INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **31**: 1758–1772 (2011)

(wileyonlinelibrary.com) DOI: 10.1002/joc.2206

Review

Coupled atmospheric and land surface dynamics over southeast Australia: a review, analysis and identification of future research priorities

Jason P. Evans,* Andy J. Pitman and Faye T. Cruz
Climate Change Research Centre, Faculty of Science, University of New South Wales, Sydney, Australia

ABSTRACT: The southeastern Australian climate and climate variability is driven primarily by large-scale climate dynamics. How these dynamics translate into local effects is influenced by the nature of the landscape, the vegetation, soil moisture, fire, snow, irrigation and orography. This local land-atmosphere coupling can enhance or moderate the large-scale dynamics and have significant influences locally and regionally. This paper reviews the state of knowledge of the coupled land-atmosphere dynamics over southeast Australia and identifies the challenges for future research. Relevant processes are investigated and if possible their importance to regional climate is identified. Many coupled land-atmosphere dynamic processes, identified as important in the Northern Hemisphere studies, remain to be studied in southeast Australia. This represents an important priority for Australian research because this will establish their role in future changes in regional climate over Australia. However, this also represents a significant international priority because the very high natural climate variability in the region provides a laboratory to examine how coupled land-atmosphere dynamic processes may change in other regions if global warming increases the range of natural variability. Copyright © 2010 Royal Meteorological Society

KEY WORDS land-atmosphere coupling; regional climate; southeast Australia; soil moisture; vegetation; fire; snow; irrigation

Received 17 November 2009; Revised 18 May 2010; Accepted 24 June 2010

1. Introduction

Australia's population and agricultural production are highly concentrated in the southeast of the country. This region includes the Murray–Darling Basin (MDB), one of the world's major river basins (Figure 1). The MDB is the focus of international research through its status as a Regional Hydroclimate Project of the Global Energy and Water Experiment (GEWEX), a project of the World Climate Research Programme (WCRP). This key agricultural region in Australia provides about 40% of the nation's agricultural product (CSIRO, 2008). Significant efforts to understand the climate and observed changes in the climate of this region have been undertaken (Murphy and Timbal, 2008). This focus partly relates to the significant economic cost to the nation for changes over the MDB (Adams *et al.*, 2002) and also because of the likely vulnerability of this region to future climate change (CSIRO, 2007) including heat stress, drought, bush fire and flood.

Murphy and Timbal (2008) provided a thorough and timely review of the recent climate variability and climate change over southeast Australia. Southeast Australia experiences one of the most variable climates on Earth (McMahon *et al.*, 1992). Like most regions, the southeastern Australian climate and climate variability is driven primarily by large-scale climate dynamics (Karoly and Vincent, 1998). This is not only an El-Niño-Southern Oscillation (ENSO) driven variability (McBride and Nicholls, 1983; Jones and Trewin, 2000). The Indian Ocean dipole exerts a significant influence on longer time scales (Ashok *et al.*, 2003; Ummenhofer *et al.*, 2009). Furthermore, tropical and extratropical Pacific Ocean sea surface variability (Nicholls, 1989; Drosdowsky and Chambers, 2001), the location of the subtropical ridge (Drosdowsky, 2005; Williams and Stone, 2009), the Southern Annular Mode (Donald *et al.*, 2006) and the Madden–Julian Oscillation (Wheeler *et al.*, 2009) all contribute to the climate and climate variability of the region.

While the climate of southeastern Australia is dominated by large-scale processes, the nature of the landscape, vegetation, soil moisture, fire, irrigation, snow and orography interact with the large-scale forcing. Murphy

---

* Correspondence to: Jason P. Evans, Climate Change Research Centre, The University of New South Wales, Sydney, NSW 2052, Australia. E-mail: Jason.evans@unsw.edu.au

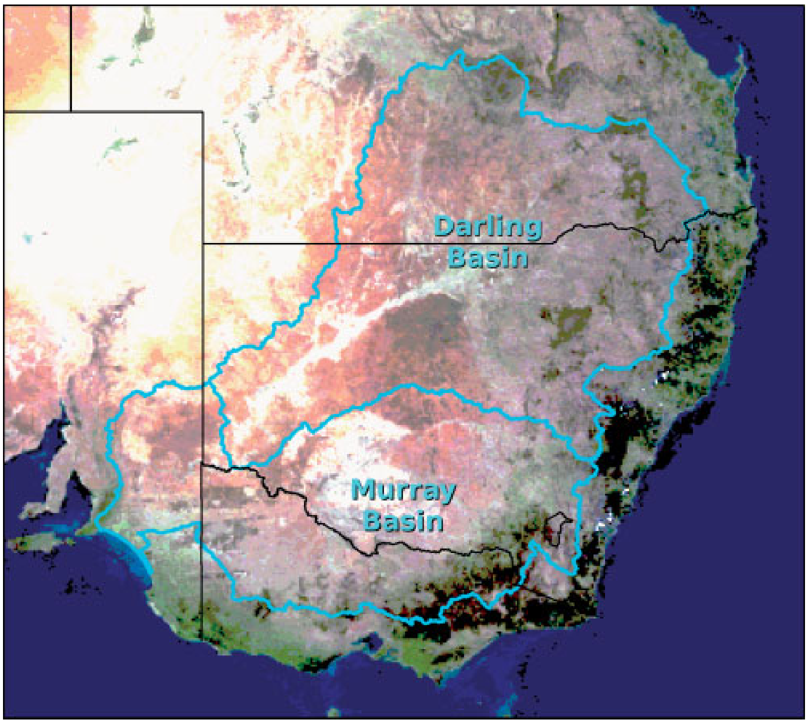

Figure 1. State of southeast Australia as viewed by the MODIS satellite sensor. Image was produced using the bidirectional reflectance distribution function applied to images taken on 1–16 June 2009. This is a natural colour composite using MODIS bands 1, 5 and 4 as RGB. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

and Timbal (2008) provide an extensive analysis of the key large-scale drivers, but do not assess whether the terrestrial components affect the regional climate. This review paper builds from Murphy and Timbal (2008) to focus on the contribution that the regional scale atmospheric and land surface dynamics make to the hydroclimatology, and hence to the natural resource management (NRM) of southeastern Australia, with a particular focus were possible on the MDB. Some of these terrestrial processes are locally important but regionally likely insignificant. Others, through spatial aggregation of the small-scale processes, may lead to the amplification or moderation of the larger-scale forcing. In many cases, in contrast to intensively studied regions in Europe and the United States, the contributions of local and regional-scale processes on the larger-scale hydroclimatology are not known. We will identify those processes which are known to be important, those that are unlikely to be important and those that we cannot currently assess in terms of their importance and thus require further research. We suggest that this review paper should be read after Murphy and Timbal (2008); their paper sets the scene and elucidates the large-scale drivers of climate and climate variability of southeastern Australia and the MDB. We extend their paper into the more local and regional drivers and processes that interact with the large-scale drivers to define the regional climate.

This article is divided into three major sections. First, the nature of the land–atmosphere coupling is discussed to provide the framework for the next section, which addresses the specific components of the terrestrial system that may be regionally important over southeast Australia. Finally, a discussion of the current state of knowledge and suggestions for future work are provided.

2. Land–atmosphere coupling

The land and atmosphere systems are coupled. Both provide feedbacks that can change the state of the other. Modelling the regional climate depends critically on the coupling between the surface energy fluxes, boundary layer clouds and radiation fields (Betts *et al.*, 1996). One important effect is the way the changes in the land surface can change albedo, thus changing the energy available to drive surface processes. Another key role is the way the land surface affects the partitioning of available energy between sensible and latent heat which is controlled by moisture availability and the capacity of the soil-vegetation system to supply water to the surfaces where evaporation occurs (Figure 2).

Figure 2 shows the primary feedback loop between the land and the atmosphere. The atmosphere provides the driving variables for surface processes (radiation and precipitation) and the surface, in turn, changes the characteristics of the planetary boundary layer (PBL) and hence clouds affect both the radiation and precipitation reaching the ground. Thus, land surface dynamics that change the albedo or evaporative fraction (EF) enter a feedback loop with the atmosphere and the magnitude of the change induced depends on the coupling strength between the land and the atmosphere. Changes in winds are not present in Figure 2. Winds near the surface

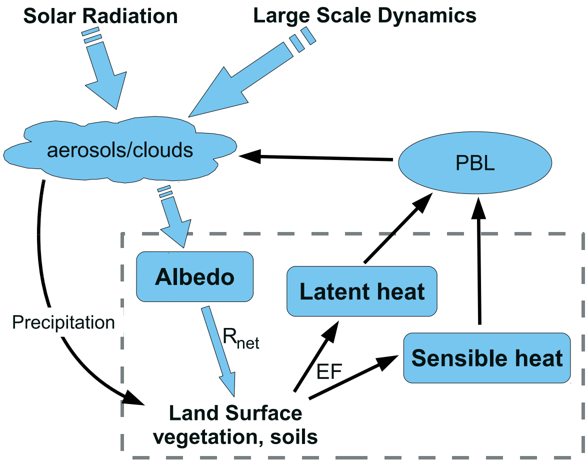

Figure 2. Schematic of the main interactions between the land surface and atmosphere. The land surface effects are contained within the dashed box. The albedo determines the net radiation (Rnet) reaching the surface. The state of the vegetation and soils determines the partitioning of this energy between latent and sensible heat, referred to as the EF. The latent and sensible heat release determines the characteristics of the PBL which impacts the growth of clouds and the advection and mixing of both clouds and aerosols. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

are affected by the surface roughness and in turn can change the EF and PBL growth, as can the production of aerosols. While these effects are usually of secondary importance, there are circumstances under which they may dominate. Almost all land and atmosphere dynamics involve some coupling between them. For example, soil moisture and irrigation have a direct influence on evaporation which can be linked to precipitation (Boucher *et al.*, 2004; Notaro, 2008). Land cover change (LCC) can affect local scale wind patterns and moisture convergence, and fire has both the immediate effects of thermal convection and aerosol production but also produces a significant regional-scale LCC. While the importance of this coupling has received increasing attention internationally, to date no work has explicitly considered it over southeast Australia.

Betts (2004) explored the nature of the coupled land–atmosphere system for the Northern Hemisphere summer. He notes that away from the monsoon regions, a large evaporation–precipitation feedback exists over the continents and the system memory of initial soil moisture anomalies is longest at high northern latitudes. Betts (2004) analysis is focused on a suite of examples in the Northern Hemisphere, but did not analyse the Southern Hemisphere systems relevant for southeast Australia.

Traditionally, each system has been considered in isolation with research into land dynamics treating the atmospheric state as a known input including variables such as air temperature, precipitation, humidity, wind speed and radiation. Similarly, atmospheric research has treated the land surface as a known lower boundary condition including variables such as soil moisture, vegetation cover, surface temperature, albedo and topography. In reality, these systems are coevolving. Perhaps the clearest example is evaporation which depends on land state variables such as soil moisture and vegetation cover and atmospheric variables such as solar radiation, temperature, humidity and wind speed. The process of evaporation changes the soil moisture and the humidity, and in the process provides a feedback that then changes the rate of evaporation.

Many other feedbacks also occur between the land and the atmosphere. For example, changes in surface temperature and albedo can change the surface pressure and wind speed, which will change the evaporation rate and feedback to the surface by changing the surface temperature. This coupling is particularly important for NRM when changes in the land surface produce instabilities in the lower atmosphere PBL that can produce precipitation which, in turn, changes the properties of the land surface. In some locations, such as the Amazon basin, this coupling between the land surface and atmosphere is particularly strong with as much as 50% of the precipitation that falls within the basin being derived from the land surface in the basin (Salati *et al.*, 1983; Salati and Vose, 1984), this is known as precipitation recycling. While the level of precipitation recycling in the MDB is unknown, the semi-arid nature of much of the basin suggests that other factors inhibit precipitation production and hence precipitation recycling would be considerably lower than values found in humid basins around the world, perhaps only 10–15%.

The precipitation recycling ratio is one way to define the strength of the land–atmosphere coupling. The first few attempts to quantify the recycling ratio were made using bulk formulations (Brubaker *et al.*, 1993; Burde and Zangvil, 2001a,b). Trenberth (1999) used a bulk formulation with an assumed length scale to create global estimates of the recycling ratio. Recently, Anderson *et al.* (2008) defined the local convergence ratio as an alternate measure to the precipitation recycling ratio. This quantifies the local evaporative contribution to the rate of precipitation rather than to the total precipitation. From a water resource's perspective, the recycling ratio within particular watersheds is more important but because natural watersheds often have complicated shapes, the application of bulk formulations to obtain recycling estimates remains difficult.

While not routinely done, efforts have been made to explicitly track the source region for water vapour within climate model simulations (Druyan and Koster, 1989; Bosilovich and Schubert, 2002). This method is attractive in theory as the tracking of water vapour fluxes is inherently consistent with the rest of the model simulation, but it is computationally expensive. It is also necessary to define the water vapour source regions of interest prior to the simulation and new simulations must be performed to investigate other water vapour source regions. Lagrangian back trajectory methods can calculate the water vapour source regions for arbitrary shapes (e.g. natural watersheds) and use existing climate model simulation output. Various studies using Lagrangian back trajectory modelling have been performed that use climate model or reanalysis output to calculate these water vapour source regions (Brubaker *et al.*, 2001; Stohl and

James, 2004; Dirmeyer and Brubaker, 2007). These back trajectory methods have the advantage of using existing data sets and are applicable to arbitrary surface areas for studies ranging in temporal scale from storm events to many years. However, they use assumptions that may be broken such as the entire atmosphere being well mixed vertically.

Koster *et al.* (2004) produced the most comprehensive study of the strength of land–atmosphere coupling. They used an ensemble of a suite of global climate models (GCMs), all performing the same experiments, to identify 'hot-spots' of coupling during the Northern Hemisphere summer. This coupling appears strongest in summer and hence almost all the areas identified were in the Northern Hemisphere. With a focus on more local scale effects Santanello *et al.* (2005, 2007) studied the coupling effect on the growth of the PBL and low level atmospheric stability. They found that diurnal conditions such as the atmospheric stability are coupled with soil moisture and this coupling is reflected in the evolution of the PBL. Work continues on the quantification of the strength of this relationship. The land–atmosphere coupling can also be important for heat waves in Europe where Fischer *et al.* (2007) found that the coupling increases the heat wave duration, accounting for 50–80% of the number of hot summer days.

The continued development of fully coupled regional climate (dynamical downscaling) models internationally has produced a suite of high quality tools for examining this land–atmosphere coupling and understanding the implications of changes in land use and climate within this coupled context. While little such work has been performed in the MDB to date, many of the techniques to quantify the importance of this coupling are mature enough to be applied to the MDB and provide an estimate of just how important these effects are in the future NRM. This may be particularly important when considering future climatic extremes where this coupling may act to amplify events.

3. Land dynamics

There are several terrestrial processes that may influence how a region responds to the large-scale forcing that defines the climate and climate variability of southeastern Australia and the MDB.

3.1. The role of soil moisture

Soil moisture is an integrator, over time, of precipitation. The role of soil moisture varies geographically. Changes in soil moisture can change both the albedo and EF on the land surface. While most of Australia is water limited, the moisture content of the soil can be a significant factor in the amount of moisture exchanged with the atmosphere at regional scales. The moisture exchanged with the atmosphere comes from varying soil depths, with ground evaporation using moisture from a shallow top layer and transpiration potentially reaching down several metres into the soil (Notaro *et al.*, 2008). Unfortunately, most of the literature on the impact of soil moisture on the atmosphere comes from highly seasonal Northern Hemisphere climates (Robock *et al.*, 1998; Entin *et al.*, 2000) and is not easily applied to southeastern Australia.

In regions of North America, Europe, Eurasia and the tropics, soil moisture is effectively reset at least annually by being brought back to saturation (Robock *et al.*, 2000; Figure 5). Low evaporative demand in winter and periods of seasonal rainfall means that the soil moisture anomalies do not typically propagate between years. Indeed, Bosilovich and Sun (1999) suggest that the typical time scales of variability in the near-surface (1 m) soil moisture are about 1.5–2.0 months.

In southeastern Australia, droughts can be sustained for many years leading to complex interactions between soil moisture and the atmosphere that may persist through multiple years (Figure 3). International evidence suggests that large-scale soil moisture anomalies can cause persistence in both drought and flood periods. Oglesby and Erickson (1989), for example, showed that droughts could cause surface warming, reduce surface pressure, perturb the location of synoptic systems and reduce rainfall; but whether this could develop over southeastern Australia is unknown since no studies have directly examined this. Bosilovich and Sun (1999) concluded that soil moisture anomalies across North America significantly enhanced the 1993 summer floods across the midwest United States, a result that helped re-enforce the findings of Beljaars *et al.* (1996) who found precipitation anomalies to be linked to soil moisture conditions. The critical point in these studies is that the atmospheric dynamics are conducive to take evaporated soil moisture and recycle it locally or regionally as enhanced precipitation. That

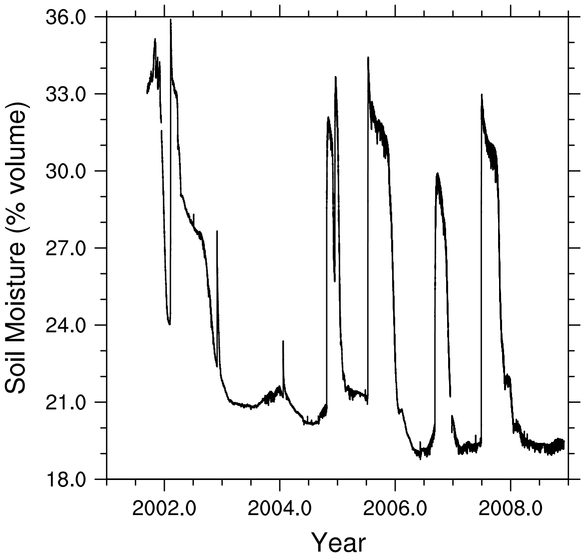

Figure 3. Soil moisture measured at Cooma airfield, every 30 min, as part of the Oznet soil moisture network (http://www.oznet.unimelb.edu.au/). The soil was saturated in early 2002 before experiencing a multi-year drought. While experiencing a recovery in 2005, the soil moisture has not been able to reach saturation again.

is, for soil moisture anomalies to have a strong regional-scale impact, a soil moisture anomaly and an atmosphere that has the potential to generate rainfall are required.

This issue was explored systematically by Koster *et al.* (2004) who identified regions where land surface processes were tightly coupled to the atmosphere and appeared to directly modify the regional atmosphere. No region of Australia represented a 'hot spot' because the study was limited to the Northern Hemisphere summer. However, many of the 'hot-spots' identified by Koster *et al.* (2004) were in the Northern Hemisphere semi-arid regions which hint that the semi-arid regions of Australia might be a significant 'hot spot' during the Australian summer. Resolving this issue requires a Southern Hemisphere summer focus but unfortunately, relative to studies overseas (particularly North America), the study of the impact of soil moisture, soil moisture variability and soil moisture anomalies in Australia is very limited.

Observationally based assessments of the role of soil moisture in influencing the regional climate are undermined by limited observations of soil moisture worldwide. Soil moisture obviously varies spatially and temporally over the MDB, as highlighted by both observations and modelling. There are two monitoring sites in southeast Australia, one in the Goulburn River catchment (Rudiger *et al.*, 2007) and the other in the Murrumbidgee River catchment (Young *et al.*, 2008). The Murrumbidgee site has 38 soil moisture monitoring instruments that have been in operation for more than 5 years. This is insufficient to establish the role of soil moisture in affecting the regional climate in a region where the large-scale climate forcing is so variable. Supplementing these *in situ* data with microwave remote sensing has been attempted (Merlin *et al.*, 2008; Panciera *et al.*, 2008; Saleh *et al.*, 2009). The microwave measurements, which estimate soil moisture on top of approximately 2 cm of soil, were reinforced with *in situ* measurements and results indicate considerable future potential for this technique. Deeper soil moisture and groundwater measurements using a combination of Gravity Recovery and Climate Experiment (GRACE) data with *in situ* and modelled hydrological data were reported by Leblanc *et al.* (2009). They showed that the propagation of the water deficit through the hydrological cycle could give rise to different types of drought. While the surface soil moisture storage dried to very low (and stationary) levels after approximately 2 years, GRACE measurements showed groundwater levels still declining 6 years after the onset of the recent drought.

Studies that directly link observations with modelling of soil moisture–atmospheric interactions are very rare in Australia. The only integrated study over the entire MDB was conducted by Liu *et al.* (2009) who compared Global Land Data Assimilation System (GLDAS) output over the MDB against retrievals from the Advanced Microwave Scanning Radiometer-Earth (AMSR-E) sensor on-board NASA's Aqua satellite. Liu *et al.* (2009) investigated the spatial distribution and coherence of soil moisture under both wetting and drying conditions. Spatially, the AMSR-E observations and GLDAS simulations show similar seasonal patterns and while there were biases, these do not appear too limiting. From the temporal perspective, the match between AMSR-E and model results vary seasonally and the authors conclude that both products contain some skill, but further research is essential to determine how to best blend the different soil moisture products.

Further insight can be gained from regionalization of global-scale studies. Notaro (2008) used the results from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4) and showed a clear correlation between higher soil moisture and subsequently higher rainfall in some regions. While the region of southeast Australia appeared to be particularly insensitive to soil moisture anomalies, the seasons examined were largely Southern Hemisphere winter which negates any large-scale impact between soil moisture and rainfall over Australia. Notaro (2008) included one estimate for the Australian summer, hinting that soil moisture is regionally important in southeast Australia. A sustained soil moisture anomaly of 40 mm caused a mean soil moisture feedback of +90 mm/month with 15 of 19 IPCC models simulating a positive feedback where higher soil moisture leads to higher precipitation (Figure 4). However, this was a sensitivity study that demonstrated a potential role, but it is difficult to translate this into a physical understanding of the real system.

Two recent studies have explored the role of soil moisture anomalies over Australia. Timbal *et al.* (2002) explored how soil moisture links ENSO to rainfall patterns over Australia. They used a low-resolution climate model, with an overly simplified land surface model which is likely to underestimate the time scale of the feedback between soil moisture and the atmosphere. The simple hydrological scheme used has a propensity towards drought-like soil moisture states which increases the autocorrelation of precipitation. Timbal *et al.* (2002) performed a series of experiments that either allowed soil moisture to vary or held it fixed to the annual seasonal

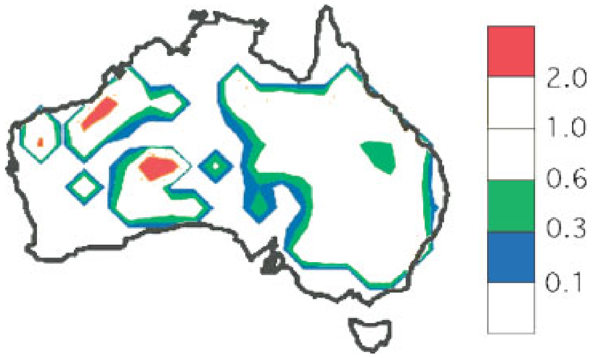

Figure 4. Mean December, January and February soil moisture feedback parameter among 19 IPCC models, which statistically estimates the impact of total soil water on precipitation. Units are (cm/month)/(40 kg/m^2). The unit 40 kg/m^2 represents a typical standard deviation in total soil water over the central United States feedback hot spot (adopted from Notaro, 2008). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

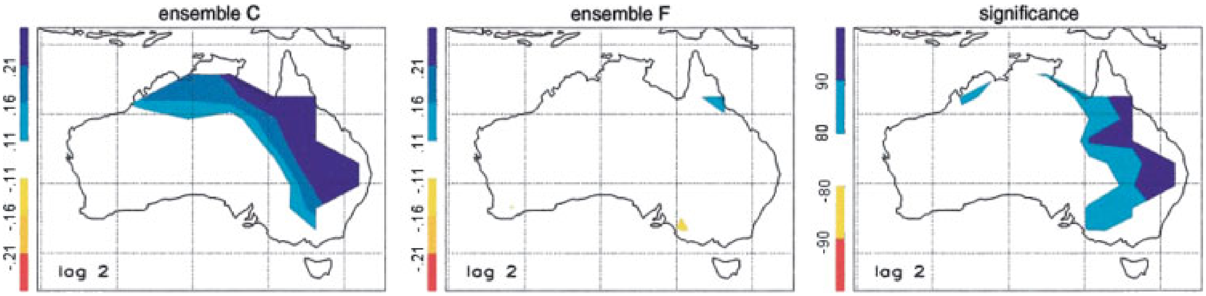

Figure 5. Correlation between precipitation and the SOI over Australia for all months during the period 1979–1988 with precipitation lagging behind SOI by 2 months: (left) with freely varying soil moisture and (centre) with fixed soil moisture. The impact shown left is statistically significant (right) at a 90% confidence level over the east (adopted from Timbal *et al*., 2002). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

cycle derived by averaging over the varying simulations. This effectively 'decouples' the role of soil moisture on atmospheric predictability. They found that the simulated variability in temperature and rainfall was reduced when soil moisture was fixed, particularly in summer. Perhaps more surprisingly, Timbal *et al*. (2002) also showed that the ability to capture the correlation between the Southern Oscillation Index (SOI, a measure related to ENSO) and precipitation was strongly moderated by soil moisture variability (Figure 5).

Finally, Zhang (2004) used results from the Atmospheric Modelling Intercomparison Experiment (AMIP) to determine whether soil moisture could affect the simulated variability. Lag-correlation analysis highlighted that the 'climatic memory' of soil moisture differed between the models. Those models that used the simple bucket-type hydrology schemes tended to have a rapid decay rate in the retention of soil moisture anomalies and showed rapid feedback between land surface and the overlying atmosphere. They also tended to show a much weaker influence of soil moisture conditions on the surface climate. In contrast, if a more sophisticated scheme was incorporated, the slower interaction between soil moisture and the atmosphere tended to cause impacts on longer time scales.

Soil moisture obviously affects the climate of the MDB. Clearly, most rainfall that reaches the surface does not flow to the ocean in this region – rather it is evaporated over time back into the atmosphere. Under conditions of high soil moisture availability, there must be a feedback between this soil moisture, atmospheric water vapour and the probability of rainfall to some degree. The studies that have explored the degree to which soil moisture might enhance the predictability of rainfall are very limited. Timbal *et al*. (2002) suggest that soil moisture does provide additional predictability and does provide a link between the SOI and rainfall – but their methodologies are limited by relatively simplistic land surface models and coarse resolution climate models. Zhang's (2004) findings conclusively highlight problems with simple land surface schemes, but do not provide a definitive answer to how important soil moisture is over the MDB.

3.2. The role of vegetation dynamics and CO_2 fertilization

There is a direct link between changes in atmospheric CO_2 and the ways the land surface interacts with the atmosphere. Observations have shown a direct impact of CO_2 on the stomates of plants (Field *et al*., 1995; Drake *et al*., 1997; Ainsworth and Long, 2005). Increased CO_2 has a fertilization effect which stimulates the rate of photosynthesis and can lead to increases in growth, above-ground biomass and crop yield in the long term (Ainsworth and Long, 2005). These plant responses vary according to species, functional groups and growing conditions (Ainsworth and Long, 2005). The CO_2 fertilization effect is generally affected by resource limitations (light, water and nutrients) and environmental stresses. The response of the leaf area index (LAI) to increases in CO_2 is likely to be small in water-limited ecosystems since these regions are typically also nutrient-limited (Field *et al*., 1995).

If stomatal function changes and the fertilization effect is significant, the net primary productivity (NPP) of individual plants and ecosystems can change. Changes in the NPP can affect the competitive advantages of some plants over other plants leading to changes in the biodiversity of ecosystems. This includes vegetation dynamics whereby species germinate, grow and compete with one another. The presence of disturbances is a driver of this competition dynamic. These drivers can be abrupt such as fire or relatively slow such as climate change which is the major driver of vegetation over long time scales. Vegetation affects the climate by modifying the radiative (albedo), momentum and hydrologic balances EF of the land surface (Pitman, 2003). The main terrestrial sink for increasing atmospheric CO_2 is via plants and if plants take up more carbon they will respond physiologically, structurally and biogeographically.

The impact of CO_2 on plant physiology has implications at the ecosystem, regional and global levels beyond the changes at the leaf and plant scale. While there have been many global-scale modelling studies (Martin *et al*., 1999; Cruz *et al*., 2008; Boucher *et al*., 2009; Cao *et al*., 2009), the impacts of higher CO_2 on plant physiology are usually highly regionalized. This requires studies focused on southeastern Australia, but a major problem is that most climate modelling is based on Northern Hemisphere vegetation types and these do not reflect the nature of Australian vegetation. This ranges from not representing the key Australian vegetation at all (e.g. *Eucalyptus*), through to combining all Eucalyptus into a singe vegetation type, through to common problems of how to capture the impact of climate and higher CO_2 on vegetation function and dynamics. In the case of endemic Australian vegetation, Eucalyptus has considerable drought tolerance and is commonly coupled with groundwater (Eamus and Froend, 2006) implying a particularly deeply rooted ecosystem in some locations. Indeed, the whole issue of roots in global change is problematic (Norby and Jackson, 2000; Feddes *et al.*, 2001). A significant change in root depths could decouple large-scale ecosystems from groundwater or allow some water-restricted ecosystems to reach groundwater and therefore survive in drought affected areas. The likelihood of these sorts of feedbacks occurring in southeastern Australia is unknown. The impact of failure to represent Eucalypts was explored by Peel *et al.* (2005). They showed that several classifications of Eucalypts were required and proposed suitable parameter values for this classification. Impacts on both rainfall and temperature were simulated if poor parameter choices were made – impacts that relate to large differences in several vegetation parameters including stomatal conductance and roughness length.

There is very little regionally specific research in this area. Almost all major assessments of the impact of climate change over southeastern Australia are based on climate modelling results that assumes a Northern Hemisphere vegetation classification, and no change in vegetation type and no change in plant physiological responses. Global studies using dynamic vegetation (Delire *et al.*, 2004) have found that the two-way coupling between the vegetation and atmosphere introduces persistent precipitation anomalies in ecological transition zones. In Australia, the transition zone is between savannah and desert and covers much of the semi-arid portion of the country. While this study was conducted at a course global scale, the results suggest that this dynamic coupling is important for the climate of southeast Australia. Using remotely sensed observations globally, Liu *et al.* (2006) identified regions of strong vegetation–climate coupling. They found an area with positive forcing of vegetation on local precipitation in Australia, though this was confined to the North.

Globally, evidence points to the greening of vegetation particularly at high northern latitudes, over the last century or more (Notaro *et al.*, 2005). There is some crucial observational evidence of large-scale vegetation change over southeastern Australia. Donohue *et al.* (2009) used the Advanced Very High Resolution Radiometer (AVHRR) data spanning 1981–2006 and calibrated for long-term analyses of vegetation dynamics. They examined whether vegetation cover has increased across Australia and whether there has been a differential response of vegetation functional types in response to changes in climatic growing conditions. Australia-wide, they found an increase over the 26 years in the fraction of photosynthetically active radiation (fPAR) absorbed by vegetation which they used as a measure of vegetation cover. They noted that some of these changes were driven by rainfall, but where vegetation cover increased at water-limited sites precipitation did not necessarily increase, which they suggested hints at an increase in water-use efficiency. While Donohue *et al.* (2009) noted that, overall, the response of vegetation over the past two to three decades has been an observable greening over Australia, a careful review of their results for southeastern Australia points to a contrasting result. Over the MDB there has been a decrease in fPAR – in fact the strongest decrease observed over the continent (Figure 6). This is largely a response to the decline in rainfall over this period although they noted that local soil conditions are also important. There is also strong observational evidence that plants in elevated CO_2 show increased growth and increased rates of photosynthesis. Pritchard *et al.* (1999) and Curtis and Wang (1998) both undertook meta-analyses and reported significant increases in above-ground biomass as a mean response to elevated CO_2 conditions. These were short-term studies and the increase in growth may not be sustained over longer time scales due to nutrient limitations (McMurtrie and Comins, 1996).

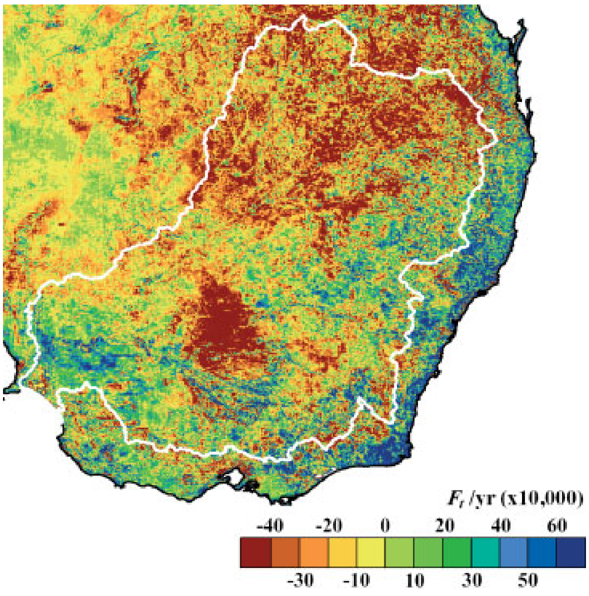

Figure 6. Trends in total fraction of photosynthetically active radiation absorbed by vegetation, 1981–2006 (adopted from Donohue *et al.*, 2009). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Increases in atmospheric CO_2 also directly affect surface–atmospheric interactions. The decreased stomatal conductance results in decreased latent heat flux and thereby warmer temperatures over southeastern Australia. Indeed, Cruz *et al.* (2010) showed that increasing leaf-level CO_2 could increase the probability of higher temperatures via daytime suppression of transpiration (from midday through the afternoon), accompanied by changes in convective rainfall. Cruz *et al.* (2010) also showed that the impact of the moisture availability on the physiological feedback over Australia could indirectly lead to more rainfall and reduce the warming effect of decreased transpiration. The influence of the availability of moisture suggests that the potential impact of the physiological feedback on the future climate may be affected by uncertainties in rainfall projections, particularly for water-stressed regions. However, this work is limited by the parametrization of these processes in climate models and the use of a single climate model.

At a global scale, Notaro *et al.* (2007) investigated the radiative and physiological forcing of CO_2 and found the radiative effect dominating in Australia, resulting in soil drying and reduced forest cover. At a regional scale, changes in vegetation type, function and cover are not included in any assessments of how southeastern Australia will respond to climate change, but Donohue *et al.* (2008) and Cruz *et al.* (2008) provide evidence that physiological and vegetation dynamics affect the basin on time scales of decades. In terms of a whole of basin modelling assessment of how southeastern Australia will respond to climate change, recent research and model development provide the framework for the explicit inclusion of the way vegetation responds to increasing CO_2. However, while the basic vegetation dynamics can now be included, the issue of nutrient–groundwater–vegetation interactions is not well developed. A major effort to understand how vegetation will react to increasing CO_2 and climate changes at fine spatial scale, and in mind of nutrient and groundwater systems is a major challenge.

The climate model results depend on the parametrization of the response of the stomates to increased CO_2 in the land surface model used, which involves an uncertainty given limits in our current understanding on the vegetation response (Ainsworth and Rogers, 2007). Thus, additional field experiments can provide helpful information to realistically represent the response of agricultural and native ecosystems over the MDB to elevate CO_2 in land surface models and to verify model results. Future experiments for the MDB will need to incorporate changes in vegetation structure and dynamics, including acclimatization, to account for the fertilization effect of increased atmospheric CO_2 and associated climate changes (Calvet *et al.*, 2008) under conditions of limited nutrient and water availability in the basin. Given the projected increase in atmospheric CO_2, it is important that future climate projections and assessments include the impact of these biospheric feedbacks to minimize the risk of underestimating the vulnerability of the MDB to climate change.

3.3. The role of land cover/land-use change

Observations (Lyons *et al.*, 1993; Lyons, 2002; Ray *et al.*, 2003) and model simulations have demonstrated that LCC is an important anthropogenic forcing of the observed regional climate changes in Australia. Most of the change in the land cover for the past 200 years has occurred in southeast, southwest and northeast regions (AUSLIG, 1990)). Narisma and Pitman (2003) found that the conversion of woody vegetation to crops and grass over southeast Australia since the European settlement in the late 1700s resulted in statistically significant warming of 0.4–1 °C with possible reductions in rainfall and changes in wind patterns in January. McAlpine *et al.* (2007) supported these results with ensemble simulations which indicated a statistically significant annual warming of 0.1–0.6 °C and 4–8% rainfall decrease with stronger responses in the summer. Unfortunately, Narisma and Pitman's (2003) results were limited to January-only simulations and McAlpine *et al.*'s (2007) results used a simple land surface model that did not represent vegetation explicitly. There is also some evidence that the LCC over southeastern Australia affects extreme climates (Deo *et al.*, 2009), but again this is based on a simple land surface model. All existing assessments on the role of LCC on southeastern Australia are fundamentally limited by the experimental design whereby only a single climate model is used.

LCC affects the regional climate through the changes in the properties of the vegetation and soil surfaces (Pitman *et al.*, 2009). Changes in the surface albedo induce a radiative forcing (Forster *et al.*, 2007) and affect the terrestrial net radiation. LCC also affects emissions of CO_2, methane and aerosols from the land surface, which may result, for example, from agricultural practices such as forest clearing and biomass burning (Pielke *et al.*, 2007). The conversion of forests and natural grasslands to crops and pastures increases albedo while decreasing the LAI and surface roughness which affects the EF (Pitman, 2003). The consequent changes in temperature, rainfall and soil moisture have been shown by model simulations over areas where land cover is perturbed (Narisma and Pitman, 2003), but results are very likely model-specific, depend on the characteristics of the replacement vegetation and are probably local to the area of LCC (Pitman *et al.*, 2009). The regional impact of LCC can be comparable to the impacts of increased CO_2 (Pitman and Zhao, 2000; Zhao and Pitman, 2002) and with large-scale sea surface temperature (SST) anomalies such as ENSO (Findell *et al.*, 2009) but whether this is true for southeastern Australia is unknown.

The impact of LCC on climate extremes in eastern Australia, particularly during El-Niño events, has the potential to increase the severity and duration of droughts (McAlpine *et al.*, 2007; Deo *et al.*, 2009). The effect of LCC combined with the enhanced greenhouse effect on the Australian climate puts water and agricultural resources, native ecosystems and biodiversity further at risk. This requires LCC to be considered in future climate risk management analysis and in the formulation of anticipatory policies (McAlpine *et al.*, 2009). However, it is important to recognize that no definitive study of how LCC affects regional climate has been done. Simulations involving transient changes in land cover using a fully coupled model would be more robust and may provide additional information, such as the interaction of LCC with natural climate variability and increasing atmospheric CO_2, as suggested by Deo *et al.* (2009). For an agricultural region, such as the MDB, crop phenology needs to be adequately represented within the climate model to avoid underestimating the radiative forcing of LCC (Nair *et al.*, 2007). Achieving this within future climate simulations would require the incorporation of a crop model into the land surface scheme of one or more high resolution regional climate models (RCMs). Overall, the scale of impact of LCC on the mean and extreme climate of the MDB is unknown, but there is clear emerging evidence that it is likely significant though secondary to increasing greenhouse gases.

3.4. Fire

Fire has played a significant role in shaping Australia's landscape for a very long time (Zylstra, 2006). Fire causes an abrupt landscape change, commonly on spatial scales of a thousand hectares but occasionally on scales exceeding 500 000 hectares (e.g. in 2003 and 2009). Following the widespread destruction of vegetation cover there can be increases in erosion and surface runoff. Once the young vegetation begins to rejuvenate a significant decrease in runoff is often observed in a manner similar to that seen after clear-cut forestry (van Dijk and Keenan, 2007; van Dijk *et al.*, 2007; Hill *et al.*, 2008), which means that a large-scale increase in the moisture flux to the atmosphere must have occurred. Fire also has a direct effect on the atmosphere through the intense surface heating and release of large amounts of aerosols during the fire, and by the large change in albedo and surface roughness that have a prolonged effect on the land–atmosphere interactions.

A number of studies have been conducted into the meteorology associated with major wildfire events; in particular, several studies have looked at the meteorology that contributed to the extremely large wildfire that occurred in January 2003 (Mills, 2005; Taylor and Webb, 2005). Traditional factors such as a prolonged dry period leading up to the fire and the presence of hot, dry and windy conditions during the fire outbreak were all present. The worst fire days tended to happen in the presence of a strong frontal system and be preceded by evenings with unusually low relative humidity. It was also found on the most severe fire days that the lower mid-troposphere was particularly dry, contributing to instability of the lower atmosphere and production of huge pyrocumulus clouds that were able to inject smoke into the stratosphere. This smoke entering the stratosphere perturbed the background weather of the Southern Hemisphere (Fromm *et al.*, 2006) as well as producing a number of other effects including the suppression of precipitation due to a large reduction in the effective cloud particle radii to well below the precipitation threshold. The aerosols trapped in the troposphere were also found to have a lasting effect with background conditions in Canberra not returning for a month (Mitchell *et al.*, 2006).

The above-mentioned studies demonstrate that the meteorology is important for the outbreak and propagation of fire and that fire can itself impact the weather. The spatial scale of forest fires has been found to match closely with the scale of the corresponding weather events (Boer *et al.*, 2008). Others have specifically looked at the impact of climate change on fire danger and fire-weather in Australia, often using indices that are sensitive to the temperature and humidity of the air. Williams *et al.* (2001) found that a doubling of CO_2 (occurs approximately 2075 in SRES A2 scenario) would increase fire danger everywhere by increasing the number of days experiencing very high and extreme fire danger. Hennessy *et al.* (2005) found a similar result of increased fire danger using various emission scenarios for the years 2020 and 2050. In a more recent study, Pitman *et al.* (2007) used probability density functions to conclude that the fire risk will increase by 25% by 2050 with substantial further increases occurring after that. Hasson *et al.* (2009) first associated extreme fire-weather events with strong cold fronts moving through the area. Using a simple measure based on the gradient of the 850 hPa temperature applied to several GCM simulations, they found that these events could be 200% more frequent at the end of the 21st century due to climate change. Thus, the literature suggests that southeastern Australia is likely to experience an increase in frequency and severity of wildfires. This has implications for natural systems where there is likely to be a change in species distribution with different physiological function and potentially therefore for the regional-scale climate.

The studies of the climate change impact on fire danger have been performed using either an ensemble of GCMs with very low spatial resolution or a single RCM with uncertainty related to model dependence. To date, these climate models have also not included any physical or chemical feedbacks from the fire to the climate; they have focussed on the impact of changes in climate due primarily to increases in radiative forcing due to increasing CO_2. However, in addition to the radiative changes, in the short term, the injection of aerosols into the atmosphere can affect the weather whereas in the longer term changes in the land surface (e.g. changes in albedo and surface roughness) can feedback on the climate itself. Indeed, elevated CO_2 may increase NPP and has the potential to increase biomass. This feedback that might increase fuel load, coupled with higher temperatures and changes in rainfall variability that might lead to longer and more intense droughts in some regions underpins the common conclusion that there is a strong likelihood of fire increasing in the future. Under these circumstances, climate feedbacks will become more important and studies that quantify the impact of these feedbacks would provide a measure of the uncertainty in future fire danger estimates.

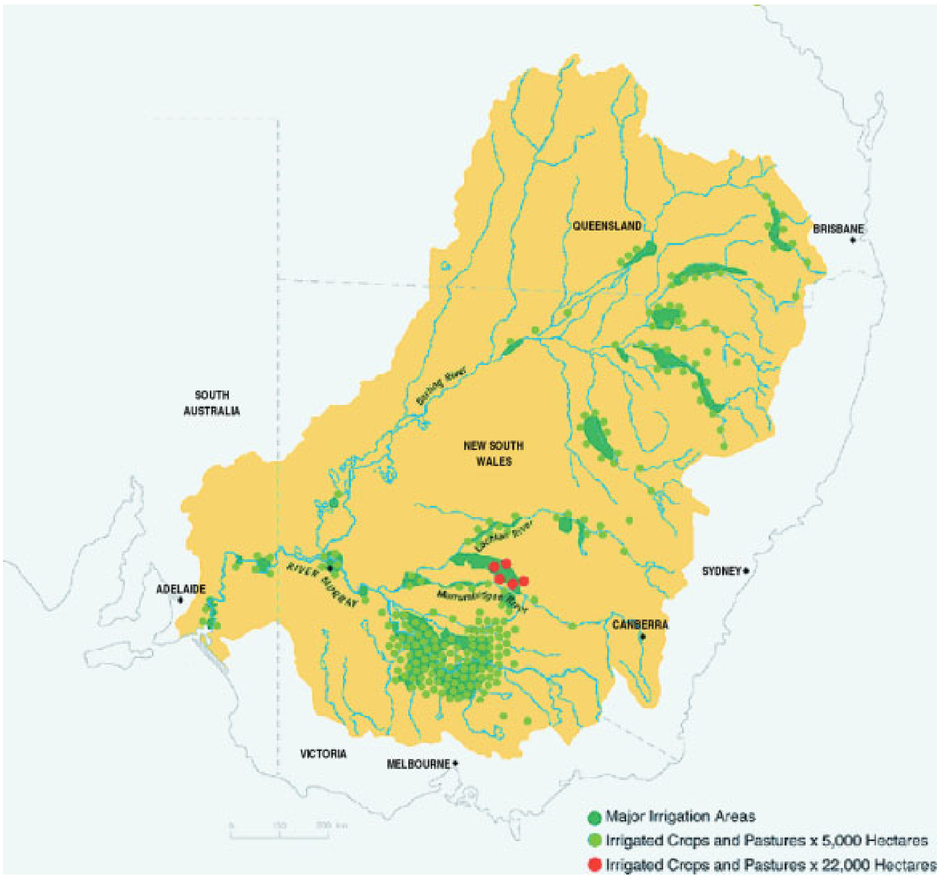

Figure 7. Major areas of irrigation and irrigated crops and pastures in the MDB. Copyright MDB Authority (adopted from http://www.mdbc.gov.au/nrm/water_issues/irrigation, accessed 20 June 2009). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

3.5. Irrigation

While only using a small proportion of the total land area of the MDB, irrigation produces a considerable proportion of agricultural income, uses the majority of the water in the basin (Meyer, 2005; ABS, 2009) and has the potential to provide significant feedbacks to the atmosphere (Boucher *et al*., 2004). The area under irrigation in Australia has increased by more than three times since the 1950s, with a majority of this being in the MDB (NPSI, 2008; Figure 7). This growth in irrigation provided some insulation from Australia's variable climate allowing agriculture to continue through dry periods. During long dry periods, however (and through 2008 and 2009), irrigators have faced significant reductions in water allocations leading to some irrigated fields being abandoned. During wet periods, when full allocations are available, irrigation can have other impacts on the land. In some cases, irrigators have applied so much water that they have raised the water table and caused salinization problems.

Several modelling studies have shown irrigated areas to have impacts on the local climate through the enhanced evaporation providing increased low level atmospheric water vapour, lower surface temperatures, higher surface pressure and associated changes in the local wind fields (Perlin and Alpert, 2001; Geerts, 2002; Zaitchik *et al*., 2005; Lee *et al*., 2009). Similar impacts on local climate have also been seen in observations (Ozdogan and Salvucci, 2004). These changes can be largely compared to the surrounding areas particularly in semi-arid regions including much of the MDB. While these surface changes impact the stability of the atmosphere and can lead to local cloud formation and precipitation, the actual impact varies depending on location and current state of the large-scale atmosphere (Lobell *et al*., 2009).

To date, there has been no study of the explicit feedback between irrigated areas and the atmosphere in the MDB. Thus, it remains unclear how strong such a feedback may be or how the downwind weather may be affected by the presence of irrigated areas. Studies that explicitly quantify this coupling between the land surface and atmosphere should be performed to understand its importance in the current climate. Under future climate conditions, this coupling may become more important in parts of the basin. For example, if the subtropical ridge moves further South, as predicted in most current GCM simulations, then the northern part of the basin will regularly experience an atmosphere that is more unstable than today and hence more likely to be triggered into precipitating by local effects such as those produced by irrigated areas. Utilization of a high resolution RCM able to capture both the feedbacks from irrigated areas and to simulate future climate change would provide evidence of the scale of impact of irrigation over this region.

3.6. Snow

Snow cover affects land–atmosphere coupling largely through its impact on the surface albedo. The Australian Alps are a relatively low and warm alpine region compared to others around the world. This results in highly variable snow cover on both inter-annual and intra-annual time scales. Within any winter, the snow cover may go through multiple melt and refreeze processes. This makes keeping track of snow-covered areas a challenge throughout winter.

Many studies of the snow accumulation, melt and effect on the atmosphere have been performed elsewhere in the world. These studies are generally performed in regions with large areas of consistent snow cover with winters cold enough that they do not experience melt and refreeze processes except at the very beginning and end of the season (Groisman *et al.*, 1994; Brown, 2000).

Few studies have been performed focusing on the snow cover of the Australian Alps with no attempt to quantify the feedback on the atmosphere. Several studies have investigated the impact of climate change on the snow cover of the region, generally concluding that snow cover will decrease over the next few decades before disappearing altogether (Nicholls, 2005; Henessy *et al.*, 2008). How this change from a seasonally snow-covered regime to a permanently snow-free regime will affect the local meteorology remains unknown.

3.7. Aerosols/dust/volatile organic compounds

Aerosols are important components of the climate system and a recent detailed review of their impact on the Australian climate is provided by Rotstayn *et al.* (2009). Aerosols can be produced from many sources including soils, biomass burning, burning of fossil fuels, sea salt and direct emissions from vegetation or biological volatile organic compounds (BVOCs).

There is strong evidence that aerosols are important on the global scale (Forster *et al.*, 2007). They affect radiative forcing – most likely slightly cooling the climate – but the impact of aerosols is highly regionalized and dependent on the specific characteristics of the aerosol shape, size and chemistry. At the global scale, the impact of short-lived aerosols and short-lived radiatively active gases do affect regional climate (Shindell *et al.*, 2008) and monsoon systems (Lynch *et al.*, 2007). Hypotheses exist that link aerosols with changing cloud characteristics and precipitation generation (Rosenfeld *et al.*, 2008). The uneven distribution of short-lived aerosols leads to varying impacts on regional climate – an impact that was shown to be very climate model-specific.

BVOCs (e.g. isoprene) are mainly produced from living vegetation. Different plant species vary greatly in the type and amount of BVOC they emit, and a broad categorization based on functional or genetic traits remains elusive (Guenther *et al.*, 1995; Kesselmeier and Staudt, 1999). Emission hot-spots include northern Australia (Lathière *et al.*, 2006). BVOCs are a crucial component of tropospheric chemical reactions at regional scales (Atkinson and Arey, 2003). The type of BVOC emitted is important to how secondary organic aerosols form and potentially affect regional climate. Emissions affect the type of reaction pathway and products formed and depend heavily on the overall chemical and physical environment. Finally, via long-range transport some compounds of (at least partial) biogenic origin can affect chemistry and climate elsewhere.

The detailed impact of aerosols on the Australian climate is poorly known. The only major studies were summarized by Rotstayn *et al.* (2009). Their work points to a possible link between rainfall changes over Australia and Asian aerosols – but the main impacts appear to be confined to northwest Australia and not the MDB. Australia is well behind international efforts to study the local production of aerosols, with perhaps the exception of dust from soil erosion (Ekström *et al.*, 2004; Leslie and Speer, 2006). Details of where aerosols are locally generated, how they interact with the local meteorology, radiation and surface energy balances and how these may evolve in the future remain unknown. It is not possible to judge whether aerosols would strongly affect the climatology of southeastern Australia or the sensitivity of the MDB to current and future global warming, but international research provides evidence that they may. They are, therefore, a significant area of ongoing and future research that Australia is poorly positioned to execute due to low levels of biologists and chemists working in atmospheric science.

4. Discussion

The climate of southeast Australia is, to first order, the result of large-scale processes (Murphy and Timbal, 2008). The future of the climate of this region is also likely to be dominated by the large-scale response to increasing greenhouse gas concentrations. As global scale climate changes affect regional scale atmospheric dynamics, rainfall, temperature and other climate variables will be affected. There are major challenges to project how the climate of this region will change in the future. The climate of this region is dominated by modes of variability including the Indian Ocean dipole, ENSO and the Southern Annual Mode. These interact in extremely complex ways to affect the strength and location of the subtropical ridge, the frequency of formation and direction of propagation of cut-off lows and cold fronts, the location of inland troughs and the magnitude and ability of coastal systems to cross the Great Dividing Range. How these phenomena will change due to global warming remains an area of significant uncertainty. It partially explains why climate projections for southeast Australia remain relatively inconsistent among climate models (CSIRO, 2007).

There has been significant work associated with the IPCC AR4 to address the uncertainties associated with climate change projections. While future climate projections for southeast Australia are inconsistent among climate models (CSIRO, 2007), those climate models with significant skill in the region tend to project quite consistent warming and drying over the basin under higher atmospheric CO_2 concentrations (Perkins and Pitman, 2009).

There are, however, a series of important or potentially important processes over southeastern Australia that are not well understood. The nature of the climate variability in this area, the prolonged duration of drought, the unusual nature and function of Australian vegetation and the lack of research undertaken in this area mean that we are poorly positioned to know how the climate of the basin will change in the future. Even if the climate models capture the large-scale dynamics well, at the scales that humans utilize major areas of southeastern Australia (in particular the MDB) we simply do not know the scale and scope of terrestrial drivers, the strength of land–atmosphere coupling or the strength of precipitation recycling. This is quite remarkable given the economic significance of this region to Australia, but understandable given the scale of research investment in this region relative to key parts of North America and Europe.

Assessing these land–atmosphere interactions observationally remains a challenge worldwide. Future research into surface dynamics should explicitly include documenting the changes in relevant coupling fields especially albedo, latent and sensible heat and perhaps other variables such as surface roughness. *In situ* observational sites should incorporate such measurements or supplement the *in situ* measurements with remotely sensed based estimates of the coupling factors. These remotely sensed based estimates themselves need further testing and development, but provide great promise for understanding region-wide land–atmosphere coupling. The evidence to date suggests that this coupling may be most important in ecological transition zones, including many semi-arid regions of the world. Most of these regions exist in countries with limited scientific observations and research capacity. Southeast Australia is arguably one of the best scientifically positioned semi-arid regions of the world to address these land–atmosphere coupling issues.

Coupled modelling efforts are needed to address many of the uncertainties surrounding these land–atmosphere interactions, with RCMs being an appropriate tool. In order to address the myriad of processes impacting the coupling, further development of RCMs for Australian conditions is required including incorporation of local hydrological models, and results from observational studies of vegetation responses to elevated CO_2, soil moisture dynamics and variability, fire, crop phenology and irrigation. Such studies need to cover temporal scales from the diurnal and synoptic to the climatic, with the long-term coupling strength being understood within the context of the various precipitation producing weather systems for the region.

The attempt to understand and quantify the land–atmosphere coupling strength is a large challenge globally. It is however necessary in order to provide policy and management advice on climate and land-use change as they relate to each other. To actually build a 21st century understanding of the functioning of the MDB and an understanding of the basin's vulnerability to human and natural drivers is a nationally significant research challenge. To build an understanding of water resource vulnerability to human and natural drivers is a significant challenge worldwide.

Acknowledgements

This work was funded by the MDB Authority and the Australian Research Council Discovery grant DP0772665. Thanks to Randall Donohue who prepared Figure 6.

References

ABS. 2009. *Water Use on Australian Farms*. Australian Bureau of Statistics: Canberra, Australia, URL http://www.ausstats.abs.gov.au/ausstats/subscriber.nsf/0/24700B5D1E4D0E7CCA2575C10012D8B6/$File/46180_2007-08.pdf [accessed June 9 2009].

Adams PD, Horridge M, Madden JR, Wittwer G. 2002. Drought, regions and the Australian economy between 2001–02 and 2004–05. *Australian Bulletin of Labour* **28**: 231–246.

Ainsworth EA, Long SP. 2005. What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. *New Phytologist* **165**(2): 351–372.

Ainsworth EA, Rogers A. 2007. The response of photosynthesis and stomatal conductance to rising CO_2: mechanisms and environmental interactions. *Plant, Cell and Environment* **30**(3): 258–270.

Anderson BT, Salvucci G, Ruane AC, Roads JO, Kanamitsu M. 2008. A new metric for estimating the influence of evaporation on seasonal precipitation rates. *Journal of Hydrometeorology* **9**(3): 576–588.

Ashok K, Guan Z, Yamagata T. 2003. Influence of the Indian Ocean dipole on the Australian winter rainfall. *Geophysical Research Letters* **30**: 1821, DOI:10.1029/2003GL017926.

Atkinson R, Arey J. 2003. Gas-phase tropospheric chemistry of biogenic volatile organic compounds: a review. *Atmospheric Environment* **37**: S197–S219.

AUSLIG. 1990. *Atlas of Australian Resources: Vegetation*. Australian Government Publishing Service: Canberra, Australia.

Beljaars ACM, Viterbo P, Miller MJ, Betts AK. 1996. The anomalous rainfall over the United States during July 1993: sensitivity to land surface parameterization and soil moisture anomalies. *Monthly Weather Review* **124**(3): 362–383.

Betts A. 2004. Understanding hydrometeorology using global models. *Bulletin of the American Meteorological Society* **85**(11): 1673–1688.

Betts AK, Ball JH, Beljaars ACM, Miller MJ, Viterbo PA. 1996. The land surface-atmosphere interaction: a review based on observational and global modeling perspectives. *Journal of Geophysical Research D: Atmospheres* **101**(D3): 7209–7225.

Boer MM, Sadler RJ, Bradstock RA, Gill AM, Griersin PF. 2008. Spatial scale invariance of southern Australian forest fires mirrors the scaling behaviour of fire-driving weather events. *Landscape Ecology* **23**(8): 899–913.

Bosilovich MG, Schubert SD. 2002. Water vapor tracers as diagnostics of the regional hydrologic cycle. *Journal of Hydrometeorology* **3**(2): 149–165.

Bosilovich MG, Sun W-Y. 1999. Numerical simulation of the 1993 midwestern flood: land-atmosphere interactions. *Journal of Climate* **12**: 1490–1505.

Boucher O, Myhre G, Myhre A. 2004. Direct human influence of irrigation on atmospheric water vapour and climate. *Climate Dynamics* **22**: 597–603, DOI:10.1007/s00382-004-0402-4.

Boucher O, Jones A, Betts RA. 2009. Climate response to the physiological impact of carbon dioxide on plants in the Met Office Unified Model HadCM3. *Climate Dynamics* **32**(2–3): 237–249.

Brown RD. 2000. Northern Hemisphere snow cover variability and change, 1915–97. *Journal of Climate* **13**(13): 2339–2355.

Brubaker KL, Entekhabi D, Eagleson PS. 1993. Estimation of continental precipitation recycling. *Journal of Climate* **6**(6): 1077–1089.

Brubaker KL, Dirmeyer PA, Sudradjat A, Levy BS, Bernal F. 2001. A 36-yr climatological description of the evaporative sources of warm-season precipitation in the Mississippi River basin. *Journal of Hydrometeorology* **2**(6): 537–557.

Burde GI, Zangvil A. 2001a. The estimation of regional precipitation recycling. Part I: review of recycling models. *Journal of Climate* **14**(12): 2497–2508.

Burde GI, Zangvil A. 2001b. The estimation of regional precipitation recycling. Part II: a new recycling model. *Journal of Climate* **14**(12): 2509–2527.

Calvet J-C, Gibelin A-L, Roujean J-L, Martin E, Le Moigne P, Douville H, Noilhan J. 2008. Past and future scenarios of the effect of carbon dioxide on plant growth and transpiration for three vegetation types of southwestern France. *Atmospheric Chemistry and Physics* **8**(2): 397–405.

Cao L, Bala G, Caldeira K, Nemani R, Ban-Weiss G. 2009. Climate response to physiological forcing of carbon dioxide simulated by the coupled Community Atmosphere Model (CAM3.1) and Community Land Model (CLM3.0). *Geophysical Research Letters* **36**: L10402, DOI:10.1029/2009GL037724.

Cruz FT, Pitman AJ, McGregor JL. 2008. Probabilistic simulations of the impact of increasing leaf-level atmospheric carbon dioxide on the global land surface. *Climate Dynamics* 1–19, URL http://www.scopus.com/inward/record.url?eid=2-s2.0-57149142825andpartnerID=40, Accessed on June, 16th 2009, DOI:10.1007/s00382-008-0497-0.

Cruz FT, Pitman AJ, McGregor JL, Evans JP. 2010. Contrasting regional responses to increasing leaf-level atmospheric carbon dioxide over Australia. *Journal of Hydrometeorology* **11**(2): 296–314.

CSIRO. 2007. *Climate Change in Australia*. CSIRO: Australia.

CSIRO. 2008. *Water Availability in the Murray-Darling Basin. A Report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project*. CSIRO: Australia.

Curtis PS and Wang X. 1998. A meta-analysis of elevated CO_2 effects on woody plant mass, form, and physiology. *Oecologia* **113**(3): 299–313.

Delire C, Foley J, Thompson S. 2004. Long-tern variability in a coupled atmosphere-biosphere model. *Journal of Climate* **17**(20): 3947–3959.

Deo RC, Syktus JI, McAlpine CA, Lawrence PJ, McGowan HA, Phinn SR. 2009. Impact of historical land cover change on daily indices of climate extremes including droughts in eastern Australia. *Geophysical Research Letters* **36**: L08705, DOI:10.1029/2009GL037666.

van Dijk AIJM, Keenan RJ. 2007. Planted forests and water in perspective. *Forest Ecology and Management* **251**: 1–9.

van Dijk AIJM, Hairsine PB, Arancibia JP, Dowling TI. 2007. Reforestation, water availability and stream salinity: a multi-scale analysis in the Murray-Darling Basin, Australia. *Forest Ecology and Management* **251**: 94–109.

Dirmeyer PA, Brubaker KL. 2007. Characterization of the global hydrologic cycle from a back-trajectory analysis of atmospheric water vapor. *Journal of Hydrometeorology* **8**: 20–37.

Donald A, Meinke H, Power B, De A, Maia HN, Wheeler MC, White N, Stone RC, Ribbe J. 2006. Near-global impact of the Madden-Julian Oscillation on rainfall. *Geophysical Research Letters* **33**: L09704, DOI:10.1029/2005GL025155.

Donohue RJ, Roderick ML, McVicar TR. 2008. Deriving consistent long-term vegetation information from AVHRR reflectance data using a cover-triangle-based framework. *Remote Sensing of Environment* **112**(6): 2938–2949.

Donohue RJ, McVicar TR, Roderick ML. 2009. Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006. *Global Change Biology* **15**(4): 1025–1039.

Drake BG, Gonzàlez-Meler MA, Long SP. 1997. More efficient plants: a consequence of rising atmospheric CO_2?. *Annual Review of Plant Physiology and Plant Molecular Biology* **48**: 609–639, DOI:10.1146/annurev.arplant.48.609.

Drosdowsky W. 2005. The latitude of the subtropical ridge over eastern Australia: the L index revisited. *International. Journal of Climatology* **25**(10): 1291–1299, DOI:10.1002/joc.1196.

Drosdowsky W, Chambers LE. 2001. Near-global sea surface temperature anomalies as predictors of Australian seasonal rainfall. *Journal of Climate* **14**(7): 1677–1687.

Druyan LM, Koster RD. 1989. Source of Sahel precipitation for simulated drought and rainy seasons. *Journal of Climate* **2**(12): 1438–1446.

Eamus D, Froend R. 2006. Groundwater-dependent ecosystems: the where, what and why of GDEs. Australian. *Journal of Botany* **54**: 91–96.

Ekström M, Mctainsh GH, Chappell A. 2004. Australian dust storms: temporal trends and relationships with synoptic pressure distributions (1960–99). *International Journal of Climatology* **24**(12): 1581–1599.

Entin JK, Robock A, Vinnikov KY, Hollinger SE, Liu S, Namkhai A. 2000. Temporal and spatial scales of observed soil moisture variations in the extratropics. *Journal of Geophysical Research* **105**: 11865–11877.

Feddes RA, Hoff H, Bruen M, Dawson T, De Rosnay P, Dirmeyer P, Jackson RB, Kabat P, Kleidon A, Lilly A, Pitman AJ. 2001. Modeling root water uptake in hydrological and climate models. *Bulletin of the American Meterological Society* **82**(12): 2797–2809.

Field CB, Jackson RB, Mooney HA. 1995. Stomatal responses to increased CO_2: implications from the plant to the global scale. *Plant, Cell and Environment* **18**: 1214–1225.

Findell K, Pitman A, England M, Pegion P. 2009. Regional and global impacts of land cover change and sea surface temperature anomalies. *Journal of Climate* **22**(12): 3248–3269.

Fischer EM, Seneviratne SI, Luthi D, Schar C. 2007. Contribution of land-atmosphere coupling to recent European summer heat waves. *Geophysical Research Letters* **34**(6): L06707, DOI:10.1029/2006GL029068.

Forster P, Ramaswamy V, Artaxo P, Berntsen T, Betts R, Fahey D, Haywood J, Lean J, Lowe D, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R. 2007. Changes in atmospheric constituents and in radiative forcing. In *Climate Change 2007: The Physical Science Basis.*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KV, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge, UK; 129–234.

Fromm M, Tupper A, Rosenfeld D, Servranckx R, McRae R. 2006. Violent pyro-convective storm devastates Australia's capital and pollutes the stratosphere. *Geophysical Research Letters* **33**(5): L05815, DOI:10.1029/2005GL025161.

Geerts B. 2002. On the effects of irrigation and urbanisation on the annual range of monthly-mean temperatures. *Theoretical and Applied Climatology* **72**(3–4): 157–163, DOI:10.1007/s00704-002-0683-7.

Groisman PY, Karl TR, Knight RW. 1994. Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science* **263**(5144): 198–200.

Guenther A, Hewitt CN, Erickson D, Fall R, Geron C, Gradel T, Harley P, Klinger L, Lerdau M, McKay WA, Pierce T, Scholes B, Steinbrecher R, Tallamraju R, Taylor J, Zimmerman P. 1995. A global model of natural volatile organic compound emissions. *Journal of Geophysical Research* **100**(D5): 8873–8892.

Hasson AEA, Mills GA, Timbal B, Walsh K. 2009. Assessing the impact of climate change on extreme fire weather events over southeastern Australia. *Climate Research* **39**: 159–172.

Hennessy KJ, Lucas C, Nicholls N, Bathols J, Suppiah R, Ricketts J. 2005. *Climate Change Impacts on Fire-Weather in Southeast Australia*. CSIRO Marine and Atmospheric Research: Aspendale, Australia.

Hennessy KJ, Whetton PH, Walsh K, Smith IN, Bathols JM, Hutchinson M, Sharples J. 2008. Climate change effects on snow conditions in mainland Australia and adaptation at ski resorts through snowmaking. *Climate Research* **35**(3): 255–270.

Hill PI, Mordue A, Nathan RJ, Daamen CC, Williams K, Murphy RE. 2008. Spatially explicit modelling of the hydrologic response of bushfires at the catchment scale. *Australian Journal of Water Resources* **12**(3): 281–290.

Jones DA, Trewin BC. 2000. On the relationships between the El Niño-Southern Oscillation and Australian land surface temperature. *International Journal of Climatology* **20**: 697–719.

Karoly DJ, Vincent DG (eds). 1998. *Meteorology of the Southern Hemisphere*. American Meteorological Society: Boston, MA.

Kesselmeier J, Staudt M. 1999. Biogenic volatile organic compounds (VOC): an overview on emission, physiology and ecology. *Journal of Atmospheric Chemistry* **33**: 23–88.

Koster RD, Dirmeyer PA, Guo ZC, Bonan G, Chan E, Cox P, Gordon CT, Kanae S, Kowalczyk E, Lawrence D, Liu P, Lu CH, Malyshev S, McAvaney B, Mitchell K, Mocko D, Oki T, Oleson K, Pitman A, Sud YC, Taylor CM, Verseghy D, Vasic R, Xue YK, Yamada T. 2004. Regions of strong coupling between soil moisture and precipitation. *Science* **305**(5687): 1138–1140.

Lathière J, Hauglustaine DA, Friend AD, De Noblet-Ducoudre N, Viovy N, Folberth GA. 2006. Impact of climate variability and land use changes on global biogenic volatile organic compound emissions. *Atmospheric Chemistry and Physics* **6**: 2129–2146.

Leblanc MJ, Tregoning P, Ramillien G, Tweed SO, Fakes A. 2009. Basin-scale, integrated observations of the early 21st century multiyear drought in southeast Australia. *Water Resources Research* **45**: DOI:10.1029/2008WR007333.

Lee E, Chase T, Rajagopalan B, Barry R, Biggs T, Lawrence P. 2009. Effects of irrigation and vegetation activity on early Indian summer monsoon variability. *International Journal of Climatology* **29**(4): 573–581.

Leslie LM, Speer MS. 2006. Modelling dust transport over central eastern Australia. *Meteorological Applications* **13**(2): 141–167.

Liu Z, Notaro M, Kutzbach J, Liu N. 2006. Assessing global vegetation-climate feedbacks from observations. *Journal of Climate* **19**(5): 787–814.

Liu YY, McCabe MF, Evans JP, Van Dijk AIJM, De Jeu RAM, Su H. 2009. Comparison of soil moisture in GLDAS model simulations and satellite observations over the Murray Darling Basin. In *Proceedings of the International Congress on Modelling and Simulation*, Cairns, Australia, 13–17 July.

Lobell D, Bala G, Mirin A, Phillips T, Maxwell R, Rotman D. 2009. Regional differences in the influence of irrigation on climate. *Journal of Climate* **22**: 2248–2255, DOI:10.1175/2008JCLI2703.1.

Lynch AH, Abramson D, Gorgen K, Beringer J, Uotila P. 2007. Influence of savanna fire on Australian monsoon season precipitation and circulation as simulated using a distributed computing environment. *Geophysical Research Letters* **34**: L20801, DOI:10.1029/2007GL030879.

Lyons TJ. 2002. Clouds prefer native vegetation. *Meteorological Atmospheric Physics* **80**: 131–140.

Lyons TJ, Schwerdtfeger P, Hacker JM, Foster IJ, Smith RCG, Xinmei H. 1993. Land-atmosphere interaction in a semiarid region: the bunny fence experiment. *Bulletin of the American Meteorological Society* **74**: 1327–1334.

Martin M, Dickinson RE, Yang Z-L. 1999. Use of a coupled land surface general circulation model to examine the impacts of doubled stomatal resistance on the water resources of the American Southwest. *Journal of Climate* **12**(12): 3359–3375.

McAlpine CA, Syktus J, Deo RC, Lawrence PJ, McGowan HA, Watterson IG, Phinn SR. 2007. Modeling the impact of historical land cover change on Australia's regional climate. *Geophysical Research Letters* **34**: L22711, DOI:10.1029/2007GL031524.

McAlpine C, Syktus J, Ryan J, Deo R, McKeon G, McGowan H, Phinn S. 2009. A continent under stress: Interactions, feedbacks and risks associated with impact of modified land cover on Australia's climate. *Global Change Biology* **15**(9): 2206–2223.

McBride JL, Nicholls N. 1983. Seasonal relationships between Australian rainfall and the Southern Oscillation. *Monthly Weather Review* **111**(10): 1998–2004.

McMahon TA, Finlayson BL, Haines AT, Srikanthan R. 1992. *Global Runoff: Continental Comparisons of Annual Flows and Peak Discharges*. Catena-Verlag: Cremlingen-Destedt, Germany.

McMurtrie RE, Comins HN. 1996. The temporal response of forest ecosystems to doubled atmospheric CO_2 concentration. *Global Change Biology* **2**(1): 49–57.

Merlin O, Walker JP, Kalma JD, Kim EJ, Hacker J, Panciera R, Young R, Summerell G, Hornbuckle J, Hafeez M, Jackson T. 2008. The NAFE'06 data set: towards soil moisture retrieval at intermediate resolution. *Advances in Water Resources* **31**(11): 1444–1455, DOI:10.1016/j.advwatres.2008.01.018.

Meyer WS. 2005. The Irrigation Industry in the Murray and Murrumbidgee Basins. CRC for Irrigation Futures. Technical Report No: 03/05.

Mills GA. 2005. On the subsynoptic-scale meteorology of two extreme fire weather days during the Eastern Australian fires of January 2003. *Australian Meteorological Magazine* **54**: 265–290.

Mitchell RM, O'Brien DM, Campbell SK. 2006. Characteristics and radiative impact of the aerosol generated by the Canberra firestorm of January 2003. *Journal of Geophysical Research* **111**: D02204.

Murphy BF, Timbal B. 2008. A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology* **28**: 859–879, DOI:10.1002/joc.1627.

Nair US, Ray DK, Wang J, Christopher SA, Lyons TJ, Welch RM, Pielke RA. 2007. Observational estimates of radiative forcing due to land use change in southwest Australia. *Journal of Geophysical Research* **112**: D09117, DOI:10.1029/2006JD007505.

Narisma GT, Pitman AJ. 2003. The impact of 200 years of land cover change on the Australian near-surface climate. *Journal of Hydrometeorology* **4**(2): 424–436.

Nicholls N. 1989. Sea surface temperatures and Australian winter rainfall. *Journal of Climate* **2**: 965–973.

Nicholls N. 2005. Climate variability, climate change and the Australian snow season. *Australian Meteorological Magazine* **54**(3): 177–185.

Norby RJ, Jackson RB. 2000. Root dynamics and global change: seeking an ecosystem perspective. *New Phytologist* **147**(1): 3–12.

Notaro M. 2008. Statistical identification of global hot spots in soil moisture feedbacks among IPCC AR4 models. *Journal of Geophysical Research* **113**: D09101, DOI:10.1029/2007JD009199.

Notaro M, Liu Z, Gallimore R, Vavrus S, Kutzbach J, Prentice I, Jacob R. 2005. Simulated and observed preindustrial to modern vegetation and climate changes. *Journal of Climate* **18**(17): 3650–3671.

Notaro M, Vavrus S, Liu Z. 2007. Global vegetation and climate change due to future increases in CO2 as projected by a fully coupled model with dynamic vegetation. *Journal of Climate* **20**(1): 70–90.

Notaro M, Wang Y, Liu Z, Gallimore R, Levis S. 2008. Combined statistical and dynamical assessment of simulated vegetation-rainfall interactions in North Africa during the mid-Holocene. *Global Change Biology* **14**(2): 347–368.

NPSI. 2008. *Irrigation in Australia – facts and figures*. Harvest note, National program for sustainable irrigation. URL http://npsi.gov.au/files/products/national-program-sustainable-irrigation/pn22088/pn22088.pdf, Accessed on June, 9th 2009.

Oglesby RJ, Erickson DJ. 1989. Soil moisture and the persistence of north American drought. *Journal of Climate* **2**: 1362–1380.

Ozdogan M, Salvucci G. 2004. Irrigation-induced changes in potential evapotranspiration in southeastern Turkey: test and application of Bouchet's complementary hypothesis. *Water Resources Research* **40**(4): W04301, DOI:10.1029/2003WR002822.

Panciera R, Walker JP, Kalma JD, Kim EJ, Hacker JM, Merlin O, Berger M, Skou N. The NAFE'05/CoSMOS data set: toward SMOS soil moisture retrieval, downscaling, and assimilation. *IEEE Transactions on Geoscience and Remote Sensing* **46**(3): 736–745, DOI:10.1109/TGRS.2007.915403.

Peel D, Pitman AJ, Hughes L, Narisma G. 2005. The impact of an explicit representation of Eucalyptus on the simulation of the January climate of Australia. *Environmental Modelling and Software* **20**: 595–612.

Perkins SE, Pitman AJ. 2009. Do weak AR4 models bias projections of future climate changes over Australia?. *Climatic Change* **93**(3–4): 527–558.

Perlin N, Alpert P. 2001. Effects of land-use modification on potential increase of convection: a numerical mesoscale study over south Israel. *Journal of Geophysical Research* **106**: 22621–22634.

Pielke RA Sr, Adegoke J, Beltran-Przekurat A, Hiemstra CA, Lin J, Nair US, Niyogi D, Nobis TE. 2007. An overview of regional land-use and land-cover impacts on rainfall. *Tellus, Series B* **59**(3): 587–601.

Pitman AJ. 2003. The evolution of, and revolution in, land surface schemes designed for climate models. *International Journal of Climatology* **23**(5): 479–510.

Pitman AJ, Zhao M. 2000. The relative impact of observed change in land cover and carbon dioxide as simulated by a climate model. *Geophysical Research Letters* **27**: 1267–1270.

Pitman AJ, Narisma GT, McAneney J. 2007. The impact of climate change on the risk of forest and grassland fires in Australia. *Climatic Change* **84**(3–4): 383–401.

Pitman AJ, de Noblet-Ducoudre N, Cruz FT, Davin EL, Bonan GB, Brovkin V, Claussen M, Delire C, Ganzeveld L, Gayler V, van den Hurk BJJM, Lawrence PJ, van der Molen MK, Müller C, Reick CH, Seneviratne SI, Strengers BJ, Voldoire A. 2009. Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study. *Geophysical Research Letters* **36**(14): L14814, DOI:10.1029/2009GL039076.

Pritchard SG, Rogers HH, Prior SA, Peterson CM. 1999. Elevated CO_2 and plant structure: a review. *Global Change Biology* **5**(7): 807–837.

Ray DK, Nair US, Welch RM, Han Q, Zeng J, Su W, Kikuchi T, Lyons TJ. 2003. Effects of land use in Southwest Australia: 1. Observations of cumulus cloudiness and energy fluxes. *Journal of Geophysical Research* **108**: 4414, DOI:10.1029/2002JD002654.

Robock A, Schlosser C, Vinnikov K, Speranskaya N, Entin J, Qiu S. 1998. Evaluation of the AMIP soil moisture simulations. *Global and Planetary Change* **19**: 181–208.

Robock A, Vinnikov KY, Srinivasan G, Entin JK, Hollinger SE, Speranskaya NA, Liu S, Namkhai A. 2000. The global soil moisture data bank. *Bulletin of the. American Meteorological Society* **81**: 1281–1299.

Rosenfeld D, Lohmann U, Raga GB, O'Dowd CD, Kulmala M, Fuzzi S, Reissel A, Andreae MO. 2008. Flood or drought: how do aerosols affect precipitation?. *Science* **321**(5894): 1309–1313.

Rotstayn LD, Keywood MD, Forgan BW, Gabric AJ, Galbally IE, Gras JL, Luhar AK, McTainsh GH, Mitchell RM, Young SA. 2009. Possible impacts of anthropogenic and natural aerosols on Australian climate: a review. *International Journal of Climatology* **29**(4): 461–479.

Rudiger C, Hancock G, Hemakumara HM, Jacobs B, Kalma JD, Martinez C, Thyer M, Walker JP, Wells T, Willgoose GR. 2007. Goulburn River experimental catchment data set. *Water Resources Research* **43**: W10403, DOI:10.1029/2006WR005837.

Salati E, Vose PB. 1984. Amazon basin – a system in equilibrium. *Science* **225**(4658): 129–138.

Salati E, Lovejoy TE, Vose PB. 1983. Precipitation and water recycling in tropical rain forests with special reference to the Amazon Basin. *Environmentalist* **3**: 67–71.

Saleh K, Kerr YH, Richaume P, Escorihuela MJ, Panciera R, Delwart S, Boulet G, Maisongrande P, Walker JP, Wursteisen P, Wigneron JP. 2009. Soil moisture retrievals at L-band using a two-step inversion approach (COSMOS/NAFE'05 Experiment). *Remote Sensing of Environment* **113**: 1304–1312, DOI:10.1016/j.rse.2009.02.013.

Santanello JA Jr, Friedl MA, Kustas WP. 2005. An empirical investigation of convective planetary boundary layer evolution and its relationship with the land surface. *Journal of Applied Meteorology* **44**(6): 917–932.

Santanello JA Jr, Friedl MA, Ek MB. 2007. Convective planetary boundary layer interactions with the land surface at diurnal time scales: diagnostics and feedbacks. *Journal of Hydrometeorology* **8**: 1082–1097.

Shindell DT, Levy H II, Schwarzkopf MD, Horowitz LW, Lamarque J-F, Faluvegi G. 2008. Multimodel projections of climate change from short-lived emissions due to human activities. *Journal of Geophysical Research* **113**: D11109, DOI:10.1029/2007JD009152.

Stohl A, James P. 2004. A Lagrangian analysis of the atmospheric branch of the global water cycle. Part I: method description, validation, and demonstration for the August 2002 flooding in central Europe. *Journal of Hydrometeorology* **5**(4): 656–678.

Taylor J, Webb R. 2005. Meteorological aspects of the January 2003 south-eastern Australia bushfire outbreak. *Australian Forestry* **68**(2): 94–103.

Timbal B, Power S, Colman R, Viviand J, Lirola S. 2002. Does soil moisture influence climate variability and predictability over Australia?. *Journal of Climate* **15**: 1230–1238.

Trenberth KE. 1999. Atmospheric moisture recycling: role of advection and local evaporation. *Journal of Climate* **12**(5): 1368–1381.

Ummenhofer CC, England MH, McIntosh PC, Meyers GA, Pook MJ, Risbey JS, Gupta AS, Taschetto AS. 2009. What causes Southeast Australia's worst droughts. *Geophysical Research Letters* **36**(4): L04706, DOI:10.1029/2008GL036801.

Wheeler M, Hendon H, Cleland S, Meinke H, Donald A. 2009. Impacts of the Madden-Julian oscillation on australian rainfall and circulation. *Journal of Climate* **22**(6): 1482–1498.

Williams AAJ, Stone RC. 2009. An assessment of relationships between the Australian subtropical ridge, rainfall variability, and high-latitude circulation patterns. *International Journal of Climatology* **29**: 691–709, DOI:10.1002/joc.1732.

Williams AAJ, Karoly DJ, Tapper N. 2001. The sensitivity of Australian fire danger to climate change. *Climatic Change* **49**(1–2): 171–191.

Young R, Walker JP, Yeoh N, Smith A, Ellett K, Merlin O, Western A. 2008. *Soil Moisture and Meteorological Observations From the Murrumbidgee Catchment*. Department of Civil and Environmental Engineering, The University of Melbourne: Australia.

Zaitchik BF, Evans J, Smith RB. 2005. MODIS-derived boundary conditions for a mesoscale climate model: application to irrigated agriculture in the euphrates basin. *Monthly Weather Review* **133**: 1727–1743.

Zhang H. 2004. Analyzing the potential impacts of soil moisture on the observed and model-simulated Australian surface temperature variations. *Journal of Climate* **17**: 4190–4212.

Zhao M, Pitman AJ. 2002. The impact of land cover change and increasing carbon dioxide on the extreme and frequency of maximum temperature and convective precipitation. *Geophysical Research Letters* **29**(6): 2–1.

Zylstra P. 2006. Fire history of the Australian Alps – prehistory to 2003, URL http://www.australianalps.environment.gov.au/publications/research-reports/fire-history.html, Accessed on May, 27th 2009.