Weather Radar Information and Distributed Hydrological Modelling (Proceedings of symposium HS03 held during IUGG2003 at Sapporo, July 2003). IAHS Publ. no. 282, 2003.

Approaching realistic soil moisture status with an improved mesoscale numerical weather prediction model

SUXIA LIU[1,2], LANCE LESLIE[1], MILTON SPEER[3], REES BUNKER[4] & RUSSEL MORISON[1]

1 *School of Mathematics, The University of New South Wales, Sydney, New South Wales 2052, Australia*
suxia@maths.unsw.edu.au

2 *Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China*

3 *Bureau of Meteorology, Sydney, New South Wales, Australia*

4 *Rural Fire Office, New South Wales, Australia*

Abstract An advanced soil moisture scheme (Richards) is coupled to a high resolution numerical weather prediction model (HIRES) replacing the original Force–Restore scheme and changing other related processes. The new scheme now provides HIRES with an upper and lower bound for soil moisture through a process of checking model precipitation that is used to calculate soil moisture. A comparison of HIRES model results is presented using the new and original soil moisture schemes applied to the Goulburn River catchment in southeastern Australia. It is shown that precipitation is the most important factor to be considered before introducing an advanced scheme to correctly simulate soil moisture. It is also shown that, based on the correct precipitation input, the Richards scheme provides a more realistic soil moisture profile. Improving model soil moisture will ultimately provide better estimates of forest fire danger indices used as guidance by weather forecasters in assessing bushfire risk.

Key words bushfire; forest fire danger index; Goulburn River catchment, Australia; numerical modelling; soil moisture

INTRODUCTION

Although widely recognized for long-term climatic simulations (Eltahir, 1998) with GCMs, the importance of soil moisture is still less emphasized in short-range forecasting (Lin *et al.*, 2002; Cassardo *et al.*, 2002) in numerical weather prediction (NWP) models. Simulating soil moisture with a NWP model presents two main challenges. Firstly, NWP models generally have relatively simple land-surface schemes, which treat soil moisture processes poorly, and generally soil moisture is not output as a model predicted variable when using these schemes. Such schemes include, for example, the Force–Restore method (Deardorff, 1977; Noilhan & Planton, 1987). Secondly, the model forecast validity period in short to medium range weather forecasting (from 48 h to several days), is not long enough for values of model output variables such as precipitation, temperature and relative humidity to affect soil moisture processes. For soil moisture processes to be assessed using values of model predicted variables, the time period should be no less than about one month.

One aim of this study is to improve soil moisture calculation in a high resolution numerical weather prediction model (HIRES). Soil moisture calculation is assessed over a period covering approximately six weeks (November/December, 1997) for the Goulburn River catchment in southeastern Australia prior to and following a large bushfire that occurred in the catchment. Given the lack of a long-term soil moisture data set that could be used to initialize HIRES, we present a methodology to develop such a data set.

The ultimate aim of this study is to improve the model prediction of Forest Fire Danger Index (FFDI), which in Australia is the main index used as guidance by fire weather forecasters to issue fire weather warnings. FFDI and most schemes that calculate a fire danger index are based on values of air temperature, relative humidity, wind speed, and a factor that represents the dryness of the vegetation based on the number of days since precipitation has occurred. Few schemes, if any, have yet considered routinely soil moisture status, which is a key factor in assessing the dryness of vegetation and hence bushfire risk. Therefore, it is anticipated that enhancing the way soil moisture is calculated in HIRES will lead to improve values of FFDI for assessing bushfire risk.

In this paper, the HIRES model is first briefly described. This is followed by a section outlining adjustments to HIRES to include more soil moisture processes. Third, the data set developed for the simulation is described. The final section presents the modelling results prior to and after the soil moisture improvements are made.

HIRES MODEL

The University of New South Wales HIgh RESolution (HIRES) model is a limited-area numerical weather prediction model developed by one of the authors, and many versions have been tested extensively in a wide range of applications. It is a primitive equation model on a Lambert–Conformal projection and utilizes the sigma coordinate system on an Arakawa C grid. A four-dimensional 6-hourly cycled statistical interpolation scheme is employed to update boundary conditions. The semi-implicit semi-Lagrangian approach (splitting the advective and gravity wave terms) is used for horizontal advection. The Mellor–Yamada boundary layer scheme (Level 2.25) is used to resolve the boundary layer meteorology. Leslie *et al.* (1985) embedded a detail physical process parameterization scheme into HIRES, which includes a stability dependent boundary layer with eddy diffusivity functions of bulk Richardson number; the vertical diffusion above boundary layer based on mixing length hypothesis, a surface heat budget with prognostic equation for surface temperature, a large-scale precipitation scheme, and a modified Kuo convection scheme. More recently, options utilizing the Kain-Fritsch cumulus parameterization scheme (Kain & Fritsch, 1990), and an explicit physics version (Wang, 1999) have been included.

For the hydrological cycle in HIRES, relative humidity is held to the value specified in the initial state by the Global Assimilation and Prognosis system (GASP) (Bourke *et al.*, 1995; Seaman *et al.*, 1995) at a horizontal resolution of 200 km and/or the Limited Area Prediction System (LAPS) (Puri *et al.*, 1998) at 75 km. If surface temperature and dew point analyses are available, then those specify the surface humidity. Otherwise the surface humidity is diagnosed as the weighted average of saturated humidity and other variables. The Force–Restore method was used in the original version of HIRES to calculate soil moisture. This two-layer soil model prognostically represents the rapid response of near-surface moisture to forcing by precipitation or evaporation and also provides a source of moisture restored from the deep soil to the surface when there is no precipitation.

REVISION TO THE HIRES MODEL

In the original version of HIRES, a lower bound for soil moisture is not included. Therefore, the soil moisture output from HIRES can be smaller than wilting level, which is unrealistic. In this study, we have added a lower and an upper bound to the model calculation of soil moisture.

In the original version of HIRES, the precipitation used to calculate soil moisture in the Force–Restore method is the quantity acquired from the specification and solution of the Helmholtz equations. In this study, the quantity used is the sum of the convective and large-scale model forecast precipitation. For convenience, hereafter this revised method is specially referred to as Precipitation Revision.

In the original version of HIRES, each subsequent nesting starts with soil moisture that was specified using surface humidity from the first nesting. In this study, the second and the third nesting uses the initial value of soil moisture from the previous nesting.

In order to compare the Force–Restore method used in the original version of HIRES with the Richards method, the latter is coupled to HIRES. The Richards method has previously been incorporated into an advanced multiple soil-layer soil moisture simulation which established the ALSIS model (Irannejad & Shao, 1998).

Theoretically, a two-layer soil scheme such as the Force–Restore model is not sufficient to fully represent processes involving soil moisture and soil temperature. The Richards model, with additional soil layers, more appropriately represents soil moisture profiles and can better describe the physical process of water flow. The flexible number of soil layers also allows a more effective treatment of root activity and hence a more representative evaporation scheme. A limitation in using additional model soil layers is that it will increase the computation time.

DATA

Unlike many other variables in HIRES, the amplitude of the soil moisture variation is small. A sufficiently long modelling period is needed to assess any differences in the two schemes used. HIRES was initially developed for short-term weather forecasting, with LAPS providing initial state and boundary conditions out to 48 h and GASP providing initial state and boundary conditions out to 168 h. In order to run HIRES over 40 days (from 1 November to 11 December 1997), which covers a sufficiently long period prior to, and following, a large bushfire in the catchment, improved data input to HIRES is needed.

By comparing the forecast results based on LAPS (75 km horiz. res.) and GASP (*c.* 200 km horiz. res.) data for 48 h with observed data of screen temperature, wind, relative humidity and sea level pressure at the closest meteorological station (not shown here), it is shown that results based on LAPS capture the upper and lower bound of sea level pressure much better than the results based on GASP. Therefore, although GASP provides archived boundary conditions out to 168 h, we use the boundary conditions covering the shorter time period out to just 48 h by LAPS, owing to its better verification against observations.

The archived LAPS data consist of two sets of 48-h forecasts per day data with analysis based either on 11 UTC observed data or 23 UTC observed data. Comparing the results based on 11 UTC and 23 UTC analysis data, there are no obvious differences (not shown here). Errors in a model forecast will grow with time due to the chaotic nature of the atmosphere and the uncertainty in specifying the initial conditions (Ibbitt *et al*., 2001). These errors will pass through the model system and contribute to errors in the forecast. In order to remove this error and to allow us to determine the accuracy of the HIRES results, only LAPS analyses at 11 UTC and 23 UTC (not 6 hourly) are used as initial and boundary conditions. The model was run for a total period of 960 h (40 days). Currently, the maximum possible period that HIRES can run is 999 hours.

The first nesting is at a horizontal resolution of 50 km within the Australian region analysis and forecast domain. The second nested domain covers the eastern half of Australia at 20 km horizontal resolution. Finally, the third nesting covers the area containing the Goulburn River catchment at 5 km resolution. A more detailed description of the Goulburn River catchment and the 1997 bushfire can be found in Liu *et al.* (2003).

RESULTS AND DISCUSSION

The difference in the results with and without the lower and upper bound of soil moisture is readily apparent. The difference in the results with each subsequent nesting starting with soil moisture that was specified using surface humidity from the first nesting and the results with the second and the third nesting using the initial value of soil moisture from the previous nesting, shows little difference in the 48-h forecast results. The logic, however, for this revision is more reasonable. Therefore, we now highlight the results before and after Precipitation Revision, the differences between the Force–Restore (FR) scheme and the Richards (R) scheme, and the differences between the results at different spatial resolutions (50 km, 20 km and 5 km).

From the results it is obvious that before the Precipitation Revision, neither the Force–Restore scheme nor the Richards scheme could capture the expected soil moisture pattern. An example is shown for Bylong station (32°21′57″S, 150°06′52″E) (Fig. 1) at 5-km resolution, where there is too much noise in soil moisture output with the Force–Restore scheme (Fig. 1(a)) and it shows almost no change with the Richards Scheme (Fig. 1(b)), even though there are precipitation peaks; nor in the Force–Restore scheme does the noise correspond to the precipitation peak.

After Precipitation Revision, there is good correspondence between peaks of simulated precipitation and simulated soil moisture (Fig. 1(c) and (d)). There is also a recessing limb of soil moisture after the precipitation peak, which is a common occurrence in soil moisture variation following rain. The CPU time using the Richards

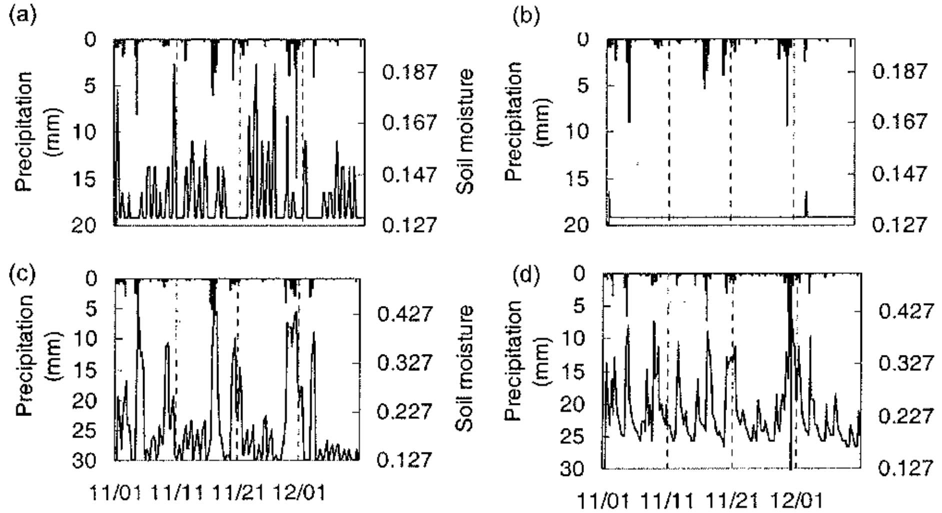

Fig. 1 The simulated precipitation (upper part) and simulated soil moisture (lower part) at the Bylong Station with the resolution of 5 km using (a) the Force–Restore scheme before Precipitation Revision; (b) the Richards scheme before Precipitation Revision; (c) the Force–Restore scheme after Precipitation Revision; and (d) the Richards scheme after Precipitation Revision.

scheme is about twice that for the Force–Restore method owing to the incorporation of nonlinear calculations.

Comparison of the results between the Richards and Force–Restore schemes reveals that changes mostly occurred in precipitation and soil moisture. All the other variables such as temperature, wind speed and sea level pressure reveal insignificant changes as expected. The reason for this is that, although there is a feedback between soil moisture and atmospheric variables in HIRES via surface humidity, the link is still weak. Steps are already underway to strengthen the links between these feedback processes.

Overall, precipitation is still, as expected, the most important factor in determining the temporal and spatial distribution of soil moisture before introducing any advanced soil moisture simulation scheme. It is also true that based on the correct precipitation input, the Richards scheme can provide more realistic soil moisture values. This conclusion is based on the assumption that within the study area the soil property remains the same. The effects of changing the soil properties will be assessed in future. These results will then be compared with the results of a study by Shao *et al.* (1997) with reference to the Australian continent.

Acknowledgements This work is sponsored by a Strategic Partnership with Industry Research and Training Grant (SPIRT) between The University of New South Wales, the NSW Rural Fire Service and the Bureau of Meteorology, Sydney. The first author acknowledges the NSFC project 90211007 and Knowledge Innovation Project of the Chinese Academy of Sciences KZCX2-310. Thanks to Mr G. Mackay and Mr Siu Wong at the Bureau of Meteorology, Sydney, Susana Realica, Allan Raine, Suzanne Bridgman at the Department of Land and Water Conservation, NSW, Australia and Pam O'Neill at National Parks and Wildlife Services, NSW, Australia in providing hydrological, meteorological and bushfire data for the Goulburn River catchment and Dr L. Qi for the help in running the HIRES model.

REFERENCES

Bourke, W., Hart, T., Steinle, P., Seaman, R., Embery, G., Naughton, M. & Rikus L. (1995) Evolution of the Bureau of Meteorology's Global Assimilation and Prediction system. Part 2: resolution enhancements and case studies. *Aust. Met. Mag.* **44**, 19–40.

Cassardo, C., Balsamo, G. P., Cacciamani, C., Cesari, D. & Paccagenella, T. (2002) Impact of soil surface moisture initialization on rainfall in a limited area model: a case study of the 1995 South Ticino flash flood. *Hydrol. Processes* **16**, 1301–1317.

Deardorff, J. W. (1977) A parameterization of ground surface moisture content for use in atmosphere prediction model. *J. Appl. Met.* **16**, 1182–1185.

Eltahir, E. A. B. (1998) A soil moisture rainfall feedback mechanism: 1. Theory and observations. *Water Resour. Res.* **34**(4), 765–776.

Ibbitt, R. P., Herderson, R. D., Copeland, J. & Wratt, D. S. (2001) Simulating mountain runoff with meso-scale weather model rainfall estimates: a New Zealand experience. *J. Hydrol.* **239**, 19–32.

Irannejad, P. & Shao, Y. (1998) Description and validation of the Atmosphere-Land-Surface Interaction Scheme (ALSIS) with HAPEX and Cabauw data. *Global Planet. Change* **19**, 87–114.

Kain, J. & Fritsch, J. M. (1990) A one-dimensional entraining/detraining plume model and its application in convective parameterization. *J. Atmos. Sci.* **47**, 2784–2802.

Leslie, L. M., Mills, G. A., Logan, L. W., Gauntlett, D. J., Kelly, G. A., Manton, M. J., McGregor, J. L. & Sardie, J. M. (1985) A high resolution primitive equations NWP model for operations and research. *Aust. Met. Mag.* **33**, 11–35.

Lin, C. A., Wen, L., Beland, M. & Chaumont, D. (2002) A coupled atmospheric hydrological modeling study of the 1996 Ha! Ha! River basin flash flood in Quebec, Canada. *Geophys. Res. Letters* **29**(2), 13,1–4

Liu, S., Leslie, L. M., Speer, M., Bunker, R & Mo, X. (2003) The effects of bushfires on hydrological processes using a paired-catchment analysis. *Met. Atmos. Phys.* (in press)

Noilhan, J. & Planton, S. (1989) A simple parameterization of land surface processes for meteorological models. *Mon. Weath. Rev.* **117**, 536–549.

Puri, K., Dietachmayer, G., Mills, G., Davidson, N., Bowen, R., Logan, L. & Leslie, L. (1998) The new BMRC regional assimilation and prediction system. *Aust. Met. Mag.* **47**(3), 203–223.

Seaman, R., Bourke, W., Steinle, P., Hart, T., Embery, G., Naughton, M. & Rikus, L. (1995) Evolution of the Bureau of Meteorology's Global Assimilation and Prediction system. Part 1: analysis and initialisation. *Aust. Met. Mag.* **44**, 1–19.

Shao, Y., Leslie, L. M., Munro, R. K., Iranneijad, P., Lyons, W. F., Morison, R., Short, D. & Wood, M. S. (1997) Soil moisture prediction over the Australian Continent. *Meteorol. Atmos. Phys.* **63**, 195–215.

Wang, Y. (1999) A triply-nested movable mesh tropical cyclone model with explicit cloud microphysics (TCM3). BMRC Research Report no. 74, Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia.