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Realisability constraints for land-surface schemes

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Abstract

It is well known that turbulent transfer models can sometimes produce results that cannot be realised in nature. In this paper we develop simple rules to check the physical robustness of parameterisations of land-surface turbulent transfer for heterogeneous surfaces. The methodology draws upon areal-averaging by parameter aggregation and by flux aggregation. Both techniques have been demonstrated to be valid. Combining the two techniques enables one to determine the surface potential temperature and specific humidity, averaged over the grid-box. When this is done the implied turbulent transfer is sometimes counter-gradient. The implications of this result are discussed. The methodology presented is general and provides a complementary way of evaluating the role of coupling land-surface schemes to atmospheric host models to that presented by Polcher et al. [Polcher, J., McAvaney, B., Gaertner, M.-A., Hahmann, A., Noilhan, J., Phillips, T., Pitman, A., Schlosser, A., Schulz, J.-P., Timbal, B., Verseghy, D., Viterbo, P., Xue, Y., 1998. A proposal for a general interface between land-surface schemes and general circulation models. Global Planet. Change, this issue.]. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) has focused attention on the important role land-surface schemes play in general circulation and mesoscale models of the atmosphere. In an attempt to unify the modelling effort in PILPS Phase 4, Polcher et al. (1998) describe a generalised method of coupling a land-surface scheme to a host model. The primary emphasis of Polcher et al. is on the details of the numerics and the coding. The present paper is complementary to the work of Polcher et al. as it addresses some of the potential limitations of the underlying physics of turbulent transfer over complex surfaces.

Elsewhere in this issue, the predictions of particular schemes are compared (inter-model comparisons) and in some cases, the performance of the schemes is compared against observations. Our intention, however, is to take a different approach. Our aim is to develop a methodology to evaluate land-surface parameterisation schemes based on general principles of physical realisability, that is whether or not particular outcomes can occur in nature. The ideas that we will develop below are suitable for the evaluation of the coupling methodologies of PILPS Phase 4 (for models both at the regional and global scales). We have chosen to illustrate the procedure with one of

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the land-surface schemes used in PILPS, but have not undertaken to perform the evaluation of a range of schemes; this we leave for other PILPS participants. The coupling methodology that we employ is termed 'explicit' coupling by Polcher et al. (1998).

Our task will be to develop some theoretical generalisations that apply to heterogeneous surface-vegetation–atmosphere-transfer models. The heterogeneity of the surface and the turbulent nature of the flow greatly complicate the problem. It is well known that turbulent transfer models sometimes can produce results that cannot be realised in nature (see for example, Schumann (1977), Du Vachat (1978), Yamada (1986), Galperin et al. (1988)). In our note we will identify several constraints for realisability. If these constraints are violated then one needs to carefully examine the way in which the parameterisation is done.

Difficulties in parameterisations can arise when linear averages are used to determine grid-box averages of parameters such as roughness length z_0 or variables such as surface temperature T_0. When large differences exist in the heterogeneity of the surfaces over the grid-box, the resulting averaging process over the grid-box is inherently nonlinear and simple direct linear methods are inadequate. Stössel and Claussen (1993) describe an extreme example of this where both ocean and rough sea ice exist within the grid-box. Most of the ideas to be presented are implicit in the discussion of flow over heterogeneous surfaces by Mason (1988), Claussen (1991), Stössel and Claussen (1993) and Hess and McAvaney (1997).

2. Methodology

The methodology is described in Hess and McAvaney (1997), but for completeness, will be briefly outlined here. Three approaches for calculating the transfer of momentum, heat and moisture from a grid-box (composed of heterogeneous surfaces) to the atmosphere have been suggested: (a) 'parameter aggregation', where grid-box mean parameters such as roughness length, albedo, leaf-area index, stomatal resistance, soil conductivity, etc., are derived in a manner which attempts to best incorporate the combined nonlinear effects of each of the different relatively homogeneous subregions ('tiles') over the grid-box; (b) 'flux aggregation', where the fluxes are averaged over the grid-box, using a weighted average with the weights determined by the area covered by each tile; and (c) a combination of the flux aggregation and parameter aggregation methods. A homogeneous surface over the grid-box can be treated as (a) or (b) [Claussen (1991, 1995) provides further discussion on these techniques.]

In the following we use angular brackets to indicate an average over the grid-box. In approach (a) (parameter aggregation) the mean sensible heat flux $\langle H_0 \rangle$ and latent heat flux $\lambda\langle E_0 \rangle$ calculated over the grid-box, where λ is the latent heat of vaporisation, are found by assuming aerodynamic bulk transfer:

$$\langle H_0 \rangle = \rho c_p U_1 C_\mathrm{H}\left[\langle \mathrm{Ri_b} \rangle, \frac{(z_1 - \langle d \rangle)}{\langle z_0 \rangle}, \frac{(z_1 - \langle d \rangle)}{\langle z_\mathrm{H} \rangle}\right](\langle \Theta_0 \rangle - \Theta_1) \tag{1}$$

$$\lambda\langle E_0 \rangle = \lambda \rho U_1 C_\mathrm{H}\left[\langle \mathrm{Ri_b} \rangle, \frac{(z_1 - \langle d \rangle)}{\langle z_0 \rangle}, \frac{(z_1 - \langle d \rangle)}{\langle z_\mathrm{H} \rangle}\right](\langle Q_0 \rangle - Q_1) \tag{2}$$

where ρ is the air density, U_1 the horizontal wind speed, C_H the bulk transfer coefficient for heat, $\mathrm{Ri_b}$ the bulk Richardson number, z_1 the height of the atmospheric lowest model level, z_0 and z_H the roughness lengths for momentum and heat, respectively, d the zero-plane displacement length, Θ the potential temperature and Q the specific humidity, and c_p the specific heat of air at constant pressure. The subscript 1 indicates the lowest atmospheric model level and the subscript 0 indicates the surface.

The parameter aggregation method (which creates an 'effective' homogeneous surface) is physically realisable as long as the gradients [$(\langle \Theta_0 \rangle - \Theta_1)$ and $(\langle Q_0 \rangle - Q_1)$] that result from the aggregation have the same sign as the fluxes [$\langle H_0 \rangle$ and $\lambda\langle E_0 \rangle$], respectively. This is a basic assumption of the bulk transfer formulation: the fluxes are determined by gradients ($\langle H_0 \rangle$ and $\lambda\langle E_0 \rangle$ are determined from Eqs. (1) and (2) after $\langle \Theta_0 \rangle$ is found by solving the surface energy equation and $\langle Q_0 \rangle$ is found by relating surface behaviour to a saturated surface).

If the surface fluxes are aggregated (approach (b)), then the mean sensible and latent heat fluxes are given by (see, for example, Claussen, 1991):

$$\langle H_0 \rangle = \rho c_p U_1 \sum_i f_i C_{\mathrm{H}i} \left[\mathrm{Ri}_{\mathrm{b}i}, \frac{(z_1 - d_i)}{z_{0i}}, \frac{(z_1 - d_i)}{z_{\mathrm{H}i}} \right] (\Theta_{0i} - \Theta_1) \tag{3}$$

$$\lambda \langle E_0 \rangle = \lambda \rho U_1 \sum_i f_i C_{\mathrm{H}i} \left[\mathrm{Ri}_{\mathrm{b}i}, \frac{(z_1 - d_i)}{z_{0i}}, \frac{(z_1 - d_i)}{z_{\mathrm{H}i}} \right] (Q_{0i} - Q_1) \tag{4}$$

where f_i is the fractional cover for surface type (tile) i.

When flux aggregation (method (b) above) is used or the methods of parameter aggregation and flux aggregation are combined (method (c) above), certain anomalies can arise (see the discussion of the 'Schmidt paradox' by Lettau, 1979; Claussen, 1991 for example). Small regions of strong turbulence in unstable conditions can dominate the grid-area averaged fluxes, but have less effect on the vertical mean value of the gradient between the surface and the lowest model level. This leads to a situation of counter-gradient transport and a conflict between method (a) and methods (b) and (c). Whether or not counter-gradient heat transfer leads to numerical problems depends on how the numerics are done. If a negative eddy diffusivity is used, then parabolic differential equations like the diffusion equation lead to singular solutions (Lamb and Durran, 1978). In some models the negative diffusivity is not actually used, but only implied from diagnostic grid-box averaged surface values. In this case the numerics are stable, but the physics of the counter-gradient relationship must still be accounted for.

These anomalies most frequently occur near neutral stability conditions. We have empirically found (using the BASE land-surface scheme, Desborough, 1997) that this situation of counter-gradient transport can be (mostly) avoided by requiring the wind speed to be equal to or greater than 0.25 m s^{-1} to compute non-zero fluxes; when the absolute values of the grid-averaged fluxes are less than 1 W m^{-2}, the mean potential temperature or specific humidity gradient is set to zero. The chosen value of 1 W m^{-2} is typically much less than the model error. In summary then, when the magnitude of the (sensible or latent) heat flux is small, either because the wind speed is light or because the sum of the product of the bulk transfer coefficient times the gradient is small, counter-gradient transport may occur in Eqs. (3) and (4). These cases can be corrected empirically, thus avoiding negative eddy diffusivity coefficients.

Often, one wishes to compare model results with observations. Appropriate observations are obtained by remote sensing and averaged over the same spatial area (see Susskind, 1993, for example). Some modellers, e.g., Giorgi (1997), suggest specifying heterogeneous forcings of variables, such as surface potential temperature and specific humidity, by employing analytical probability density functions and determining the grid-box average of these variables through integration.

An alternative method, which we recommend, is to diagnose these variables from Eqs. (1) and (2), when the grid-averaged fluxes are known from Eqs. (3) and (4). However, to close this system of equations, it is necessary to introduce the associated parameter- and flux-aggregation equations for momentum:

$$\langle u_*^2 \rangle = \left[\frac{k}{\ln\left(\frac{(z_1 - \langle d \rangle)}{\langle z_0 \rangle} \right)} \right]^2 \times F_{\mathrm{m}} \left[\langle \mathrm{Ri}_{\mathrm{b}} \rangle, \frac{(z_1 - \langle d \rangle)}{\langle z_0 \rangle} \right] U_1^2 \tag{5}$$

$$\langle u_*^2 \rangle = \sum_i f_i \left[\frac{k}{\ln \frac{(z_1 - d_i)}{z_{0i}}} \right]^2 \times F_{\mathrm{m}} \left[\mathrm{Ri}_{\mathrm{b}i}, \frac{(z_1 - d_i)}{z_{0i}} \right] U_1^2 \tag{6}$$

and equations for effective roughness. The effective roughness for momentum (based on skin friction only), is found from:

$$\left[\ln\left(\frac{l_{\mathrm{b}}}{\langle z_0 \rangle} \right) \right]^{-2} = \sum_i f_i \left[\ln\left(\frac{l_{\mathrm{b}}}{z_{0i}} \right) \right]^{-2} \tag{7}$$

where l_b is the 'blending height', that is, the height at which the air flow senses the blended influence from the whole grid-box [we take $l_b = 75$ m; for more detailed treatments, see Mason (1988) and Claussen (1991)]. The effective roughness length for heat $\langle z_H \rangle$ in Eqs. (1) and (2) is less certain. One estimate is given by Beljaars and Holtslag (1991):

$$\ln\left(\frac{l_b}{\langle z_H \rangle}\right) = \frac{\ln\left(\frac{l_b}{z_0}\right)\ln\left(\frac{l_b}{z_H}\right)}{\ln\left(\frac{l_b}{\langle z_0 \rangle}\right)} \tag{8}$$

where z_0 and z_H are the local values of the dominant surface cover.

The mean grid-averaged momentum flux is calculated from Eq. (6). If this value is substituted into Eq. (5) and the effective momentum roughness length is eliminated using Eq. (7), the resulting equation can be solved for $\langle \mathrm{Ri_b} \rangle$. The average zero-plane displacement length can be estimated on the basis of a weighted average over different tiles. The aggregated parameter version of the bulk transfer coefficient C_H can now be determined (since $\langle \mathrm{Ri_b} \rangle$, $\langle z_0 \rangle$, $\langle z_H \rangle$ and $\langle d \rangle$ are all known). Hence, the grid-average surface values of potential temperature (or temperature) and specific humidity can be found from Eqs. (1) and (2).

3. Discussion

Our experience while incorporating heterogeneous surfaces (land, ocean and sea ice) in a single grid-box with a simple 'bucket' scheme as well as with a more sophisticated land-surface scheme [BASE, Desborough, 1997] has led us to propose a number of physical realisability statements that flow from the development in the previous section.

(1) Momentum transfer should be included as an integral part of land-surface parameterisation schemes which aggregate fluxes. This information is needed to obtain grid-averaged surface values of potential temperature and specific humidity.

(2) In near-neutral conditions the sign of the grid-averaged fluxes may oppose the sign of the grid-averaged gradients (indicating counter-gradient transport). This poses a problem. It means the parameter aggregation method [method (a) above] and the flux aggregation method [methods (b) and (c) above] are no longer consistent with each other. The conflict between the fluxes and the gradients can be removed by applying empirical rules (based on the particular land-surface scheme employed). We found that restricting non-zero sensible and latent heat fluxes to conditions where the wind speed was greater than or equal to 0.25 m s^{-1} and limiting the absolute value of the fluxes to 1 W m^{-2} were necessary and sufficient conditions for our scheme.

(3) If the fluxes are aggregated and yet the signs of the fluxes and gradients oppose each other for large values of the fluxes (for example, under extreme conditions such as for flow over snow and trees; for conditions of dew formation; etc.), then one should carefully examine the formulation of the land-surface scheme. Averaging temperature over different tiles, rather than the sensible heat flux, can be a source of problems. The grid-averaged surface values of potential temperature and specific humidity are diagnosed from Eqs. (1) and (2), knowing the fluxes.

(4) If the latent heat flux is determined by a combination of resistance methods (by parameter aggregation of the stomatal resistance for example) and the sensible heat flux is found by flux aggregation, then the sign of the sensible heat flux and the potential temperature gradient should agree and the grid-averaged surface potential temperature is found from Eq. (1). But adding a stomatal resistance means that Eq. (2) is no longer applicable to the entire system. In this case a consistent surface value of the specific humidity is found by defining the Bowen ratio:

$$\beta = \frac{\langle H_0 \rangle}{\lambda \langle E_0 \rangle} = \frac{c_p(\Theta_1 - \langle \Theta_0 \rangle)}{\lambda(Q_1 - \langle Q_0 \rangle)} \tag{9}$$

Eq. (9) may be solved for $\langle Q_0 \rangle$ since all of the other variables are known.

(5) If both the sensible and latent heat fluxes are obtained by parameter aggregation, then Eqs. (1) and (2) ensure that the fluxes have the same sign as the gradients, because the gradients are determined first. The surface potential temperature is found by solving the surface energy balance. The surface specific humidity is found by relating the surface behaviour to a saturated surface. Although in principle, one should be able to carry out all of the necessary

calculations by parameter aggregation [see for example Mason, 1988; Wood and Mason, 1991], in practice there are limitations to this method. For example, the Schmidt paradox is a real phenomenon. The parameter aggregation method however is unable to model it (i.e., the gradients and the fluxes will always be of the same sign). In addition, there is another drawback to the method of parameter aggregation. This is the difficulty of defining the necessary aggregated parameters in circumstances where they are strongly varying. Especially troublesome are the soil heat conductivity (with both water and soil tiles present) and stomatal resistance (Claussen, 1995). The method of parameter aggregation works best when the surfaces within the grid-box are similar in their properties.

4. Conclusions

Turbulent transfer models can sometimes produce results that cannot be realised in nature. Our experience using a heterogeneous surface-vegetation–atmosphere scheme (including some independent analyses of model results used in PILPS Phase 3) has shown us that this can happen for land-surface interaction with the atmosphere. It is manifested by a counter-gradient flux over the grid-box when the fluxes are large. We suggest that, in the process of coupling a land-surface scheme to an atmospheric model, due attention be paid to the calculation of grid-box averaged surface potential temperature and specific humidity. Also, the momentum transfer needs to be included in the land-surface coupling in a manner which is consistent with the determination of the sensible and latent heat fluxes. The formulation of the parameterisation scheme should be checked very carefully in any case of failure of the realisability constraints suggested above. The methodology developed here, based on physics, is complementary to the unification of the numerics and coding of land-surface schemes presented by Polcher et al. (1998).

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