Meteorological aspects of the 31 March 2009 Coffs Harbour flash flood

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Flash flooding from short duration, torrential rain occurred in the city of Coffs Harbour on the New South Wales north coast during the afternoon and evening of 31 March 2009 when totals of more than 300 millimetres were recorded in the hills immediately to the west of the city. Meteorological analysis of the event showed that several factors combined to produce the flooding. These included a moist, convergent low-level airflow onto the hills five to ten kilometres inland from Coffs Harbour, a strongly backing vertical wind profile favourable for broadscale ascent, and the presence of a mid-tropospheric trough to the west which assisted upmotion and reduced the static stability in the region. A southwesterly surface flow, induced by the orientation of the hills near Coffs Harbour, also enhanced the backing of the wind with height (and implied ascent through warm air advection) further intensifying the vertical motion in the trough and was coincident with the heaviest period of rainfall. This slow moving pattern provided an efficient dynamical mechanism that anchored the rain over the hills for several hours, similar to a Coffs Harbour severe flash flood event thirteen years earlier.

Model forecast guidance of these factors, combined with using a multiple of approximately three times the maximum ensemble-predicted rainfall amounts over the highest topography nearby, is capable of providing valuable information to forecasters of the potential for dangerous flash flooding in the Coffs Harbour Creek catchment.

Introduction

On the afternoon of 31 March 2009 heavy continuous rain fell for several hours on the hills surrounding the city of Coffs Harbour (CH), which is situated on the New South Wales (NSW) north coast (Fig. 1(a)). The heavy rain in the CH creek catchment (see inset Fig. 1(a)) occurred within a general flood–rain event on Australia’s subtropical east coast in which there was extensive flooding on rivers north and south of CH from rain over a three day period (Fig. 1(b)). All major roads in and around CH were closed, cutting access to several towns. During the afternoon of 31 March, highest recorded falls in the CH Creek catchment were 286 mm in four hours from 1300 EST (0200 UTC) to 1700 EST (0600 UTC) at Red Hill, 305 mm at Shepards Lane in the six hours from 1300 EST (0200 UTC) to 1900 EST (0800 UTC) and 247 mm at Perry Drive in the six hours from 1300 EST (0200 UTC) to 1900 EST (0800 UTC). These falls led to a peak flood level of 5.1 m in CH Creek by 1800 EST (0700 UTC). This compares to a record maximum level of 5.4 m in the 23 November 1996 flash flood event (Flood Manager 2009). CH Creek is tidal and its height normally varies between 0 and 1.0 m. Prior to these two CH events the heaviest Australian short duration rainfall outside the tropics occurred in the Dapto flash flood (Shepherd and Colquhoun 1985) when 600 mm fell in eight hours. The twenty-four hour rainfall total of 445 mm to 0900 EST (0700 UTC) on 1 April 2009 at Red Hill is the highest April total over the nine years of record. There were also many other twenty-four hour rainfall records for April broken at nearby locations on the same day (see Table 1). For Urunga, it can be seen that the April 2009 total is the highest recorded monthly total while for the other stations April is generally the second or third highest monthly total on record (not shown). The total damage bill reported by the Insurance Council of Australia was $30 million in the Coffs Harbour area for the three day period. Several flash floods resulting from short duration heavy rainfall over
southeastern Australia have been documented (e.g. Fox-Hughes 2009; Speer and Leslie 2000; Mills and Bao-Jun 1995). Prior to these, Speer and Geerts (1994) lists both NSW and overseas examples from previous decades.

The most severe flash flood rain event to affect CH in recent decades occurred on the evening of 23 November 1996. In comparison with the 31 March 2009 event, the highest recorded rainfall totals for the November 1996 event were 388 mm in four and a half hours at Sandra Close and approximately 240 mm in six hours at Boambee—both sites are located in the hills west of CH (Speer and Leslie 2000). Apart from the rainfall totals, there were other similarities in both the March 2009 event and the November 1996 event, including strong, moist onshore winds with cloud that appeared to remain stationary over the topography, a few kilometres to the west of CH central business district (CBD), and which produced the continuous, heavy rain. Another feature common to both events was low static stability provided by a mid-tropospheric trough.

With two similar, severe flash flood rain events having occurred in the same area within thirteen years, the main aim of this study is to highlight important ingredients and mechanisms for this type of flash flood event in order to alert forecasters to the potential for dangerous flash flooding.
in the CH creek catchment. A secondary aim is to briefly describe the adequacy of numerical weather prediction (NWP) guidance available at the time. However, a detailed modelling study such as that for the November 1996 event (Speer and Leslie 2000) is outside the scope of this work and is thus left to future study. Following a description of the data sources used in the study, the next two sections concentrate on a meteorological analysis of the March 2009 event and a comparison with similar recent CH flash flood rain events including the November 1996 and November 2009 events. The section ‘Implications for flash flood warnings’ discusses the implications for flash flood warning systems and a summary and conclusions section is then presented.

Data

In addition to Australian Bureau of Meteorology (BoM) rainfall observations, several rainfall recording sites within the CH creek catchment owned by the CH City Council are used to analyze rainfall totals over the period of the study. Mesoscale meteorological analyses of the CH and surrounding area just prior to and following the heaviest rain on 31 March are derived from BoM MSLP data. BoM synoptic-scale analyses of MSLP and other derived tropospheric variables from the limited area prediction system (LAPS), MesoLAPS (a higher-resolution version of LAPS) and the European Centre for Medium Range Weather Forecasting (EC) are utilized in describing the setting of the general three-day rain period and also the day of the heaviest rain (31 March) in the following section. LAPS was the BoM’s Australian region limited area prediction model detailed in Puri et al. (1998) and at the time was running at 37.5 km horizontal resolution with 61 vertical levels. The southeast Australian domain of the higher resolution MesoLAPS version of LAPS was operating at 12.5 km horizontal resolution with 29 vertical levels. At this model resolution the topography of the hills immediately to the west of CH is only broadly depicted (see Fig. 12(a) in Speer and Leslie 2000 for a depiction of 8 km model resolution topography). The EC is a global atmospheric model with the version running over Australia at the time equivalent to about 25 km horizontal resolution and 91 vertical levels. Comprehensive documentation of this analysis and forecasting system is given at http://www.ecmwf.int/products/forecasts/guide.

In the section ‘model guidance’ predicted and derived fields from the same models based at 1200 UTC 30 March 2009 and earlier are analyzed in helping to determine key guidance to forecasters on 31 March 2009, the day on which the heaviest rain occurred. In addition, rainfall predictions for 31 March 2009 available to forecasters called the ‘Poor Man’s Ensemble’ (PME) are discussed. The PME is based on a probability-matched mean approach to combine precipitation fields from the models of seven different national weather services (including LAPS) to arrive at a consensus prediction (Ebert 2001).

Meteorological analysis

Synoptic-mesoscale overview

Showers occurred on the NSW north coast from 28 March 2009 and warnings were current for general river flooding as a result of a persistent, moist southeast air stream generated between high pressure over the Tasman Sea and a low pressure area near New Caledonia. At 0000 UTC 29 March, a surface pressure trough was analyzed in the southeast air stream near 160° E over the northern Tasman Sea (Fig. 2(a)).
The trough moved west and by 0100 UTC 31 March, it had intensified such that a low was analyzed within it adjacent to the NSW north coast (Fig. 2(b)). The heaviest rain over the Coffs Harbour (CH) Creek catchment occurred between 0100 UTC and 1200 UTC on 31 March. During this time the vertical structure of the low and trough system reached its maximum intensity over the NSW north coast. At 0100 UTC 31 March, the MSLP mesoscale manual analysis shows a broad low pressure trough in the easterlies over the NSW north coast and a small low just north of CH (Fig. (3)). By 1000 UTC 30 March, the surface wind at CH was southeast averaging near 40 km/h gusting to around 60 km/h. This wind direction and strength was maintained until 0100 UTC 31 March when it turned southwesterly and decreased to about 20 km/h, gusting to 30 km/h. Generically, this change in wind direction and speed is indicative of a trough moving onshore in an easterly wind regime. Speer and Geerts (1994) described a similar mechanism in reference to several Sydney metropolitan area flash flood events.

The heaviest rain on 31 March at Red Hill occurred between 1200 EST (0100 UTC) and 2100 EST (1000 UTC) (Fig. 4(a)) and a few hours later further south and west at Dorrigo and Bellingen on the Bellingen River (Figs. 4(b) and (c)). By 2300 EST (1200 UTC), the surface wind at CH was westerly about 10 km/h, implying that a circulation within the trough had passed to the south (Fig. 4(d)). At 1500 EST (0400 UTC) the 850 hPa and 700 hPa observed winds were east-southeast at about 60 km/h and 80 km/h, respectively. The upper-level trough over eastern Australia and the surface low/trough system over the NSW north coast were reaching maximum intensity as a system sloping westward with height. This intensification occurred as the upper-level jet strengthened and dipped polewards and westwards towards the NSW coast. As a result there was a maximum in upper-level divergence in the right exit region of the jet in a band about 100 km south of CH (Fig. 5(a)) implying convergence in the low to mid-tropospheric levels (Figs. 5(b)). This large-scale lifting mechanism enhanced the twenty-four hour rainfall totals southwest of CH (see Bellingen and Dorrigo in Figs. 4(b) and (c)). Further north, strong surface southeasterly winds onto the hills of the CH creek catchment close to the coast were deflected to the southwest owing to the orientation of the hills as the surface trough and low moved west over the coast, thereby creating enhanced confluence and convergence with the moist, southeast winds. The southwesterly surface flow also enhanced the backing of the wind with height (and implied ascent through warm air advection) further enhancing the low-level ascent, very close to the time when the heaviest rain commenced at Red Hill. Cells were able to remain anchored over the hills, as northwesterly winds above 300 hPa provided an uninterrupted outflow region for the ascending air mass.
Fig. 4 Hourly recorded rainfall covering the twenty-four hours from 2400 EST (1300 UTC) 30 March to 2400 EST (1300 UTC) 31 March 2009 for: (a) Red Hill; (b) Dorrigo; (c) Bellingen; and (d) Coffs Harbour wind speed (red) and direction (blue) for 31 March 2009, indicating a shift from southeast to southwest winds by 1200 EST (0100 UTC), about the time of the start of the heaviest rain at Red Hill (histogram chart), and a shift to westerly by 2100 EST (1000 UTC), indicating the trough had moved inland.

Fig. 5 (a) LAPS derived divergence analysis ($10^{-5}$s$^{-1}$) at 300 hPa for 0000 UTC 31 March 2009. Divergence is indicated within solid contours. Convergence is indicated within dashed contours. Selected contour values are labelled (interval = $2 \times 10^{-5}$s$^{-1}$ except where maximum value is shown). LAPS wind speed and direction analysis is also indicated. (b) LAPS derived vertical motion analysis (Pa s$^{-1} \times 10^{-1}$) at 850 hPa for 0000 UTC 31 March 2009. Upward vertical motion is indicated by negative values. Selected contour values are labelled (interval = 4 Pa s$^{-1} \times 10^{-1}$).
Model guidance
Both the BoM’s LAPS and MesoLAPS +48 h MSLP forecasts for 0000 UTC 31 March 2009 (Figs. 6(a) and (b)) indicated only the Coral Sea low without the easterly trough development further south. The initial movement of the easterly trough towards the NSW north coast and subsequent MSL low pressure development within it over the coast was best shown by the EC forecast. Both the EC +48 h and +24 h MSLP forecasts for 0000 UTC 31 March (Figs. 6(c) and (d) respectively) show the deepening trough just north of CH and closely match the manual analysis at 0100 UTC (Fig. 3). Subsequent EC +3 h MSLP forecasts based at 1200 UTC 30 March also showed the westward moving trough and low crossing the coast (not shown), although about 3 to 6 h faster than observed. Both LAPS and MesoLAPS +24 h MSLP model predictions were similar to the +48 h forecasts and so are not shown.

Each six-hourly LAPS 700 hPa vertical motion forecast based at 1200 UTC 30 March placed the maximum upward vertical motion 100 to 200 km south of CH (Figs. 7(a)–(d)). The reason for this is that the upper-tropospheric forcing mechanism of maximum divergence was produced in the same area at 300 hPa under the right exit region of the jet maximum. This can be seen in the LAPS analyses (Figs. 7(b), (c) and (d)) and most likely explains why the maximum +24 h forecast LAPS rainfall is indicated for the same location—that is, about 100 km further south, well away from the heavier, topographically induced convective rain on the hills just west of CH (Fig. 8(a)). The higher-resolution twenty-four hour MesoLAPS forecast rainfall based at 1200 UTC 30 March indicates 160 to 200 mm in the same location (Fig. 8(b)). The EC +24 h forecast rainfall placed the main maximum well east of the coast (Fig. 8(c)) while the +24 h PME forecast rainfall guidance produced a maximum between 100 to 150 mm over the CH area (Fig. 8(d)). The LAPS +48 rainfall forecast with a maximum over 200 mm located just west of CH (Fig. 9(a)) verifies much better than the location of a similar maximum value further south at +24 h (Fig. 8(a)). Similarly, the MesoLAPS +48 h rainfall forecast (Fig. 9(b)) with a maximum around 280 mm just west of CH verifies much better than the +24 h forecast (Fig. 8(b)) with its maximum about 400 mm well south of CH. The +48 h EC

Fig. 6   (a) LAPS +48 h MSLP forecast (hPa) for 0000 UTC 31 March 2009. (b) As in (a), except for MesoLAPS. (c) As in (a), except for EC. (d) EC +24 h MSLP forecast (hPa) for 0000 UTC 31 March 2009.

(a)  
(b)  
(c)  
(d)
rainfall forecast (Fig. 9(c)) is similar to the +24 h EC forecast (Fig. 8(c)) in that the maximum is well east of the coast. The PME +48 h rainfall forecast (Fig. 9(d)) produces a maximum (150 to 200 mm) very near to CH just as the +24 h forecast indicated a maximum (100 to 150 mm) over CH. In other words, the spatial guidance provided by the PME was more consistent at both +48 h and +24 h, than LAPS, MesoLAPS or EC.

Comparison with recent Coffs Harbour flash flood events

A comparison of the 31 March 2009 flash flood event is now presented with the 23 November 1996 event and more briefly with an event on 6 November 2009. There were notable similarities between the two events of 31 March 2009 and 23 November 1996. These included strong, moist onshore winds with cloud that appeared to remain anchored over the hills to the west of CH and low static stability provided by a mid-tropospheric trough to the west. In the November 1996 event, Speer and Leslie (2000) comment that, in addition to the focusing of the heavy rain by the adjacent hills, CH was also in an area of strong, upper-tropospheric divergence created by the right exit region of a jet maximum. In the November 1996 event the +12 h model maximum upward vertical velocity at 850 hPa was located over the CH catchment, whereas in the March 2009 event, the maximum model forecast upward vertical velocity for 850 hPa at the time of the heaviest rain was located about 100 km further south (see Fig. 5(b)).

For the 6 November 2009 event, 367 mm of rain was recorded at Perry Drive (about 3 km west of CH) in the eleven hours from 0600 UTC (1700 EST) 6 November until 1700 UTC (0400 EST, 7 November) (Table 2). This rainfall was enough to cause the CH creek to peak at 4.3 m (compared to 5.1 m on 31 March when 307 mm was recorded in six hours at Red Hill). In this case there was no tropospheric trough to the west and hence no enhanced large-scale mid-tropospheric lift. A possible explanation for the lower rainfall in this case, is that while the heaviest rain fell on the highest topography, it did not remain anchored owing to a more uniform

Fig. 7 (a) LAPS derived vertical motion forecast at 700 hPa (Pa s^{-1} \times 10^{-1}) for 1800 UTC 30 March 2009. Upward vertical motion is indicated by negative values. Selected contour values are labelled (interval = 4 \text{ Pa s}^{-1} \times 10^{-1}). (b) as in (a), except for 0000 UTC 31 March 2009. (c) as in (b), except for 0600 UTC. (d) as in (c), except for 1200 UTC.
northeasterly wind direction with height. This vertical wind structure advected the rain towards the southwest along the topography. The key feature in differentiating the 31 March 2009 event and 23 November 1996 event was the location of the large-scale vertical motion positioned well south of CH on 31 March 2009 compared to over the CH area itself on 23 November 1996. While a mid-tropospheric trough to the west was present in both cases, the position of their large vertical motion fields was determined by the dynamics of the jet stream structure in each case.

Implications for flash flood warnings

The small size of the catchment which includes the hills just a few kilometres from the coast makes CH a vulnerable location for severe flash flooding when heavy, continuous rain occurs. A similar location vulnerable to short duration heavy continuous rain is along the escarpment of the Great Dividing Range near Wollongong and Dapto south of Sydney. For this location, Shepherd and Colquhoun (1985) describe the topographical influence as the prime mechanism for generating about 600 mm in the eight hours between 0400 UTC (1500 EST) and 1200 UTC (2300 EST) on 18 February 1984. Prior to this event the heaviest rainfalls in Australia for most durations have been in tropical areas.

As mentioned in the introduction, the 31 March 2009 event occurred after several days of rain over the catchment. Prior to the 23 November 1996 event there was one day of rain (93 mm at Coffs Harbour Meteorological Office). The antecedent soil moisture conditions may have enhanced the rainfall runoff for both these events and is another factor in addition to the small size and steep nature of the catchment in considering whether severe flash flooding is likely to occur. From a meteorological perspective, to alert forecasters to the possibility of issuing a flash flood warning for the CH creek catchment requires an assessment from model forecast guidance of the ingredients discussed in the ‘Meteorological analysis’ section.

Fig. 8  (a) LAPS model derived twenty-four hour rainfall forecast (mm) for the period 1200 UTC 30 March to 1200 UTC 31 March 2009 based at 1200 UTC 30 March. (b) as in (a), except for MesoLAPS. (c) as in (a), except for EC. (d) PME +24 h rainfall prediction for 1200 UTC 30 March to 1200 UTC 31 March 2009.
November 1996 event and the March 2009 event had common key atmospheric ingredients that should raise the awareness of forecasters. These key ingredients consist of strong and convergent low-level, moist onshore airflow combined with a mid-tropospheric trough to the west. The topography provides enhanced low-level lift to the moist convergent airflow. The low-level airflow is typically strong southeasterly (60–80 km/h in the low levels) turning lighter southwesterly close to the surface and backing through the north in the mid- to upper levels. These sources of low-level lift (topography, convergence and a backing wind profile implying ascent through warm air advection), can be further enhanced by mid-tropospheric lift as a result of the divergence created by the right, exit region of the upper jet maximum. The mid-tropospheric trough provides low static stability with the potential for deep, moist convection or thunderstorms and an efficient northwesterly outflow wind regime in the upper troposphere. A conceptual model of these processes is illustrated schematically in Fig. 10. Many of the synoptic-scale ingredients identified here are similar to those documented in other heavy rain producing systems affecting the east coast of Australia (e.g. the conceptual model proposed by Mills et al. (2010, p 27), based on the common upper-tropospheric characteristics of a number of previous East Coast Low events).

Table 2. Rainfall recorded between 1700 EST (0600 UTC) 6 November and 0400 EST 7 November 2009 (1700 UTC 6 November) at Red Hill, Perry Drive and Shepards Lane.

<table>
<thead>
<tr>
<th>Location</th>
<th>Total rainfall (mm) in the 11 hours between 5.00 pm 6 November and 4.00 am 7 November 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perry Drive</td>
<td>367.5</td>
</tr>
<tr>
<td>Red Hill</td>
<td>304.0</td>
</tr>
<tr>
<td>Shepards Lane</td>
<td>284.0</td>
</tr>
</tbody>
</table>
In terms of model forecast rainfall guidance, both the spatially consistent +48 h and +24 h PME forecast rain amounts (150–200 mm and 100–150 mm, respectively) were approximately one third the maximum observed twenty-four hour rainfall total at Red Hill (445 mm), which is located on the hills a few kilometres to the west of CH. The PME forecasts based twelve and twenty-four hours earlier for the same period were spatially consistent (not shown). LAPS and MesoLAPS rainfall forecasts showed that the rainfall maxima were located south of CH. In the LAPS rainfall forecast for the CH flash flood event of 23 November 1996, the forecast maximum was also located to the south (Speer and Leslie 2000). MesoLAPS and PME forecasts were not operational at that time.

A subsequent event on 6 November 2009 with rainfall 367 mm (Perry Drive) exhibited similar dynamic features except for the lack of a mid-tropospheric trough to the west. The key model diagnostics identified in this paper provided excellent guidance to forecasters in this instance.

**Summary**

On 31 March 2009 severe flash flooding in CH resulted from short duration, heavy rain in the CH creek catchment. The insurance costs associated with damage and disruption from this event and a similar event in November 1996 ran into tens of millions of dollars. The aims of this study were twofold: firstly, to highlight to forecasters the key synoptic and mesoscale mechanisms; and secondly, to focus on the most important model forecast guidance in relation to the CH Creek catchment. Specifically, forecasters should be alert in synoptic situations where there is strong, low-level, moist, convergent airflow onto the hills just west of CH. The key model diagnostics and forecast fields identified here are surface/low-level convergence in a trough such as that implied by the EC model forecast MSLP and which is enhanced by lift over the coastal orography accompanied by upper-tropospheric divergence and low static stability from a mid-tropospheric trough to the west as depicted by the LAPS model, rainfall totals of about 400 mm in less than six hours and the possibility of rainfall underestimates of approximately 1/3 the PME 24 h and 48 h totals. The model diagnostics also imply that deep, moist convection or thunderstorms are likely to occur over the topography. For the 31 March 2009 event and the 23 November 1996 event a mid-tropospheric trough to the west of CH over eastern Australia provided low static stability, and the resulting vertical wind structure over the CH creek catchment would have aided ventilation of updrafts and hence also precipitation efficiency.

For the March 2009 and November 1996 flash flood rainfall events, the ensemble-based rainfall predictions provided the most reliable guidance in terms of spatial consistency. A multiple of about three times the maximum PME forecast is suggested as a general guide to forecasters.

The reasons for model underestimation of rainfall totals—particularly intense, short duration rainfall totals—and errors in location of rainfall maxima can only be determined from a detailed modelling study. However, poor horizontal and vertical resolution of model physical processes and topography are likely to be factors.

**References**


