ELSEVIER

Global and Planetary Change 19 (1998) 247–260

GLOBAL AND PLANETARY CHANGE

Intercomparisons of land-surface parameterizations coupled to a limited area forecast model

B. Timbal [a,*], A. Henderson-Sellers [b]

[a] Bureau of Meteorology Research Centre, GPO Box 1289k, Melbourne, VIC 3001, Australia
[b] Royal Melbourne Institute of Technology, Melbourne, Australia

Received 10 September 1997; accepted 9 February 1998

Abstract

The goal of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) is to improve the understanding of the interactions between the atmosphere and the continental surface in climate and weather forecast models. In PILPS Phase 4(b), selected schemes are coupled to the Limited Area Prediction System (LAPS) developed by the Australian Bureau of Meteorology. To facilitate the comparison of PILPS schemes' behavior within LAPS, a single mode of coupling is selected: explicit coupling. This type of coupling is more flexible and avoids most of the problems raised when interchanging the surface schemes. Exploratory tests are conducted. Initially, experiments are run in which the land-surface schemes use the same parameters as in their original host models. Then, in other runs, the most important surface parameters are set constant in an attempt to reduce the scatter amongst the schemes' results. In order to understand the impact of initialisation of soil moisture on the schemes' results some extreme cases (wet and dry) are performed. The partitioning between surface fluxes is studied as well as the soil moisture budget. Both regional and local results are analysed. Sensitivity between LSS is found in the precipitation field with rainfall over the Australian continent altering by about 20%, but no significant change is found in the net radiation. The scatter in the surface energy fluxes amongst the schemes is large (up to 300 W m^{-2} locally, during the daytime peak) but is seldom affected by the choice of surface parameters. The dynamical range of flux partitioning between extremely dry and wet initialisation varies strongly amongst the schemes. Some major shortcoming with the BUCKET approach are seen in the re-evaporation of convective precipitation over dry land, in the very large evaporation from wet surfaces and the diurnal cycle of surface temperature.

Keywords: land-surface processes; intercomparison; coupling; weather forecast; limited area model

1. Introduction

During previous phases of PILPS, off-line experiments were performed using the same atmospheric forcing to drive the participating Land Surface Schemes (LSS). In Phase 1, the forcing was derived from a GCM. In Phase 2, it was derived from field experiments. In both cases, a significant scatter was observed among the PILPS schemes (Pitman et al., 1993; Henderson-Sellers et al., 1995).

Offline intercomparison, however, does not address the issue of the importance of the atmospheric feedbacks: i.e., does this feedback reduce or increase

* Corresponding author. Fax: +61-03-9669-4660; e-mail: b.timbal@bom.gov.au

PII: S0921-8181(98)00051-4

the differences amongst the schemes? This issue is the main concern of Phases 3 and 4 of PILPS (Timbal et al., 1997).

This paper presents the main achievements in Phase 4(b) of PILPS, focusing on the impact of LSS on a numerical Weather Prediction (NWP) model. The host NWP model chosen is the Limited Area Prediction System (LAPS) developed by the Australian Bureau of Meteorology Research Centre (BMRC) (Puri et al., 1998).

The main goals of Phase 4(b) are (1) to investigate the importance of atmospheric feedbacks on the scatter observed among the schemes during the previous offline PILPS intercomparisons and (2) to study the impact of sophisticated LSS on weather forecasting. It is now recognized that continental surface processes affect short term forecasts (Beljaars et al., 1996). However, more work needs to be done to compare the impact of several LSS on short-term weather predictions.

For Phase 4(b), a set of four PILPS schemes had been chosen in order to perform this intercomparison.

The simplest method of coupling, an explicit coupling, was chosen. This type of coupling offers a consistent link between each LSS and LAPS. The coupling developed for this study is not an attempt to produce a general interface as proposed by Polcher et al. (1998), (this issue). However, some technical problems relevant to the issue of plug-compatibility of LSS modules have been revealed and are described below.

In Section 2, the atmospheric model and the selected LSS are described together with the main features of the coupling. Section 3 presents the methodology used to validate and intercompare the coupled schemes. The main results are discussed in Section 4. Conclusions and strategies for future experiments are given in Section 5.

2. The numerical tools

The host atmospheric model is part of a recently developed limited area numerical weather prediction model and data assimilation (LAPS) used by the Australian Bureau of Meteorology to provide twice-daily 48-h forecasts over the Australian region. This system has been operational since July 1996, over a large area encompassing Australia (65°S–10°N and 65°E–175°W), with a horizontal latitude/longitude spacing of 0.75° and on a subdomain with a resolution of 0.25°. This large window ensures that the limited area is sufficiently large and guarantees that the boundary-generated error has insufficient time to reach the area of interest before the end of the forecast period (Chouinard et al., 1994). There are 19 vertical levels with five levels below 850 hPa (Puri et al., 1998). For briefness, only the features relevant to this work are mentioned here. The radiation scheme is the Fels–Schwarzkopf scheme, which uses a combination of Lacis and Hansen (1974) parameterization for solar wavelengths and the Fels and Schwarzkopf (1975) method for terrestrial wavelengths. It includes diurnal variation. Cloud amounts and heights are diagnosed following Rikus (1991). LAPS has optional packages for convection and boundary layer clouds. For this study, the mass flux scheme following Tiedtke (1989) was used and the boundary layer scheme described by Louis et al. (1981).

The surface parameterization for hydrology used in the operational LAPS is a BUCKET approach as described by Manabe (1969). There are three soil layers for temperatures calculations. The surface characteristics are fixed according to an existing climatology. The albedo is derived from a global map updated quarterly. The topography is derived from a global $1° \times 1°$ grid. The soil moisture calculated by the BUCKET model has to be re-initialised fortnightly from a climatological surface wetness given on a $4° \times 5°$ grid, to avoid unrealistic values.

To compare with the BUCKET scheme which is already coupled to LAPS, three LSS, (BASE, BATS, ISBA) were also chosen. The selection criteria included (a) the schemes were developed to be coupled to a GCM and/or NWP and were already successfully coupled to such a host model; (b) they were part of previous phases of PILPS and did not show any serious shortcomings in the stand-alone experiments (Phases 1 and 2); (c) they were generally close to an 'average' behavior, whilst retaining a range of sensitivities in the Phase 2(a) experiments (Qu et al., 1997); and (d), they represent different theoretical approaches to the soil-vegetation parameterization. Their main features are summarised in (Table 1) and

Table 1
The main documentation, physical concepts and number of layers used by the land-surface schemes participating in the Phase 4(b) of PILPS

Scheme Reference	BUCKET (1)	BASE (2)	BATS (3)	ISBA (4)
No. of layers				
Temperature	3	3	2	2
Soil moisture	1	3	3	2
Roots	0	3	2	1
Canopy	0	1	1	1
Hydrology	bucket	Darcy's Law	Darcy's Law	force restore
Heat budget	heat balance	diffusion	force restore	force restore
Canopy	none	supply and demand	supply and demand	stomatal resistance

(1)Manabe (1969).
(2)Desborough and Pitman (1998).
(3)Dickinson et al. (1993).
(4)Noilhan and Planton (1989).

compared to those of the BUCKET scheme. Some aspects are omitted, in particular numerous details concerning the frozen part of the hydrological cycle (snow cover, melting and frozen soil moisture). They are not relevant in this study.

In order to set up a similar coupling between all schemes and LAPS, a minimal list of tasks to be performed was defined. It included: solving the surface energy equation and computing latent, sensible and ground heat fluxes as well as the surface temperature; closing the surface water budget; calculating drag coefficients and determining a surface roughness. It is assumed that downward radiation is computed by the atmospheric model and the net radiation is then deduced by the surface scheme. Therefore, a coupling with a unique call/access to the LSS could be chosen. This unique entry point within the boundary layer gives access to calculation of the subsurfaces tendencies and allows updates of the scheme's internal variables. This approach has been used successfully by several groups (Bonan, 1994). The flow diagram of the coupling within LAPS structure is given in Fig. 1. It is worth noting that this requirement imposes some modifications of the way these schemes have been coupled originally to their host model. In particular BATS whose original coupling to the CCM model requires a two entry points with a direct link to the radiative scheme (Dickinson et al., 1993). ISBA was also originally designed to be implicitly coupled with the boundary layer although it has been previously coupled explicitly to a mesoscale atmospheric model. The schemes' results did not demonstrate that the balance of the parameterizations was affected.

In an explicit coupling, the surface fluxes are calculated using the new surface conditions and the atmospheric conditions prior to any adjustment of the profiles above the surface. The emphasis is put on a coherent calculation of the surface energy balance. This equation is then solved by linearizing it or by an iterative procedure. The computing cost of this type of coupling is usually more expensive than an implicit coupling where atmospheric profiles of temperature and humidity are solved synchronously with the surface conditions (Mahfouf et al., 1996; Viterbo and Beljaars, 1995) and therefore no iteration is needed. Despite the mathematical strength and numerical stability of implicit coupling, explicit coupling was chosen for this project due to the con-

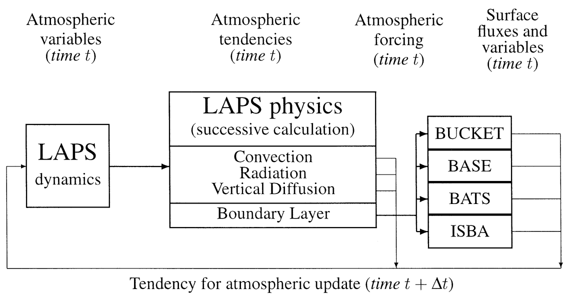

Fig. 1. Flow diagram of the coupling of the four LSS within LAPS calculation.

straint of using several LSS for which the solution of the energy balance equation differs.

The overall cost of the addition of more detailed LSS and the coupling code has proved to be no more than 6% of the 48-h forecast, with a $4° \times 4°$ horizontal resolution using the operational physics package including the BUCKET scheme (see Table 2).

The main drawback to the explicit approach is that the feedback of the surface to the atmosphere is not synchronous. All the surface variables are passed to the atmosphere at time t and used in the atmospheric calculation valid at time $t + \Delta t$. This can lead to numerical instabilities (Kalnay and Kanamitsu, 1988), when the iteration method does not converge, or when sudden changes occur in atmospheric conditions (e.g., sun rise). However, in the case of our experiments, LAPS uses a short time step Δt: 90 s for the dynamics and 12 min for most of the physics calculations, including the surface (the radiation, however, is updated every hour). This has proved to be sufficient to avoid instabilities and the coupling appears to be adequately robust.

The level of complexity of each individual scheme is different and will modify the exchange of information between the atmosphere and the surface in the coupling. Table 3 summarizes the variables involved in explicitly coupling each scheme to LAPS.

Every surface scheme needs common information on the state of the lowest atmospheric level: height, temperature, pressure, mixing ratio and wind. However some require the two horizontal wind components while others only need the horizontal wind speed. Furthermore, some schemes require the potential temperature or the air density. In terms of fluxes, all the schemes need the total precipitation and the longwave and shortwave radiative fluxes (either the downward component or the net flux). The BATS scheme requires a threshold temperature to partition between snowfall and the rainfall. BATS requires further details about the radiative fluxes: direct, diffuse components and visible and near-infrared partitioning as well as the solar flux absorbed by the vegetation and finally the solar zenith.

Table 2
The relative extra cost of each sophisticated LSS compared to a run with the physics of the operational version of LAPS, including the BUCKET scheme

Scheme	BUCKET	BASE	BATS	ISBA
Cray J90's CPU time	420 s	+5%	+3%	+6%

Table 3
The complexity of the coupling is detailed for each scheme in terms of atmospheric forcing variables, prognostic surface variables and geographically varying surface parameters

Scheme	BUCKET	BASE	BATS	ISBA
Atmospheric forcing				
Lowest level (T, Q, P, H)	4	4	4	4
Lowest level wind	1	1	2	2
Lowest level others (Θ, ρ)	2	2	2	0
Precipitation	1	2	1	1
Radiative fluxes	1	2	5	2
Solar zenith angle	0	0	1	0
Total	9	11	15	9
Internal variables				
Soil temperature	4	4	3	2
Soil reservoir	1	6	3	2
Canopy	0	2	4	1
Snow variables	2	3	3	3
Other	0	2	4	0
Total	7	17	17	8
Surface characteristics				
Vegetation coefficients	0	15	16	8
Soil coefficients	0	5	8	10
Total	0	20	24	18

The number of prognostic (or quasi-prognostic) variables is another source of diversity among LSS; varying from 8 (ISBA) to 17 (BATS). This variation is partially due to the number of layers in the soil, but is also due to special requirements of the schemes: BATS carries two fluxes relative to CO_2 exchanges; BATS and BASE, which use a supply and demand technique for calculating the energy fluxes, need the previous values of these fluxes.

Finally each scheme, except for the BUCKET scheme requires information about vegetation and soil type. This information is based on the maps produced by Wilson and Henderson-Sellers (1985) or the ISLSCP dataset (Sellers et al., 1996). However, the number of parameters derived, to describe the vegetation and the soil properties varies from 18 (ISBA) to 24 (BATS). All the other parameters are chosen amongst the values found in the literature and are independent of the vegetation and soil type.

3. Experimental design

Several exploratory tests were conducted on a coarse horizontal grid (4° × 4° with 19 vertical levels). This enabled hypotheses on the impact of initial conditions and surface parameters to be tested quickly and inexpensively. Such a low resolution grid is adequate to compare the behavior of the different

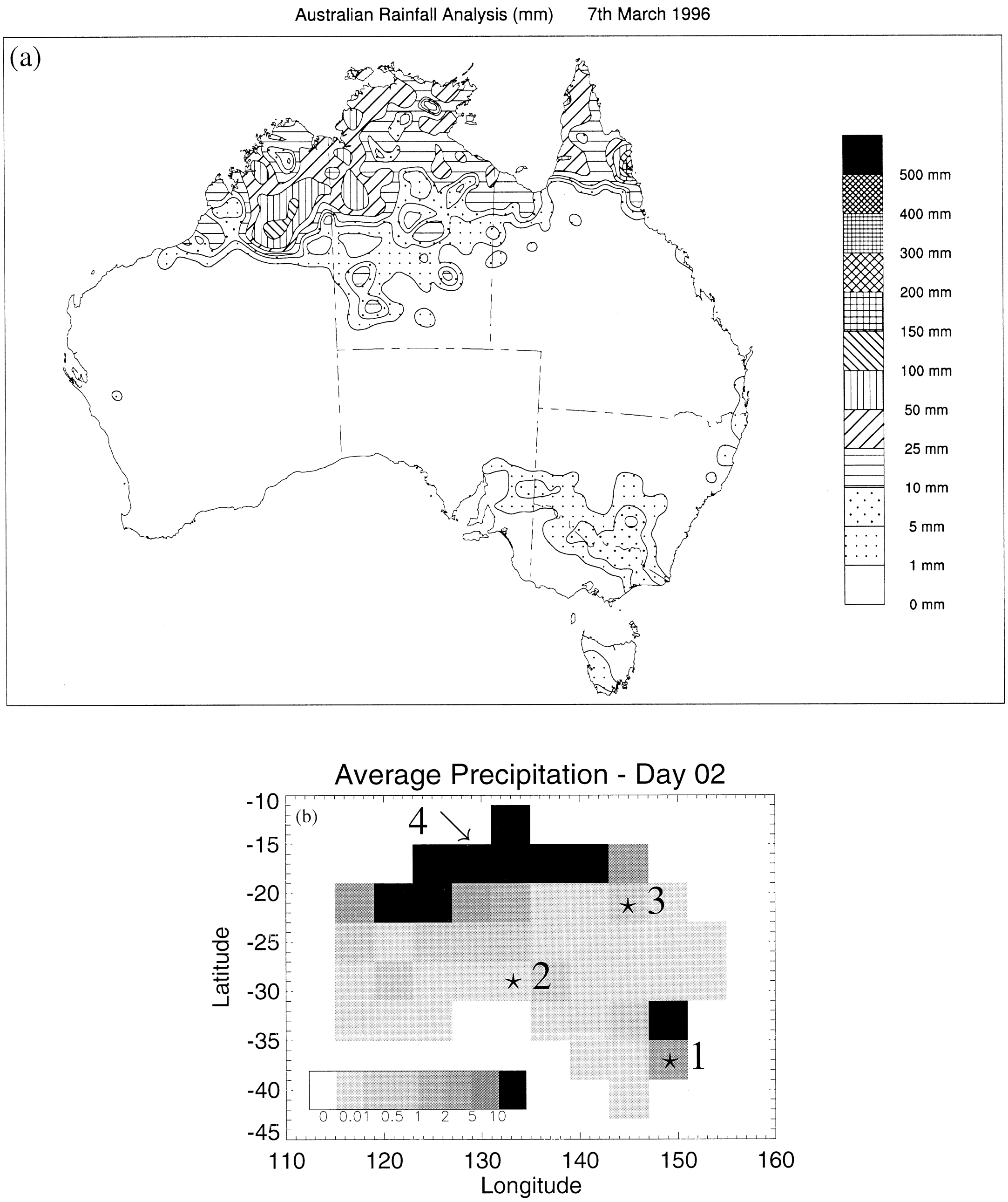

Fig. 2. (a) The 24-h rainfall analysis for the 7 March 1996 and (b) the forecast rainfall for the same period given by the operational LAPS model coupled to BUCKET. Continental average are respectively 5.5 mm d^{-1} and 8.4 mm d^{-1}.

schemes, but insufficient to evaluate the quality of the forecasts given by these schemes. The atmospheric model was run in it usual operational configuration over the entire Australian domain for a 48-h forecast period. It was nested in the global operational model boundary conditions every 12 h. The initial state was also given by the global model. A particular case (6–7 March 1996) was chosen. This is a typical austral summer situation, with significant rainfall (up to 100 mm d^{-1}) over the northern third of the continent with dry conditions elsewhere. There is a cold front moving through the south–east corner which produces a modest amount of rainfall (Fig. 2a). This synoptic situation allows an intercomparison of the LSS at local points where the atmospheric forcing (precipitation, radiative fluxes and temperature range) is very different.

Although a coarse resolution was used, LAPS was able to represent the main features of the meteorological situation (Fig. 2b). Results are presented in terms of the overall average over the Australian continent and at 4 locations which have contrasting atmospheric forcing. These points are $4° \times 4°$ grid centers at 37°S–149°E, 29°S–133°E, 21°S–145°E and 17°S–129°E and are shown on Fig. 2b. They are all located at least 3000 km from the boundaries of the host model. Therefore it is anticipated that the penetration of the boundary conditions will not affect these points during 48-h forecast.

The first issue raised is to discern what similarities and differences to retain among land surface schemes and their coupling. Two extreme scenarios are possible: retaining the parameters from their original host models; and all parameters are specified to be the same (including such things as the number of soil layers and soil depth). The latter approach has two drawbacks, first this solution is difficult to set up as the choice of many parameters is intimately linked to the internal physics of the schemes, and secondly, it might be feared that the resultant simulations would be so alike that the intercomparison loses its meaning. Instead a compromise was employed in which only first-order parameters are held constant. To accomplish this specification a single surface type was chosen for the entire Australian continent: grassland growing in a medium coarse soil type.

Two types of simulations were performed. In the first one (referred to hereafter as default run), the parameters deduced for this type of surface were chosen from the internal tables of the schemes and were allow to differ from scheme to scheme (see Table 4 for values). The parameters for BUCKET are as described in Manabe (1969). In the second one (referred to hereafter as control run), some parameters were fixed equal for all schemes (BUCKET included when applicable). The parameters chosen to be fixed are: surface albedo, roughness length, fraction of vegetation and Leaf Area Index (LAI). Preliminary tests showed that LAI and minimal stomatal resistance are related to the control of evapotranspiration and therefore, fixing the LAI forces each scheme to use identical minimal stomatal resistance

Table 4
The surface characteristics for each scheme in the default runs

Scheme	BUCKET	BASE	BATS	ISBA	Control
Soil properties					
Depth 1st layer (mm)	1000	100	100	10	nf
Depth 2nd layer (mm)	–	900	900	1500	nf
Depth 3rd layer (mm)	–	4000	4000	–	nf
Soil saturation (%)	15	44	50	45	nf
Field capacity (%)	11	31	35	26	nf
Wilting point (%)	0	16	18	17	nf
Vegetation properties					
Vegetation cover (frac.)	–	0.75	0.80	0.85	0.80
Maximal LAI (ratio)	–	3	2	1	2.5
Minimal r_s, (s m^{-1})	–	200	200	40	200
Roughness length (m)	0.168	0.075	0.05	0.02	0.05

The fixed values chosen in the control run appears in the 6th column (nf: not fixed).

(Table 4). These parameters are the most important to explain differences amongst the schemes (Henderson-Sellers, 1993). This list is also limited to parameters for which reasonable observations exist on a global basis. It also excludes parameters which are intimately linked to the internal physics of the scheme.

In the default experiment, the surface albedo could be modified by the surface scheme, leading to noticeable differences to the net radiation, particularly with BASE and BATS; this will be discussed later. In the control runs, the schemes' internal calculation for the albedo (when they existed) was disconnected, and the value given by LAPS was used everywhere by all schemes.

Another important issue to investigate is the initialisation of the sub-surface prognostic variable, soil moisture. A linear extrapolation of the initial value of the BUCKET soil moisture depth W_{BUCKET} was used in both the default and control runs. The soil wetness index ($\theta_{i,j}$), for each layer i of each scheme j was initialised as:

$$\theta_{i,j} = W_{\mathrm{BUCKET}} \times \left[\frac{\theta_{\mathrm{fc},j} - \theta_{\mathrm{wilt},j}}{W_{\mathrm{fc,BUCKET}} - W_{\mathrm{wilt,BUCKET}}} \right] + \theta_{\mathrm{wilt},j}$$

This is equivalent to:

$$\theta_{i,j} = \left[\frac{W_{\mathrm{BUCKET}}}{112.5} \times \left(\theta_{\mathrm{fc},j} - \theta_{\mathrm{wilt},j} \right) \right] + \theta_{\mathrm{wilt},j}$$

Where the subscripts fc and wilt refer to field capacity and wilting point. Therefore, the initial soil wetness index ($\theta_{i,j}$) ranged between field capacity and wilting point. The threshold value of 112.5 is 75% of the bucket capacity: 150 mm. Above this value, the BUCKET scheme evaporates at the potential rate, i.e., the soil acts like a saturated surface. (NB: These values are from the original BUCKET scheme defined by Manabe (1969) although, in his article he referred to the bucket capacity as being the wilting point while here we referred to it as the saturation value.)

This simple technique has some major drawbacks. First it does not allow a vertical profile of soil moisture to be established commensurate with a rainfall history. This could seriously affect the partitioning between latent and sensible heat at the surface and is a major issue in the use of such sophisticated LSS in operational weather forecasting. Also previous PILPS research (Koster and Milly, 1997) has shown that the LSS have a different dynamical range in terms of soil moisture. Therefore using the same initial soil moisture in all schemes does not mean that the schemes will achieve the same energy flux partitioning.

To perform experiments in which soil moisture could be initialised to a single value in all the schemes: extreme scenarios were chosen: (i) saturation, (ii) field capacity, (iii) wilting point (for BUCKET, 1 mm was left in the soil reservoir) and (iv) zero soil moisture. All these experiments were performed using the 'controlled' surface parameters (albedo, roughness length, fraction of vegetation, Leaf Area Index and minimal stomatal resistance fixed equal for all schemes) to limit the scatter among the schemes.

In every run, the other water reservoirs (canopy interception and snow cover) were initialised to zero. Soil temperatures were initialised using the value for the nearest level in the BUCKET scheme. Canopy or leaf temperature was initialised to the lowest level air temperature of the atmospheric model (around 50–60 m). To limit the impact of these initial values, all the runs were started at night-time: 2300 h, eastern standard time.

4. Preliminary results

Before going into the details concerning the results given by the four LSS, a preliminary check was made to ensure that each scheme coupled to LAPS conserved energy and water. Each scheme solves the surface energy and water balances, expressed as:

$$R_{\mathrm{n}} = \mathrm{SH}\uparrow + \mathrm{LH}\uparrow + G_{\mathrm{o}}\downarrow \tag{1}$$

and

$$\Delta W = \mathrm{Prec} - \mathrm{Evap} - R_{\mathrm{f}} \tag{2}$$

Where R_{n} is the net radiation, LH and SH are the fluxes of latent heat and sensible heat leaving the surface and G_{o} the heat flux entering the soil. ΔW is the evolution of the moisture reservoirs calculated by each scheme and R_{f} the total run-off. The balance residual is plotted (Fig. 3) for the (a) energy and (b)

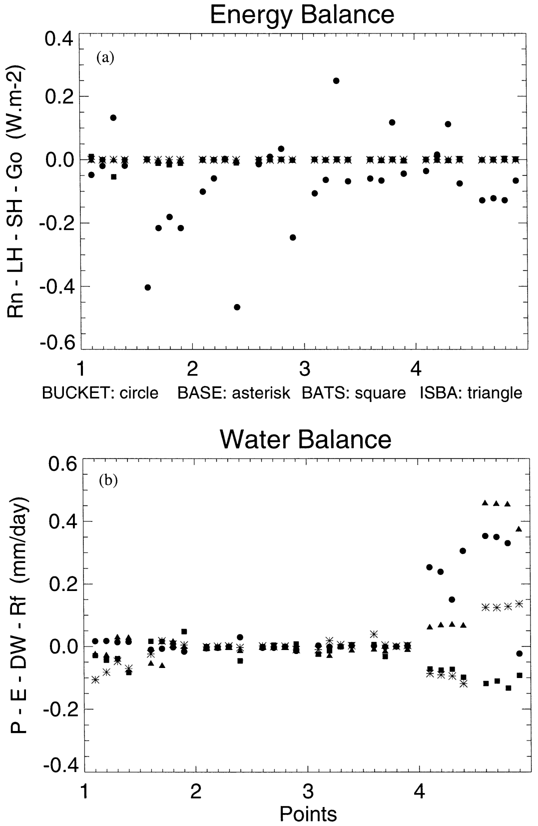

Fig. 3. Validation of the (a) energy balance and (b) water balance at the interface of the atmospheric and surface models at the four points defined in Section 3, for the two successive 24-h averages of the 48-h forecast of four experiments (default, control, wilting point and field capacity).

water fluxes. Each result between 1 and 2 on the *x*-axis represents a 24-h average over the first selected grid box identified in Section 3 and so on for the four selected grid boxes. Each cluster presents the results of four experiments (default, control, wilting point, field capacity). The first cluster is for the 0–24 h average and the second for the 24–48 h, the closure of the surface equation is reasonable in most cases: within 0.5 mm d^{-1} for the surface hydrology and 0.3 W m^{-2} for the radiative balance. These results suggest that the exchange of information between the atmosphere and the surface scheme is coherent.

Averages of two atmospheric forcings have been calculated over the entire Australian continent for a 24-h period during the 2nd day of the forecast, for each experiment (Table 5). The feedbacks of the LSS on the hydrological cycle is visible in the domain-average precipitation. All schemes with a canopy layer predict less total precipitation by 15 to 20% with respect to BUCKET, in the default experiment. These lower values are closer to the similar average obtained from the rainfall analysis (Mills et al., 1997) which gives a value of 5.5 mm d^{-1}. In the control experiment, where the same roughness length is used in each scheme, the scatter among the schemes is reduced from 1.7 mm d^{-1} to 0.8 mm d^{-1}. The amount of precipitation associated with BUCKET is reduced between the default and the control experiments, as the respective roughness length is reduced from 0.168 to 0.05. Conversely, the amount of precipitation associated by ISBA increases when the roughness length is increased from 0.02 (default) to 0.05 (control). In the control experiment, the two schemes are no longer clear outliers. These results suggest that more accurate roughness lengths would strongly modify LAPS' results when coupled to BUCKET. Precipitation calculated using the BUCKET scheme also shows a very high sensitivity to the soil moisture. The total amount is reduced by more than 5 mm when the soil moisture is initialised

Table 5
Daily average of precipitation and net radiation during the last 24 h of a 48-h forecast over the Australian continent

Scheme	BUCKET	BASE	BATS	ISBA
Precipitation (mm d^{-1})				
Default	8.4	7.1	7.2	6.7
Control	7.8	7.3	7.0	7.4
Saturation	9.5	7.4	7.7	8.1
Field capacity	9.5	7.4	7.6	7.8
Wilting point	4.5	7.3	7.0	6.8
Zero soil moisture	4.4	6.8	6.1	6.7
FC–Wilt (mm d^{-1})	5.0	0.1	0.6	1.0
Net Radiation	W m^{-2}	%	%	%
Default	429	−14	−11	−14
Control	426	−4	−4	−2
Saturation	413	0	−1	+1
Field capacity	413	0	−1	0
Wilting point	406	+1	0	0
Zero soil moisture	405	+1	−1	0

The difference (mm d^{-1} for precipitation and % for net radiation) for each scheme is expressed with respect to the values obtained for the BUCKET scheme.

at wilting point instead of field capacity. Precipitation associated with BASE, BATS and ISBA show a smaller sensitivity to soil moisture initialisation (reduction varying between 0.1 and 1 mm d^{-1}).

Net radiation appears to be less sensitive than precipitation to the choice of LSS. In the default experiment, where schemes are allowed to calculate their own albedo, net radiation values vary up to 14%. However, in the control run, when the albedo is held constant for all schemes, the scatter among the schemes is less than 4%. This reduction given by the four more complex schemes compared to BUCKET is due to the increased importance of black body cooling above warmer surface. The behavior of the effective surface temperature will be discussed in more detail later in this chapter.

This analysis demonstrates that the impact on the radiative fluxes of different schemes is very limited. Furthermore, the scatter on the drag coefficient for heat and momentum (not shown) is small in the control experiment. This was anticipated as all schemes used a similar boundary layer algorithm based on Louis et al. (1981). It is therefore, mostly, the partitioning between latent, sensible and ground heat which explains the precipitation differences. Although, as stated previously, the total amount is clearly dependant of the roughness length imposed.

Domain averages have been calculated for latent and sensible heat (Table 6). The scatter among the schemes is 127 W m^{-2} for latent heat and 74 W m^{-2} for sensible heat in the default run and 120 W m^{-2} and 89 W m^{-2}, respectively, in the control run. These ranges are not reduced when surface parameters have the same values for all the schemes. Two hypotheses could be formulated to explain this feature. First, the surface parameters chosen are not crucial to control the surface energy partitioning. Second, the set up of the surface characteristics is strongly linked to the internal physics of the scheme and therefore, it is not possible to reach a simple value to fit any scheme. The fact that each individual scheme shows a marked sensitivity between the default and the control runs: the latent heat is affected up to 16 W m^{-2} and the sensible heat up to 53 W m^{-2}, suggesting that the second hypothesis is more likely.

The BUCKET scheme gives the highest Bowen ratio (latent heat over sensible heat) and BATS the smallest. The differences between schemes are enhanced in the extreme wet cases (saturation and field capacity initialisation) and closer agreement is obtained in the dry cases.

Table 6
The same as Table 5, except for domain averaged latent and sensible heat

Scheme	BUCKET	BASE	BATS	ISBA	Scatter
Latent heat (W m^{-2})					
Default	252	188	125	192	127
Control	239	204	119	178	120
Saturation	368	229	196	297	172
Field capacity	365	230	196	267	169
Wilting point	43	143	68	96	100
Zero soil moisture	31	60	55	88	57
LH range	322	87	128	171	235
Sensible heat (W m^{-2})					
Default	145	137	211	168	74
Control	149	160	238	221	89
Saturation	32	144	191	102	159
Field Capacity	35	144	192	133	157
Wilting point	307	213	273	296	94
Zero soil moisture	315	290	307	306	25
SH range	272	69	81	163	203

The range for the fluxes are calculated as the absolute difference between the run with the initialisation set at field capacity and the one set at wilting point.
The last column shows the absolute scatter among the schemes.

Finally, the BUCKET scheme shows a larger sensitivity to soil moisture in the partitioning between latent and sensible heat (up to 300 W m^{-2}) compared to the other schemes (between 69 and 171 W m^{-2}). The limitation of evapotranspiration by the canopy and root transfer in schemes using a canopy layer is very important, although the scatter among these schemes is still large.

The domain averaged partitioning between latent and sensible heat is very different in the four schemes. The hydrological cycle at the surface is scheme dependant and a clear feedback due to latent heat transfer can be seen on the atmospheric forcing (e.g., precipitation). The issue of the significant different forcings in coupled intercomparisons is clear even in these preliminary results.

The scatter of latent heat fluxes among schemes participating in PILPS offline experiments has been studied on a diurnal time scale using both model forcing (Pitman et al., 1993) and observed measurements (Mahfouf et al., 1996). Using HAPEX–Mobilhy dataset (André et al., 1986), Mahfouf et al. show that the scatter among 11 schemes varies from 200 W m^{-2} during cloudy days to 600 W m^{-2} when the atmospheric forcing is strong. In the coupled experiments, the scatter among the four schemes is frequently up to 300 W m^{-2} (Fig. 4).

The importance of surface parameterization for precipitation has been studied, e.g., Blyth et al. (1994). In our coupled experiments, the land-surface parameterization is found to have a significant impact on convective precipitation (Fig. 5). In the case of a dry soil (initialised to wilting point), the failure of the BUCKET scheme to re-evaporate precipitation quickly, compared with LSS with a canopy layer which allow interception and fast re-evaporation, leads to a strong reduction of the moisture availability for convective precipitation (e.g., the mixing ratio at the lowest level of the model is significantly lower than for the other schemes). The precipitation obtained with LAPS coupled to BUCKET scheme agrees with the others schemes only during the second day of the forecast when the soil reservoir starts to fill up (10 mm).

In addition to precipitation, some important differences can be observed between the schemes even in extreme cases. In the forecast where soil moisture is initialised at wilting point (Fig. 6a), evaporation in BASE is surprisingly high. In the case of the supply and demand approach used by BASE, the lack of water availability affects the evaporative rate only above 200 W m^{-2} the first day and 100 W m^{-2} the second. Below these thresholds, due to the high atmospheric demand, evaporation occurs at the potential rate.

In the case where the soil moisture is initialised at the field capacity (Fig. 6b), the BUCKET scheme is a clear outlier and the absence of canopy resistance

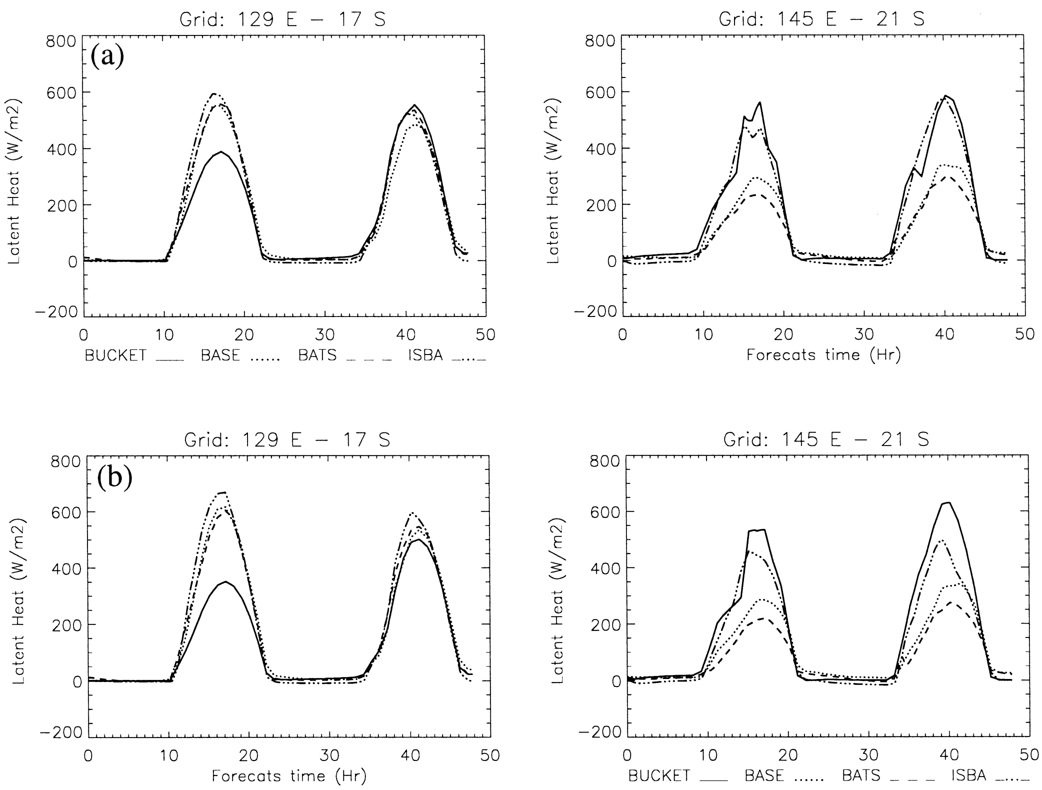

Fig. 4. 48-h forecast of latent heat fluxes given by the four schemes for two single grid boxes, see Fig. 2 (left, point 4 and right, point 3) in (a) the default run and in (b) the control one.

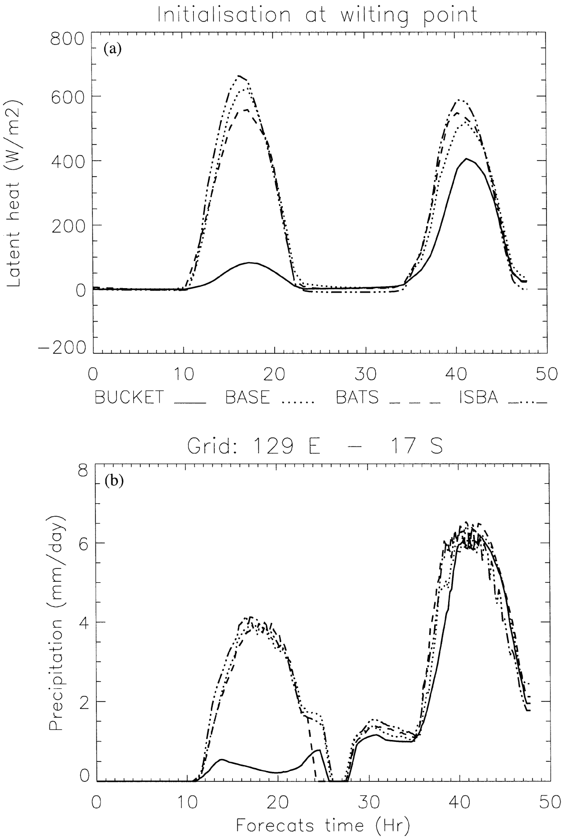

Fig. 5. 48-h forecast of (a) latent heat and (b) convective precipitation given by the four schemes with soil moisture initialised at wilting point.

for the evaporation leads to values up to 600 W m^{-2}, while schemes with a canopy layer cluster around 300 W m^{-2} apart from ISBA (450 W m^{-2}).

Finally, the last component of the surface energy budget is the flux of heat entering the ground (Fig. 7a). The total energy entering the ground in the BUCKET scheme is smaller than for other schemes and the effective surface temperature reaches a lower value during day time. Furthermore, the daily time-scale evolution of the ground heat flux in BUCKET differs from the other schemes which tend to show a maximum earlier in the day. The BUCKET scheme was not designed to represent the diurnal cycle and shortcomings appear at this time-scale. Surface temperature scatter (Fig. 7b) among the schemes is large but this is partially due to the difference of meaning of this variable which can be the skin temperature (BASE, BATS) or an average over a surface thin layer (ISBA). This definitional difference for ISBA's surface temperature explains why it does not capture the rapid temperature drop prompted by the onset of precipitation during the first day of the forecast (not shown) simulated by the other schemes (grid 149°E–37°S).

The impact of the LSS is also detectable in the lower layer of the atmosphere. Differences of up to 5°C are obtained for the lowest atmospheric temperature and up to 3 g kg^{-1} for mixing ratio (not shown). The largest differences among the schemes' prediction are obtained when one of the surface mechanisms detailed previously leads to very large difference for energy partitioning, the entire boundary layer is then affected. In most other cases the impact

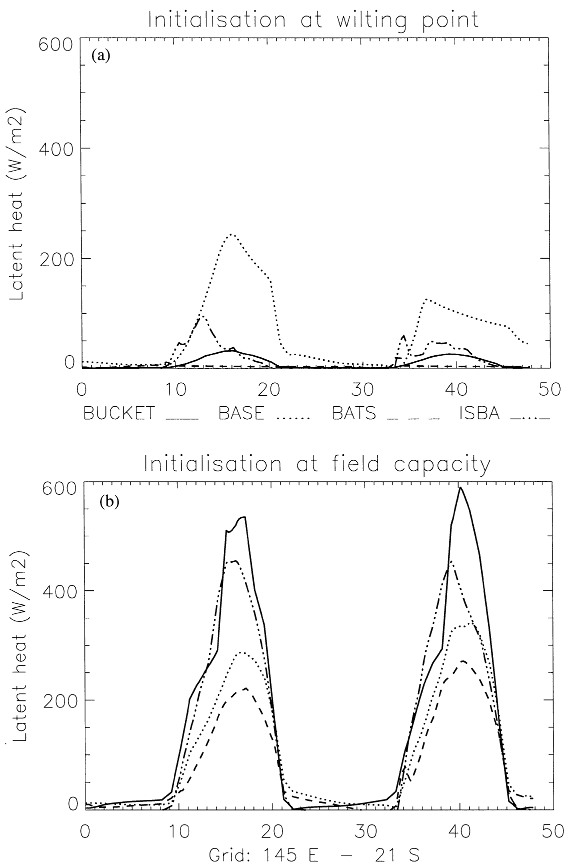

Fig. 6. 48-h forecast of latent heat given by the four schemes with soil moisture initialised at (a) wilting point and at (b) field capacity.

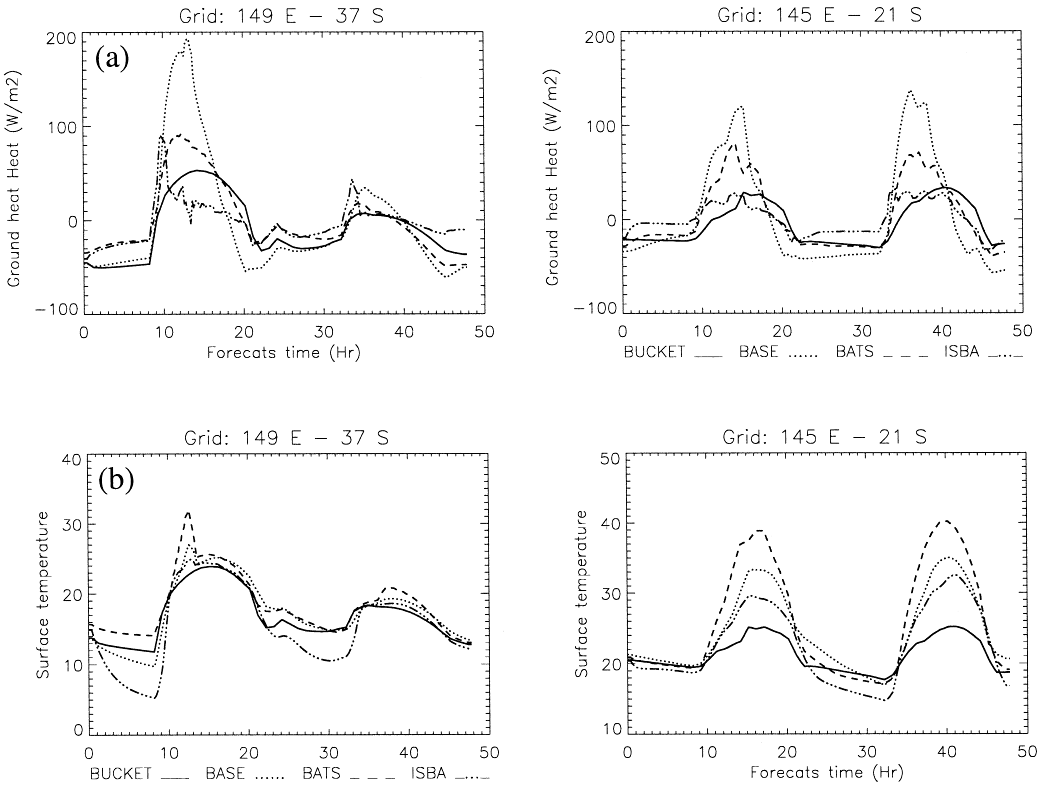

Fig. 7. 48-h forecast of (a) ground heat flux and (b) surface temperature for two grid boxes, see Fig. 2 (left, point 1 and right point 3), given by the four schemes.

on the atmospheric boundary layer is fairly small and the stability is not affected.

5. Conclusions and future plans

The coupling of four land-surface schemes to a regional numerical weather prediction model (LAPS) has been implemented and tested. The schemes are coupled to LAPS using a numerically explicit method. This coupling method was chosen to provide a simple framework for this intercomparison. The coupling was found to be satisfactory in as much as no numerical instabilities appeared and the residual of the water and energy balances remained within reasonable limits for most experiments.

Several preliminary tests were performed to determine the impact of land-surface characteristics and soil moisture initialisation. This issue is crucial for short term (48-h) forecast and is one of the major limitation of these exploratory experiments.

The results gathered from this set of simulations have revealed several short comings of the BUCKET scheme compared to the more detailed schemes which include several soil layers and a representation of the canopy effect. The sensitivity of the BUCKET scheme to soil moisture available is strong, affecting the surface energy partitioning and feeds back on the precipitation over land. Because the BUCKET scheme is not able to represent either canopy interception of precipitation or vegetative resistance to soil evaporation, it is a clear outlier in several cases compared to the more complex LSS. It is worth noting that Milly (1992) has shown that some of these negative features can be mitigated by simple improvements to the BUCKET scheme. Moreover, very noticeable scatter still remains among the more complex LSS schemes. It was found that fixing the surface albedo reduced the range of net radiation calculated by the schemes. Similarly, the use of the same roughness length reduce the scatter among the schemes' precipitation forecasts. However, setting the main vegetation characteristics (fraction of vegetation cover, LAI and minimal stomatal resistance) to same values in the different schemes does not reduce the scatter in the Bowen ratio, but does for other quantities: the interception reservoir and the drag coefficients for heat and momentum. Results suggest that while these surface characteristics do affect the individual scheme Bowen ratio, their interplay with the physics is strong and therefore, did not reduce the scatter of the schemes' Bowen ratio.

Of particular concern are the remaining differences among the participating schemes in the extreme cases, such as initialisation of soil moisture to field capacity or wilting point. The parameterization of the basic mechanisms involved in these cases are represented in ways that lead to significant differences. The scatter observed among the schemes coupled to LAPS is of the same order of magnitude as that observed during the PILPS off-line experiments; Phases 1 and 2. This paper showed significant differences in calculated precipitation due to the surface feedbacks of the different LSS. Further detailed investigation is required to determine if the atmospheric-surface feedbacks will enhance or reduce the differences among the schemes.

Further experiments are planned using off-line forcing given by the results of a selected coupled scheme to force all the other schemes. The comparison between the results of these simulations and the coupled ones will provide further explanations of the interplay between LSS and atmospheric models.

New evaluation of land-surface parameterizations on weather forecasts will be conducted at higher resolution. The main surface characteristics will be fixed using land-use dataset accurately describing ground cover over Australia. The importance of initialisation may prompt the use of more elaborate initialisation techniques, e.g., Mahfouf (1991), Bouttier et al. (1993).

Acknowledgements

The authors wish to thank A. Pitman, C. Desborough, R. Dickinson, A. Hahmann, J. Noilhan and F. Habets for providing the PILPS schemes used in this intercomparison and for their kind help during the coupling. We are particularly grateful to J. Noilhan for in depth discussion in the genesis of the manuscript. We thank D. Hess, K. Puri, E. Wood, L. Hopkins and an anonymous reviewer for constructive remarks. Australian rainfall analysis plot and average were provided by D. Jones. This work was supported by grants from the Australian Research Council (ARC) and the NOAA Office of Global Programs through the University of Arizona.

References

André, J.-C., Goutorbe, J.-P., Perrier, A., 1986. HAPEX–MOBILHY: a hydrologic atmospheric experiment for the study of water budget and evaporation flux at the climatic scale. Bull. Am. Meteorol. Soc. 67, 138–144.

Beljaars, A.C.M., Viterbo, P., Miller, M.J., 1996. The anomalous rainfall over the United States during July 1993: sensitivity to land surface parameterization scheme and soil moisture anomalies. Monthly Weather Rev. 124, 362–383.

Blyth, E.M., Dolman, A.J., Noilhan, J., 1994. The effect of forest on mesoscale rainfall: an example from HAPEX–MOBILHY. J. Appl. Meteorol. 33, 445–454.

Bonan, G.B., 1994. Comparison of the land surface climatology of the national center for atmospheric research community climate model 2 at R15 and T42 resolutions. J. Geophys. Res. 99 (D5), 10357–10364.

Bouttier, F., Mahfouf, J.-F., Noilhan, J., 1993. Sequential assimilation of soil moisture from atmospheric low-level parameters: Part II. Implementation in a mesoscale model. J. Appl. Meteorol. 32, 1352–1364.

Chouinard, C., Mailhot, J., Mitchell, H.L., Staniforth, A., Hogue, R., 1994. The Canadian regional data assimilation system: operational and research applications. Monthly Weather Rev. 122 (6), 1306–1325.

Desborough, C.E., Pitman, A.J., 1998. The BASE land surface model. Global Planet. Change, same issue, accepted.

Dickinson, R.E., Henderson-Sellers, A., Kennedy, P.J., 1993. Biosphere–Atmosphere Transfer scheme BATS. Version 1e as coupled to the NCAR Community Climate Model. Technical Report NCAR/TN387 + STR et al. Technical Report NCAR/TN-387 + STR, National Center for Atmospheric Research, Boulder, CO, 59 pp.

Fels, S.B., Schwarzkopf, M.D., 1975. The simplified exchange approximation: a new method for radiative transfer calculations. J. Atmos. Sci. 32, 1475–1488.

Henderson-Sellers, A., 1993. A factorial assessment of the sensitivity of the BATS land-surface parameterization scheme. J. Climate 6 (2), 227–247.

Henderson-Sellers, A., Pitman, A.J., Love, P.K., Irannejad, P., Chen, T.H., 1995. The project for intercomparison of landsurface parameterization scheme (PILPS): phases 2 and 3. Bull. Am. Meteorol. Soc. 76, 489–503.

Kalnay, E., Kanamitsu, M., 1988. Time schemes for strongly non-linear damping equations. Monthly Weather Rev. 116, 1945–1958.

Koster, R.D., Milly, P.C.D., 1997. The interplay between transpiration and runoff formulations in land surface schemes used with atmospheric models. J. Climate 10, 1578–1591.

Lacis, A.A., Hansen, J.E., 1974. A parameterization for the absorption of solar radiation in the earth's atmosphere. J. Atmos. Sci. 31, 118–133.

Louis, J.-F., Tiedtke, M., Geleyn, J.-F., 1981. A short history of the operational PBL parameterization of the ECMWF. In: Workshop on planetary boundary layer, pp. 59–79. ECMWF.

Mahfouf, J.-F., 1991. Analysis of soil moisture from near-surface parameters: a feasibility study. J. Appl. Meteorol. 30, 1534–1547.

Mahfouf, J.-F., Ciret, C., Ducharne, A., Irannejad, P., Noilhan, J., Shao, Y., Thornton, P., Xue, Y., Yang, Z.-L., 1996. Analysis of transpiration results from the RICE and PILPS Workshop. Global Planet. Change 13, 73–88.

Manabe, S., 1969. Climate and ocean circulation: 1. The atmosphere circulation and the hydrology of the earth's surface. Monthly Weather Rev. 97, 739–773.

Mills, G.A., Weymouth, G., Jones, D., Ebert, E.E., Manton, M., Lorkin, J., Kelly, J., 1997. A national objective daily rainfall analysis system. BMRC Techniques Development Report No. 1, Bureau of Meteorology Research Centre, Melbourne, Australia.

Milly, P.C.D., 1992. Potential evaporation and soil moisture in general circulation models. J. Climate 5, 209–226.

Noilhan, J., Planton, S., 1989. A simple parameterization of land surface processes for meteorological models. Monthly Weather Rev. 117, 536–549.

Pitman, A.J., Henderson-Sellers, A., Abramopoulos, F., Avissar, R., Bonan, G., Boone, A., Cogley, J.G., Dickinson, R.E., Ek, M., Entekhabi, D., Famigliettiand, J., Garratt, J.R., Frech, M., Hahmann, A., Koster, R., Kowalczyk, E., Laval, K., Lean, J., Lee, T.J., Lettenmaier, D., Liang, X., Mahfouf, J.-F., Mahrt, L., Milly, C., Mitchell, K., de Noblet, N., Noilhan, J., Pan, H., Pielke, R., Robock, A., Rosenzweig, C., Running, S.W., Schlosser, A., Scott, R., Suarez, M., Thompson, S., Verseghy, D., Wetzel, P., Wood, E., Xue, Y., Yang, Z.-L., Zhang, L., 1993. Results from the off-line Control Simulation Phase of the Project for Intercomparison of Land surface Parameterization Schemes (PILPS). Technical Report 7, GEWEX technical note, IGPO Publication Series, 47 pp.

Polcher, J., Gaertner, M.-A., Hahmann, A., McAvaney, B., Mahfouf, J.-F., Noilhan, J., Phillips, T., Pitman, A., Schlosser, A., Schulz, J.-P., Timbal, B., Verseghy, D., Viterbo, P., Xue, Y., 1998. A proposal for a general interface between land-surface schemes and general circulation models. Global Planet. Change 19, 263–278.

Puri, K., Dietachmayer, G., Mills, G., Davidson, N., Bowen, R., Logan, L., 1998. The new BMRC Limited Area Prediction System. Aust. Meteorol. Mag., in press.

Qu, W., Henderson-Sellers, A., Pitman, A.J., Chen, T.-H., Abramopoulos, F., Beljaars, A.C.M., Boone, A., Chang, S., Chen, F., Dai, Y., Desborough, C.E., Dickinson, R.E., Dümenil, L., Ek, M., Garratt, J.R., Gedney, N., Gusev, Y.M., Kim, J., Koster, R., Kowalczyk, E.A., Laval, K., Lean, J., Lettenmaier, D., Liang, X., Mahfouf, J.-F., Mengelkamp, H.-T., Milly, P.C.D., Mitchell, K., Nasonova, O.N., Noilhan, J., Polcher, J., Robock, A., Rosenzweig, C., Schaake, J., Schlosser, C.A., Schulz, J.-P., Shmakin, A.B., Verseghy, D.L., Wetzel, P., Wood, E.F., Xue, Y., Yang, Z.-L., Zeng, Q., 1997. Sensitivity of latent heat flux from PILPS land-surface schemes to perturbation of surface air temperature. J. Atmos. Sci., Submitted.

Rikus, L., 1991. The role of clouds in global climate modelling. Technical Report Research Report No. 25, Bureau of Meteorology Research Centre, Melbourne, Australia, 37 pp.

Sellers, P.J., Los, S.O., Tucker, C.J., Justice, C.O., Dazlich, D.A., Collatz, G.J., Randall, D.A., 1996. A revised land surface parameterisation (SiB_2) for atmospheric GCMs: Part II. The generation of global fields of terrestrial biophysical parameters from satellite data. J. Climate 9, 708–737.

Tiedtke, M., 1989. A comprehensive mass flux scheme for cumulus parameterisation in large scale models. Monthly Weather Rev. 117, 639–664.

Timbal, B., Hahmann, A.N., Pitman, A.J., Qu, W., Henderson-Sellers, A., Slater, A., 1997. Integrating land surface and atmospheric models. EOS 78, 173–181.

Viterbo and Beljaars, 1995.

Wilson, M.F., Henderson-Sellers, A., 1985. A global archive of land cover and soils data for use in general circulation climate models. Int. J. Climatol. 5, 119–143.