Australian east coast cyclones III: case study of the storm of August 1986

Amanda H. Lynch
Bureau of Meteorology Research Centre, Melbourne, Australia

(Manuscript received November 1987; revised December 1987)

The Australian east coast cyclone of August 1986 caused the worst flooding event in metropolitan Sydney in over a century. The formation and evolution of the system is described in detail, with reference to the general classification of Australian east coast cyclones presented in Holland, Lynch and Leslie (1987). The performance of the operational numerical weather prediction (NWP) model was inadequate for this event. Hindcasts are presented using the research version of this model to demonstrate the predictability of the cyclone, and to identify mechanisms contributing to the development. It was found that the research model produced much better guidance, especially at higher resolution, although it is considered that sub-grid scale parametrisation is still inadequate for such an event. The model hindcasts reflected the cyclone's failure to intensify explosively, and the placement in time and space of the maximum precipitation. The amount of precipitation was severely underestimated, however.

The formation of the system was consistent with a large-scale baroclinic process, with minimal convective activity which was identified with the explosive intensification in an earlier case study. These results are compared with the conclusions of this earlier case study to determine the applicability of these conclusions to the east coast cyclone of August 1986.

Introduction
The worst flooding incident to occur in metropolitan Sydney on the Australian east coast for more than a century was the storm of 5 to 8 August 1986. This storm resulted in six deaths and approximately 100 million dollars worth of damage, as almost half Sydney's average annual rainfall fell on that city. A three-day total of 450 mm was recorded at Observatory Hill, Sydney, with the 24-hour maximum of 337 mm, which is 20 per cent higher than the previous record. The torrential rains and gale-force winds were not forecast effectively by experienced forecasters or the operational numerical model.

The depression which caused this deluge belonged to a class of cyclones which form over the Australian mid-latitude coastal waters which are known as east coast cyclones (Holland, Lynch and Leslie 1987; Leslie, Holland and Lynch 1987; hereafter referred to as HLL and LHL respectively). HLL gave a limited climatology for these systems, presented an overview and classification of these systems in general, and described a detailed case study of three events. LHL examined the mechanisms of formation and intensification using a limited area numerical model and one of these events.

The aim of the present paper is to investigate the applicability of the general conclusions drawn by the first two papers to this extreme rainfall event. The region of interest is shown in Fig. 1.

Fig. 1 (a) Map of the east coast of Australia, showing coastal topography and place names.
(b) Map of the region affected by the east coast cyclone of August 1986.
East coast cyclones – a brief summary

As described in HLL, these intense mesoscale cyclones form in a synoptic-scale cyclonic environment known locally as an 'easterly dip'. The easterly dip is a common phenomenon, particularly over the Australian east coast, occurring approximately ten times per year. About once a year, this environment spawns an intense east coast cyclone. These were classified in HLL into three types, according to whether they form to the east, on, or to the west of the easterly dip axis. Sometimes the formations are complex, with several cyclones, of the same or differing type, forming within the life-cycle of a single easterly dip. Thus, in practice, it may be difficult to classify any one system as a Type 1, 2 or 3, since it may be a combination of several types.

The east coast cyclones of 24 to 26 July 1984, studied in HLL, included an example of a complex development. As an easterly dip formed over central eastern Australia, a Type 1 east coast cyclone formed on the coast near Fraser Island. As the dip reached the coast, this system slowed in its trajectory down the coast and amalgamated with a low pressure region near Sydney to form a Type 2 cyclone, which subsequently became meso-synoptic in scale. It is this second system which, due to its larger scale, became the subject of the numerical modelling study of LHL. It was found that both large and small-scale processes are required in the mesoscale model formulation to simulate the cyclone development accurately, with a lead time of at least 24 hours. While the formation of the system is consistent with a large-scale baroclinic process, the small-scale processes of cumulus convection, surface vertical turbulent fluxes and the influence of coastal topography were necessary to produce the explosive deepening. This study also highlighted the importance of the sea surface temperature (SST) structure in the intensification. This region is often subject to a strong gradient of SST along the coast, with a cold pool close to the coast and anomalously warm water off the coast (see Fig. 6 for example). This structure is maintained by transient warm eddies along the coast (HLL) and has a dual effect. First, the warm area increases surface fluxes of heat and moisture to the system. Secondly, potential vorticity arguments can be used to show that the strong gradient deflects the flow cyclonically (LHL). Both of these effects, as discussed in the first two papers, aid the intensification of the cyclone. These basic conclusions will be tested in the 'numerical experiments' section of this paper.

East coast cyclone of August 1986

The easterly dip shown on the coast in Fig. 2 at 2300 UTC on 3 August had formed over southwestern Australia and slowly moved northeastwards towards the coast during the preceding 48 hours. During this time at least two small-scale low pressure systems formed near the coast, as shown in Fig. 2(a) (re-analysis performed by H. De Wit, personal communication, 1987). The system of interest, however, did not form until the dip reached the coast, at 1100 UTC on 4 August. Typical of the easterly dip formation, mid-tropospheric air was subsiding around the western side of the dip, as low-level tropical air to the east rose and flowed around the poleward side. At the interface between these two flows, indicated by the northern edge of the convective line associated with the dip (Fig. 2(b)), the system of interest formed, on the coast near Port Macquarie. It then intensified rapidly as it moved down the coast towards Sydney, reaching its minimum of 999 hPa by 1700 UTC on 5 August (Fig. 6). In the 24-hour period from 1700 UTC on 4 August to 1700 UTC on 5 August, the system sustained an intensification rate of 0.5 hPa/hour, or 1.0 Bergeron using the latitude corrected intensity requirement for the 'bombs' of Sanders and Gyakum (1980). As shown in Fig. 3, two centres were evident – the northernmost being the probable amalgamation of the two systems which formed before the dip reached the coast, and the
southern being the system of interest in this study. The strong convection developing along the coast is apparent in Fig. 3(b), which also shows the cloud associated with the mid-level cold cored cyclone and the upper-level jet to the north of the surface signature. The position of the east coast low is indicated by a cross.

Figure 4 shows the east coast cyclone at the end of the maximum 24-hour rainfall period, 2300 UTC 5 August. Unfortunately, hand analyses were not available for this time. The low resolution analysis from the archive does not show the detail of the dual centre, but is adequate for broad comparisons. By this time the mid-level cyclone had moved over the coast as the easterly dip started to move out towards the Tasman Sea. The flow at the surface and lower level was strongly confluent, as evidenced by the wide band of cloud with deep convection at its leading edge (Fig. 4(b)). Figure 5 shows the 24-hour cumulative rainfall up to this time, for the purposes of comparison with numerical results.

The trajectory of the system of interest (the southeastern low centre in Fig. 3(a)) was extremely erratic and not well defined due to the small size and complex nature of the system. Figure 6 shows the track for this centre, superimposed over the observed sea surface temperatures at that time (a weekly average). For the first nine hours from formation, the system moved rapidly down the strong gradients of sea surface temperature (SST) which ran parallel to the coast. The maximum intensification occurred as the cyclone moved across the strongest gradients, into the cold pool near the coast, with an observed drop of 3 hPa in three hours. The system then remained quasi-stationary over the cold pool for the next 24 hours, maintaining a moist airstream over the Sydney area. This resulted in the extended period of continuous heavy rainfall. Subsequently the cyclone moved out over the Tasman Sea and began to weaken. This was accompanied by a contraction of the rainfall to the southeast.
Figure 5 Isobets (mm) for the 24-hour period up to 2300 UTC on 5 August. Analysis produced by Hank de Wit.

Figure 7 shows a time-section of MSLP, wind and cumulative rainfall at Norah Head, just north of Sydney, from the standard observations taken at the time. There are no observations between 2100 EST and 0600 EST on each day, but a good indication of the passage of the system is given. The sharp drop in MSLP, accompanied by a windshift from the strong southerlies to weaker easterlies in the early hours of 6 August indicates the passage of the system from the north to the west of Norah Head. The rainfall rate slackens significantly during this short period, as does the cloud cover, indicating the presence of the clear ‘eye’ nearby.

Operational performance

The operational forecasts issued by the Sydney Regional Office of the Australian Bureau of Meteorology for the period immediately preceding and during the storm significantly underestimated the severity of the event. Initially, on 0501 EST 4 August (1901 UTC 3 August) the forecast was for showers on 4 August with showers decreasing on 5 August. By 1431 EST 4 August, this was amended to heavy rainfall periods with no strong winds indicated. The first strong wind warning was issued at 2246 EST 4 August after the first reports of strong winds from Norah Head (25 knots at 1800 EST), and Tuncurry (30 knots at 2200 EST). A priority gale warning was issued at 1540 EST 5 August for the entire coastal area south of 33°S.

A warning of minor to moderate flooding was issued at 1500 EST 5 August, after minor flooding had already occurred at Liverpool. The forecast was changed to major flooding at 0430 EST 6 August (1830 UTC 5 August) after reports such as flooding in excess of 10 m at North Richmond at 0300 EST. The forecast peak of 14 m was not reached, however.

The prognoses produced by the operational numerical models (BIRDPROG and FINEST) gave only a limited indication of the severity and movement of the storm. BIRDPROG was the only Australian
Numerical forecast available to Sydney forecasters and, being dry, gave no warning of the precipitation. FINEST was then running in parallel with BIRDPROG in testing mode in Melbourne. It went fully operational shortly thereafter. The MSLP forecast is shown in Fig. 8. The maximum 24-hour precipitation (forecast at 16.4 mm) was well below the observed value of 337 mm. The time of the maximum was well placed in the 24-hour period preceding 0900 EST 6 August (2300 UTC 5 August).

It is clear from the above description that this event was not forecast in any quantitative sense by the NWP model in the form which was operational at that time. The subjective forecast was hampered by the eccentric motion of the system and the poor NWP guidance. A post-analysis of the situation produced in the Sydney Regional Office has shown that improvements to the existing operational model are required to provide useful guidance to such events (J. Colquhoun, personal communication, 1987).

The numerical model

The NWP model used in the numerical experiments in this study is the research version of FINEST, and is known as ARPE model, the Australian Regional Primitive Equation model. This model, like the operational version, is initialised from analyses on a 250 km grid, but utilises higher resolution (1° x 1°) surface analyses and perfect boundary conditions (which cannot be available to the operational environment). A new data assimilation scheme is currently being tested which will provide even further advantages over the operational model version in use during the August 1986 storm. The ARPE model has variable horizontal and vertical resolution, and may be nested within itself in the horizontal to provide higher resolution over a limited area. In the simulations presented in the following sections, the model is run with 12 sigma levels in the vertical and 150 km horizontal resolution on a 65 x 40 grid, with a one-way nested region at 50 km resolution on a 50 x 50 grid. The experiments are 24-hour forecasts from the initialisation time of 2300 UTC 4 August to 2300 UTC 5 August (0900 EST 5 August to 0900 EST 6 August). This interval was the maximum 24-hour rainfall period mentioned before. The details of the numerical formulation and physical parametrisations are given in Leslie et al. (1985), with a summary in LHL.

Numerical experiments

A series of numerical experiments was performed in order to assess first the basic forecastability of the system, and secondly, the physical processes contributing to the development. A summary of these experiments is given in Table 1, and they are discussed in detail below.

<table>
<thead>
<tr>
<th>Simulation Number</th>
<th>Test</th>
<th>Maximum Precipitation</th>
<th>Minimum SLP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Observed</td>
<td>337 mm*</td>
<td>999 hPa</td>
</tr>
<tr>
<td>1</td>
<td>Benchmark</td>
<td>50 mm</td>
<td>1004 hPa</td>
</tr>
<tr>
<td>2</td>
<td>No large-scale precipitation</td>
<td>6 mm</td>
<td>1007 hPa</td>
</tr>
<tr>
<td>3</td>
<td>No cumulus parametrisation</td>
<td>44 mm</td>
<td>1005 hPa</td>
</tr>
<tr>
<td>4</td>
<td>No surface fluxes</td>
<td>48 mm</td>
<td>1005 hPa</td>
</tr>
<tr>
<td>5</td>
<td>No topography</td>
<td>46 mm</td>
<td>1004 hPa</td>
</tr>
<tr>
<td>6</td>
<td>Actual sea surface temperatures</td>
<td>50 mm</td>
<td>1002 hPa</td>
</tr>
<tr>
<td>7</td>
<td>50 km horizontal resolution</td>
<td>53 mm</td>
<td>1000 hPa</td>
</tr>
</tbody>
</table>

*This observed maximum is, in fact, a point value. For true comparison an accurate area average would be required. An estimate of this average over a 150 km grid square is 150 mm, and for the 50 km grid square, 200 mm.

Forecastability

A 24-hour forecast, Experiment 1, was performed using the basic model with all physical parametrisations as detailed in Leslie et al. (1985), and at 150 km resolution in order to address the problem of basic forecastability, given the advantages of the ARPE model over the operational model, FINEST. The 24-hour predictions of MSLP and cumulative rainfall are shown in Fig. 9. The intensity of the event is underestimated with the minimum central pressure being 5 hPa too high compared to observation (4 hPa higher than analysed), and the rainfall falling far short of the observed. However, it is difficult to ascertain a true comparison of the rainfall totals, since the observations are taken at points and the model gives an area average, here for a 150 km square. The approximate area average observed is 150 mm, and hence the prediction gives one-third of observed precipitation. The rainfall prediction of 50 mm should be enough in an operational environment to alert forecasters to the possibility of a significant development. It has been suggested by J. Colquhoun (personal communication, 1987) that the failure of the precipitation forecast may be attributed to the absence of a parametrisation of the ‘feeder-seeder’ mechanism (Browning et al. 1974; Browning et al. 1975). This parametrisation will not be possible until ice phases are included in a true mesoscale model.
Fig. 9 24-hour forecast of (a) MSLP and (b) precipitation produced by the research NWP model at 150 km resolution (benchmark). Analysis time is 2300 UTC on 4 August. Forecast valid at 2300 UTC on 5 August.

The position of the cyclone and the general details of the structure are well represented with the position at 2300 UTC 5 August at 1° latitude north of the observed. The horizontal grid length is too large at this stage to resolve the complex double centre. This forecast indicates that the ARPE model can represent the system with sufficient skill to perform sensitivity experiments, and to alert forecasters to the development.

Effect of precipitation

The observations indicate that a significant portion of the rainfall associated with this system was large-scale, orographic rainfall, interspersed with thunderstorms embedded within the stratiform. In order to determine whether the model rainfall reflected this partition, and to examine the effect of the rainfall on the development of the system, two experiments were performed. The first simulated the development with no large-scale rainfall, the second with no cumulus convection.

Experiment 2 produced a forecast from the ARPE model with no large-scale rainfall. The moisture is removed artificially with no release of latent heat. The rainfall forecast for this experiment was only 6 mm, indicating that in the model system, as in the observed cyclone, the major part of the rainfall is large-scale. From the MSLP chart, there is reduced cyclonic development throughout the entire forecast period. Thus, large-scale precipitation is necessary for the development.

Experiment 3 produced predictions from the ARPE model with no cumulus convection parametrisation. The resulting forecasts are not so affected compared to the removal of the large-scale precipitation. This concurs with the observations, and indicates that the diabatic heating by cumulus convection was not a major component in the development of the Sydney storm. However, it did provide a proportion of the heavy rainfall associated with the storm.

Effect of surface fluxes

Experiment 4 was conducted to investigate the role of vertical turbulent fluxes of heat and moisture in the development and intensification of the system. (Note that the vertical turbulent fluxes of momentum i.e. frictional dissipation, are included.) In this experiment the system starts to fill after 12 hours, and is significantly less intense than the benchmark. The results are virtually indistinguishable from Experiment 3, the simulation with no convective parametrisation. This is consistent with previous results, indicating a strong coupling between these fluxes and the mechanism of cumulus convection.

Effect of topography

Experiment 5 replaces all topography with a flat land surface, retaining the roughness characteristics and land-sea contrasts. Although the system reaches the same intensity as the benchmark, and the rainfall is only decreased by 8 per cent it is significantly affected by the missing orography. The rainfall maximum is displaced well to the east. The cyclone trajectory is faster down the coast, giving a position which is further south than the benchmark. The ridging along the coast evident in the benchmark forecast is no longer present, giving a much more symmetrical system. This is due to the effect on the potential vorticity field of the orography along the coast (Fandry and Leslie 1984).

Effect of sea surface temperature structure

The preceding experiments were performed using the climatological sea surface temperatures for August (Fig. 10). Since the sea surface temperature structure observed at this time (Fig. 6) is not reflected by these long-term averages, Experiment 6 performs the benchmark forecast with actual SSTs over the region in which data are available. These additional data are available routinely from RANL (Royal Australian Naval Laboratories), over a large portion of the east and southeast coastal waters. Despite the fact that at 150 km horizontal resolution, the structure is not well captured, the resulting forecast shows a significant improvement. The forecast minimum central pressure is 2 hPa lower than the benchmark of 1004 hPa. The observed minimum central pressure at this time was 999 hPa, and was numerically analysed at 1000 hPa. This improvement is due to a two-fold effect of the SST
Fig. 10 Climatological sea surface temperatures for the month of August.

structure. First, the warm anomaly acts as a source of latent and sensible heat. Secondly, the gradient along the coast acts as equivalent orography, deflecting the flow cyclonically (Fandry and Leslie 1984; LHL), and hence aiding the development. The precipitation forecast was not improved by the additional data, however. It is proposed that this is due to the nature of the convective parametrisation, in which the surface is not included as a source.

Effect of increased horizontal resolution

The benchmark experiment was repeated with a reduced horizontal grid length of 50 km over a limited region, which is nested within the original forecast. The results of Experiment 7 are shown in Fig. 11. The increased resolution produces a much improved forecast, with a minimum central pressure of 1000 hPa, identical to the numerically analysed value and only 1 hPa above the observed minimum central pressure. The structure of the system is well captured, with the double centres clearly defined, although the second, weaker system is displaced somewhat south of its relative position. The system of interest is placed 1° of latitude north of that observed, but is placed accurately compared to the numerically analysed system. The distribution of rainfall appears to be quite accurate compared with the observations, although none are available over the ocean. The concentration of maximum rainfall over the Sydney area, and the minimal rainfall associated with the second system, are borne out by the observations. Since the average over the grid square (50 km x 50 km) is observed to be 200 mm, the amount of precipitation predicted is only 25 per cent of that observed, and hence still inadequate.

Discussion

It has been shown that this small-scale system requires true mesoscale resolution for an accurate forecast of the event. Improved physics provided better guidance, particularly in the precipitation field. It is significant that the two types of development, the explosive intensification observed in the storm of July 1984, and the absence of this extreme development in August 1986, were well captured by the model. The other aim of this study was to examine the physical mechanisms contributing to the extreme development, and to compare these results with those of Leslie, Holland and Lynch (1987). Adequate representation of both the large and small-scale processes was necessary to give the most accurate simulation of the event. However, in this case, the coupled small-scale processes of convection and turbulent fluxes from the boundary layer did not have the extreme impact that they had in the storm of July 1984. In LHL it was found that the large-scale baroclinic development was sufficient to
account for the initial formation and intensification to about 1000 hPa. It was the small-scale processes of anomalous sea surface fluxes and the convection associated with them which were required to account for the further 20 hPa fall observed in this earlier storm. The results of this study are consistent with these conclusions, since the observed formation and intensification were consistent with the large-scale environment, and the small-scale processes did not interact to enhance intensification, although they did contribute significantly to precipitation. The further question of why the storm did not become dominant, cannot be answered by this study.

The model physics are continually evolving as a result of studies like this. It is obvious that deficiencies in the sub-grid scale parametrisations adversely affect predictions of violent rainfall events. Some improvements which will result in a significantly better forecast of this event are:

(a) variable resolution analysis to provide the initial data set, and an improvement in the quality of this data set. The moisture analyses in particular had a large effect on the accuracy of the forecast.

(b) the addition of full column convergence and evaporation from the surface as sources for the Kuo convection scheme, which uses boundary layer convergence only at this time. This would result in a more realistic amount and distribution of moisture available to the convection scheme.

(c) actual SSTs rather than climatological SSTs. As demonstrated above and in LHL, routinely available sea state data would improve all forecasts where small-scale processes play a role.

These changes are expected to improve the performance of the model in many situations, particularly the extreme weather events such as east coast cyclones.

Acknowledgments

The author is grateful for the fruitful discussions with John Colquhoun, Lance Leslie and Greg Holland. Extra data and discussion were supplied by the members of the Special Services Section of Bureau of Meteorology Sydney Regional Office. Some analyses are the work of Hank de Wit. Thanks to Kathy McInnes and Graham Mills for computing (and moral) support, and to Pay Stroumos for fast turnaround of drafts and for typing the final manuscript.

References


