# TESTING THE AUSTRALIAN BUREAU OF METEOROLOGY'S LAND SURFACE SCHEME USING SOIL MOISTURE OBSERVATIONS FROM THE MURRUMBIDGEE CATCHMENT

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## Abstract

For a number of decades numerical weather prediction (NWP) models have been an important tool for weather forecasting. These models simulate atmospheric processes and interactions between the atmosphere and the earth surface. Land surface schemes (LSS) are used to describe the interaction between the land surface and the atmosphere. This paper provides a general overview of NWP modelling and, in particular, current research issues related to LSSs. These include the initialisation of soil moisture, specification of landscape (soil and vegetation) properties, scale effects related to the importance and representation of subgrid variability of land surface states and parameters, and validation of predicted soil moisture fields.

As part of a research program aimed at improving modelling of the land surface in the Australian Bureau of Meteorology's suite of NWP models, a major experimental campaign is being conducted in the Murrumbidgee River basin. This experiment will provide information on variations in soil moisture and soil temperature across the basin that will be used in testing and further development of the LSS and its implementation.

**Key Words:** Soil moisture, Surface energy balance, Weather forecast, Land surface scheme

## Introduction

Today Numerical Weather Prediction (NWP) models are one of the standard weather prediction tools used by meteorological agencies around the world. NWP models are highly complex grid-based models of atmospheric processes, ocean-atmosphere and land-atmosphere interaction processes. These models undergo continuing modification and testing as our scientific understanding of atmospheric and other relevant processes improves.

Over the last decade, there has been a substantial international effort to further our understanding of land-atmosphere interaction processes (Entekhabi, 1995; Entekhabi et al., 1999). This has been motivated by both the desire to improve (long-term) climate models and (short-term) NWP models, and to further our basic understanding of hydrologic processes.

This paper presents a brief overview of numerical weather prediction and a summary of some of the key issues in land-atmosphere interaction. We then summarise a large-scale soil moisture monitoring project covering the Murrumbidgee River Basin, present early results from the monitoring and discuss the proposed testing of the land surface scheme used in the Australian Bureau of Meteorology's Limited Area Prediction System (LAPS).

## Numerical Weather Prediction

At the core of NWP models are quantitative descriptions of the atmospheric circulation, as well as energy and water transfer, transport and transformation. In addition, there are parameterisations of many different processes that occur at subgrid scales, such as cloud formation, rainfall, radiative transfer and the land-atmosphere interaction processes.

Typical global NWP models have horizontal grid resolutions between tens to one hundred kilometres and limited area or mesoscale models between five and fifty kilometres. These models use tens of levels to resolve vertical variations in atmospheric conditions. These levels are closely spaced (tens of metres) near the ground where there are rapid vertical changes, and they become more widely spaced (order of kilometres) as altitude increases. Spatial domains vary from a few hundred kilometres squared to coverage of the entire globe. For computational reasons (i.e. numerical stability) the models must run at high temporal resolutions that match their spatial resolutions (time steps of seconds to minutes). NWP models are generally run on supercomputers and take roughly an hour of computation time to produce a forecast.

A very important issue in NWP modelling is the specification of initial conditions. There are many three-dimensional fields of atmospheric state variables that need to be specified with sufficient accuracy at the start of the forecast period. These include air temperature, humidity, pressure and wind speed and direction. In addition, the schemes that describe the ocean-atmosphere and land-atmosphere interactions have state variables that need to be initialised. The land variables include soil moisture and soil temperature, usually in a number of soil layers.

The initialisation of the operational Australian NWP models involves a period of simulation before the beginning of the forecast period. First, most of the model variables are set on the basis of previous model output. Then the model "assimilation" run starts, and observations are used to make periodic corrections to the model variables. A 12 hour initialisation period is used in the Australian Bureau of Meteorology's Mesoscale Limited Area Prediction System (Meso-LAPS). Meso-LAPS is run every twelve hours. Thus, in effect, the initialisation of the model takes into account a long series of historic observations via previous model outputs. Observations for the initialisation of the Meso-LAPS model come from a network of hundreds of surface monitoring stations across Australia and adjacent areas, from ~40 atmospheric soundings, from aircraft data, ship and buoy data, and from satellite sensors that effectively provide continuous spatial fields.

NWP forecasts provide guidance for weather forecasters on the future evolution of weather patterns. Among the most important forecast fields are rainfall and temperature forecasts over periods of 1-2 days. High-resolution mesoscale models also provide guidance concerning the likelihood of severe weather. The land surface scheme (LSS) within Meso-LAPS predicts soil moisture and soil temperature fields down to nearly 3 metres of soil depth.

## Land-atmosphere interactions

The surface of the Earth constitutes a lower boundary to the atmosphere. Transfers of energy and water across this boundary are important to both atmospheric dynamics and to ocean and land processes. The land in particular is a highly heterogeneous surface. Fluxes of water and energy between the land and atmosphere are spatially and temporally variable. Predicting these variations at appropriate spatial and temporal scales is the key role of a LSS within a NWP model.

LSSs solve the water and energy balance equations for each land grid cell in the NWP. Energy balance computations involve partitioning incoming (to the land surface) radiative energy into latent (evapotranspiration), sensible and ground heat fluxes and outgoing radiative energy. Radiation is split into shortwave and longwave components. Water balance computations involve partitioning incoming precipitation into runoff and infiltration (as well as modelling snow processes where appropriate) and using soil moisture and surface atmospheric states in conjunction with soil and vegetation properties to estimate evapotranspiration (latent heat flux). The energy and water fluxes are intimately linked via evapotranspiration processes. Evapotranspiration is controlled by soil moisture availability and soil and vegetation characteristics. Most of the soil moisture-related processes described by the LSS are nonlinear.

Most LSSs are one-dimensional models that either ignore subgrid scale variability, or treat the landsurface as a few uniform patches (tiles) within each grid cell. All LSSs require specification of soil and vegetation parameterisations that relate soil water content to soil water availability for evapotranspiration and that describe transfers of water and heat within the soil. They also require specification of a variety of surface properties relevant to the radiative processes (vegetation cover, albedo and emissivity) and estimation of the momentum transfer from the atmosphere (the aerodynamic roughness).

Land surface heterogeneity affects flux estimation and atmospheric circulation. Many of the processes simulated in NWP systems and LSSs are nonlinear. This means that using spatial averages at the grid scale (i.e. ignoring sub-grid variability) can bias flux estimation, unless algorithms are modified appropriately (Giorgi and Avissar, 1997). In particular soil moisture is known to vary at scales from metres (Rodríguez-Iturbe et al., 1995; Western et al., 1998) to hundreds of kilometres (Entin et al., 2000; Vinnikov and Robock, 1996; Western et al., 2002). The amount of variability (the variance) is dependent on the soil moisture state, as well as other landscape characteristics (Western et al., 2001). Soil properties and vegetation patterns also vary over a wide range of scales.

Variability in the land surface can also have a significant impact on atmospheric processes (Pielke Snr, 2001). For example, land surface heterogeneity can enhance convection in the boundary layer if the heterogeneity is at appropriate spatial scales. Weaver and Avissar (2001) showed that spatial variations in latent and sensible heat fluxes associated with vegetation patterns and moisture availability, which had characteristic scales of 20-100km, led to stronger simulated mesoscale atmospheric circulations developing under a range of synoptic conditions. These circulations led to moisture being transported higher into the atmosphere and potentially to increased cloud formation and precipitation. The atmospheric simulations were also compared with satellite cloud images, which could not be simulated realistically when ignoring the spatial variability of surface latent and sensible heat fluxes.

Mills (1995) has shown that variations in soil moisture specification in the initial state of a mesoscale NWP forecast can make sufficient difference to surface temperatures over land that the movement of a cold front through Victoria is well forecast with a realistic soil moisture field, but the front is completely absent if a climatological soil moisture field is specified. This sensitivity of near-surface temperatures to soil-moisture specification in the NWP forecast has been demonstrated in many other studies.

In summary, some of the key hydrology-related issues with LSSs for NWP applications are:

- Initialisation of soil moisture (which techniques and data sources are best?);
- Specification of soil and vegetation parameters at appropriate scales (and clarifying what these scales are);
- Scale effects related to the importance and representation of subgrid variability of land surface states (moisture, temperature, vegetation?) and parameters (soils and vegetation); and
- Validation of predicted soil moisture fields (these fields are useful for both model initialisation purposes and as a product in their own right).

## Meso-LAPS

The Australian Bureau of Meteorology operationally runs a Mesoscale Limited Area Prediction Scheme for short range forecasting (0-36 hours). Meso-LAPS is one of a suite of NWP models run at different spatial scales. It is the highest resolution model routinely run over the entire Australian continent (Figure 1). It operates over an area extending well into the Southern, Indian and Pacific Oceans and north beyond the equator (95ºE-170ºE and 55ºS-5ºN). Meso-LAPS has a horizontal grid spacing of about 12.5km, uses 29 layers vertically and a time step of 10 seconds. It is run twice a day and forecasts up to 36 hours in advance. Describing the surface hydrologic and energy transfer processes accurately over the continent at these time and space scales is a major challenge.

The LSS used in Meso-LAPS is the VB95 scheme (Viterbo and Beljaars, 1995). The LSS currently treats each 12.5km grid cell as being spatially uniform, and it describes the vertical variation of soil moisture and soil temperature using the following four layers: 0-7cm, 7-28cm, 28-100cm, 100-289cm. Soil water simulations are based on solution of Richard's equation and soil temperature simulations are based on a solution of the heat diffusion equation. One soil type is used for all of Australia and, among the vegetation parameters, only the fraction of cover is varied. The vegetation condition is assumed to be uniform in time.

The LSS interacts with the atmospheric component of the Meso-LAPS model via the land-atmosphere moisture and energy fluxes. Soil moisture influences the partitioning between the latent and sensible heat fluxes.

To initialise the soil moisture, a different hydrologic model is currently run off-line, forced by observed rainfall data, to estimate available soil water. This soil moisture field is then input into the LSS and is subsequently corrected by a nudging scheme that uses screen-level (2m above the ground) humidity observations.

As noted above, we know that Meso-LAPS forecasts are sensitive to soil moisture specification (Mills, 1995). We also know that there is a range of applications for which knowledge of soil moisture status is likely to be useful. The initialisation process used in Meso-LAPS provides an estimate of current soil moisture status across the continent. What is unknown is how well the soil moisture field is initialised, or how well its evolution in time predicted by the LSS.

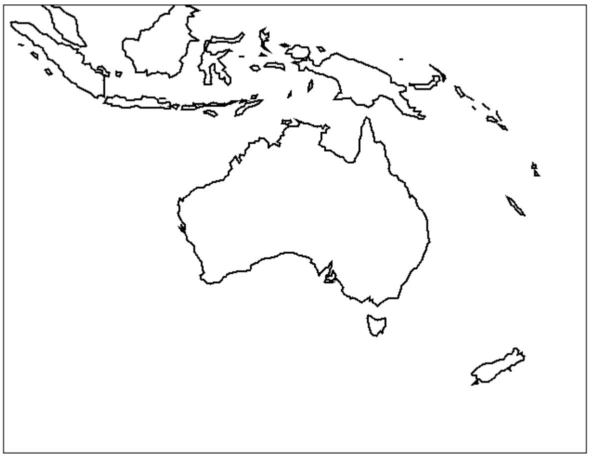

**Figure 1. The spatial domain of the Australian Bureau of Meteorology's Meso-LAPS model.**

## Murrumbidgee monitoring network

To test the soil moisture and soil temperature predictions of the LSS and to evaluate its overall performance within the LAPS framework, a major mesoscale monitoring exercise is being undertaken across the whole Murrumbidgee catchment (Figure 2).

The Murrumbidgee was chosen for a variety of reasons including the following. Firstly, it is one of the five catchments selected as focus catchments for the CRC for Catchment Hydrology. Secondly, it is a large catchment with an area of 100,000 $km^2$ or about 600 grid cells of Meso-LAPS. Thirdly, there is significant spatial variability in climate (alpine to semi-arid), soils, vegetation and land use, and these variations are well documented. Hydrological monitoring in the basin is sufficient to allow the overall water balance to be estimated. The area is therefore an ideal location for the development and testing of the land surface components of Meso-LAPS.

The monitoring network is structured to target two scales: the whole Murrumbidgee and the Meso-LAPS grid scale. Eight monitoring stations are distributed at points across the catchment (Figure 3) to gain an overall picture of soil moisture variations on the Meso-LAPS grid scale. Two groups of five monitoring stations are located in each of Kyeamba and Adelong Creek catchments. Kyeamba and Adelong Creeks have gauged areas of approximately 150$km^2$, corresponding to the Meso-LAPS grid scale. By incorporating gauged catchments it will be possible to make an overall assessment of how well the water balance is modelled in these areas. These catchments will also allow us to investigate the impact of sub-grid-scale variations on model parameterizations and simulations.

Figure 3 shows the catchment topography in addition to the monitoring network. Elevations vary from 50m in the west of the catchment to in excess of 2000m in the east. Climate variations are primarily associated with elevation and climate varies from semi-arid in the west, where the average annual precipitation is 300mm, to temperate in the east, where average annual precipitation reaches 1900mm in the mountains (Figure 2).

Soils in the Murrumbidgee vary from sandy to clayey, with the western plains being dominated by finer-textured soils and the eastern half of the catchment being dominated by medium-to-coarse textured soils (Figure 4). Landuse in the catchment is predominantly agricultural with the exception of steeper parts of the catchment, which are a mixture of native eucalypt forests and exotic forestry plantations (Figure 5). Agricultural landuse varies greatly in intensity and includes

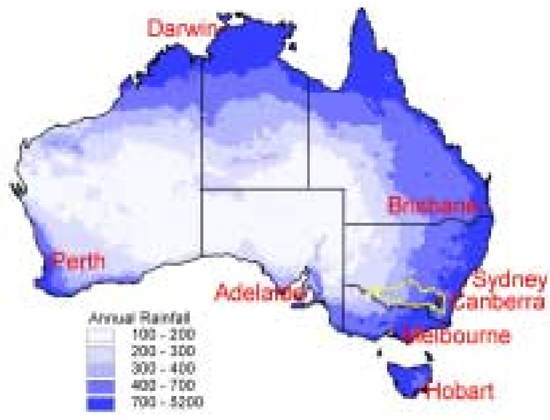


**Figure 2. Variation in annual rainfall across Australia. The Murrumbidgee catchment is outlined in yellow.**

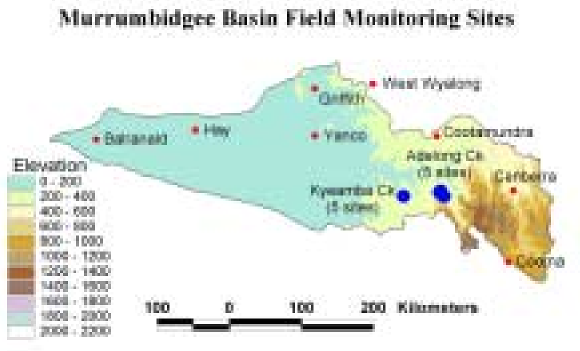


**Figure 3: The Murrumbidgee Soil Moisture Monitoring Network. The catchment topography is also shown.**

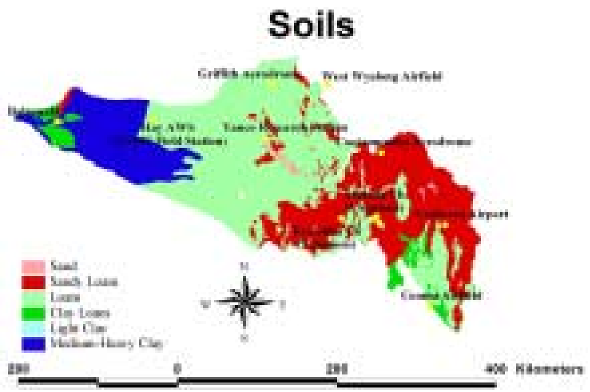


**Figure 4. Variation in soil texture across the Murrumbidgee catchment. Compiled using data from (Bureau of Rural Sciences after Commonwealth Scientific and Industrial Research Organisation, 1991) and soil property interpretations by McKenzie et al., (2000).**

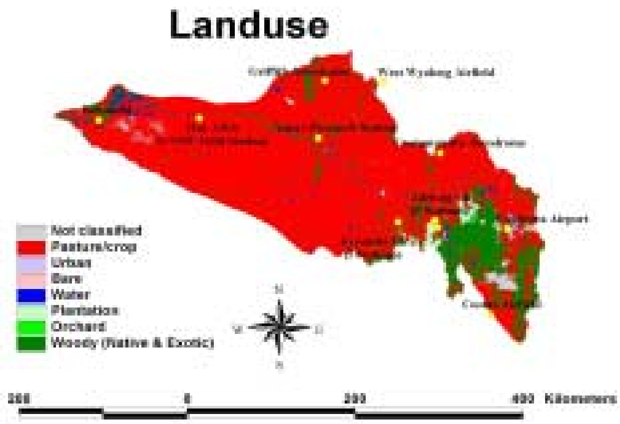


**Figure 5. Land use variation across the Murrumbidgee catchment. Compiled using data from Barson et al. (2000).**

pastoral, more intensive grazing, broad-acre cropping, and intensive agriculture in irrigation areas along the mid-lower Murrumbidgee.

## Soil Moisture Monitoring stations

The monitoring stations installed in the Murrumbidgee measure soil temperature and soil suction (in the 60-600kPa range) at the midpoints of layers at 0-7 cm, 0-30 cm, 30-60 cm and 60-90 cm. Depth average volumetric soil moisture is measured for each of the above layers using Campbell Scientific CS615 sensors (Figure 6). Depths roughly correspond to the top three layers in the LSS. Precipitation is also measured.

Soil moisture sensors will be calibrated against field gravimetric samples. Spatial representativeness of the point measurements will be assessed by spatial soil moisture sampling using mobile TDR. Time domain reflectometry (TDR) sensors are also installed at each layer and will be monitored when sites are visited to provide additional calibration information and ongoing checks on CS615 sensor performance.

Mobile telephone technology is used to allow weekly downloading and checking of the data. In due course these data, along with key data from Bureau of Meteorology stations, will be made publicly available via the WWW.

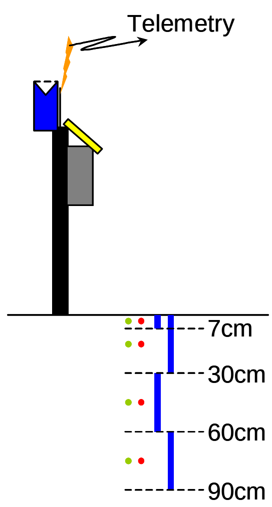


**Figure 6. A schematic of the soil moisture monitoring stations. The blue lines indicate soil moisture sensors (every 30 minutes) and red and green dot indicate soil suction (every 30 minutes) and soil temperature (every 6 minutes) sensors. Rainfall is also measured every 6 minutes.**

The eight soil moisture stations distributed across the Murrumbidgee are located at (or near) Bureau of Meteorology automatic weather stations (only Balranald is a manually read station) that provide air temperature, humidity, wind [at the AWSs], precipitation and air pressure.

The first monitoring stations were installed in September 2001, and all eighteen sites were installed by mid November 2001. Figure 7 shows early results from the West Wyalong station. Strong diurnal variations in temperature are obvious at 3.5cm and these variations rapidly become damped with depth and are insignificant at 45cm. Synoptic time scale variations in temperature are evident at all depths, as is the seasonal warming trend.

The soil moisture content in the top 30cm responds to episodic wetting during rainfall events and decreases due to evapotranspiration between events. About one third of the evapotranspiration comes from the top 7cm (i.e. top quarter) of the soil profile and two thirds comes from the 7-30cm layer during this period at this site. The soil moisture recessions appear quite linear, indicating a constant evapotranspiration rate for the conditions encountered. The diurnal variations in soil moisture are likely to be partly related to temperature effects on the sensor electronics.

The soil moisture content in the 30-60cm layer at this site is quite high and appears to be at field capacity. It responds slightly as moisture drains from above, but rapidly returns to a steady moisture value. The 60-90cm layer wets up episodically as moisture flows from above during and shortly after the two largest (in volume terms) rainfall events.

Soil suction is measured using gypsum blocks, which work over the range from 60 to 600kPa. For significant periods soils are wet and soil suction is less than 60kPa at this site during the 6 weeks of available data. As the surface layer dries, suction rapidly increases. The soil suction data should be useful for understanding soil moisture control on evapotranspiration. For example, the current data shows no evidence of a decrease in evapotranspiration rates associated with the increases in soil suction, although the only moderate values of soil suction have been encountered, the record length is short, and the instruments need a settling in period before providing the best quality data.

## Proposed Meso-LAPS testing

Data from the monitoring stations will be used in a variety of ways to test and improve the land surface description in Meso-LAPS. Currently planned activities include the following.

1. Testing of a stand-alone version of VB95 against point soil moisture and soil temperature data.

2. Assess the benefits of incorporating state-of-the-art spatial soil and spatial and temporal vegetation information.

3. Assess the accuracy of the operational Meso-LAPS forecasts of soil moisture in the Murrumbidgee River basin.

4. Examine the impact of subgrid variability on VB95 predictions of water and energy balance.

5. Compare model predictions of the water budget with observations over the catchment.

6. Improve the implementation of the soil moisture initialisation in Meso-LAPS.

Ultimately we will also compare the predictive performance of MesoLAPS precipitation estimates with different LSS parameterisations. The quality of rainfall forecasts will be important in this comparison. The rainfall verification system RAINVAL, developed by Ebert and McBride (1997), provides an objective means of assessing the sensitivity of model precipitation forecasts to changes in land-surface specification. This system is used routinely in both research and operational areas of the Bureau of Meteorology.

## Conclusions

Numerical weather prediction (NWP) models are an important tool for weather forecasting. These models simulate atmospheric processes and interactions between the atmosphere and the earth's surface. Land surface schemes (LSS) are used to describe the interaction between the land surface and the atmosphere. Typically these are one-dimensional surface water and energy balance models lumped at the atmospheric model grid scale.

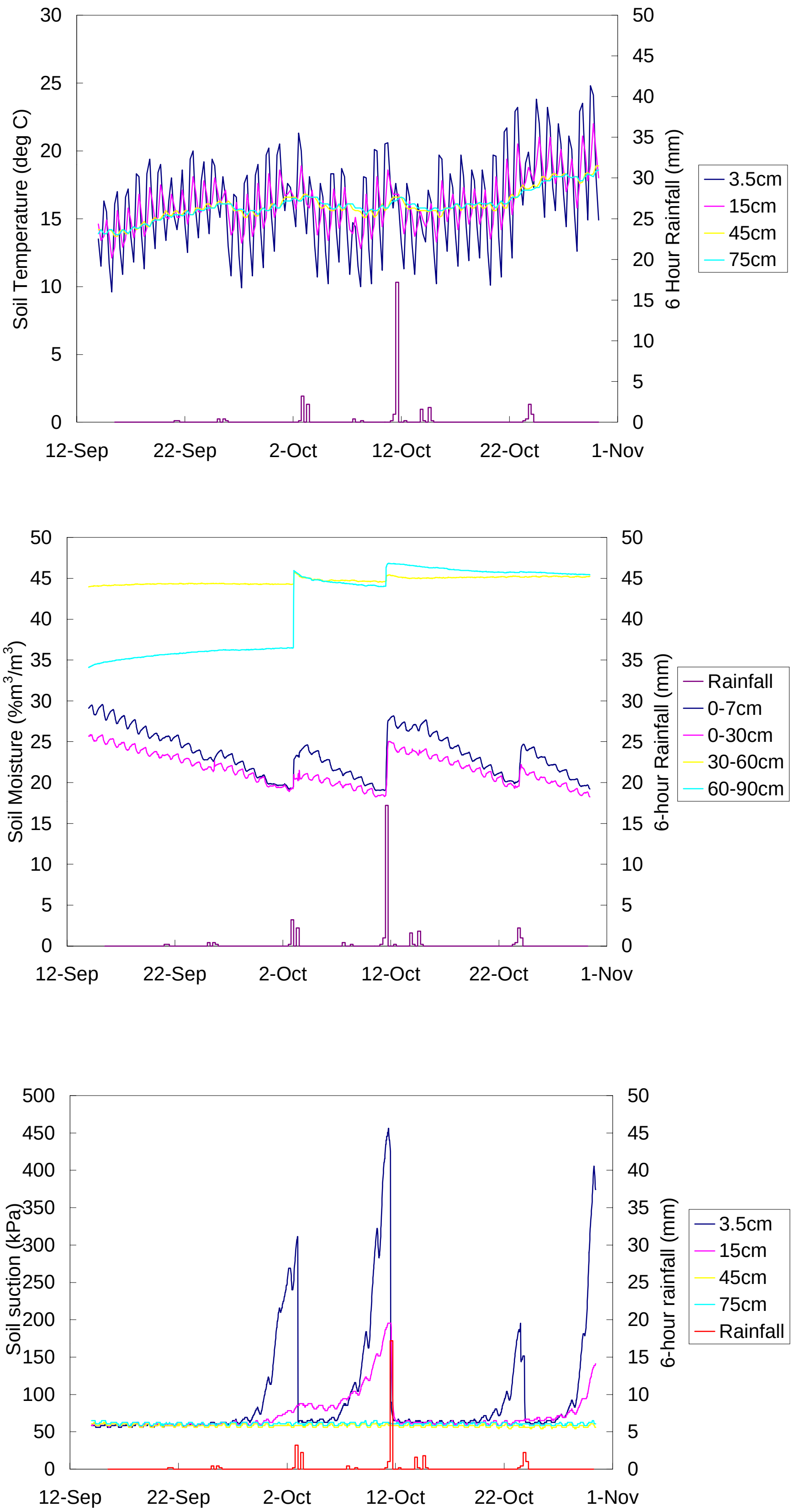


**Figure 7. Early results from West Wyalong. Top. Soil temperature. Middle. Soil moisture. Bottom. Soil suction.**

There are a variety of important research areas related to the LSSs used in NWP models. These include: initialisation of soil moisture, specification of landscape (soil and vegetation) properties, scale effects related to the importance and representation of subgrid variability of land surface states and parameters, and validation of predicted soil moisture fields.

As part of a research program aimed at improving modelling of the land surface in the Australian Bureau of Meteorology's suite of NWP models, a major experimental campaign is being conducted in the Murrumbidgee catchment. This experiment will provide information on variations in soil moisture and soil temperature across the basin that will be used in testing and further development of the LSS and its implementation.

Because of the nature of the data being monitored, it is likely to be of use to other researchers. The data will be made available on the WWW progressively as it is collected and quality assured. There are also possibilities for collaborative use of the data and we would welcome any such opportunities.

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