Cut-off low pressure systems over southern Australia: a numerical modelling study and sensitivity experiments

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A series of numerical model simulations of a cut-off low over southeastern Australia on 1 to 2 September 1997 is described. The aim was to determine the model configuration and variables that are vital to achieving a skillful forecast of the intensity of the cut-off low and of its associated precipitation. The first step was a control run which used only the archived real-time initial and boundary conditions. The control predictions of sea-level pressure (SLP) and precipitation amounts and distribution were evaluated by both subjective and objective measures of skill. The predictions were rated as good to very good, but it was also noted that the forecast central pressure of the cut-off low was too weak, the position of the low was located too far to the west, and that the precipitation totals were generally under-predicted.

Sensitivity experiments were then carried out to examine the role of the model configuration and a range of meteorological variables in determining the skill of the numerical simulation. The impact on the control forecast of: horizontal and vertical model resolution; the topography; the sea-surface temperature (SST); the upper-level jet; the surface fluxes of momentum and heat, and the use of an improved, explicit cloud microphysics scheme, were assessed. The simulations of the locations and intensities of both the SLP and the precipitation fields of the cut-off low pressure system were found to be sensitive, in varying degrees, to almost all the sensitivity variables. The most important factors were found to be the horizontal resolution, the SST patterns, the strength of the upper-level jet, the surface momentum fluxes, and whether an explicit or a parametrised moist convection scheme was used. Clearly, careful attention must be given to representing variables that are found to contribute significantly to the skill of forecasts, as adequately as possible in numerical models.

Introduction

Recent studies have been carried out by the authors on the cut-off low pressure systems that form over and move across southern Australia (Qi et al. 1999; Qi et al. 2000). These so-called southern Australian cut-off lows are synoptic-scale low pressure systems which have closed circulations at the surface and at 500 hPa, and which usually have developed from a deep trough in the westerlies. They often are accompanied by a Southern Ocean cold front. This definition of the...
southern Australian cut-off lows is employed deliberately to exclude other very important cyclonic systems, such as east coast lows, that are not of interest to this study. East coast lows have been studied extensively elsewhere and there is a large amount of literature available (see, for example, Leslie et al. 1987; McInnes et al. 1992; Katzfey 1996).

Cut-off low pressure systems are of great importance to southern Australia as they occur frequently, they often produce severe weather, and they bring moderate to heavy rainfall that is vital to agricultural areas, especially the Murray-Darling Basin. They can affect much of southeastern Australia, especially the larger and more intense cut-off lows. The Qi et al. (1999) study focused on two aspects of these systems. First, a relatively short climatology was produced. Second, the dynamics and thermodynamics of the cut-off lows were investigated, using a detailed case study. The climatology was carried out over the 14-year period (1983-1996) and included almost 1,500 days on which cut-off lows were present in the operational analyses. The climatology revealed a number of significant aspects of southern ocean cut-off lows. There is a maximum in the frequency of cut-off lows in southern Australia during the period May to October. The most active area for the genesis of cut-off lows in southern Australia is the western part of that region. The vast majority of cut-off lows move either eastward (36 per cent of all lows) or southeastward (45 per cent). The remaining northeastward moving systems (19 per cent) are those that most affect Australia because they are the cut-off lows most likely to bring either beneficial rainfall or severe weather to large areas of southeastern Australia. Turning to the case study, for the period 1 to 2 September 1997, the synoptic analysis for that event revealed that the moisture supply for the precipitation was transported from the tropical ocean (the Coral Sea) to higher latitude regions by a low-level jet (LLJ). A narrow moist tongue was formed, which interacted with the cut-off low and its associated cold front. It also was found that there was strong baroclinicity in the mid-upper troposphere, favourable for the intensification of the low. The presence of an upper-level jet (ULJ) also was shown to have an impact as the location of an associated jet streak was highly favourable for the development of the cut-off low.

In this paper, a numerical weather prediction (NWP) model developed at The University of New South Wales, and referred to as HIRES (High RESolution model), is employed to simulate the cut-off low of 1 to 2 September 1997. This case was chosen because it has already been studied in detail by the authors and because it is a ‘classical’ example of this kind of weather system. The numerical modelling program carried out here had two goals. First, it confirmed and quantified, by subjective and objective assessments, the results of Qi et al. (2000) in addressing how well the HIRES model can forecast the location and intensity of the cut-off low and its associated precipitation, using only the archived (operational) initial and boundary conditions. Conventionally, such an ‘operational’ forecast is referred to as the control model run. Second, in an attempt to understand and improve the control model forecast, an assessment is made of the roles of the model resolution and representation of physical processes in the development of the cut-off low. To this end, a series of sensitivity experiments was carried out on the impact of a selection of model configurations, meteorological and other variables. The variables selected for sensitivity impact included the model horizontal and vertical resolutions, the topography, the sea-surface temperature (SST) field, the ULJ, the surface momentum and heat fluxes, and cloud microphysics.

The next section provides a brief outline of the features of the HIRES NWP model and of the initial fields and boundary conditions in the simulation of the cut-off low case studied here. It also describes the nesting strategy. In the following section the results of the control experiment and the sensitivity experiments are presented in detail. Finally, there is a discussion and conclusions section.

Model description

The HIRES model has been very widely used over many years and is documented extensively elsewhere (see, for example, Leslie and Skinner (1994); Leslie and Purser (1997) and Buckley and Leslie (2000)). HIRES is presently used in both real-time and research modes. In real-time mode it is run twice-daily over a wide range of domains and resolutions. In research mode it is used at a number of centres in Australia and elsewhere. Only a very brief description is needed here.

The initial fields

The initial conditions and the lateral boundary conditions used in this paper for the HIRES simulations were obtained by interpolation from the LAPS (Limited Area Prediction System) operational regional model, archived by the Australian Bureau of Meteorology. At the time of this study, LAPS had a horizontal resolution of 75 km and had 19 vertical levels.

The NWP model

The University of New South Wales (UNSW) numerical weather prediction model, HIRES, is a hydrostatic, primitive equations model in which there are between
15 and 40 sigma levels in the vertical and which employs a split semi-implicit time integration on an Arakawa C-grid. The spatial differencing used here for the advective terms is a second order, centred, energy-conserving scheme. Normally, HIRES is used for short to medium-range forecasts, from 12 hours up to eight days ahead. As mentioned above, HIRES is used in both real-time and research modes. It has a multiple self-nesting capability. The first nesting region is at 50 km horizontal resolution, covering the entire Australian continent and with all lateral boundaries located over the oceans, to avoid a mismatch at the boundaries between the LAPS fields and the HIRES model. Such a mismatch can cause major problems, for example, over high topography or when the diurnal cycles of the different models produce widely differing surface temperature and moisture fields. This domain occupies an area covering the region 2°S to 44°S, 113°E to 178°E, and there are 15 internal sigma levels in the vertical (at 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.78, 0.85, 0.90, 0.95, 0.975, 0.99, 0.995, 0.999). For the second, self-nested HIRES model run, referred to as the control experiment, the grid spacing is slightly less than 20 km, over a domain covering 20°S to 42°S and 120°E to 165°E. The number and disposition of the sigma levels remains the same. This region was chosen because the starting location of the cut-off low is almost exactly in the centre of the model domain. A series of experiments with a different (larger) domain size revealed no significant change to the control run. The main physical processes in the model include a modified Kuo convection scheme, horizontal diffusion, and a Mellor-Yamada level 2.25 scheme for vertical turbulent transfer in the boundary layer. The lateral boundary conditions are updated from the LAPS output every six hours. The topography was retrieved from 1° by 1° resolution data by interpolation with a light smoothing procedure. The albedo and deep soil temperature fields were selected from a monthly climatology. Climatological roughness lengths also were interpolated to the grid. Over the ocean, the standard Charnock roughness length approximation was used. Recently, an explicit, six water-ice phase microphysics convective scheme developed by Wang (1999) has been incorporated as an option in HIRES and used in a comparison with the standard modified Kuo deep convection scheme used in HIRES (see Qi et al. 2000).

Results of the numerical simulations

The control experiment

The initial field (Fig. 1(a)) is a numerical analysis valid at 0000 UTC 1 September 1997. It is the analysis-forecast domain of relevance in this study, taken
from the full Australian region LAPS analysis field valid at that time. It is also part of the initial analysis region for the HIRES model. The cut-off low at this stage is weak and was located over east central South Australia, with a minimum SLP of 1009 hPa. Figure 1(b) is the 24-hour forecast of the sea-level pressure (SLP) field at 0000 UTC 2 September 1997. The forecast SLP minimum has now dropped significantly to 1003 hPa and the cut-off low has moved to a position (38.5°S, 138°E) south of Adelaide. Compared with the verifying analysis (Fig. 1(c)), which shows a central pressure of about 1000 hPa, the simulated low-pressure centre is too weak. The model forecast central pressure has intensified but is almost 3 hPa too high. The forecast centre is also in error, being located over 2° to the southwest of the observed centre. On the other hand, the simulated anticyclone over the Tasman Sea is too strong and has not moved far enough to the east of the continent. Despite these limitations, the control experiment has captured the overall development and movement of the cut-off low pressure system quite well, and would have provided the forecasters with valuable guidance. This assessment is supported by a subjective evaluation carried out by three meteorologists at the Australian Bureau of Meteorology. Their evaluation is summarised in Table 1(a). The overall rating given by the forecasters is mostly in the upper part of the ‘good’ range, on a scale that has four categories: excellent, good, moderate and unsatisfactory. Each of the forecasters used four indicators of skill, two for the intensity and location of the cut-off low SLP and two for the rainfall amount and pattern.

An objective assessment of the skill of the control run also has been carried out, as seen in Table 1(b). The objective errors in the SLP central pressure and location are shown, along with mean absolute error per grid-point (1.2 mm/grid-point), the correlation coefficient between the predicted and observed rainfall (0.76) and the rainfall bias in mm per grid-point (-0.7 mm/grid-point). These objective numbers support the subjective ratings that the forecast is good but could be improved upon. The objective assessments were based on the observed rainfall analysis scheme of the Australian Bureau of Meteorology. The 24-hour rainfall analysis is shown in Fig. 2(a). This rainfall analysis is the operational analysis run each day by the Bureau of Meteorology (Mills et al. 1997) and is the best available 24-hour rainfall analysis the authors are aware of. There are three significant maxima (25 mm or more) in the 24-hour observed rainfall. These are located near Adelaide, in central New South Wales (NSW), and over far northern NSW and southern central Queensland. In the last two locations the observed rainfall amounts were greater than 50 mm. The HIRES model 24-hour rainfall control prediction, using a version of the Kuo convective parametrisation scheme captured the main precipitation patterns fairly well (Fig. 2(b)). The overall distribution and amounts were quite good, the maximum near Adelaide was forecast well, and the maximum over the border region between NSW and Queensland border was reasonably located. However, the control model precipitation forecast produced spurious maxima over northeastern Victoria (36°S, 148°E) and coastal northern New South Wales (32°S,

| Forecaster 1 | 8 | 7 | 8 | 6 |
| Forecaster 2 | 7 | 6 | 7 | 6 |
| Forecaster 3 | 8 | 7 | 7 | 7 |
| Mean Score | 7.7 | 6.7 | 7.3 | 6.3 |

Table 1(b). Objective assessment for the forecast SLP and rainfall from the control run. The assessment measures used here were standard. For the SLP prediction they comprised the error in the central pressure and the location error. For precipitation, the mean absolute error, the correlation between the forecast and observed rainfall and the bias were used. The term ‘gp’ stands for grid-point.

<table>
<thead>
<tr>
<th>SLP</th>
<th>Rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central pressure error (hPa)</td>
<td>Location error (degrees, direction)</td>
</tr>
<tr>
<td>+2.9</td>
<td>2.1 SW</td>
</tr>
</tbody>
</table>
Fig. 2 (a) Observed rainfall (mm) for 24-hour period to 0000 UTC 2 September 1997 and (b) the 24-hour control model forecast rainfall (mm) to 0000 UTC 2 September 1997.

152°E). It also seriously under-predicted the very important maximum over central NSW (33°S, 147°E), although a maximum contour of 20 mm was forecast over southern central NSW.

The sensitivity experiments
In this section, the results from an extensive series of sensitivity experiments of the model forecast to changes in a range of variables, is described. The six sensitivity variables chosen, in order, are the horizontal and vertical HIERES NWP model resolution, topography, the SST field, the UL, the surface momentum and heat fluxes, and cloud microphysics. The sensitivity experiments had two goals. The first was to quantify the impact of the range of sensitivity variables on the intensity, location and precipitation patterns produced by the cut-off low. The second, related, goal was to provide a deeper understanding of the processes underlying the intensification of the cut-off low. The results of the sensitivity experiments using the six variables are presented in turn, below.

The objective measures of skill for the sensitivity experiments were the same as those calculated in Table 1(b). The objective skill assessments of all sensitivity experiments are summarised in Table 2.

Horizontal and vertical resolution. The effects of changing model resolution were examined in two experiments. All of the physical processes used in the control experiment were the same in these two experiments. The first sensitivity experiment used a horizontal resolution of 50 km, compared with the 20 km resolution of the control model run. Figure 3(a) shows the 24-hour simulated SLP for the 50 km model resolution forecast. The position of the centre of the low is close to that obtained by using 20 km horizontal resolution (Fig. 1(b)), but there is a 2 hPa difference in the minimum central pressure. That is, the lower horizontal resolution (50 km) had a significant weakening effect on the intensity of the cut-off low. This result is not surprising as it is consistent with experiments carried out elsewhere (e.g. Leslie et al. 1987). Moreover, the simulated rainfall (not shown here) is very similar in distribution to the control forecast but was far too smooth and the rainfall totals were almost uniformly lower than that of the control run.

The second experiment employed 25 vertical levels with the 20 km horizontal resolution of the control run. The 24-hour SLP simulation (Fig. 3(b)) was very close to that of the control model forecast, as was the simulated rainfall distribution (not shown).

Topography. In this experiment, all topography (Fig. 4(a)) in eastern Australia was removed and the land surface height was re-set to 1 metre (not shown), to examine the effects of topography. Naturally, the distinction between land and sea was retained. Only the elevations were altered.

The results of the simulation with the modified orography revealed that the effect of topography on the simulated SLP field is minor. The 24-hour forecast SLP field (Fig. 4(b)) is very close to that of the control experiment (Fig. 1(b)), in terms of the intensity and the position of the cut-off low pressure system. There are some expected differences present. For example, the low-level airflow over the southeastern highlands is deflected by the topography in the control run but naturally is not in the 1 m topography experiment.
Table 2. Objective assessment for the forecast SLP and rainfall from the sensitivity experiments. The measures are the same as in Table 1(b). The sensitivity experiments are defined as follows and should be clear from the text: E1a: 50 km horizontal resolution experiment E1b: 25 vertical levels experiment E2: Topography experiment E3: SST experiment E4: ULJ experiment E5a: Momentum flux experiment E5b: Heat flux experiment E5c: 1/10th heat flux experiment with modified SST E6: Explicit cloud physics experiment The units in the SLP location assessment are degrees followed by the direction of the error, e.g. 2.0W means a central pressure location error that is 2 degrees to the West.

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>SLP central Pressure Error (hPa)</th>
<th>SLP Location Error</th>
<th>Rain Mean Error (mm/gp)</th>
<th>Rainfall Correlation Coeff.</th>
<th>Rainfall Bias (mm/gp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1a</td>
<td>4.0</td>
<td>1.9W</td>
<td>1.6</td>
<td>0.78</td>
<td>-1.2</td>
</tr>
<tr>
<td>E1b</td>
<td>2.7</td>
<td>2.0W</td>
<td>1.0</td>
<td>0.76</td>
<td>-0.6</td>
</tr>
<tr>
<td>E2</td>
<td>3.9</td>
<td>2.0SW</td>
<td>1.9</td>
<td>0.71</td>
<td>-1.3</td>
</tr>
<tr>
<td>E3</td>
<td>8.9</td>
<td>2.9NW</td>
<td>2.3</td>
<td>0.61</td>
<td>-1.7</td>
</tr>
<tr>
<td>E4</td>
<td>3.9</td>
<td>3.0W</td>
<td>1.2</td>
<td>0.76</td>
<td>-0.8</td>
</tr>
<tr>
<td>E5a</td>
<td>-1.4</td>
<td>3.0W</td>
<td>0.9</td>
<td>0.77</td>
<td>-0.6</td>
</tr>
<tr>
<td>E5b</td>
<td>4.0</td>
<td>3.15W</td>
<td>1.3</td>
<td>0.76</td>
<td>-0.7</td>
</tr>
<tr>
<td>E5c</td>
<td>4.0</td>
<td>3.1W</td>
<td>1.2</td>
<td>0.75</td>
<td>-0.7</td>
</tr>
<tr>
<td>E6</td>
<td>1.0</td>
<td>1.8W</td>
<td>1.1</td>
<td>0.84</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Fig. 3 (a) The 24-hour forecast SLP field (hPa) with 50 km horizontal grid spacing, 15 vertical levels, at 0000 UTC 2 September 1997 and (b) the 24-hour forecast sea-level pressure (SLP) field (hPa) with 20 km horizontal grid spacing, 25 vertical levels, at 0000 UTC 2 September 1997.

The main impact of the topography was on the rainfall distribution (Fig. 4(c)). There was a new spurious maximum rainfall area over far southwestern NSW at approximately (25°S, 144°E). However, the forecast was improved by the disappearance of two of the spurious orographic rainfall maxima over northeastern Victoria and southeastern NSW near (36°S, 148°E) and over northern coastal NSW (32°S, 151°E), present in the control run. These results indicate that the lifting effect of the elevated areas over southeast Australia played a significant, but incorrect role in determining the rainfall distribution in this case study.

Sea-surface temperature. The numerical simulation study of Leslie et al. (1987) and others showed that Australian east-coast lows have a close connection with SST values and gradients. Similar results were anticipated for the southern ocean cut-off lows. Figure
Figure 4 (a) The original topography (m) used in the control run over eastern Australia; (b) the 24-hour forecast SLP field (hPa) in the topography sensitivity experiment; and (c) The 24-hour rainfall forecast (mm) in the topography sensitivity experiment.

(a)

(b)

(c)

5(a) is the mean SST field for September 1997 used in the control run. There was a warm tongue to the southwest of Adelaide. To answer the question of what might happen to the development of the low-pressure system without the presence of this warm SST region, we conducted the following experiment. Using the modified SST field (Fig. 5(b)) in which the warm pool close to Adelaide was replaced by a latitude-mean SST distribution, a 24-hour prediction was made. This reduction in the SST field of about 2°C over the region of interest is within the limits of the long-term observed climate variability. That is, the modified SST field is not outside observed values of SST for this area and this month.

The 24-hour forecasts were found to be very sensitive to the SST field. The new forecast (Fig. 5(c)) produced a minimum central pressure that was significantly higher, by about 4 hPa, than the control run without the warm SST tongue. Moreover, when compared with the control experiment (Fig. 1(b)), the low-pressure system moved more slowly, being located at (37°S, 138°E) instead of (38.5°S, 138°E).

Upper-level Jet. Based on well-established synoptic theory (see, for example, Alford et al. (1995)), upper-level jets frequently play a decisive role in the development of surface low pressure systems because of the distribution of the divergence/convergence patterns. When there is mass divergence in the upper levels, conditions support the development of further convergence in the lower levels of the atmosphere, when there is a surface low present.

Figure 6(a) is the wind field analysis at 200 hPa valid at 0000 UTC 1 September 1997. There were two main wind speed maxima. One was over Western Australia and the other was over the northern border region of New South Wales. Figure 6(b) shows the wind field analysis at 300 hPa, at the same time.

In order to assess the importance of the upper-level jet in this case, a sensitivity experiment was conducted. Figures 6(c) and (d) are the modified wind fields at 200 hPa and 300 hPa respectively. The maximum wind speed at 200 hPa and 300 hPa was reduced to 2/3 of the original strength. This was achieved by targeting the region of strong winds and multiplying wind velocities above 40 m/s by a factor of 2/3. For example, this procedure reduced the maximum wind in the model at 200 hPa from about 65 m/s to about 45 m/s, as can be seen by comparing Figs 6(a) and (c). An essential aspect of changing the initial wind field is to ensure that the other initial fields remain consistent with the new wind fields. This was achieved using the dynamical initialization procedure available in the HIRES system. Spin-up problems were thereby avoided, particularly the generation of gravity waves.
Fig. 5  (a) The September 1997 monthly mean SST field (°C) over the ocean and the model simulated surface temperature over the land at 0000 UTC 1 September 1997; (b) the modified SST field over the ocean and the model simulated surface temperature over the land at 0000 UTC 1 September 1997; and (c) the 24-hour SLP forecast (hPa) in the SST sensitivity experiment at 0000 UTC 2 September 1997.

Fig. 6  (a) The wind field analysis (m/s) at 200 hPa at 0000 UTC 1 September 1997. The length of the arrows is proportional to the wind speed, and the contours are isotachs. (b) The wind field analysis at 300 hPa at 0000 UTC 1 September 1997. (c) The modified wind field analysis at 200 hPa for the sensitivity experiment. (d) The modified wind field analysis at 300 hPa for the sensitivity experiment.
With the modified initial upper-level wind fields, the 24-hour model simulations (Fig. 7) produced a cut-off low pressure system that was slightly, but noticeably, weaker than that in the control experiment (Fig. 1(b)), by just over 1 hPa. Figure 7(a) is the simulated SLP at 0000 UTC 2 September. The area covered by the 1004 hPa contour was considerably smaller than that of the control forecast (Fig. 1(b)). However, the simulated rainfall pattern (Fig. 7(b)) is similar to that of the control (Fig. 2(b)) over most of the domain. Over the ocean near the cut-off low, the rainfall amounts are up to about 15 mm less than those in the control run. This is consistent with the weaker cut-off low.

A difference map showing the forecast with the modified ULJ minus the control run has now been included. Note the expected negative values in the vicinity of the cut-off low (Fig. 7(c)).

**Surface fluxes.** In order to investigate the impact of the surface fluxes, a series of experiments have been conducted. In the first experiment, only the surface drag coefficient was set to zero, so there is no surface friction. In theory, the low should be stronger as there is less resistance to inflow towards the centre of the low. This expectation was confirmed by the 24-hour
forecast (Fig. 8(a)) which shows that the minimum SLP of the low system is about 999 hPa compared with 1003 hPa for the control run and about 1000 hPa for the verifying analysis. In this experiment, the central pressure forecast was actually lower than the analysed value. However, the main result is the strong sensitivity to the removal of surface drag, suggesting that the drag over the ocean is possibly too high in the present configuration of the model.

In the second experiment, only the surface heat transfer coefficient was set to zero. Little difference (Fig. 8(b)) is found between the sensitivity and the control forecasts. This finding is not as surprising as it might appear to be, as will be discussed below.

In the third experiment the surface drag coefficient was not changed but the surface heat transfer coefficient was set to a fraction (1/10th) of its value, and run with the modified SST field. Figure 8(c) shows the corresponding 24-hour forecast SLP field. Compared with the previous SST experiment (Fig. 5(c)), the cut-off low is weaker, with a forecast minimum SLP 2hPa higher. This result explains the null result of the second experiment, namely, that the importance of the surface heat fluxes is connected closely with the surface gradients in temperature. In the control run over the oceans, the near-surface temperature gradients were very small. However, in the case of the modified SST field the sensible heat fluxes are much larger and do have a very significant impact, except when the heat transfer coefficient is reduced, as was the case here. In other words, the surface heat fluxes are important, but in this particular case study the influence on the atmosphere is almost entirely due to the effect of the SST field.

The fourth experiment was to turn off all vertical turbulent transfers above the surface layer. The results indicate (not shown here) that during the forecast period (24 hours) vertical diffusion away from the surface has little impact on the forecast. This is not at all surprising as the vertical diffusion processes are relatively slow, so in a short-term forecast of 24 hours its impact would be expected to be small.

**Improved cloud microphysics.** Although the control experiment with the Kuo convective parametrisation scheme captured many of the main features of the system, it was noted above in the control run that there were some significant errors in the precipitation forecast. In particular, the large and very significant area of convective rainfall over central New South Wales was not captured in the control forecast. In that sensitivity experiment, an explicit cloud microphysics scheme, available as a model option (Wang 1999), was employed to access its impact on the control simulation. In the scheme, the grid-resolved precipitation and evaporation are calculated by the method of Lin et al.
Fig. 9 (a) The 24-hour SLP forecast (hPa) using the explicit cloud microphysics scheme; (b) The 24-hour rainfall forecast (mm) with the explicit cloud microphysics scheme; and (c) The difference field between Fig. 9(b) and the control run, Fig. 2(b).

(1983), and Rutledge and Hobbs (1983, 1984). The cloud microphysics parametrisation considers water vapour, cloud water, cloud ice, snow, rainwater and graupel, including aggregation, accretion, evaporation, deposition, sublimation, melting and freezing processes. Full details of the scheme are given in Wang (1999). As already mentioned, the new explicit scheme has already been examined in a previous study (Qi et al. 2000), but the results were not assessed quantitatively, nor were the results compared with the impact of the many other sensitivity variables as been done here.

The simulation confirmed the Qi et al. (2000) finding that the explicit scheme also significantly improved both the minimum central pressures of the SLP field (Fig. 9(a)) and also the rainfall forecast (Fig. 9(b)). They are much closer to the observed than that of the control run with the Kuo scheme. The minimum SLP is now 1001 hPa, compared with 1003 hPa for the control. This central pressure is very close to the analysed value (Fig. 1(c)). It is also noteworthy to see that there is now a marked maximum rainfall region over central New South Wales and that the maximum rainfall totals exceed 55 mm. The observed rainfall amount over that region was over 50 mm. Figure 9(c) gives the difference between the 24-hour simulated rainfall amount by the explicit scheme and that by Kuo scheme. It shows that the rainfall amount in central New South Wales has been increased over 30 mm in the explicit scheme, which matches the observations very well. Another significant difference is present to the north of Melbourne, where there is over 15 mm more precipitation than in the explicit scheme. For the remainder of the forecast region, the simulated rainfall amounts are increased, except for part of southern Queensland and the northern part of New South Wales. The significant improvement in the SLP and rainfall predictions is quantified in the last row of Table 2.

**Discussion and conclusions**

One of the most significant features of the weather patterns over southern Australia is the so-called 'cut-off low' that brings both beneficial rainfall and destructive severe weather to Australia. This is true particularly of coastal and inland southeastern Australia, including the Murray-Darling basin, which is Australia’s most important agricultural region.

Hitherto, there have been few studies of cut-off lows, particularly modelling studies. More focus has been directed on other systems that affect southern Australia, most notably cold fronts and east-coast lows. In earlier studies (Qi et al. 1999; Qi et al. 2000), the authors produced a 14-year climatology of southern Australian cut-off lows; carried out a case study that
identified the main processes that were responsible for the rapid intensification of the cut-off low; and simulated the event using two different schemes for representing convective precipitation. The earlier studies both highlighted the need for a far more thorough investigation of southern Australian cut-off lows.

In this paper, we have conducted a control run and a series of sensitivity experiments on the impact of horizontal/vertical resolution, topography, sea-surface temperature, the upper-level jet and surface fluxes in order to assess the relative roles of these factors. In addition, the impact of an improved, explicit cloud physics scheme on the simulation also is examined. It was found from both subjective and objective assessments that the HIRES model performs well in this case and captures most of the synoptic features of this process. The 24-hour forecasts of the track, intensity and rainfall patterns are reasonably close to the verifying analyses. When an explicit microphysics process was introduced into the model, the forecast was significantly improved, especially the rainfall field.

The results also show that the main impact of the topography was on the rainfall distribution, and the upper-level jet could slightly enhance the strength of the low centre and resulted in more rainfall. Sea-surface temperatures were found to influence the strength of the low pressure system. The simulated results in 20-km horizontal resolution provide more details of the system and are more skillful than the 50-km resolution forecasts. In this study, increasing the vertical resolution had little impact on the simulation.

Both the subjective and objective assessments revealed that the control run had deficiencies that needed to be improved upon. The sensitivity experiments therefore have achieved a number of significant goals. First, they showed that the cut-off low control simulation could indeed be improved upon, to the extent that there were very little error in the central pressure, the location error could be reduced by almost two-thirds, to about 1°, and the precipitation pattern could be improved markedly. Second, the very positive impact of the sensitivity variables on the forecasts demonstrated the need to pay careful attention to those variables that contributed to the improved forecasts. For example, the resolution must be adequate, the SST field should be representative of current conditions and not be overly biased on climatological means, and an explicit convective scheme is very effective at high model resolutions. Third, and finally, the sensitivity experiments provided an understanding of the factors that were important in the intensification of the cut-off low; such an understanding would not have been possible using a standard synoptic approach.

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References


