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The impact of realistic biophysical parameters for eucalypts on the simulation of the January climate of Australia

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Abstract

Climate models use broad definitions of vegetation-based biophysical parameters that may not represent the continentally-specific nature of Australian vegetation well. This paper explores the impact on the January simulation of climate over Australia of this common simplification. First, we map the Australian distribution of vegetation types onto the default classification used in one high-resolution climate model. Second, through a search of the literature we chose replacement values for the biophysical parameters to better reflect the properties of eucalypts. Third, we choose several sets of biophysical parameters and allow these to vary regionally. We assess the impact of these changes on simulated rainfall, temperature and latent heat flux over an ensemble of six different Januaries. We find that the model simulates rainfall and temperature reasonably well over Australia in January and that replacing the default parameter set with a single set of more appropriate values degrades model performance slightly. Allowing the biophysical parameters to vary regionally leads to some small improvements in the simulation of temperature and precipitation. We find large impacts on the simulated latent heat flux. Overall, the model is not substantially improved by careful selection of eucalypt parameters. We comment that given the shortage of observed data on eucalypts and the almost total absence of biophysical parameters for other Australian vegetation types, this lack of sensitivity to the biophysical parameters is reassuring since it implies that the lack of data is not presently seriously limiting to our particular modelling capability.

Keywords: Climate modeling; Biophysical parameters; Eucalypt; Regional Atmospheric Modeling System; Atmospheric modeling; Land surface processes

1. Introduction

The numerical modelling of weather and climate has a long history. Recently, developments in computing and information technology have led to the increased accessibility of climate models to the user community and several are now freely available on the internet (see, for example, http://www.ucar.edu/ucar/fac-data.html). The term ‘climate models’ is used here to mean any type of numerical model used to simulate weather or climate at spatial scales from global to a few kilometre grid interval. These models have all been developed in North America or Europe and have been extensively used in those regions. There is no Australian community model to parallel these developments, although within CSIRO and the Bureau of Meteorology the capacity exists to provide a community model if the funding was made available. In effect, at the present time, if someone wishes to use a numerical model to explore the Australian climate, or the interaction between the climate and the terrestrial biosphere, it is common to import one of the European or North American models.

To use a climate model, a variety of biospheric parameters have to be specified. Some of these are geographically variable (e.g. vegetation and soil type). Climate models commonly use a plant functional type classification based on between about 6 and about 30 different vegetation types (see Bonan et al., 2002). The

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tendency is, perhaps naturally, to build this classification with a bias toward vegetation types that seem generic: 'broad-leaf forest', 'tundra', etc. There is little evidence that this is unsatisfactory for the vast majority of terrestrial vegetation types in the Earth System. However, the Australian vegetation is very different compared to the vegetation of North America or Europe (Barlow, 1994) as a result of isolation, geological history and climatic history. The distribution and structural characteristics of Australian plant communities can be largely understood as a response to soil characteristics and rainfall. Many Australian soils are very infertile by Northern Hemisphere standards, as a result of millions of years of weathering, together with a lack of tectonic activity and Quaternary glaciation (Lindsay, 1985). Approximately one third of the continent is covered by unconsolidated sands, and the overall proportion of soils lacking in nitrogen and phosphorus, in particular, is very high (Lindsay, 1985). Vegetation on these soils is mostly woody and sclerophyllous, characterized by the presence of small, rigid, long-lived leaves (Barlow, 1994). The deciduous habit is very rare and a large proportion of Australian plant species are endemic; of the 21–23 000 Australian plant species, 85% occur nowhere else (Augee and Fox, 2000). Fire is also an important influence on many Australian plant communities.

Two large tree and shrub groups, the eucalypts and the acacias dominate almost all the plant associations of the continent, whilst having very limited natural occurrence outside Australia. Eucalypts comprise approximately 700 species (in the genera *Corymbia, Angophora* and *Eucalyptus*) and dominate most of the forest, mallee and woodland areas of Australia. The genus *Acacia*, with about 950 species, dominates much of the semi-arid regions while in the most arid areas, the main vegetation is spinifex (*Triodia*) grasslands. Rainforests occur on less than 1% of the continent and are confined to fragmented pockets of higher fertility soils along the east coast.

The domination of Australian vegetation by sclerophyllous, evergreen, woody species means that most Australian plant communities do not fit easily into global vegetation classifications. Early attempts to classify Australian vegetation using categories developed for Northern Hemisphere communities proved unsatisfactory (Hnatiuk, 2003) and from about the 1920s, gave impetus to the development of several distinctly Australian schemes such as that of Specht (1970) which uses a two-way table of height and projective foliage cover of the tallest stratum to classify vegetation at the level of Formations. There have also been several continental-scale attempts to describe vegetation in floristic units, such as the one used in the present study, developed by the Australian Surveying and Land Information Group (AUSLIG) (see Section 2.5). At present, no climate model, in selecting the vegetation types to represent, explicitly includes the common Australian vegetation types, or includes any of the plant traits that makes many Australian plant species unusual.

There are four steps to building an Australian-based vegetation classification for a climate model. The simplest step is to take the distribution of Australian vegetation from an existing data set and map these vegetation types onto the existing classification used in the numerical model. Thus, *Eucalyptus* is represented as broadleaf evergreen tree, *Banksia* is represented as evergreen shrub, etc. The second step is to recognize that explicitly including *Eucalyptus*, for example, in terms of the ecological and physiological characteristics of this genus, might improve modelling capability. A third step might be to recognize that traits of eucalypts vary too greatly within the genus to be represented by a single set of biophysical parameters and thus several types of eucalypts might need to be included. The final step involves adapting the biophysical parameterizations included in the climate model to reflect knowledge of the behaviour of Australian vegetation.

The aim of this paper is to explore the first three of these steps. First, we test whether mapping Australian vegetation onto a general vegetation classification leads to a reasonable simulation of the surface climatology by a high-resolution climate model (experiment *control*). We then explore the impact of including the eucalypt group (including the genera *Eucalyptus, Corymbia* and *Angophora*) explicitly in the model by replacing the biophysical parameters by ones more representative of eucalyptus obtained through a thorough search of the literature (experiment *Eu1*). Eucalypts are the dominant trees on the Australian continent, constituting over 700 species and dominating the overstorey of all habitats except in the arid zone (Williams and Brooker, 1997). We then separate the eucalypt classification by region to permit the description of eucalypts in the model to vary geographically (experiment *EuM*). We explore whether these three steps improve the simulation of the surface climatology by the model with the ultimate aim of determining whether the effort to adapt the model to include explicit parameterizations of Australian vegetation function would be worthwhile. This last step is a major undertaking requiring the replacement of the algorithms used to describe the physiological and ecological behaviour of the vegetation in the model by new approaches appropriate to Australian plants. We note that our original intent was to develop a biophysical parameter-based description of a significant fraction of the Australian plant species, but following an extensive search of the literature, we failed to find enough independent measures of biophysical parameter values for Australian plant types other than eucalypts to generate reliable estimates.

2. Methodology

2.1. Overview of RAMS

In order to simulate the climate of Australia we employed the Regional Atmospheric Modeling System (RAMS) (Version 4.3.0) (Pielke et al., 1992; Liston and Pielke, 2001). RAMS is a comprehensive meteorological prediction model designed to explore issues relating to the atmosphere or to land surface-atmosphere interactions (e.g. Pielke et al., 1992; Walko et al., 1995; Greene et al., 1999). RAMS is a three-dimensional, non-hydrostatic model that employs the fundamental equations of heat, moisture, motion and continuity that govern atmospheric motions. For the land surface, the Land Ecosystem-Atmospheric Feedback model (LEAF-2) was used to account for vegetation, open water, soil and snow related surface energy, water and carbon fluxes (see Section 2.2).

RAMS can be used with a variety of physics options. We used a standard configuration including the Kuo (1974) cumulus convection scheme as modified by Tremback (1990). Studies by Lee (1992), Pielke et al. (1992) and Lu et al. (2001) have evaluated the performance of RAMS and demonstrated that the model can simulate the key aspects of weekly and seasonal feedbacks between the atmosphere, hydrosphere and biosphere at a variety of spatial scales.

2.2. Overview of LEAF-2

LEAF-2 represents the energy and moisture budgets for the soil and vegetation as well as the exchange of this energy and moisture between these components and the atmosphere (Lee, 1992; Lee et al., 1995; Walko et al., 2000; Liston and Pielke, 2001). It simulates soil moisture and soil temperature, vegetation temperature and surface water (including dew and intercepted rainfall). LEAF-2 includes exchange terms such as turbulent exchange, longwave and shortwave radiative transfer, transpiration, precipitation, heat conduction and water diffusion and percolation in the soil (Walko et al., 2000).

LEAF-2 represents small-scale variations in surface characteristics such as vegetation type, soil type and moisture, water bodies and terrain slope (Walko et al., 2000). The grid element in LEAF-2 is divided into vegetation (represented by a single layer), soil and snow (represented by multiple layers) (Walko et al., 2000; Eastman et al., 2001). The grid element is also divided horizontally into patches, allowing multiple surface types to co-exist under a single grid-resolved atmospheric column (Walko et al., 2000). Separate surface energy budget calculations are performed for the water, bare and shaded soil, snow and vegetation contained in each sub-grid patch (Eastman et al., 2001). Interception of rainfall is parameterized using a simple ‘dump bucket’ method and a multi-layer soil model simulates the vertical transfer of soil water. Evaporation from soil and wet leaves and transpiration from dry leaves are evaluated separately (Lee, 1992) and water is extracted from the moistest soil layer to support transpiration. The quality of this approach, relative to other methodologies used to parameterize water extraction by roots, is unknown (Feddes et al., 2001). Further information on LEAF-2 can be found in Lee (1992), Lee et al. (1995), Walko et al. (2000), Eastman et al. (2001), Lu et al. (2001), Liston and Pielke (2001), Strack et al. (2003), and at: http://rams.atmos.colostate.edu/.

2.3. Model initialization and configuration

In order to use RAMS, a grid-size and a model domain must be selected. RAMS was used with a 50-km horizontal grid spacing over mainland Australia. The 50-km resolution was chosen as a compromise between a higher resolution that provides greater detail (but was too computationally expensive) and a lower resolution that was computationally cheap (but too limiting in geographical detail). While the 50-km horizontal grid spacing is too coarse to allow mesoscale fluxes, driven by small-scale heterogeneity to develop (cf. Avissar, 1992), it is adequate to obtain a good estimate of the impact of realistic biophysical parameters on large-scale climate.

To provide RAMS with information on the atmosphere outside of the selected domain, 6-hourly reanalysis data from the National Center for Environmental Prediction (NCEP) (Greene et al., 1999) were used to define lateral boundary conditions. These same reanalysis data were also used to initialize the atmosphere within the selected domain. The use of reanalysis data in this way forces the large scale atmospheric patterns simulated in the model to be broadly consistent with observed patterns, while allowing the model to adjust to surface changes within the domain (Greene et al., 1999). In general, this model configuration is typical when RAMS is used (Liston and Pielke, 2001). Soil temperature and soil moisture within the domain were initialized identically in all simulations using results from the end of earlier experiments. Since we are exploring questions of model sensitivity to vegetation biophysical characteristics in this paper, the accuracy of soil moisture initialization is not as important as in forecasting experiments.

In common with many land surface schemes, a series of biophysical parameters in LEAF-2 are defined as maximum values (e.g. maximum LAI, maximum fractional vegetation cover) and then a second parameter defines the seasonal variation in these parameters by imposing a sine wave on this maximum. The seasonality is usually defined as a function of temperature so that the maximum is reached in mid-summer and the minimum in mid-winter. Since we focus on January simulations (mid-summer) we ignored seasonally-driven variations in these parameter values. We did explore how significant this omission could be, and at most it would have led to a difference in LAI of 0.001 $m^2\ m^{-2}$ and a similar difference in actual fractional vegetation cover.

In numerical modelling, reaching conclusions from a single simulation can be misleading since it is possible that results could be sensitive to the selection of a particular month. For example, if the chosen month happened to be a severe drought, different conclusions would be likely than if the chosen month happened to be a wet year. For this reason, and to ensure that the statistical analysis of the results is robust, multiple simulations of a given day, month or year should be performed. In this paper, each experiment comprises six simulations using boundary conditions from six different Januaries (1985–1990 inclusive). January was chosen because Narisma and Pitman (2003) showed that RAMS tended to produce a clearer response to changes in surface conditions in January compared to July.

2.4. Statistical methodology

The assessment of any statistical significance of a change in a simulated quantity is not trivial in climate modelling. Standard *t*- or *F*-tests cannot be reliably used due to problems of spatial autocorrelation and unknown sampling distribution problems (Wigley and Santer, 1990). The development of the pool permutation procedure by Preisendorfer and Barnett (1983) and the work of Santer and Wigley (1990) and Wigley and Santer (1990) provide a suite of robust statistical tests suitable for use in climate modelling. Specifically, using the same terminology as Wigley and Santer (1990) (see Table 1) we used the "T1" statistic to test the differences in grand means. NT5 and NF5 test the differences in the point-by-point temporal means and temporal variances and SPRET and SPREX test the overall difference in the temporal and spatial variances. In all tests, a statistical significance level of 95% is used and we use 1000 permutations for the pool permutation procedure (see Wigley and Santer, 1990). *P* values for the statistical tests shown in Table 1 were calculated, and *P* values that exceed 0.95 or are below 0.05 are statistically significant at the 95% confidence level.

Table 1
Summary of the test statistics used in this paper, following Wigley and Santer (1990)

Statistic	Designed to test:
NT5	Differences in time means, grid point by grid point. NT5 is the fraction of grid points with significant differences at the 5% significance level. This is a two-tailed *t*-test
T1	Differences between grand means (overall variances)
NF5	Differences in temporal variances, grid point by grid point. This is a two-tailed *F*-test
SPREX	Overall difference in spatial variances
SPRET	Overall differences in temporal variances

2.5. Land cover data

To provide the geographic distribution of vegetation over Australia, the vegetation classification from the Australian Surveying and Land Information Group (AUSLIG) was used. These descriptions of vegetation cannot be used directly within RAMS since AUSLIG consists of 21 taxonomic groups (typically a family or genus). The taxonomic group designated for a particular area represents the vegetation found in the tallest stratum, or for the next layer, where the vegetation cover of the tallest stratum is less than 10% (AUSLIG, 1990). To use these data, the AUSLIG taxonomic groups must be mapped to the LEAF-2 plant functional type-based classification. For the control experiment, the AUSLIG vegetation classification was mapped onto the most structurally similar LEAF-2 vegetation class (see Table 2).

Table 2 shows that the 21 taxonomic groups represented in the AUSLIG classification collapsed into 12 LEAF-2 vegetation types. Fig. 1a shows the distribution of these vegetation types and demonstrates

Table 2
The AUSLIG to LEAF-2 mapping used in the control experiment

LEAF-2 vegetation type		AUSLIG vegetation type	
Name	Code	Name	Code
Evergreen shrub	12	*Banksia*	1
		Hakea	4
Evergreen needleleaf forest	3	*Casuarina* incl. *Allocasuarina*	2
		Conifers	9
Evergreen broadleaf forest	6	*Eucalyptus*	3
		Melaleuca	6
		Nothofagus	7
Woodland	23	*Acacia* incl. *Racosperma*	12
Wooded grassland	24	*Owenia* (Desert Walnut)	8
		Myoporum (Sugarwood)	10
		Heterodenrum (Rosewood)	11
Open shrubland	26	*Chenopodiaceae* (e.g. Saltbush, Bluebush)	5
Grassland	27	*Triodia* and/or *Plectrachne*	13
		Astrebla (Mitchell Grass)	14
		Graminoids	17
		Other grasses	20
Short grass	7	*Dichanthium* (Bluegrass)	15
Tall grass	8	*Saccharum* (Sugar cane)	19
Crop/mixed farming	15	*Fabaceae* (incl. Clovers and medics)	16
Tundra	11	*Asteraceae* (Daisies)	21
Mixed cover	22	Mixed or other	22

Several LEAF-2 types encompass a suite of AUSLIG vegetation types illustrating the coarseness of the classification used in RAMS for Australian conditions.

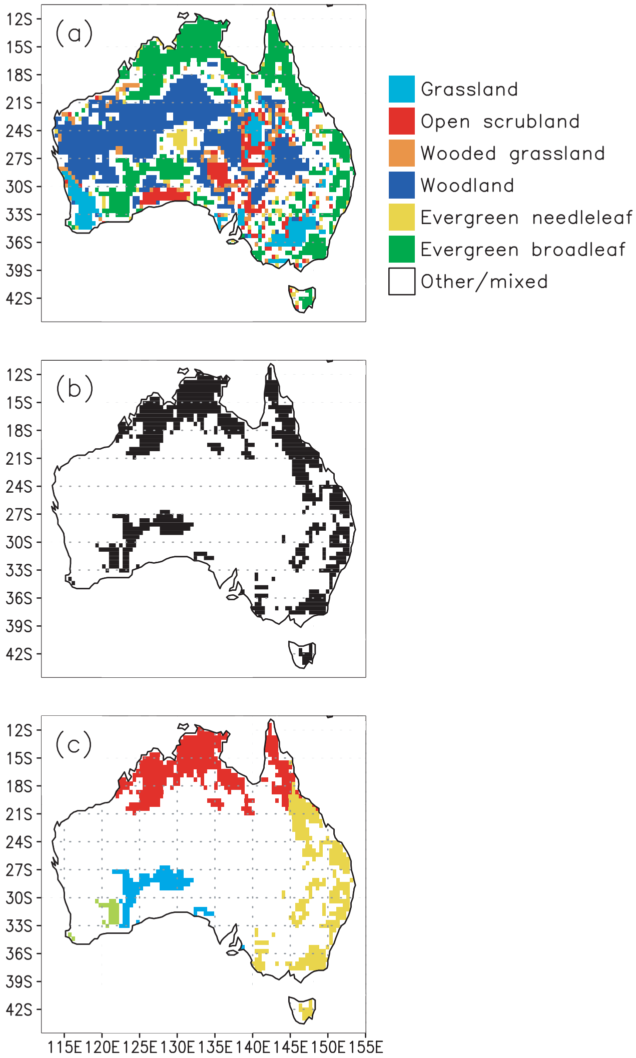

Fig. 1. (a) The vegetation distribution map according to the LEAF-2 classification. (b) The points changed through the explicit inclusion of eucalypts into the LEAF-2 classification. (c) The four regions defined for the *EuM* experiments (Table 6).

Table 3
List of the LEAF-2 biophysical parameters discussed in this paper

Symbol	Description	Units
α	Surface albedo	fraction
LAI_m	Maximum leaf area index	$m^2\ m^{-2}$
σf_m	Maximum fractional vegetation cover	fraction
Z_0	Roughness length (for energy and momentum)	m
R_d	Average maximum root depth	m
d_{smax}	Maximum stomatal conductance	$m\ s^{-1}$

that virtually all of Australia is covered by six basic types. Only the evergreen broadleaf forest and woodland classification cover a large fraction of the vegetated surface in Australia, with grassland, open scrubland and wooded grassland covering relatively small areas. It is significant that Table 2 shows that three AUSLIG vegetation types map onto the LEAF-2 type 'evergreen broadleaf forest'. The mapping of *Eucalyptus, Melaleuca* and *Nothofagus* onto evergreen broadleaf forest leads to the dominance of this vegetation type over Australia within RAMS (Fig. 1a), through the northern, eastern and southern regions. Inland, and in western Australia, woodland is dominant.

RAMS, in common with all climate models, does not use vegetation type directly. Rather, RAMS uses vegetation type as a key or pointer to a look-up table to associate key biophysical parameters (Table 3) with the vegetation type. The vegetation classification used in LEAF-2 is divided into 31 types with values assigned for key biophysical parameters (Table 4, note only those vegetation classes found over Australia are listed). Table 4 lists the vegetation parameters used in the *control* experiment for those vegetation types present over Australia. We note that we did not include Australian-specific variations in soil characteristics in our simulations.

3. Choosing single biophysical parameter values representative of eucalypts

The large fraction of Australia covered by evergreen broadleaf forest within RAMS (Fig. 1a) suggests that a careful choice of parameter values to represent this vegetation type might be worthwhile. To represent the *Eucalyptus* component of the evergreen broadleaf forest classification requires parameter values to be selected for the biophysical parameters listed in Table 3 and eucalypts (comprising species in the genera *Eucalyptus, Corymbia* and *Angophora*) to be separated from *Melaleuca* and *Nothofagus*. Fig. 1b shows the area of just eucalypts and demonstrates that most of the area covered by evergreen broadleaf forest in Fig. 1a has

Table 4
The values of six key vegetative parameters for the LEAF-2 land surface types used for the *control* experiment

LEAF-2 vegetation type	α	LAI_m	σf_m	Z_0	R_d	d_{smax}
Evergreen shrub	0.14	5	0.8	0.1	1.5	0.002
Evergreen needleleaf forest	0.14	6	0.8	1	1.5	0.002
Evergreen broadleaf forest	0.12	6	0.9	2	1.5	0.002
Woodland	0.14	6	0.8	0.8	1.5	0.002
Wooded grassland	0.14	6	0.8	0.5	1.5	0.01
Open shrubland	0.17	4	0.22	0.08	1.5	0.002
Grassland	0.2	3	0.8	0.04	1.5	0.01
Short grass	0.2	2	0.8	0.02	1.5	0.01
Tall grass	0.19	3	0.8	0.1	1.5	0.01
Crop/mixed farming	0.2	6	0.85	0.06	1.5	0.01
Tundra	0.2	3	0.6	0.04	0.5	0.02
Mixed cover	0.14	6	0.8	0.8	1.5	0.002

been changed to eucalypts with *Melaleuca* occupying just small areas of northern Australia.

The search for realistic eucalypt parameter values was conducted via an extensive exploration of the literature. On-line data bases and the citation lists at the end of published papers were explored for key words and other evidence that these publications may contain useful biophysical parameter values. Once the search for parameter values had been completed, a single value had to be chosen for each biophysical parameter that would best reflect eucalypts (in LEAF-2, only one value is used to represent each parameter for each vegetation class). To select this value, frequency distributions of each parameter were graphed (Fig. 2), and mean and median values for each parameter calculated (Table 5). The values found for each biophysical parameter, along with their source, can be found in Appendix A.

The median value was chosen for each parameter to represent eucalypts in LEAF-2 in order to reduce the influence of outliers which appear anomalous, but could not be omitted for any physical reason. The main outliers were in the maximum root depth and in the maximum leaf area index (see Appendix A). Hutley et al. (2001) found that the 'average' maximum root depth for *E. tetrodonta* and *E. miniata* was approximately 10 m (at Howard Springs, approximately 35 km south-east of Darwin) and Westman and Rogers (1977) found that the 'average' maximum root depth of *E. signata* and *E. umbra* subsp. umbra (at North Stradbroke Island) was also 10 m (Fig. 2). These values were retained to preserve consistency because they represent estimates of the average maximum R_d at a specific location. The apparently anomalous maximum leaf area index values, reported by Greenwood et al. (1985) also represent average estimates and while they appear high, they may be reliable estimates of LAI. Only two values for albedo were found and these are not shown in Fig. 2. However, in general, the mean and the median parameter values are very similar and the use of either would not affect the results reported here. Table 5 shows the actual median, mean and the eventual value chosen for experiment *Eu1*.

Fig. 2 shows that quite large numbers of observations were found to support parameter choices for the roughness length and maximum stomatal conductance. Many of the roughness length values were obtained using the assumption that roughness length is $0.1h$ (where h is the vegetation height). We also obtained consistent displacement heights using the assumption of displacement height is $0.67h$ (Oke, 1978). Note that the frequency distributions for roughness length and maximum stomatal conductance are relatively normal. Smaller numbers of observations were found for maximum vegetation cover (effectively the actual January LAI), but again the distribution is quite normal. The lack of observations for maximum root depth and maximum LAI (effectively the actual LAI in January), and the lack of any normal-like distribution is of some concern. It is noteworthy that the ecological and physiological traits of eucalypts have been well studied compared to other plant taxa.

Following the collection of these parameter data (Fig. 2) and the calculation of the median and mean values (Table 5), a single value was chosen to represent eucalypts (Table 5) for experiment *Eu1*. In the case of albedo and the roughness length, the chosen values are similar to the default values defined in LEAF-2 and used in the *control* experiment (Table 5). However, the use of a default maximum leaf area index (6.0) grossly overestimates the observed median value (2.83) and the maximum fraction vegetation cover is also grossly overestimated (0.9 cf. 0.25). The default values are more typical of evergreen broadleaf forest in the tropics (this classification is used in RAMS to represent tropical forest) and the Australian forests are far less dense and have far lower leaf area indices.

Many of the selected parameter values are significantly lower than the default values. Specifically, the lower maximum leaf area index, maximum vegetation cover, and root depths should tend to contribute to lower transpiration during times of moisture limitation and a change in the partitioning of available energy from latent heat to sensible heat exchange. This should tend to warm the surface. In contrast, the higher maximum stomatal conductance and higher roughness length should enhance the transpiration rate and tend to cool the surface. These two competing mechanisms are appropriately explored through the modelling approaches described here.

4. Choosing biophysical parameter values for a multiple classification of eucalypts

While incorporating a single description of eucalypts into RAMS (experiment *Eu1*) is a step forward toward a more realistic description of Australian vegetation in the model, it is clear that not all eucalypts are accurately described by a single set of biophysical parameters. We therefore split the eucalypt group into four broad ecogeographical regions to capture some of the diversity present (see Fig. 1c). To select values for the biophysical parameters representative of the four ecogeographical groups, the data (Appendix A) were divided according to ecogeographical group and the median for each region calculated (Table 6). This division has no impact on the parameter value for albedo and little impact on the maximum stomatal conductance. However, other parameters vary significantly with region. The eucalypts of northern Australia have a low maximum leaf area index, quite a high vegetation cover and are characterized by very deep roots. The eucalypts of eastern

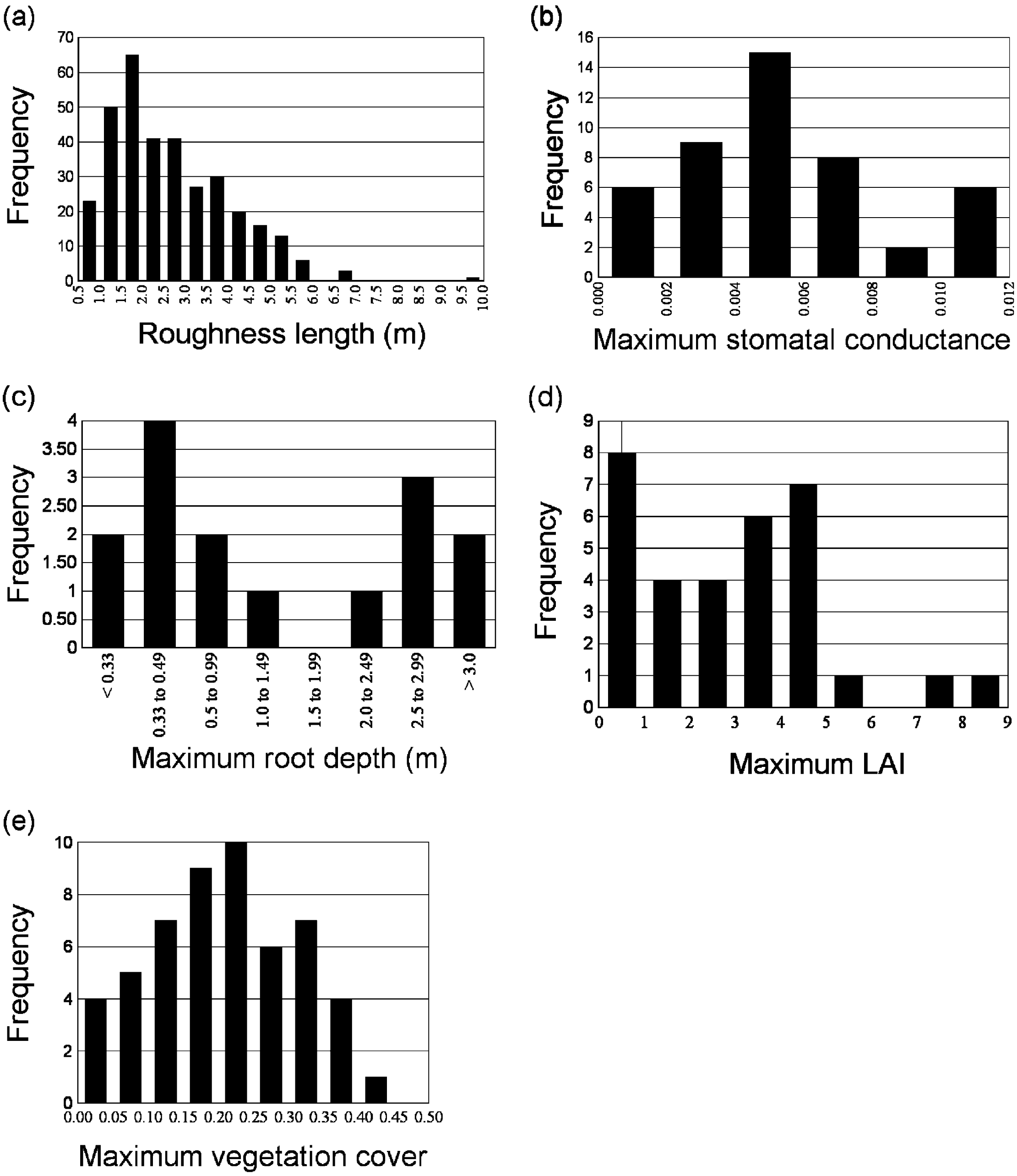

Fig. 2. The frequency distribution for the five biophysical parameters (see Appendix A). Note that the values shown for LAI and vegetation cover are 'maximum' values. A seasonality is imposed on these values within LEAF-2 such that these maximum values are realized in mid-summer. Since our experiments are for January, these 'maximum' values represent actual values in our simulations.

Australia have a high maximum leaf area index but quite a low vegetation cover. They are characterized by quite shallow roots and are aerodynamically very rough. The eucalypts of southern Australia are similar to those of eastern Australia but have a lower maximum leaf area index and are aerodynamically smoother. Finally, the eucalypts of southwestern Australia have quite a high maximum vegetation cover, but are aerodynamically smooth.

These differences in parameters should allow us to explore the sensitivity of the simulations to the division of the eucalypts as a group into the four subdivisions, based on broad structural characteristics and geographical location.

5. Control experiment results (*control*)

We calculated an average of major climate-related quantities by producing land-only monthly averages over the combined six January simulations (i.e. 1985–1990 inclusive). The results from the *control* simulation (using the default parameter values shown in Table 5) were then compared to available gridded

Table 5
The median and mean values for the six parameters and the parameter value selected for Eucalypt in experiment *Eu1*

Parameter	Default value	Mean	Median (selected value)
α	0.12	0.14	0.14
LAI_m	6	2.79	2.83
σf_m	0.9	0.33	0.25
Z_0	2	2.48	2.21
R_d	1.5	2.3	0.6
d_{smax}	0.002	0.0048	0.005

The default value from RAMS used in the *control* experiment is shown for ease of comparison and is the same as evergreen broadleaf forest in Table 4.

observed data from New et al. (2002). The main quantities that can be compared against these observed data are surface air temperature and precipitation.

5.1. Results

Fig. 3a shows the *control* simulation by RAMS of the mean January temperature over Australia. This can be compared with the observed climatology from New et al. (2002) (Fig. 3b). Fig. 3c also shows the difference of these two estimates of the January surface air temperature. The model simulates a warm bias of up to 2 °C over central Australia and a cold bias in many of the coastal regions, but this rarely exceeds 2 °C. Fig. 4 shows the same quantities for precipitation. A modelled dry bias is apparent along all of the east coast and in the extreme north of Australia. This dry bias is usually less than 3 mm d^{-1} but exceeds 5 mm d^{-1} in the extreme north. A wet bias is clear in a band between 15°S and 18°S of mainly 1–3 mm d^{-1} but locally more than 3 mm d^{-1}.

Overall, this is an adequate simulation of the Australian surface air temperature and rainfall given that RAMS was developed for continental USA and contains no Australian-specific parameterizations (relating to soil type for example). The use of the AUSLIG data provides some spatially variable Australian vegetation information, but the common approach of remapping these vegetation types onto the LEAF-2 classification means that while some information is retained on the geographic distribution of vegetation, LEAF-2 in its default implementation, knows nothing about the Australian-specific characteristics of the vegetation.

Table 6
Eucalypt parameter values for the four regions of Australia used in experiment *EuM*

Region	α	LAI_m	σf_m	Z_0	R_d	d_{smax}
Northern Australia	0.14	0.75	0.5	1.95	10	0.005
Eastern Australia	0.14	3.2	0.25	2.41	0.55	0.004
Southern Australia	0.14	1.7	0.25	1.69	0.6	0.004
Southwestern Australia	0.14	2	0.63	0.29	0.6	0.005

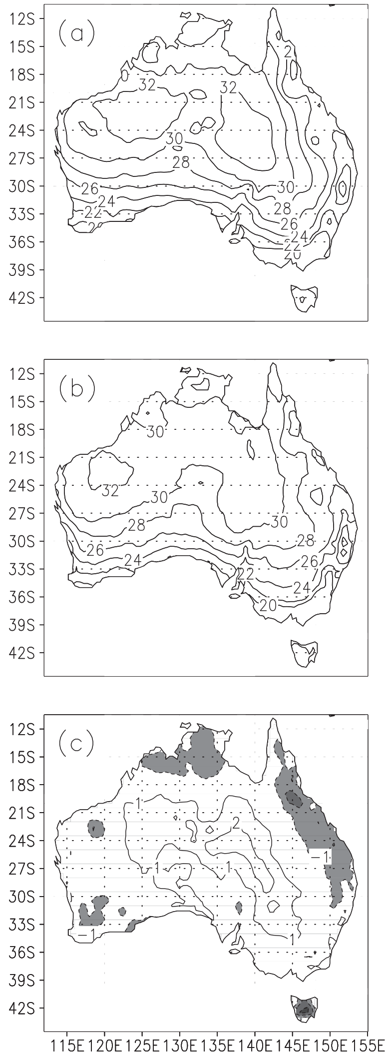

Fig. 3. Results from the *control* experiment using the default biophysical parameters (Table 4) (a) Simulation of surface air temperature by RAMS, averaged over the six Januaries; (b) observed surface air temperature from New et al. (2002); (c) difference between the modelled and observed surface air temperature. All temperatures are in °C and in the difference figure, temperatures less than −1 °C are shaded.

The key purpose of this paper is to determine whether this simplification matters and whether representing eucalypts explicitly in RAMS enhances the January climatology of the model shown in Figs. 3 and 4. The secondary aim of this paper is to determine whether eucalypts can be represented as a single plant functional type (experiment *Eu1*) for the entire continent, or whether several types of eucalypt (experiment *EuM*) need to be captured in RAMS.

6. Experiment *Eu1*: using a single set of biophysical parameters to represent eucalypts

The impact of including a single set of biophysical parameters to represent eucalypts in RAMS can be

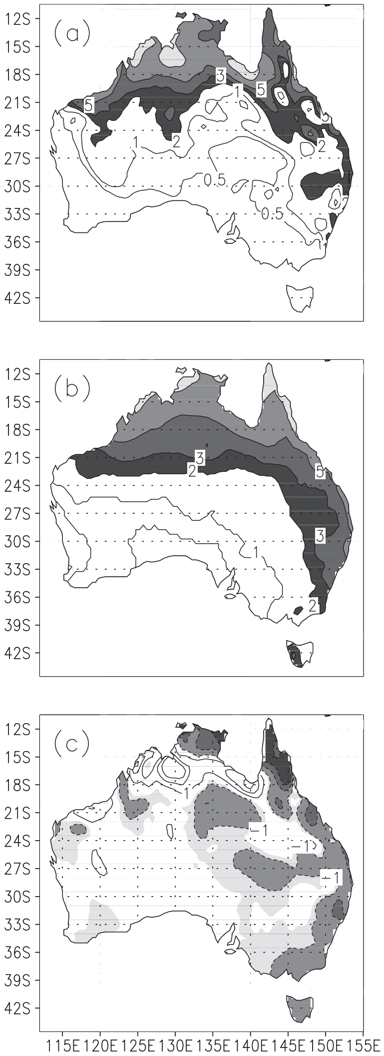

Fig. 4. As Fig. 3 but for precipitation. In the modelled and observed figures, rainfall in excess of 2 mm d^{-1} are shaded. In the difference plot, differences of less than -1 mm d^{-1} are shaded.

measured in several ways. Within LEAF-2, the change in the parameter values shown in Table 5 most directly affect the partitioning of available energy between sensible and latent heat since many of the parameters directly affect the capacity of the biophysical system to supply water through the root system (R_d) to the plant and then to transpire the water through the stomates (d_{smax}). Other parameters affect the amount of leaf (LAI_m) or canopy in contact with the atmosphere (σf_m), or the efficiency through which turbulent energy exchange can occur (Z_0). If the latent heat flux is affected by the inclusion of specific eucalypt biophysical parameters then changes in surface air temperature would be expected following these changes. Further, it is possible that, should the change in the latent heat flux be large enough, significant changes in precipitation may occur. It is therefore useful to explore the impact of replacing the default parameters with a single set of biophysical parameters representative of eucalypts has on the latent heat flux, surface air temperature and precipitation.

We found that the major impact of representing eucalypts in RAMS was to affect the simulated latent heat flux (Fig. 5a). The increase in the latent heat flux of 30–50 Wm^{-2} over Northern Australia is to be expected. This region is very wet (5–10 mm d^{-1} of precipitation, Fig. 4a) and the latent heat flux is therefore not moisture limited. The changes in leaf area index, fractional vegetation cover and the maximum root depth (Table 5) are therefore unlikely to have a significant impact on the latent heat flux. In contrast, the controls on turbulent energy exchange (the aerodynamic roughness length) and controls on transpiration (the maximum stomatal conductance) will affect the latent heat flux. The roughness length is increased from 2.0 to 2.21 m from the control simulation and the conductance increased from 0.002 m s^{-1} to 0.005 m s^{-1} (Table 5). These changes also affect the latent heat flux simulated by the model along the east coast and in western Australia, the two other major regions of vegetation change (Fig. 1b).

The increase in the latent heat flux cools the surface (Fig. 6a) by 0.1–0.2 °C, slightly increasing the cold bias in RAMS (Fig. 3a). More significant is the local decrease in precipitation over northern Australia (Fig. 7a) which is small (0.3 mm d^{-1}) but increases a dry bias over the extreme north of Australia (Fig. 4a). This change in the simulation of precipitation is not caused by the local changes in the latent heat flux (which is increased) but by a reduction in the moisture convergence onto the continental surface, following the increase in roughness length.

Overall, the impact of using a single set of biophysical parameters to represent eucalypts in LEAF-2 does not lead to a dramatic change. However, the impact of including realistic biophysical parameters for eucalypts on the latent heat flux is statistically significant in the point-by-point time mean (NT5, Table 7) over northern Australia and southwestern Australia, but the changes are not statistically significant over the whole of the continent or over eastern Australia (see Fig. 8 for the definition of the regions). The point-by-point temporal variance is statistically significant for the latent heat flux for most regions (NF5, Table 7). The change in the overall spatial (SPREX) and temporal (SPRET) variances suggests that only over northern Australia are the changes statistically significant.

In the case of temperature and rainfall there is no evidence that the inclusion of realistic biophysical parameter values for eucalypts leads to a statistically significant change in the overall mean (T1) or the spatial or temporal variances in any region (Table 7). There is, however, a strong statistically significant result for all regions for temperature in the point-by-point time mean

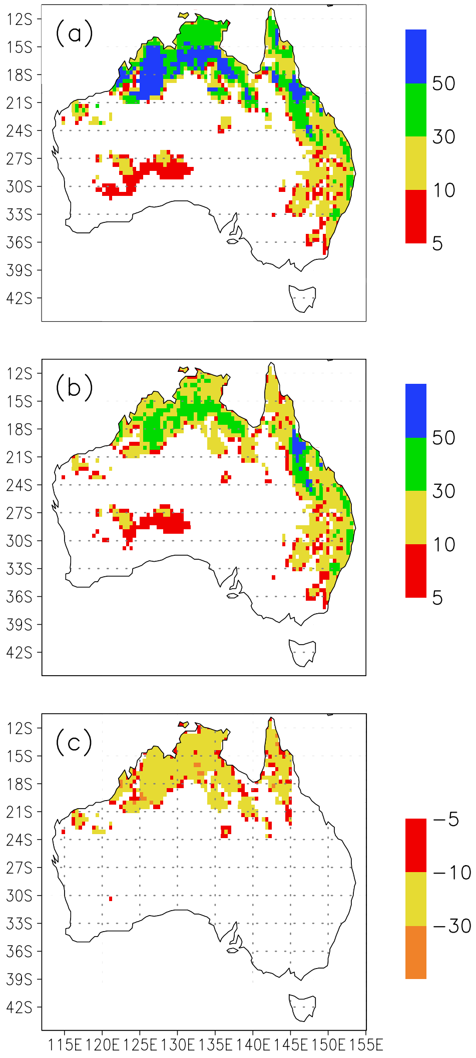

Fig. 5. The difference in the latent heat flux (W m^{-2}) simulated by RAMS with (a) an explicit representation of eucalypts as a single set of parameters (experiment *Eu1*, difference from the control); (b) with four types of eucalypts represented (experiments *EuM*, difference from the control) and (c) the difference between experiments *Eu1* and *EuM*.

and temporal variance. The changes in precipitation are also statistically significant over northern Australia for these two measures.

The overall sense of the results for the incorporation of realistic eucalypt parameters in experiment *Eu1* is a statistically significant impact on the simulation of the latent heat flux in all measures over northern Australia, but only in terms of the point-by-point temporal mean and variance in temperature and, over northern Australia, in precipitation. The impact on precipitation and temperature is to reduce the skill of the model over northern Australia. In general, the result suggests that the incorporation of a single set of realistic eucalypt parameters in LEAF-2 does not improve the model.

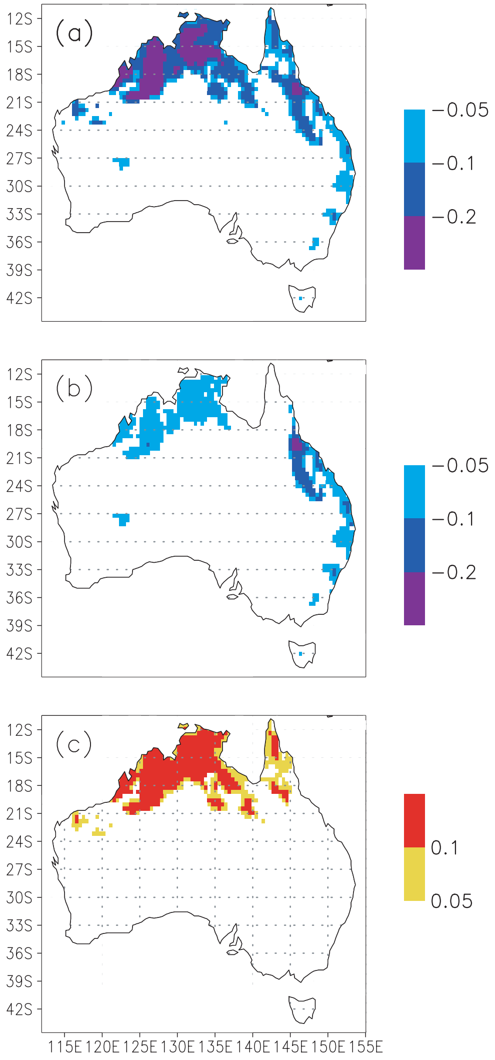

Fig. 6. As Fig. 5 but for temperature (°C).

7. Experiment *EuM*: using four sets of biophysical parameters to represent eucalypts

The separation of eucalypts into four types of forest was described in Section 4 and the biophysical parameters used in experiment *EuM* are shown in Table 6. Fig. 5b shows the impact of the geographic variation in eucalypt biophysical parameters on the latent heat flux. Overall, the pattern of change from the control is similar to when a single set of eucalypt parameters was used (experiment *Eu1*, Fig. 5a). In particular, there are negligible differences over eastern, southern or southwestern Australia (Fig. 5c). However, over northern Australia the difference between experiments *Eu1* and *EuM* reach 10–30 W m^{-2} over a large region (Fig. 5c). This leads to 0.1 °C *less* cooling in *EuM* and hence the results are closer to the observed values than in *Eu1* (Fig. 6c). The differences between *Eu1* and *EuM* in rainfall are small and restricted to the extreme northern edge of Australia. Here, the negative result

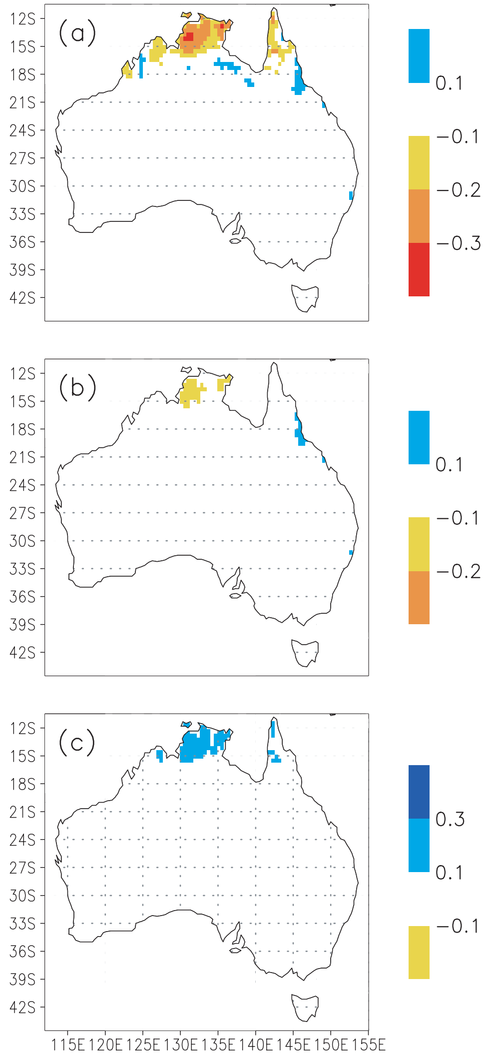

Fig. 7. As Fig. 5 but for precipitation (mm d^{-1}).

found in *Eu1* is largely reversed, and *EuM* is similar to *control*. Thus, while *Eu1* degrades the simulation of precipitation, using multiple parameter sets for *EuM* leads to an improved simulation of temperature and no degradation in the simulation of precipitation. The statistical significance of these results for *EuM* on the latent heat flux, temperature and rainfall is shown in Table 8. The results are very similar to those for *Eu1* (e.g. Table 7).

8. Discussion and conclusions

The representation of the vegetation at the Earth's surface is generally recognized to be an important component of climate models (Arora, 2003; Pitman, 2003). Significant effort has been invested in the choice of parameter values via local observations and remote sensing (e.g. Dorman and Sellers, 1989; Sellers et al., 1996). It was therefore reasonable to hypothesize that the mapping of Australian vegetation, as represented by AUSLIG (1990) onto a coarse classification used in LEAF-2 could have a significant impact on RAMS.

Table 7
P values for the differences between the *control* experiment and the simulations describing eucalypts using a single set of parameters (experiment *Eu1*)

	NT5	NF5	SPREX	SPRET	T1
Latent heat flux					
Australia	0.33	**1**	**0**	0.13	0.06
Northern Australia	**1**	**0.99**	**0**	**0**	**0.03**
SW Australia	**1**	**0.99**	0.33	0.32	0.39
Eastern Australia	0.28	0.84	**0.01**	0.06	0.2
Temperature					
Australia	**1**	**1**	0.59	0.57	0.55
Northern Australia	**1**	**1**	0.35	0.38	0.65
SW Australia	**1**	**1**	0.55	0.54	0.51
Eastern Australia	**1**	**1**	0.52	0.55	0.54
Precipitation					
Australia	0.24	0.83	0.51	0.51	0.52
Northern Australia	**1**	**1**	0.45	0.46	0.46
SW Australia	**1**	0.54	0.53	0.52	0.54
Eastern Australia	0.19	0.52	0.47	0.5	0.5

Statistically significant results, at a 95% confidence level, are in bold.

The simulations using a single set of eucalypt parameters (experiment *Eu1*) showed that using more reasonable biophysical values did lead to a statistically significant impact on the simulated latent heat flux (Fig. 5a). This had a relatively small (but negative) impact on temperature in northern and eastern Australia (Fig. 6) and a small (but negative) impact on precipitation. Allowing the biophysical parameters to

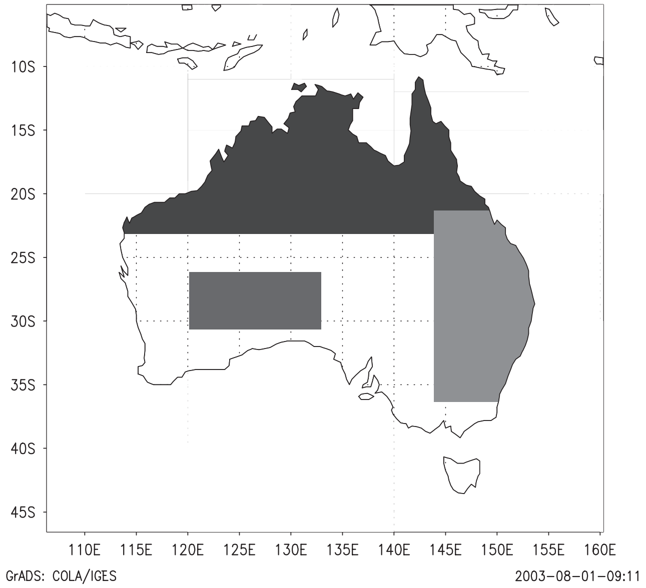

Fig. 8. The domains over Australia where the statistical tests were undertaken. The fourth region representing all mainland continental Australia is not shown.

Table 8
P values for the differences between the *control* experiment and the simulations describing eucalypts using a multiple sets of parameters (experiment *EuM*)

	NT5	NF5	SPREX	SPRET	T1
Latent heat flux					
Australia	0.58	**1**	**0.01**	0.17	0.14
Northern Australia	**1**	**1**	**0**	**0**	0.12
SW Australia	**1**	0.99	0.35	0.34	0.41
Eastern Australia	0.29	0.82	**0.01**	0.06	0.2
Temperature					
Australia	**1**	**1**	0.54	0.57	0.53
Northern Australia	**1**	**1**	0.44	0.44	0.57
SW Australia	**1**	**1**	0.55	0.53	0.51
Eastern Australia	**1**	**1**	0.52	0.55	0.54
Precipitation					
Australia	0.24	0.83	0.51	0.51	0.52
Northern Australia	**1**	**1**	0.45	0.46	0.46
SW Australia	**1**	0.55	0.53	0.53	0.54
Eastern Australia	0.18	0.52	0.47	0.5	0.5

Statistically significant results, at a 95% confidence level, are in bold.

vary according to four ecogeographical regions (experiment *EuM*, Fig. 1c) led to a similar overall change in latent heat flux (Fig. 5b), a smaller impact on temperature (Fig. 6b) and a small impact on precipitation (Fig. 7b). The results from *EuM* were better, in terms of simulated temperature and precipitation, than those from *Eu1*.

Overall, in terms of observable measures of climate (surface air temperature, precipitation), the results from our experiments do not encourage the development of biophysical parameter data sets for eucalypts. Our results indicate that any systematic errors in RAMS were insensitive to the biophysical parameters used to represent eucalypts and the net impact of representing them more accurately was limited. However, while the model was insensitive to the biophysical parameters in the simulation of temperature and precipitation, it was not insensitive in the simulation of the latent heat flux. The changes shown in Fig. 5a and b represent a 20% change in the simulated latent heat flux. This would lead to an impact on soil moisture, runoff and ground water recharge. The changes shown in Fig. 5a and b represent changes in the simulated transpiration which would affect the gross carbon balance of the canopy. LEAF-2 does not include any capacity for carbon balance modelling and hence we could not explore this issue. However, we suspect that the more sophisticated land surface models under development (Arora, 2003) may be more sensitive to biophysical parameters because they model carbon exchange. This suggests that field work to collect suitable biophysical parameter data remains a priority.

Our recommendation for groups modelling the Australian climate using imported models is therefore to take the first few steps toward recognizing the uniqueness of the local flora. We recommend that when mapping Australian land cover data onto the climate model, a vegetation class is allocated to eucalypts and the parameter values selected for our multi-eucalypt experiment (experiment *EuM*, Table 6) are used. This appears to capture most of the role of eucalypts within large -cale land–atmosphere interactions. We note that using a single definition of eucalypts leads to a worse simulation of temperature and precipitation than using a multiple classification, and we therefore do not recommend replacing the default parameters with a single parameter set (Table 5).

Overall, our results can be viewed in two contrasting ways. They are in one sense disappointing because we expected to find more improvement in the simulation of the Australian climate by representing the biophysical characteristics of eucalypts more realistically. Our results suggest that the systematic errors in RAMS in the simulation of the Australian January climate are not related to the use of a very coarse classification of vegetation. However, in terms of our capacity to simulate the Australian January climate, our results are more encouraging. First, the default simulation of the Australian January climate captures the observed temperature and precipitation quite well, indicating that RAMS is a useful tool over Australia. Second, there is a remarkable lack of observed biophysical parameter data for eucalypts but there appears to be far less available data for other vegetation types. If our results had shown a strong sensitivity in the simulated January climate to the biophysical parameters it would have been logical to assume that other vegetation types would also be important, and that the lack of available data for these vegetation types would have represented a major constraint on our capacity to develop models for the Australian continent.

Finally, it is important to note several major caveats to our study. First, we used a single climate model with a single set of parameterizations for land surface processes, clouds, the boundary layer, radiative transfer etc. We do not think our results are likely to be model-sensitive but we cannot discount the possibility that different results would be obtained if we used a different meteorological or land surface model. We also used a relatively coarse grid and repeating our simulations at much higher resolution would be interesting (if extremely computationally demanding). Second, we only explored the January climate. Narisma and Pitman (2003) showed that the sensitivity of the climate to land surface processes was greater in January than July, which suggests that our results would have been less sensitive to the eucalypt parameters if we had used July. However, we have not explored this using RAMS due to computational constraints and thus caution should be exercised in assuming the results reported in this paper can be extended to other seasons.

Acknowledgements

We thank Dr Barbara Rice for advice on the mapping of the AUSLIG taxonomic groups onto the LEAF-2 vegetation classes.

Appendix A Literature sources for the eucalypt biophysical parameters

Maximum fractional vegetation cover

Value	Reference	Value	Reference
0.02	Clayton-Greene and Ashton (1990)	0.25	Clayton-Greene and Ashton (1990)
0.024	Ashton and Chappill (1989)	0.26	Clayton-Greene and Ashton (1990)
0.04	Landsberg and Gillieson (1995)	0.3	Clayton-Greene and Ashton (1990); Pierce et al. (1993)
0.05	Clayton-Greene and Ashton (1990)	0.33	Clayton-Greene and Ashton (1990); Dawes et al. (1997)
0.07	Dawes et al. (1997)	0.35	Clayton-Greene and Ashton (1990)
0.09	Clayton-Greene and Ashton (1990)	0.4	Clayton-Greene and Ashton (1990)
0.1	Clayton-Greene and Ashton (1990)	0.45	Clayton-Greene and Ashton (1990)
0.12	Ash and Helman (1990)	0.46	Westman and Rogers (1977)
0.13	Ash and Helman (1990)	0.5	Myers et al. (1997); Hutley et al. (2001)
0.14	Ash and Helman (1990); Landsberg and Gillieson (1995)	0.52	Landsberg and Gillieson (1995)
0.15	Clayton-Greene and Ashton (1990); Ash and Helman (1990)	0.58	Landsberg and Gillieson (1995); Dawes et al. (1997)
0.16	Ash and Helman (1990); Landsberg and Gillieson (1995)	0.6	Pierce et al. (1993)
0.17	Ash and Helman (1990)	0.62	Landsberg and Gillieson (1995)
0.18	Ash and Helman (1990)	0.66	Landsberg and Gillieson (1995)
0.2	Westman and Rogers (1977); Clayton-Greene and Ashton (1990)	0.68	Lyons (2002)
0.21	Clayton-Greene and Ashton (1990)	0.7	Landsberg and Gillieson (1995)
0.22	Clayton-Greene and Ashton (1990)	0.72	Myers et al. (1986)
0.23	Clayton-Greene and Ashton (1990)	0.84	Landsberg and Gillieson (1995)
0.24	Clayton-Greene and Ashton (1990)	0.86	Landsberg and Gillieson (1995)

Maximum leaf area index ($m^2\ m^{-2}$)

Value	Reference	Value	Reference
0.07	Hutley et al. (2001)	3	Anderson (1981); Dunin and Mackay (1982)
0.2	Westman and Rogers (1977); Dawes et al. (1997)	3.12	Pook (1984b)
0.49	Westman and Rogers (1977)	3.2	Pierce et al. (1993)
0.75	Hutley et al. (2001)	3.5	Westman and Rogers (1977)
0.95	Dawes et al. (1997); Hutley et al. (2001)	4	Pook (1985, 1986)
1.2	Lyons (2002)	4.3	Pook (1984a)
1.3	Pate et al. (1998)	4.5	Greenwood et al. (1985)
1.6	Pierce et al. (1993)	4.6	Greenwood et al. (1985)
1.7	Dawes et al. (1997)	4.9	Coops et al. (1997)
2	Greenwood et al. (1985)	4.95	Coops et al. (1997)
2.1	Pate et al. (1998)	5	Pook et al. (1997)
2.4	Linder (1984)	7.2	Greenwood et al. (1985)
2.65	Greenwood et al. (1985)	8	Greenwood et al. (1985)

Average maximum root depth (m)

Value	Reference	Value	Reference
0.3	Ashton (1975)	1	Ashton (1975)
0.35	Ashton (1975)	2.4	Ashton (1975)
0.4	Ashton (1975)	2.5	Ashton (1975)
0.45	Ashton (1975)	2.6	Ashton (1975)
0.5	Ashton (1975)	2.7	Ashton (1975)
0.6	Ashton (1975)	10	Westman and Rogers (1977); Hutley et al. (2001)

Stomatal conductance (ms^{-1})

Value	Reference	Value	Reference
0.001	Colquhoun et al. (1984); Sinclair (1980)	0.006	Myers and Neales (1984)
0.002	Sinclair (1980)	0.006	Sinclair (1980); Hutley et al. (2001)
0.003	Colquhoun et al. (1984)	0.007	Sinclair (1980); Colquhoun et al. (1984)
0.003	Sinclair (1980); Myers and Neales (1984)	0.008	Myers and Neales (1984); Dawes et al. (1997)
0.004	Sinclair (1980); Colquhoun et al. (1984); Myers and Neales (1984)	0.01	Colquhoun et al. (1984); Dawes et al. (1997)
0.005	Sinclair (1980); Colquhoun et al. (1984); Myers and Neales (1984); Hutley et al. (2001)		

Roughness length (m)

Value	Reference			Value	Reference
0.04	Xinmei et al. (1993)	1.19	Parsons (1909)	3.25	Howard (1973); Ashton (1975); Feller (1980); Unwin (1989); Melick and Ashton (1991); Myers et al. (1997); Prior et al. (1997)
0.05	Xinmei et al. (1993)	1.3	Ladiges and Ashton (1974); Westman and Rogers (1977); Withers and Ashton (1977); Anderson and Ladiges (1978); Sinclair (1980); Myers et al. (1986); Unwin (1989); Clayton-Greene and Ashton (1990); Slatyer and Morrow (1997); Prior et al. (1997); Hutley et al. (2001)	3.38	Howard (1973); Ashton (1975); Westman and Rogers (1977)
0.06	Xinmei et al. (1993)2.99	1.33	Russell-Smith et al. (1993)	3.51	Howard (1973); Ladiges and Ashton (1974); Ashton (1975); Unwin (1989); Pate et al. (1998)
0.07	Xinmei et al. (1993); Lyons (2002)	1.35	Russell-Smith et al. (1993)	3.64	Howard (1973); Westman and Rogers (1977); Pate et al. (1998)
0.08	Xinmei et al. (1993)	1.37	Landsberg and Gillieson (1995)	3.74	Russell-Smith et al. (1993)
0.09	Xinmei et al. (1993)	1.43	Withers and Ashton (1977); Anderson and Ladiges (1978); Myers et al. (1986); Ashton and Chappill (1989); Landsberg and Gillieson (1995); Hutley et al. (2001)	3.77	Howard (1973); Unwin (1989); Pate et al. (1998)
0.1	Xinmei et al. (1993)	1.5	Landsberg and Gillieson (1995)	3.9	Howard (1973); Ladiges and Ashton (1974); Ashton (1975); Westman and Rogers (1977); Anderson and Ladiges (1978); Unwin (1989); Melick and Ashton (1991); Slatyer and Morrow (1997); Prior et al. (1997); Pate et al. (1998)
0.11	Xinmei et al. (1993)	1.56	Withers and Ashton (1977); Anderson and Ladiges (1978); Myers et al. (1986); Hutley et al. (2001)	4.03	Howard (1973); Anderson and Ladiges (1978); Unwin (1989); Pate et al. (1998)
0.12	Xinmei et al. (1993)	1.69	Westman and Rogers (1977); Anderson and Ladiges (1978); Myers et al. (1986); Unwin (1989); Melick and Ashton (1991); Landsberg and Gillieson (1995); Pook et al. (1997)	4.16	Howard (1973); Ashton (1975); Anderson and Ladiges (1978); Melick and Ashton (1991); Pate et al. (1998)

Roughness length (m) (*continued*)

Value	Reference			Value	Reference
0.13	Xinmei et al. (1993); Prior et al. (1997); Lyons (2002)	1.82	Westman and Rogers (1977); Anderson and Ladiges (1978); Sinclair (1980); Myers et al. (1986); Ashton and Chappill (1989); Pook et al. (1997); Hutley et al. (2001)	4.29	Howard (1973); Anderson and Ladiges (1978); Unwin (1989); Pate et al. (1998)
0.14	Xinmei et al. (1993)	1.89	Landsberg and Gillieson (1995)	4.42	Howard (1973)
0.15	Xinmei et al. (1993); Lyons (2002)	1.95	Westman and Rogers (1977); Feller (1980); Myers and Neales (1984); Myers et al. (1986); Unwin (1989); Melick and Ashton (1991); Landsberg and Gillieson (1995); Pook et al. (1997); Dawes et al. (1997); Prior et al. (1997); Hutley et al. (2001)	4.55	Ashton (1976); Anderson and Ladiges (1978); Unwin (1989); Pate et al. (1998)
0.2	Lyons (2002)	1.99	Landsberg and Gillieson (1995)	4.59	Ashton (1976)
0.26	Westman and Rogers (1977); Prior et al. (1997); Lyons (2002)	2.04	Russell-Smith et al. (1993)	4.68	Howard (1973); Ashton (1975); Anderson and Ladiges (1978)
0.33	Lyons (2002)	2.08	Ladiges and Ashton (1974); Westman and Rogers (1977); Anderson and Ladiges (1978); Feller (1980); Sinclair (1980); Pook (1984a); Myers et al. (1986); Pook et al. (1997)	4.81	Anderson and Ladiges (1978); Florence (1981)
0.39	Prior et al. (1997); Lyons (2002)	2.21	Ashton (1975); Anderson and Ladiges (1978); Feller (1980); Myers et al. (1986); Unwin (1989); Pook et al. (1997)	4.94	Ashton (1975); Anderson and Ladiges (1978)
0.46	Landsberg and Gillieson (1995); Lyons (2002)	2.34	Ladiges and Ashton (1974); Ashton (1975); Westman and Rogers (1977); Anderson and Ladiges (1978); Feller (1980); Unwin (1989); Landsberg and Gillieson (1995); Pook et al. (1997)	5.07	Anderson and Ladiges (1978)
0.52	Westman and Rogers (1977); Lyons (2002)	2.37	Parsons (1909)	5.2	Ladiges and Ashton (1974); Ashton (1975); Anderson and Ladiges (1978); Feller (1980); Pook (1984a); Unwin (1989); Ash and Helman (1990); Coops et al. (1997)
0.59	Landsberg and Gillieson (1995); Lyons (2002)	2.38	Ashton and Chappill (1989)	5.33	Feller (1980)
0.65	Anderson and Ladiges (1978); Clayton-Greene and Ashton (1990); Lyons (2002)	2.43	Landsberg and Gillieson (1995)	5.46	Feller (1980); Unwin (1989)
0.72	Lyons (2002)	2.47	Ladiges and Ashton (1974); Ashton (1975); Feller (1980); Unwin (1989); Clayton-Greene and Ashton (1990)	5.59	Feller (1980); Unwin (1989)
0.78	Westman and Rogers (1977); Anderson and Ladiges (1978); Sinclair (1980); Myers et al. (1986); Clayton-Greene and Ashton (1990); Lyons (2002)	2.6	Prior et al. (1997); Unwin (1989); Clayton-Greene and Ashton (1990); Melick and Ashton (1991); Landsberg and Gillieson (1995)	5.66	Ashton (1976)

(*continued on next page*)

Roughness length (m) (*continued*)

Value	Reference			Value	Reference
0.85	Landsberg and Gillieson (1995)	2.73	Ladiges and Ashton (1974); Ashton (1975); Feller (1980); Sinclair (1980); Unwin (1989); Clayton-Greene and Ashton (1990); Myers et al. (1997)	5.72	Feller (1980)
0.91	Anderson and Ladiges (1978); Sinclair (1980); Myers et al. (1986); Clayton-Greene and Ashton (1990); Slatyer and Morrow (1997)	2.86	Ashton (1975); Westman and Rogers (1977); Feller (1980); Unwin (1989); Clayton-Greene and Ashton (1990); Myers et al. (1997)	5.85	Feller (1980); Unwin (1989)
1.04	Cremer (1975); Sinclair (1980)	2.99	Ashton (1975); Feller (1980); Unwin (1989); Myers et al. (1997)	6.5	Unwin (1989)
1.11	Ashton and Chappill (1989)	3.08	Landsberg and Gillieson (1995)	6.76	Unwin (1989)
1.17	Sinclair (1980); Myers and Neales (1984); Myers et al. (1986); Clayton-Greene and Ashton (1990)	3.12	Howard (1973); Ashton (1975); Westman and Rogers (1977); Feller (1980); Sinclair (1980); Myers et al. (1997)	9.75	Ashton (1975)

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