The new BMRC Limited Area Prediction System, LAPS


Bureau of Meteorology Research Centre, Melbourne, Australia

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In July 1996 a new limited area numerical weather prediction model and data assimilation system was implemented operationally by the Australian Bureau of Meteorology to provide twice-daily 48-hour forecasts over the Australian region. The forecast model has a horizontal latitude/longitude grid spacing of 0.75° in its operational form, but routinely runs over an inner mesh with a grid spacing of 0.25°. This system, known as LAPS, was developed in the Bureau of Meteorology Research Centre (BMRC). It is the purpose of this paper to provide a detailed description of the new system, to document the results of the pre-operational trials in the BMRC, to present examples of its performance in significant weather events, and to indicate directions of further development.

Introduction

The use of limited area models for operational weather prediction over Australia by the Australian Bureau of Meteorology (ABM) has a long history. The first real-time forecasts commenced in 1969 using a quasi-geostrophic model (Maine 1967), and the first operational limited area primitive equations model was implemented in 1977 (McGregor et al. 1978). This model had a horizontal resolution of 250 km with six vertical levels. In 1986 significant improvements were made in both model resolution (150 km with 12 levels) and the representation of physical processes (Leslie et al. 1985). In 1989 an intermittent data assimilation procedure was introduced (Mills and Seaman 1990). This latter system, the Regional Assimilation and Prediction (RASP) system, had a horizontal resolution of 150 km with 11 pressure levels for the analysis and 15 sigma levels in the forecast model. The analysis used a univariate statistical interpolation scheme with mass-wind blending using variational methods. RASP had a relatively simple parametrisation of physical processes which included a stability-dependent boundary layer with eddy diffusivities given as functions of bulk Richardson number, vertical diffusion above the boundary layer based on a mixing length hypothesis, a surface heat budget with a prognostic surface temperature equation, large-scale precipitation and a Kuo-type cumulus parametrisation. In 1994 the resolution of the RASP model was increased to 75 km and 17 sigma levels and the number of analysis levels was increased to 12.

The RASP system was designed specifically for extratropical numerical weather prediction (NWP). However, approximately half of the area of the Australian continent lies in the tropics and there is a need for improved forecasts there. The Tropical Analysis and Prediction System, TAPS (Puri et al. 1992; Davidson and Puri 1992) which was implemented operationally in November 1992 was developed to address this need and overcome some of the problems specific to tropical NWP. TAPS has a horizontal resolution of 95 km and 19 levels in the vertical. The analysis scheme is an adaptation of the scheme used in RASP. The model includes detailed parametrisation of physical processes which are similar to the ABM's operational Global Assimilation and Prediction (GASP) system (Seaman et al. 1995; Bourke et al. 1995). TAPS also incorporates a number of novel fea-

* Corresponding author address: Dr K. Puri, Bureau of Meteorology Research Centre, GPO Box 1289K, Melbourne, Victoria 3001, Australia.

* Current affiliation: Aeronautical Research Laboratory, Melbourne, Australia.
tures which include the use of profiles of tropospheric moisture derived from GMS IR cloud imagery to supplement the standard observing network (Mills and Davidson 1987), tropical cyclone bogus data (Davidson et al. 1993), satellite imagery to prescribe convective heating and a diabatic dynamical nudging scheme for assimilation and initialisation (Davidson and Puri 1992). These features have led to improved model performance in predicting severe weather events, such as tropical cyclone tracks, monsoon circulation and heavy rainfall events in the Australian tropics (see Davidson and Puri 1992).

The last few years have seen a significant increase in the ABM's computing power. In addition there have been significant developments in most areas of NWP including improved numerics, parametrisation of physical processes, a considerable increase in the number of meteorological observations, particularly satellite-based observations, greater utilisation of these data through improved analysis methods, and developments in initialisation techniques. There was thus a clear need to upgrade RASP which has not had any recent major improvements. There was also a need to unify the running of both RASP and TAPS within a single system. Furthermore both RASP and TAPS were developed in an era of scalar computers and were therefore not suited to the current supercomputers which rely on efficient vectorisation and parallelisation.

The following sections of this paper will describe the design and structure of the components of LAPS, present results of forecast trials in the form of skill scores, and present some case studies demonstrating its performance in a variety of weather situations.

Model
The model equations are formulated on a latitude/longitude grid. The governing equations are the multilevel primitive equations for momentum, mass, temperature and moisture written in the advective form (except for the mass equation which is written in the flux form) and using the sigma coordinate representation in the vertical. Details of the form of the equations are as in McDonald (1986) and will not be repeated here.

The Arakawa A grid (non-staggered) is used, rather than the more usual C grid. Purser and Leslie (1988) have demonstrated that the loss in accuracy associated with the A grid can be regained by using higher order differencing (see below), and moreover high-order schemes are simpler to implement on an A grid. A (and B) grids suffer from mode-splitting; however, correction terms have been introduced as suggested by Mesinger (1973) and Janjic (1984) which significantly ameliorate this problem.

The model can be run either as a fully-explicit code, or in an operator-split form in which the horizontal advection terms are updated separately on a slower time-scale. The split form offers savings in computing time over the fully explicit method. Within each of these categories there are four possible time-stepping schemes available: Miller-Pearce, Heun, Matsuno, and Adams-Bashforth (see Miller and Pearce (1974); Mesinger and Arakawa (1976) for details). The Heun and the Matsuno schemes were included primarily as part of the development process. The Miller-Pearce scheme, which is routinely used in LAPS, is a two time-level scheme so it has low memory requirements. It is the cheapest of the two time-level schemes to run, requiring only three evaluations of the right-hand side (RHS) of the prognostic equations per two time-steps. Here the RHS of the prognostic equation is defined as the sum of all terms of that equation except for the local time derivative term. The Adams-Bashforth scheme requires more memory (three time-level scheme), but is faster to run (one RHS per time-step).

High-order spatial differences have been used wherever possible to ensure that the accuracy is at least that of second-order C grid models. In the horizontal momentum equations there are three options for the surface pressure gradient and geopotential gradient terms: second, fourth, or sixth-order central differencing. The default option is fourth-order differencing. In the calculations for the surface pressure tendency it was felt desirable to use a mass conservative formulation, and this is most easily achieved using second-order differencing. The momentum equations are not in the conservative form. Vertical advection terms are roughly second-order accurate. There are six possible options for the horizontal advection terms; first, third and fifth-order upwinding and second, fourth, and sixth-order
central differencing. These options can be used on a field-by-field basis, i.e., one scheme can be used for the momentum components, another for the mixing ratio. The third-order upwind scheme (see, for example, Takacs (1985) for details) is the routinely used option. It has excellent phase properties, at the cost of introducing some numerical dissipation. However, in practise, this dissipation is no greater than the horizontal diffusion used in models. When the Courant number is less than unity, the relationship between Eulerian and semi-Lagrangian schemes is much closer than one might at first expect. In the context of one-dimensional advection of a passive scalar by a constant velocity field, Dietachmayer (1990) has demonstrated the formal equivalence of the (Eulerian) single-step Lax-Wendroff scheme and the semi-Lagrangian scheme based on quadratic interpolation. The methodology used to develop the Lax-Wendroff scheme can be readily extended to construct arbitrary nth-order methods, which, under the same conditions as above, can also be shown to be equivalent to semi-Lagrangian schemes using the nth-order polynomial interpolation. Given this equivalence for admittedly simple equations, one might expect to see very similar performance between Eulerian and semi-Lagrangian methods when applied to more complex problems. This conjecture is substantiated by the results of Leslie and Dietachmayer (1997), in which the quality of numerical simulations of two-dimensional 'hot bubble' experiments was found to have virtually no dependence on the choice (semi-Lagrangian or Eulerian) of advection scheme used. Thus, efficiency considerations aside, the arguments used to support the adoption of third-order semi-Lagrangian in NWP models apply equally well to our choice of Eulerian third-order upwinding.

Physical processes
The physical parametrisations used in the model are the same as used in the Global Assimilation and Prediction system (GASP). The constant flux layer is parametrised using the Monin-Obukhov formulation with stability-dependent drag coefficient. The vertical eddy transports in the free atmosphere are parametrised using the mixing length formulation with stability-dependent mixing lengths. The model has options to use either the Tiedtke mass flux convection scheme (Tiedtke 1989) or the Kuo cumulus convection parametrisation (Kuo 1974); the mass flux scheme which includes shallow, mid-level and deep convection is the normal option. A separate shallow convection scheme (Tiedtke 1987) is used to simulate transport of heat and moisture by low-level non-precipitating clouds when the Kuo cumulus convection is used. Large-scale condensation is applied if the relative humidity exceeds a specific threshold. Linear second-order horizontal diffusion is applied to all model variables (except surface pressure). Ground hydrology and heat conduction through the soil are also included. The radiation scheme is the Fels-Schwarzkopf scheme which uses a combination of Lacis and Hanson (1974) parametrisation for solar wave lengths and the Fels and Schwarzkopf (1975) method for terrestrial wavelengths, and includes diurnal variation. Cloud amounts and heights are diagnosed following Rikus (1991). Details of the various parametrisations are given in Hart et al. (1990) and Puri et al. (1992).

The analysis system
The analysis system is a limited area adaption of the global multivariate statistical interpolation (MVSI) analysis described in detail by Seaman et al. (1995), and which closely follows Lorenc (1981). Fields are analysed on the same latitude/longitude/sigma coordinate system used by the forecast model, the sigma vertical coordinate being used to keep vertical interpolation between coordinate systems to a minimum during the assimilation process. The MVSI analysis interpolates to the analysis grid the observed increments from a first guess of geopotential height, geopotential thickness, and winds to produce three-dimensional grid-point fields of geopotential and wind components. Surface pressure data are transformed to increments of geopotential before use.

Briefly, the analysed increment at a grid-point \( f_g \) is a linear weighted sum of the observed increments \( f_i \), where both observed and analysed increments are normalised by pre-specified root mean square six-hour forecast (guess field or prediction) errors. That is,

\[
f_g = \sum w f_i \quad \ldots 1
\]

The weights are determined by least-squares minimisation of ensemble error, solving the following equation,

\[
w = (P + O)^{-1} q \quad \ldots 2
\]

where \( P \) and \( O \) are the normalised covariance matrices of prediction error and observation error for all pairs of observations, and \( q \) is the vector of normalised prediction error covariances between observation points and a grid-point.

The specification of observational error and prediction error has followed Seaman et al. (1995) for the initial implementation of this system, but the prediction errors will be refined based on statistics from this system as they accumulate. Horizontal correlations use a Gaussian correlation function, following Lorenc (1981), with a length scale of 500 km. The height-wind correlation functions are adjusted for geostrophic consistency outside the tropics, but are progressively decoupled equatorward of 30°, and allow the analysis of divergent wind increments following Daley (1985). The vertical correlation functions
follow Hollingsworth and Lönnberg (1986), and a Gaussian temporal correlation function with a time-scale of six hours is used to account for synoptic observations.

The MVSI is formulated to use large data volumes, and smaller analysis subvolumes within which the same data selection is made for all grid-points within the analysis subvolume. Data used for the analysis within a subvolume are chosen from an area larger than the analysis subvolume itself. The maximum number of data points which can be selected in a subvolume is 1000. In the application described in this paper, two data volumes are used, and analysis subvolumes are typically of the order of 1000 km on a side, and overlap by two grid rows. Analysis subvolumes may be further subdivided in the vertical if data density indicates that this is necessary. Quality control consists of a preliminary very wide gross error check followed by 'cross-validation', in which each datum is compared with an analysis with that datum withheld. The reader is referred to Seaman et al. (1995) for more detail on all aspects of the analysis system.

The moisture fields are analysed using a three-dimensional univariate SI analysis (Steinle and Seaman 1996) with mixing ratio as the analysed variable.

Data used in the analysis comprise all available sea-level pressure data, radiosonde geopotential, radar winds, TOVS thickness and moisture data received over the GTS and also locally processed TOVS data (LeMarshall et al. 1994a), cloud-drift winds produced by the ABM (Le Marshall et al. 1994b) and by the Japan Meteorological Agency, wind observations received from commercial airliners (AMDAW winds), and bogus moisture data based on the cloud classification scheme of Mills and Davidson (1987). Over the oceans south and west of Australia bogus sea-level pressure observations generated in the Bureau's National Meteorological Operations Centre (Guymer 1978) are used. Bogus data to represent the tropical cyclone vortex (see Davidson et al. 1993) are used when there is a named cyclone in the LAPS domain. Data distributions are shown in Fig. 1, which shows typical distributions for mean sea-level.

Fig. 1 Typical data distributions available for LAPS analysis - MSLP (top left), 500 hPa temperature and bogus moisture (top right), 850 hPa winds (bottom left) and 200 hPa winds (bottom right).
pressure (MSLP), 500 hPa temperature and bogus moisture, and 850 and 200 hPa wind. Most of the surface observations over the oceans south and west of Australia are synthetic data generated in the ABM's National Meteorological Operations Centre; the wind plots show a mix of radar wind data over land, fleets of cloud-tracked wind vectors (particularly over the oceans at 850 hPa), and AMDAR wind data, with long flight tracks at the upper levels. The temperature data are seen as widely spaced radiosonde reports over the land, and dense swathes of TOVS data marking the orbital tracks of the NOAA series of satellites.

First guess fields for the analyses are provided either from the operational GASP fields, or from short-term forecasts from LAPS generated during the data assimilation process. As part of the routine monitoring and verification of LAPS, data-fitting statistics for all fields, levels, and observation types are routinely computed for the guess, analysis and initialised analysis gridded data, using the quality control flags generated by the analysis to exclude erroneous or doubtful data. Typical examples of these statistics are shown in Fig. 2 for a 10-day period at both 1100 and 2300 UTC during pre-operational trials of LAPS. The statistics are for the fit of MSLP data from SYNOP stations, 500 hPa geopotential height from radiosonde data, and 250 hPa root mean square vector wind error for rawin data, to the guess field (six-hour forecast), the analysed field, and to the analysed field after initialisation (see below) for the final analysis. Statistics for radiosonde height are only shown for the 2300 UTC analysis times due to the limited number of radiosonde observations over Australia at 1100 UTC. It can be seen that the guess fields are being corrected to fit the data to near the specified observational errors. It can be further seen that the initialisation makes relatively little adjustment to the analyses. For the MSLP analyses, particularly, this is a considerable reduction in the adjustment of the fields from the RASP system (see, for example, Table 2 of Mills and Seaman (1990)). As both the analysis and initialisation schemes are different for the two systems, it cannot be determined whether it is the improved balance in the MVSI analyses or the differing characteristics of the digital filter initialisation (see below) to the RASP vertical mode initialisation, or a combination of the two which is producing the improvement.

There is some suggestion that the fit of observations to the analysed fields is less good when the guess field errors are greater. This is a consequence of the assumptions of the MVSI analysis.

**Surface boundary conditions**

The model topographic heights and land/sea/sea-ice mask are obtained by weighted averaging of the US Navy six-minute global dataset to the appropriate model grid. The weighting used is the Cressman (1959) influence function with a decreasing radius of influence as a function of increasing resolution. Similar procedures are used to derive the sea-surface temperature (SST) on the model grid. The dataset used is the operational ABM one degree SST analysis (Smith 1995). Examples for the topography generated for the 0.75° and 0.25° model grids are shown in Fig. 3.
Fig. 3 Topography (m) for the 0.75°(top) and 0.25°(bottom) resolution models. Contours plotted are 100, 300, 500, 700, 900, 1200, 1500, 2000, 2500 and the maximum values are denoted in metres.
Initialisation

The initialisation scheme used in the model to control spurious gravity-inertia oscillations is the digital filter scheme of Lynch and Huang (1992, LH92). In this scheme an adiabatic initialisation is performed by carrying out two short model integrations, one forwards and one backwards from the initial time. For each model variable at each grid-point and level, this produces a sequence of values centred on the initial time. Each sequence is processed with a simple low-pass filter and the resulting values comprise the initialised data. LH92 used a filter based on the Fourier transform of an ideal frequency response function, modified by a Lanczos window. For a cut-off frequency corresponding to a period of six hours, a filter span of six hours is required; this requires forward and backward integrations of three hours. In order that the backward integration be physically reasonable, all irreversible processes must be disabled. Therefore, both the forward and backward integrations are performed with the physics switched off.

The major advantage of digital filter initialisation (DFI) is its simplicity and ease of implementation in any model. The DFI technique can be applied without knowledge of the model normal modes which is especially useful for limited area models or global models using other than standard geographical coordinates. The technique uses values produced by the model, with the same horizontal and vertical levels used for the forecast. Thus any changes to the model formulation automatically apply to the filtering process. The DFI technique is very effective in suppressing high frequency noise. An example of this effectiveness can be seen in Fig. 4 which shows the variation in the surface pressure with time at four different model grid-points for integrations with and without initialisation. The small variations in the initialised pressure traces probably reflect the switching off and on of diabatic processes during initialisation and model forecasts respectively. They could be reduced further by the inclusion of diabatic processes during initialisation, as described below.

A disadvantage of DFI is that it is more expensive in terms of computer time, although as discussed in LH92 this can be reduced by careful design of digital filters which allows the use of a shorter filter time span. Although adiabatic initialisation is currently used, LH92 have also proposed a simple extension to include diabatic processes and Huang and Lynch (1993) have demonstrated the effectiveness of this extension.

Fig. 4 Variation in the surface pressure (hPa) with time at four different grid-points for integrations with (full line) and without (dotted) initialisation.
For tropical numerical weather prediction, Davidson and Puri (1992) have shown the beneficial impact of using dynamical nudging. This simple form of physical initialisation has been used operationally by ABM in TAPS. LAPS includes an option for dynamical nudging with heating rates inferred from satellite IR imagery to achieve thermodynamic balance in the model. The observationally reliable rotational wind component is preserved while the less reliable divergent wind component is replaced by the model-generated divergence forced by the imposed heating. Nudging of the surface pressure and temperature fields is also necessary to adequately preserve the mass fields over the limited area of the model. No nudging of the moisture is performed. In this way the moisture field is allowed to come into balance with the imposed heating and vertical motion and constitutes a form of moisture initialisation.

**Filtering**

Some spatial filtering can be introduced through the use of odd-order schemes for horizontal advection, and the corrective terms which act to prevent grid-splitting can also be regarded as a filter. In terms of explicit dissipation, the model has both scale-selective filters, and horizontal diffusion as selectable options. In practice, linear second-order horizontal diffusion is applied to all model variables except for the surface pressure, for which spatial filtering is applied (an option for fourth-order diffusion is also available). Application of diffusion on sigma surfaces causes spurious diffusional temperature, moisture and momentum in areas of elevated terrain. In order to minimise this effect, a correction term is applied to account for the variation of pressure along a constant sigma surface.

In some respects LAPS can be regarded as much less noisy than RASP or TAPS as it runs successfully with a much lower diffusion coefficient. However the extra dissipation built into the advection scheme and grid-splitting prevention terms needs to be borne in mind.

**Lateral boundary conditions**

The model is designed to be nested within analyses or other model data. A lateral sponge zone is used to smoothly incorporate boundary data. Boundary information can be included in terms of absolutes, tendencies or a combination of both. Absolute boundary conditions prevent large-scale model drift, but may constrain the model so tightly that artificial discontinuities may arise along the edge of the sponge zone. Tendencies avoid the latter problem, but lead to drift. Thus a combination of absolute/tendency condition may provide the best combination. However the absolute boundary condition option is used routinely as it has been more comprehensively tested compared to the other options.

The use of a sponge zone can be shown to create spurious vorticity around its edges. The sponge has been chosen in such a way as to minimise this effect by ensuring that the sponge coefficient and its derivative both go to zero together. It is also possible to include extra terms to avoid this spurious vorticity generation (Davies 1976), and the model has this option.

**Software design considerations**

A strong attempt has been made to write modular, internally documented code. This modularity has been central in allowing the model to support the number of options that it does. It is intended that every individual routine could be used without reference to the rest of the code. To this end, no common blocks are used (with the exception of the interface to the physics), and subroutine interfaces are written in a format which clearly shows which parameters are required by the subroutine, which are modified and which are defined by the subroutine. Every subroutine includes a standardised block of comments listing the routine purpose/method, and describing all the subroutine interface parameters.

The relative simplicity of the time-discretisations used was intended to allow for the straightforward vectorisation and parallelisation of the code. Most of the code is set up so that there is a 'j' (south-north index) loop which calls subroutines, and within these routines there are 'i' and 'k' (east-west and vertical indices respectively) loops over which the three-dimensional variables are calculated. This framework allows both parallelisation (different processors can work on different j-indices) on the large scale, and vectorisation on a smaller scale within subroutines (which are generally written to have the i loop innermost to provide reasonable vector lengths). This framework has the advantage that it is implemented at the FORTRAN level, i.e., the dynamics code is not restricted by hardware-specific commands. Efficient vectorisation of the upwind advection code (which, if implemented crudely, introduces an IF statement inside the vector loop) was achieved, again without loss of portability, by the use of pointer arrays to regions of positive and negative flows.

**Summary of the components of LAPS**

The main features of LAPS can be summarised as follows:

- state-of-the-art high order numerics;
- detailed parametrisation of physical processes;
- multivariate statistical interpolation analysis;
- options for data assimilation and diabatic nudging;
- use of locally retrieved temperature soundings and cloud-drift winds;
- use of GMS-based heating rates;
- use of synthetic moisture and tropical cyclone data.

Table 1 summarises some of the standard options used in LAPS. A major feature of the system is the ease
Table 1. Summary of standard options used in LAPS.

1. MODEL

<table>
<thead>
<tr>
<th>Option</th>
<th>Details</th>
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<tbody>
<tr>
<td>Finite difference grid</td>
<td>Arakawa A, latitude-longitude grid</td>
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<tr>
<td>Time discretisation</td>
<td>Fully explicit, two time-level Miller-Pearce</td>
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<tr>
<td>Spatial discretisation</td>
<td></td>
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<tr>
<td>Horizontal momentum equations</td>
<td>Fourth-order centered differences for surface</td>
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<td></td>
<td>pressure and geopotential gradient terms</td>
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<tr>
<td>Horizontal advection</td>
<td>Third-order upwind scheme</td>
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<tr>
<td>Horizontal diffusion</td>
<td>Second-order applied to all model variables except</td>
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<td></td>
<td>surface pressure</td>
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<tr>
<td>Lateral boundary conditions</td>
<td>Sponge zone with boundary information included in</td>
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<td></td>
<td>terms of absolute values</td>
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<tr>
<td>Initialisation</td>
<td>Digital filter</td>
</tr>
<tr>
<td>Standard operational domain</td>
<td>65°S - 15°N; 65°E - 185°E</td>
</tr>
<tr>
<td></td>
<td>0.75° horizontal resolution with 19 vertical</td>
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<td></td>
<td>sigma levels</td>
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2. PHYSICAL PROCESSES

<table>
<thead>
<tr>
<th>Process</th>
<th>Details</th>
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<tr>
<td>Constant flux layer</td>
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<td>dependent drag coefficient</td>
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<td>Vertical eddy transports</td>
<td>Mixing length formulation with stability</td>
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<td>Convection</td>
<td>Tiedtke mass flux</td>
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<td>Large-scale condensation</td>
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<tr>
<td>Ground hydrology</td>
<td>Bucket with heat conduction through soil</td>
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<tr>
<td>Radiation</td>
<td>Lacis-Hanson for solar wavelengths, Fels-Schwarzko</td>
</tr>
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<td></td>
<td>For terrestrial wavelengths</td>
</tr>
<tr>
<td>Clouds</td>
<td>Diagnosed</td>
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of moving domains and the option of running at very high resolutions over reduced domains. This aspect will be considered further below.

Figure 5 shows a schematic of LAPS. Starting from the GASP analysis at T-12 h, where T is the base time for a forecast, an analysis is performed on the LAPS grid in which all available conventional data, local TOVS and cloud-drift winds and bogus data (moisture profiles and TC data if a cyclone is present in the domain) are used. After initialisation, this is followed by two six-hour cycles of data assimilation after which the forecast is carried out. The boundary conditions during the assimilation and forecast are obtained from the GASP forecast. Note that since LAPS runs before GASP, the boundary files are obtained from an earlier GASP forecast. Thus, for the 48-hour LAPS forecast, the GASP boundaries are from a 60-hour forecast and this does have a deleterious impact on the LAPS forecast.

All components of LAPS were extensively tested by running twice daily in quasi-real-time since February 1995. LAPS has shown significant improvement over the previously operational RASP. One measure of this improvement is shown by the skill scores in Fig. 6, which shows the monthly mean scores for 24 and 36-hour LAPS and RASP forecasts for the period between June 1995 to June 1996. The lower values for the skill scores for LAPS show the substantial gains over RASP. Another indication of the consistent improvement of LAPS over RASP can be seen in Figs 7(a) and 7(b) which show scatter plots for the 24 h and 36 h sea-level pressure forecast skill scores from the 1100 UTC analyses for January and June 1996. These scatter plots show that the average skill score improvements in Fig. 7 are not the result of the average of large positive or negative differences, but rather that LAPS is consistently significantly more skillful than RASP. Based on these scores and subjective evaluation of the synoptic performance, LAPS became operational on 3 July 1996 after operational trials.

In its standard operational configuration, LAPS has a horizontal resolution of 0.75° and a vertical resolution of 19 levels for both the analysis and the forecast (LAPS75). The LAPS domain stretches into the northern hemisphere (65°S-15°N; 65°E-185°E) and forecasts to 48 hours are performed from an analysis generated by two six-hour cycles of data assimilation. The LAPS domain together with orography is shown in Fig. 3 and
Fig. 5  A schematic for running of LAPS.

Fig. 6  Monthly mean S1 skill scores for 24 h and 36 h MSLP forecasts for LAPS and RASP from February 1995 to June 1996. The 24 h and 36 h forecasts for LAPS are ‘solid’ and ‘solid-dash-dash’ respectively, while those for RASP are ‘long dash’ and ‘short dash’ respectively.
Fig. 7(a) Scatter plots for 24 h LAPS and RASP sea-level pressure forecast skill scores for January 1996 (top) and June 1996 (bottom).

Fig. 7(b) As in Fig. 7(a) but for 36 h forecast skill scores.

the 19 sigma levels are shown in Table 2. As noted above, an important component of LAPS is the flexibility to run at much higher resolutions over reduced domains. High resolution versions of LAPS (0.25° with 19 levels, LAPS25) were run daily in an experimental mode for the southeast, southwest and northeast Australian domains and assessed by the respective Regional Forecast Offices. The SE and SW Australian domain versions were implemented operationally on 8 May 1997. The domain and orography for the southeast Australian model is also shown in Fig. 3.

A notable feature of LAPS is the use of an explicit time integration algorithm which requires rather small timesteps. Thus for example the LAPS75 and LAPS25 models are run using timesteps of 90 seconds and 30 seconds respectively. However the timestep restrictions for the physics are much less restrictive and the physical processes are activated every 12 minutes. Such a com-
bination for the dynamical and physical processes leads to substantial savings in computing time and allows the models to run within operational time schedules.

The remainder of the paper concentrates on specific examples which give an indication of the synoptic performance of LAPS.

Case studies with operational LAPS (LAPS75)

The first case covers the period 1100 UTC 27 September 1996 to 2300 UTC 28 September 1996 during which a low moved southeastwards from over southern Western Australia and deepened over the Great Australian Bight to such an extent that record low sea-level pressures were recorded at several stations in Victoria. Figure 8 shows the LAPS analyses at 1100 UTC 27 September, the base time for the forecast, the analysis 36 hours later, and the 36-hour LAPS 0.75° forecast. LAPS produced a remarkably accurate forecast of the position and intensity of the low to the west of Victoria, forecasting a deepening of some 15.5 hPa – within 1.5 hPa of what was observed.

The second case also shows the intense development of a low as it moves from land to sea. In this case it is east-coast cyclogenesis – a situation of critical importance as these lows produce flood rains on the eastern seaboard of Australia, and also affect maritime operations due to the extremely strong winds associated with
these systems. Figure 9 shows the MSLP analyses at 12-hour intervals from 2300 UTC 29 August 1996, and Fig 10 shows the corresponding 12, 24 and 36-hour forecasts. The model predicts the intensification of the low from a central pressure of 1010 hPa while over southern Queensland to 996 hPa off the NSW coast 36 hours later. The band of strong winds to the south of the low centre is also well indicated by the extremely strong pressure gradient there in both the analyses and the forecasts. Figure 11 shows the 0 to 24 hour and 24 to 48-hour precipitation forecasts over land only from the same model run. Verifying 24-hour rainfall analyses, using the daily rainfall reporting network over Australia (Mills et al. 1997) corresponding to the forecasts in Fig. 11 are shown in Fig. 12. While the 0.75° grid spacing of the operational LAPS model is insufficient to resolve the peak rainfalls on the coast, the model has forecast areas of heavy rain which correspond very well with the verifying analyses in both location and shape.

The prediction of tropical cyclone development and subsequent tracks in the Australian region pose a considerable challenge during the cyclone season, with the pre-

**Fig. 9** MSLP analysis at 12 h intervals from 2300 UTC 29 August 1996. Contour interval is 1 hPa and values less than 1000 hPa are dashed.
Fig. 10  As in Fig. 9 but for 12 h, 24 h and 36 h LAPS forecasts starting from 2300 UTC 29 August 1996.

Diction of tropical cyclone genesis a particularly difficult problem. Although many problems remain, LAPS has shown encouraging potential in meeting this challenge. An example of a successful 36-hour forecast of the genesis of tropical cyclone Jacob is shown in Fig. 13. The initial analysis (top panel) shows a heat low over the north of Western Australia (WA). Thirty-six hours later (bottom panel) the forecast model (LAPS75) has developed a cyclonic circulation (TC Jacob) off the northern coast of WA. Comparison with the verifying analysis (middle panel) shows that the model has performed well in the difficult task of predicting the formation of a tropical cyclone. It should, however, be noted that accurate simulation of the detailed internal structure of TCs requires a number of important factors which are not currently resolved in LAPS75. Some of these include significantly increased model resolution, improved specification of the initial conditions and improved parametrisation of physical processes, particularly convection, the boundary layer and cloud-radiation interaction.
Case studies with high resolution LAPS (LAPS25)

As noted above, the SE and SW domain versions of LAPS25 were implemented operationally in May 1997. Currently LAPS25 is run by interpolating the LAPS75 analyses to the high resolution LAPS25 grid, the lateral boundary conditions being provided by the LAPS75 forecasts. Some examples to indicate the potential of the high resolution model are now presented. Detailed case studies will be presented in a companion paper by Puri and Mills.

An important forecast problem in the Victorian region, especially during summer, is the timing of the passage of ‘cool changes’. Two examples are presented here. The first, the frontal passage of 6 March 1996, was typical of the southeastern Australian summertime ‘cool change’, with a pre-frontal trough developing ahead of a weak Southern Ocean trough. This pre-frontal trough then produces the major wind change through southern Victoria. Figure 14 shows the 18-hour wind forecast on the model’s lowest sigma level with the verifying analysis and observed wind speeds and directions at the same time (the wind vectors are not plotted at the full resolution – every third vector is plotted, to avoid cluttering in the figure). The cold front on the verifying analysis marks the pre-frontal trough, which is seen in the forecast as the change from northerly to northwesterly winds, while the gradual change to southwesterly winds over western Victoria marks the remnants of the Southern Ocean cold front. The model accurately predicts the timing of the passage of the cool change through southern Victoria, and the ‘bowing out’ of the front along the east coast as the northern parts of the front are retarded by the high topography in northeast Victoria, although some of the fine-scale structure of the front is still not resolved at this model resolution.

The second event is quite different: at the initial time for the forecast, 1100 UTC 14 December 1995, an anticyclone was west of Tasmania, and a weak trough was present in the easterly flow over southeast Australia. On the afternoon of 15 December an east-west shear zone developed in the near-surface wind flow over southern Victoria as the westward advection of cool maritime air along the Victorian coast produced by the eastward movement of the high cell and daytime heating of warmer air from the northeast over northern Victoria combined to produce a zone of strong thermal gradient and convergence east-west across Victoria. The 18-hour forecast low-level wind field from the fine-mesh LAPS model and the surface wind observations and streamline analysis for the same time presented in Fig. 15 show that the model has successfully captured the development of this mesoscale shear.
Fig. 13  As in Fig. 8 but for initial analysis for 1100 UTC 31 January 1996.

Fig. 14  18 h LAPS25 wind forecast from 1100 UTC 5 March 1996 at the lowest sigma level (top panel) and verifying analysis and observed wind speeds and directions (bottom panel).

zone. However the prediction of low-level winds (and sea breezes) is highly sensitive to the specification of the soil moisture in the model. Currently in LAPS25 the soil moisture is initialised using the daily soil moisture analysis scheme developed by Pescod (1994). There are, however, considerable shortcomings in these analyses due mainly to lack of data, and more research is needed in order to improve their reliability. Moreover, use of the bucket scheme for ground hydrology parametrisation in the model is also inadequate, and work is ongoing to implement a more detailed land-surface scheme.

The prediction of heavy rainfall events provides a major challenge for NWP models. These events can be of a local nature which are heavily influenced by features such as details of local topography, for example. Inadequate model resolution, sparsity of data and deficiencies in the parametrisation of physical processes can result in serious errors in model forecasts for precipitation. However, progress has been made in recent years and the following example is shown to indicate
As in Fig. 14 but for starting analysis for forecast at 1100 UTC 14 December 1995.

Fig. 16(a) 0-24 h LAPS25 forecast starting from 2300 UTC 30 April 1996 (left panel) and the verifying 24 h rainfall analysis (right panel).

Fig. 16(b) As in Fig. 16(a) but for forecast starting from 2300 UTC 1 May 1996.

this. The example considered is for Queensland, where commencing on 30 April 1996 and continuing into early May, the southeast corner of the State experienced extreme weather conditions which led to major, widespread flooding. The weather conditions and flooding were responsible for the loss of five lives. Details of the event can be found in Bureau of Meteorology (1996). The 24 h LAPS25 rainfall predictions (over land only to facilitate comparison with analyses) starting from 2300 UTC 30 April and 2300 UTC 1 May 1996 are shown in Figs 16(a) and (b) together with the verifying rainfall analyses (Mills et al. 1997). The analyses show the heavy rainfall over a wide area of southeast Queensland with maximum 24 h totals of 200 mm. For both cases the model also predicts heavy rainfall in about the correct area with maximum totals up to 150 mm. Bearing in mind the model resolution and uncertainties in initial state specification at these smaller scales, the model predictions have the potential to provide good guidance for these severe weather cases and thus are highly encouraging.
As noted above, model precipitation forecasts are highly dependent on model resolution. The following case is presented to provide an example. The case chosen is in early August where there was significant precipitation (snowfall) in the Victorian Alps. The analysis for the 24 h period starting from 2300 UTC 2 August 1996 is shown in Fig. 17 together with the LAPS75 and LAPS25 forecasts over land only. The analysis shows the precipitation to be confined to a narrow region over the topography (see Fig. 3 for topography for LAPS75 and LAPS25) which is also a feature of the LAPS25 forecast. The high resolution model forecast for precipitation amount shows reasonable agreement with the analysis, but the LAPS75 forecast rainfall is much less focussed, and also underestimates the amounts. A further feature of note in Fig. 17 is the much better depiction of precipitation over Tasmania by LAPS25.

The results shown above indicate the potential of LAPS25 for precipitation prediction. However, this high resolution model has some systematic biases which need to be corrected. The model has a tendency to predict rainfall too frequently particularly in the drier regions such as South Australia, western New South Wales and southwestern Queensland (Ebert, unpublished note). Similar to LAPS75, the LAPS25 model has a tendency to predict light rain too frequently, although for the latter, this is also carried onto the heavier rain rates. Some of the factors that could be responsible for the biases and which need to be addressed include lack of thermodynamic balance in the initial fields which result in model spinup, deficiencies in the specification of soil moisture, and the need to adjust parameters in the convection scheme with increased model resolution.

![Fig. 17 24 h precipitation forecasts from LAPS75 (bottom left), LAPS25 (bottom right) and verifying analysis (top).](image-url)
**Future directions**

The operational implementation of LAPS marks the completion of the first phase of a long-term project which provides a good base-level system with exciting avenues for continuing developments. The design of LAPS allows easy paths for further development of all components of the system. LAPS is the pivotal component of a large number of current and future ABM systems. Some of these include transport modelling, quantitative precipitation forecasts, tropical cyclone prediction, severe weather systems, and model output statistics. The system has also demonstrated its usefulness in diagnostic applications such as severe weather events, tropical cyclone landfall (Li et al. 1997) and the dynamics of an extreme rainfall event (Davidson et al. 1997). These studies not only provide insights into these important weather events, but also identify possible deficiencies in the modelling system.

There is a considerable amount of ongoing work at various stages of development which have direct relevance to the topics listed above. Some of the work includes:

- Improved analysis specifically for the high resolution model.
- Improved usage of data from polar-orbiting and GMS-5 satellites. These data include temperature and moisture soundings, cloud-drift winds and diabatic heating.
- Implementation of semi-implicit and semi-Lagrangian formulations which will facilitate the use of higher resolution systems with more detailed physics.
- Development of improved packages to display model output.

The acquisition of the new joint ABM/CSIRO supercomputer which provides significantly increased computing power in terms of speed and memory, will allow LAPS to be run routinely at much higher resolutions and with more detailed parametrisations of physical processes.

**Conclusion**

A new limited area prediction system, LAPS, has been developed at BMRC. The model component includes high order numerics, detailed parametrisation of physical processes and an initialisation scheme based on digital filters. The analysis component uses multivariate statistical interpolation analysis and, in addition to the data available on the GTS, makes use of locally retrieved temperature soundings and cloud-drift winds, and synthetic data such as moisture profiles from GMS.

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*Fig. 18* 12-month running means of the Australian region skill scores for 24 h and 36 h forecasts from the ABM’s operational limited area models since 1970. Major changes in the systems are indicated with arrows.
and tropical cyclone data. An important feature of the design of LAPS is the ease of moving domains and the option of running at very high resolutions over reduced domains. All components of LAPS were extensively tested for over 12 months in quasi-real-time and these tests showed a significantly improved performance over the then-operational RASP. Based on these tests and further operational trials, LAPS became operational on 3 July 1996. The operational impact of LAPS75 can be seen in Fig. 18 which shows the 12-month running means of the skill scores for 24 h and 36 h MSLP forecasts since 1970 when limited area models were first used for operational weather prediction over Australia. The dramatic reduction in the skill scores since the operational implementation of LAPS is a clear indication of its significant positive impact, with the 36 h LAPS forecasts now better than the 24 h RASP forecasts. A higher resolution version of LAPS (LAPS25) for the southeast and southwest Australian regions was implemented operationally in May 1997 and has shown promising skill in predicting severe weather events.

LAPS is now the pivotal component of a large number of current and future ABM systems which include transport modelling, quantitative precipitation forecasts, prediction of tropical cyclone and severe weather events and model output statistics. The operational implementation of LAPS marks the completion of the first phase of a long-term project which provides a good base-level system with well-defined paths for future development of all system components. These developments should allow continued improvement in the promising start made with LAPS75.

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