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Modelling land surface–atmosphere interactions over the Australian continent with an emphasis on the role of soil moisture

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Abstract

Soil moisture is a major natural state resistor variable in the global energy cycle as it influences the partitioning of both surface available energy into sensible and latent heat fluxes, and of precipitation into evapotranspiration and runoff. Consequently, physically based models of the biosphere need to simulate land surface conditions by including parameterisations for soil moisture. Soil moisture content is also important for determining the status of agricultural production since water in soil represents the major component of the hydrological cycle that is available to plants. Soil moisture is therefore important in ecological processes, and most biomass production models will include estimates of soil water availability. Given the identified importance of the soil moisture variable, it is perhaps surprising that there is a paucity of reliable long-term measurements, particularly over the major agricultural regions of Australia. Consequently, a diverse range of approaches, such as physically based models, stochastic modelling and remote sensing, have often been required to compensate for a dearth of actual measurements. This paper describes recent advances in soil water content simulation and prediction, utilising a numerical weather prediction model incorporating an improved land surface schema. This schema was developed in collaboration with the University of New South Wales and the Bureau of Resource Sciences. The land surface schema is essentially a surface hydrological model for prediction of evapotranspiration, surface and subsurface runoff and deep soil drainage, by parameterisation and solving the Richards' equation and the temperature diffusion equation for multi-soil layers. Soil moisture simulations obtained from this model for the Australian continent are presented. The model is shown to perform well, and further parameterisation work is progressing to improve the agreement between simulated and observed results.

Keywords: Australia; Soil moisture; Simulation; Numerical weather prediction

1. Introduction

Soil moisture is a major resistor variable in the global energy cycle since it influences the partitioning of both surface available energy into sensible and latent heat fluxes, and of precipitation into evapotranspiration and runoff. Consequently, all of the major physically based models of the biosphere attempt to simulate land surface conditions by including parameterisations for soil moisture. From biophysical and agricultural perspectives, the measurement of soil moisture and the estimation of soil water content (depth-integrated soil moisture) are important activities for determining the status of agricultural production, since water in soil represents the major component of the hydrological cycle that is available to plants. Soil moisture is therefore also important in ecological processes, and most biomass production models will include estimates of soil water availability.

Soil moisture simulation for a continental coverage poses three major challenges. Firstly, soil moisture predictions with land surface schemes will be limited by the empirical or semi-empirical nature of the parameterisations. Opinions differ on how reliable soil moisture predictions with land surface schemes are. An assessment of various schemes for soil moisture simulation, with prescribed atmospheric forcing data and prescribed land surface parameters for soil hydraulic properties, aerodynamic properties and vegetation characteristics for a single point, has been examined in

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Shao et al. (1994) and related studies (Shao and Henderson-Sellers, 1996). The differences for each of the schemes that was demonstrated in these studies can mainly be attributed to the different treatment of soil hydrological processes in the schemes. Secondly, as soil moisture evolution involves interactions between the atmosphere, soil, and vegetation, land surface schemes are usually complex. The prediction of soil moisture depends critically on the input parameters that describe soil hydrological properties, surface aerodynamic properties and vegetation features (e.g. leaf area index). Finally, the interactions between the land surface and the atmosphere involve complex feedback processes that are not yet well understood, but are known to have a significant impact on climate variability.

In the case of soil moisture simulation, it appears that the uncertainties in the choice of land surface parameters and in the lower boundary condition of the soil layer exceed those arising from the atmospheric data. In current general circulation models, the land surface parameters contain significant uncertainties and the lower boundary is crudely treated. Therefore, it is likely that soil moisture predictions from current general circulation models are not sufficiently accurate to facilitate meaningful analysis of land surface processes.

Our intention in this study is to provide a simulation of soil moisture for the Australian continent. To this end there are three major tasks: the first is the development of a new land surface scheme with an improved treatment of surface soil hydrology. The second task is to establish a set of up-to-date parameters for the land surface, including soil and vegetation over the Australian continent using a geographical information system (GIS), and the third task is to couple the land surface scheme with an atmospheric model for the four-dimensional assimilation of soil moisture.

The soil moisture is calculated using the atmospheric land surface interaction scheme (ALSIS) driven by the output of the new University of New South Wales (UNSW) high-resolution limited-area atmospheric model (HLAM). This modelling approach and results are described in detail in the following sections of this paper. The aim of this paper is to describe preliminary results from an evolving system that is used to assist in the development of Australian Government policies concerning sustainable land-use management.

2. Simulation of soil moisture

For most simulation studies, soil moisture is typically obtained across both a spatially varying and time-independent domain. An important distinction thus needs to be made with field-based observations of soil moisture, which typically represent the time-integrated observations from point locations. Soil moisture prediction (and simulation) consequently encounters additional problems due to landscape and atmospheric heterogeneity. Topography, spatial variability in soil and vegetation characteristics, and the variability of weather systems all result in large spatial and temporal variations in soil moisture patterns. Variations in soil type, geology, preferred flow-direction pathways formed by plant material and fauna, and atmospheric forcing phenomena (e.g. spatial variability in precipitation, radiation exposure) also contribute to heterogeneity in soil moisture fields across a large range of scales. Previous work by Entekhabi and Rodriguez-Iturbe (1994) and others (see for example Beven, 1989) have identified the key roles of topography and precipitation variability in defining the spatial and temporal characteristics of soil moisture at various scales. Clearly there is no easy solution to these issues apart from the self-evident fact that simulation studies require an enhanced treatment of the physical mechanisms governing the soil–atmosphere interaction, and an improved statistical characterisation of the scales governing physical processes. This may only be achieved by more intensive field-based observations of important variables such as soil moisture.

Where simulations are made for point locations, it is also important to note that the purpose of most simulations of soil moisture has been to maintain consistent partitioning of incoming inputs of precipitation and radiation, into hydrological variables (infiltration, runoff, evapotranspiration) and energy fluxes. Direct comparisons with field observations of soil moisture and this type of model output data cannot usually be directly made. This remains an intransigent problem for many soil moisture models, particularly those that attempt to provide operationally consistent estimates of soil moisture fields.

Within the context of the foregoing issues, the past decade has seen a rapid development of sophisticated land surface schemes for atmospheric, hydrological, and ecological modelling (e.g. Sellers et al., 1986; Noilhan and Planton, 1989; Dickinson et al., 1992; Liang et al., 1994; Wetzel and Boone, 1995). A land surface scheme is composed of three major components: bare soil transfer processes, vegetation canopy transfer processes, and soil thermal and hydrological processes. Almost all land surface schemes are based on the one-dimensional conservation equations for temperature and soil moisture:

$$\frac{\partial T}{\partial t} = -\frac{1}{C}\frac{\partial G}{\partial z} \tag{1}$$

$$\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial z} - S_w \tag{2}$$

where T is soil temperature, θ is volumetric soil heat capacity, C is volumetric soil water content, S_w is a sink term that includes runoff and transpiration (it has been assumed that the temperature sink term is zero), G is the soil heat flux, and q is the soil water flux. A land surface scheme is the algorithm required to solve this system for a particular soil layer configuration. For modelling purposes, parameterisations occur in the boundary conditions, in soil hydraulic and thermal properties, and in the treatment of the sink terms. The upper boundary conditions at the atmosphere and land surface interfaces include sensible and latent heat fluxes.

In most land surface schemes, there is little conceptual difference in the formulation for atmospheric transfer, such as the calculation of sensible and latent heat fluxes. There is also little difference in the treatment of canopy (the ‘big leaf’ assumption), with a possible exception of the simple biosphere model of Sellers et al. (1986). However, the treatment of soil hydrological processes, which can be reflected in the number of soil layers, may be significantly different. Depending on the number of computational soil layers, the schemes can be grouped into bucket-type single-layer schemes (Manabe, 1969), force-restore two-layer schemes (Noilhan and Planton, 1989) and diffusion-type multi-layer schemes (Wetzel and Boone, 1995). Most schemes have less than three soil layers, as they are designed mainly for use in general circulation models in which the demand on computational efficiency is important. Clearly, land surface schemes with a small number of soil layers may represent soil moisture distribution poorly, and have shortcomings in the treatment of the functioning of plant roots and evaporation from bare surfaces. Although these schemes might be adequate for global climate models, for ecological modelling more soil layers are required.

2.1. The ALSIS landsurface schema

One of the major new ingredients of ALSIS is the improved treatment of soil surface hydrology. In ALSIS, the one-dimensional (vertical) Richards’ equation is used directly to describe the evolution of soil moisture. Soil temperature and soil moisture are simulated with finite difference solutions of Eqs. (1) and (2). The parameters suggested by Broadbridge and White (1988) are used to characterise the hydraulic properties of various soils. The forms of their hydraulic functions have the unique property of making solutions of both differential and finite difference from Eq. (2) determinate under all conditions, including saturated soil and completely dry soil. This eliminates the numerical failures that have previously made routine numerical solution impracticable. Numerical speed is greater than that of a generalisation of the Green and Ampt (1911) model with infinitely sharp wetting fronts (Short et al., 1995). This is due to a combination of determinacy and numerical strategy (e.g. Redinger et al., 1984; Ross, 1990), whereby mixed dependent variables are used directly in a Newton–Raphson solution scheme. This feature allows ALSIS to incorporate as many soil layers as required to provide a better vertical resolution of soil moisture and better treatment of heterogeneity (in the vertical) of soil hydraulic properties. This flexibility in choosing the number of soil layers also facilitates a more effective treatment of root activities.

As previously noted, ALSIS is essentially a surface hydrological model for the prediction of evapotranspiration, surface and subsurface runoff and deep soil drainage, by parameterisation and solving the Richards’ equation and the temperature diffusion equation for multi-soil layers. The Richards’ equation requires closure relationships between hydraulic conductivity, soil water diffusivity, matric potential and soil water content. These relationships depend on the morphology of soil pores, with the average pore size being an important indicator for soil types. The closure relationships, as solved in ALSIS, are based on the Broadbridge–White soil model, although more recent versions of ALSIS allow for hydraulic processes to be described using the water retention functions of Clapp and Hornberger (1978) and other workers (e.g. Campbell, 1985).

In ALSIS, the land surface is divided into areas of bare soil and areas covered by different types of vegetation. The energy transfer processes over bare soil surfaces are described using aerodynamic resistance laws, while the description of the canopy transfer processes is based on studies as summarised in Raupach (1988).

A more detailed description of ALSIS can be found in Irannejad and Shao (1996). Irannejad et al. (1997) have also described the treatment of the surface hydrology and the functioning of vegetation roots by ALSIS, and the reader is referred to those papers for a further discussion of ALSIS.

2.2. Soil moisture simulations using ALSIS

Shao et al. (1997) have presented verification studies of ALSIS using the HAPEX-MOBILHY dataset as atmospheric and biophysical forcing data. HAPEX was conducted in 1986 in southern France and has been well documented by a series of papers (e.g. Goutorbe et al., 1989; Goutorbe, 1991; Goutorbe and Tarrieu, 1991). The ALSIS model was demonstrated to have excellent agreement with the observations obtained from the intensive field experimentation phase of HAPEX. Further validation for other locations has also been undertaken by Lyons et al. (1997a, b); Shao et al. (1997). Sensitivity analyses were also undertaken by Shao et al. (1997) and demonstrated the importance of selecting appropriate land surface parameters, particularly the parameterisation of soil hydraulic properties for different soil types. For this paper, effort has been directed at redefining the soil hydraulic properties for the soils under investigation (Table 1), subsequent to those chosen by Shao et al. (1997).

Table 1
List of parameters required by the ALSIS land surface schema

Parameter	Dimension
Saturated hydraulic conductivity	$m^2\ s^{-1}$
Saturated volumetric water content	$m^3\ m^{-3}$
Air dry volumetric water content	$m^3\ m^{-3}$
Macroscopic capillary length scale	m
Soil hydraulic characteristic parameter	–
Volumetric water content at field capacity	$m^3\ m^{-3}$
Volumetric water content at wilting point	$m^3\ m^{-3}$
Heat diffusivity for dry soil	$m^2\ s^{-1}$
Soil surface albedo	–
Fraction of vegetation cover	–
Height of vegetation	m
Leaf area index	–
Minimum vegetation stomatal resistance	m^{-1}
Root fraction in different soils	–
Vegetation albedo	–

2.3. Soil moisture prediction over the Australian continent

A continuous simulation of soil moisture over the Australian continent over a 2 month period from 1 January to 1 March 1996 has been performed. The depth of the soil layer is 2 m and is assumed to be vertically homogeneous (this will be modified in a future study). The 2 m soil layer is divided into five layers with a thickness of 0.05, 0.15, 0.3, 0.5 and 1.0 m, respectively. Soil texture information at a horizontal resolution of 5 $\times$ 5 km was derived from the *Atlas of Australian Soils* (a digital dataset available from the Bureau of Resource Sciences). Atmospheric forcing data was supplied using the HIRES model of Leslie and Purser (1991). This model was run over the Australian continent with a 20 $\times$ 20 km horizontal resolution and 30 vertical layers. The atmospheric data are stored every 30 min and averaged to a 50 $\times$ 50 km grid for soil moisture simulation. The model has been tested extensively in both research and operational modes (Leslie and Skinner, 1994; Leslie and Purser, 1995). Standard statistical evaluation, averaged over 30 stations in the Murray–Darling Basin, has shown that the model performance is very good. For near-surface air temperature predictions, the RMS error is 2.1 K with a mean absolute error of 1.7 K; for near-surface wind speed the RMS error is approximately 3 $m\ s^{-1}$.

An example of the predicted soil moisture pattern is shown in Fig. 1, where soil moisture content of layer 1 (0–0.05 m), layer 2 (0.05–0.2 m) and layer 4 (0.5–1 m) are illustrated, together with the total soil water in the top 1 m, for 10:00 UTC 15 February 1996 (day 46 of the simulation). The basic soil moisture pattern is typical for the Australian continent in summer. As expected, for this time of the year (late summer in the southern hemisphere), in large areas in the north-western part of Australia, including the Great Sandy Desert, Gibson Desert, Great Victoria Desert and Nullarbor Plain, the soil moisture content is very low. Although there is a slight increase in soil moisture towards deeper layers, for a considerable soil depth, the soil moisture content falls in the range between 0.05 and 0.15 $m^3\ m^{-3}$, with the total soil water in the top 1 m of soil being around 100 mm. Away from the desert areas, there is a gradual increase in soil moisture both towards the east and west coasts. In large areas of the ‘Channel Country’ of western Queensland and the Murray–Darling Basin, typical values of soil moisture are around 0.25 $m^3\ m^{-3}$ in layer 1 and 2, and 0.3 $m^3\ m^{-3}$ in layer 4. Total soil water in the top 1 m of soil is around 250 mm.

Further towards the east coast, soil moisture is over 0.3 $m^3\ m^{-3}$, under the influence of rainfall that occurred during the simulation period. One obvious feature of the spatial distribution of soil moisture is that the spatial patterns are closely related to soil hydraulic properties. For instance, the low soil moisture content in the desert areas is characteristic of the predominant sandy soils in the region. It is well recognised that the region has little precipitation, and as the sandy soils have a high (saturated) hydraulic conductivity and low air dry soil moisture content, soil moisture is low for most of the time. The exception is immediately after rainfall. In the desert areas, soil moisture is rapidly lost through drainage or evapotranspiration. Soil moisture content is significantly higher towards the east coast, apart from patches of very dry areas in Queensland. For a very large area in the eastern parts of Australia, the volumetric soil moisture content is around 0.3 $m^3\ m^{-3}$, as the soils in this region are predominantly sandy clay or silty clay with high values of θ_r (residual water content). For some of these areas, however, the absolute soil moisture content is quite high when compared with that of sandy soils. The strong similarity between soil moisture patterns and soil type patterns supports the notion that the Australian continent in summer is predominantly under water stress.

The simulation also provides detailed information in space and time of soil moisture distribution. As shown in Fig. 2, for example, across large areas of North Queensland, available soil moisture is very high for 17 February 1996, due to the rainfall influence of a tropical system. On 18 February 1996, rainfall in Western Australia also resulted in extensive areas of high soil moisture regions. These changes in soil moisture are also found to be consistent with the atmospheric quantities of the forcing data.

3. Discussion and conclusions

This paper describes a system to model soil moisture patterns and their evolution over the Australian conti-

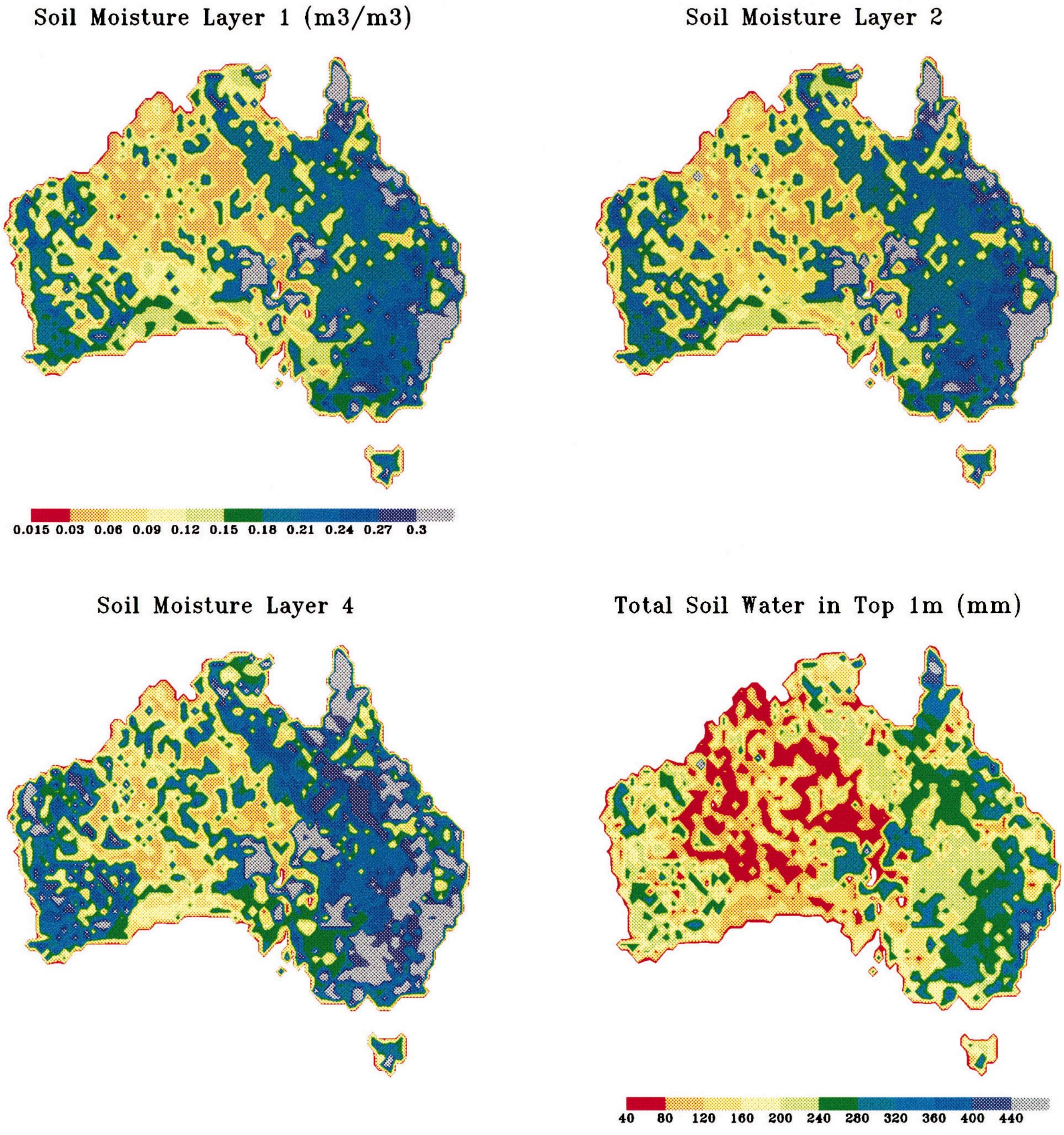

Fig. 1. Soil moisture distribution over the Australian continent for 15 February 1996. (a) Predicted soil moisture in m^3 m^{-3} for layer 0–0.05 m; (b) for layer 0.05–0.20 m; (c) for layer 0.5–1.0 m; and (d) total soil water in mm for the top 1 m soil.

nent. The land surface scheme, ALSIS, differs from many other schemes in the treatment of surface hydrology and the numerical formulation of the scheme. The non-linear relationships between soil hydraulic conductivity, matric potential and soil moisture content are based on the Broadbridge and White (1988) soil water retention model. The soil hydraulic parameters used to represent these relationships differ considerably from those of Clapp and Hornberger (1978), which are widely used in current land surface schemes. The scheme can accommodate as many soil layers as are required and the algorithms used in the scheme are numerically efficient. Nevertheless, it cannot be overstated that all land surface schemes are sensitive to the choice of soil hydrological parameters. Consequently, an additional emphasis of the work described in this paper is the development of a suitable set of land surface parameters based on the best GIS data currently available. In comparison to Global Climate Models (GCMs), the land surface information used in this study is more detailed.

This study provided a prediction of soil moisture evolution and distribution over the Australian continent in

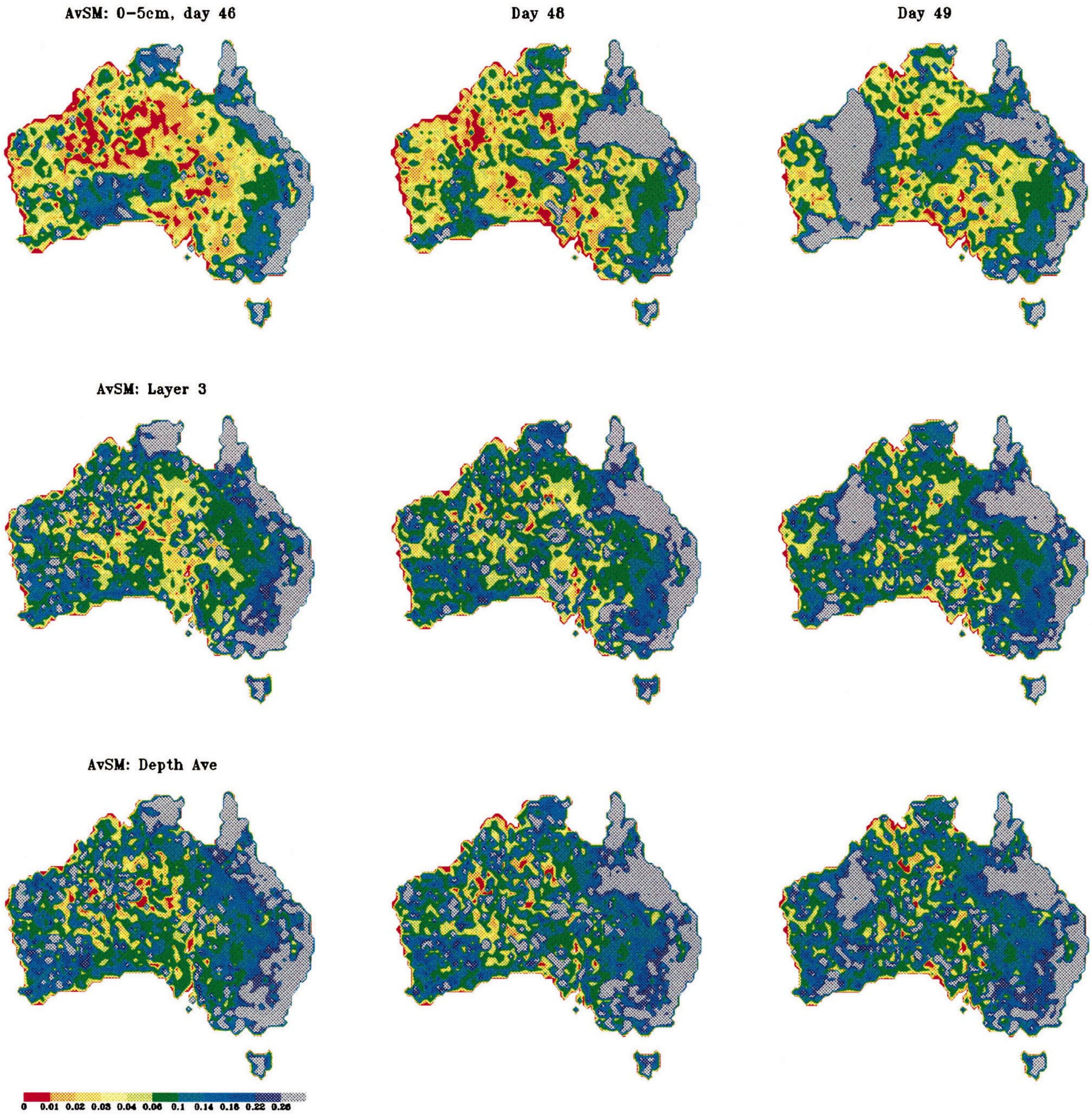

Fig. 2. Available soil moisture for 15 February 1996 (left column); 17 February 1996 (middle column) and 18 February 1996 (right column). In each column, available soil moisture for soil layer 0–0.05 m, layer 0.20–0.50 m and depth average over the top 1 m soil are shown.

summer. Although there is not yet a comparison of the predictions through independent studies, apart from single point evaluations with observational data such as HAPEX, the results are in good agreement with expectations. The simulations showed that over the Australian continent in summer, the soil moisture pattern is closely related to the distribution of soil types. This implies that, apart from isolated areas and times under the influence of precipitation, the response of soil types to drying factors such as evapotranspiration and drainage are primarily responsible for the soil moisture status. The results also suggest that a simulation at regional scales for broad-scale (continental) assessment of soil water content may be possible.

High resolution atmospheric predictions and geographical data were used in the simulation, and as a result simulations of spatial distribution and time evolution of soil moisture was obtained. With higher resolution datasets these simulations may be useful for many practical purposes, such as plant growth modelling and soil erosion prediction. This paper represents the first attempt of an ongoing effort in four-dimensional simulation of soil moisture. In addition to the feedback process between the atmosphere and the land surface, there is considerable scope for further improvement of the database used in this study. Notably, the addition of topography, soil depth, the lower boundary for soil moisture prediction and the temporal changes in vegetation cover. These necessary geographical data are currently being collated by the Bureau of Resource Sciences and will lead to a further improvement of soil moisture simulation.

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