{s,i} T_{s,i}^4}{\sum_i a_i \epsilon_{s,i}}\right]^{1/4}\right) - e_a}{\sum_i a_i [e^*(T_{s,i}) - e_a]/(r_{a,i} + r_{s,i})} - \frac{\left[\frac{\sum_i a_i \epsilon_{s,i} T_{s,i}^4}{\sum_i a_i \epsilon_{s,i}}\right]^{1/4} - T_a}{\sum_i a_i (T_{s,i} - T_a)/r_{a,i}}, \tag{15b}$$

which is also a weighted harmonic average. These two aggregation schemes for aerodynamic and surface resistances also have their physical bases. For example, for aerodynamic resistance, assume that surface temperature is homogeneous, then from (15a), we have

$$\frac{1}{r_a} = \sum_i a_i \frac{1}{r_{a,i}}. \tag{16}$$

This is similar to the equivalent resistance for parallel connections of resistors in an electrical circuit. If the voltage drop across the resistors is the same then the resistance for n resistors in parallel is

$$\frac{1}{R_T} = \sum_{i=1}^{n} \frac{1}{R_i}. \tag{17}$$

Equations (16) and (17) are similar except that we need to consider the relative area for effective aerodynamic resistance.

In summary, given spatially distributed land surface parameter values over subgrid scales, one can determine the effective land surface parameters at the grid-scale level by using the proposed aggregation scheme. Our proposed scheme ensures that the original land surface parameterizations that are developed over small scales (i.e., subgrid) are still valid at larger (i.e., grid) scales, and all the flux components and the surface energy balance equation are conserved or valid at larger scales.

3.1. SIMPLIFICATIONS OF OUR PROPOSED AGGREGATION SCHEME

Our proposed aggregation scheme (Scheme I) can be summarized as follows:

$$G = \sum_i a_i G_i \tag{18a}$$

$$\alpha = \sum_i a_i \alpha_i \tag{18b}$$

$$\epsilon_s = \sum_i a_i \epsilon_{s,i} \tag{18c}$$

$$T_s^4 = \sum_i \left(a_i \frac{\epsilon_{s,i}}{\epsilon_s} \right) T_{s,i}^4 \tag{18d}$$

$$\frac{1}{r_a} = \sum_i \left(a_i \frac{T_{s,i} - T_a}{T_s - T_a} \right) \frac{1}{r_{a,i}} \tag{18e}$$

$$\frac{1}{r_s + r_a} = \sum_i \left(a_i \frac{e^*(T_{s,i}) - e_a}{e^*(T_s) - e_a} \right) \frac{1}{r_{s,i} + r_{a,i}}. \tag{18f}$$

This aggregation scheme obeys the energy balance equation exactly and partitions the surface fluxes accurately at different scales. Notice, however, that this scheme requires information about atmospheric parameters (e.g., air temperature and air vapor pressure) to estimate aggregated surface parameters. To simplify the aggregation scheme, we assume that $\epsilon_{s,i}/\epsilon_s \simeq 1$ in (18d), $(T_{s,i} - T_a)/(T_s - T_a) \simeq 1$ in (18e), and $[e^*(T_{s,i}) - e_a]/[e^*(T_s) - e_a] \simeq 1$ in (18f). Scheme I (18a) –(18f) then reduces to another aggregation scheme (Scheme II):

$$G = \sum_i a_i G_i \tag{19a}$$

$$\alpha = \sum_i a_i \alpha_i \tag{19b}$$

$$\epsilon_s = \sum_i a_i \epsilon_{s,i} \tag{19c}$$

$$T_s^4 = \sum_i a_i T_{s,i}^4 \tag{19d}$$

$$\frac{1}{r_a} = \sum_i a_i \frac{1}{r_{a,i}} \tag{19e}$$

$$\frac{1}{r_s + r_a} = \sum_i a_i \frac{1}{r_{s,i} + r_{a,i}}. \tag{19f}$$

This simplified scheme is motivated by the need to eliminate the effects of atmospheric parameters (e.g., air temperature and air vapour pressure) and the compounding effects of surface parameters (e.g., $\epsilon_{s,i}$, ϵ_s, $T_{s,i}$, T_s, $e^*(T_{s,i})$ and $e^*(T_s)$) on the aggregation of surface temperature and aerodynamic and surface resistances. It is expected that the error introduced by assuming $\epsilon_{s,i}/\epsilon_s \simeq 1$, $(T_{s,i} - T_a)/(T_s - T_a) \simeq 1$ and $[e^*(T_{s,i}) - e_a]/[e^*(T_s) - e_a] \simeq 1$ will be large when the surface is very heterogeneous. We note that underlying assumptions related to Scheme II may not be very well justified for surfaces with very high degree of heterogeneity. As an approximation, however, especially when some of the desired surface parameters are not available (e.g., $\epsilon_{s,i}$), such a simplified scheme is easier to implement. For the estimation of surface fluxes, Scheme I is applicable even though it requires atmospheric parameters, because atmospheric parameters are necessary anyway for the calculation of surface sensible and latent heat fluxes.

Aggregation Scheme II is similar to that of Chehbouni et al. (1995) except for the formulation of aggregated temperature. Since we will compare and contrast results from our scheme to those of Chehbouni et al. (1995), we will summarize their aggregation scheme below:

$$T_s = \omega \sum_i \frac{a_i T_{s,i}}{\omega_i} \tag{20a}$$

$$\frac{1}{\omega} = \sum_i \frac{a_i}{\omega_i} \tag{20b}$$

$$\frac{1}{r_a + r_s} = \sum_i \frac{a_i}{r_{a,i} + r_{s,i}} \tag{20c}$$

$$\frac{1}{r_a} = \sum_i \frac{a_i}{r_{a,i}} \tag{20d}$$

$$G = \sum_i a_i G_i \tag{20e}$$

$$\alpha = \sum_i a_i \alpha_i \tag{20f}$$

$$\epsilon_s = \sum_i a_i \epsilon_{s,i}, \tag{20g}$$

where ω is defined by

$$\omega = 1/[1/r_0 + 1/r_a + s/\gamma(r_a + r_s)] \quad \text{(Lhomme, 1992)},$$

r_0 is a notional resistance to radiative transfer (Monteith, 1973)

$$r_0 = \rho C_p / 4\epsilon\sigma T_a^3,$$

and s is the slope of the saturated vapour pressure curve determined at the air temperature.

Our aggregated temperature is based on simple physical laws and is easily measurable through remote sensing. In contrast the aggregated temperature proposed by Chehbouni et al. (1995), although not a simple areally weighted average of component temperatures, cannot be easily measured and would require the knowledge of subgrid scale resistances. To summarize, Scheme I is the original aggregation scheme that guarantees conservation and partitioning of each surface flux and the energy balance equation. Scheme II eliminates the influence of atmospheric parameters on aggregated aerodynamic and surface resistances, and neglects the compounding heterogeneity effect of other surface parameters on the aggregated surface parameters.

4. Numerical Evaluation of Different Schemes and Assumptions

4.1. DIFFERENCE BETWEEN AREALLY WEIGHTED TEMPERATURE (AT) AND TEMPERATURE FROM AREALLY WEIGHTED ENERGY (ET)

In order to evaluate the difference between areally weighted average temperature (AT) and the aggregated temperature based on the Stefan–Boltzmann law (ET), we need some heterogeneous temperature fields. From (13) and (14), one could infer that the difference between ET and AT would depend on the distribution of surface temperature. Here, we use a normal distribution to generate heterogeneous temperature fields at subgrid scales. We use nine different land surface types within a grid. With $F(Z) = (1/\sqrt{2\pi}) \int_{-\infty}^{z} e^{-t^2/2}\,\mathrm{d}t$ and $f(x) = (1/\sqrt{2\pi})\, e^{-x^2/2}$, Table I shows nine levels of discretization corresponding to nine different land surface types and their relative areas.

In Table I, we discretize the cumulative normal distribution function into nine levels and then find the values of Z_i that will be used to generate surface temper-

TABLE I

Discretization of normal distribution.

Level	1	2	3	4	5	6	7	8	9
$F(Z_i)$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Z_i	−1.285	−0.875	−0.525	−255	0.0	0.255	0.525	0.875	1.285
$f(Z_i)$	0.1747	0.2721	0.3476	0.3862	0.3989	0.3862	0.3476	0.2721	0.1747
a_i	0.063	0.099	0.126	0.140	0.144	0.140	0.126	0.099	0.063

TABLE II

Temperature (K) for nine surface types over eleven grids.

σ	Surface type	1	2	3	4	5	6	7	8	9
0	Grid 1	298.16	298.16	298.16	298.16	298.16	298.16	298.16	298.16	298.16
2	Grid 2	295.59	296.41	297.11	297.65	298.16	298.67	299.21	299.91	300.73
4	Grid 3	293.12	294.66	296.06	297.14	298.16	299.18	300.26	301.66	303.30
6	Grid 4	290.45	292.91	295.01	296.63	298.16	299.69	301.31	303.41	305.87
8	Grid 5	287.88	291.16	293.96	296.12	298.16	300.20	302.36	305.16	308.44
10	Grid 6	285.31	289.41	292.91	295.61	298.16	300.71	303.41	306.91	311.01
12	Grid 7	282.74	287.66	291.86	295.10	298.16	301.22	304.46	308.66	313.58
14	Grid 8	280.17	285.91	290.81	294.59	298.16	301.73	305.61	310.41	316.15
16	Grid 9	277.60	284.16	289.76	294.08	298.16	302.24	306.56	312.16	318.72
18	Grid 10	275.03	282.41	288.71	293.57	298.16	302.75	307.61	313.91	321.29
20	Grid 11	272.46	280.66	287.66	293.06	298.16	303.26	308.66	315.66	323.86

ature. From the Z_i values and probability density function, we get the corresponding relative area of each subgrid land surface type, a_i. The temperature T_i is related to the Z_i by $T_i = Z_i\sigma + \mu$. Now, by specifying the population standard deviation and the mean, we can generate a set of surface temperatures that will represent subgrid-scale heterogeneity. We use eleven different standard deviations to reflect different strengths of surface temperature heterogeneity. By setting standard deviation at 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, we have eleven grids of temperature fields with each grid consisting of nine land surface types (Table II). Here, we set μ = 298.16 K; as we will show later the influence of different μ is not significant on the difference between AT and ET. Each grid corresponds to one level of standard deviation; variability increases with increasing grid number implying that Grid 1 is homogeneous while Grid 11 is the most heterogeneous.

TABLE III

Sample standard deviation and mean temperature (K) for different grids.

Grid #	Mean	Sample standard deviation	Population standard deviation
1	298.16	0.0	0
2	298.16	1.3376	2
3	298.16	2.6753	4
4	298.16	4.0129	6
5	298.16	5.3505	8
6	298.16	6.6881	10
7	298.16	8.0258	12
8	298.16	9.3634	14
9	298.16	10.7010	16
10	298.16	12.0387	18
11	298.16	13.3763	20

In Table III, the mean is the same for the sample and the population but the sample standard deviation is smaller than population standard deviation except for Grid 1. This is because some level of averaging has already been done due to the discretization.

With these heterogeneous distributions of temperature, Figure 1 plots the difference between the ET and AT as a function of sample standard deviation. As the sample standard deviation increases, ET minus AT also increases. For a sample standard deviation of about 10 K in our Grid 9 example, the maximum temperature minus the minimum temperature is 41.12 K for the nine land surface types. Based on observations over a typical grid, the standard deviation is around 10 K or smaller (Garratt and Prata, 1996). Then, ET minus AT will be less than 1 K. One can also notice that the effect of mean temperature on the difference between ET and AT is small.

The above results are based on a normally distributed subgrid-scale variability with nine different surface types. Three other distributions for subgrid-scale heterogeneity are also used to evaluate the difference between the two aggregated temperatures (Table IV). Now, if we keep the values of the nine subgrid-scale temperatures the same but change the relative area of each contributing surface type according to distributions in Table IV, the sample mean and standard deviation will be different from those of Table III. However, for the same level of standard deviation, ET minus AT remains the same. This result implies that the distribution

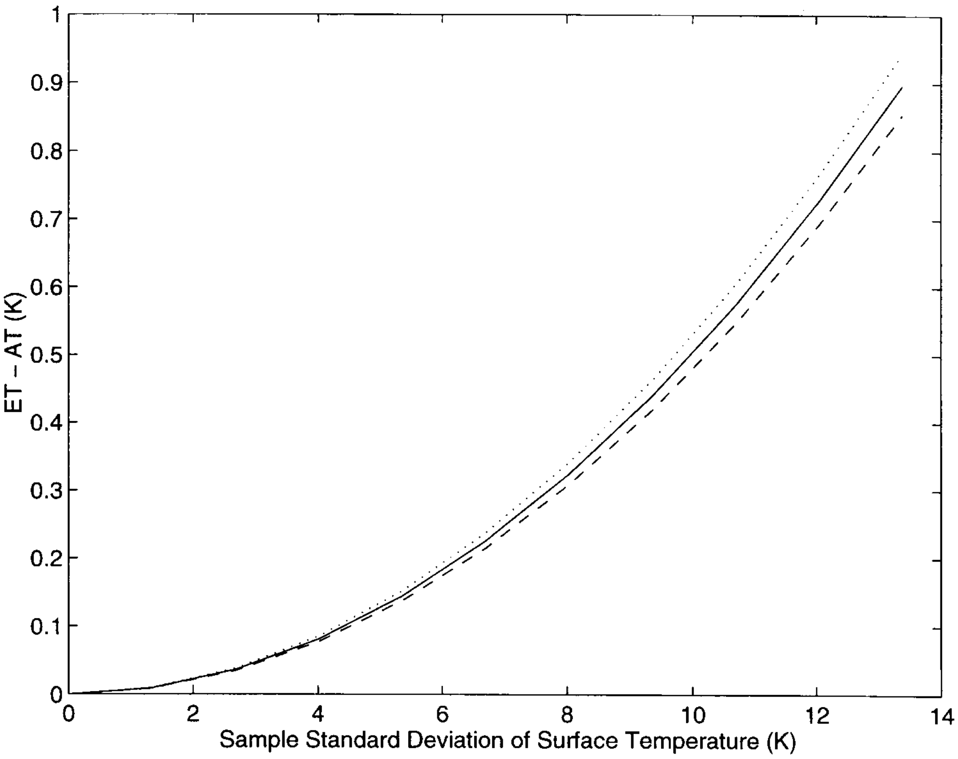

Figure 1. Difference between areally weighted average temperature (AT) and temperature from the areally weighted energy (ET) depends on the strength of the surface temperature heterogeneity (e.g., sample standard deviation). Solid line is for the average temperature of 298.16 K; dotted line is for 283.16 K and dashed line is for 313.16 K. The influence of the average temperature in a grid is not significant.

of relative area has no influence on the difference between ET and AT. Thus, the difference between ET and AT is usually less than 1 K. From this, we can conclude that we can use areally weighted surface temperature in the estimation of surface radiation energy and the error introduced will be small. However, a small error in the effective temperature estimation can result in a large error for the estimation of grid-level sensible and latent heat fluxes since these fluxes are quite sensitive to the surface temperature. For example, if the difference between ET and the air temperature is 4 K and the difference between ET and AT is 1 K, keeping all other variables the same, one would make an error of 25% in the estimation of sensible heat flux by using areally weighted temperature. This suggests that the effective surface temperature be estimated by using the areally weighted energy method (10) rather than areally weighted temperature. The computation for our effective temperature is slightly more complicated than for the areally weighted temperature. However, we hope the advantages we gained with accurate effective temperature and accurate grid flux estimations outweigh this inconvenience, because the use of

TABLE IV

Other distributions for the relative area a_i.

Surface type	1	2	3	4	5	6	7	8	9
Left skewness	0.063	0.130	0.144	0.140	0.130	0.122	0.110	0.098	0.063
Right skewness	0.063	0.098	0.110	0.122	0.130	0.140	0.144	0.130	0.063
Uniform	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9

TABLE V

Summary of surface types (case number) and parameters used in the simulations. Here α is the surface albedo; ϵ is the surface emissivity; z_0 is the roughness length (m); r_R is the reference stomatal resistance (s m^{-1}); and T_s is the surface temperature (°C). Subscripts 1 and 2 refer to the values for the two surface types in each case. (Adopted from Chehbouni et al., 1995.)

Surface types	Case no.	α_1/α_2	ϵ_1/ϵ_2	z_{0_1}/z_{0_2}	r_{R_1}/r_{R_2}	T_{s_1}/T_{s_2}
Crop/tree	Case 1	0.15/0.15	0.99/0.98	0.25/0.4	350/500	30/26
Forest/soil	Case 2	0.15/0.25	0.98/0.95	0.7/0.02	350/550	35/40
Shrubs/desert	Case 3	0.20/0.30	0.97/0.94	0.25/0.01	500/10000	40/50
Water/soil	Case 4	0.05/0.25	0.96/0.96	0.001/0.05	0/300	25/35
Grass/crop	Case 5	0.20/0.18	0.97/0.98	0.35/0.35	350/150	34/35

ET ensures an accurate estimation of sensible, latent and radiation fluxes from the surface.

4.2. NUMERICAL EVALUATION OF DIFFERENT SCHEMES

To compare and contrast our proposed scheme (Scheme I) and its simplification (Scheme II) with an existing scheme, Scheme C of Chehbouni et al. (1995), described in Equations (20a)–(20g), we will use a simulated set of heterogeneous land surfaces used by Chehbouni et al. (1995). Each simulated surface has two elements with contrasting surface albedo, surface emissivity, roughness length, reference stomatal resistance, and surface temperature, and there are five cases shown in Table V. For each case, the relative area covered by each surface type is varied between fractional cover of 0.20, 0.40, 0.50, 0.60, and 0.80. As a result, there are 25 different experiment settings. These surface types and associated parameter values are chosen from Chehbouni et al. (1995) to provide a unified framework for comparison. Atmospheric parameters – wind speed, air temperature, vapour pressure, and incoming shortwave radiation – for this study, similar to Chehbouni et al. (1995), are assumed to be constant over the study area (Table VI).

TABLE VI

Summary of environmental conditions used in the simulations. Here R_s is the incoming shortwave radiation (W m^{-2}); e_a is the vapour pressure (hPa); T_a is the air temperature (°C); u_m is the wind speed (m s^{-1}). (Adopted from Chehbouni et al., 1995.)

Case	R_s	e_a	u_m	T_a
1	800	15	3.5	25
2	1000	12	2	30
3	1000	8	1.5	35
4	800	15	2.5	24
5	900	10	1.2	25

We will evaluate the effects of different aggregation schemes described by Equations (18a)–(18f) for Scheme I, (19a)–(19f) for Scheme II, and (20a)–(20g) for Scheme C on the computed sensible and latent heat fluxes for five different combinations of heterogeneous surface as described in Table V. Fluxes estimated using a particular aggregation scheme will be referred to as ‘effective’ fluxes. Effective fluxes will be compared with the ‘composite’ fluxes defined as the area average fluxes computed from each component surface element. An implicit assumption here is that the composite fluxes may be considered to be the ‘true’ fluxes. Clearly, there is no objective way to verify the implication of this assumption. Nevertheless, this provides a uniform framework to compare different aggregation schemes. For each of the three aggregation schemes (I, II and C), the difference between aggregated surface temperature and the composite surface temperature is calculated. The percentage differences between the composite (F_c) and effective (F_e) surface fluxes are estimated as, PD = $[((F_c - F_e)/F_c) \times 100]$. For each surface type combinations, average percentage differences are obtained by averaging the individual percentage difference for each value of fractional cover.

Figures 2–4 compare the aggregated surface temperature estimated by Schemes I, II and C with that of the composite surface temperature. Our Schemes I and II produce smaller error compared to those of Scheme C of Chehbouni et al. (1995). Although we use composite surface temperature as the true surface temperature, because of the physical soundness of surface temperature aggregation from our Scheme I, it is likely that the surface temperature aggregated by Equation (18d) is closer to the ‘true’ effective surface temperature.

Figure 5 compares average percentage difference in latent heat flux among three aggregation schemes for the five surface type combinations. Our proposed scheme (Scheme I) exactly reproduces composite fluxes and hence the percent difference for this scheme is zero for all surface type combinations. For other schemes, there

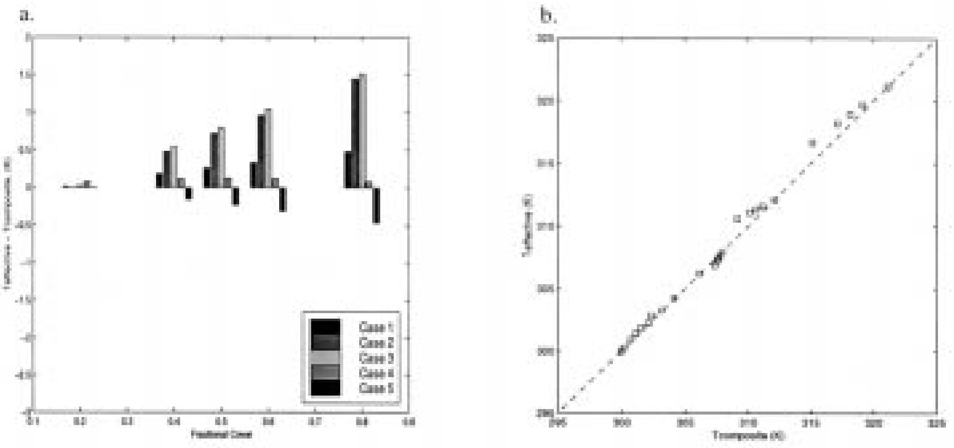

Figure 2. (a) Difference between effective (estimated using Scheme I) and composite temperature for five combinations of surface types (cases 1–5, see Table V for a detailed description), as a function of fractional cover; (b) Scatter plot for the effective and composite temperature in Figure 2(a).

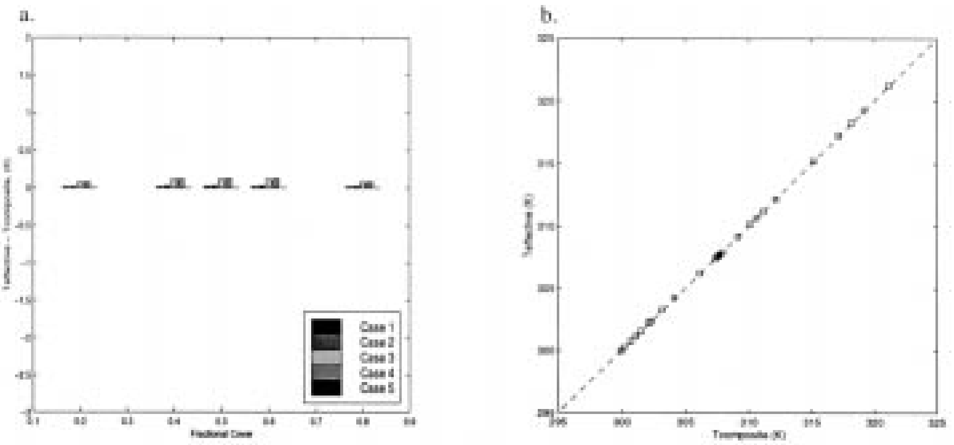

Figure 3. Similar to Figure 2 but for Scheme II.

is a dependence of performance for different combination of surface types. For example, our simplified scheme (Scheme II) is comparable to or better than Scheme C of Chehbouni et al. (1995) for all surface combination types except case 3. For case 3, Scheme C has a lower percentage error than our simplified Scheme II. For sensible heat fluxes (Figure 6), on the other hand, Scheme C performs better than our simplified Schemes II. Our proposed scheme (Scheme I), however, reproduces composite sensible heat flux exactly.

It would be rather difficult to generalize any inference based on this limited set of numerical experiments. Nevertheless, based on these numerical results one could argue that performance of our simplified Scheme II and Scheme C of Chehbouni et al. (1995) are comparable. A close comparison of Scheme C and II shows that

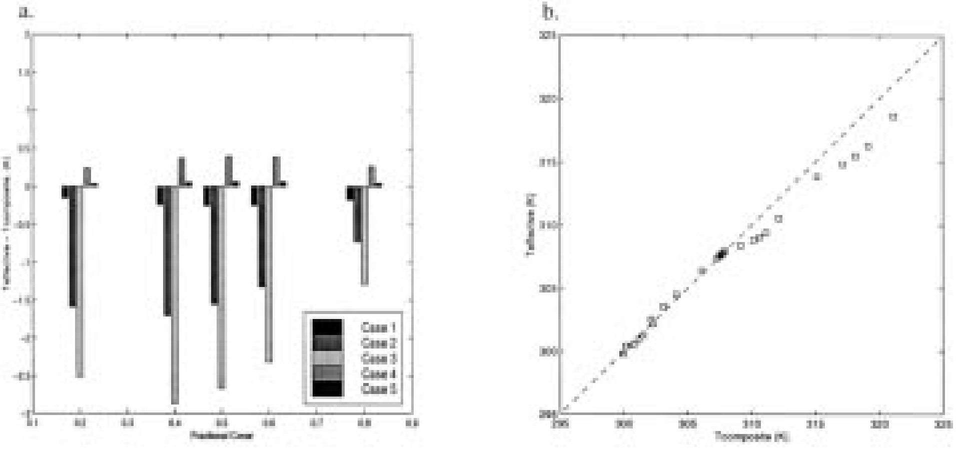

Figure 4. Similar to Figure 2 but for Scheme C.

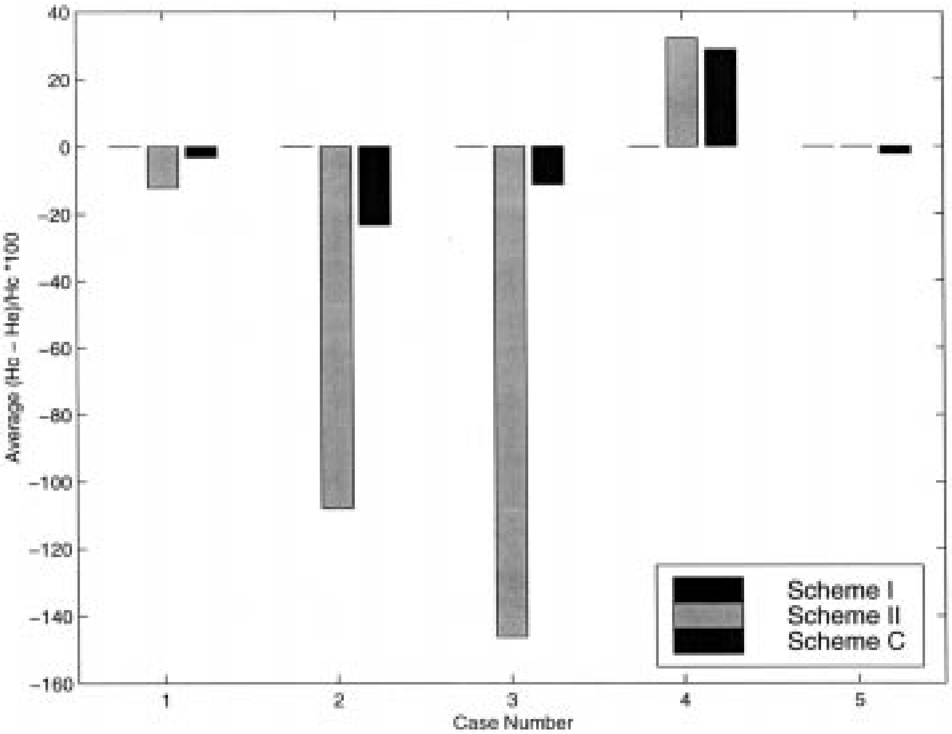

Figure 5. Comparison of average percentage difference from the composite flux for the four aggregation schemes (proposed Scheme I and its simplification II and Scheme C of Chehbouni et al. (1995)) for latent heat flux.

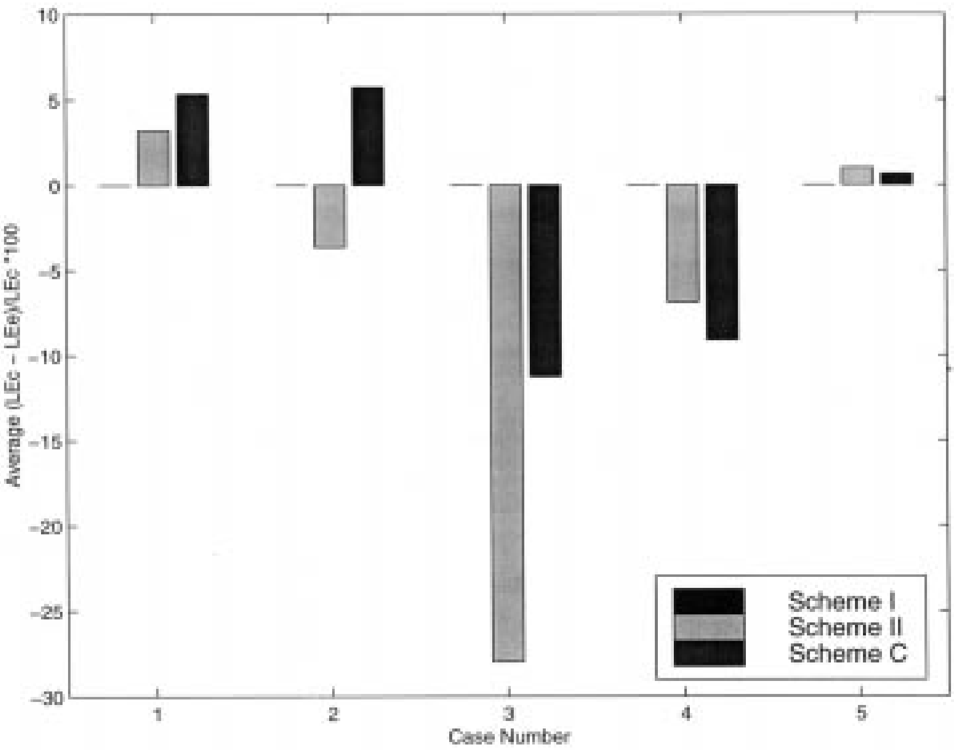

Figure 6. Similar to Figure 5 but for sensible heat flux.

the ground heat flux, albedo, and surface emissivity are the same. The aerodynamic and surface resistances in Chehbouni et al. (1995) can be derived using our proposed scheme with an additional assumption that the surface temperature and vapour pressure are homogeneous. Only the effective surface temperature is entirely different. For practical implementation, our simplified Scheme II may be more desirable because of the ease it provides for the aggregation of temperature from remote sensing measurements.

5. Concluding Remarks

A method has been developed to obtain a unique set of effective parameters that can be used as inputs to large scale models. The effective surface parameters derived here produce an accurate representation of surface fluxes over a heterogeneous surface. The proposed scheme not only ensures the validity of energy balance equation at the grid and subgrid scales, it also guarantees an accurate partitioning of fluxes at different scales.

Previous aggregation schemes fail to preserve either the energy balance or the partitioning among the surface fluxes. Term-by-term matching methodology and numerical errors introduced by the linearization of the surface radiation flux and surface-air vapour pressure difference might contribute to the problems inherent to previous aggregation schemes. As pointed out by Chehbouni et al. (1995), term-by-term matching methodology does not guarantee a unique set of expressions for the effective parameters. Linearizations of the surface radiation flux and surface-air vapour pressure difference with respect to the air temperature and combination with the sensible heat flux in the energy balance equation lead to the partitioning problem among the surface radiation, sensible and latent heat fluxes. Furthermore, incautious use of term-by-term matching methodology leads to aggregation schemes that provide multiple solutions for the same effective parameter. Since most previous schemes used term-by-term matching methodology, or linearizations of the surface radiation flux and the surface-air vapour pressure difference, caution should be taken when using those aggregation schemes.

Our original scheme (Scheme I), on the other hand, circumvents the above mentioned problems and provides a unique set of effective parameters that can be obtained from small-scale measurements and can be used as inputs to large scale models. We note, however, this scheme requires atmospheric parameters and involves compounding effects of related surface parameters. Two simplified schemes are presented to overcome these difficulties. A numerical evaluation of our proposed scheme and its simplifications suggests that our simplified Scheme II is comparable to Scheme C of Chehbouni et al. (1995). Scheme II may be more desirable for operational purposes because of the ease it provides for the aggregation of temperature from remote sensing measurements. Accuracy of these simplified schemes, however, needs to be further tested and validated using observational data. We must emphasize, however, that to keep the analytical approach tractable and simple, we have made at least two major assumptions: (i) surface heterogeneity is taken to be disorganized such that near-surface atmospheric conditions can be assumed to be horizontally homogeneous, and (ii) neglect the contributions of interactions at the subgrid level associated with lateral advection and lateral redistribution of soil moisture in the subsurface.

Our assumption of disorganized surface heterogeneity and associated homogeneous near-surface atmospheric conditions have been a focus of several recent studies (e.g., Wieringa, 1986; Mason, 1988; Claussen, 1991; Blyth et al., 1993; Claussen, 1995a, b; von Salzen, 1996; Grotzner et al., 1996). In these studies the concept of blending height – a scale height for a heterogeneous surface above which the atmospheric flow does not depend on surface features – is intensively studied using observational data analysis and numerical simulations. The blending height concept has been incorporated in various numerical studies to account for the effects of surface heterogeneity (Claussen, 1991; Blyth et al., 1993; Claussen, 1995a, b; von Salzen, 1996; Grotzner et al., 1996). The concept of the blending height is applicable when the scale of surface heterogeneity is small (a few kilometres) and the lower atmosphere is not in unstable conditions. Grotzner et al. (1996) argued that when the scale of the heterogeneity gets larger, and the lower atmosphere is in more unstable conditions, the blending height will be in the troposphere above the convective boundary layer. Then the similarity law for the flux estimation will not be applicable. A detailed review of the blending height concept and its application to characterize the effect of surface heterogeneity may be found in Raupach and Finnigan (1995) and references therein. If the conditions for blending height assumptions are met, our proposed approach would provide an efficient estimation method for aggregating heterogeneous surface parameters and fluxes.

As the blending height is determined by ensuring a dynamical balance between horizontal advection and vertical flux divergence, it is expected that effects of advection will be reflected in the weights associated with individual subgrid-scale surface elements. Recently, Bunzli and Schmid (1998) have shown that if the blending height is estimated accurately then areally-averaged surface fluxes can be estimated reasonably well without explicitly considering the effects of lateral advection. We also note that with significant heterogeneity in topography, there can be appreciable redistribution of soil moisture such that the valley bottoms would evaporate at nearly the potential rate whereas evaporation would be very low elsewhere. In such cases, a more detailed latent heat flux parameterization must be used to characterize the effects of heterogeneity. Nevertheless, our proposed approach would be applicable to estimate aggregation errors from such detailed parameterization as well.

Another caveat we must acknowledge here is that we have used a quadratic objective function to obtain a set of effective parameters. This implicitly assumes that errors in latent, sensible, and ground heat fluxes are equally weighted. It is possible to redefine the quadratic objective function in terms of a weighted least square scheme. With our current state of knowledge about land surface parameters and their interdependence, we feel more empiricism needs to be introduced if we were to adopt a weighted least square scheme. Finally, we hope our proposed scheme and its simplifications would provide a forum for continued investigation and future refinements of aggregation schemes for climate and mesoscale models.

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