Surface Energy Fluxes on Different Scales

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For atmospheric modelling, the treatment of subgrid surface energy fluxes is a closure to atmospheric boundary conditions. The essence of the problem is how energy fluxes over a complex landscape can be scaled up and down. In this study, we study surface energy fluxes on different scales using an integrated system consisted of an atmospheric prediction model, an atmosphere-landsurface interaction scheme and a geographic information data base. The system is used to simulate surface sensible and latent heat fluxes over Australian with a 50 km resolution and over New South Wales with a 10km resolution. Surface energy fluxes for the two cases are compared.

1 Introduction

For atmospheric modelling, closure is necessary to take into account the effect of subgrid motion on atmospheric systems. The subgrid effect is often described as a diffusion process that can be parameterized through the introduction of eddy diffusivity. This type of closure involves understanding the interaction of motion on different scales of the dynamic system.

At the interface between the atmosphere and land, energy, mass and momentum exchange takes place. This exchange occurs on all scales. For many years, the atmospheric processes are assumed to be adiabatic in weather prediction model, and only grid averaged fluxes are crudely calculated in climate models. In recent years, sophisticated land surface schemes have been developed to parameterize the energy, mass and momentum flux by taking into consideration of the soil hydrological and vegetation biochemical processes. The subgrid treatment of the surface energy, mass and momentum fluxes can be considered as a closure of second kind. This type of closure also involves the relationship between large scale and small scale motions of the atmosphere, but more importantly, it must involve a more complex system including atmospheric, hydrological and ecological processes. One important aspect of subgrid treatment of surface energy fluxes is that we must consider the spatial distribution of land surface properties, including aerodynamic, soil hydrological and ecological properties that are in general heterogeneous. The laws governing the subgrid scales are complex, and may not be universal.

We consider, for instance, atmospheric specific humidity, q, that obeys the following conservation equation,

$$\frac{\partial q}{\partial t} + \frac{\partial u_i q}{\partial x_i} = 0 \qquad (1)$$

where the source term is assumed to be zero. For a given numerical grid (or resolution), we have

$$\alpha = \tilde{\alpha} + \alpha^s$$

where the tilde represents the spatial average over the grid and α^s is the deviation. We obtain from Equation (1) that

$$\frac{\partial \tilde{q}}{\partial t} + \frac{\partial \tilde{u}_i \tilde{q}}{\partial x_i} = -\frac{\partial \widetilde{w^s q^s}}{\partial z} \qquad (2)$$

where $\widetilde{w^s q^s}$ is the vertical subgrid flux of specific humidity, and the horizontal subgrid fluxes are neglected. At the surface, the term $\widetilde{w^s q^s}$ differs from evaportranspiration by a constant.

Suppose the atmospheric model is applied to a higher spatial resolution, we have

$$\alpha = \bar{\alpha} + \alpha'$$

where the bar also represents the spatial averaging for the higher resolution case. Applying the averaging operation to Equation (1), we obtain that

$$\frac{\partial \bar{q}}{\partial t} + \frac{\partial \bar{u}_i \bar{q}}{\partial x_i} = -\frac{\partial \overline{w'q'}}{\partial z} \qquad (3)$$

where $\overline{w'q'}$ is vertical subgrid flux of specific humidity on the higher resolution grid.

The following relationships exist between the two averaging operations

$$\begin{aligned} \alpha &= \tilde{\alpha} + \alpha^s && (4) \\ \alpha &= \bar{\alpha} + \alpha' && (5) \\ \bar{\alpha} &= \tilde{\alpha} + \alpha^* && (6) \\ \alpha^s &= \alpha^* + \alpha' && (7) \end{aligned}$$

where α^* is a newly introduced deviation due to increased spatial resolution. Most importantly, we have

$$\widetilde{w^s q^s} = \widetilde{w^* q^*} + \widetilde{\overline{w' q'}} \qquad (8)$$

For subgrid closure of surface energy fluxes, it is crucial to understand how the last two terms in the above equation behave.

A subgrid treatment of surface energy fluxes will always be required regardless of the spatial resolution. Therefore, it is necessary to consider what governs the surface transfer processes. Or specifically, how surface fluxes should be related to surface properties specified by data. In this study, we use an integrated system of a limited area high resolution atmospheric model, an atmosphere and land surface interaction scheme and a high resolution geographic information data base to model surface energy fluxes on different scales and examine the behavior of surface energy fluxes with increased spatial resolution. The integrated system is first applied to the Australian continent with a 50km spatial resolution and then applied to NSW with a 10km resolution. Results from the two cases will be compared. The comparison is a necessary step for developping methods for upscaling and downscaling of surface energy fluxes.

2 Land Surface Model

Recent years have seen a rapid development of sophisticated land surface schemes for atmospheric, hydrological, and ecological modeling (e.g., Dickinson *et al.*, 1993; Noilhan and Planton, 1989; and Liang *et al.*, 1996). It can be concluded from recent comparative studies (e.g. Shao and Henderson-Sellers, 1996), these land surface models are more reliable than expected.

The Atmospheric and Land Surface Interaction Scheme (ALSIS) is a new land surface model developed at the University of New South Wales (Shao et al. 1997, Irannejad and Shao, 1997). The scheme models the energy transfer at the land surface and the surface soil thermal and hydrological processes. The scheme employs aerodynamic resistance laws to estimate the surface energy fluxes and the big-leaf model for canopy evaportranspiration and radiative processes. The Richards' equation, with linearized diffusion term by the Kirchhoff transform, and the temperature diffusion equation are solved simultaneously for soil moisture and soil temperature evolution, using implicit method. APSIS assumes the soil as a vertically heterogeneous medium for calculating water and heat fluxes through soil, and employs as many soil layers as required. To describe the relationships among soil hydraulic properties, the scheme uses anyone of the soil hydraulic models of Brooks and Corey (1966), Broadbridge and White (1988), Clapp and Hornberger (1978) and van Genuchten (1980) (Shao and Irannejad, 1997).

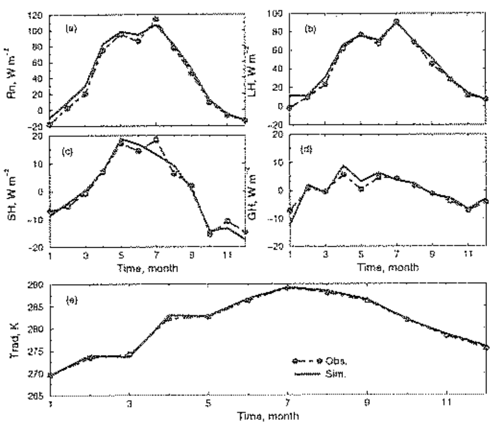

Figure 1: Comparison of simulated monthly mean surface energy fluxes and surface temperature with observations from Cabauw.

In the stand-alone mode, the performance of ALSIS has been tested rigorously with several data sets, including the HAPEX-MOBILHY in southern France (Goutorbe and Tarrieu, 1991), Cabauw in the Netherlands (Beljaars and Viterbo, 1994), the Murray-Darling Basin in Australia and the RedArk Basin in the United States. The validation of ALSIS has been described in detail in Irannejad and Shao (1997). Compared with observed data, the performance of the model is good both in simulating the soil moisture and the surface energy fluxes. As an example, Figure 1 shows a comparison of the simulated and observed monthly means of surface heat fluxes and surface temperature at Cabauw. The annual trend of energy fluxes is well captured by the model, although the simulated net radiation and sensible heat flux show a systematic small overestimation almost all over the year. The simulated diurnal fluctuation of surface fluxes and temperature for the period of Julian days 253 to 262, for the same experimental site, are compared with observations in Figure 2. Figure 2 shows that ALSIS can also well capture short time fluctuations of surface energy fluxes.

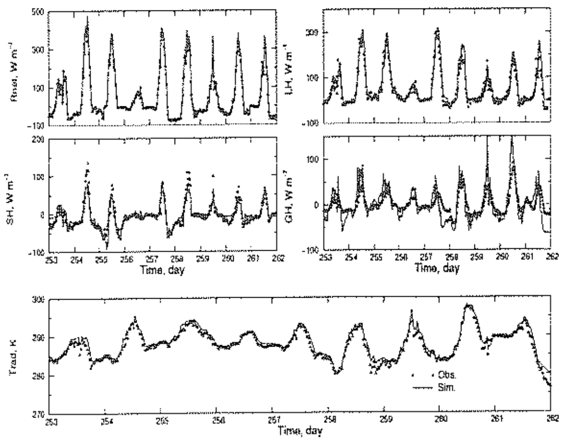

Figure 2: Comparison of simulated diurnal cycle of surface fluxes and surface temperature with observations from Cabauw for the Julian days 253 to 262.

3 Regional Scale Land Surface Modelling

At the University of New South Wales, we have developed an integrated numerical system composed of an atmospheric prediction model, the land surface model and a detailed geographic information data base. The atmospheric prediction model is the High Resolution Limited Area Model (HIRES, see Leslie and Purser, 1991).

Continuous simulation over the Australian continent with a 50km resolution and over New South Wales with a 10 km resolution has been performed since July 1997. The depth of the soil layer is 2m and is assumed to be vertically heterogeneous. The 2m soil column is divided into five layers with a depth of 0.05, 0.15, 0.3, 0.5 and 1.0m, respectively. The coupled system has been run first over Australia and then self-nested for running over NSW with increased spatial resolution and increased geographic information.

The land surface parameters required for soil moisture simulation are derived from the GIS data available for the Australian continent, including soil types and vegetation. The parameters are derived from the geographic data based on the *Atlas of Australian Resources Volumes* 1, 3 and 6 (1980, 1986, 1988). The complete data set has the spatial resolution of 5×5 km, but for some parameters, the resolution can be as high as one kilometer. In the data base, Australian soils are classified into 28 soil classes. For each soil class, there is a qualitative description of the soil hydraulic properties. The soil hydrological parameters are derived from these qualitative data for different soil hydraulic models.

The vegetation data sets provide a range of parameters such as vegetation height, fractional vegetation cover, leaf area index (LAI), minimum vegetation stomatal resistance, vegetation albedo and root distribution. The source of vegetation data is the *Atlas of Australian Resources*, vol. 6 (1988) complemented with a data set for land use. In this data set, vegetation was divided into 35 classes according to height, density and number of canopy layers. Among the 35 vegetation types, the most extensive vegetation cover is tall shrublands in its sparse open form (S2 and S1, 31.5%). Low woodlands (L2) and low open woodlands (L1) occupy nearly 27%, while other medium and short vegetation (M2, M1, Z1, G2 and G3) covers collectively about 22% of the continent. From the vegetation data base, a reasonable estimation can be made for quantities such as vegetation height, fraction of vegetation cover, vegetation albedo and minimum vegetation stomatal resistance.

The estimation of LAI for the simulation period draws on the remotely sensed NDVI (Normalized Difference Vegetation Index) data. NDVI data are derived from AVHRR (Advanced Very High Radiometric Resolution) satellite records of reflective radiation in the red region (0.55 - 0.68 μm) and the near infrared region (0.72 - 1.1 μm) of the electromagnetic spectrum. A composite of satellite images over a period of two weeks in February 1996 was used in this study. For major vegetation types, empirical relationships between NDVI and LAI previously established by for instance McVicar *et al.* (1996) using field observations. This type of empirical relationship has been used to estimate the LAI for the whole continent.

For soil moisture simulation, the lower boundary condition, specified either by given soil moisture content or given soil moisture flux, can significantly influence the numerical outcome. There are numerous techniques in parameterizing the lower boundary conditions, but none of these parameterizations will be effective unless there is sufficient knowledge of the soil hydraulic properties in deep soils. In the present work, a deep bottom soil layer (10 meters) is used and at the lower boundary of this deep layer, soil is assumed to be always at saturation.

An accurate initialization of land surface quantities such as soil moisture and soil temperature for the whole continent is virtually impossible. Therefore, all soils are assumed to be saturated and having a constant temperature at the beginning of the simulation. Numerical tests show that the effect of this unrealistic initialization on land surface modelling lasts only for a few days for the very top soil layer, but persists for about a month in deeper soil layers, provided that the simulation begins with saturated soil. Other numerical aspects are as described fully in Shao et al. (1997).

4 Surface Energy Fluxes

Simulated surface sensible and latent heat fluxes over NSW with 50km and 10km resolutions are shown in Figure 3. Some similarities in the overall distribution of the energy fluxes can be found. For the particular case, the profound feature of the energy flux distribution pattern is low latent heat flux accompanied by high sensible heat flux in the mountain areas. However, the difference between the simulations with different resolution is surprisingly large. For instance, the high resolution case reveals an area with strong latent heat flux and weak sensible heat flux around (150E, 36.5S). This phenomena cannot be seen from the lower resolution case.

Figure 4 compares simulated soil moisture and temperature with two different resolutions. Volumetric soil moisture in soil layer 1 (0.05m) and soil layer 3 (0.25-0.5m), and soil temperature for soil layer (0.05m) are shown. Again, the distribution pattern of these quantities contains similarities, but are profoundly different in detail.

To understand the differences, two major factors need to be considered. The first factor is the numerical behavior of the atmospheric model with increased spatial resolution. It is known that atmospheric waves propagate at different speed on different numerical grid. The physical schemes employed in the atmospheric model, such as the radiation and cloud scheme, can also behave differently on different resolutions. As a consequence, the atmospheric forces driving the land surface processes can be different. Among all atmospheric variable, precipitation is the most important one. These aspects of the problem are under active investigation. The second factor is the atmosphere-landsurface interactions and the dependence of these interaction on the intrinsic physical and biochemical properties of the land surface, which are generally irregular. Both factors are extremely difficult to examine. At the time when this short paper is written, our research on these two problems is not yet conclusive.

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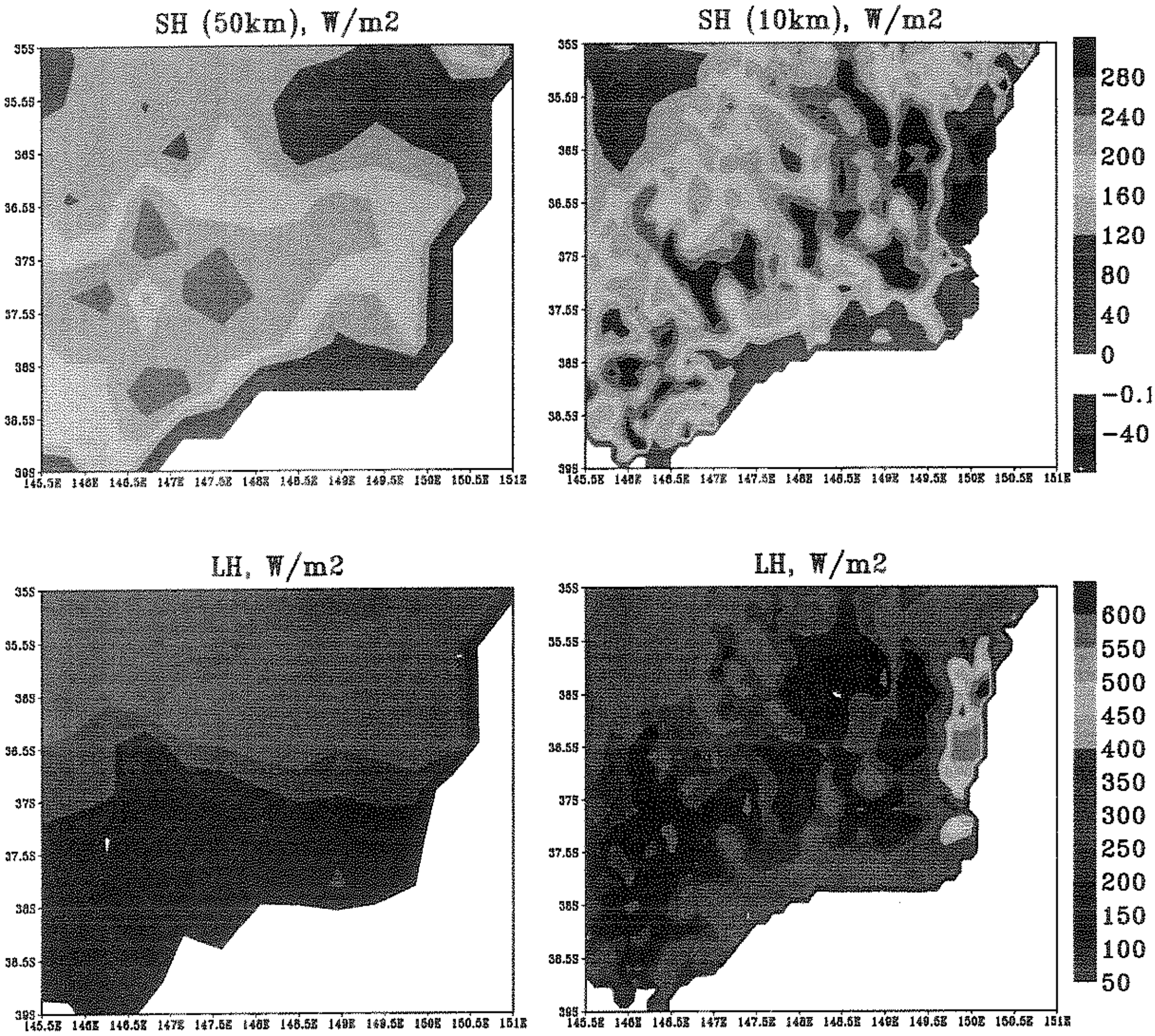

Figure 3: Comparison of sensible and latent heat fluxes simulated with the coupled system with a 50km resolution and a 10km resolution over the south-east region of NSW. The night time situation.

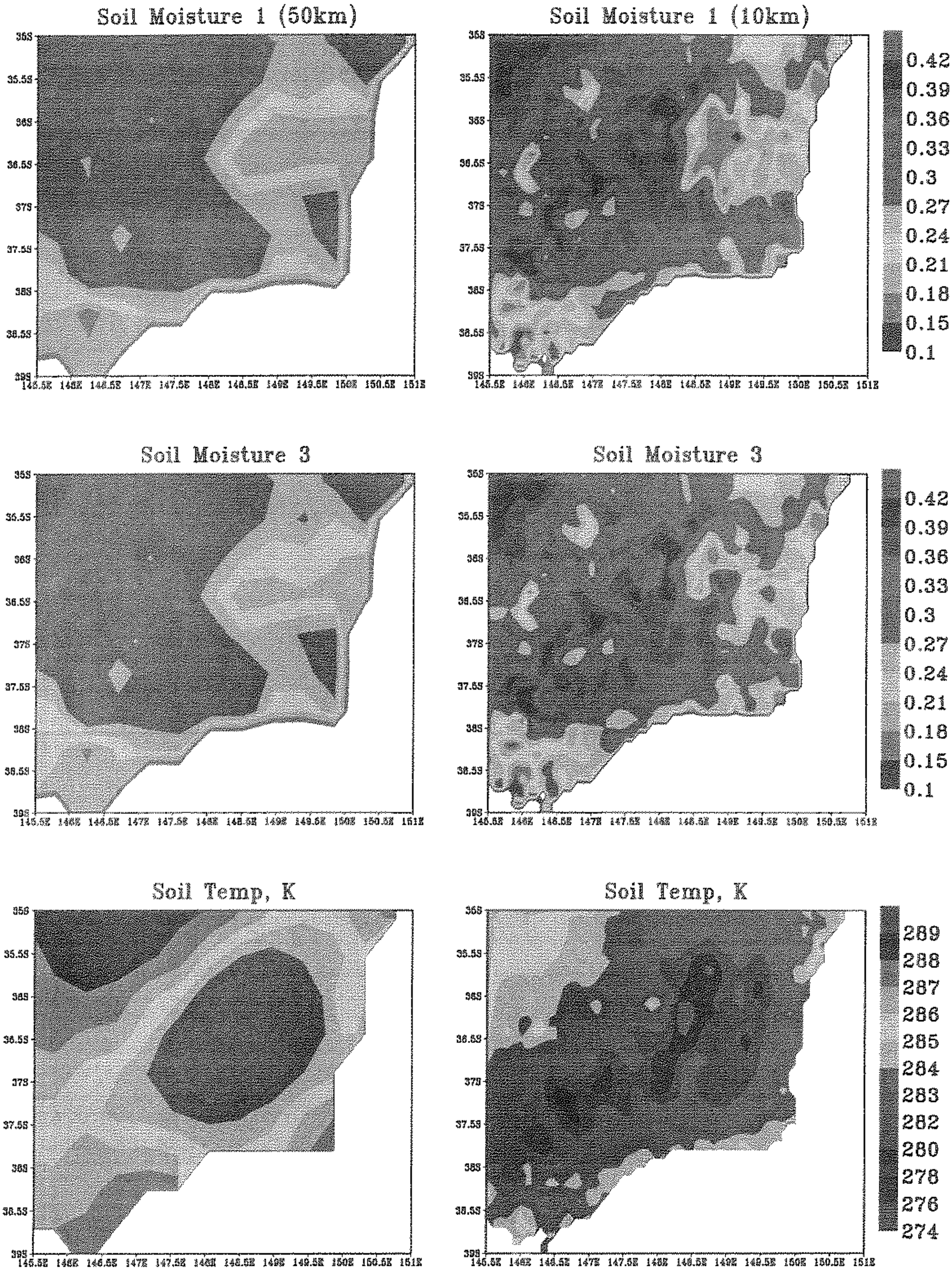

Figure 4: Comparison of simulated soil moisture (layer 1 and layer 3) and soil temperature (layer 1) with two different resolutions.