THE SYDNEY 2000 WORLD WEATHER RESEARCH PROGRAMME FORECAST DEMONSTRATION PROJECT

Overview and Current Status

BY T. KEENAN, P. JOE, J. WILSON, C. COLLIER, B. GOLDING, D. BURGESS, P. MAY, C. PIERCE, J. BALLY, A. CROOK, A. SEED, D. SILLS, L. BERRY, R. POTTS, I. BELL, N. FOX, E. EBERT, M. EILTS, K. O'LOUGHLIN, R. WEBB, R. CARBONE, K. BROWNING, R. ROBERTS, AND C. MUELLER

Nine nowcasting systems deployed in part during the 2000 Olympic Games in Sydney, Australia, demonstrated the capability of modern forecast systems and quantified the benefits of a real-time nowcast service.

In 1998, the International Science Steering Committee of the World Weather Research Programme (WWRP) established a process for undertaking Forecast Demonstration Projects (FDPs). These FDPs aim to demonstrate the benefits of disseminating real-time forecasts—based on improved understanding and technology—to users in high impact weather situations. The first WWRP FDP, described herein, focused on urban nowcasting and very short-term prediction of boundary layer conditions and associated weather. It was held in part during the 2000 Olympic games in Sydney, Australia.

The Sydney Organising Committee for the Olympic Games (SOCOG) and the Sydney Paralympic Organising Committee (SPOC) required weather service support for planning and coordination of the

AFFILIATIONS: KEENAN, MAY, BALLY, POTTS, AND EBERT—Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia; JOE AND SILLS—Meteorological Service of Canada, Downsview, Ontario, Canada; WILSON, CROOK, CARBONE, ROBERTS, AND MUELLER—National Center for Atmospheric Research, Boulder, Colorado; COLLIER AND FOX—University of Salford, Manchester, United Kingdom; GOLDING—Met Office, Braknell, Berkshire, United Kingdom; BURGESS AND EILTS—National Severe Storms Laboratory, Norman, Oklahoma; SEED—Bureau of Meteorology, Hydrology Branch, Melbourne, Victoria, Australia; BERRY—James Cook University, Townsville, Queensland, Australia; BELL—Bureau of Meteorology Central Training Centre, Melbourne, Victoria, Australia; O'LOUGHLIN AND WEBB—Bureau of Meteorology, Sydney, New South Wales, Australia; BROWNING—University of Reading, Reading, United Kingdom

CORRESPONDING AUTHOR: Dr. Tom Keenan, Bureau of Meteorology Research Centre, Melbourne, Victoria, Australia
E-mail: t.keenan@bom.gov.au
DOI: 10.1175/BAMS-84-8-1041

In final form 20 December 2002

Sydney 2000 (S2000) games. Important issues concerned the effect of weather on individual sports and potential impacts on the large number of people outdoors and on property. With potential for severe weather, nowcasts were a particularly important component of the weather service. The Bureau of Meteorology (BOM) in Australia was selected as the provider of the S2000 weather services and an enhanced operational service was mounted to support these activities. The WWRP FDP S2000 was built on experiences gained during the Atlanta Olympics in 1996 described by Rothfusz et al. (1998).

The goal of the S2000 FDP was "to demonstrate the capability of modern forecast systems and to quantify the associated benefits in the delivery of a real-time nowcast service."

The S2000 FDP was not just about providing new and improved systems for forecasters but also about demonstrating the benefits to end users. To this end, the WWRP did and is providing ongoing support for verification and impact studies.

The S2000 FDP emphasized the 0–6-h time frame, employing state-of-the-art observationally based nowcasting systems from the United States, United Kingdom, Canada, and Australia. This brought together for the first time a diverse range of operationally proven nowcasting systems and applied them to real-time forecasting for an operational environment. The collocation of researchers and operational forecasters in a common operational setting was also unique. Both factors enhanced BOM nowcasting service to the Olympics and other BOM clients from September to November 2000.

SYDNEY ENVIRONMENT AND OBSERVING NETWORK. The observing network in and around Sydney (Fig. 1) is in the coastal subtropical plains 100–150 km east of the Australian Great Dividing Range (with peaks > 1000 m high). The S2000 Olympics were conducted during spring when the weather is usually pleasant with mild to warm maximum temperatures (~20°C) and cool evenings (10°–12°C). However, the weather can be variable with potential for thunderstorms, lightning, hail, rain, and wind events primarily during frontal passages and east coast lows.

The BOM observational network and associated systems were significantly enhanced for this project. A network of automatic weather stations (15 units) was installed in the Sydney metropolitan area including at Olympic venues. Five portable stations developed by the Bureau of Meteorology Research Centre (BMRC) were deployed specifically for the WWRP. An additional network of 10 anemometers was installed around Sydney Harbour. During the S2000 FDP, rawinsonde soundings were available up to 4 times per day depending on the weather.

As shown in Fig. 1, three radars supported the S2000 FDP. Two of these were existing operational radars located at Wollongong (S-band, 2° beamwidth, reflectivity only) and Kurnell (C-band, 1° beamwidth, Doppler radar). These radars provided BOM standard 1-km range resolution products prior to the S2000 FDP. As part of the FDP, the Kurnell radar signal processor was upgraded to provide 250-m range resolution data in over 1000 range bins (to support high-resolution radar data requirements of WWRP systems) and a dual pulse repetition frequency scheme described by May (2001) was adopted to avoid velocity aliasing problems in WWRP detection algorithms.

From July 2000, the C-band Polarimetric radar (CPOL) described by Keenan et al. (1998) was located at Badgerys Creek some 40 km west of Sydney. CPOL was deployed to enhance the boundary layer monitoring of convergence zones shown to be important by Wilson and Megenhardt (1997). Inland sea-breeze penetration, boundary layer rolls, and outflow boundaries inland were not readily detectable by the coastally located Kurnell radar. In addition, the polarimetric measurements allowed microphysical species identification (Vivekanandan et al. 1999) and improved radar-based rainfall estimates (Zrnic and Ryzhkov 1996).

As a result of cross-calibration and intercomparison, radar reflectivities from the three radars were generally within 1 dB by the start of the S2000 FDP.

Boundary layer wind profilers installed at Sydney airport provided additional high-resolution vertical wind structure.

S2000 WWRP SYSTEMS. The following nowcast systems were deployed as part of the S2000 FDP.

Canadian Radar Decision Systems (CARDS), 0–1.5 h. The Meteorological Service of Canada CARDS is a Web-based system that assists forecasters in decisions on the severity of weather (Lapczak et al. 1999). It ingests three-dimensional Doppler radar data and estimates rainfall with automated algorithms and provides diagnostic information on hail size, mesocyclone, tornadoes, downbursts, and other cell properties. Point forecasts of precipitation occurrence are provided out to 90 min.

Warning Decision Support System (WDSS), 0–2 h. The National Severe Storms Laboratory (NSSL) WDSS

(Eilts et al. 1996) ingests Doppler radar, lightning, and surface data and numerical weather prediction (NWP) forecasts as available. WDSS includes algorithms for tracking cells and detecting mesocyclones, tornadoes, hail, downbursts, and lightning.

Thunderstorm Identification, Tracking, Analysis and Nowcasting (TITAN), 0–1 h. The National Center for Atmospheric Research (NCAR)–developed TITAN (Dixon and Weiner 1993) undertakes real-time automated identification, tracking, and short-term forecasting of thunderstorms based on volume scan weather radar data.

AutoNowcaster (AN), 0–2 h. The NCAR AN (Mueller et al. 2000) is an expert system that provides time- and space-specific forecasts of thunderstorms. A unique feature is the ingest of output from a numerical model and its adjoint using the Variational Doppler Radar Assimilation System (VDRAS) of Sun and Crook (1994, 1997) and Crook and Sun (2001). The AN automatically detects, extrapolates, and characterizes boundary layer convergence lines and convective storms. It forecasts thunderstorm initiation, growth, and dissipation by considering stability, storm motion relative to convergence lines, low-level shear, storm characteristics, and the presence of cumulus clouds in the vicinity of convergence lines. The AN forecasts precipitation rate on a 1-km grid every 5 min for 30- and 60-min periods.

CPOL Hydrometeor Classification (CHYD) and Rainfall. The BMRC has developed a "fuzzy" logic microphysical classification scheme described by Keenan (1999). CHYD deduces 10 hydrometeor species (drizzle, rain, rain/hail mixture, small hail, large hail, dry graupel, wet graupel, dry high density snow, dry low density snow, and wet snow) and derives rain-rate estimates for each by polarimetric techniques every 10 min.

Generating Advanced Nowcasts for Deployment in Operational Land-Surface Flood (GANDOLF) Forecasts, 0–3 h. The United Kingdom Met Office (UKMO) and the University of Salford developed GANDOLF (Pierce et al. 2000). Cell development from one stage to the next may be instigated using a life cycle model with an objective method of recognizing cell characteristics from three-dimensional radar data linked to satellite and mesoscale model data. Every 10 min GANDOLF produces a 1-h forecast of the precipitation field.

Spectral Prognosis (SPROG), 0–1 h. SPROG (Seed and Keenan 2001) is an advection-based rainfall nowcasting system that exploits the observation that rainfields commonly exhibit both spatial and dynamic scaling properties—that is, the lifetime of a feature in the field is dependent on the scale of the feature (large features evolve more slowly than small features)—and that features at all scales between the outer and inner observed scales are present in the field. Every 5 min, SPROG produced 0–1-h nowcasts at 10-min intervals.

Nimrod, 0–6 h. Nimrod (Golding 1998) is a very short-period forecasting system for precipitation, cloud, and visibility that has been operational in the UKMO since 1995. The basic approach is to use linear extrapolation of present features and to incorporate nonlinearities of evolution from the NWP model. Forecasts of 0–6 h are made with a 30-min update cycle, although a 15-min cycle is possible. For S2000, only the precipitation component of Nimrod was employed and NWP data was sourced from the BOM Limited Area Prediction System (LAPS; Puri et al. 1998).

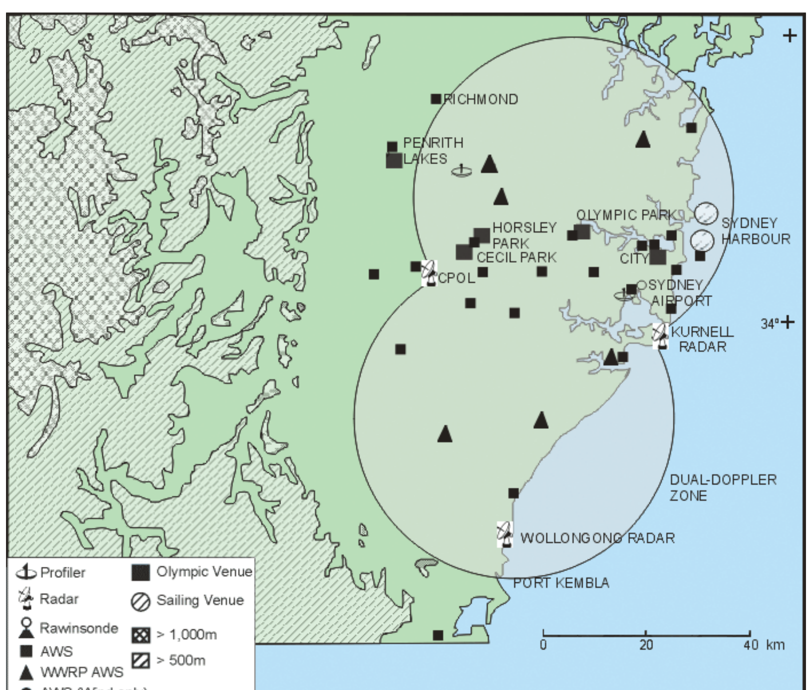


Fig. 1. Sydney area and observational network of the WWRP S2000 FDP.

Thunderbox. The BMRC-developed Thunderbox (Bally 2001) was the WWRP forecast product preparation system and was used to collate and view Web-based summary displays of WWRP products both locally and remotely in a consistent manner. It enabled interactive modification of WWRP products, generation of storm "threat" areas, and automated production of text and Web-based products for dissemination to forecasters and end-user clients.

Overall the WWRP systems provided new precipitation estimation and forecasting techniques and a range of automated severe weather detection algorithms not available previously to the BOM in Sydney. The WWRP provided nowcasting systems focused on the 0–6-h time frame that were a clear advance over existing operational technology.

It should be noted that NWP models, with the exception of the BOM-upgraded LAPS and VDRAS employed in the AN, were not a major part of the S2000 FDP.

CONDUCT OF S2000. The FDP involved a 2-yr program leading up to the S2000 games. During August–September 1999, a pilot program in Sydney focused on installation, testing, interfacing, and initial data collection. A second trial during February 2000 focused on interaction with forecasters and product generation. Final system set up was complete in mid-August 2000 with all algorithm tuning "frozen" for the FDP. The formal FDP was conducted through the period 4 September–21 November 2000.

Forecasters were located primarily at the BOM New South Wales Regional Forecast Centre (RFC) in central Sydney with a smaller group at Rushcutters Bay (in support of the sailing community) and another group at SOCOG headquarters (see Fig. 2). Each WWRP nowcasting/forecasting system had a representative at the BOM Sydney RFC at all times during the prime S2000 period. These representatives—the "champions" or experts on their respective systems—interacted with BOM staff. WWRP managers in this group rotated as the local overall WWRP advocate. This advocate, who was trained on the various S2000 systems, interacted directly with BOM forecasters to present the consensus WWRP FDP forecast position. All WWRP systems operated 24 h per day during the FDP.

Training of BOM forecasters on the WWRP systems was essential and was undertaken in formal lectures and on a case by case basis as required, including real-time situations. This training proved to be essential for optimal use of WWRP FDP products.

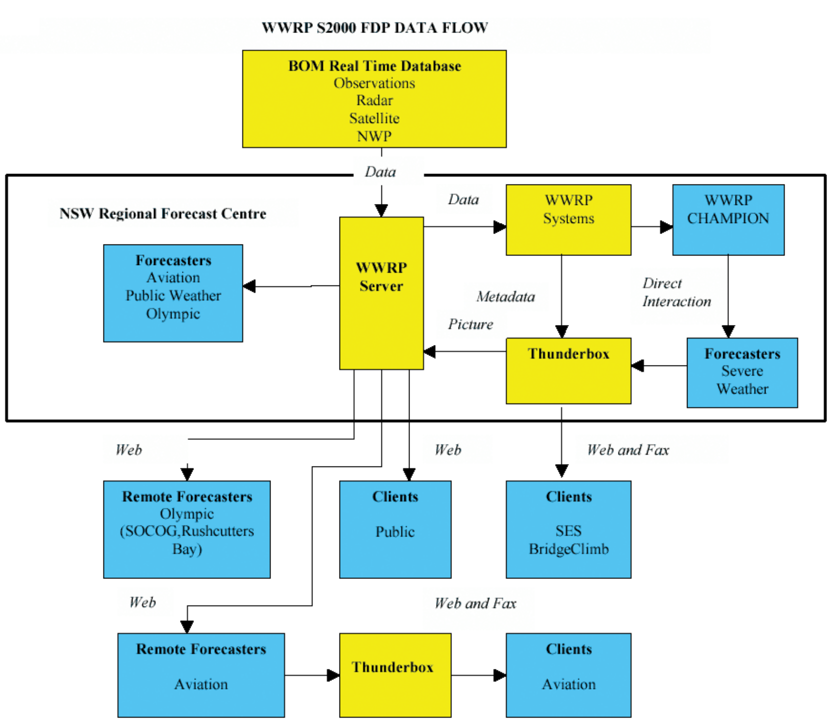


FIG. 2. Conceptual diagram showing functional layout of WWRP S2000 FDP components. Data flows are indicated with locations of various personnel (BOM, WWRP, clients) indicated in blue and supporting WWRP systems in yellow.

WWRP FORECAST PRODUCTS. Diagnostic and end-to-end WWRP FDP forecasts were provided in real time, meeting the same operational deadlines as the BOM. Early testing showed that it was impossible for forecasters to use the diverse and unfamiliar systems effectively in a busy warning environment. Hence, the Thunderbox was devised as an interface to the WWRP systems, providing automated guidance from all systems in an integrated fashion. Using this Web-based approach both local and remote forecasters could view summary information from anywhere in the system (see Fig. 2).

Simplified cartoon-type representations of objects denoted storm outputs from the nowcasting systems such as storm cell locations and forecast tracks (see example in Fig. 3). Storm cells were color-coded by inten-

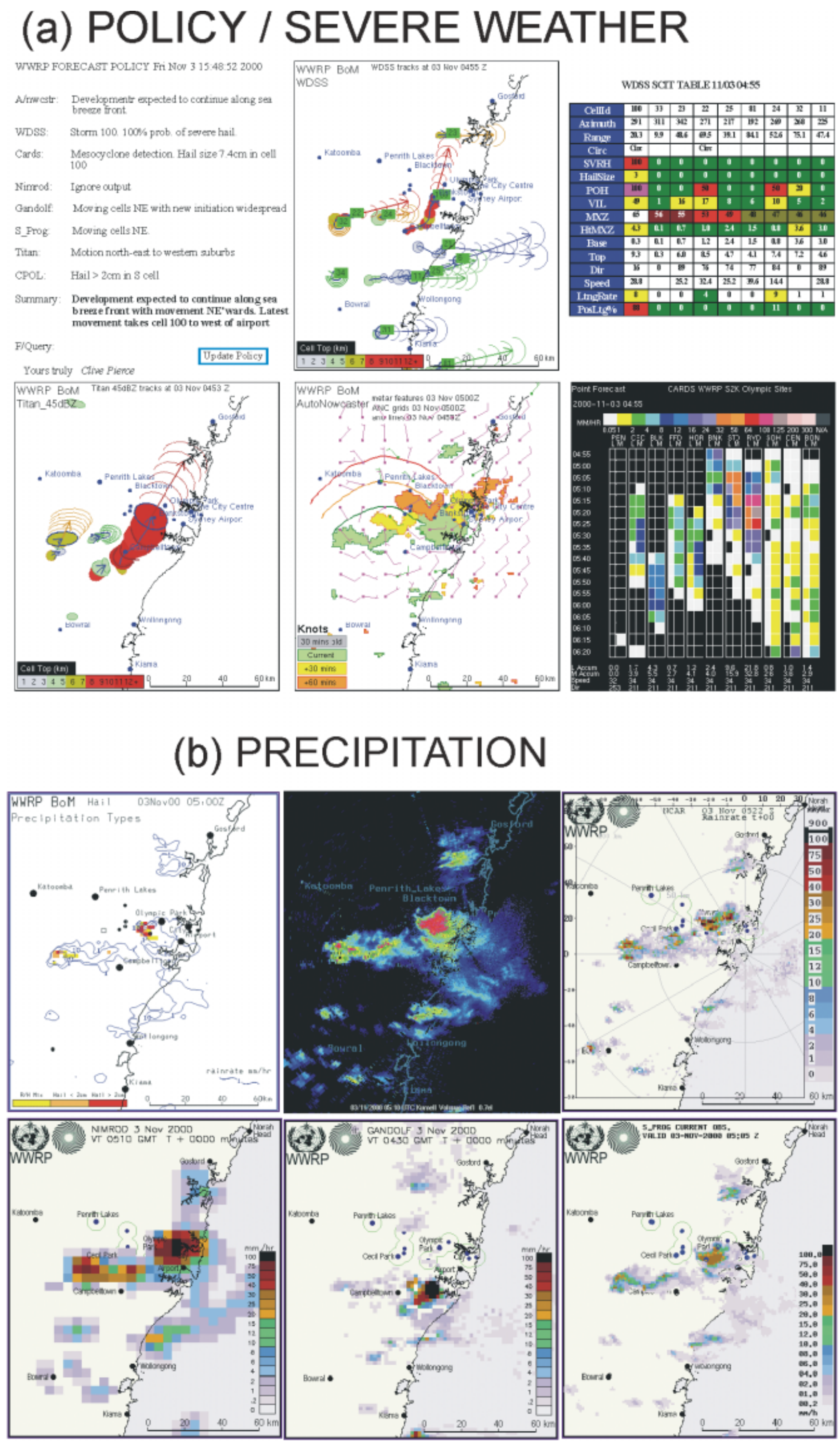


Fig. 3. Example of WWRP S2000 FDP Forecaster Web-based guidance products, (a) WWRP policy information and severe weather guidance products. (top left) System status and WWRP guidance summary with capability for forecaster query. Next two panels show WDSS Storm Cell Identification and Tracking Algorithm (SCIT) tracks and in tabular form summary cell information from WDSS SCIT, hail detection algorithm, mesocyclone algorithm, and tornado detection algorithm. (lower left to right) TITAN cell tracks (cells > 45 dBZ) and forecasts; AN VDRAS-derived winds with convergent boundaries and projected storm locations over next hour and CARDS point forecasts of rainfall. (b) Precipitation forecast products. (top left to right) CHYD-derived rain-rate analysis with superimposed hail sizes; a standard BOM radar reflectivity and AN-derived rain-rate analysis. (lower left to right) Forecast precipitation fields from Nimrod, GANDOLF, and SPROG. Animated loops are available for each product.

sity and the display indicated locations of other significant phenomena like mesocyclones, tornadic signatures, microbursts, hail, sea breezes, outflow boundaries, and surface wind.

This provided significant new information to the forecasters in Sydney. High-resolution radar products provided new insights into mesoscale circulations in the Sydney region including sea breezes and other outflow boundaries. The nowcasting systems also provided automated precipitation amounts, forecast fields of precipitation, future tracks of thunderstorms and severe weather including hail size, occurrence of downbursts, and rotating thunderstorms. Areas of potential storm initiation, growth, and decay were also available from some of these techniques.

Selected WWRP products were developed for dissemination to the general public and a set of established BOM weather users. The users targeted for the impact study included the aviation industry, the New South Wales (NWS) State Emergency Services, and Bridge Climb, a private company providing tours that climb the Sydney Harbour Bridge. Products for these end users were generated in real time by WWRP but vetted and sourced through the BOM. The Thunderbox system was used to render processed output data from WWRP systems—for example, WDSS Storm Cell Tracking Algorithm or TITAN storm tracks—and then automatically prepare end products in a common graphics format. The emphasis was on providing more geographic details and time specification in warnings, site-specific information, text products, and simple pictures not requiring specialist meteorological training for product interpretation. Dissemination of products was via facsimile and the Web with support from direct interaction with users. This was the first time that these types of high-precision nowcast products were provided directly to nonmeteorological users.

Examples of these products are shown in Fig. 4. In this case the WWRP Web-based product provided to the NSW State Emergency Services on 3 November 2000 during a tornadic storm is shown. Where appropriate, other significant events were represented in these products (e.g., a downburst and tornado). The tornado was diagnosed automatically by the WWRP systems. It should be noted that the Thunderbox enabled the forecasters to fully edit the tracks, cells characteristics, threat area, etc. Automated production of text products conforming to BOM standards followed any such editing. This feature was essential to overcome possible errors in automated product generation, to resolve differences in the algorithm outputs, and to maintain consistency with other official BOM warnings.

WEATHER AND EXAMPLES OF SIGNIFICANT NOWCAST EVENTS. A wide range of events required nowcasting during the S2000 FDP, as described by Webb et al. (2001). Challenging nowcast issues included the movement of thunderstorms off the mountains and into the Sydney basin, sea-breeze development, possible inland motion of coastal showers, and pre- and postfrontal precipitation associated with southerly wind changes and major east coast lows off the coast. Normally the sea breeze moved inland without generating thunderstorm activity. Convective events occurred on some 39 days during the S2000 FDP. Severe thunderstorms occurred in Sydney on 12 days during the FDP.

Winds. A case in which convection was absent but with complex wind changes is shown in Fig. 5. The sea-breeze front (SBF) is clearly evident in the "clear air"

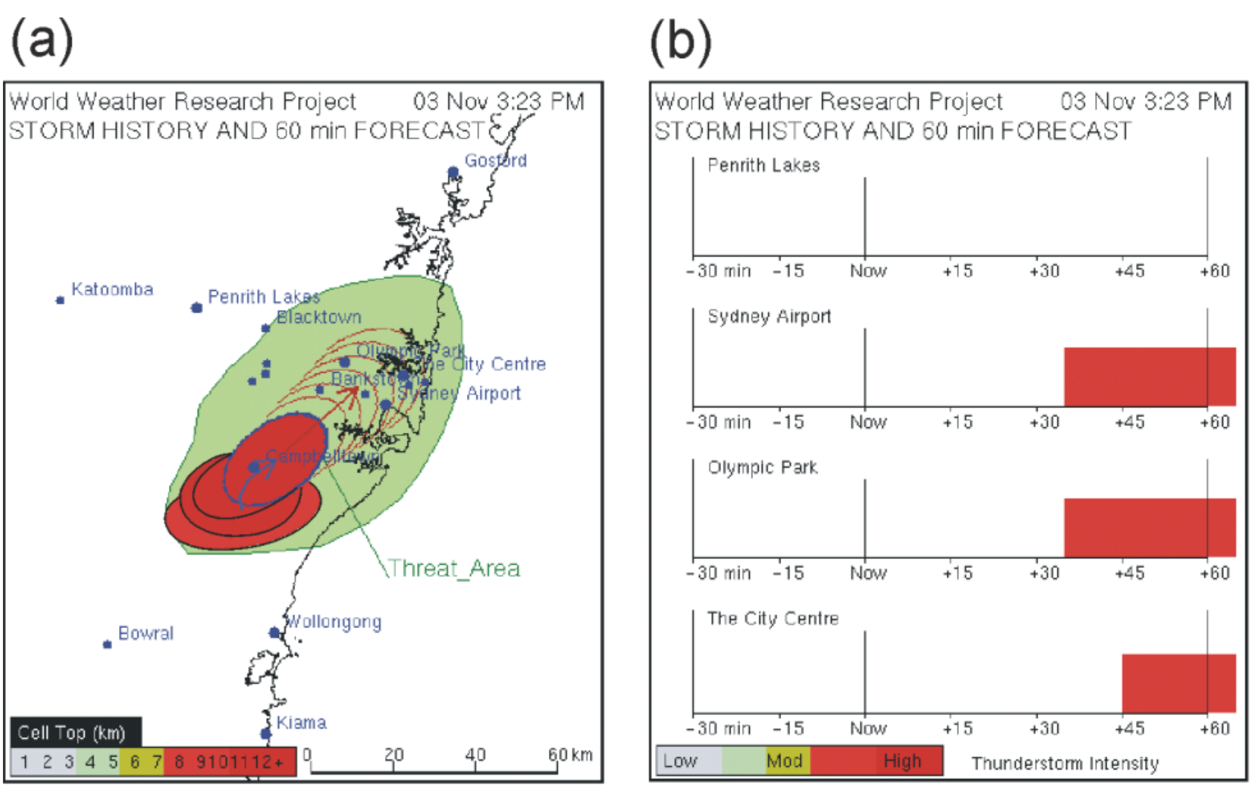


FIG. 4. Example of WWRP S2000 FDP product delivered via Web to NSW State Emergency Service. (a) Storm track, coded by storm intensity with projected storm track, and "storm threat area" for next hour. (b) Point specific time series for the occurrence of precipitation, color-coded by intensity.

signature of the radar data as a thin line "bowing" to the west across the Sydney basin as it moves to the west at ~3 m s^{-1}. The bowing is thought to be associated with higher terrain to the north and south of Sydney slowing advancement of the SBF. Winds at 100-m height derived from the AN VDRAS are superimposed on the radar data in Fig. 5 and show onshore southeasterly flow associated with the sea-breeze circulation behind the SBF. In the convergent westerlies ahead of the SBF, an east-to-west-oriented fine line is evident. This east–west convergence (EWC) zone was observed on several occasions in the Sydney basin and is thought to be associated with the interaction of westerly flow with the mountains to the west of Sydney. In this case, a weak southerly wind change was also progressing from the south through the Sydney domain and is shown by the AN VDRAS winds in Fig. 5. Enhanced convergence along the EWC zone and the southern part of the SBF results. The AN VDRAS analysis was able to capture the convergence along the SBF and the EWC.

Sometimes the establishment of low-level westerly winds across the domain was evident behind a bowing fine line radar echo moving to the east (mirror image of the SBF in Fig. 5). This could "overrun" the SBF and be associated with a late afternoon increase in temperature.

Tracking such wind shifts and providing onset times of fronts gives valuable information to aviation authorities. Typically Sydney airport has 50 slots (take-offs or landings) per hour, but can lose about eight slots in an unplanned runway reconfiguration versus five slots in a planned loss. The cost of keeping a Boeing 747 in holding for seven minutes at Sydney is typically AUD $2000. The ability of the WWRP S2000 FDP systems to monitor and forecast these wind changes, as on 18 September, is obviously important. With the S2000 FDP, forecasters had unprecedented access to this capability in Sydney.

Webb et al. (2001) note other examples where the FDP made an important contribution to wind change nowcasting. For instance, forecasts of the timing of wind and temperature changes are crucial for fire fighters. Identifying the edge of the gusty westerly winds, as shown in Fig. 5, in conjunction with mesonet data (Fig. 1) contributed to nowcasts that enabled fire agencies to reposition personnel prior to the onset of dangerous conditions. Timing of wind and temperature changes associated with southerly "bursters" (Colquhoun et al. 1985) was another important use of S2000 FDP systems.

Severe weather. On 3 November 2000, a severe thunderstorm event generated several weak tornadoes, hail to 7 cm in diameter, flash floods, and strong surface winds in the Sydney metropolitan area. Meteorological conditions of this storm are described in detail by Sills et al. (2001). In this case, within a large-scale trough, heating in the mountains initiated storms but it was additional lift and shear encountered at the sea-breeze front and forcing from outflow boundaries that forced the severe thunderstorm. A long-lived storm moved to the north along the sea-breeze front. At about 0400 UTC, the outflow boundary from the main storm intersected a combined gust front/sea breeze. A hook echo ensued (Fig. 6a). A large bounded weak echo region had echo tops near 19 km. Several short-lived

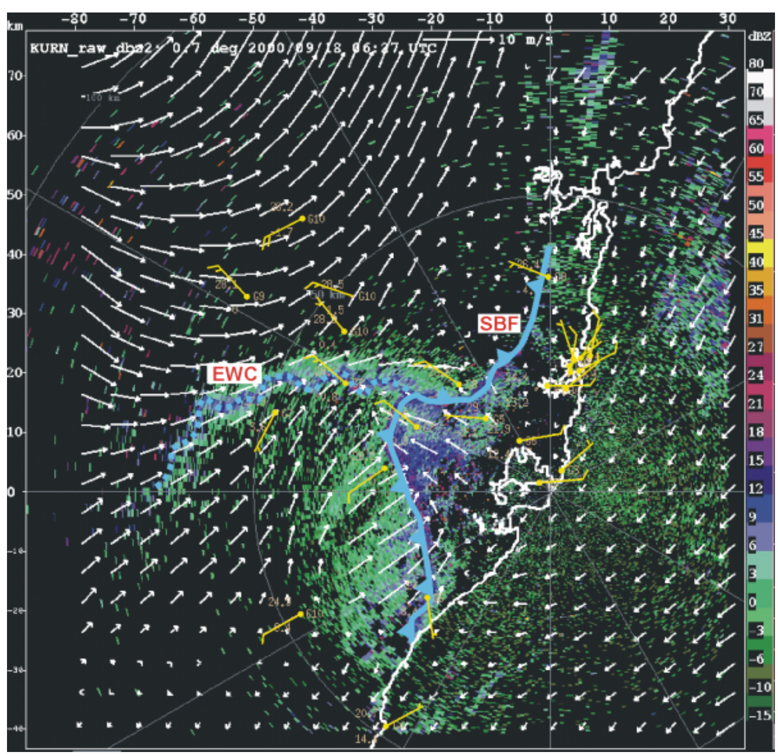


FIG. 5. Example of the capability of WWRP systems to diagnose wind shifts affecting the Sydney area. Kurnell Doppler radar reflectivity at 0626 UTC 18 Sep 2000 with superimposed wind vectors at a height of 180 m. The SBF moving to the west is indicated along with a stationary EWC boundary to the west of Sydney.

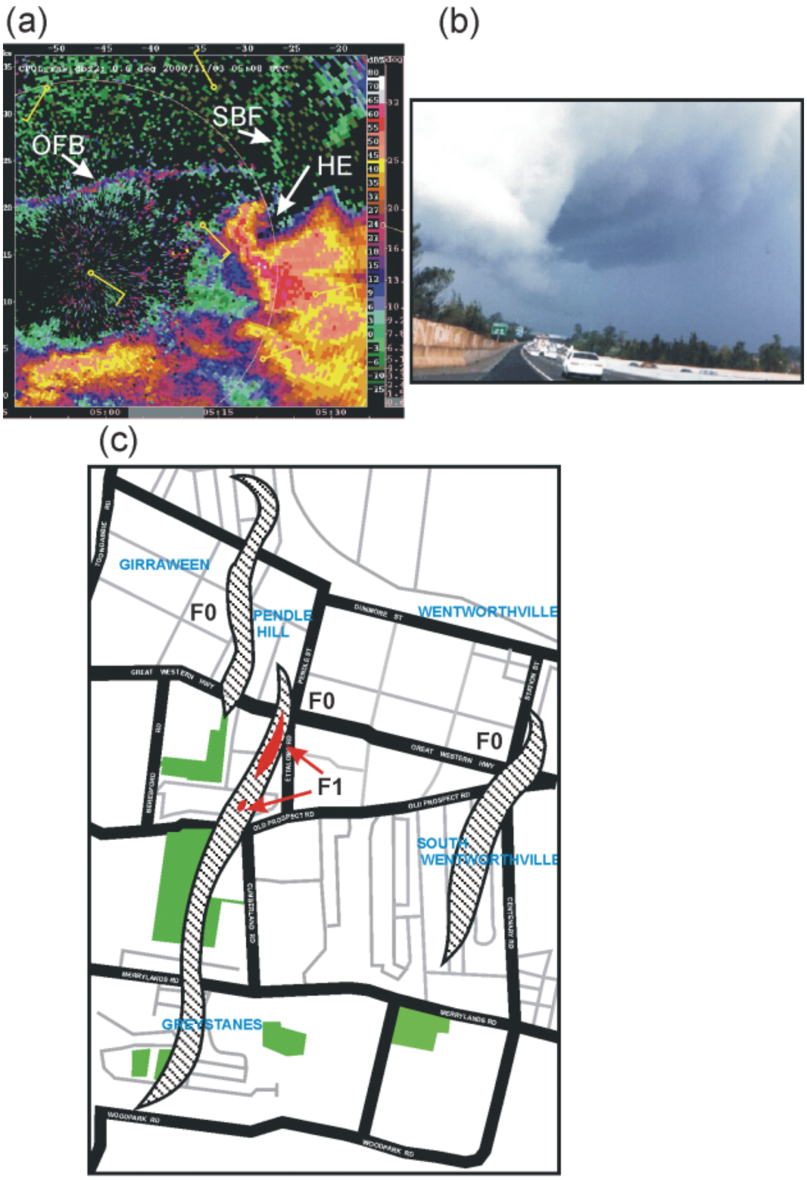


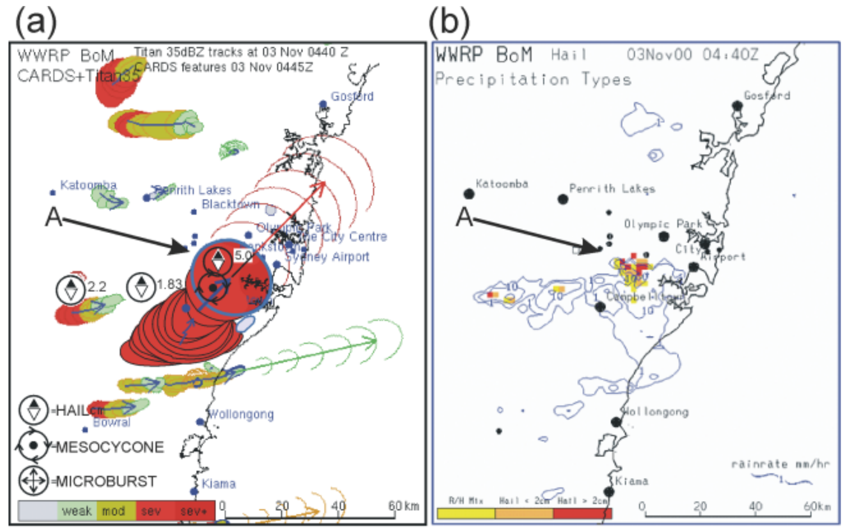
Fig. 6. (a) Hook echo signature observed by CPOL at 0508 UTC 3 Nov 2000. Winds from mesonet stations are overlaid. Note hook echo (HE) at intersection of outflow boundary (OFB), and combined SBF/gust front convergence zone. (b) Photograph taken at 0523 UTC of rotating and lowering cloud base associated with the tornadic storm (image courtesy of Matthew Smith). (c) Damage tracks associated with the 3 Nov 2000 tornadic storm.

tornadoes were observed during the following 30 min below a rotating and lowering cloud base (Fig. 6b). There was widespread hail, with whole neighborhoods covered in some places to a depth of several centimeters. Large roofs collapsed under the weight of the hail, and wind also destroyed roofs and uprooted and snapped trees. A damage track survey, compiled in part by the WWRP representatives (Fig. 6c), shows three 400-m-wide distinct damage swaths clustered in an area 6 km wide by 10 km long. One tornado caused F1 damage on the Fujita (1981) scale over a 6-km path and the others caused F0 damage.

In WWRP S2000 FDP guidance valid in the period 0440–0450 UTC prior to the tornado occurrence (Fig. 7), the main storm (denoted A) is evident along the coastal zone. Weaker storms are evident to the north, west, and south of the tornadic storm A. Analyzed and projected cell locations based on TITAN are represented in schematic form in Fig. 7a with severe weather algorithm output from the CARDS overlaid. At this time, TITAN projected the storm to move across Sydney as was observed. The tornadic storm A is coded severe and at this time the CARDS algorithms indicate it has a mesocyclone and up to 5-cm hail. Smaller hail is implied in storms to the west. CHYD (Fig. 7b) implies that at 0440 UTC storm A has a mixture of rain/hail, small hail, and large hail (> 2 cm) and that small hail with a mixture of rain/hail is present in the storm located to the west. WDSS guidance was consistent with the others. During the 10 min encompassing 0450 UTC (not shown), WDSS indicated a 100% probability of hail of any size, and 80%–100% probabilities of severe hail (> 2.5 cm) in storm A.

The WDSS mesocyclone algorithm implied rotation in storm A between 0440 and 0525 UTC. At this time, based on input from WWRP, BOM forecasters upgraded their severe weather warning to emphasize the hazard from strong winds. At 0525 UTC, at the time the tornado was observed, as shown in Fig. 7c (tornadic storm has CELLID 1), WDSS indicated the presence of a tornadic vortex signature with a mesocyclone (TVSMES). The other WDSS guidance included a severe convective downburst (SEVCNV), a 100% probability of hail of any size, and a 60% probability of hail > 2.5 cm. The CARDS guidance suggested the maximum hail size during the event was 7 cm, and hail this size was observed some 5 km south of the tornadoes.

For this event, the severe weather guidance from the various WWRP S2000 FDP systems was internally consistent and corresponded well to observations. In the context of the FDP, this was particularly encouraging, supporting the contention that the algorithms have the robustness to be operated successfully in varied climatic regimes and with new and independent data sources. Additionally, the WWRP systems and "champions" made a significant contribution to the real-time nowcasting of a rare and important severe weather event.



(c)

NSSL Cell Algorithm Output for Volume 46

CELLID	AZ	RAN	CIRC	BURST	SVRH	SIZE	HAIL	VIL	MAXZ	HT MXZ	BASE	TOP	DIR/SP
1	316	14	TVSMES	SEVCNV	60%	<1.00	100%	47	63	4	1	33	207/10
4	283	21		SEVCNV	0%	<1.00	50%	22	56	2	2	19	230/19
3	276	33		SEVCNV	0%	<1.00	40%	25	56	6	3	25	247/14
2	339	65	CIRC	SEVCNV	0%	<1.00	30%	23	55	8	8	34	239/14
20	237	50			0%	<1.00	40%	21	54	10	6	20	257/19

Fig. 7. Comparison of WWRP S2000 FDP forecaster guidance information near 0440 UTC during the 3 Nov 2000 tornadic storm. (a) TITAN (45-dBZ threshold) observed cell locations and forecast cell locations at 10-min intervals. Output from CARDS algorithm superimposed. Main cell generating the tornado is denoted by A. (b) CYHD polarimetric rain-rate analysis with hail species superimposed. (c) WDSS SCIT summary information on within storm rotation (CIRC), downburst (BURST), severe hail (SVRH) probability of hail of any size (inches), and other radar parameters for various cells. Note CELLID 1 is storm A.

Rainbands. Figure 8 shows WWRP S2000 FDP input to nowcasts as successive rainbands moved from the northwest at 17.5 m s^{-1} through the Sydney area. All guidance retains a two-band structure evident in the verifying analysis. However, differences do exist, particularly in the intensity of precipitation, with Nimrod showing much more intense precipitation than the others. The precise location of the bands also varies (with AN and SPROG moving the bands too rapidly to the east). In this case, use of GANDOLF was probably inappropriate, given it was developed for "airmass" thunderstorm activity. The weakening of convective precipitation in SPROG is also consistent with the expected model behavior.

With a large component of stratiform rain in this case, significant differences occur in the guidance when considering 30-min point forecasts. The general pattern considered on a rain/no rain basis is, however, reasonably consistent. Verification studies are presently assessing the predictability of such point and gridded pattern nowcasts (see below).

IMPACT STUDIES. A societal and economic impacts assessment project was a key component of the S2000 FDP. The impact study intended to determine and measure the uses, benefits, and value of enhanced nowcasts, warning systems, and information provided by S2000 FDP. Primary questions were "how is the enhanced S2000 FDP information used to produce more useful nowcasts?" and "are the (enhanced) nowcasts used and acted upon by the end users?"

The impact studies focused attention on

- forecasters responsible for public, severe weather, and aviation forecasting within the NSWRFC—included were a special set of forecasters employed for the provision of Olympic weather services; and
- end users from the New South Wales State Emergency Services (SES), the Air Traffic Control Authority (AoA), airlines (Ansett Australia, QANTAS, and United Airlines), BridgeClimb, and the general public.

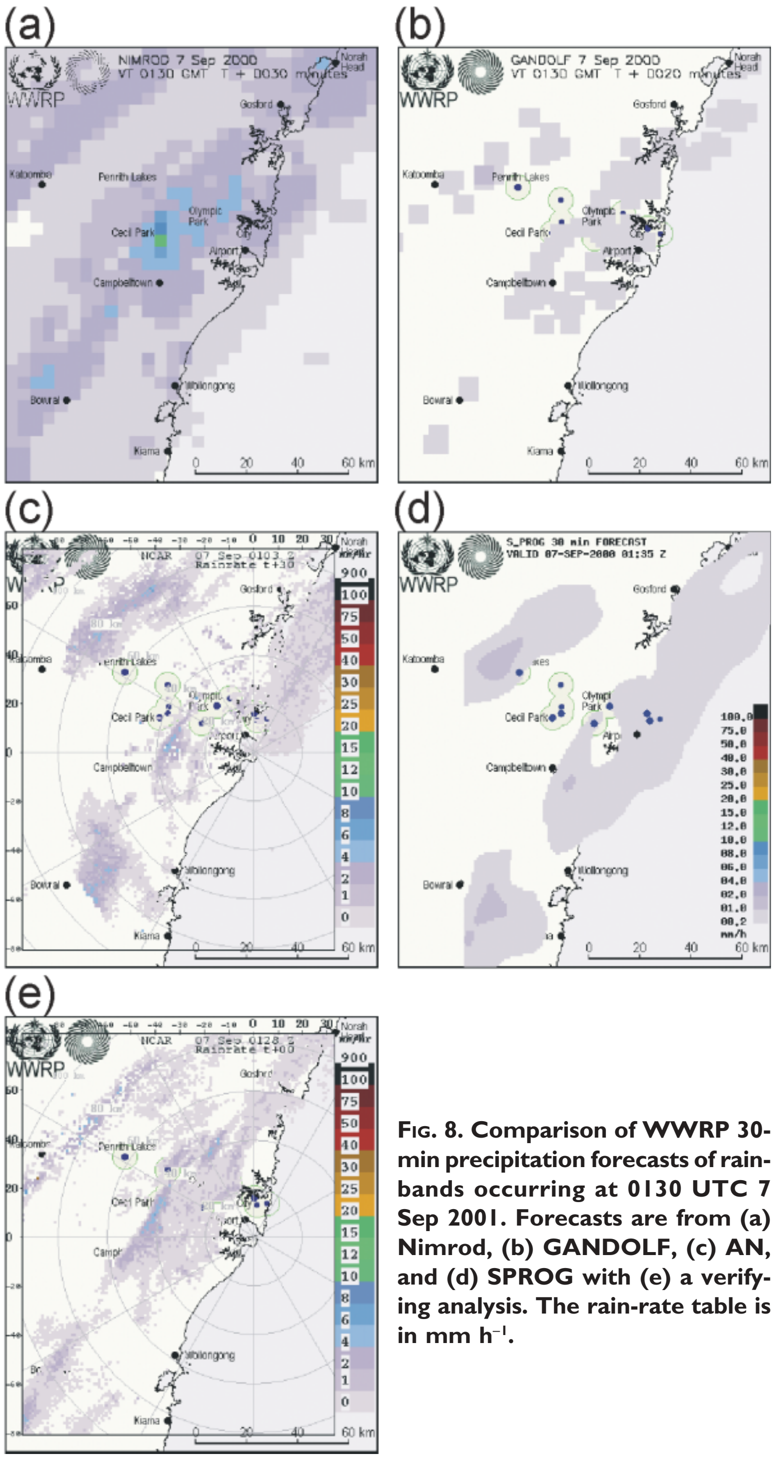


Fig. 8. Comparison of WWRP 30-min precipitation forecasts of rainbands occurring at 0130 UTC 7 Sep 2001. Forecasts are from (a) Nimrod, (b) GANDOLF, (c) AN, and (d) SPROG with (e) a verifying analysis. The rain-rate table is in mm h⁻¹.

The overwhelming response from WWRP product users was positive. All groups, including the general public, demonstrated utility and potential utility of the WWRP products.

Direct economic benefits were less well demonstrated, primarily because of the limited duration of the trial. However, BridgeClimb was able to reduce financial loss and inconvenience to the "climbing" public by minimizing weather-related suspension of operations. Air Services Australia, airlines, and the NSW SES were able to identify potential cost saving and loss reduction using the high-definition WWRP nowcast products.

Forecasters felt that involvement in the FDP had given them a unique opportunity to embrace new technology and extend their forecasting capability. As experience, practice, and increased interaction with WWRP system champions reinforced initial training, the use of WWRP products in the forecast process increased. However, WWRP products were not used in isolation by forecasters and they had access to familiar procedures and technology. In this sense, nowcasting during the FDP employed a combination of existing techniques and new information from WWRP. The impacts study clearly demonstrated the importance of training and communication in establishing new technology and processes. Direct involvement of the system developers and forecasters in a common operational setting was seen as most beneficial to both camps.

The impacts study established a greater awareness to end-user requirements, raising the level of communication and feedback associated with the provision of BOM weather services. This applied to both the forecasters and end users. During the Olympics, not only was precipitation onset time important for event organizers, but its cessation time was equally or more important. For the SES, past storm tracks were just as important as future tracks, given resource deployment issues. During planning, potential weather impacts on exposed spectators and participants became important for Olympic event managers.

Perception of forecast quality depended somewhat on a person's role. Forecasters generally considered issues of technical accuracy as most important. Users considered product "effectiveness" in terms of timeliness and comprehensibility and suitability for decision-making. Communication between producers and users often facilitated better nowcasts in terms of end-user utility.

In terms of overall impact, aviation and severe weather products developed as part of WWRP are now being developed and integrated into the provision of BOM services.

VERIFICATION STUDIES. An international team assembled by the WWRP from Australia, Canada, Finland, Germany, the United Kingdom, and the United States is verifying S2000 FDP products. They are considering six areas of nowcasting:

- convective cell nowcasting and prediction of speed and direction;
- accuracy of quantitative precipitation nowcasting, including rain rate and occurrence;
- accuracy of nowcasts of boundary layer convergence;
- accuracy of severe thunderstorm wind gust nowcasts;
- accuracy of hail location and size detections and nowcasts; and
- improvements by forecasters to automated nowcasts.

To date, considerable effort has been devoted to defining particular verification objectives and the production of suitable datasets for the verification activities. Assessment of the accuracy of predicted storm strength and cell location based on gridded fields is one example of current convective cell–based verification work. The verification of a 30-min SPROG nowcast is shown in Fig. 9. The quantitative assessment of the forecast is provided using pattern matching, following Ebert and McBride (2000). In Fig. 9, the arrow shows the forecast position was ~10 km northeast of the observed position. Approximately 50% of the forecast error was associated with displacement and the rest with pattern error. Rain volume error was relatively small and after adjustment for the displacement error, the correlation (see graph insert in Fig. 9 for plot) between the forecast and observed rainfall was 0.543.

Further information on the verification activities is summarized by Brown et al. (2001).

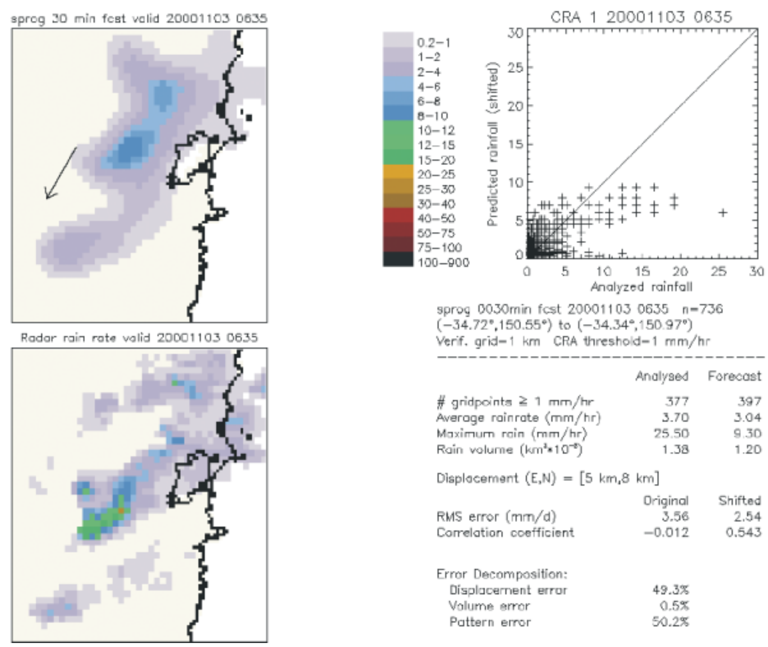


FIG. 9. Entity-based verification for a SPROG prediction at 0635 UTC 3 Nov. Contiguous rain areas (CRAs) within a prescribed isohyet (1 mm h^{-1} in this case) are defined in the forecast and analysis. The vector displacement of the forecast position from the observed position is derived by translating the forecast until the total squared error between the forecast and observed fields is minimized over the CRA. The mean-square error is then decomposed into location, rain volume, and finescale pattern errors. (upper left panel) 30-min SPROG forecast with corresponding validating analysis below. (top right) Graph of forecast and verified rainfall (mm) after correction for displacement error as defined in text. (lower right) Summary statistics for entity verification.

LESSONS LEARNED AND PRESENT STATUS. The project did provide a major advancement on "current" nowcast capabilities for BOM forecasters in Australia. Australian forecasters were experienced in using modern Doppler radar technology that is so important in nowcasting. But the S2000 FDP took the next step and provided automated guidance and interpretation from complex radar data signatures that previously relied on manual interpretation. Issues associated with identifying and nowcasting wind changes became simpler through the identification of radar-detected boundary layer features associated with sea breezes, gust fronts, and synoptic fronts. Site specific and area quantitative rainfall prediction became available. In addition, hail guidance and associated severe weather information was provided automatically and in a timely manner.

However, it is a major challenge to take new systems developed by the research community in different regions and countries and implement them in a new operational environment in a foreign country, making them work effectively for both forecasters and end users. This was the goal of the S2000 FDP and in the process many lessons were learned.

Implementing the WWRP system was a big undertaking for the BOM host and the various WWRP participants. Getting the various systems to operate within the BOM infrastructure required upgrades to the BOM systems with tuning and associated rationalization in the operations of the WWRP systems. The BOM required upgrades to radar signal processing, communication, and data servers before the WWRP systems could function adequately. Policy decisions and clarification of the respective roles of standard BOM and the enhanced WWRP products were very important and required before the BOM would support the FDP. Issues included potential problems associated with conflicting information in BOM and WWRP forecast products, responsibilities for products issued via BOM sources, the extent to which "experimental" WWRP products should be used to enhance "official" BOM products and the role of WWRP in forecast product evaluation given established BOM clients were involved.

For the WWRP, the Australian data sources required significant algorithm tuning—for example, C-band versus S-band radar data (Nyquist interval smaller, more frequent occurrence of attenuation effects), occurrence of extensive sea clutter, restriction to hourly satellite data (AN cloud-detection algorithms could not be invoked), and a different NWP source (Nimrod and GANDOLF). As a result, the implementation required longer lead times and more preoperation trials than expected.

Earlier implementation of final WWRP products would probably have resulted in more effective training, quality assurance, real-time verification, and increased initial forecaster confidence. More effective end-user product design and the associated impact study implementation and on-going monitoring would have occurred. With stable end products, clients would have been more experienced in their interpretation and use. Unfortunately, for many reasons it was not possible to establish new integrated observing networks, nine new and foreign WWRP forecast systems, and undertake training of forecasters and end users to an optical extent in the one year allocated.

Hence to a certain degree the three-month evaluation period of the FDP was at best minimal and issues discussed above were compounded because of time constraints. More time would have ensured more frequent and significant weather events and of course more use of WWRP systems. The impact of new technology on the forecast process and ultimately the impact on end products typically requires several years, as indicated in data presented by Crum et al. (1998) for the Next Generation Weather Radar (NEXRAD).

Implementation of more explicit NWP products would have enhanced our knowledge of dynamical factors affecting nowcasting and significantly improved guidance for the associated outlook period (say 24 h). This sort of guidance would have been valuable in enhancing the production of many BOM products, especially during Olympic events that extended beyond the 3-h validity period on which WWRP systems focused. These longer-term forecasts were often time consuming and based essentially on assessment of NWP information. Although nowcasting is often significant for large impact events (e.g., severe storms, flooding), systems for more routine and regular generic products such as Terminal Area Forecasts can also have significant impact on issues and work practices directly affecting a forecaster. More FDP contribution to those issues would certainly have made a stronger impact across all forecast activities.

This FDP did involve state-of-the-art systems and applications. In many cases the applications performed well and were obviously robust for operations. Many participants felt that a store of these applications in a more modular, independent form would assist case-by-case-type nowcast developments under way in many countries. Under this scenario, full implementation of entire WWRP systems would not be necessary.

SUMMARY AND CONCLUSIONS. The S2000 FDP brought together diverse nowcast systems that for the first time covering many nowcast timescales and applications. No single system provided this capability and in totality they provided a glimpse of the future. Consistent with its goal, the S2000 FDP demonstrated that advanced nowcast systems were robust and transferable to a new location and could be operated successfully in an operational forecast environment. The FDP showed that international collaboration can be focused on local problems and demonstrates that global solutions exist to many nowcasting problems with significant economic and societal impact.

The S2000 FDP was very successful in bringing developers, forecasters, and end users together to work on common problems in an operational setting. In this respect it acted as a bridge between all three groups with significant cross-fertilization of ideas, on-going evaluation of systems and concepts in a way that no research workshop environment can ever simulate. This was especially the case for the international group of researchers involved in the project. The FDP presented a cost-effective approach to gain in-depth understanding and evaluation of the various systems involved in the S2000 FDP. The gains from this unique and effective approach should be recalled when people ask about the possible benefits of participating in a nowcasting project on the other side of the planet. All nations involved are building on the lessons learned during S2000.

A unique training workshop (see sidebar) held during the S2000 FDP provided the attendees unprecedented access to the WWRP systems, champions, and to the lessons learned. However, training, a fundamental issue often not developed and maintained to the degree required in the implementation of new approaches, again proved important during S2000 FDP. The human role was also important in understanding why differences appeared in WWRP guidance. For the AN, which attempts to forecast the growth and decay of storms, human intervention was employed routinely to enter and interpret convergent zones in the boundary layer; that is, it employed a mix of machine and man. Hence training of people is integral to nowcasting.

The S2000 FDP has spawned nowcasting impact and verification studies that are continuing. For the first time an independent international group is focused on verification of nowcasts using a common dataset generated under operational conditions using the latest nowcast approaches. The impact studies have taken the evaluation beyond the more usual in-house measures relating to forecast office experience and the system errors. The usage and understanding of information presented to end users is ultimately as important as the nowcasting process itself and clearly needs to be incorporated in any evaluation process.

Importantly, all involved saw advantages in the continuation of the project and many of the WWRP systems are still being employed by the BOM in Sydney.

ACKNOWLEDGMENTS. This project was conducted with the direct and indirect support of many agencies and individuals. The BOM, as host, provided considerable ongoing and infrastructure support for the FDP and many individuals contributed much to ensure the projects success. The participation of the Autonowcaster and NCAR personnel was made possible by the U.S. Weather Research Program and NSF base funds to NCAR.

THE S2000 TRAINING WORKSHOP

The operation of these diverse nowcasting systems in a common operational setting provided a unique opportunity to conduct an international WMO-sponsored training workshop in conjunction with the S2000 FDP. The workshop was aimed at providing training and experience in the use of modern nowcast systems and procedures enabling participants to

- **further their understanding of the latest nowcasting science;**
- **assess the current status of advanced nowcasting systems;**
- **assess the potential and value, as well as relative strengths and weaknesses, of the various nowcasting methods; and**
- **be aware of the issues involved in the development and deployment of various nowcasting systems.**

The workshop involved introductory theory, lectures focused on understanding the FDP systems, familiarization with Sydney weather, and gaining an appreciation of the aims and operation of the FDP, including the verification and impact studies. Hands-on experience followed using "canned" Sydney-based nowcast case studies with the various S2000 FDP systems, and when possible, real-time cases as they evolved.

REFERENCES

Bally, J., 2001: Generating severe weather warnings from TITAN and SCIT thunderstorm tracks. Preprints, *30th Conf. on Radar Meteorology,* Munich, Germany, Amer. Meteor. Soc., 489–491.

Brown, B., and Coauthors, 2001: Forecast verification activities for the Sydney 2000 Forecast Demonstration Project. Preprints, *30th Conf. on Radar Meteorology,* Munich, Germany, Amer. Meteor Soc., 500–502.

Colquhoun, J. R., D. J. Sheperd, C. E. Coulman, R. K. Smith, and K. McInees, 1985: The southerly burster of southeastern Australia: An orographically forced cold front. *Mon. Wea. Rev.,* **113,** 2090–2107.

Crook, N. A., and J. Sun, 2001: Assimilating radar, surface, and profiler data for the Sydney 2000 Forecast Demonstration Project. Preprints, *30th Conf. on Radar Meteorology,* Munich, Germany, Amer. Meteor. Soc., 480–483.

Crum, T., R. E. Saffle, and J. Wilson, 1998: An update on the NEXRAD program and future WSR-88D support to operations. *Wea. Forecasting,* **13,** 253–262.

Dixon, M., and G. Wiener, 1993: TITAN: Thunderstorm identification, tracking, analysis, and nowcasting—A radar-based methodology. *J. Atmos. Oceanic Technol.,* **10,** 785–797.

Ebert, E. E., and J. L. McBride, 2000: Verification of precipitation in weather systems: Determination of systematic errors. *J. Hydrol.,* **239,** 179–202.

Eilts, M., and Coauthors, 1996: Severe weather warning decision support system. Preprints, *18th Conf. on Severe Local Storms,* San Francisco, CA, Amer. Meteor. Soc., 536–540.

Fujita, T. T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.,* **38,** 1511–1534.

Golding, B. W., 1998: Nimrod: A system for generating automated very short range forecasts. *Meteor. Appl.,* **5,** 1–16.

Keenan, T., 1999: Hydrometeor classification with a C-Band polarimetric radar. Preprints, *29th Int. Conf. on Radar Meteorology,* Montreal, QC, Canada, Amer. Meteor. Soc., 184–187.

——, K. Glasson, F. Cummings, T. Bird, J. Keeler, and J. Lutz, 1998: The BMRC/C-band polarimetric (CPOL) radar system. *J. Atmos. Oceanic Technol.,* **15,** 871–886.

Lapczak, S., and Coauthors, 1999: The Canadian National Radar Project. Preprints, *29th Int. Conf. on Radar Meteorology,* Montreal, QC, Canada, Amer. Meteor. Soc., 327–330.

May, P., 2001: Mesocyclone and microburst signature distortion with dual PRT radars. *J. Atmos. Oceanic Technol.,* **18,** 1229–1233.

Mueller, C. K., T. Saxen, R. Roberts, and J. Wilson, 2000: Evaluation of the NCAR thunderstorm Auto-Nowcast system. Preprints, *Ninth Conf. on the Aviation, Range and Aerospace Meteorology,* Orlando, FL, Amer. Meteor. Soc., J40–J45.

Pierce, C. E., P. J. Hardaker, C. G. Collier, and C. M. Haggett, 2000: GANDOLF: A system for generating automated nowcasts of convective precipitation. *Meteor. Apps.,* **7,** 341–360.

Puri, K., G. S. Dietachmayer, G. A. Mills, N. E. Davidson, R. A. Bowen, and L. W. Logan, 1998: The new BMRC Limited-Area Prediction System: LAPS. *Aust. Meteor. Mag.,* **47,** 203–223.

Rothfusz, L. P., M. R. McLaughlin, and S. K. Rinard, 1998: An overview of NWS support to the XXVI Olympiad. *Bull. Amer. Meteor. Soc.,* **79,** 845–860.

Seed, A., and T. Keenan, 2001: A dynamic and spatial scaling approach to advection forecasting. Preprints, *30th Conf. on Radar Meteorology,* Munich, Germany, Amer. Meteor. Soc., 492–494.

Sills, D., J. Wilson, C. Mueller, N. Fox, D. Burgess, P. Joe, P. Dunda, and R. Webb, 2001: Meteorological aspects of the 3 November 2000 severe storms in Sydney, Australia. Preprints, *30th Conf. on Radar Meteorology,* Munich, Germany, Amer. Meteor. Soc., 495–497.

Sun, J., and A. Crook, 1994: Wind and thermodynamic retrieval from single-Doppler measurements of a gust front observed during Phoenix II. *Mon. Wea. Rev.,* **122,** 1075–1091.

——, and ——, 1997: Dynamical and microphysical retrieval from Doppler radar observations using a cloud model and its adjoint. Part I: Model development and simulated data experiments. *J. Atmos. Sci.,* **54,** 1642–1661.

Vivekanandan, J., D. S. Zrnic, S. M. Ellis, R. Oye, A. V. Ryzhkov, and J. Straka, 1999: Cloud microphysics retrieval using S-Band dual polarization radar measurements. *Bull. Amer. Meteor. Soc.,* **80,** 381–388.

Webb, R. M., A. Treloar, J. Colquhoun, R. Potts, J. Bally, T. Keenan, and P. May, 2001: Overview of Sydney weather during the Forecast Demonstration Project. Preprints, *30th Conf. on Radar Meteorology,* Munich, Germany, Amer. Meteor. Soc., 477–479.

Wilson, J. W., and D. L. Megenhardt, 1997: Thunderstorm initiation, organization, and lifetime associated with Florida boundary layer convergence lines. *Mon. Wea. Rev.,* **125,** 1507–1525.

Zrnic, D. S., and A. Ryzhkov, 1996: Advantages of rain measurements using specific differential phase. *J. Atmos. Oceanic Technol.,* **13,** 454–464.