Numerical modelling and land–atmosphere feedback of drought in southeast Australia

X. H. MENG[1], **J. P. EVANS**[1] **& M. F. McCABE**[2]

1 *Climate Change Research Centre, University of New South Wales, Sydney, Australia*
x.meng@unsw.edu.au

2 *School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia*

Abstract Albedo and vegetation fraction play important roles in land–atmosphere interactions and local climate change. In this paper, the influence of these land surface parameters on the evolution of the drought that occurred in southeastern Australia between 2000 and 2008 is investigated. To examine the impact of variable land surface conditions on the hydrometeorology of the region, the Weather Research and Forecasting (WRF) model was used to perform a twin-study under two distinct scenarios. In the first instance, WRF was run in control mode with the default climatological surface albedo and vegetation fraction data sets. Then, these key surface variables were run in experiment mode with data sets derived from available satellite data. Comparison of these simulations demonstrates the importance of capturing the dynamic nature of land surface fields as the climate moves into, and then out of, a persistent multi-year drought. Both simulations capture the drought reasonably well, emphasizing changes in the large-scale circulation as a primary cause. Differences in the surface conditions do, however, provide local influence on the intensity and severity of drought.

Key words Murray-Darling Basin; albedo; vegetation fraction; drought; land–atmosphere interaction

INTRODUCTION

The Murray Darling Basin (MDB) located in southeastern Australia, covers approximately 14% of the Australian land mass and produces one third of Australia's food supply, making it one of Australia's most important agricultural regions (Fig. 1). Three quarters of Australia's irrigated crops and pastures are grown in the basin. However, the water resources of the MDB have been threatened by periods of extended drought. In recent years, the average annual rainfall between 1997 and 2006 was about 16% lower than the climatology value across the whole MDB, which led to a reduction in runoff of 39%. The 7-year averaged rainfall for the period between October 2001 and September 2008 is close to the lowest since 1900 (Potter *et al*., 2010).

The exchange of moisture and heat between the Earth's surface and the atmosphere affects both the dynamics and the thermodynamics of the climate system (Guillevic *et al*., 2002). These interactions have been the focus of much recent inquiry into questions ranging from the maintenance of extreme drought or flood conditions, to the influence of deforestation on rainfall, to responses to increases in atmospheric concentrations of greenhouse gases (Findell & Eltahir, 2003). As two of the most important factors of land surface conditions, albedo and vegetation play important roles in the partitioning of water and energy between the Earth's surface and the atmosphere. In this paper, the time-varying MODIS albedo and vegetation fraction data are used to update the surface boundary condition in the WRF (Weather Research and Forecasting) model to investigate the influence of land–atmosphere interaction on the depth and duration of the drought that happened in the MDB in southeastern Australia. Through this experiment it is anticipated that insight into the function of dynamic as opposed to static surface parameterizations will be gained.

MODEL AND METHODOLOGY

Regional climate model

The WRF model is a widely-used numerical model developed under a collaborative partnership between the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL), the Air Force Weather Agency (AFWA), the Naval Research

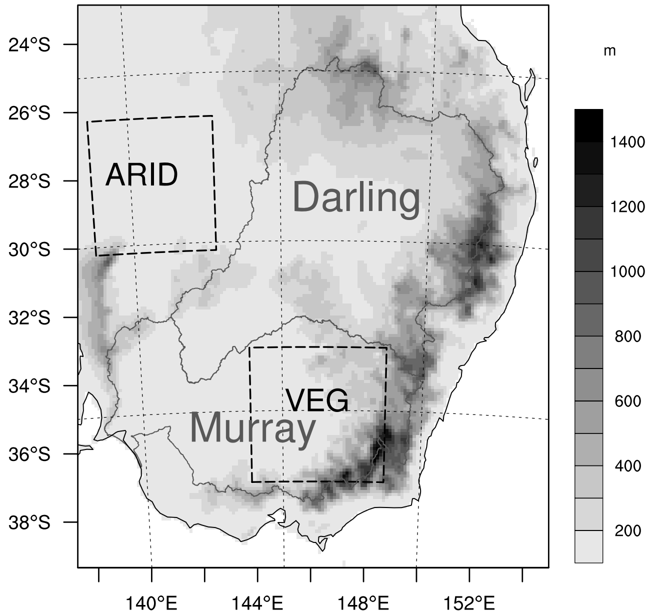

Fig. 1 Topography of the Murray Darling Basin from regional climate model terrain (10-km resolution domain).

Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). The WRF version 3.1.1 was run in this study using the following physics schemes: WRF Single Moment 5-class microphysics scheme; the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme; the Dudhia shortwave radiation scheme; Monin-Obukhov surface layer similarity; Noah land-surface scheme; the Yonsei University boundary layer scheme; and the Kain-Fritsch cumulus physics scheme.

The model simulation uses 6-hourly boundary conditions from the NCEP/NCAR reanalysis project (NNRP) with an outer 50-km resolution nest and an inner 10-km resolution nest that covers southeastern Australia (Fig. 1). Both nests use 30 vertical levels in the planetary boundary layer. The deep soil temperature was allowed to vary slowly with a 150-day lagged averaging period, while the atmospheric CO_2 concentration changed monthly following measurements taken at Baring Head, New Zealand (Evans & McCabe, 2010).

Modelling experiments

The WRF model physics does not predict sea-surface temperature, vegetation fraction, albedo and sea ice. For long simulations, the model reads in these time-varying data and continually updates the lower boundary condition. In this work, WRF was restarted based on the simulations in Evans & McCabe (2010) from 2000 through 2008, using the WRF default climatological albedo and vegetation fraction data and MODIS data. Hereafter these simulations are referred to as WRF_CTL (default data), WRF_ALB (MODIS albedo), WRF_VEG (MODIS vegetation fraction) and WRF_BOTH (MODIS albedo and vegetation). The model had a 15 year "spin-up" of the soil moisture states in a coupled environment.

DATA

WRF climatological data

The albedo product used in the current WRF model was derived from monthly means of clear-sky, surface, broadband, snow-free albedo for overhead sun illumination angle determined using the data captured by AVHRR from April 1985–December 1987 and January 1989–March 1991.

Details of the WRF default albedo can be found in Csiszar (2009). WRF climatological vegetation fraction data was produced by the global 5-year AVHRR NDVI climatology with the same time period as the climatological albedo data. Details of the data can be found in Gutman & Ignatov (1998).

MODIS data

The MODIS albedo data used in this paper is produced by the Nadir BRDF-Adjusted Reflectance (NBAR) at 1000-m spatial resolution and 8-day interval with a 16-day data composite (MCD43B4.005) from 2000 through 2008 based on Liang's (2000) algorithm. The individual band information comes from the MODIS Land Mosaics for Australia in the Water Resources Observation Network (WRON) programme of Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). The original data used to produce the MODIS Land Products for Australia were supplied by the Land Processes Distributed Active Archive Center (LPDAAC), located at the US Geological Survey (USGS) Earth Resources Observation and Science Center (EROS). More details about the data can be found in Paget & King (2008).

Satellite vegetation fraction data used to refresh the WRF lower boundary conditions is produced by the NBAR based on MCD43A4.005, which provides 500-m reflectance data. Detail of the data can be found from Guerschman *et al*. (2009). All of the reflectance and vegetation fraction data can be downloaded from the WRON website (http://wron.net.au/Data/index.html).

To maintain consistency between the MODIS products and WRF climatology, MODIS data were quality controlled then reprojected and resampled temporally and spatially to be consistent with the WRF simulation. The difference between the control and satellite derived albedo and vegetation fraction can be seen in Fig. 2.

To better address albedo changes over the different underlying surfaces, examples of sparsely and densely vegetated areas were selected (Fig. 1), referred to here as ARID and VEG, respectively. Both data sets display similar seasonal cycles in terms of the timing of maximum and minimum values, though WRF_CTL displays a larger cycle in the ARID region and a smaller cycle in the VEG region. Being a monthly climatology, WRF_CTL has no inter-annual variations. On the other hand, MODIS albedo displays significant inter-annual variability. In the ARID region there is a clear step increase in albedo after 2002, after which it remains fairly consistent. In the VEG region, albedo increases from 2001 until 2003, decreases in 2004 before increasing again until 2007.

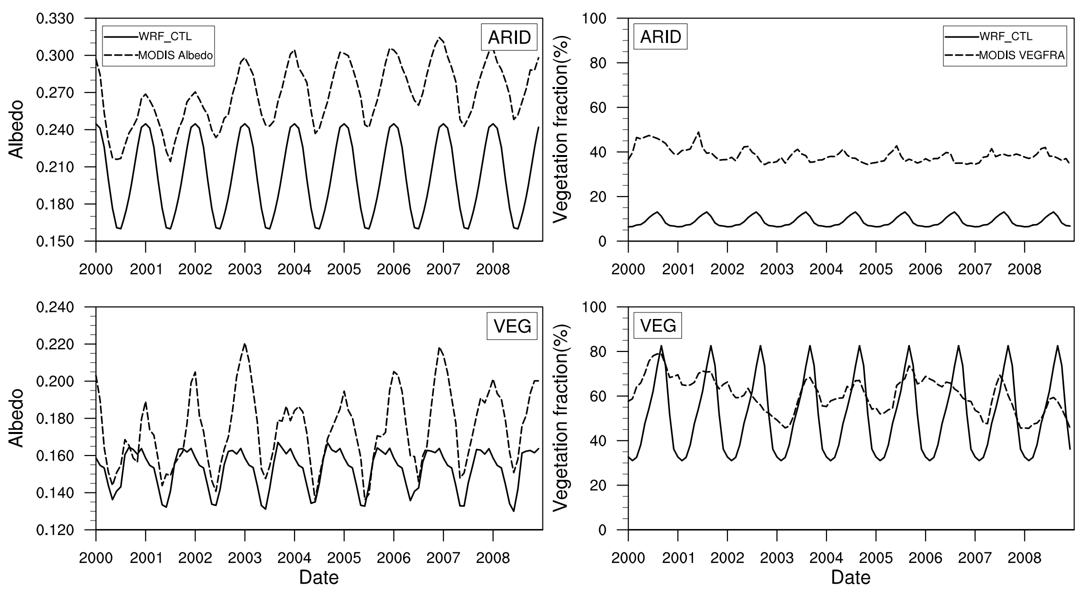

Fig. 2 Default WRF and satellite based albedo and vegetation fraction for the arid and vegetated regions.

As expected, the vegetation fraction minima occur in the summer following the precipitation minima, indicating a clear impact of drought on vegetation density. WRF_CTL shows larger seasonal cycles while MODIS data has more obvious interannual change for both regions, especially for VEG region. MODIS data has larger values for the ARID region and smaller values for the VEG regions most of the time, suggesting that vegetation degradation may have occurred. In addition, vegetation over the VEG region decreased from 2000 to 2003, with a minimum in 2003, but exhibiting partial recovery in late 2003 and 2007 after periods of reduction in 2002 and 2006 respectively.

RESULTS AND DISCUSSION

Results from comparing the simulations with the observations are shown in Fig. 3. All simulations reflect the main trend of air temperature and precipitation. The applications of the MODIS satellite data clearly improve the simulation for air temperature, although WRF_ALB presents a slight degradation in precipitation compared to WRF_CTL. All simulations capture the severe drought period of 2002 and 2006, suggesting that the majority of the changes in temperature and precipitation depend upon the large-scale circulations. Differences between the simulations and WRF_CTL should assist in characterizing the influence of land–atmosphere interactions due to changes in albedo and vegetation density on the local scale climate.

Figure 4 shows the time series of difference for air temperature and precipitation between the new simulations and WRF_CTL. Results show that all MODIS satellite simulations lead to lower air temperature, especially in the case of WRF_BOTH. WRF_ALB and WRF_BOTH produce reductions in precipitation while WRF_VEG enhances precipitation slightly. In addition, the peaks of the precipitation reduction in WRF_ALB and WRF_BOTH simulations occur in 2002, 2006 and early 2008, indicating that the increased albedo amplifies the intensity of the severe drought. At the same time, enhanced vegetation slightly alleviates the drought.

Examining the transition from the relatively wet year of 2000 into the extreme drought year of 2002 shows that the introduction of satellite albedo causes a more rapid decrease in the precipitation, hastening the onset of the drought. Introducing the vegetation fraction change alone tended to slow the decrease in precipitation. The combination of both, however, produced the most rapid decrease in the precipitation and caused the peak of the precipitation deficit to occur earlier than in the CTL simulation.

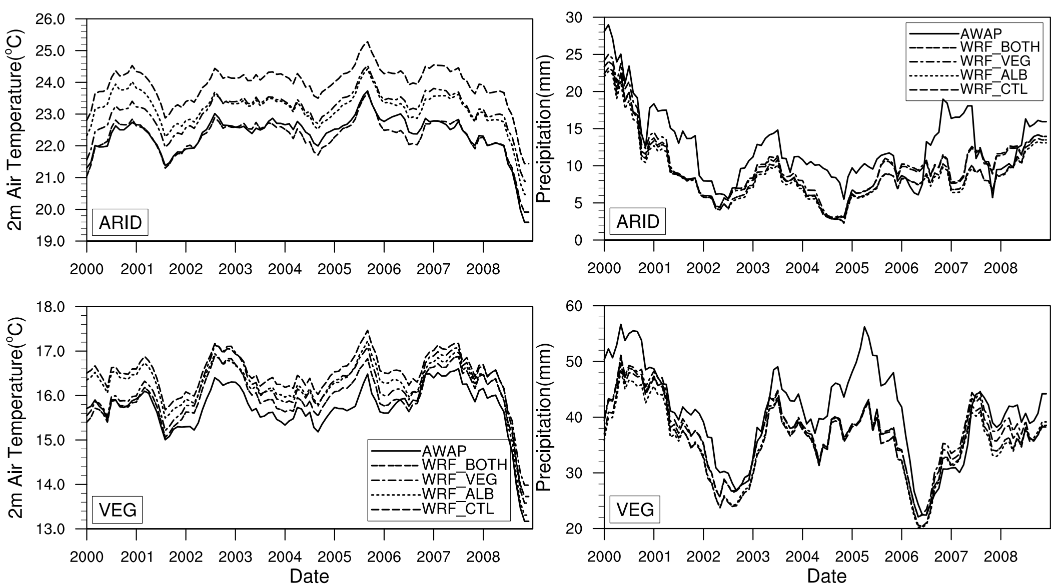

Fig. 3 Simulations for 2-m air temperature and precipitation for the simulations and observations (12- month running average).

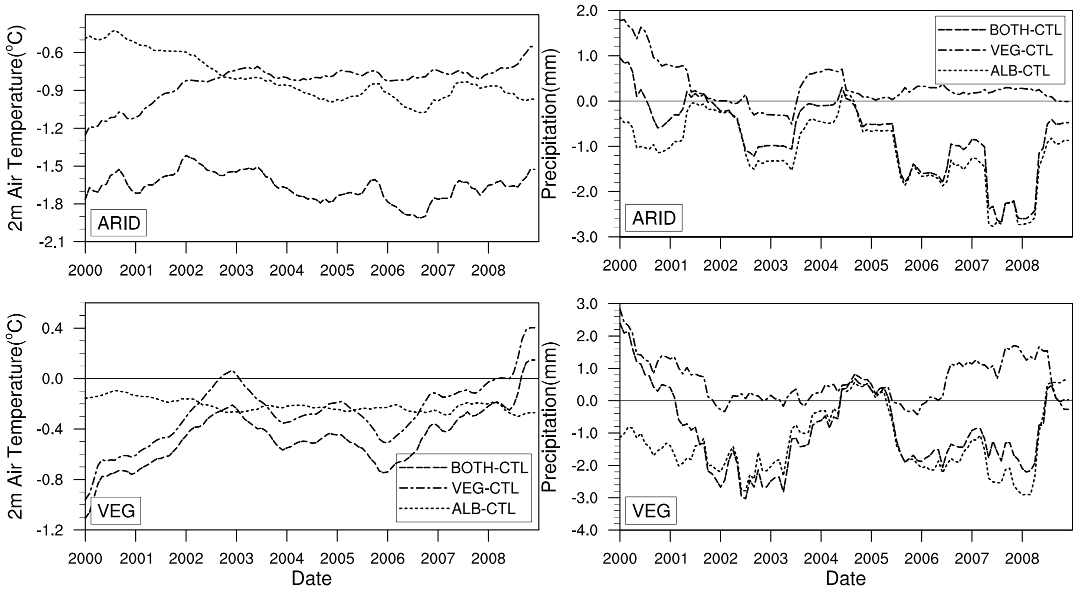

Fig. 4 12-month running average of difference for air temperature and precipitation.

The impact on various components of the surface energy balance is shown in Fig. 5. The change in albedo has the largest effect on the net radiation. In the ARID region these changes are reflected almost completely in the change in sensible heat, while in the VEG region the change in net radiation affects both the sensible and latent heat in a more complicated manner. A similar situation is achieved when changing the vegetation fraction, though a clear decline in latent heating can be seen in the early years. The simulations that change both the albedo and vegetation fraction show that the albedo affect dominates in the ARID region while both contribute to the overall change seen in the VEG region.

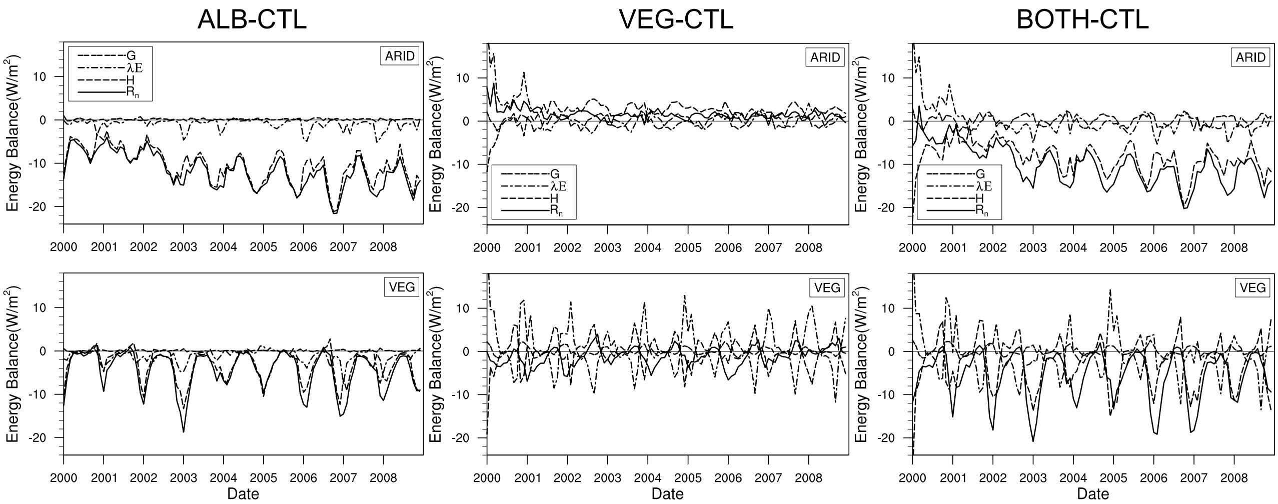

Fig. 5 Monthly average difference in energy components.

The impact on precipitation in different seasons is shown in Fig. 6. Albedo reduces precipitation while vegetation increases it the most in late SON and DJF. The change in albedo does not have a large effect on precipitation in JJA or in early SON. In MAM, albedo decreases the precipitation while vegetation density increases the precipitation. Overall, the combination of changed albedo and vegetation fraction reduces air temperature and precipitation in MDB.

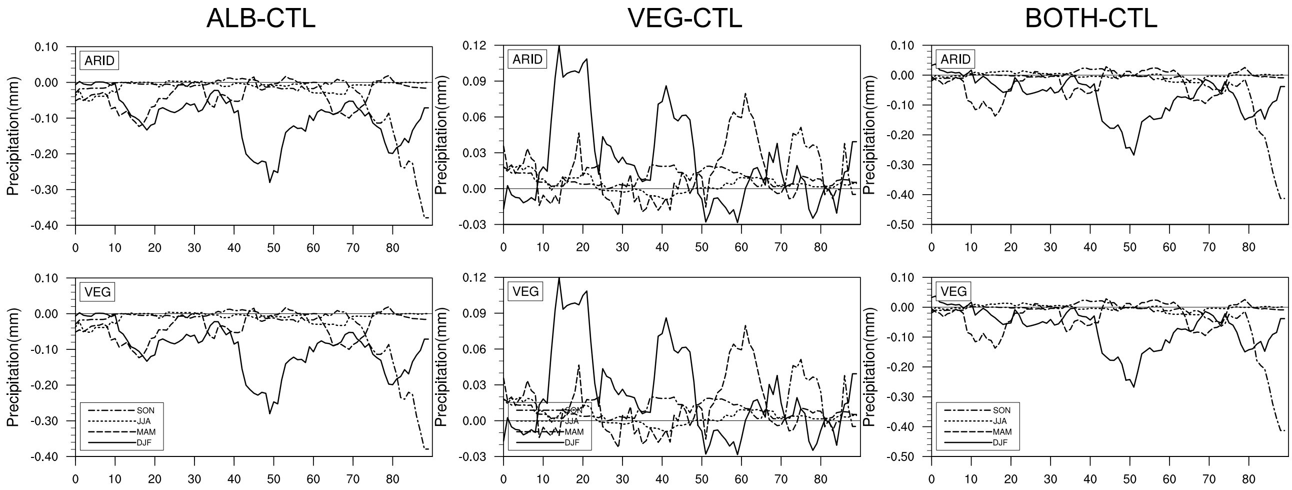

Fig. 6 Daily average of precipitation in different seasons (Dec, Jan, Feb – DJF; Mar, Apr, May – MAM; Jun, Jul, Aug – JJA; Sep, Oct, Nov – SON).

CONCLUSIONS

Dynamic MODIS-derived albedo and vegetation fraction data were used to update the boundary conditions of the WRF model, to simulate the drought that occurred in the Murray Darling Basin and study the influence of the satellite data introduction on the drought. The primary results are:

– analysis shows that the inter-annual variability of the satellite data provides a clear distinction from that of the control data, which are climatological values and do not reflect the changes that occur at the surface throughout the drought;
– introduction of MODIS albedo reduces the precipitation and enhances the drought while the vegetation fraction eases the drought slightly;
– the combination of the two satellite data sets produces the most rapid decrease in the precipitation and caused the peak of the precipitation deficit to occur earlier than in the CTL simulation; and
– influences of land–atmosphere interactions on precipitation differ through the seasons, impacting most in DJF, while relatively small in JJA.

These early results suggest that local land surface feedbacks tend to hasten the onset of drought and increase the severity by 10–15%.

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