A proposal for a general interface between land-surface schemes and general circulation models

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Global & Planetary Change, 19 (1998) 261-276

Abstract

The aim of this paper is to propose a general interface for coupling general circulation models (GCMs) to land-surface schemes in order to achieve a plug compatibility between these complex models. As surface parameterizations included more processes they have moved from being subroutines to GCMs to independent schemes which can also be applied for other purposes. This evolution has raised the problem within climate modeling groups of coupling these schemes to GCMs in a simple and flexible way. The larger independence land-surface schemes have reached makes it possible to exchange them within the community which also calls for a general interface. This paper discusses the tasks land-surface schemes have to fulfill when coupled to a GCM after a review of the current state of the art and the likely future evolutions of both components. The numerical schemes used for the processes which couple the land-surfaces to the atmosphere are reviewed to ensure that the interface can be applied to all land-surface schemes and GCMs after only minor changes.

Keywords : PILPS, Land-surface schemes, general circulation models, coupling Land-surface schemes.

1 Introduction

A primary goal of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) (Henderson-Sellers et al., 1996) is to compare land surface schemes used in general circulation models. The first step was to evaluate the different schemes forced by the same atmospheric conditions (Phases 1 and 2). This type of inter-comparison does not take into account the atmospheric feedback which might reduce or increase the differences between schemes. In order to study the possible importance of this feedback all schemes have to be coupled to the same atmospheric model. This is the aim of phase 4 of PILPS, with phase 4a focussed towards general

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circulation models and 4b focussed towards regional numerical weather prediction models.

At this point in time, coupling a range of land surface schemes to one general circulation model is very labor intensive, due to two main problems. The first one is practical and is linked to the way the FORTRAN code is organized and how variables are managed by individual schemes. The second problem is more fundamental and is related to the fact that the different numerical schemes used to solve the surface energy balance equation require different atmospheric forcing at different time-steps. This difficulty could be overcome by imposing one numerical scheme and asking, for instance, the land surface scheme to provide the land surface fluxes or the parameters needed to compute them (e.g., the ratio between potential and actual evaporation, surface roughness, albedo). This solution raises an important problem, as changes to the numerical framework of the land surface scheme may have a strong impact on the behavior of the scheme. In all surface parameterizations the equations used have been formulated according to the numerical method chosen, or the numerics have been adapted to the equations. Imposing a single numerical framework could destroy this equilibrium and might require a major rewriting of the scheme and in some cases a reformulation of the algorithms employed. The turbulent mixing in the planetary boundary layer is the parameterization where this problem is most acute because its' main forcing is from the surface, the time-scales are very short and the processes are highly non-linear.

This calls for the "plug compatibility" of land surface schemes. Kalnay et al. (1989) discussed this issue for the physical parameterizations of general circulation models but in the present case these recommendations need to be extended to a complex subsystem. A general coupling interface for land-surface schemes will be different from the one used for oceans models in OASIS (Terray, 1994) as the time-scales are much shorter thus requiring surface processes to be solved within the time-stepping of the GCM. The flux coupler (Bryan et al., 1997) used at NCAR is another attempt to have one interface to all surfaces. It imposes a numerical scheme which might not be the best choice for in all cases, a severe limitations.

In the present note we would like to describe a method for easily coupling any land surface scheme (LSS) to a general circulation model (GCM) that can accommodate most (if not all) numerical schemes used for modeling surface processes. The first problem which has to be dealt with is to define clearly the tasks of a land surface scheme in order to choose the information which needs to be exchanged between the LSS and the GCM. This will be discussed in the first section. Then we will address the problems raised by coupling radiation and the vertical diffusion in a manner which is independent of the numerical schemes chosen in the GCM and the LSS. Finally it will be described where in the GCM this interface needs to be placed and which other steps can be taken to simplify the coupling.

2 Tasks of a land-surface scheme coupled to a GCM

This attempt to define a general interface between land-surface processes and the atmosphere will be limited to fluxes of energy (radiation, sensible and latent heat) and momentum. This restriction is motivated by the known importance of these fluxes for atmospheric processes (Polcher, 1997) but it should not present any difficulty to include, at a later stage, into such an interface the fluxes of passive tracers or chemical components. This will be required when LSSs close the carbon cycle in coupled ocean atmosphere models or when they provide the source terms for aerosols and chemical species.

Before defining the interface, the tasks of the LSS in determining the surface energy fluxes must be decided. In current GCMs the tasks of the LSS have evolved over time and they are not the same in all models. For instance, albedo calculations have been considered part of the radiation scheme in the past. The albedo computations have shifted towards the land surface scheme in more recent models (Chalita and Le Treut, 1994; Douville et al., 1995), following the recognition that albedo depends on fast surface processes, such as the presence of snow on vegetation. Thus some GCMs will include these calculations in the radiation scheme while others include them in the LSS. These differences are partly historical, as new developments in land-surface modeling had to be put into the older context of the GCM, avoiding costly rewriting of code. The coupling between the surface and the atmosphere has very often been guided by numerical and computational constraints rather than theoretical consideration on the physical system to be solved.

For this interface we will define the tasks of the LSS based on theoretical consideration on the closure of the atmospheric processes which interact with the surface. The LSS should provide the lower boundary conditions for all atmospheric processes but there are two ways of achieving this, the Neumann and the Dirichlet closures (Richter, 1978). In the former case the fluxes have to be given to the atmosphere, thus leading to more complex computations within the surface scheme than would be needed if only state variables were provided as is the case for the Dirichlet closure. In the cases discussed here, the Dirichlet and Neumann closures are equivalent from an analytical point of view but not in their numerical implementation. When the discretized equations are considered, both closures will induce discontinuities in the systems but at different locations. In some cases a mixed Dirichlet Neumann closure is also possible and leads to a simultaneous solving of the atmospheric processes and the surface conditions. Physical considerations on the role of the fluxes considered and the characteristic time-scales will allow us to decide which solution is best when modeling the interactions between the surface and the atmosphere. Once this is decided the role of the surface scheme will be well defined.

While defining the tasks of the LSS and its interface to the GCM attention will be paid to energy conservation. The number of operations needed on fluxes of energy will be held to a minimum, thus reducing the risk of errors on either side of the interface. We will also be guided by a set of more practical considerations :

- The interface should not place any restrictions on the numerical scheme used by the LSS or the GCM.
- Calculations relative to physical processes of the atmosphere should not be duplicated in the LSS
- Priority will be given to the parameterizations in the GCM.
- This definition should take into account, as far as possible, new developments in the modeling of the climatic system.

Their role is to ensure that the resulting interface is robust and easy to use.

In defining such a coupling scheme there is always the temptation for variables computed in the GCM, but which could also be recomputed in the LSS to postpone the issue and allow both solutions in the interface. This can be achieved by increasing the redundancy in the interface but at the cost of major problems in its practical use. The interface will be more complex, more difficult to use and increase the risk of errors. Thus an effort will be made to reduce redundancies.

The resulting interface will be just another compromise but perhaps one built on better theoretical grounds and which can be used to couple with a minimum of work and a maximum likelihood of success any GCM to any other LSS.

2.1 The energy balance equation

The surface energy balance equation is the major interaction point between the LSS and the GCM. Solving it is the most important component of any land-surface scheme as it closes the energy balance at the lower boundary of the atmosphere and determines the temperature of the surface with which the atmosphere is in contact. Implicitly it also defines the surface with which the atmosphere interacts. This definition differs between LSSs and can be the surface of the ground (a "layer" of infinitesimal thickness at the surface/atmosphere interface) or some level within the canopy. In the following no assumptions are made on this definition, thus ensuring the generality of the discussion. In this section we will try and define the interface by discussing the elements of this equation.

The surface energy balance equation may be written for a "layer" at the surface in contact with the atmosphere as:

$$C_s \frac{\partial \theta_s}{\partial t} = L_n + S_n + LE + H + G. \tag{1}$$

Here θ_s is the temperature representative of the surface "layer" (Hereafter surface temperature), and C_s the "layer" heat capacity per unit area. Note that the heat capacity may become very small as the thickness of the "layer" tends towards zero. L_n is net long-wave radiation at the surface, S_n net short-wave radiation at the surface, LE latent heat flux, H sensible heat flux and G the ground heat flux. All fluxes are positive downward. For each of these five fluxes we need to determine its relation to the atmosphere and which of its components need to be calculated by the land-surface scheme.

2.2 Ground heat flux

The ground heat flux and its underlying model is closely linked to the way the surface energy balance is solved. The choice of the equations used to represent the thermodynamics of the ground and/or the vegetation will determine the heat capacity and the physical meaning of the surface temperature. The only input needed to solve the ground model is the surface temperature. As a consequence the ground thermodynamics are internal to the land surface scheme and it does not need to be considered for the interface with the atmosphere.

2.3 Radiation

The radiation is the driving flux in the surface energy balance. The solar part of the spectrum is the forcing and the long-wave is in most situations a sink of energy. In the absence of moisture the surface temperature is dominated by the balance between these two radiative fluxes. Thus special attention has to be paid to them at the interface.

All radiation calculations are performed in the GCM but they need the surface conditions as a lower boundary condition. In the case of short-wave radiation the typical time-scale is faster than the variations of the boundary condition, thus a Dirichlet solution is well adapted. This is achieved by providing surface albedo to the radiation scheme which will then compute all fluxes and balance them at the surface. The LSS will expect in return the net short-wave flux from the GCM and the zenith angle. This last variable will be used to compute the next value of albedo. When, in the future, bi-directional reflectances are modeled in land-surface schemes this choice may have to be revisited. Reflection will not only depend on the zenith angle but also on the intensity of direct and diffuse light and thus will change at the time scale of the incoming flux.

As the long-wave radiation emitted from the surface is largely independent of the atmospheric conditions the Neumann and Dirichlet closures are equivalent. Thus the upward flux in the required spectral bands or an equivalent radiative temperature can be provided to the GCM . Traditionally this problem has been solved by providing the surface temperature to the radiation scheme because of practical considerations. Indeed this solution has the advantage of not requiring in the LSS any knowledge about the choice of spectral discretization made in the radiative code. For the down-welling radiation the flux is the best quantity to exchange as it is the result of the balance of fluxes computed in the radiative code at the lowest level of the GCM and it enters directly the surface energy balance equations 1.

Albedo, emissivity and surface radiative temperature are the quantities which are computed by the LSS while it will expect in return from the GCM net solar radiation, the zenith angle and down-welling long-wave radiation . A method of exchanging this information in such a way that it can be applied to any GCM is proposed in section 3.

2.4 Turbulent fluxes

The vertical turbulent diffusion in the lower layers of the atmosphere is strongly coupled to the surface processes which are the main source of energy. This link is formed by the latent, sensible heat and momentum fluxes at the surface. As the surface fluxes and the turbulent diffusion are very non-linear and share similar time-scales they will have the same time-step within a GCM thus simplifying the coupling. This time-scale however is usually shorter than the typical time-step in GCMs, thus great care has to be taken when choosing a numerical scheme for the turbulent fluxes.

As surface temperature is the result of the balance of fluxes and at the same time the turbulent fluxes have a strong dependence on this same temperature they need to be determined while solving equation 1, or at least be varied with the temperature change. Temperature and relative humidity from the lowest level of the GCM are also needed to compute the turbulent fluxes in equation 1 but their variations are generally slower than the surface conditions. Thus it appears that the vertical diffusion scheme is best closed with the two turbulent fluxes provided by the LSS. Some LSS will not use a Dirichlet closure for the turbulent fluxes in equation 1, but rather a mixed closure. As this choice has strong implications for the design of the LSS, a general interface should not restrict this diversity. On the other hand most vertical diffusion schemes already use surface fluxes as lower boundary conditions. This will be discussed in detail in section 4.

2.4.1 Modeling surface layer turbulence

An important component in the calculation of the turbulent surface fluxes is the diffusion coefficient, which depends on the surface roughness and on the stability of the lower layers of the atmosphere. The first component is within the domain of the land-surface scheme but varies only at a seasonal scale, while the second one is more atmospheric in nature and evolves rapidly.

Some LSS compute the diffusion coefficient, while in others the value is obtained from the vertical diffusion parameterization of the GCM. Both methods have their advantages which justifies that the interface should not exclude either one. On the other hand each one has problems which might affect the coupled system and should be controlled by the interface.

Because of the continuity of the turbulent surface fluxes and the vertical diffusion within the planetary boundary layer (PBL), allowing the LSS to compute its own diffusion coefficient risks losing the consistency of the diffusion coefficients. The parameterizations of the planetary boundary layer used in GCMs may be different from the one of the LSS. Thus if the LSS is allowed to compute its own diffusion coefficient, the mismatch with the GCM might affect the result. For instance, moisture or heat might accumulate in an unrealistic way at the lowest level only because the formulation of the surface layer produces a diffusion much too large for the PBL. But LSSs which solve the surface energy balance through iterations need to recompute the stability function included in the formulation of the surface transfer coefficient to improve convergence. This can only be done if the LSS has control over this formulation.

When the surface layer diffusion coefficients are computed by the GCM, modeling the heterogeneities at the surface is limited. The PBL scheme of the GCM only provides one diffusion coefficient per grid-box and more subtle methods are needed to propagate the surface heterogeneities into the surface layer and the PBL.

At present it is not possible to decide if one approach should be favored over the other and it is reasonable to allow for both solutions, but work is needed on this issue.

2.4.2 Momentum diffusion and orography

In the case where the LSS computes the surface layer transfer coefficient for latent and sensible heat fluxes, which are part of equation 1, one may wish it to calculate the momentum flux as well. This would then ensure the internal consistency of all surface transfer calculations. Including the momentum diffusion in the LSS raises the issue of the interaction of the orography with the flow for the LSS. Depending on the treatment of gravity wave drag within the GCM the momentum diffusion may have to take into account the form drag by modifying the roughness length or the stability. As this is still a topic of research, the interface could for the moment be restricted to providing the LSS with the orography from the GCM and returning the momentum diffusion coefficient of the surface layer.

The LSS can not be permitted to use its own orography or land/sea mask because it might induce inconsistencies in the coupled model. For instance, spectral models construct their orography in such a way that it is well behaved in the spectral transforms. This elevation map is used in the physical parameterizations of the GCM and thus has to be applied to the LSS as well.

2.5 Closing the hydrological cycle

So far only the exchange of variables which intervene in the calculation of the surface turbulent fluxes and energy balance have been discussed. To allow the surface scheme to close the water balance, it needs to be provided with precipitation. The distinction between snow and ice is a delicate issue here because it touches on the parameterization of clouds within the GCM and it may affect the conservation of energy in the coupled system.

Over the last few years, GCMs have started to simulate cloud liquid water and it has been recognized that the description of the water particles forming clouds are essential in order to compute the interaction with radiation. In order to distribute correctly within the atmosphere the energy of condensation, GCMs will have to determine where in the column snow or liquid precipitation is formed. Thus it seems reasonable to assume that precipitation schemes will in the not too distant future determine if snow, ice or water reaches the surface. In the design of the interface it has to be assumed that the GCM will provide at least rainfall and snowfall.

This raises the issue of a consistent use of latent heat of evaporation and sublimation by the GCM and the land surface scheme. To conserve energy in the coupled system GCM/LSS the same physical constants have to be used. This will easily be achieved if the GCM provides the LSS with all physical constants through the interface.

With the coming of age of coupled ocean/atmosphere models, LSS will have to include a river routing scheme and thus model the river outflow. The interface has thus to include the runoff of rivers into the ocean. This field is different from the grid-box runoff produced by LSSs as it will be non zero over ocean points along the coast. The grid-box runoff is internal to the land-surface scheme.

2.6 Sub-grid scale variability

The above discussion of a general interface also applies to schemes which consider a mosaic of surfaces within the grid-box of the GCM or use a delocalized physics (Vintzileos and Sadourny, 1997), as all tiles only view one set of atmospheric conditions. In the special case where the surface scheme uses a grid different from the one of the GCM, it will have to do the disaggregation, as it holds all the information needed.

More complex is the issue of the sub-grid scale variability of atmospheric forcings provided by the GCM. The special case of precipitation is discussed here as some models already take this aspect into account by distinguishing between stratiform and convective precipitation. This distinction is problematic, as it relies on distinctions between parameterizations of GCMs rather than physical quantities. Some GCMs do not produce these two types of precipitation but have a single parameterization which covers all cases.

A more physical solution would be to provide with precipitation an extra variable which for each grid box describes its distribution. This could be either the spatial variance of the field within the grid-box or the parameter to a spatial distribution function. In the case of variance we would have zero for the stratiform precipitation and some small value for convective rainfall. This choice has the advantage that the GCM has a finer control over the sub-grid scale variability assumed in the LSS. This approach could also be extended to other variables if needed. In the present situation we will choose the variance as it is the simplest description of the second momentum of the sub-grid scale distribution.

3 Coupling the radiation scheme

As explained in section 2.3, the land surface scheme of current GCMs should provide the radiation scheme with albedo, emissivity and surface radiative temperature as lower boundary conditions and receive in return the net short-wave flux, the zenith angle and the down-welling long-wave flux.

As the radiation parameterizations are computationally very expensive, their time-step is usually longer than the one used by the other components of the GCM. This contrasts to the LSS which uses the shortest time-step of the physical parameterizations as it is closely linked to the turbulent diffusion. Thus the LSS is called more often that the radiation scheme and special attention has to be paid at the interface to ensure conservation of energy.

It should be noted here that in the case where the radiation scheme uses the same time-step as the LSS another coupling method is possible. The long-wave flux balance can be solved with a mixed closure, thus coupling the surface energy balance equation to the radiation code. This approach will certainly result in a better simulation of the radiative cooling of the surface in regions where this process is dominant. However, only one model is known where this approach has been used; the version of the BMRC GCM coupled to the bucket scheme described in

McAvaney et al. (1978). Later this coupling was abandoned at BMRC because of its computational cost.

Most radiation schemes will require from the LSS albedos for direct and diffuse sunlight in the spectral band below and above $0.7\mu m$. In order to compute this, the land surface scheme will require the zenith angle, fraction of diffuse radiation and the incoming solar radiation. The latter will have to be computed by the LSS from the net solar radiation and the albedo it provided at the last call. The downward solar flux is only used to compute albedo and photosynthetically active radiation and may thus tolerate numerical approximations if needed. The same argument applies to the choice of fraction of diffuse short-wave radiation instead of a flux.

Priority is given to the net flux because it is the energy received by the surface as computed in the radiation scheme and it is used in the surface energy balance. This ensures energy conservation through the interface even with the different time-stepings. The LSS will receive the same net solar flux at each time-step between two calls to the radiation scheme. The radiation scheme may choose to use the last albedo provided by the LSS or the average of all values obtained since the last radiation time-step. The GCM has also the responsibility of providing the zenith angle for the next point in time to ensure a correct computation of albedo by the LSS for such critical situation as sunrise.

In the long-wave part of the spectrum the radiation scheme will provide incoming radiation at the surface. On the other hand it needs to receive from the LSS the emissivity to determine the fraction of this flux which will be reflected.

Providing a radiative temperature through the interface has practical advantages but also a few pitfalls. While solving the surface energy balance the land surface scheme can use a limited expansion of the surface temperature around its old value to obtain a value for the emitted radiation closer to the new temperature. For instance the upward long-wave flux ($L_\uparrow$) may be determined by :

$$L_\uparrow = \epsilon\sigma(\theta_s^t)^4 + 4\epsilon\sigma(\theta_s^t)^3(\theta_s^{t+1} - \theta_s^t) \tag{2}$$

where ϵ is surface emissivity and σ the Stefan-Boltzman constant. The benefits of this approach is to stabilize the numerical scheme used to solve equation 1 in situation where the long-wave radiation dominates the energy balance. The intermediate temperature used to determine the upward long-wave flux will be called the radiative temperature (T) and is defined by:

$$L_\uparrow = \epsilon\sigma T^4 \tag{3}$$

It needs to be recomputed once the surface energy balance is solved. As can easily be seen, without the Taylor expansion the radiative temperature is the surface temperature at time t. If this is not done energy will not be conserved in the coupled system as the GCM will receive a long-wave flux different from the one used in the LSS.

When the radiative temperature and the emissivity are passed to the radiation scheme, they have to be averaged over the time-steps at which the radiation is not called so that the mean flux emitted from the surface, as calculated by the LSS, is given to the radiation. This averaging has to be linear for the emissivity and in the 4th power of the radiative temperature. In order to perform this process on the fly we propose the following equations which yield the new averages ($\overline{X}^{n+1}$, n is the time-step at which radiative temperature is available between two calls to the radiation) from the mean over the previous time-steps and the new values:

$$\overline{\epsilon}^{n+1} = \frac{n\overline{\epsilon}^n + \epsilon}{n+1} \tag{4}$$

$$\overline{T^4}^{n+1} = \frac{1}{n+1}\left(n\frac{\overline{\epsilon}^n}{\overline{\epsilon}^{n+1}}\overline{T^4}^n + \frac{\epsilon}{\overline{\epsilon}^{n+1}}T^4\right) \tag{5}$$

Using $\overline{\epsilon}^{n+1}$ and $\overline{T^4}^{n+1}$ in the next call to the radiation scheme will ensure that the time-averaged balance of the long-wave radiative fluxes is conserved.

If the land surface scheme includes a sub-grid scale variability of the surface temperature it has to perform the same type of averaging to obtain a mean radiative temperature for the grid. It will also need to compute an averaged emissivity.

4 Coupling the land surface scheme to the vertical diffusion

In section 2.4 the turbulent surface fluxes have been identified as the quantities which should be provided to the vertical scheme as a lower boundary condition. To compute them, the LSS will need the atmospheric conditions at the previous time-step. Depending on the numerical scheme of the LSS it may also require other information from the atmosphere so that an equation can be written for the atmospheric conditions of the next time-step.

In the present section we will discuss the possibilities opened to LSSs for solving the surface energy balance and describe the methods currently in use. A knowledge about the methods used for solving the vertical turbulent diffusion is needed to appreciate the different couplings. In Appendix A the standard "explicit coefficient, implicit temperature" (Kalnay and Kanamitsu, 1988) method is presented for reference. In the following discussion only a local diffusion scheme is considered but it can be shown that the same equations can be written for a non-local scheme.

The numerical schemes used for solving equation 1 are discussed using its discretized formulation which integrates from θ_s^t to θ_s^{t+1}. The fluxes which make up the coupling to the vertical diffusion are then written as follows :

$$LE^{t+1} = L\rho C_h|\vec{V}|\beta(q_a^j - q_{sat}(\theta_s^i)) \tag{6}$$
$$H^{t+1} = \rho C_h|\vec{V}|(\theta_a^j - \theta_s^i). \tag{7}$$

Where i and j are time indices. It is only in these fluxes that the lowest level prognostic variables of the GCM come into play in the energy balance equation. To simplify the discussion we have chosen to use a "β-formulation" (Mahfouf and Noilhan, 1991) in the equations for the latent heat flux presented here. The reasoning can easily be extended to an "α-formulation" or bulk aerodynamic formulas which use resistances to control evaporation. Some LSSs use a threshold formulation for the latent heat flux, that is below a given flux or amount of available moisture the method for determining evaporation changes. We will point out in which numerical schemes this formulation cannot easily be implemented.

The choice of the time step at which the atmospheric variables in the sensible and latent heat fluxes are taken determines the type of coupling. It will also dictate the time in the GCM at which the surface energy balance has to be solved and the approximation that need to be made. In the following we will use a simple nomenclature for describing these schemes :

$i = t + 1, j = t + 1$ **:** Implicit coupling,

$i = t, j = t + 1$ **:** Semi-implicit coupling,

$i = t + 1, j = t$ **:** Explicit coupling.

$i = t, j = t$ **:** Open-explicit coupling.

The discussion in this section can also be applied to the coupling between the surface energy balance and the ground heat flux which is the result of a diffusion equation of the same type as the one used for the atmospheric PBL. As pointed out earlier, the ground heat flux is internal to the land-surface scheme and is thus irrelevant to the coupling with the atmosphere.

To simplify the equations in this section, we will not consider the surface temperature dependence of the emitted radiation in the net radiative flux (R_n). It is sufficient to say that the surface temperature at time-step t can be used, or with the help of a Taylor expansion and the value at $t+1$, an approximation of the emitted radiation at $t+1$ can be obtained. This topic is discussed in detail in section 3.

4.1 Implicit coupling

The aim of this method is to keep the atmospheric profiles of temperature and humidity and the surface conditions synchronous. This scheme has been used in most GCMs when they were coupled to the simple bucket model (Manabe, 1969). Only a few models have kept this method when they moved to more complex land surface schemes, among them are the LMD-GCM coupled to SECHIBA (Ducoudré et al., 1993) and the UKMO-GCM (Warrilow et al., 1986). Newly developed schemes have also adopted it; the ECMWF model (CY 48) (Viterbo and Beljaars, 1995) and ISBA coupled to ARPEGE (Mahfouf et al., 1995).

In order to implement this method, information on the dependence of the atmospheric conditions on the surface forcing is needed. As shown in appendix A the atmospheric variables can be given as functions of the surface conditions (see eq. 16) within the PBL. This information can be provided to the LSS by passing through the interface the coefficients $A_{X,1}$ and $B_{X,1}$. this introduces a much stronger coupling between the two systems. It means that the closure of equation 1 is transformed from a Dirichlet to a mixed boundary condition problem.

Applying this to the discretized version of equation 1 a fully implicit equation for the energy balance is obtained:

$$\begin{aligned}
C_s \frac{\theta_s^{t+1} - \theta_s^t}{\Delta t} &= R_n + G \\
&+ L\rho C_h |\vec{V}| \beta ((A_{q,1}^t q_{sat}(\theta_s^{t+1}) + B_{q,1}^t) - q_{sat}(\theta_s^{t+1})) \\
&+ \rho C_h |\vec{V}| ((A_{\theta,1}^t \theta_s^{t+1} + B_{\theta,1}^t) - \theta_s^{t+1}). \qquad (8)
\end{aligned}$$

As the saturated water-vapor mixing ratio is a nonlinear function of surface temperature, we need to replace it by its truncated expansion:

$$q_{sat}(\theta_s^{t+1}) = q_{sat}(\theta_s^t) + \left.\frac{\partial q_{sat}}{\partial \theta_s}\right|_{\theta_s^t} (\theta_s^{t+1} - \theta_s^t). \qquad (9)$$

Thus equation 8 can be solved and θ_s^{t+1} computed. During these steps we have implicitly computed the sensible and latent heat flux which need to be diagnosed from the new values of temperature and moisture at the surface and the first level. These fluxes can then be used to do the back-substitution which solves the vertical diffusion equations.

Besides its mathematical elegance and low computational cost, this method has the advantage of displaying numerical stability. In the case of constant transfer coefficients it can be shown to be unconditionally stable (Davies, 1983) else it is linearly stable (Kalnay and Kanamitsu, 1988). It conserves energy, as at any point in time the surface fluxes are coherent to the profiles of temperature and moisture in the atmosphere. The disadvantage of this method is that the solution of equation 8 may become very difficult as land surface schemes become more complex and include sub-grid scale variability. If a threshold method is used in the land surface scheme then equation 8 will have to be supplemented by a predictor-corrector method, which will make it computationally more expensive. This need arises from the fact that in equation 8 the fluxes are computed implicitly and thus no conditions can be applied while it is being solved.

In SECHIBA the coupling of the thermodynamical soil model to the surface energy balance is also accomplished with an implicit method leading to a closed set of equations which describe the diffusion from the top of the PBL to the bottom of the soil. In a similar way the equations for soil water transfer in the ECMWF scheme are solved with an implicit method from the surface throughout the entire soil column depth.

4.2 Semi-implicit coupling

This coupling scheme uses the surface temperature at the last time-step to close the vertical diffusion equations. It simplifies the solution of the surface energy balance equation, as surface temperature is obtained independently of the vertical diffusion scheme. This method is used by a few complex land surface schemes coupled to GCMs. We may cite the Blondin scheme in the ECMWF model (Blondin, 1988) and the ECHAM model (Dümenil and Todini, 1992).

As in the implicit scheme, the coefficient $A_{X,1}$ and $B_{X,1}$ need to be computed in order to solve equation 16 to obtain the new values at the first level. The simplification lies in the fact that instead of using θ_s^{t+1} the old surface temperature θ_s^t is used. The following equations are then used to compute the turbulent fluxes :

$$\begin{aligned} LE^{t+1} &= L\rho C_h|\vec{V}|\beta((A_{q,1}^t q_{sat}(\theta_s^t) + B_{q,1}^t) - q_{sat}(\theta_s^t)) \quad (10) \\ H^{t+1} &= \rho C_h|\vec{V}|((A_{\theta,1}^t \theta_s^t + B_{\theta,1}^t) - \theta_s^t). \quad (11) \end{aligned}$$

These fluxes are then given back to the vertical diffusion which computes the new temperature and humidity profiles.

The derivative of the new surface fluxes with respect to surface temperature are then used to solve the surface energy balance which yields the new surface conditions. Equation 1 is then discretized as :

$$C_s \frac{\theta_s^{t+1} - \theta_s^t}{\Delta t} = R_n - LE^{t+1} + \left.\frac{\partial LE}{\partial \theta_s}\right|_{\theta_s^t} (\theta_s^{t+1} - \theta_s^t) - H^{t+1} + \left.\frac{\partial H}{\partial \theta_s}\right|_{\theta_s^t} (\theta_s^{t+1} - \theta_s^t) - G. \quad (12)$$

As this step is usually done after the vertical diffusion parameterization is called, the surface fluxes which correspond to the new surface temperature are different from those received by the atmosphere (eq. 10, 11). To avoid an energy imbalance, this difference has to taken into account in the temperature calculation of the next time step. By design, the semi-implicit coupling only allows for surface temperature changes to feed back to the atmosphere at the next time step.

As the coupling scheme proposed here only requires one call to the land surface parameterization, the new surface temperature will have to be computed just after the surface fluxes. This opens the possibility for the schemes using the semi-implicit coupling to reduce the problem of energy conservation. If a threshold formulation is used for evaporation, equation 12 cannot be solved in the general case. The discontinuity introduced into the calculation of evaporation makes it difficult to compute the derivatives needed in the semi-implicit coupling.

The way this scheme has been implemented amounts to a Dirichlet closure for the vertical diffusion and a Neumann closure for the surface energy balance.

4.3 Explicit coupling

As in the previous method, the explicit coupling uses the atmospheric and surface values at different time steps to compute the fluxes. In the present case the emphasis is put on a coherent calculation of the surface energy balance. The old atmospheric conditions are used, as it can be assumed that their variations over time are smaller than those at the surface. This method is used in CCM2 coupled to BATS (Dickinson et al. 1993) and in CCM3 coupled to LSM (Bonan, 1996).

The first step is to solve the surface energy balance using the old atmospheric conditions. Equation 1 is thus discretized as:

$$\begin{aligned} C_s \frac{\theta_s^{t+1} - \theta_s^t}{\Delta t} &= R_n + G + L\rho C_h |\vec{V}| \beta (q_a^t - q_{sat}(\theta_s^{t+1})) \\ &+ \rho C_h |\vec{V}| (\theta_a^t - \theta_s^{t+1}). \end{aligned} \tag{13}$$

It may be solved either by expanding the saturated humidity as is done in the implicit coupling or by using an iterative procedure. The latter one is suited for land surface schemes with a threshold formulation for evaporation. When solving equation 13 for the new surface temperature an iteration scheme has to be chosen which ensures convergence towards a physical correct solution. This is not a trivial task for all atmospheric conditions. If the stability dependence of the surface transfer coefficients is updated at each step of the iteration convergence is improved (Desborough, personal communication). Thus, these schemes may need to modify the surface transfer coefficient given by the GCM. It must be noted that when an iterative procedure is used, the scheme can become computationally very expensive and does not always converge to an unique solution.

The surface fluxes determined for the new surface temperature will then be used to complete the back-substitution of the vertical diffusion after computing the new variables at the first atmospheric level.

This approach has the advantage over the semi-implicit coupling that energy will be conserved. The fluxes obtained by solving the surface energy balance are those which are given to the atmosphere. Its drawback, on the other hand, is that the atmospheric feedback to the surface is only felt from one time step to the other. As in general temperature variations are slower at the lowest level of the atmosphere than at the surface, this approximation seems to be better than the one used in the semi-implicit coupling. This needs to be verified in numerical experiments.

This type of coupling facilitates the "tile" modeling as is allows multiple surface energy balances to be computed. The fluxes are then averaged before they are passed to the vertical diffusion.

4.4 Open-explicit coupling

This coupling scheme is presented here for completeness but to the knowledge of the authors it is not in use in any GCM because of numerical stability problems. Its main difference to the semi-implicit scheme is that when the surface energy balance is solved the fluxes computed for the next time-step by the vertical diffusion are not used. The ones of the previous time-step are applied. Just as for the semi-implicit scheme energy conservation may be difficult to fulfill if in the surface energy balance the fluxes are modified. The open-explicit coupling becomes an option for mesoscale models, because they use a time-step that is significantly smaller than GCM time steps (e.g. ISBA in Meso-NH). Due to the fact that the PBL and the surface energy balance are solved separately they are allowed to diverge during the time-step.

5 The coupling

After having defined the variables that need to be exchanged through the interface it needs to be determined where within the GCM the coupling has to occur. As the vertical diffusion has the strongest interaction with the LSS and also displays the largest diversity in numerical schemes, it will dictate the choice.

Depending on the type of coupling chosen for the vertical diffusion by the land surface scheme the atmospheric variables at the lowest atmospheric level are needed at time t or $t+1$. The only point where both of these values are available is within the resolution of the vertical diffusion after equations 17-19 have been solved and before the back-substitution is performed. It is at this point that the land surface scheme needs to be called.

If the land surface scheme is provided with the values for X_1^t, $\frac{K_{X,1+1/2}}{\delta z_1}(A_{X,2}^t - 1)$, $\frac{K_{X,1+1/2}}{\delta z_1}B_{X,2}^t$ and $\frac{K_{X1/2}}{\delta z_0}$ it is able to compute $A_{X,1}^t$ and $B_{X,1}^t$ from equations 17-19 (X is either θ or q, see Appendix A). This choice of variables allows the land-surface scheme to use its own values for the surface drag by modifying $\frac{K_{X1/2}}{\delta z_0}$. As pointed out in section 2.4, this opens the door to problems of consistency between the formulations used in the vertical diffusion and the LSS.

With these arguments the land surface scheme obtains the variables at the lower atmospheric level and their sensitivity to changes in the surface conditions. This allows the surface scheme to compute, simultaneously with the surface conditions, the atmospheric variables at the lowest level for the new time step (Equation 16 is used for this step) as needed for the implicit coupling. The flow diagram of such a coupling scheme is given in Figure 1. Only one call to the land surface scheme is needed further facilitating the inclusion of many land surface schemes in a single GCM.

As there is only one call to the LSS the other variables of the interface have to be passed at this point as well. A list of the quantities which are inputs and outputs of the LSS are presented in tables 1 and 2. Whether the calls to radiation or the precipitation scheme are before or after the vertical diffusion and the LSS does not matter to the interface. This will only affect the choice of variables the GCM has to write to the restart files.

The practical issues of coupling two FORTRAN codes have not been dealt with in the present note. All the basic coding rules set-up by Kalnay et al. (1989) apply here as well but a few specific recommendation for LSSs can be made from the present discussion. Only one call needs to be made to the land-surface scheme within the GCM and this will be within the vertical diffusion scheme. A call to the initialization of the LSS will also be needed to set up the vegetation map, soil types and other internal parameters.

In order to simplify the coupling of the land-surface scheme it should have its own restart and history system. This avoids the problem of passing the prognostic variables of the LSS through the interface and having to handle them with the restart and history system of the GCM. Land-surface schemes are so different in their conception that they all have a different number of prognostic variables. Furthermore an independent restart and history facility has the advantage of making the LSS more independent of the GCM, simplifies its use in an off-line mode and allows for a different grid than the one of the GCM.

The LSS should be written in such a way that the GCM has control over which grid-points the LSS is going to perform the calculations on. This is an important aspect for running the model efficiently on parallel computers.

Developing the software to perform off-line experiments, as in PILPS phase 1 and 2, with land surface schemes which are coupled according to this interface will be a trivial exercise. This is a more practical advantage of this interface.

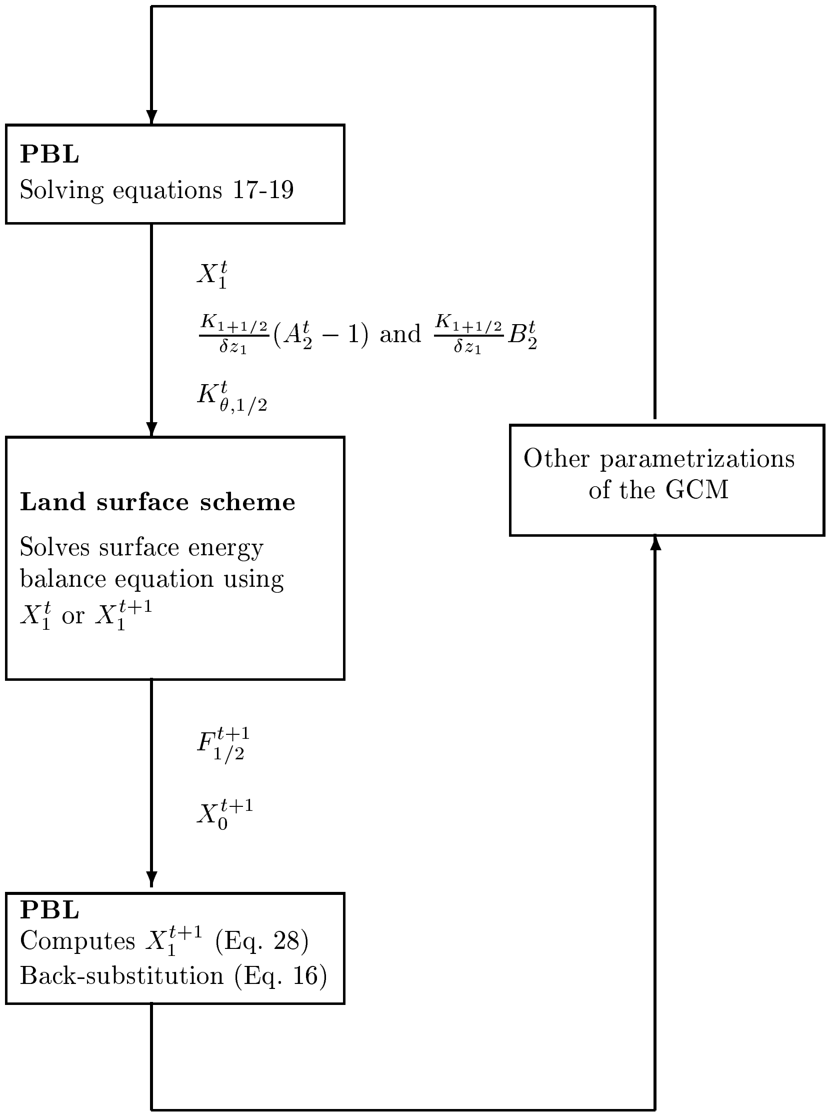

Figure 1: Flow diagram of the coupling scheme that would allow the three types of closure of the vertical diffusion equations to be used by land surface schemes. Only the variables linked to the vertical diffusion are given here.

Group	Variable	Symbols
Initialization	Geographical coordinates Land/sea mask Orography	
Physical constants	Latent heat of evaporation Latent heat of sublimation Latent heat of fusion Gravitational constant Specific heat capacity	L c_p
Surface layer description	height of first layer Density	δz_0 ρ
Hydrological cycle	Rainfall Sub-grid variance of rainfall Snowfall Sub-grid variance of snowfall	
Radiation	Solar zenith angle Net surface short-wave flux Fraction of diffuse short-wave radiation Down-welling long-wave flux	 S_n $L_\downarrow$
Turbulent diffusion	Lowest level potential enthalpy Lowest level specific humidity Lowest level wind speed concentration of passive tracer Surface layer diffusivity for : temperature moisture Potential enthalpy sensitivity Specific humidity sensitivity	θ_a q_a $K_\theta/\delta z_0$ $K_q/\delta z_0$ $\frac{K_{\theta,1+1/2}}{\delta z_1}(A_{\theta,2}-1), \frac{K_{\theta,1+1/2}}{\delta z_1}B_{\theta,2}$ $\frac{K_{q,1+1/2}}{\delta z_1}(A_{q,2}-1), \frac{K_{q,1+1/2}}{\delta z_1}B_{q,2}$

Table 1: Input to the land-surface scheme

Group	Variable	Symbols
Hydological cycle	Moisture flux River runoff	E
Radiation	Albedo Emissivity Surface radiative temperature	 ϵ T
Turbulent diffusion	Latent heat flux Sensible heat flux Flux of of passive tracer Surface roughness displacement height Surface layer diffusivity for : temperature moisture momentum Surface temperature Actual over potential evaporation	H LE z_0 d $K_\theta/\delta z_0$ $K_q/\delta z_0$ $K_m/\delta z_0$ θ_s β

Table 2: Output from the land-surface scheme

6 Conclusion

In this paper we have identified the variables which should be exchanged between a general circulation model and its land surface scheme. An effort was made not to take into account practical considerations, such as the current state of GCMs and LSSs, but rather to rely on physical and numerical arguments with the aim of being as general as possible. The resulting list of variables to be exchanged are presented in tables 1 and 2.

The authors are not aware of any reason why this general interface could not be implemented in all current GCMs and LSSs with a minimal effort. In some GCMs it will mean splitting the calculations of the planetary boundary and some LSSs will need to gather all computations related to the surface and which are now distributed throughout the GCM. This effort will make it possible to exchange land-surface scheme between GCMs thus opening new doors to intercomparison projects such as AMIP (Gates, 1992) and PILPS (Henderson-Sellers et al., 1996). It has to be expected that in the years to come progress will be made on the radiation or vertical diffusion schemes used in GCMs. This may lead to a rethinking of certain aspects of the coupling and eventually to an extension of the interface.

The interface defined here is general enough to be also applied to the coupling of the atmosphere to the ocean and sea-ice. Beside offering the plug-compatibility of surface parameterizations to the GCM it also has the advantage of making the lower boundary conditions a truly autonomous model within the GCM. This opens a new range of possibilities for the development and validation of the schemes at a global scale.

This proposal is only a first step towards a “plug compatibility” of land-surface schemes. It will certainly evolve as LLSs and GCMs evolve and as it is implemented. In order to give the interested reader the opportunity to follow the evolution a Web page exists at the following location: *http://www.lmd.jussieu.fr/pilps4c.html*. It will give informations on the evolution of the interface, its current status, where it is used and which points are currently being discussed.

Acknowledgments

We are grateful to Prof. Ann Henderson-Sellers for organizing PILPS and making this work possible. Without her energy and determination PILPS would not have been such a success.

References

Blondin, C. (1988). Research on land-surface parameterisation schemes at ECMWF. Workshop on parametrization of fluxes over land surface, Oct. 1988. European Centre for Medium-Range Weather Forecasts.

Bonan, G. (1996). The NCAR land surface model (LSM version 1.0) coupled to the NCAR community climate model. Technical Report NCAR/TN-429 + STR, NCAR Boulder, Colorado.

Bryan, F., Kauffman, B., Large, W., and Gent, P. (1997). The NCAR CSM flux coupler. Technical Report NCAR/TN-424 + STR, NCAR Boulder, Colorado.

Chalita, S. and Le Treut, H. (1994). The albedo of temperate and boreal forest and the northern hemisphere climate: A sensitivity experiment using the LMD AGCM. *Climate Dyn.*, 10:231–240.

Davies, H. (1983). The stability of some planetaryboundary layer diffusion equations. *Mon. Weather. Rev.*, 111:2140–2143.

Dickinson, R., Henderson-Sellers, A., and Kennedy, P. (1993). Biosphere-atmosphere transfer scheme (BATS) version 1e as coupled to the NCAR community climate model. Technical Report NCAR/TN-387 + STR, NCAR Boulder, Colorado.

Douville, H., Royer, J.-F., and Mahfouf, J.-F. (1995). A new snow parametrization for the Météo-France climate model part i: validation in stand-alone experiments. *Climate Dyn.*, 12:21–35.

Ducoudré, N., Laval, K., and Perrier, A. (1993). SECHIBA, a new set of parametrizations of the hydrologic exchanges at the land/atmosphere interface within the LMD atmospheric general circulation model. *J. Climate.*, 6(2):248–273.

Dümenil, L. and Todini, E. (1992). A rainfall-runoff scheme for use in the hamburg climate model. In O'Kane, J., editor, *Advances in Theoretical Hydrology, A tribute to James Dooge*, pages 129–157. Elsevier Press, Amsterdam.

Gates, W. (1992). The Atmospheric Model Intercomparison Project. *Bull. Am. Meteorol. Soc.*, 73:1962–1970.

Henderson-Sellers, A., McGuffie, K., and Pitman, A. (1996). The project for intercomparison of land-surface schemes: 1992 to 1995. *Climate Dyn.*, 12:849–859.

Kalnay, E. and Kanamitsu, M. (1988). Time schemes for strongly non-linear damping equations. *Mon. Weather. Rev.*, 116:1945–1958.

Kalnay, E., Kanamitsu, M., Pfaendtner, J., Sela, J., Suarez, M., Stackpole, J., Tucillo, J., Umscheid, L., and Williamson, D. (1989). Rules for interchange of physical parameterizations. *Bull. Am. Meteorol. Soc.*, 70(6):620–622.

Mahfouf, J., Manzi, A., Noilhan, J., Giordani, H., and Deque, M. (1995). The land surface scheme ISBA within the Météo-France climate model ARPEGE. *J. Climate.*, 8(8):2039–2057.

Mahfouf, J. and Noilhan, J. (1991). Comparative study of various formulations of evaporation for bare soil using in situ data. *J. Appl. Meteorol.*, 30:1354–1365.

Manabe, S. (1969). Climate and the ocean circulation 1. the atmospheric circulation and the hydrology of the earth's surface. *Mon. Weather. Rev.*, 97(11):739–774.

McAvaney, B., Bourke, W., and Puri, K. (1978). A global spectral model for simulation of the general circulation. *J. Atmos. Sci.*, 35:1557–1583.

Polcher, J. (1997). The sensitivity of the tropical climate to land surface processes. Seminar on Atmosphere-Surface interactions. European Centre for Medium-Range Weather Forecasts.

Richter, E. (1978). *Joos/Richter Höhere Mathematik für den Praktiker*. Verlag Harri Deutsch, Thun und Frankfurt am Main, 12 edition.

Richtmyer, R. and Morton, K. (1967). *Difference method for intial-value problems*. Interscience Publishers, second edition.

Terray, L. (1994). The OASIS coupled user guide version 1.0. Technical Report TR/GMGC/94-33, Centre Européen de Recherche et de Formation Avencée en Calcul Scientifique, Toulouse, France.

Vintzileos, A. and Sadourny, R. (1997). A general interface between an atmospheric general circulation model and underlying ocean and land surface models: delocalized physics scheme. *Mon. Weather. Rev.*, 125:926–941.

Viterbo, P. and Beljaars, C. (1995). An improved land surface parametrization scheme in the ECMWF model and its validation. *J. Climate.*, 8:2716–2748.

Warrilow, D., Sangster, A., and Slingo, A. (1986). Modelling of land surface processes and their influence on European climate. Technical Report No 38, 92p, U.K. Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ U.K.

A The vertical diffusion and its numerical scheme

The vertical diffusion of sensible heat and humidity through turbulent mixing can be described by the following generic equation:

$$\frac{\partial X}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial X}{\partial z}\right) \tag{14}$$

where X is potential enthalpy (θ) (As defined in equation 21.) or specific humidity (q) and K is the "eddy-diffusivity". In the following it will be assumed that the diffusion coefficients are the same for both variables. The sensible and latent heat fluxes at the surface are also computed using this equation but with diffusion coefficients which take into account the surface properties. At the surface we will write K_θ and K_q in order to distinguish the diffusion coefficients for each of the fluxes. Land surface schemes are thus intimately linked to the vertical diffusion scheme.

To solve equations 14 over the atmospheric column boundary conditions are needed. Above the planetary boundary layer vertical diffusion becomes sufficiently small that the flux can be considered to vanish. This leads to a zero flux upper boundary condition. The surface is the source of the transported energy and the closure of the equation there is a delicate problem which is discussed in section 4.

A.1 The numerical scheme used

In the parameterization of vertical diffusion in a GCM equation 14 is discretized over the vertical and in time. In the following discussion we will assume that the calculation is performed over N levels. Variables are located at the full levels and fluxes are computed at intermediate levels, represented by dashed lines in Figure 2. Level 0 is the surface. The basic time step starts at time t when all variables are know and ends at time $t+1$ when all calculations are completed.

When equation 14 is descretized in the vertical and an implicit time-stepping is used we obtain the following finite difference formula for level l:

$$\frac{X_l^{t+1} - X_l^t}{\Delta t} = \frac{1}{\Delta z_l}\left(K_{l+1/2}\frac{X_{l+1}^{t+1} - X_l^{t+1}}{\delta z_l} - K_{l-1/2}\frac{X_l^{t+1} - X_{l-1}^{t+1}}{\delta z_{l-1}}\right) \tag{15}$$

In order to solve this system of equations from the surface ($l=0$) to the top of the atmosphere or the planetary boundary ($l=N$) the method proposed by Richtmeyer and Morton (1967) is used. The aim is to reduce the system to a set of equation of the type:

$$X_l^{t+1} = A_{X,l}^t X_{l-1}^{t+1} + B_{X,l}^t \tag{16}$$

where the coefficients $A_{X,l}^t$ and $B_{X,l}^t$ can be computed in a descending order and then used in a back-substitution from bottom to top which yields the profile for X

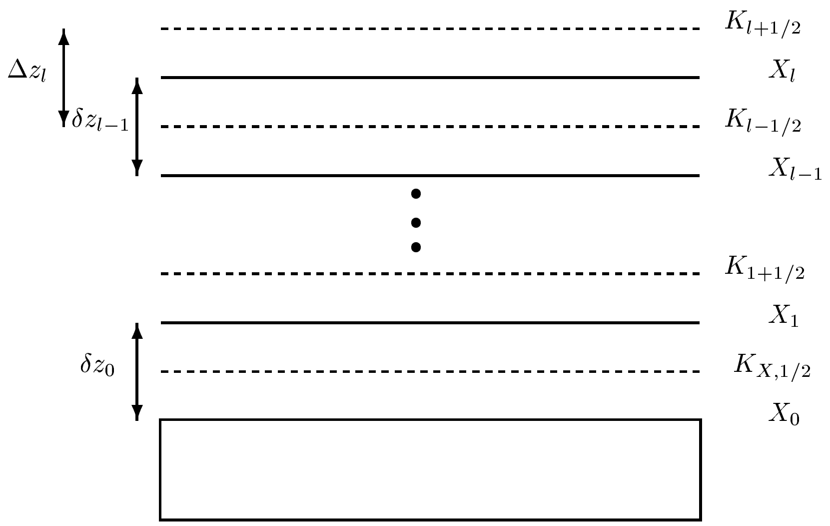

Figure 2: Levels used for the discretization of the equations.

at time $t+1$. It is assumed here that the eddy-diffusivities K_l are computed before using atmospheric conditions at time t.

To satisfy the zero flux condition at the top in equation 16 we have to set $A^t_{X,N+1} = 1$ and $B^t_{X,N+1} = 0$. This allows to start an iteration from top to bottom which determines $A^t_{X,l}$ and $B^t_{X,l}$ over the entire column. The following iteration formulas are obtained :

$$C = 1 - \frac{\Delta t}{\Delta z_l}\left(\frac{K_{l+1/2}}{\delta z_l}(A^t_{X,l+1} - 1) - \frac{K_{l-1/2}}{\delta z_{l-1}}\right) \tag{17}$$

$$A^t_{X,l} = \frac{\Delta t}{\Delta z_l}\frac{K_{l-1/2}}{\delta z_{l-1}}C^{-1} \tag{18}$$

$$B^t_{X,l} = \left(X^t_l + \frac{\Delta t}{\Delta z_l}B^t_{X,l+1}\frac{K_{l+1/2}}{\delta z_l}\right)C^{-1} \tag{19}$$

In this set of equations only $K_{X,1/2}$ contains information from the surface. This implies that without any knowledge of the surface the downward iteration can only be performed up to $l = 2$. The back substitution can not be performed independently from the land surface scheme for $l = 1$, but once X^{t+1}_1 is known equation 16 can be solved for all $l \in (2, N)$.

In order to obtain a general interface between the land surface scheme and the vertical diffusion scheme of the GCM a formulation has to be derived for computing X^{t+1}_1 using only surface fluxes ($F_{X,1/2}$).

A.2 The surface fluxes

The sensible and latent heat fluxes at the surface can be written in a generic form :

$$F^t_{X,1/2} = \frac{K_{X,1/2}}{\delta z_0}\left(X^t_1 - X^t_0\right) \tag{20}$$

Depending on the type of closure chosen by the land surface scheme the flux will be computed with variables at time t or $t+1$. For surface sensible heat ($F^t_{\theta,1/2} = H$) flux the following correspondences are used :

$$X^t_1 = \theta^t_a = c_p T^t_a\left(\frac{p_s}{p}\right)^\kappa \tag{21}$$

$$
\begin{aligned}
X_0^t &= \theta_s^t = c_p T_s^t && (22)\\
\frac{K_{X,1/2}}{\delta z_0} &= \frac{K_{\theta,1/2}}{\delta z_0} = \rho C_h |\vec{V}| && (23)
\end{aligned}
$$

where T_a is the temperature at the first atmospheric level, p is the pressure at this level, p_s pressure at some reference level, T_s is surface temperature, C_h is surface transfer coefficient for heat and moisture (Assumed to be same here.), ρ is the density and $\vec{V}$ is the wind speed at the first level. Equation 20 yields evaporation ($F_{q,1/2}^t = E$) if the following definitions are used :

$$
\begin{aligned}
X_1^t &= q_a^t && (24)\\
X_0^t &= q_{sat}(\theta_s^t) && (25)\\
\frac{K_{X,1/2}}{\delta z_0} &= \frac{K_{q,1/2}}{\delta z_0} = \frac{K_{\theta,1/2}}{\delta z_0}\beta && (26)
\end{aligned}
$$

where q_a is the water vapor mixing ratio at the first atmospheric level, $q_{sat}(T_s)$ is the saturated humidity for the surface temperature and β is the aridity coefficient. β is defined as the ratio between actual and potential evaporation.

Computing these fluxes is the responsibility of the land surface scheme and our aim is to derive an equation for X_1^{t+1} using $F_{X,1/2}^t$ as sole information from the surface. This ensures to the land surface scheme a maximum of freedom in the choice of the numerical scheme used for solving the surface energy balance equation. Inserting equation 20 into equation 15 yields :

$$
\begin{aligned}
C &= 1 + \frac{\Delta t}{\Delta z_l}\frac{K_{1+1/2}}{\delta z_1}(A_{X,2} - 1) && (27)\\
X_1^{t+1} &= C^{-1} X_1^t - \frac{\Delta t}{\Delta z_l}\left(\frac{K_{1+1/2}}{\delta z_1} B_{X,2} + F_{X,1/2}\right) C^{-1}. && (28)
\end{aligned}
$$

Thus the only knowledge required for computing X_1^{t+1} and iterating equation 16 from $l = 2$ to the top are the old values of potential enthalpy and humidity at the lowest atmospheric level, the surface fluxes and finally the values of $A_{X,l}^t$ and $B_{X,l}^t$ for $l \in (2, N)$ obtained during the descent.