The end-to-end severe thunderstorm forecasting system in Australia: overview and training issues

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An overview of the Australian Bureau of Meteorology's end-to-end Thunderstorm Forecasting System is presented. This system relies substantially on three components: (a) the National Thunderstorm Forecast Guidance System (NTFGS), a software package that specifically displays those output fields from the 0.125° Australian operational Numerical Weather Prediction (NWP) model (MesoLAPS) that are particularly relevant to diagnosing thunderstorm potential out to 48 hours, (b) a nowcasting visualisation tool called 3D-Rapic, which displays volumetric radar data as well as output from radar-based algorithms, and (c) the Thunderstorm Interactive Forecast System (TIFS) for the dissemination of thunderstorm forecasts and severe thunderstorm warnings. TIFS can ingest algorithm-diagnosed thunderstorm positions and tracks which are automatically diagnosed from the radar data.

An Australian supercell hailstorm case study is then presented to showcase how forecasters can use the system outputs to facilitate decision making at various stages of the severe thunderstorm forecast process. Training and assessment issues associated with implementation of the forecast systems are discussed. In particular, it is concluded that forecasters must have an in-depth understanding of the NTFGS and radar algorithms for them to be used meaningfully. Such algorithms can facilitate the warning and decision-making process when used carefully in conjunction with the base data and other data types.

Introduction

The *Meteorology Act 1955* (Commonwealth of Australia 1955) states in Section 6.1.c as one of the functions of the Australian Bureau of Meteorology (Bureau) ' the issue of warnings of gales, storms and other weather conditions likely to endanger life or property, including weather conditions likely to give rise to flood or bush fires.' This serves to highlight the fundamental importance of severe weather forecast services from the Bureau.

For the Bureau's (severe) thunderstorm forecast service, two distinct forecast phases are involved, requiring differing forecaster toolsets to produce differ-

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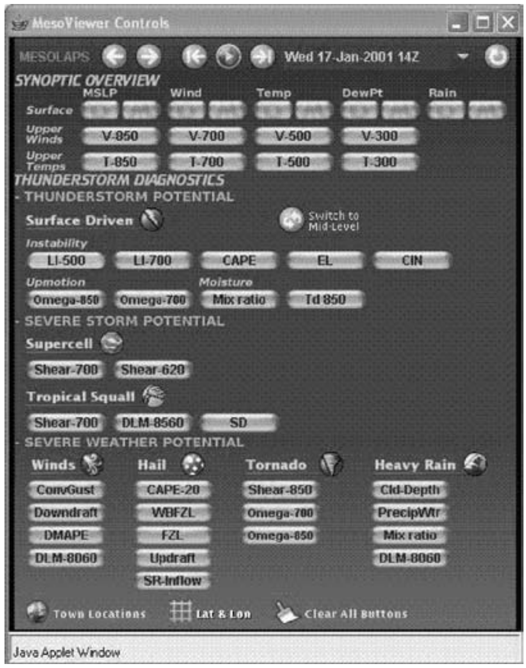
ing forecast products. The first is the outlook phase, prior to any thunderstorm development. The potential of the environment to support (severe) thunderstorms and severe weather is routinely assessed on a daily basis in a number of Australian State and Territory-based Regional Forecast Centres (RFCs). Forecast products defining the likelihood of (severe) thunderstorms and severe weather for that day are disseminated to various clients. NWP guidance is particularly important for assessing the pre-storm environment. Correctly diagnosing the potential of the environment to support (severe) storms and associated severe weather is essential for developing effective warning strategies.

The second distinct forecast period is the nowcasting phase. This occurs once thunderstorms have started to form and continues until the cessation of storms. The main tools during this period are data analysis and warning production software.

The purpose of this paper is first to explore both the role of the forecaster and the system integration across the two forecast phases by describing the end-to-end severe thunderstorm forecasting system as presently used in Australia (see also Richter (2006)).We then use an Australian supercell hailstorm case study to showcase how forecasters use the system outputs to facilitate decision making at various stages of the severe thunderstorm forecast process. In particular, we attempt to demonstrate that radar-based algorithms add value to the warning decision-making process when used carefully in conjunction with the radar base data and other data types. The second purpose of this paper is to highlight training and assessment issues associated with this implementation.

In order for the forecaster to utilise these forecast systems in a meaningful way, it is important that the service requirements and forecast process be well defined and that forecasters have a clear understanding of these. The chosen training approach uses radar and severe thunderstorm forecast competencies as its core. The competencies embody the scientific knowledge and system skills obtained by analysing the forecast process itself. These competencies are the cornerstone of a focused, service-relevant, training program that forecasters undertake as an integral part of the introduction of these new systems to RFCs in Australia.

Fig. 1 **The mesoviewer GUI of the NTFGS which allows forecasters to view three-hourly NWP fields, threat maps of thunderstorm and severe weather type and the component model diagnostics that constitute the threat.**



System overview

Outlook period to 48 hours – National Thunderstorm Forecast Guidance System (NTFGS)

The NTFGS is a software package that displays those output fields from the 0.125° Australian operational NWP model (MesoLAPS) that are relevant in diagnosing (severe) thunderstorm potential out to 48 hours from model initialisation (Hanstrum 2003). Relevant fields are based on thunderstorm conceptual models relating up-motion, moisture, instability and shear to thunderstorm initiation, development and structure. One of the key elements of the system is a web-based graphical user interface (GUI) referred to as the mesoviewer (Fig. 1). Forecasters can view three-hourly MesoLAPS NWP data (Puri et al. 1998) in a way that reinforces the (severe) thunderstorm forecast process.

Algorithms used to determine threat areas for thunderstorms, supercell thunderstorms, tropical squall lines, damaging winds, large hail, tornadoes and heavy convective precipitation potential utilise an ingredients-based approach. A level of threat at a model grid-point is displayed when the component diagnostics that constitute the threat simultaneously exceed pre-determined threshold values. The NTFGS thresholds used are based on published values (e.g. supercell and tornado parameters from Rasmussen (2003)) with modification in some cases on the basis of operational experience. An example subset of the NTFGS threat algorithms and associated ingredients appears in the Appendix.

One of the major features of the NTFGS mesoviewer is that it allows forecasters to efficiently overlay and composite model fields and algorithm threat maps. The algorithm ingredients can also be readily viewed. 'In an operational setting this guidance can be used to focus the attention of forecasters onto observations in the threat areas to determine whether the signal in the model is also present in the real atmosphere' (Hanstrum 2003).

Nowcasting visualisation – 3D-Rapic

3D-Rapic (Purdam 2007) is a system designed specifically for the display of volumetric (three-dimensional) weather radar data. The display allows the volumetric data to be interactively viewed in a number of different ways (Fig. 2), such as:

- PPI (Plan Position Indicator, constant radar elevation view);
- RHI (Range Height Indicator, constant radar azimuth view);
- Echo Tops (shows the highest echoes that exceed a given threshold. These are colour coded and 3D rendered according to height);
- VIL (a Vertically Integrated Liquid product calculated from the volumetric data to show the mass of water in a column above the earth's surface (units of $kg.m^{-2}$);
- CAPPI (Constant Altitude PPI, assembled from each PPI scan closest to the desired altitude).

A number of different radars and representations may be simultaneously displayed on the display screen. A key feature of the system is the speed and flexibility of use. The user has full control over viewing the volumetric data.

The system was designed and built by the Australian Bureau of Meteorology and is now used operationally in several southeast Asian countries as well as being the main radar data viewing platform in the Bureau. It contains the necessary communications and database infrastructure to allow data from a number of volumetric and standard surveillance radar sites to be automatically collected, viewed and stored.

Nowcasting, radar-based algorithms

Thunderstorm Identification, Tracking Analysis and Nowcasting (TITAN). The TITAN system (Dixon and Wiener 1993) is a radar-based application that identifies and tracks storm cells and provides short-term forecasts of their movement and size based on extrapolation of past movement. Thunderstorm detection and forecasts are based on 3D Cartesian radar data. The application tracks various parameters of the storm cell such as maximum dBZ* value, cell top and bottom, and has some geometric logic to deal with thunderstorm mergers and splits. The application was initially developed at the National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA, and has been integrated with the 3D-Rapic system for use in Australia.

In the TITAN system a 'storm' is defined as a contiguous volume that exceeds specified thresholds for reflectivity and size. The current reflectivity thresholds used in Australia are 35, 40 and 45 dBZ, which from experience cover the vast majority of Australian storms, from the tropics to mid-latitudes, and winter to summer. The 40 and 45 dBZ thresholds are used for summer storms, especially in the tropics. 35 dBZ data relate more closely to mid-latitude winter storms.

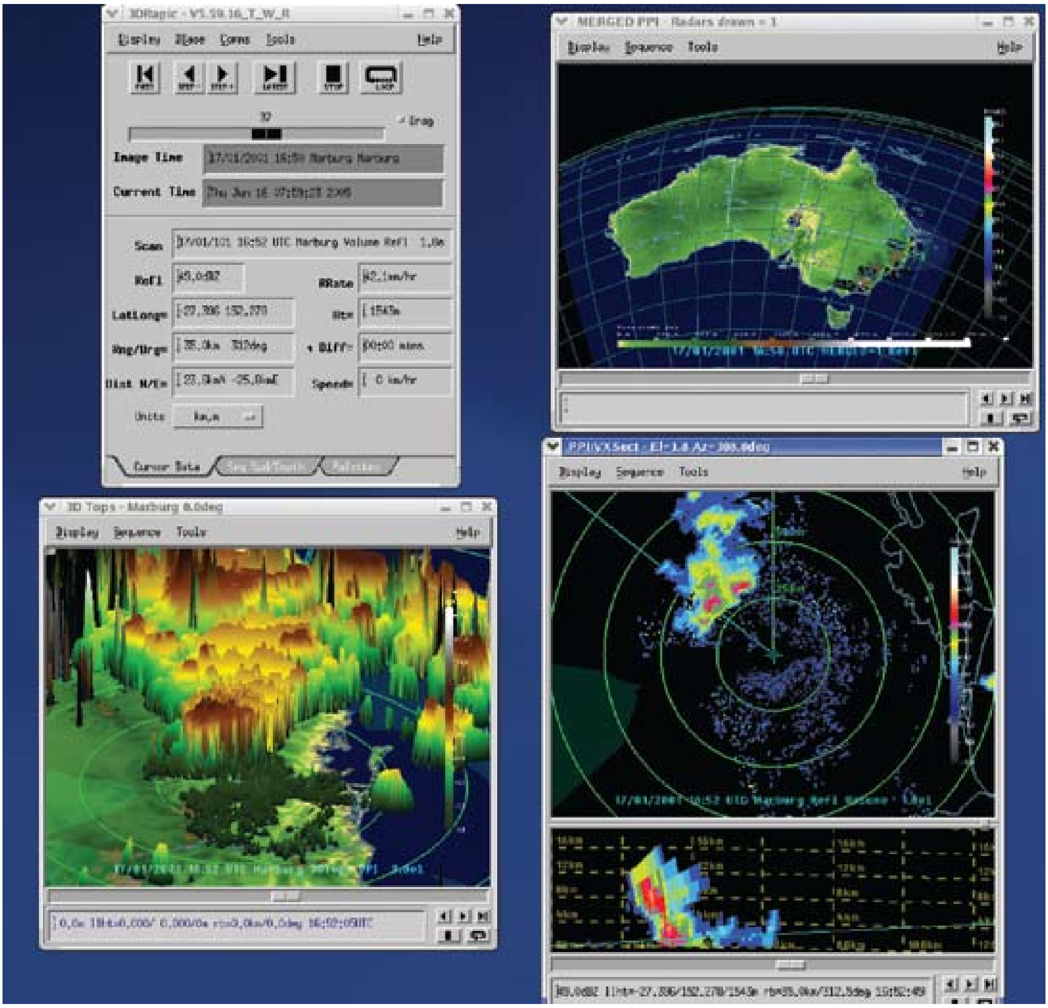
Warning Decision Support System (WDSS). The Centre for Australian Weather and Climate Research (CAWCR), incorporating the former Bureau of Meteorology Research Centre (BMRC), has adapted the Severe Storm Analysis Program (SSAP) of the National Severe Storms Laboratory's severe-weather Warning Decision Support System (NSSL WDSS) for use with Australian radar data, with 3D-Rapic being the primary viewing platform. SSAP consists of severe weather detection and prediction algorithms. The SSAP components currently used in Australia are the Storm-Cell Identification and Tracking (SCIT) algorithm (Johnson et al. 1998) and the cell-based Hail Detection Algorithm (HDA, Witt et al. (1998a)).

The SCIT algorithm works differently to TITAN in that the radar data is used in its native polar state and a 'storm cell' is defined as the smallest contiguous volume with the largest contiguous reflectivity that exceeds a size threshold, using seven reflectivity thresholds (30 – 60 dBZ in steps of 5 dBZ). In essence SCIT identifies and tracks individual storm cores, whereas TITAN identifies and tracks the 'whole' storm, defining the exterior of the storm by a reflectivity threshold. Like TITAN, WDSS tracks various cell parameters. The HDA provides various output products for the SCIT cells defined by the SCIT algorithm. The most operationally useful product is the Maximum Expected Hail Size (MEHS), which gives an indication of the hail size that could be expected with a given SCIT cell. Currently this is used to rank the SCIT cells. The SCIT cell with the largest MEHS value is given the top rank. The MEHS algorithm uses dBZ values above the freezing and –20°C levels in an empirical formula to compute a hail size. HDA is currently being assessed in the Australian context but initial work indicates similar results to those reported in the USA (Witt et al. 1998b).

As new Doppler radars are installed in Australia the Meso-cyclone Detection Algorithm (MDA, Stumpf et al. (1998)), Tornado Detection Algorithm (TDA, Mitchell et al. (1998)), and Damaging Downburst Prediction and Detection Algorithm (DDPDA, Smith et al. (2004)), will be tested and brought online if proved successful.

* logarithmic scale for measuring radar reflectivity factor.

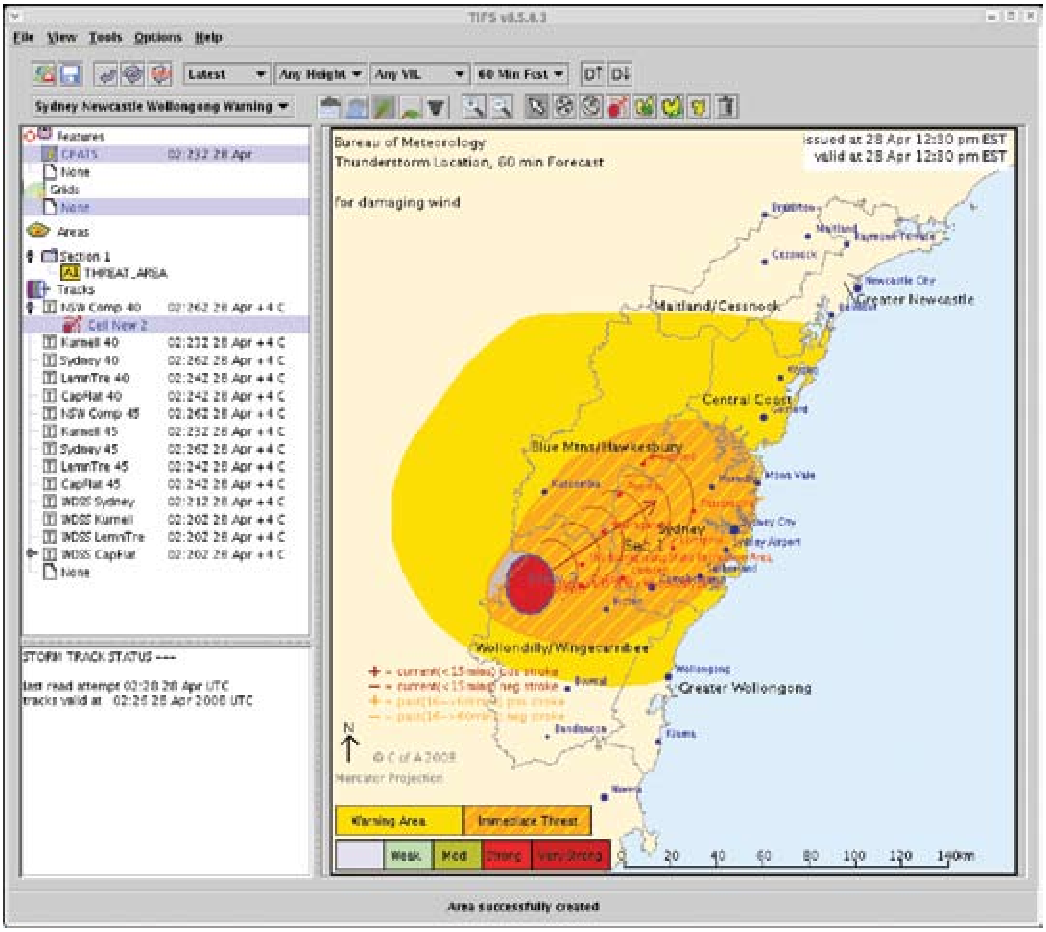
Fig. 2 3D-Rapic interface showing in clockwise order from the top left; the main GUI, a time – synchronized display of multiple radar PPI displays, PPI/RHI window and a 3D-Tops window (height – contoured display of the 1 dBZ level).



Forecast production – Thunderstorm Interactive Forecast System (TIFS)

The Bureau of Meteorology developed the Thunderstorm Interactive Forecast System (TIFS) (Bally 2004) for interactively producing severe weather warnings and other forecasts from thunderstorm tracks. TIFS is designed to apply recent advances in radar-based thunderstorm cell detection and tracking techniques to the efficient production of operational forecasts and warnings. The system ingests automated thunderstorm cell detections and tracks, lightning and forecast guidance from NTFGS, allows graphical editing by forecasters, and produces graphical and text products from the edited data. The text generator uses a simple template filling approach. The graphical products include a map of areas that have been affected and are forecast to be affected, as well as meteograms for selected locations. The current TIFS GUI is shown in Fig. 3 and it is presently being introduced into forecasting operations in Australia. Further examples of products generated by TIFS are presented in the case study that follows.

Fig. 3 **TIFS GUI with a display of a graphical severe thunderstorm warning for the Sydney metropolitan area.**



Case study

Background

The purpose of this case study is to showcase the end-to-end forecasting system and forecast process. From 17 to 19 January 2001 a surface trough, in conjunction with a vigorous upper-air system, produced three consecutive days of severe thunderstorms in eastern Australia as it moved from northern New South Wales into southeast Queensland and then into central Queensland. The storms were notable for both their severity and their persistence beyond the usual diurnal cycle.

Between 0200 and 0400 local standard time* (LST) on 18 January 2001 a long-lived supercell thunderstorm carved a strip of hail damage across Brisbane's northern suburbs. Reported hailstone sizes ranged from golf ball through to tennis/cricket ball. Some examples are shown in Fig. 4. This case study highlights the use of algorithms in aiding forecast decisions during this severe weather event.

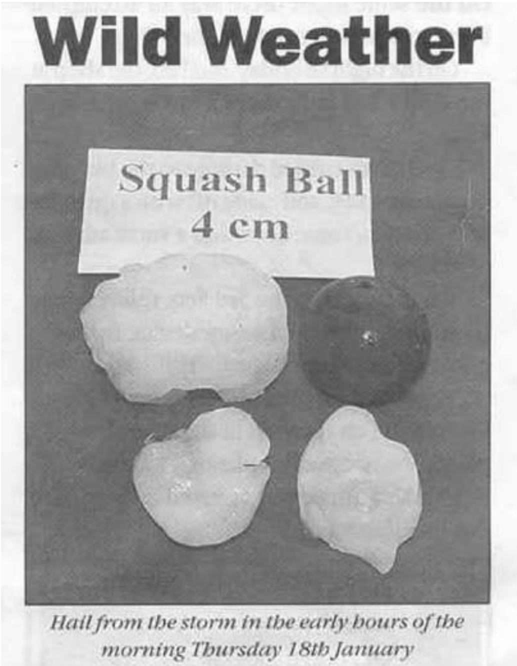
* Note that local standard time (Eastern Standard Time) = UTC + 10 hours.

Phase 1 – Outlook: diagnosing the pre-storm environment using NTFGS

Although the NTFGS data used in this case study would have become operationally available just as the storms had begun to develop, it is still very instructive to use this data to demonstrate the forecast process.

We will first direct our attention to what threat is revealed to a forecaster by the NTFGS algorithm guid-

Fig. 4 Examples of hail during the event compared with a squash ball. *Source: Samford Village Pump*



ance. We then discuss how an experienced, and well-trained, forecaster might analyse the model data to develop a conceptual model for the overnight dynamic forcing that would be consistent with the initiation of elevated, nocturnal convection. Such a conceptual model can then be reinforced or refined by observations. The mesoviewer facilitates easy viewing of the constituent algorithm ingredients.

Composite maps of NTFGS threat and diagnostic fields valid at +3 hours (0000 LST) and +6 hours (0300 LST) on 18 January are shown in Fig. 5. The +3-hour NTFGS threat map (Fig. 5(a)) indicates the potential for surface-based thunderstorms over the largely unpopulated southern inland region of Queensland. However the +6-hour forecast (Fig. 5(b)), valid at 0300, and subsequent forecasts indicate no further overnight threat of surface-based thunderstorms for southeast Queensland.

Note that in the +3-hour model forecast valid for 0000 LST on 18 January (Fig. 5(a)) the surface-based thunderstorm threat area is co-located with the inland portion of a NW-SE aligned trough and also coincides with areas of relatively small convective inhibition (CIN, defined in the Appendix) magnitude (< 25 J kg^{-1}). In the +6-hour forecast valid at 0300 LST (Fig. 5(b)) the CIN magnitude for near-surface parcels in the vicinity of the trough increases to values > 25 J kg^{-1}. This increase in CIN magnitude near the trough is driven by decreases in the model surface temperature (not shown) and is primarily responsible for shutting down the surface-based thunderstorm threat after midnight.

However forecast maps of high-based (i.e. not near-surface based) thunderstorm threat (Fig. 6) show the potential for the initiation and persistence of non-surface-based thunderstorms throughout the night over southeast Queensland. The model-based algorithms indicate no overnight super-cell thunderstorm threat or large hail threat across southeast Queensland (threat maps not shown). The nocturnal intensification of inland Australian troughs and associated fronts is a feature noted in previous studies (e.g. Deslandes et al. 1999). Figure 7 shows maximum values of ascent (between 850-700 hPa) above the nocturnal boundary layer more than doubling between 0000 and 0300 LST to the west-southwest of Oakey.

Figure 8 shows the +3-hour forecast (valid 0000 LST) of near surface to mid-level shear. It is calculated by using the greatest shear value between the 0.9875 sigma* level wind and any of the model winds in the 2.5-4 km layer at each grid-point. The exclusion of a forecast surface-based thunderstorm threat over southeast Queensland precluded a warm-season supercell threat being painted in the guidance at this time, as the first implementation of the NTFGS only proceeded to look for supercell potential if surface-forced thunderstorms were already deemed possible. However the co-location of the +3-hour forecast of elevated thunderstorm threat (Fig. 6) simultaneously with significantly large values (30-40 kn) of near-surface to mid-level shear (Fig. 8) over southeast Queensland warrants further investigation to see whether a significant shear signal might exist in the real atmosphere.

The exclusion of an overnight forecast surface-based thunderstorm threat over southeast Queensland also precludes a hail threat being displayed in the NTFGS. Nine hour forecasts (valid at 0600 LST) of the hail algorithm ingredients of updraft speed and wet-bulb freezing level (WBFZL) height appear in Fig. 9. The threat threshold requirements of updraft speed $\geq$ 75 kn and WBFZL height < 3.5 km that (in part) determine a favourable hail environment threat are met over parts of southeast Queensland. In essence two of the three NTFGS hail criteria were met: strong updraft speed and relatively low freezing level, but the lack of surface-based thunderstorm threat meant that no hail threat was indicated.

In summary then, the NTFGS surface-based thunderstorm threat forecasts indicate the potential for

* ratio of the pressure difference between the model pressure level and the top of the model to that of the pressure difference between the model surface and the top of the model.

Fig. 5 **MesoLAPS forecasts of low-level winds and convective inhibition (CIN) for (a) +3-hour forecast valid 0000 LST 18 January 2001 and (b) +6-hour forecast valid 0300 LST 18 January 2001. Vector winds are at $\sigma = 0.9988$ (~10 m above ground level (AGL)). The thick dashed line delineates the surface trough position. CIN contour interval is 10 J kg^{-1}. Major towns are included for reference. The shaded area in (a) is surface-based thunderstorm threat area as diagnosed by NTFGS. The cross southwest of Oakey indicates the radar-observed position of convective initiation for the event.**

(a) **(b)**

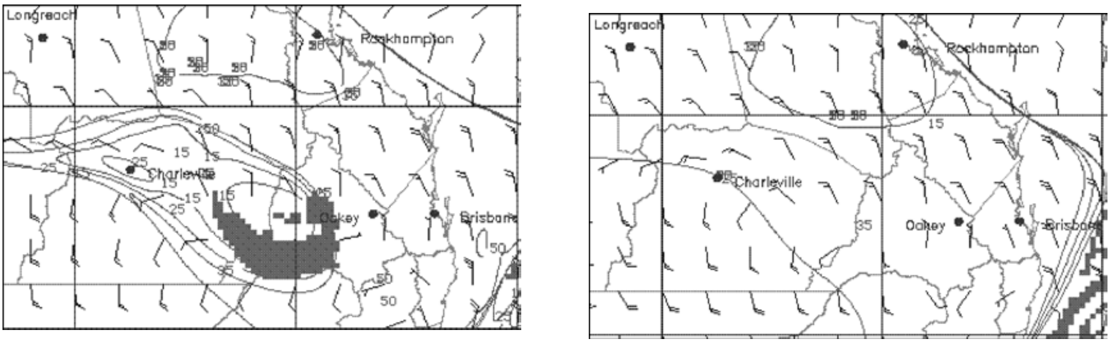
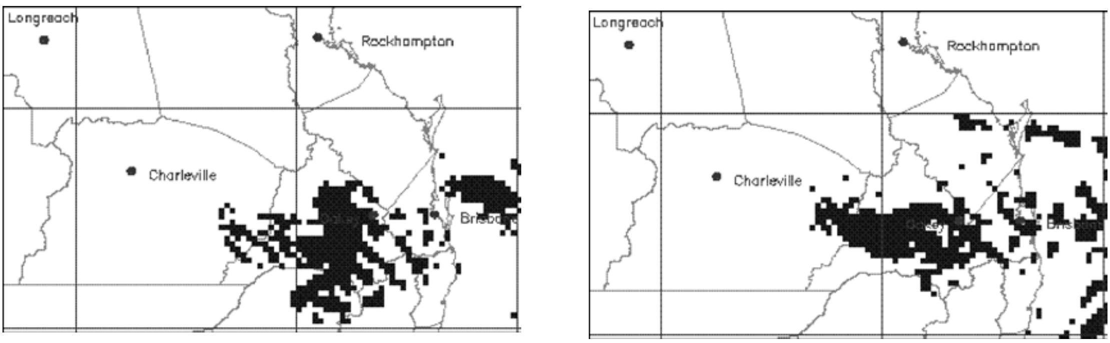


Fig. 6 **NTFGS forecasts of elevated thunderstorm threat area. Individual squares are centred on model grid-points. (a) +3-hour forecast valid 0000 LST 18 January 2001. (b) +6-hour forecast valid 0300 LST 18 January 2001.**

(a) **(b)**



surface-based thunderstorms initiating over inland southern Queensland at 0000 LST. However forecast values of low-level ascent three hours later at 0300 are not strong enough to maintain lifting of near-surface parcels to their level of free convection (LFC) in the presence of the aforementioned increasing values of CIN. Elevated parcels in the presence of stronger lifting above the boundary layer are able to become positively buoyant and an elevated thunderstorm threat is depicted in the NTFGS algorithm output overnight over southeast Queensland (Fig. 6). These areas also coincide with forecast regions of deep shear, appropriately strong forecast updrafts and low wet-bulb freezing-level heights conducive to large hail formation. Elevated supercellular convection has been documented by Davies (2004).

Such a conceptual model, derived from analysis of the model forecasts, is consistent with the observed sounding for Brisbane Airport in Fig. 10 (valid 2100 LST on 17 January). Although the distance of the Brisbane sounding from the area of interest near Oakey is about 150 km and may not necessarily represent conditions in threat areas over southern inland Queensland, it is the closest actual observation and does reinforce the conceptual model built from the NTFGS output. It is a common forecasting issue in Australia to have no observations near an area of interest, especially at night. In Fig. 10 there is an elevated inversion layer near 850 hPa. Parcels rising from above this elevated inversion level would be significantly buoyant

Fig. 7 **MesoLAPS forecasts of omega (maximum ascent values). Contours of minimum values of omega in hPa h^{-1} in the 850-700 hPa layer. Contour interval is 10 hPa h^{-1}. Major towns are included for reference. (a) +3-hour forecast valid 0000 18 January 2001. (b) +6-hour forecast valid 0300 18 January 2001.**

(a) **(b)**

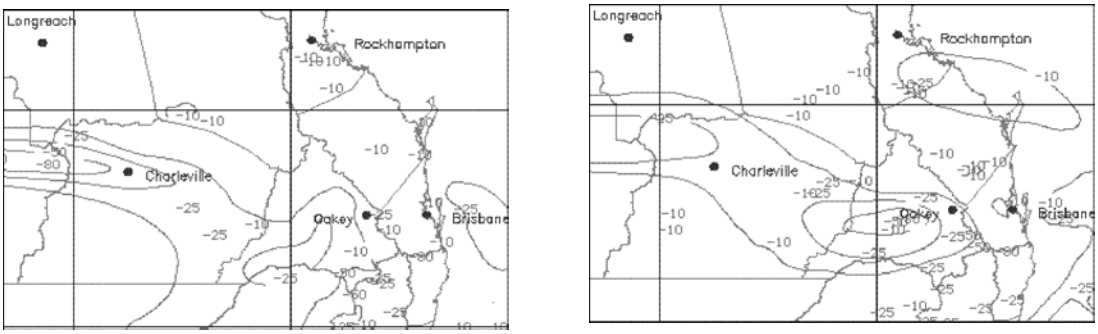
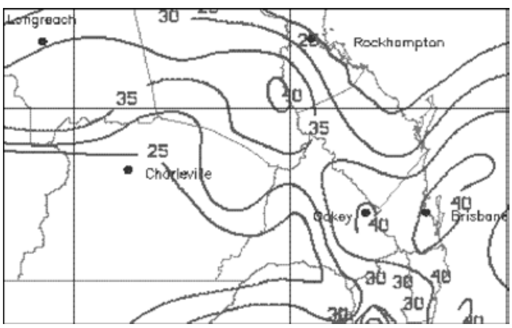


Fig. 8 **MesoLAPS +3-hour forecast of maximum values of shear in the near-surface to 2.5-4 km layer. Contour interval is 5 kn. Valid 0000 LST 18 January. Major towns are included for reference.**



through depth above their LFC and the CIN of these parcels would be less than those parcels rising from below the inversion layer.

Vertical wind shear is important in determining convective organisation and the theory is largely based on the work of Rotunno and Klemp (1985). Tilting of the horizontal vorticity inherent in the ambient shear by a storm updraft leads to a feedback loop between the updraft and the horizontal vorticity with resultant updraft regeneration and propagation. Organised storms lead to increased probability of associated severe weather (Weisman and Rotunno 2000). In this case the 850-500 hPa layer is taken to be a representative shear layer for convection originating from above the elevated inversion, as deduced from the sounding in Fig. 10. Table 1 shows 850-500 hPa shear values of 28 kn.

Estimated values of shear at midnight over southeast Queensland are computed by coupling upper winds from the observed Brisbane wind flight (valid at 2100 LST 17 January) and 0000 LST automatic weather station surface winds from Brisbane and Oakey. Observed shear values in Table 1 are consistent with the +3 hour model shear forecast (Fig. 8). Thus a forecaster who intelligently explored the NTFGS output and had assessed the overnight environment would have been aware of the possibility of elevated severe convection in SE Queensland in the early morning period of 18 January. We now move to the monitoring/nowcasting phase.

Nowcasting phase, 3D-Rapic – diagnosing storms on radar

In this section we will primarily demonstrate the current Bureau of Meteorology approach to diagnosing large hail as summarised in Richter and Deslandes (2007), using as an example the storms which developed over southeast Queensland early on 18 January. The first detectable echoes, associated with an initiating cell, were evident over southern inland Queensland some 230 km to the west southwest of the Marburg 10 cm weather watch radar (situated 50 km west southwest of Brisbane) at 1412 UTC (0012 LST). The TITAN and WDSS algorithms greatly enhance the forecaster's ability to be able to diagnose and forecast the evolution of the storm core. For example, in the 10-minute period to 1452 UTC (0052 LST) WDSS HDA MEHS output values increased rapidly from 6 mm to 30 mm. Figure 11(a) shows the cell at this time. The 1.8° elevation PPI scan is overlain with WDSS past cell track and 10-minute forecast positions of the core out to 60 minutes. The core is forecast to track to

Fig. 9 **MesoLAPS +9 hour forecast. Valid 0600 LST 18 January 2001. (a) Updraft speed (knots) - a function of the buoyant energy to -20°C and the storm-relative inflow. (b) WBFZL height (km).**

(a) **(b)**

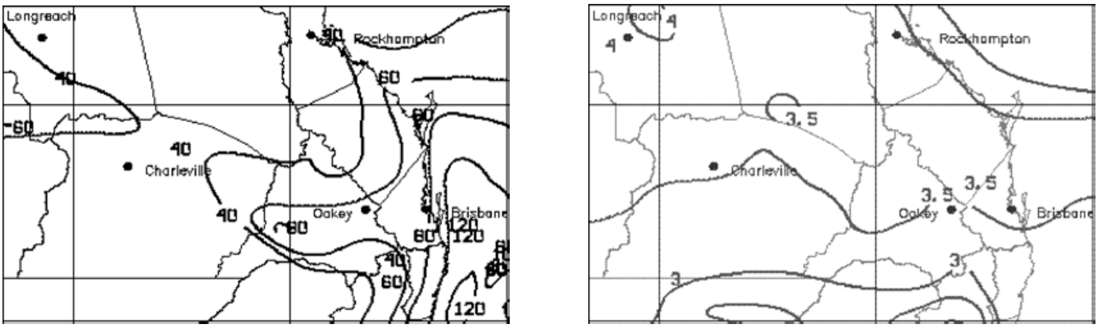
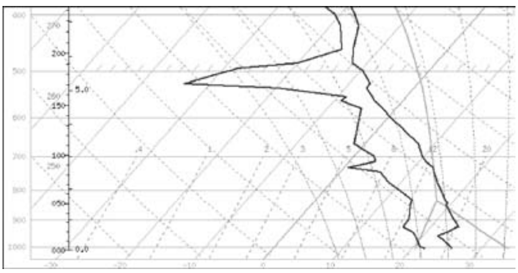


Fig. 10 **Brisbane observed sounding valid 2100 LST 17 January 2001. The right-most bold line indicates temperature with height, the bold line to the left indicates dew-point with height.**



the northeast at 83 km h^{-1}.

Using a more traditional nomogram approach (Treloar 1998), based on a climatology of hail events, forecasters set the CAPPI (Constant Altitude PPI) level to a threshold height based on the height of the environmental freezing level. Storms displaying 50 dBZ reflectivity values through this CAPPI threshold are considered to have a significant likelihood of producing large hail and warrant further analysis using the 3D-Rapic radar display software.

In Fig. 11(b) the CAPPI display height has been set close to 8 km based on the 1100 UTC (2100 LST) Brisbane Airport sounding's freezing-level height of 4.5 km. 50 dBZ reflectivity values clearly extend through 8 km at 1452 UTC (0052 LST) indicating the possibility of large hail. 3D-Rapic software allows forecasters to quickly and easily view a dynamically generated, simulated RHI scan in real time simply by dragging a radial through the storm core on the PPI display. The simulated RHI shown in Fig. 11(c) indicates a strong elevated core of reflectivity extending

Table 1. **Shear values at Brisbane and Oakey computed using the 2100 LST 17 January Brisbane wind flight and 0000 LST surface observations at Brisbane and Oakey.**

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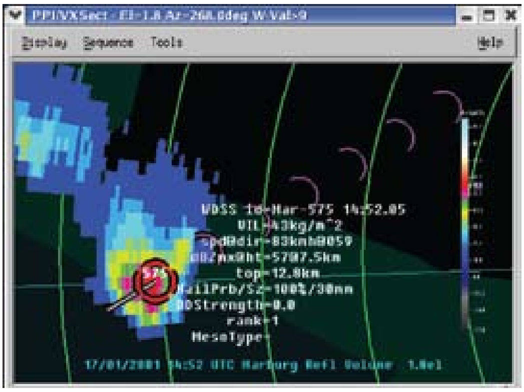
Shear	*Brisbane*	*Oakey*
Surface – 700 hPa	39 kn	35 kn
Surface – 500 hPa	44 kn	40 kn
850—500 hPa	28 kn	28 kn

from 4 km through to 12 km, indicating a powerful updraft. The WDSS HDA MEHS output indicates severe (3 cm) hail for the first time (not shown); this reinforces the presence of severe hail indicated by the hail nomogram and inspection of the radar data.

Australia has two severe thunderstorm warning products. A more general warning that is intended to indicate areas of general threat, can cover regions not under radar coverage and is valid for up to three hours. A cell-based warning is more specific, is based on radar coverage and is confined to metropolitan areas around State capitals. At this stage forecasters must address what type of environment the cell is moving into, whether the storm is likely to persist and whether to issue a severe thunderstorm warning for the region using the TIFS forecast preparation software. WDSS forecast tracks also indicate that this storm may enter the Brisbane metropolitan warning area within 60 minutes if it persists on its present track. Such considerations are made difficult by the lack of observations in the vicinity of the storm. It is clear that forecasters coming to the radar at this time without knowledge of the pre-storm environment would be greatly disadvantaged without a pre-storm diagnosis similar to that

Fig. 11 3D-Rapic display from Marburg radar at 1452 UTC (0052 LST). (a) PPI display with WDSS cell overlay of a cell some 205 km west of Marburg radar. The WDSS past track is in grey, the WDSS 10 minute forecast positions out to 60 minutes in purple. (b) CAPPI set to 8.0 km, showing the same cell as in (a). (c) Simulated RHI display of the same cell as in (a).

(a)



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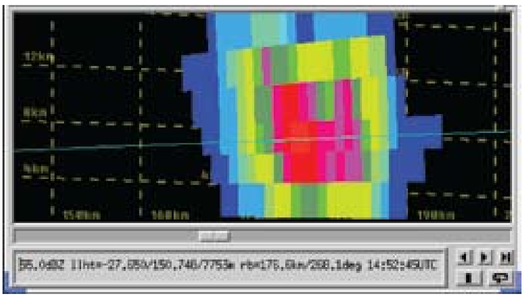
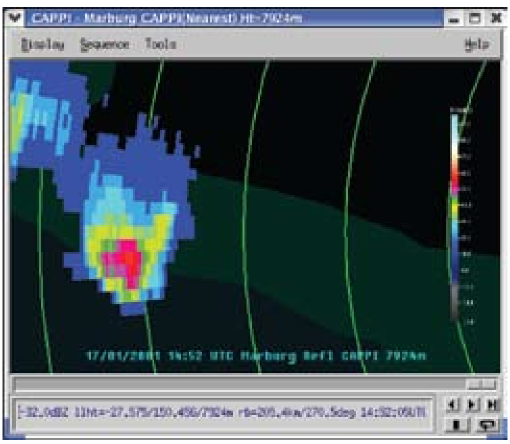


(c)



presented in the outlook section of this paper.

Over the ensuing hour the cell is tracked as the top-ranked feature by the SCIT algorithm. At 1552 UTC (0152 LST) the long cell track path history (~95 km), is as displayed in Fig. 12(a). The storm lifetime of 80 minutes is now well beyond the ordinary cell convective time-scale of 25 minutes (Doswell 2001). The forecaster now has direct evidence of an immediate storm environment that is capable of supporting long-lived convection. MEHS continues to indicate the threat of severe (≥2 cm) hail at this time. WDSS and TITAN forecast tracks show the cell continuing to move northeast through the Brisbane metropolitan warning area. The WDSS SCIT algorithm identifies a weak VIL core on the southern flank of the original core. A close inspection of the radar base data in Fig. 12 indicates the formation of new updrafts, and associated elevated echoes in this area (Fig. 12(b)). Ten minutes later at 1602 UTC (0202 LST) (radar data not shown) the southernmost core (WDSS cell 1062) becomes the dominant, top-ranked feature in the SCIT table. Over the ensuing 50 minutes this new cell tracks towards the east-northeast while the previous dominant cell (WDSS cell 575) collapses.

At 1652 UTC (0252 LST) Fig. 13 shows two storm cores indicated by the WDSS algorithms (WDSS cells 1526 and 1062) approximately 30 km to the northwest of the Marburg radar. The most intense core displays maximum reflectivity values of 60 dBZ to 7.4 km in height. Both TITAN and WDSS forecast tracks (Fig. 13) continue to the east northeast (which is across the northern suburbs of Brisbane). MEHS indicates 3.3 cm diameter hail. Analysis of the RHI display (Fig. 13(a)) reveals a Weak Echo Region (WER) on the southeast flank of the cell complex which is an indication of a strong updraft (Bluestein and Parks 1983).

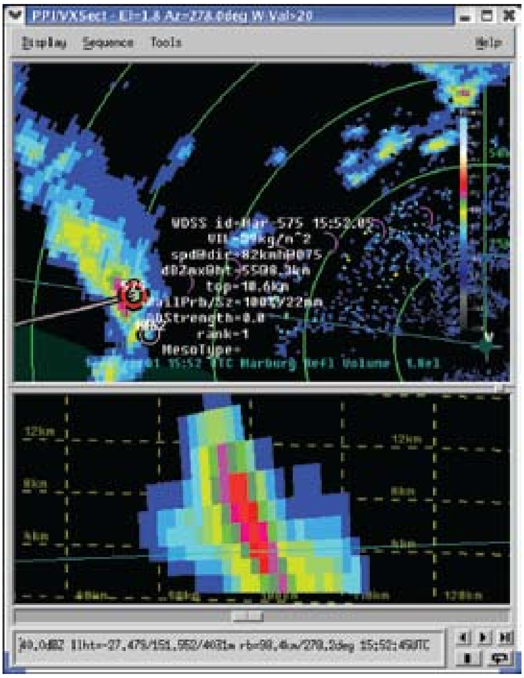
Warning preparation - TIFS

The forecaster now has evidence of sustained severe convection, forecast to track across part of the Brisbane metropolitan area. It is now time to issue warning products to the public and emergency services. Figure 14 shows a graphical warning and associated meteogram constructed using the TIFS warning preparation software, based on the TITAN overlay as displayed in Fig. 13(b), i.e. using the 1652 UTC (0252 LT) radar image with the TITAN cell advected forward eight minutes using the current TITAN speed and direction. In operations the TIFS TITAN cell is advected forward in time to allow for the delay in the forecaster receiving the radar image, as well as the time needed to create the warning product.

The philosophy behind TIFS is that the forecaster graphically selects and edits guidance to create a warning, TIFS then saves these forecast decisions and automatically generates a range of graphical and text

Fig. 12 **3D-Rapic display from Marburg radar at 1552 UTC (0152 LST). (a) PPI and simulated RHI display centred on WDSS cell 575. WDSS tracks as described in Fig. 11(a). (b) PPI and simulated RHI display centred on WDSS cell 1062. WDSS tracks as described in Fig. 11(a).**

(a)



(b)

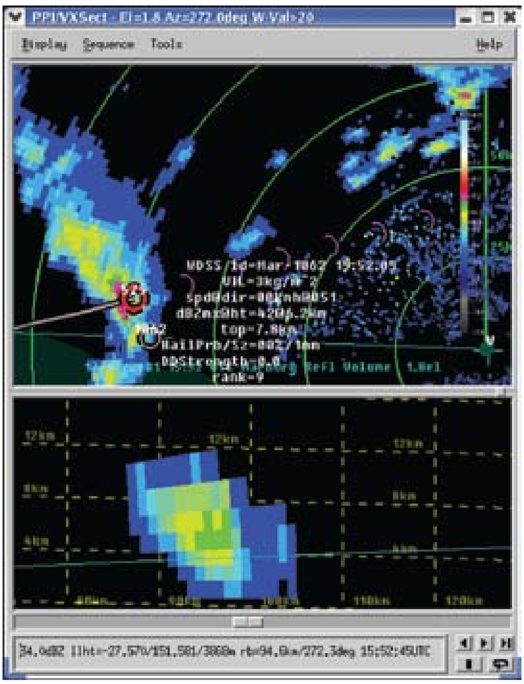
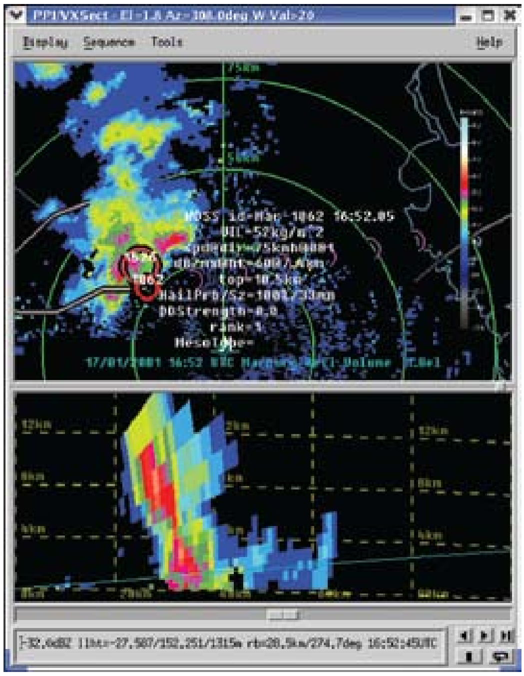
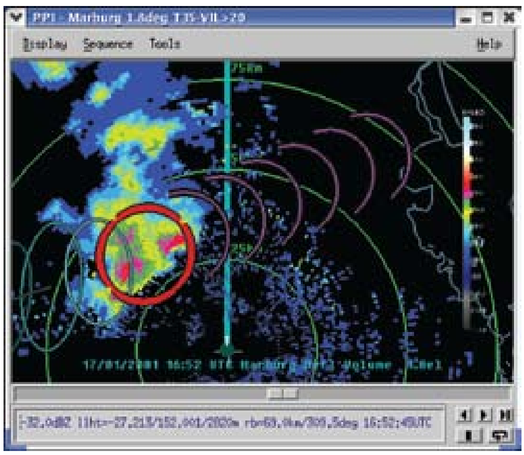


Fig. 13 **3D-Rapic display from Marburg radar at 1652 UTC (0252 LST). (a) PPI and simulated RHI display (along light blue line through cell 1062 in PPI) with WDSS overlay. WDSS tracks as described in Fig. 11(a). (b) PPI display with TITAN overlay. Past 10-minute TITAN positions in light blue, TITAN 10-minute forecast positions out to 60 minutes in purple.**

(a)



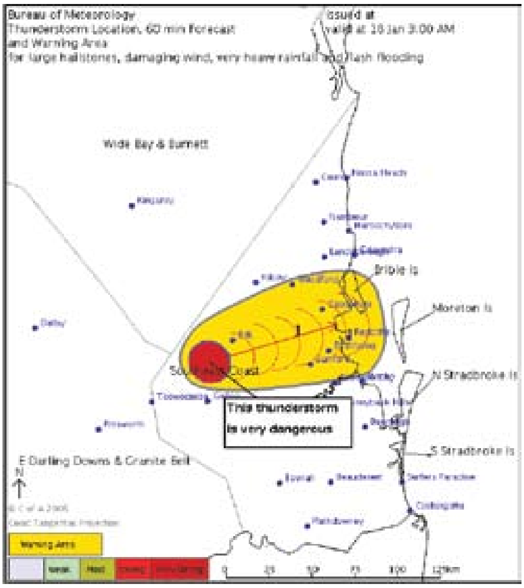
(b)



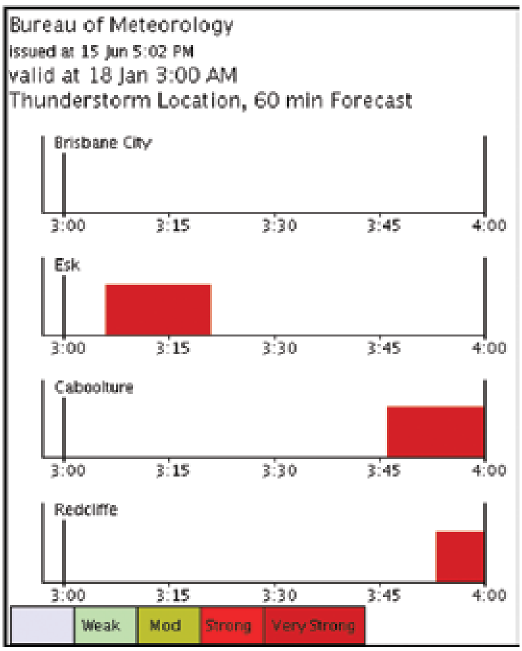
warning products, guaranteeing consistency. For example, in Fig. 14(a) with the forecaster having decided on the validity of the TITAN forecast track (the option exists to interactively change the forecast track) and adding the warning area, Fig. 14(b) (a site-specific

Fig. 14 TIFS produced graphical severe thunderstorm warning products. The grading from weak to very strong is for the indicated thunderstorm and is based on simple thresholds. (a) Threat area map with the severe thunderstorm and its expected track in red and the warning area in yellow. (b) Site-specific meteogram product where the blocks of red colour indicate the time during which the thunderstorm is expected to affect the given location.

(a)



(b)



meteogram product) is automatically generated. Text warning products (not shown) are also automatically produced. Forecaster feedback from Australian forecast offices where TIFS is being used operationally is that the warning preparation time has been significantly reduced while the range of warning products has been increased (Bally 2004). The TIFS infrastructure also allows products to be easily tailored for different clients, while ensuring consistency.

The unfolding of the event

In the ensuing 40 minutes the storm (WDSS cell 1062) displays maximum reflectivity values of 63 dBZ to 7 km in height and maximum VIL values of 60 kg m^{-2}. A Bounded Weak Echo Region (BWER) is evident in the 3D-Rapic RHI display at 1732 UTC (0332 LST, not shown) whilst the storm is over the northern suburbs of Brisbane. Such reflectivity features are indicative of supercell storms (Doswell 1985). MEHS indicates the potential for 3.5 - 4.0 cm diameter hail. By 1802 UTC (0402 LST) the cell had moved out over water and from 1822 UTC rapidly weakened as indicated by the time series of various WDSS cell parameters shown in Fig. 15.

As described in the introduction, between 0200 and 0400 local time a long-lived supercell thunderstorm carved a strip of hail damage across Brisbane's northern suburbs before moving off the coast. Hailstones from golf ball through to tennis/cricket ball sized were reported.

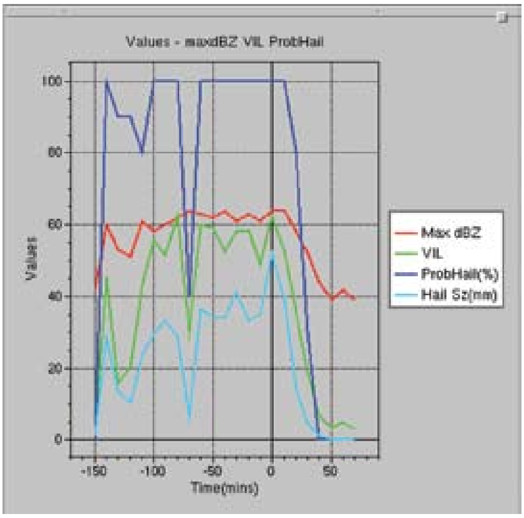
Training and assessment issues

The process of developing the training programs and associated radar-based case studies has also facilitated improvements in the ongoing development of the systems themselves and associated operational service procedures. For example, severe convection decisions have since been linked to the non-surface based convection in the operational version of NTFGS.

The approach to training adopted for this project is rooted in severe thunderstorm and radar competencies (Bell 2003). These competencies are derived as a set of skills and concept knowledge that fully span the actual forecast process. The competency approach ensures that the training resources are sharply focused on addressing the skills and knowledge that forecasters require.

Individual training programs are rolled out into the regional forecast offices employing a train-the-trainer model. Regional trainers are brought together and taught by content experts. The development of training material is carried out by the regional trainers themselves, coordinated through a central workshop forum and follow-up train-the-trainer days to revisit

Fig. 15 **3D-Rapic display of a time series of Max dBZ, VIL, Probability of Hail (%) and Hail Size (mm) for WDSS cell 1062 where time = 0 minutes is 1822 UTC (0422 LST).**



the supporting background knowledge. This methodology has ensured a strong sense of ownership and understanding of the training material by the local trainers. Beyond the training material development, regional trainers have a much stronger understanding of the local office culture and local forecast procedures than centrally based trainers and are directly available to office staff after the official training has concluded.

Training and assessment methods follow a three-tiered structure. Core competencies address the basic capability of using the systems involved (e.g. 'which button does what' in the volumetric radar data visualisation software). Training is delivered through hands-on exercises and assessed by means of core competency tick sheets. Meteorological concepts needed to understand radar and thunderstorm behaviour used to be taught through lecture-style 'powerpoint' sessions, but are now increasingly rolled into web-based modules that are self-guiding. Concepts are assessed explicitly through web-based quizzes as part of a learning management system. Finally, the application of core competencies and concepts are drawn together in either self-paced case studies or time-synchronised simulations via the displaced real-time simulator (DRTS) where a forecaster is taken through an event as if in real time. The forecaster is provided with the data he/she would have had at the time, thus matching as closely as possible the pressures and time constraints that occurred during the event. Increasingly, the most important form of forecaster competency assessment is carried out through individual DRTS simulations.

An increasing problem in the delivery of the training has been the difficulty in releasing operational staff for training. Various strategies have been used to overcome this problem, including reducing the length of learning modules, self-guided training and other techniques.

Discussion and conclusions

It is clear from the case study event that NTFGS and radar-based algorithms can support decision making throughout the severe thunderstorm warning process. If forecasters are to make the best possible decisions based on the data at hand it is important that they are able to understand and assess the validity of algorithm output by analysing the (NWP or radar) data in the context of observations from the storm environment. The NWP data provides a dynamically, spatially, and temporally consistent dataset in which to apply conceptual models and interpret observations. Specifically, in this event the National Forecast Guidance System (NTFGS) indicated the potential for elevated, nocturnal convection over southeast Queensland.

Despite no overnight supercell or hail threat being indicated by the NTFGS (due to the logic at the time of hail threat with only surface-based convection, since changed), further analysis of the underlying MesoLAPS numerical model data showed the ingredients for both to be in place overnight throughout southeast Queensland. Forecasters validating the NTFGS algorithm ingredients against sparse observations over southeast Queensland would have found such signals later existed in the real atmosphere.

This points to the value of (a) providing the ingredients as well as the threat areas in the NTFGS guidance, (b) training in understanding the ingredients and (c) the role of the human in putting all the information together. Senior forecasters prepared for the possibility of overnight severe storms are in a better position to deploy staff appropriately in order to facilitate the issue of severe thunderstorm warnings. Forecasters are much more likely to react earlier to a developing situation if they are already aware of the environmental potential. Any extra warning lead-time is invaluable.

Once storms had formed, the WDSS HDA indicated that the long-lived cores were likely to be associated with severe hail. The current Australian implementation of the radar-based algorithms have no 'knowledge' of the immediate storm environment (apart from the freezing level and –20°C height information utilised by MEHS within the WDSS HDA).

Forecasters must use other data such as observations, coupled with NWP data, to determine whether cells might encounter environments that are conducive to continuing convection and severe weather.

In this particular case the task of using surface observations to assess the buoyancy of the immediate storm environment was made difficult because the storms initiated in relatively data sparse regions. Indeed if the updrafts associated with elevated cores over southern inland Queensland were drawing inflow from above the overnight inversion as postulated, then surface observations in the path of the storm cannot be used to assess updraft buoyancy in the immediate storm environment.

Forecasters must exercise extreme radar vigilance during events and analyse the base radar data for storm structure features such as Weak Echo Regions or Bounded Weak Echo Regions that are indicative of self-sustaining, powerful updrafts such as were observed as the storm cores approached and traversed the Brisbane suburbs. Once forecasters decide to issue severe thunderstorm warnings for an event, the use of the graphical severe thunderstorm warning dissemination software TIFS facilitates the timely issuing of consistent graphical and text cell-based warnings.

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Appendix

Ingredients used are:

- Lifted Index (500 hPa) - the temperature difference between a near-surface parcel lifted dry-adiabatically to saturation and then moist-adiabatically to 500 hPa and the environmental temperature at 500 hPa.
- Upmotion – the maximum upmotion value at any

sigma level between 0.9988 and 0.8500.

- Convective inhibition (CIN) – the energy needed to lift an air parcel vertically and pseudoadiabatically from its originating level to its level of free convection.
- Deep Shear – maximum value of any of the 2.5-4 km wind vectors minus the near surface wind vectors.
- Updraft speed *w* – calculated by

$$w = \sqrt{(SRI)^2 + (2CAPE_{to\ -20°C})},$$

where SRI is the storm relative inflow, storm motion is the 800-600 hPa mean wind and the inflow layer is the lowest 100 hPa above ground level (AGL). $CAPE_{to\ -20°C}$ is the Convective Available Potential Energy of a surface parcel lifted to the -20°C level in the atmosphere.

- Wet-bulb freezing level (WBFZL) – is the height at which the temperature of an air parcel is zero, having been cooled adiabatically to saturation at constant pressure by evaporation of water into it, all latent heat being supplied by the parcel.

Storm type	*Ingredients*
Surface-based Thunderstorm (warm-season, 850 hPa temperature > 12°C)	- Lifted Index (500 hPa) ≤ -1.0 for lowest 50 hPa mixed layer - Upmotion > 10 hPa h^{-1} - $\|CIN\| < 25$ J kg^{-1} - Cold cloud depth > 3.0 km - Updraft reaches -20°C or colder in order that electrification can occur
Thunderstorm (elevated)	As for surface-based decisions except check for up-motion and instability above the surface up to 500 hPa.
Supercell (warm-season, 850 hPa temperature > 12°C)	Conditions for surface-based convection met and:
Favourable:	- Lifted Index (500 hPa) ≤ -4.0 - Deep Shear ≥ 30 kn
Very favourable:	- Lifted Index (500 hPa) ≤ -5.0 - Deep Shear ≥ 35 kn
Severe weather type	*Ingredients*
Large hail (hail size ≥ 2 cm)	Conditions for surface-based convection met and:
Favourable:	- 75 kn ≤ updraft speed (w) < 100 kn - WBFZL < 3.5 km
Or	- w ≥ 100 kn - WBFZL ≤ 4.2 km
Very favourable:	- w ≥ 100 kn - WBFZL ≤ 3.5 km