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The Sydney Hailstorm of April 14, 1999: Synoptic description and numerical simulation

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With 10 Figures

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Summary

During the evening of April 14, 1999 an intense hailstorm struck the most densely populated region of Australia, the eastern suburbs of Sydney. This thunderstorm, which transformed into a high precipitation supercell when it moved into a region of enhanced surface moisture convergence and increased helicity on the coast, maintained its identity for 5.5 hours. It produced the largest verified hail in Australia's history with the biggest stones being 11 cm in diameter. A microburst was recorded at Sydney Airport. The damage inflicted by this hailstorm was immense with three deaths, numerous injuries and insured losses exceeding $1.7 billion Australian dollars. This storm is the most expensive Australian natural disaster since severe weather records commenced in 1975.

The thunderstorm initially formed from surface heating of relatively dry air in a low shear environment but was advected by middle level west to south westerly winds into a region where the surface to 500 hPa wind shear had increased to $17\,\mathrm{ms}^{-1}$ west south westerly. The storm relative helicity in this region was $-180\,\mathrm{m}^2\mathrm{s}^{-2}$, in the layer between the surface and 700 hPa. Diagnostics from the 1500 Australian Eastern Standard Time (AEST) radiosonde released from Sydney Airport, 150 km north of where the thunderstorm initially formed, are thought to be representative of the pre-storm environment. The Convective Available Potential Energy (CAPE) was moderately high at 1713 J/kg with a relatively low Convective Inhibition (CIN) value of 50 J/kg. The Total Totals Index (TT) was 55 and the Surface Lifted Index (SLI) was -5.5, capable of supporting severe convection. The freezing level was at 2900 m, near average for the time of the year. Convective cloud tops would be expected to reach the tropopause at 250 hPa. The coastal environment was assessed as being able to support a supercell thunderstorm.

A preliminary high resolution numerical simulation of the severe thunderstorm has been conducted. The model was triply nested, with its highest resolution grid spacing being 1 km. It incorporates a multi (six) water – ice phase microphysics, enabling it to simulate hail growth associated with supercell developmet. The initial generation and subsequent northward propagation of a hail-producing thunderstorm are captured in this simulation.

1. Introduction

Severe thunderstorms, most notably supercells, are a recurring cause of severe weather across New South Wales (NSW), with significant impacts on Australia's largest city, Sydney (see Fig. 1 for location of places mentioned in this study). Severe phenomena associated with these storms (tornadoes, hail 2 cm in diameter or greater, wind gusts in excess of 48 knots ($23\,\mathrm{ms}^{-1}$), flash floods defined as a one in 10 year one hour rainfall) permit only short lead time warnings, issued by meteorologists who are severe thunderstorm specialists.

April is not a month when large hail is likely in Sydney. The hailstorm that is the subject of this study occurred on April 14, 1999, outside the NSW severe thunderstorm season of October to March. The synoptic situation prevailing at the time was significantly different from other Sydney supercell situations experienced over the past

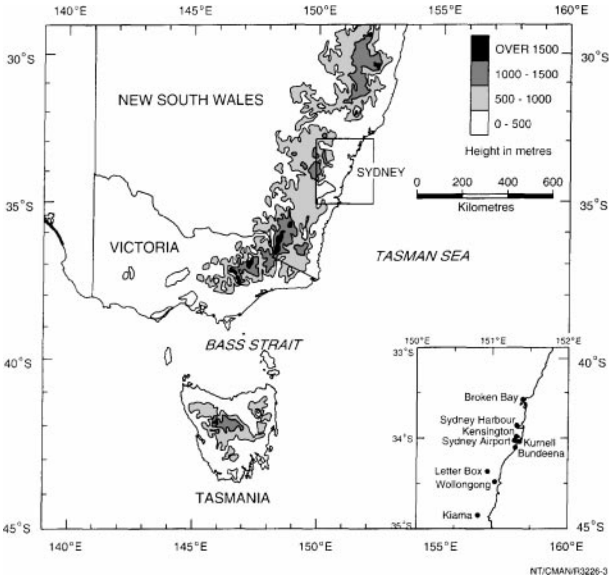


Fig. 1. Location map of south eastern Australia

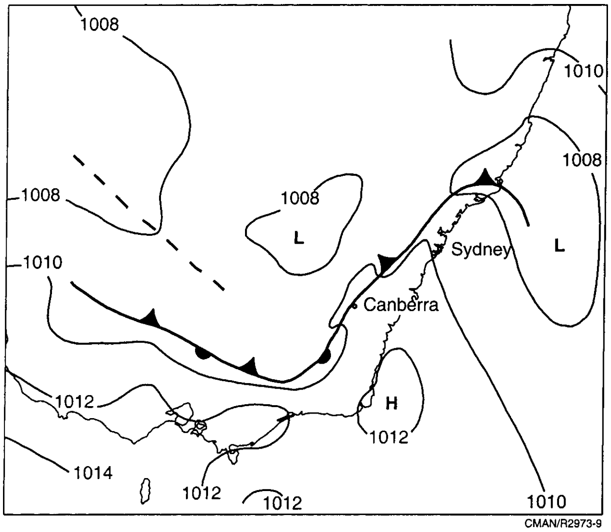


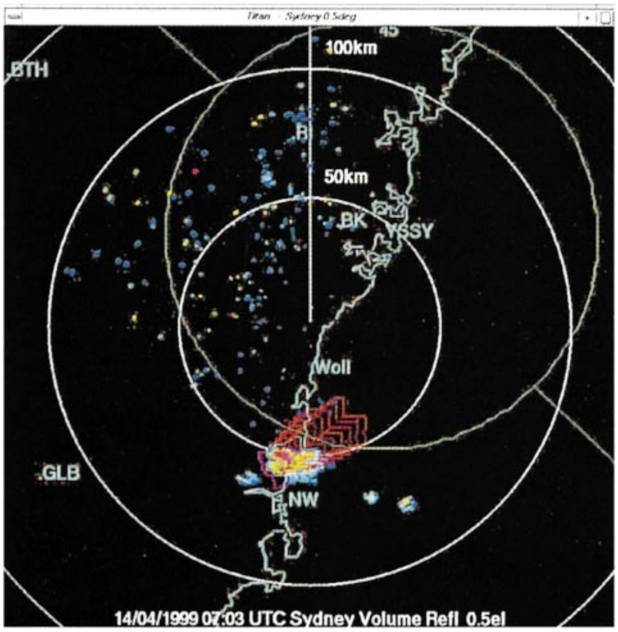
Fig. 2. Synoptic situation for the January 21, 1991 supercell thunderstorm

decade. Figure 2 shows the synoptic situation for 0900 Australian Eastern Standard Time (AEST) on the day of the very destructive January 21, 1991 (Bureau of Meteorology 1997) supercell, more "typical" of a severe weather pattern over the central NSW coast.

Late in the afternoon of April 14, 1999 a thunderstorm was identified on radar, south west of the town of Kiama, 120 km south of Sydney. Subsequent radar images (see Fig. 3a–c) showed the storm moving towards the northeast, being steered by the west to south westerly middle level environmental airflow that prevailed across the area. The storm moved over the Tasman Sea where its structure changed abruptly. The thunderstorm became a high precipitation supercell (Moller et al., 1990) and began to move at approximately 30° to the left of the environmental steering flow. The altered path of the supercell thunderstorm brought it over the populous eastern suburbs of Australia's largest city, Sydney. The storm also passed over Australia's principal airport, Sydney Airport, during the evening peak period (see Fig. 3b). It reached peak intensity soon after (Fig. 4a), with the radar cross section (Fig. 4b) showing its structure at this time. In a five-and-a-half hour period giant hail of up to 11 cm diameter from the storm created a path of destruction that led to the death of three people and produced an insured damage bill in excess of \$1.7 billion Australian dollars, making this thunderstorm the most expensive natural disaster, in dollar terms, in Australia's recorded history.

Although numerical model data has been employed in NSW to identify broad areas of increased potential for severe thunderstorm development (Mills and Colquhoun, 1999), to date no numerical technique has been available that directly simulates the growth of large hail. There have been numerous successful simulations of supercells in other countries such as the USA and Europe and these are discussed briefly below. However, the purpose of the present study is to concentrate on the simulation of a supercell in the Australian operational context. We therefore simply point to a number of key references and discuss briefly how they differ from our aims. Lack of detailed surface and upper air observations are a serious impediment to the successful simulation of locally severe convection in the Australian environment. To achieve our goals, time is required to move this technique into operations. The numerical modelling capacity is almost available, and is expected to take a further two to three years.

In Sect. 2, the climatology of severe thunderstorm events in NSW, with particular attention given to the Sydney area, is summarized in order to better understand the rarity of the April 14 hailstorm. The details of the hailstorm event and its impacts are outlined in Sect. 3, with the



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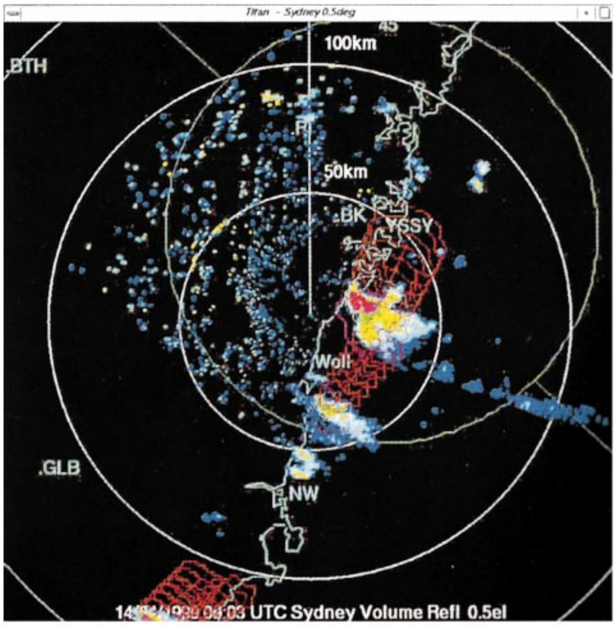

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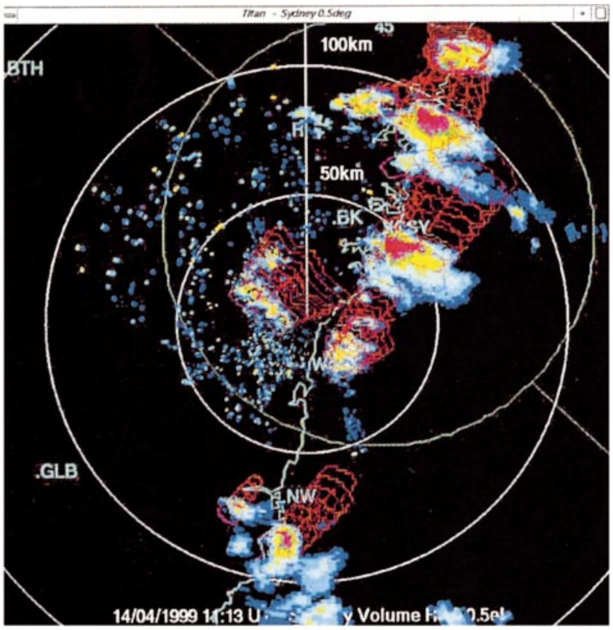

c

Fig. 3. Radar plan position indicator images from the Letterbox radar showing the severe thunderstorm and other convection during April 14, 1998 at the following times: **a** 1700 AEST; **b** 1900 AEST; and **c** 2100 AEST. The red outlines are nowcast positions at 10 minute intervals

synoptic influences that triggered the storm discussed in Sect. 4.

The hailstorm was poorly predicted in real-time by the Bureau of Meteorology. In an attempt to increase the lead-time and predictability of future storms of this type, a high resolution post-event numerical simulation was carried out for the eastern seaboard of central NSW, covering the full life cycle of the severe thunderstorm. This investigation constitutes the first attempt to do so for eastern Australian supercell thunderstorms. The numerical simulations are described in Sect. 5. Conclusions and areas requiring further research are discussed in Sect. 6.

Elsewhere, notably in the USA, Europe and Asia, mesoscale numerical models models have been used for several decades to simulate severe convective systems. For brevity we confine our short summary of these simulations to research and operations in the USA. Amongst the earliest

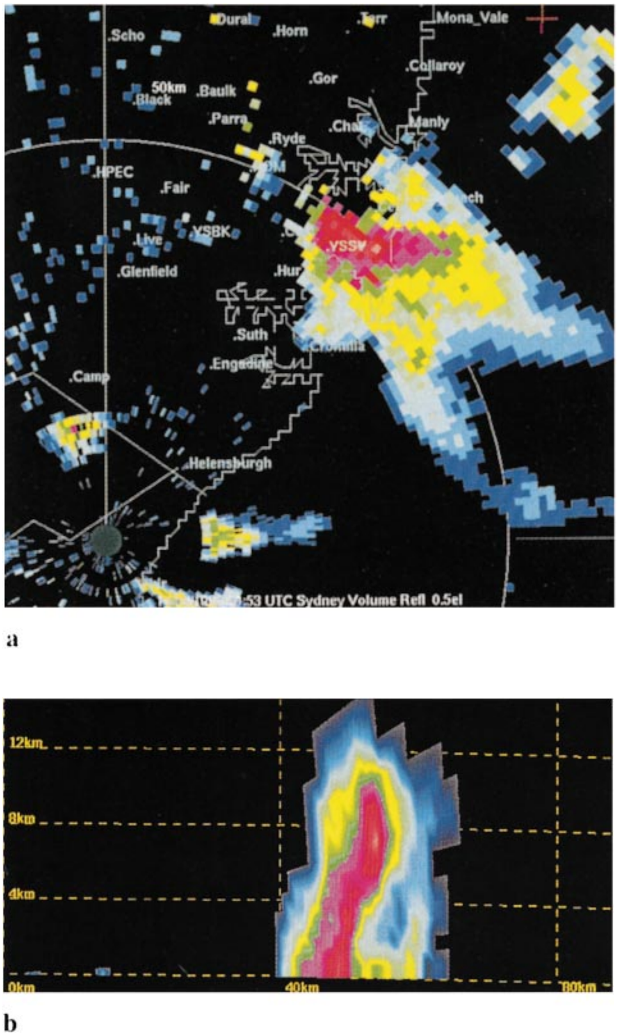

Fig. 4. Radar plan position indicator and corresponding range height indicator images from the Letterbox radar showing **a** plan, and **b** elevation views of the severe hailstorm at peak intensity (1920 AEST)

mesoscale simulations of severe convection, were those of Klemp and Wilhelmson (1978), and Zhang and Fritsch (1986). Since that time much progress has been made in the modelling of severe storms. In the context of this paper, modelling of severe convection is divided into two categories. The first category is the very high resolution modelling (1 km down to 100s of metres) of the life cycles of specific severe convective systems such as individual supercells, squall lines and local circulations that produce very heavy rainfall. Excellent results have been achieved and as the studies are far too numerous to mention, we refer only to a very small selection of these. We refer to only a small selection of these (e.g., Jewett and Wilhelmson, 1996; Davis et al., 2000; and Guo et al., 2000). The second category, within which the model used by the present authors fits, is the mesoscale modelling of severe convection on horizontal scales of approximately 5 to 15 km. This category is probably best referred to as mesoscale NWP. The aim of this approach is the routine prediction, in real-time, of severe convection over relatively large areas. In many cases the models are either located at major NWP centres or are community models such as MM5, ARPS, RAMS, COAMPS, Meso-ETA and MASS models. These model acronyms are so well known that there is no need to further define them or to provide individual references for each of these systems. Mass and Kuo (1998), and Kuo (2000) provide an overview of these models.

Our study fits squarely into the second category of a mesoscale NWP model adapted for real-time operational usage. As such, as far as the authors are aware, this simulation is the first successful attempt of this kind to be carried out using a model developed in Australia. We report on it here for that reason and also because of the singular importance of the hailstorm and as one of the early products of our program of research and operations in the modelling of severe convection in Australia.

2. Climatology of severe thunderstorms in New South Wales

Severe thunderstorm reports used to generate climatologies, including hail size, are largely supplied by a 1,300 strong volunteer storm spotter network. This network, sparse away from the main urban areas, is quite substantial across the city of Sydney itself. Additional reports are supplied by the Bureau's paid observers with wind and rain information provided by a network of approximately 100 automatic weather stations. April is a month when severe thunderstorms are uncommon in New South Wales, as illustrated in the histogram in Fig. 5a, which shows the occurrence of severe thunderstorms for NSW, of all types, by month. This is particularly the case for Sydney. The severe thunderstorm season for New South Wales, including Sydney, is defined as the start of October through until the end of March. The marked seasonality of large hail for

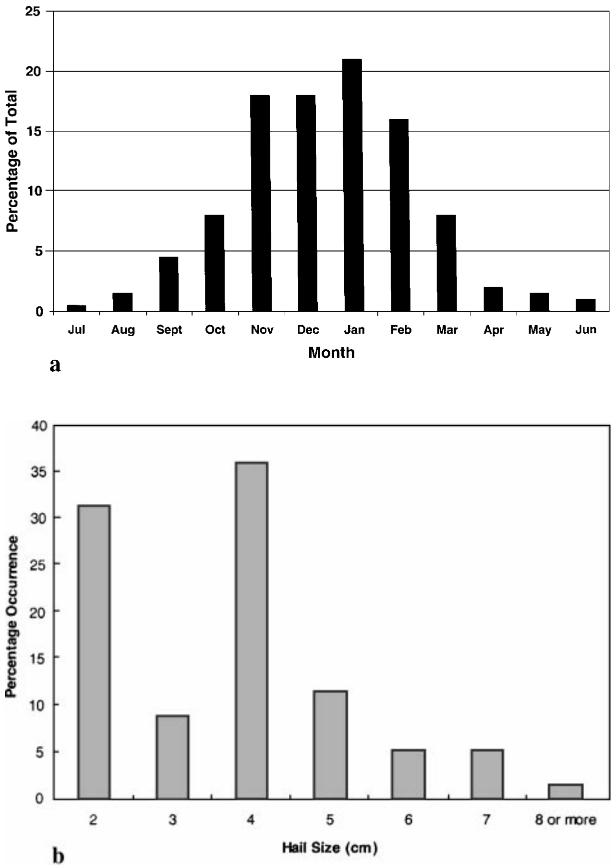

Fig. 5a. Histogram illustrating the climatology of severe thunderstorms in the state of New South Wales; **b** Histogram illustrating the climatology of hail size across Sydney

Sydney is clearly evident from the figure. The climatology of hail size, showing the relative number of events where large or giant hail has occurred in the Sydney metropolitan area, is given in Fig. 5b. Large hail is defined as having a diameter of 2 cm or greater. Giant hail has a diameter of 5 cm or greater. Giant hail is reported on approximately 25% of severe hailstorm events in Sydney. The peak month for large hail in NSW is December with the greatest number of reports of giant hail occurring one month earlier in November. The tendency for large hail to be reported in the first half of the severe thunderstorm season is attributed to the fact that incursions of middle level cold pools of polar origin in a moderately sheared environment are more common during the transition period from winter through to summer. During this time NSW falls under the influence of thermal troughs associated with mid-latitude frontal systems that progressively retreat southwards as summer approaches. This also is the time of the year when the highest values of CAPE (Moncrieff and Green, 1972) are likely. The latter half of the severe thunderstorm season is characterized by a low shear environment with few cold pools present. Prior to this event there had been only one report of large hail in Sydney during the month of April, a report of 2.5 cm hail in 1994. There have only been three reports of giant hail in all of NSW during the month of April. However, severe hailstorms are a recurring feature of the weather in the Sydney basin, particularly during the warmer months. The hailstorm was the seventh to produce hail with a diameter of 6 cm or greater in Sydney this decade, with other storms occurring on March 6 and 18, 1990, January 21, 1991, February 12, 1992, October 28, 1995 and November 12, 1997. Unlike the six other severe thunderstorms that initially formed on the ranges inland from the eastern coast of Australia and then moved north east across Sydney, this storm moved towards the north north east, approaching Sydney from over the Tasman Sea. There has been no other severe hailstorm in Sydney's recorded history that has followed a similar track.

3. The hailstorm of April 14, 1999

April 14, 1999 began with calm winds and scattered middle and high-level cloud. Surface dew points were moderate at around 18 °C at 0600 AEST. There was no pre-existing convection evident in Sydney or the surrounding regions on the weather watch radars that provide weather surveillance across this region.

Weather radar coverage of the greater Sydney region in provided by two radars. The first is a 1.8° beam-width S Band radar located at Letterbox Hill, some 60 km to the south of the city. This radar provides continuous weather watch coverage for the greater Sydney area. This coverage is complemented by a 0.9° beam-width C Band Doppler radar located at Kurnell, 15 km south of the city. The latter radar is newly installed specifically to provide enhanced monitoring of evolving wind and precipitation fields near Sydney, with particular emphasis on monitoring the pre-storm environment. They both operate in a volumetric scan mode, scanning at 15 different

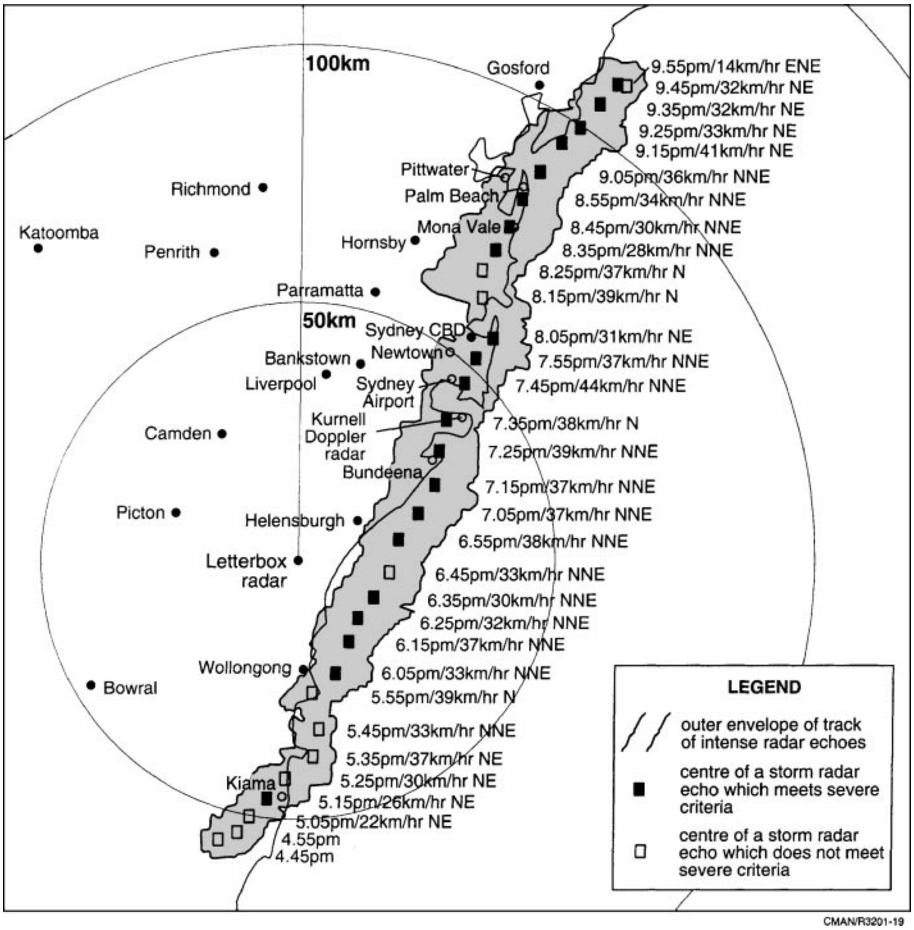

Fig. 6. Path of the thunderstorm, derived from the surface projection of the most extensive 35 dBZ radar reflectivity contour as viewed by the S Band weather watch radar located at Letterbox

radar tilt angles, with a 10 minute repetition period.

The earliest radar signature for this thunderstorm was at 1625 AEST on the afternoon of April 14, 1999. The storm was located to the south west of the town of Kiama, with Fig. 6 illustrating the radar derived path of the storm cell as defined by the surface projection of the volumetric 35 dBZ reflectivity contour. This contour was selected so as to eliminate less significant convective activity from the display, a technique routinely used in severe thunderstorm forecasting in NSW. The central box provides a simple measure of the intensity of the thunderstorm for each volume scan. If the 49 dBz radar reflectivity contour, as measured by the S Band radar at Letterbox, reaches 8 km above sea level the box is shaded, otherwise it is left open. This criterion was selected because locally it has been identified that the threshold for large hail occurs when the 49 dBZ contour attains a height of 8 km above sea level, with the reflectivity contours being displayed in 3 dBZ intervals on operational displays. It should be noted that there were two radar scans which depicted the initial stages of convection that are not shown on this track due to the lack of a 35 dBZ contour at this stage of the storm's development. It was the first thunderstorm to develop that day, although there had been short-lived towering cumulus development over the land areas east of the ranges throughout the afternoon. The storm initially moved towards the north east until it reached the warm waters of the Tasman Sea. Sea surface temperature (SST) measurements from an instrumented wave rider buoy moored 3 km off the Sydney coast indicated the 1 metre depth water temperature was 23.6 °C. At this point the thunderstorm structure transitioned rapidly into that of a high precipitation supercell, as shown in the radar image from the Letterbox radar in Fig. 3a. Its movement altered towards the north north east. The thunderstorm, now severe, moved

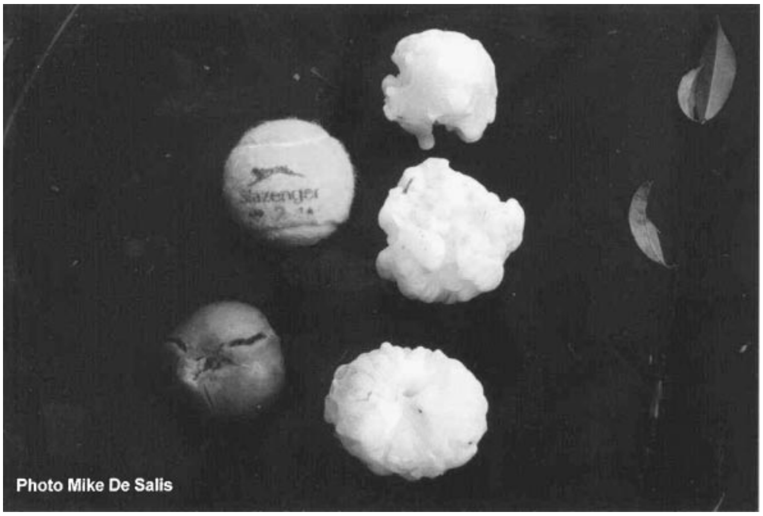

Fig. 7. Photograph comparing hail, of diameter up to 8.5 cm with a tennis ball and damaged apple (photo courtesy of Mike De Salis)

across the town of Bundeena then over Sydney's International Airport (see Fig. 1). Hail up to 8 cm in diameter fell in this area (see Fig. 6), rendering 23 commercial aircraft insufficiently airworthy for commercial flight operations. The storm reached peak intensity as it moved over the Sydney suburb of Kensington towards the city centre. The Letterbox radar Plan Position Indicator (PPI) and Range Height Indicator (RHI) scans for this time are shown in Fig. 4a,b. Peak reflectivity values in the vicinity of 65 dBZ were recorded at this time and the 49 dBZ contour attained a height of 10.5 km above ground level. The extensive suspended hail and overhang are quite clearly visible in the RHI. It was in this area that the largest confirmed hail over to fall in Australia was reported, with a maximum diameter of 11 cm.

A significant regeneration occurred on the left flank of the thunderstorm as it moved to the northern side of Sydney Harbour. The very early stages of this cell can be seen as the small cell located approximately 10 km to the north west of the major cell in Fig. 4. No additional surface or upper air information is available to fully explain the mechanisms behind the regeneration of this new but less severe supercell. However, careful study of the sequence of radar images has concluded that this regeneration was triggered by the enhanced convergence from the confluence of the downdraft produced by the large hail-fall with the warm, moist air associated with the leading edge of the low level southeasterly change. This left flank development would also have been favoured by additional lift provided by the rising topography in this region. Although less intense from this point onwards, the storm continued to produce large hail until the thunderstorm eventually moved offshore near Broken Bay, some five and a half hours after it was first detected. Such longevity of an individual thunderstorm is unusual for New South Wales, even for a supercell.

The damage the hailstorm produced during its passage of the eastern suburbs of Sydney was huge. Figures from the Insurance Council of Australia (Henri 1999, personal communication, July 1999) placed the insured damage bill in excess of $1.7 billion Australian dollars. Three deaths were attributed to this thunderstorm. An estimated 170,000 people were adversely affected by the hailstorm. The emergency clean-up operation was one of the largest in Australia's history. Volunteers from the State Emergency Service unit in NSW were fully committed for several weeks, with the personnel from the NSW Rural Fire Service contributing 215,000 hours of effort to the clean-up. The response effort was estimated by the emergency services to be eight times greater than the previous largest severe thunderstorm response effort required in New South Wales.

4. Synoptic description

The broad scale synoptic situation during April 14, 1999 was relatively benign, as is shown in the 1600 AEST mean sea-level pressure analysis of Fig. 8a. The pressure gradient across the central NSW coastline was weak. The tail end of a cold

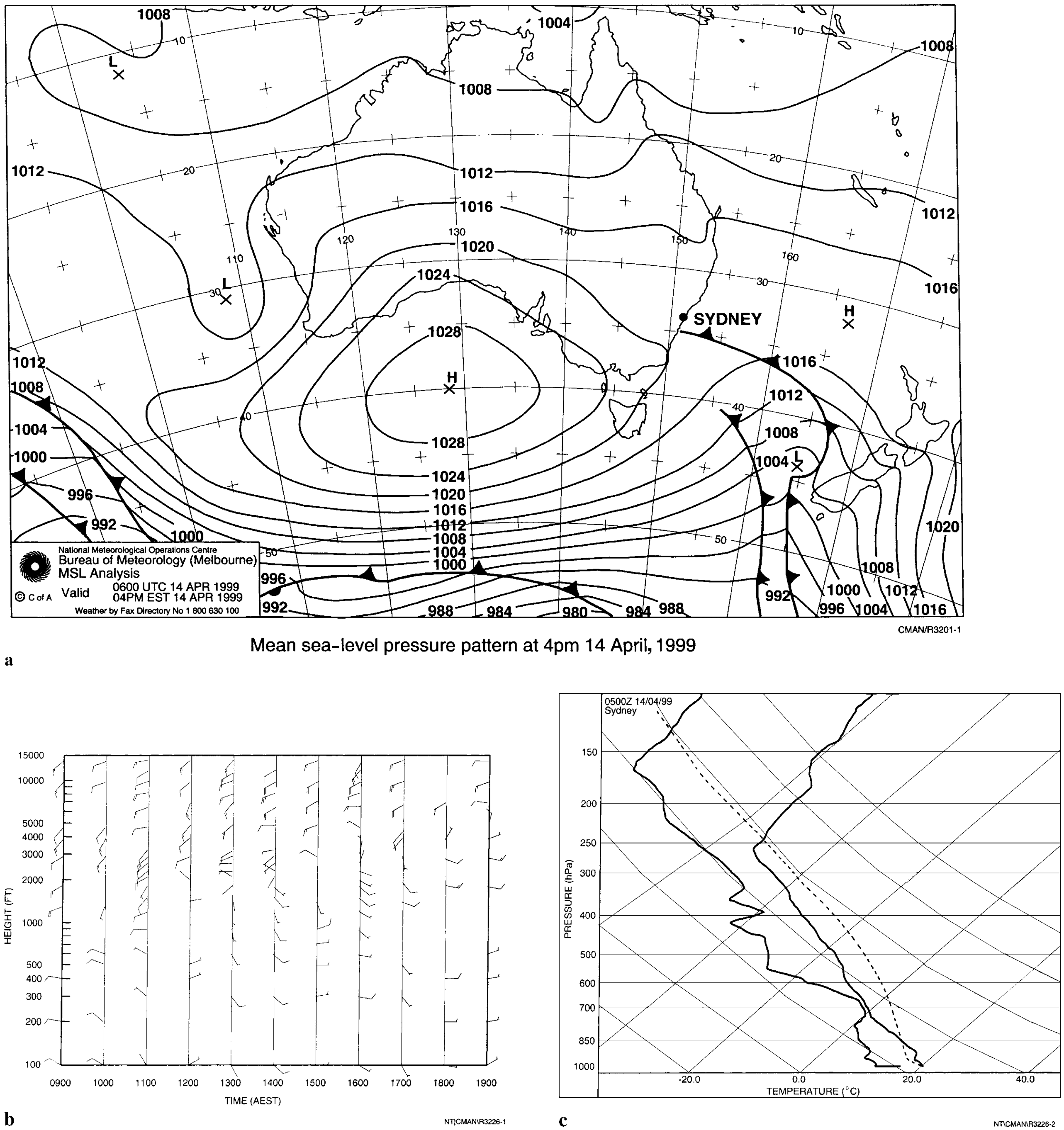

Fig. 8a. Australian region sea-level pressure (SLP) analysis for 1600 AEST April 14, 1999; **b** Time series of upper level winds from selected aircraft operating through Sydney Airport between 0900 AEST and 1900 AEST April 14, 1999. Aircraft reports are routinely reported in feet above mean sea level; **c** Upper level temperature and humidity profile for Sydney Airport in the pre-storm environment at 1500 AEST April 14, 1999

front that was moving across the Tasman Sea was brushing the southern NSW coastline. A ridge from a 1030 hPa high pressure system located over the Southern Ocean to the south of the Australian continent was developing along the southern NSW coastline in the wake of the weak cold front. Ahead of the weak frontal system was a deep layer of moderate strength west to south westerly winds, extending from 1,000 m through to the tropopause, located near 10,000 m. Figure

8b shows a time series of upper level winds, routinely reported in feet above sea level, from selected aircraft flights at approximately hourly intervals operating into and out of Sydney Airport during the afternoon and evening of April 14, 1999.

Temperatures ahead of the cold front were a few degrees warmer than normal for April. Maxima in the western suburbs of Sydney climbed to around 26 °C. However, as the 1500 AEST upper air flight from Sydey Airport shows (Fig. 8c), there was only a very shallow layer of surface moisture, with the middle and upper levels remaining moderately dry, apart from a layer of moisture between 3,000 m and 4,000 m in the pre-storm environment. However, there was a moderately high CAPE (Moncrieff and Green 1972) at this time with a computed value of 1713 J/kg and the TT Index was a high 55. The SLI of -5.5 indicated the environment had the potential to support severe convection. The presence of a weak low-level isothermal layer resulted in the CIN value of a relatively low 50 J/kg. It was only in the region just inland of Kiama that the strong surface heating was sufficient to break through this stable layer to form a thunderstorm. The critical changes in low-level wind structure that led to the transition of the ordinary thunderstorm into a well organized supercell are well illustrated in the wind profiles of Fig. 8b. This was assisted by warmer than normal SSTs, with an instrumented buoy moored 3 km east of Sydney's coastline recording a value of 23.6 °C at 1 m depth. These anomalously warm seas provided an additional source of moisture for the thunderstorm. There was an increase in helicity caused by a subtle strengthening and deepening of the pre-frontal easterly that preceded the arrival of the weak cold front. The first evidence of an easterly can be seem from the 1200 AEST aircraft wind profile, with the depth of the easterly deepening to approximately 1,500 m (5,000 feet) by 1900 AEST. At 1500 AEST the storm relative helicity at Sydney Airport for the layer from the surface to 3000 m was $-180\,\mathrm{m}^2\mathrm{s}^{-2}$, a value that continued to increase throughout the afternoon. This increased helicity is an indication of the increased ability of the vertical wind structure to sustain organized up-drafts and down-drafts in the storm. The boundary layer moisture convergence also increased as this change approached, with the moist easterly airflow reaching its maximum depth of 1500 m immediately before the storm arrived. The moisture and wind shear available to the thunderstorm was therefore at a maximum right on the change. A weak and shallow sea breeze formed shortly before midday on April 14, 1999. Easterly winds were only about 6 knots (3 m/s) and confined to the lowest 300 m of the atmosphere. The sea breeze had the effect of masking the movement and intensity of the synoptic scale low level south easterly change that was concurrently moving up the NSW coastline. By 1500 AEST the sea breeze had increased only slightly, averaging 10 knots (5 m/s) and extending 600 m into the atmosphere. The environmental flow immediately ahead of the thunderstorm is illustrated by the aircraft derived wind profile at 1900 AEST (Fig. 8b). An increase of the wind at 900 m to 16 knots (8 m/s) is evident, as is the sudden increase in the depth of the boundary layer easterly airflow to 1500 m. Post analysis of the available data showed that a shallow mesoscale low had formed on a prefrontal trough which preceded the weak frontal system. This development occurred on the edge of the escarpment immediately adjacent to the coast between Wollongong and Sydney, further enhancing the low-level convergence and assisting in the transition of the thunderstorm into a supercell.

Once the thunderstorm airflows were organized by the environmental flow, it propagated to the left of the environmental steering flow, maintaining its supercell structure for over five hours. On two occasions during its life a middle-level mesocyclone was detected by the Kurnell Doppler weather radar. Other thunderstorms subsequently developed, with one that closely followed the track of the major storm. It produced a short lived burst of hail up to 3 cm in diameter. However, none of the subsequent thunderstorms displayed a severity close to that of the initial storm.

5. Numerical simulation of the April 14, 1999 hailstorm

a) Motivation for the numerical study of the hailstorm

The mode of operation of the severe thunderstorm warning service in Australia has two phases. The first phase is the identification of general atmospheric conditions conductive to the formation of convective weather, with special attention given to subareas where severe convection is likely. This evaluation normally takes place early in the day and provides advance identification of the regions that are most likely to require closest attention by skilled operational forecasters as the day progresses. A decision tree approach developed by Colquhoun (1998) is used to refine further the process, to identify sub-regions conductive to the occurrence of supercells, tornadoes, microbursts and storms with a high flash flood potential. This technique has been incorporated into the Australian Bureau of Meteorology's *Meso*scale **L**ocal **A**rea **P**rediction **S**ystem, MesoLAPS (Puri et al., 1998), to provide geographical representations of the areas with severe thunderstorm potential (Mills and Colquhoun, 1999). On this occasion the assessment, based upon available observations and numerical guidance, was that the environment was too dry, the shear too low and the steering winds directed too strongly offshore for severe thunderstorms to be of concern for the Sydney Basin. The second phase of the warning service relies heavily on the identification of severe thunderstorm signatures on weather watch radar, complemented by a range of other information sources including storm spotter reports, satellite imagery, surface weather observations from trained observers or from automatic weather stations, upper level observations from aircraft and weather balloons, and information from a lightning detection network that covers the eastern part of Australia. For greatest success the first phase of the warning service must be as accurate as possible, as it ensures that severe weather specialists are available to monitor the available realtime information and to issue short lead time, location specific, severe thunderstorm warnings and advices.

In the case of the April 14, 1999 hailstorm, the operationally available guidance did not indicate an environment capable of supporting severe thunderstorms over the land. The second phase of the warning service was therefore ineffective. The very fine scale of the meteorological factors that were critical in triggering the transition of the initial non-severe thunderstorm into a supercell thunderstorm, in particular the strength, depth and timing of the south easterly change and the erosion of the low-level temperature inversion, dictated that higher resolution numerical simulations than those currently operationally available were required. Land – sea and terrain interactions have been found by operational forecasters to be of importance in triggering severe thunderstorm events along the NSW coast line. A very high resolution numerical weather prediction model which included a recently developed multi (six) water–ice phase microphysics parameterisation scheme was therefore selected for this study. The complex cloud microphysics package was obviously necessary for the prediction of large hail producing convection.

It was noted above in the Introduction that there has been very limited success in modeling significant convective weather events in Australia to date unlike, for example, the USA and Europe. In these regions modellers have achieved success in their simulations of various severe weather phenomena. However, none have adopted the approach taken for this study. The sparse surface and upper air observing networks over the large ocean areas surrounding Australia have been a significant contributing factor working against the successful operational simulation of fine-scale severe weather events. One earlier study of a flash flood produced by severe convection on the NSW east coast was conducted by Speer and Leslie (1998). It was captured well because the main ingredients were moisture availability and strong topographic forcing. The severe thunderstorm studied here developed relatively late in the afternoon with the first radar signature evident at 1625 AEST. Currently, operational forecasters rely heavily on their previous experience of severe weather events to estimate their time of development. The ability of the numerical model to provide guidance on the time of initiation of the thunderstorm is of great interest. These factors provided the motivation for the very high resolution numerical simulation of this storm. The numerical model chosen for the present investigation was the model used in the Speer and Leslie (1998) study, but enhanced by the explicit cloud physics. It is referred to as the **Hi**gh **Res**olution numerical model, **HIRES**, developed at the School of Mathematics, The University of New South Wales, Sydney (see, for example, Leslie and Speer (1998a, 1998b), Leslie and LeMarshall (1997), Leslie and Purser (1997), Leslie and

Skinner (1994)). In a recent study, Buckley and Leslie (2000) have used HIRES at a resolution of 2 km to simulate detailed temperature and moisture gradients across the Sydney basin, showing its ability to resolve features important for the prediction of convective scale features.

b) HIRES configuration

The difficulty in accurately predicting the genesis areas of severe convection in Australia is well known to all operational meteorologists. For this reason the model initialisation time was selected at 0000 UTC (1000 AEST) on April 14, 1999, the time of maximum density of surface and upper air observations in Australia. This would provide the numerical model with the most comprehensive surface and upper air analysis fields upon which to base its predictions and an adequate lead time of about 6 hours.

HIRES was first run across the entire Australian region domain at a horizontal resolution of 50 km and sixteen levels in the vertical. It was then self nested at 10 km then 1 km over successively smaller domains (see Fig. 9). The vertical levels were most closely spaced in the boundary layer and the resolution of the orography was set at 2 minutes. This approach was used to ensure there would be no boundary problems in the area of interest caused by nesting the high-resolution model directly in another prediction system. The resolution of the topography around the eastern sea-board was re-interpolated with the increase in model resolution from the original 2′ topographical data-set to ensure the key topographic interactions were adequately simulated. The 50 km resolution run of HIRES was nested in the Australian Bureau of Meteorology **L**imited **A**rea **P**rediction **S**ystem, LAPS, (Puri et al., 1998). This model domain covered the area from 10° S to 45° S and 105° E to 170° E. The 10 km domain was reduced to 29° S to 44° S and 137° E to 155° E. This domain was selected as it is suitable for future operational purposes, given a sufficiently fast computing platform, as it is broad enough to incorporate key mesoscale meteorological factors important to the development of the south easterly change that was critical in this instance. The dynamic effects of the cold front moving across the Tasman Sea and the ridge that was developing in its wake needed to be accurately modelled. This domain also minimises the influences of any unwanted boundary effects over the key southern New South Wales coastal region. The final, 1 km resolution, simulation used a much smaller domain of 32.5° S to 35.5° S and 149.5° E to 152.5° E.

The influence of the warm sea surface temperatures in the East Australian Current that flows southwards on the western edge of the Tasman Sea were well captured by the input of seven day average sea surface temperatures with 2 minute resolution into the model. Fundamental to the prediction of the severe convection was the

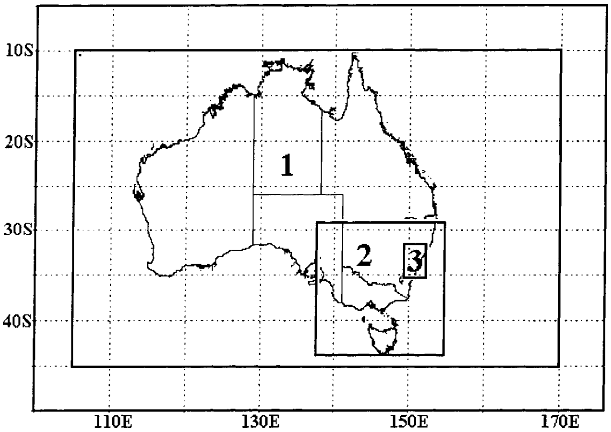

Fig. 9. Diagram showing the three domains for the triple nesting of HIRES as employed in this study

Table 1. Key model parameters used in the high resolution numerical prediction model, HIRES, for this simulation

HIRES model feature	Details
Horizontal resolution	50 km, 10 km, 1 km
Numerical scheme	Split explicit
Vertical levels	31, concentrated in boundary layer and near tropopause
Assimilation	6 hour cycling
Initialisation	Diabatic, dynamic
Orography	2 minute
Surface layer scheme	Mellor–Yamada 2.5
Boundary-layer scheme	Louis scheme (ECMWF)
Radiation scheme	Fels–Schwarzkopf
Precipitation scheme	Explicit microphysics
Sea surface temperatures	7 day average, 2 minute resolution
Boundary conditions	Bureau of Meteorology LAPS

inclusion of a complex convection scheme into HIRES that contained the all important water and ice phase processes into the numerics. This convection scheme was used in the model to simulate hail growth in any convective cells depicted by the simulation. HIRES employs a high order split – explicit numerical scheme, a 6 hour cycling assimilation scheme and a level 2.5 Mellor–Yamada surface layer scheme. The Fels–Schwarzkopf scheme was used to simulate radiation effects. Table 1 provides a summary of the key model parameters used in this very high-resolution numerical simulation.

c) Parameterisation of microphysical precipitation processes

The key to the successful simulation of large hail in the April 14, 1999 event was the inclusion of a comprehensive suite of schemes representing the cloud droplet and precipitation growth processes. For complete details see Wang (1999).

d) Results of HIRES run initialized 0000 UTC April 14, 1999

The HIRES simulation of this extreme hail event was initialised with the 0000 UTC April 14, 1999 LAPS analysis. Although not an ideal configuration for future operational application, the larger domain of the LAPS model ensures the broader scale developments were accurately captured by the higher resolution simulations. This was the latest time a very high resolution model could be run given the Australian operational schedule, because there are only two major upper air observation times each day, at 0000 UTC and 1200 UTC. It should also be remembered that the major impact of the severe thunderstorm that was to develop occurred between six and ten hours after this initialisation time. For the model output to be useful to assist in the delivery of a timely warning service, the very high resolution model results must be available prior to the initial onset of convection, which was at 0625 UTC in this case. Sufficient time is required for severe weather forecasting staff to be brought in to operate the radar based short lead time warning service.

The results from the numerical simulation were encouraging. A narrow band of liquid precipitation of convective origin was generated with an orientation parallel to the coast, as is shown in Fig. 10a. A precipitation rate of up to 25 mm/hour is depicted, close to the precipitation rate recorded during the initial stages of development of the storm. It is evident immediately that the orientation of this precipitation is different to the middle level steering winds, indicating that it was being influenced by low level land-sea and topographical influences. Another area of precipitation is shown over the west of the Sydney basin. This precipitation is clearly less well organised. In reality this corresponds to the area where other non-severe thunderstorms, not described in this paper, formed midway through the major event. The amount of precipitation actually recorded in this area was less than that in the simulation. Closer scrutiny of the hourly model output showed that the organised coastal band of precipitation commenced as a localised region of intense convection in the Kiama region at approximately 0600 UTC (see Fig. 10b), very close to where the initial thunderstorm was first identified on radar and at a similar time of the day. It should be recalled that 0625 UTC was the earliest radar detection of the convective cell that was to become the supercell. The region of organised precipitation extended progressively to the north north east, analogous in behavior to the supercell that formed on the afternoon of April 14. This modelled precipitation had a high ice content, with an area of giant hail predicted near Wollongong, the area where the thunderstorm first turned into a supercell. Fig. 10c shows a small area where hail up to 8 cm at ground level was modelled, which would have alerted operational meteorologists of the potential for a severe hail producing thunderstorm to form.

The band of simulated liquid precipitation was displaced to the west of where it actually occurred by approximately 15 kilometres. However, the hail swath was more accurately depicted. The modelled hail swath in Fig. 10c and the radar derived path of the hail bearing supercell in Fig. 6 are quite close. Moreover, the model was run without the benefit of a data assimilation scheme that could ingest the detailed asynoptic data that was crucial in identifying the fine-scale structure of the event. Further investigation is planned, incorporating more comprehensive data analysis techniques and the use of synthetic data in an

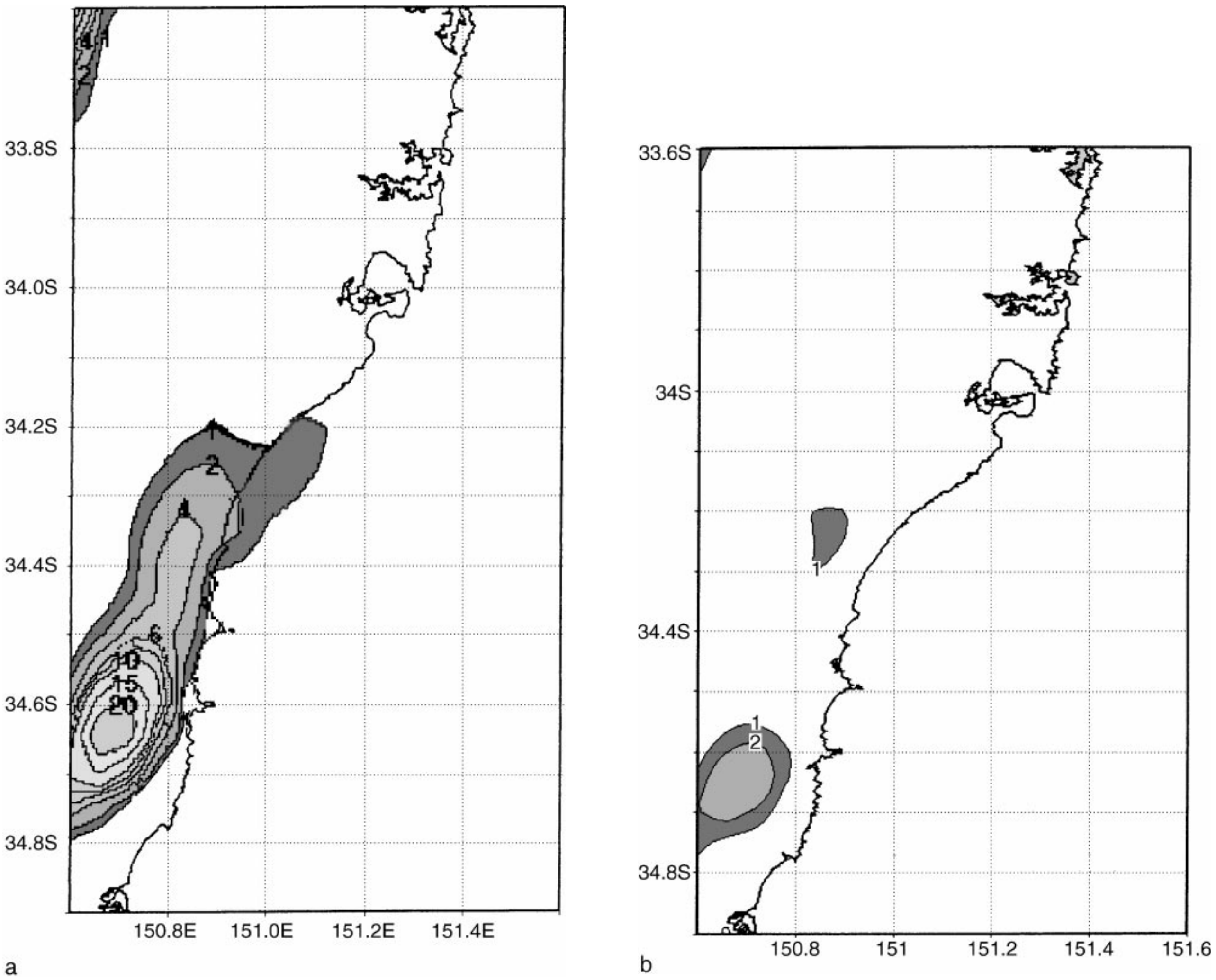

Fig. 10a. One kilometre horizontal resolution HIRES model output showing the accumulated liquid precipitation (mm) for the 6 hour period from 1300 AEST to 1900 AEST April 14, 1998. This interval encompasses the period of the severe hailstorm; **b** One kilometre horizontal resolution HIRES model output showing the liquid precipitation rate (mm/hour), for the hour ending 1600 AEST (0600 UTC) April 14, 1999; **c** One kilometre horizontal resolution HIRES model output showing the accumulated maximum hail size, at the surface, for the 10 hour period ending 2200 AEST (1200 UTC) April 14, 1999; **d** One kilometre horizontal resolution HIRES time series of cloud ice content $(10^{-3}\ \mathrm{g\ m}^3)$ for Sydney Airport spanning the time period of the severe hailstorm event of April 14, 1999

attempt to determine the extent to which these predictions may be improved.

In Fig. 10d, a vertical time section is presented of the high resolution modelled cloud ice content (displayed in units of 10^{-3} g m^3) for the grid point centred on Sydney Airport is presented. Sydney Airport was selected rather than an area further south where the modelled storm intensity was greater, as the airport is the location where a continuous record of surface observations are made by qualified weather observers. The simulation shows the main cell crossing the airport in the space of 40 minutes, commencing at 1815 AEST. It is noted that evaporation is occurring beneath the cells, with no surface impact expected from the first of the three cells depicted. The vertical extent of the cells is under-predicted at this location, as the accumulated surface hail output in Fig. 10c shows. Further modelling experiments are planned to see if the intensity of the thunderstorm can be maintained for a longer period than the current model predictions. In reality, this

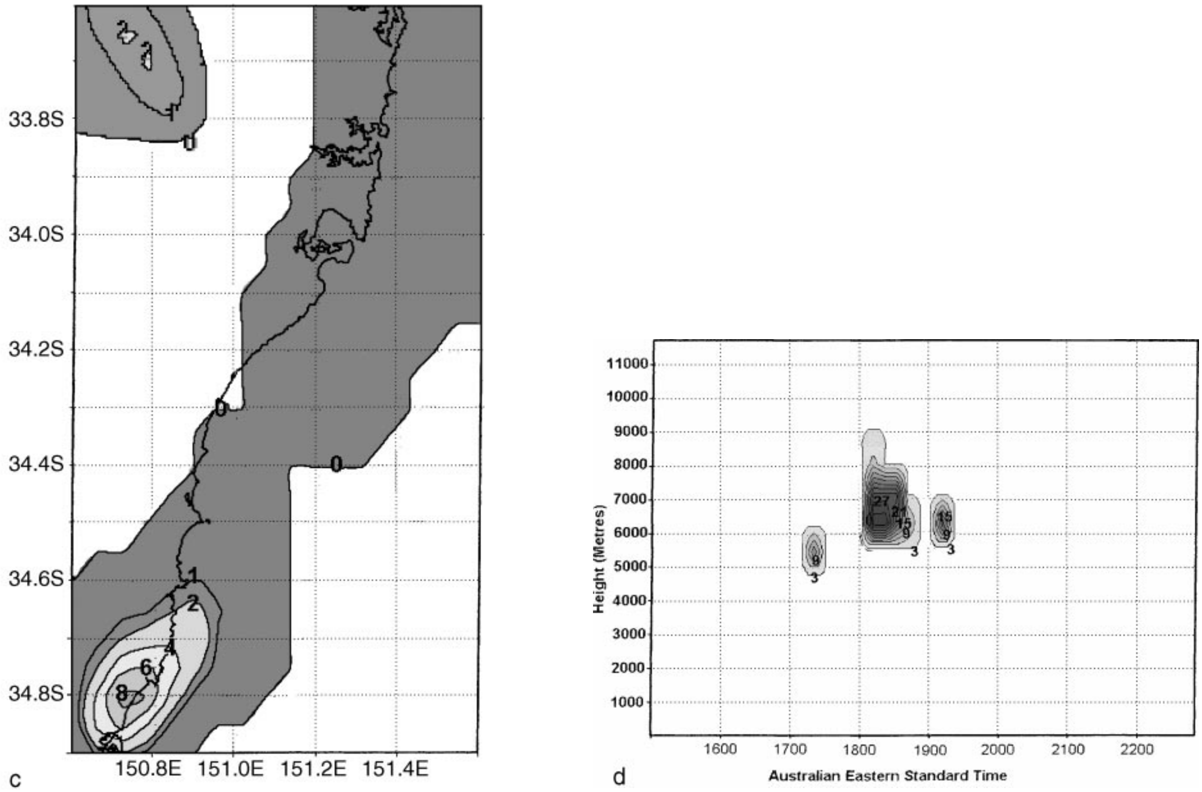

Fig. 10 (*continued*)

modelled storm cell arrived approximately one and one half hours earlier than the actual storm. The existence of a weak leading convective cell and a trailing convective cell of intermediate intensity arriving one hour after the main storm cell was similar to the sequence observed at the airport.

6. Discussion and conclusions

This paper describes the key synoptic features associated with the supercell thunderstorm that formed on the afternoon of April 14, 1999 on the east coast of Australia and moved across eastern Sydney. Hail of up to 11 cm in diameter was produced by this thunderstorm, being the largest confirmed hail every to be recorded in Australia. In dollar terms, it was the most expensive natural disaster in Australia's history with a damage bill exceeding $1.7 billion. A climatology of severe thunderstorms in NSW was prepared spanning the 10 year period from January 1988 to mid 1998. The climatology shows severe thunderstorms to be rare for April, although a recurring phenomena for the Sydney region at other times of the year. In particular the April 1999 storm was unprecedented in its severity for April over more than 200 years since records began. The climatology also confirmed the strong seasonality of severe thunderstorm activity across the state of NSW. Most severe thunderstorms are shown to occur between the months of November to February with the shoulder months of October and March being much reduced but still significant. With a life span of five and a half hours, this supercell was found to be long lived in comparison to other supercells that have impacted upon the Sydney region during the past decade.

The synoptic analysis revealed the conditions prevailing during the morning and early afternoon would not support a supercell thunderstorm due to a lack of low level moisture and very limited vertical wind shear. The diagnosis was confirmed by the formation of a single thunderstorm that was non-severe in its early stages. This thunderstorm eventually became the supercell. Increased vertical shear and a good low level moisture supply are essential for supercell formation. The analysis revealed the development of a shallow south easterly change that was not well forecast because it was heavily masked by the pre-existing, but weak, easterly sea breeze. This change produced a sudden increase in vertical wind shear and, coupled with the anomalously warm SST over the Tasman Sea, increased the low-level moisture availability in the region near Wollongong. The thunderstorm experienced a rapid transition into a supercell when it encountered the region of increased vertical wind shear and low-level moisture over the Tasman Sea.

The second component of the investigation was to apply a high resolution numerical weather prediction model, suitably configured with recently developed multi-phase cloud physics, to simulate the life cycle of the supercell. A model resolution of 1 kilometre was selected so that the key boundary layer and convective processes could be adequately resolved. A supercell thunderstorm was produced by the simulation. The modelled hail was not quite as large as that recorded but nevertheless the simulated thunderstorm had a high ice content, with hail up to 8 cm diameter predicted at the surface close to the location where the storm turned into a supercell. A band of liquid precipitation was displaced to the west of where it actually occurred. Significantly, the modelled surface hail swath was very close to the radar identified storm track. The timing of onset of the initial convection and arrival time of the main convective cell at Sydney Airport was within a couple of hours of reality. Further investigations are planned, incorporating more comprehensive data analysis techniques and the use of synthetic data in an attempt to refine the model simulations. The ultimate aim is to run the HIRES system operationally in real-time and computational demands suggest that this will be possible in about two to three years.

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