Perspectives on operational weather forecasting and warning in tropical Australia

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Operational weather services in the Australian tropics have been influenced by such external pressures as tropical cyclone disasters, the growth of commercial aviation, the Second World War, and post-war development. Important post-war responses included the establishment of the Darwin Tropical Analysis Centre and the emergence of research interest in tropical meteorology.

Our current public weather services focus on routine short to medium-range forecasts and severe weather warnings. The former are not well matched to scientific capabilities, and leave important forecasting time-scales unserviced. Future service developments are likely to see more attention directed to very short-range forecasts, and to the intra-seasonal and seasonal time-scales.

Tropical cyclone warning accuracy in Australia can be expected to improve in the short to medium term, reaping the benefits that new remote sensing systems and improved surface observations will provide to cyclone tracking and intensity estimation, and from the operational use of improved objective prediction models. An important area for attention is the communication of cyclone warning information in ways that will optimise the socio-economic benefits of the warning system.

Historical Perspective

The major developments in weather forecasting in the Australian tropics can be traced to several important influences. The first is the destruction wrought by tropical cyclones. Our earliest Queensland weather forecaster, Clement Wragge (Fig. 1), provided a flamboyant beginning to operational tropical cyclone warning during the term of his appointment as Queensland Government Meteorologist (1887–1903). It was he who first introduced the practice of naming tropical cyclones (as well as other weather systems), calling them after figures from the classics, the Bible, history, and even current politicians! In conjunction with the Brisbane Postmaster, Wragge introduced a system of storm signals which were hauled up at lighthouses from Cape Moreton to Thursday Island and Karumba, by direct instructions telegraphed from the Weather Bureau.

On 1 January 1908 meteorological services became a Commonwealth function. The periodic disasters along the coast and at sea (Table 1) maintained a focus on tropical cyclone warning in the Queensland Divisional Office of the Bureau of Meteorology (BOM).

A period of cyclone and flood disasters in Queensland from 1949 through the 1950s gave impetus to the development of a more rigorous cyclone warning organisation, and the Tropical Cyclone Warning Centre was institutionalised in Brisbane in the 1954–55 cyclone season. An in-house Tropical Cyclone Conference, held in Brisbane in September 1955, saw the beginnings of the modern attack on tropical cyclone warning problems. An extract from the proceedings of this conference was prophetic:

‘Illustrations were presented at the conference showing how radar had been actually utilised overseas in the tracking of tropical cyclones...’

Australia’s first international tropical cyclone conference was held in the Physics Department of the University of Queensland in December 1956, where a paper presented by Brann et al. (1956) described an Australian first, the issuance of cyclone warnings assisted by radar observations from the BOM’s Townsville radar. Major development of the Bureau’s early warning network of coastal radar stations and offshore automatic
weather stations took place during the 1960s and early 1970s.

The cyclone Tracy disaster in Darwin on 25 December 1974 provided a new dimension to our perception of the tropical cyclone problem in Australia, and in 1976 a Government Committee of Inquiry into the Bureau of Meteorology recommended that tropical cyclone warning be a function of the Bureau of the highest priority. The landmark Symposium on the Impact of Tropical Cyclones on Oil and Mineral Developments in North-west Australia, held in Perth in 1976, resulted in the establishment of a Tropical Cyclone Industrial Liaison Committee and the provision of focused cyclone advisory services to industrial clients by the Perth Bureau. User consultation became a prominent philosophy of the cyclone warning service, with public surveys and seminars, media seminars, post-event surveys and radio talk-back programs all part of the job. After cyclone Tracy there were enormous pressures for the warning system to perform flawlessly, though resources for significant service developments were wanting.

An important milestone was realised in 1987 with the provision by the Government of specialist staff and funding for the development of severe weather warning services, with a major focus on tropical cyclone and flood warning.

The next important influences were the growth of commercial aviation, which led to the establishment of operational forecasting offices at Darwin, Rockhampton, Townsville, Port Moresby and Lae during the late 1930s, and the Second World War (Gibbs 1982). The massive deployment of forces in the Pacific theatre of war focused the attention of the Royal Australian Air Force (RAAF) Meteorological Service on tropical weather forecasting. The dominating influence of topography and diurnal variation within the nearly barotropic air mass was soon recognised and, as a consequence, attempts to transverse into the tropics the principles of air mass and frontal analysis, and the associated prediction models that had been developed in middle latitudes, had to be modified or abandoned. By the end of the war an appreciation of air parcel modification in the trades and the non-frontal nature of convergence zones within a nearly barotropic equatorial air mass was emerging (e.g. Gibbs 1945). The interest and debate in tropical forecasting and supporting research during the war is preserved in the RAAF Tropical Weather Research Bulletins.

Although tropical cyclone warning became a very high priority during the 1950s, for nearly two decades after the war research interest in the general problems of tropical meteorology in Australia received little attention. A significant exception was the work of A.J. Troup and F.A. Berson on the southern oscillation and aspects of the monsoon (e.g. Troup 1961, 1965; Berson 1961; Berson and Troup 1961).

The BOM’s aviation offices continued to grapple with the problems of tropical forecasting and, in recognition of the needs in an important area of operational meteorology, a small tropical analysis group was established at the aviation forecast office in Darwin in the early 1960s. Under the leadership of Robert Southern, who employed manual streamline analysis techniques acquired at the Advanced Tropical Meteorology Course at the University of Hawaii, this group was expanded to become the Tropical Analysis Centre, and a Regional Meteorological Centre (RMC) under the World Weather Watch in 1967.

The establishment of the tropical meteorology program at Darwin had an important impact on research as well as tropical operations. An operational analysis set straddling the equator from 40°N to 40°S; from 70°E to the dateline, encompassing the global hot box of the ‘maritime continent’ and the Indo-Asian monsoons, became available in Australia for the first time since the war. Forecasters in Darwin soon observed the
Table 1. Some major cyclone impacts on Queensland.

| January 1884 | Bowen       | Nearly whole town unroofed and many places completely wrecked. 3 m storm surge at Pool Is. |
| March 1887   | Burketown   | 5 killed. Nearly every building damaged. |
| March 1903   | Townsville  | Bowen  | Nearly wrecked the whole town of Townsville. 10 killed. |
| March 1911   | Port Douglas | Cairns | 2 killed and most buildings at Port Douglas damaged. Severe damage at Cairns. |
| January 1918 | Mackay      | 30 killed. 3.9 m storm surge, and one million pounds property damage at Mackay. Barometer 933 hPa. |
| March 1918   | Innisfail   | 16 killed. Great damage Innisfail and Babinda districts. 3 m storm surge. |
| March 1934   | Port Douglas area Cardwell, Ingham | 75 killed, many luggers lost. 1.9 m storm surge at Port Douglas. Extensive damage Cardwell to Townsville. Barometer 965 hPa at Ingham. |
| February 1940 | Mackay     | Cape Capricorn | 8 killed at sea. Barometer 957 hPa at Mackay. |
| March 1955   | Townsville  | Extensive damage Townsville to Cairns. 4 killed by floods. Townsville barometer 961 hPa. |
| April 1958   | Bowen       | Extensive damage. 77 houses and various other buildings destroyed. 1 killed. $2M property damage. Barometer 948 hPa. |
| February 1959 | Ayr, Home Hill | Bowen/Proserpine |  |
| January 1970 | Whitsunday Islands | Townsville | Ada. 13 killed mostly at sea. More than $12M damage to resorts. Althea. 3 killed, $50M damage. 3 m storm surge. Barometer 952 hPa. |
| December 1971 | Mornington Island | Burketown | Ted. $8M damage Mornington Island and Burketown. Barometer 950 hPa. |
| December 1976 | Cairns to Cardwell | 3 killed. $130M damage to property and crops. Barometer 958 hPa. |
| February 1986 | Ayr, Home Hill region | Aivu. 1 killed. $90M damage to property and crops. Barometer 959 hPa. |

importance of large-scale forcing in the tropics. Their analyses enabled them to develop synoptic forecasting models which invoked interactions from the subtropics of both hemispheres, including inter-hemispheric forcing of tropical cyclone genesis events (e.g. Love 1985).

In September 1982, at the height of the most severe El Niño-Southern Oscillation (ENSO) event this century, the Darwin RMC commenced issuing its Large-Scale Diagnostic Statements, providing a near real-time summary of the tropical circulation in its analysis area. Diagnostic outputs from the BOM’s automated tropical analysis scheme (Davidson and McAveney 1981) have since been incorporated in these bulletins.

An advantage of the Darwin program has been the blend of experience in a formal large-scale analysis program and in operational forecasting and warning provided to meteorologists at the centre. Moreover, staff mobility has spread this experience to many areas of the Bureau. With the establishment of the tropical analysis program came a resurgence of interest in tropical research, which gained momentum during the late 1960s and 1970s and continues as a major program in the Bureau of Meteorology Research Centre (BMRC). It might be mentioned here that three of the Darwin forecasters, Bill Kininmonth, Geoff Love and Greg Holland, obtained higher degrees in tropical meteorology at Colorado State University under Professors Riehl and Gray. In the late 1970s work was commenced on a numerical tropical analysis scheme at the Australian Numerical Meteorology Research Centre (ANMRC) for both operational use in Darwin and for research purposes (Davidson and McAveney, op. cit.). At about the same time, a monsoon experiment, AMEX (Holland et al. 1986), was being conceived by the BOM’s Synoptic Research Group. The successful realisation of both of these goals under the auspices of the new BMRC involved very fruitful collaborations between the research establishments in Melbourne and operational staff working in the tropics.

Current operational services

In this section the efficacy of current forecasting and warning services in the tropics and a near subtropical station, Brisbane, are reviewed with a
view to suggesting profitable directions for future service developments.

The tropical cyclone warning service

As mentioned, tropical cyclone warning is considered to be the Bureau's highest priority operational function. Whilst improving the accuracy and timeliness of tropical cyclone warnings present scientific and technological challenges on several fronts, complex sociological questions are involved in attempting to optimise the socio-economic benefits of the warning system.

Tropical cyclone tracks are so variable in the Australian region that climatology contributes very little to the forecasting of cyclone motion (Keenan 1982; Pike 1985). This is illustrated by Fig. 2 from Keenan, which shows the relative contributions of persistence, climatology and synoptic geopotential height fields to the reduction in variance of track forecast errors. The operational reality of Fig. 2 is demonstrated by verifications of 12-hour cyclone movement predictions in Australia's Eastern and Northern regions shown in Fig. 3. Forecasts on this time-scale are critical as cyclones approach landfall. The similarity of average operational 12-hour movement forecasts to real-time persistence forecasts is striking. In the Northern region, where radar and offshore automatic weather station networks are less developed, notable improvements in forecast accuracy have coincided with improvements in surveillance facilities: first with the commencement of the Japanese GMS satellite program in 1978–79, and likely again with the commissioning of the Weipa and Gove radars in 1986–87. In the Eastern region the coastal radar and offshore automatic weather station networks were comparatively well developed by the early 1970s, and subsequent improvements in performance have been much smaller. The indications from Fig. 2 are that forecasts beyond 12 hours become increasingly skillful relative to persistence, however, the magnitude of the average forecast position error at 24 hours is about 250 km, considerably larger than the typical destructive radius of tropical cyclones.

Tropical cyclone warning strategies necessarily recognise the probabilistic nature of cyclone movement forecasts. The Cyclone Warning Centre in Brisbane currently adopts a quite conservative procedure by declaring areas under Cyclone Watch and Cyclone Warning guided by whether there is a better than 5 per cent chance of a cyclone strike within 48 hours and 24 hours respectively, having regard to the forecast track and the distributions of historical track forecast errors.

Tropical cyclone intensities and intensity trends are mostly estimated from satellite data. The pattern recognition methodology developed and periodically refined by Dvorak (e.g. Dvorak

Fig. 2 Reduction of error variance in regression forecasts of Australian region tropical cyclone motion obtained with predictor sets based on persistence, climatology, synoptic analyses and a combination of all three. After Keenan (1982).

Fig. 3 Three-year running means of annual average 12-hour tropical cyclone forecast position errors for (a) Australia's Eastern region and (b) Australia's Northern region. (A — operational forecasts, B — real-time persistence forecasts, C — best track persistence hindcasts (Eastern region only).)
1984) has been a cornerstone of cyclone warning centre operations for nearly a decade, and while most forecasters consider the technique to be indispensable to their operations, there have been few opportunities to verify intensity estimates in the Australian region. A serious under-estimation of the intensity based on satellite data was revealed by a NOAA research aircraft investigation of cyclone Kerry (Holland 1981). The uncertainty in current intensity estimates, paucity of 4-dimensional observational data in tropical cyclones, and incomplete dynamical understanding, are inhibiting skillful forecasts of cyclone intensity changes (Keenan 1982).

On the socio-economic side, our public extension activities after cyclone Winifred (Bureau of Meteorology 1986) showed that responses to cyclone warnings may benefit from improved public understanding of the nature of tropical cyclones, from improved communication during the warning process of the level and nature of the threat, and what people should be doing to prepare. As a result of the Winifred experience we have modified our warning messages, and have arranged for community service messages to be broadcast advising of telephone recorded warning message services, and of material including cyclone tracking maps, cyclone hazard descriptions, and preparedness advice contained in telephone directories. As a further step, the BOM plans to introduce a simple tropical cyclone intensity scale for use in the Australian region in late 1989.

**Nowcasts**

The only regular weather forecast services specifically focused on time-scales of three hours or less in Australia are severe thunderstorm warning services for the capital cities, and trend type forecasts (TTF) for aerodromes.

Holland et al. (1987) provided a verification of predictions of hazardous conditions (thunderstorms, low cloud, fog, reduced visibility in heavy rain) in short-range forecasts (TAF period 4–10 h) and nowcasts (TTF period 0–3 h) for Darwin aerodrome during the rainy seasons of 1983 and 1984. The interesting result is that the TAF issued 4 hours before the verification period for a 6-hour window showed more skill than the TTF issued at the commencement of its 3-hour window. Although this comparison is not strictly fair, an interpretation of the TTF verification was that non-linear developments and a natural forecaster bias on the side of safety often defeat the 3-hour ‘nowcast’.

Verification of severe thunderstorm warnings for Brisbane for the seven seasons shown in Fig. 4 suggests the warning service has improved dramatically during the period. We believe this can be attributed to new technology, such as colour radar display systems, in the Regional Forecasting Centre. While the lead times of thunderstorm warnings have not been systematically verified, our experience suggests that lead times of about an hour are often achievable. However, lead times are often very short or non-existent in part of the affected areas. Furthermore, there may be intolerable delays in the chain of events between identification of a threat and the broadcast of warnings by the media. The following case serves to illustrate the significance of very short-range forecasting problems.

**Fig. 4** Severe thunderstorm warning accuracy for Brisbane for summers 1981/82 to 1987/88 as indicated by plots of the probability of detection (POD), the false alarm ratio (FAR), and the critical skill index (CSI). Lines show three season running means. POD = A/(A + B), FAR = C/(A + C), CSI = A/(A + B + C) where A refers to a correct forecast, B is a forecast event that fails to occur, and C is a forecast of a non-event that occurs as an event.

A forecasting case study: the Brisbane thunderstorm of 18 January 1985. Between 1600 and 1700 LST on the afternoon of 18 January 1985, Brisbane was struck by a severe thunderstorm. During the 10 to 15-minute peak of the storm, a wind gust of 184 km/h was recorded at Brisbane Airport and hail was reported up to the size of tennis balls. Insured losses were placed at $192M along a strip 10 km wide. Included were damages
to over 20,000 buildings, and 29,512 insurance claims on motor vehicles. Claims on vehicle fleets and car sales yards were counted as single claims (source: Insurance Council of Australia).

The development and subsequent movement of the storm, as indicated in Fig. 5, were monitored by the Bureau of Meteorology radar at Brisbane Airport, and a lightning location system (LLS) operated by the Southeast Queensland Electricity Board and Telecom (not available to forecasters at the time). The radar became inoperative because of a lightning strike at about 1700 LST.

Fig. 5 Path of the area of hail associated with the severe thunderstorm of 18 January 1985 determined from radar. Area (a) shows radar hail echo at 1510 LST and lightning ground strike registrations 1430 to 1500 LST, (b) shows radar hail echoes at 1620 and 1650 LST (shortly before the radar failed) and ground strikes 1600 to 1630 LST.

A diagnostic assessment revealed that the thunderstorm resulted from the interaction of a vigorous surface front which had progressed steadily up the east coast of Australia with a typical Queensland summer air mass. Instability indices based on the Brisbane radiosonde ascent at 0900 LST and shown in Table 2 suggested the likelihood of thunderstorms with the arrival of the front. These had been included in the morning forecasts, but the indices gave no indication of the severity of the impending event. The 0900 LST upper-level analyses indicated a thermal trough close to the NSW coast with a 300 hPa jet exit near Sydney, some 600 km south of Brisbane. Strong unbalanced southerly flow behind the cold front evident in the 1500 LST MSL analysis (Fig. 6) suggests exceptional low-level convergence with the tropical air mass to be a key factor.

The first severe thunderstorm warning for Ipswich and metropolitan Brisbane was issued at 1600 LST, with subsequent issues at 1700 and 1800 LST. The storm struck Ipswich and the surrounding areas from about 1615 and the inner city at 1650 LST. It is understood that there were significant delays in the receipt and broadcast of warnings by some media outlets.

In this case, the persistence of the major storm cell for nearly two hours, and its relatively straight track, proved tractable to a simple extrapolation forecasting procedure. Significant problems related to delays in the communication of warnings to the public via the media, and the apparent lack of effective responses to reduce some of the storm's major impacts (for example by protecting vehicles from hail).

Short-range forecasts

Recently, Friedrich and Leslie (1988) compared six techniques for the short-term (0-12 h) forecasting of precipitation at Darwin during a 3-

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<tr>
<th>Table 2. Instability indices based on Brisbane radiosonde at 0900 LST 18 January 1985. Suggested critical values for severe thunderstorms in brackets.</th>
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<td>Showalter Index</td>
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<td>Whiting Index</td>
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<td>Total-totals Index</td>
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<td>Bradbury Index</td>
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Fig. 6 MSL pressure analysis and observations of surface winds for 1500 LST 18 January 1985. Gradient-level winds are also shown (direction by heavy arrows, speed in knots in brackets).
month trial occupying the core of the wet season. Techniques included the subjective operational forecasts, climatology, persistence, numerical weather prediction (NWP) rainfall from the Australian FINEST model, MOS rainfall using FINEST, a statistical Markov chain model, and linear combinations of some of the techniques. The only method to demonstrate accuracy greater than that of climatology was the Markov chain model. The Markov chain technique involves the use of immediately available single station surface observations to predict the probability of precipitation during the half-day period 0600 to 1800 LST. Even better results were demonstrated using a linear combination of the Markov chain and persistence.

Beyond 12 hours the Markov chain technique loses skill, and the 0–12 h time interval appears to be a characteristic time-scale for point forecasts in tropical areas. It is a typical time for the passage of a mesoscale system and perhaps currently represents an approximate upper threshold of predictability of the general effects of such a system at a locality. To further illustrate this point, consider the predictability of tropical cyclones, which are the most conservative of tropical mesoscale systems. At a locality, their most significant effects typically last for the order of 12 hours. However, by the end of this interval, the predicted track is on average over 100 km in error, a similar dimension to the cyclone’s destructive core. Frazier and Leslie (personal communication) have suggested the wider application of stochastic models, based on a combination of the Markov chain technique and persistence, to provide skillful forecasts for up to 12 hours ahead at tropical localities with prominent dry and wet spells, like Darwin.

Medium-range forecasts
The tropical cyclone warning service apart, routine meteorological services provided in tropical Australia have evolved along the same lines as those provided in the populous southeast of the continent. Short to medium-range forecasts for 1 to 4 days account for virtually all of the routine public weather forecasts issued by the BOM’s Regional Offices. Fuelled by public demand and the improvements afforded by global numerical forecast models, outlooks are now issued for discrete periods for up to 4 days ahead in the southern States. There are pressures from the media to emulate this service in the tropics.

Routine public weather forecasts have been verified at Brisbane and Townsville since 1984. Verification scores for the operational forecasts and for a persistence forecast, defined as a repeat of yesterday’s weather, for Brisbane (lat 27° 26’S), Townsville (lat 19° 15’S) and Darwin (lat 12° 24’S) are shown in Table 3. The forecasts are for periods of 24 hours issued at 0500 LST and for 36 hours issued at 1700 LST. Verification scores are calculated for discrete time intervals within the forecast period and aggregated. The occurrence and type of precipitation, phenomena such as fog, dust, frost and smoke, and wind and temperatures are all scored. The overall result is that the medium-range forecasts for Brisbane score marginally better than persistence forecasts, while those for Townsville and Darwin in the deep tropics are indistinguishable from persistence. In part this illustrates the importance of persistence as a predictor in tropical Australia; it also represents a failure of the forecaster, assisted by diagnostic experience and limited objective guidance including NWP products, to regularly improve on the persistence forecast over the 24 to 36-hour interval. Holland et al. (1987) and others have questioned whether the recent improvements provided by NWP in higher latitudes can be repeated in the tropics. Anthes (1986) summarised the results of studies of deterministic predictability as follows; predictability decreases with decreasing horizontal scale, predictability is less in the tropics than in middle and higher latitudes, and predictability varies with the synoptic type.

Experience suggests NWP is providing useful guidance to the tropical forecaster with certain synoptic types. Changes in the large-scale forcing often result from significant subtropical events such as anticyclogenesis, which can be satisfactorily handled by the global or regional NWP models. Recently Puri (personal communication) has suggested from the experience of AMEX, that the onset of the monsoon in the deep tropics can be predicted one to one and a half days in advance. However even where the large scale is reasonably well predicted, predictive detail in the tropics at the mesoscale level needed for local forecasting is generally deficient.

Intra-seasonal and seasonal forecasts
There are two low frequency modes (excluding the annual cycle) in the Australian tropics which are synoptically prominent, conservative, and evidently have predictability. These are the 30 to 60-day oscillation and ENSO. There is no doubt that the potential predictability of climatic variables on the intra-seasonal and seasonal time-scales has important ramifications for a wide range of activities. Modern observations and data processing systems provide forecasters with the tools to monitor these large-scale, low frequency signals and, with the benefit of experience and synoptic insight, to assess their contribution to forecasts on various time-scales.

A forecasting case study: an intra-seasonal forecast at Darwin. From spring to late summer during the 1987–88 rainy season, the 30 to 60-day signal in the Indo-Australian tropics was synoptically prominent. Lacking the persistence in the Australian deep monsoon flow signi-
Table 3. Annual public weather verification scores for Brisbane, Townsville and Darwin. Forecasts are issued at 5 am valid for 18 h, and 5 pm valid for 30 h. F is the operational forecast, P is a persistence forecast. A 'perfect' forecast scores 1.

<table>
<thead>
<tr>
<th>Time of Issue</th>
<th>Brisbane</th>
<th>Townsville</th>
<th>Darwin</th>
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<tr>
<td></td>
<td>F</td>
<td>P</td>
<td>F</td>
</tr>
<tr>
<td>0500</td>
<td>0.76</td>
<td>0.73</td>
<td>0.75</td>
</tr>
<tr>
<td>1700</td>
<td>0.75</td>
<td>0.75</td>
<td>0.75</td>
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<tr>
<td>1984</td>
<td>0.82</td>
<td>0.82</td>
<td>0.79</td>
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<td>1985</td>
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<td>1986</td>
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<td>1987</td>
<td>0.82</td>
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<td></td>
<td>*0.82</td>
<td>*0.83</td>
<td>*0.80</td>
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*April–December only

Thunderstorm activity was felt during 1–4 November. Increasing thunderstorms occurred during the first half of December, then a major burst of the monsoon during 18–24 December. The rainfall total for December, 543.0 mm, was in decile range 10. A monsoon break commenced on 24 December and lasted through January, when the monthly total was only 233.4 mm, in decile range 3. On 4 February a Darwin BOM spokesman told a newspaper that a continuation of the dry conditions through February and March was unlikely. In providing this 'unofficial' outlook the forecaster was drawing on his intuitive appreciation of the 30 to 60-day cycle, backed by the knowledge that although there is considerable intra-seasonal variability in Darwin's rainfall, the annual (July–June) rainfall has relatively small variability. This was an example of 'nowcasting' the 30 to 60-day oscillation at a station where the signal is known to be prominent (McBride 1985), and it was successful. A second burst of monsoonal weather occurred in Darwin from about 9 to 15 February. The oscillation can be traced from the history of pressure and rainfall at Darwin shown in Fig. 7. The prominent peaks of monsoonal rainfall corresponding with pressure minima around 20 December, 12 February and 28 March corresponded with periods of large-scale monsoonal cloudiness and westerly lower tropospheric winds (not shown), resembling aspects of the oscillation described by Madden and Julian (1972) and Madden (1986). Interestingly, the largest daily rainfall event at Darwin in Fig. 7 occurred after the conclusion of a monsoonal period.

Seasonal forecasts
Relationships between ENSO indices such as Darwin pressure and the Southern Oscillation Index (SOI) in autumn to winter, and the rainfall over large areas of Australia during succeeding months in winter to early summer are well known (e.g. Quayle 1929; Nichols and Woodcock 1981; McBride and Nichols 1983). Nichols (1984a, 1984b) has also shown relationships between Darwin pressure in winter, the date of onset of the north Australian wet season, and the number of tropical cyclones observed during the north Australian cyclone season.

Over the past few years, seasonal outlooks based on ENSO have been provided informally from the BOM's Regional Offices, and more recently as part of the drought watch service. A routine seasonal prediction service based on ENSO was introduced by the Bureau in June 1989. Nicholls (personal communication) argued that lagged correlation coefficients between the SOI and regional rainfall in the range 0.4 to 0.6 provide a basis for seasonal forecasts that should be comparable in accuracy to some of the Bureau's daily (medium range) weather forecasts. Furthermore, there are indications (e.g. Wright 1985) that stronger seasonal lag correlations, and hence more confident predictions, might be obtained from an improved thermal monitoring of the equatorial eastern Pacific, overcoming to some extent the inherently 'noisy' nature of the atmospheric SOI.

The future
Our experience indicates that significant requirements exist for weather forecasts (or warnings) on all time-scales from nowcasts to the decadal timescale of the Greenhouse effect. The first sys-
tematic survey of users' requirements for operational weather services in Queensland has recently been conducted by the Bureau's Services Policy Branch and the Queensland Regional Office. Matching an analysis of these requirements to our forecasting capabilities will be an essential step in designing future weather services.

A perception of the operational effectiveness relative to climatology of various approaches to weather forecasting in the Australian tropics is provided in Fig. 8 which has been adapted and extended with respect to time interval from Doswell (1986, Fig. 29.8). Nowcasts of the convection scale should be effective in the 0 to 2 hour time range, while the Markov chain or other stochastic models representing the mesoscale should be effective to about 12 hours.

**Fig. 8** The perceived effectiveness of different approaches to forecasting in the Australian tropics. An indication of the smallest scales of disturbance currently considered tractable at increasing forecasting time-scales is included.

Over forecasting time intervals from 12 hours to a few days, it appears that improvements in skill over the current persistence-climatology performance 'barrier' for point forecasts will be slow, due to the severe limitations of NWP in the convective tropics. Nevertheless, there is promise that short to medium-range forecasts of specific large-scale processes, such as monsoon onset, can be supported by NWP.

At time-scales beyond about a week, stochastic models of ENSO and yet to be developed forecasting models of the 30 to 60-day oscillation appear to provide a sound basis for forecasts in certain areas and seasons. The development of operational monitoring programs to support ENSO predictions is well advanced. Forecasters need more information about the 30 to 60-day oscillation, in particular the most efficient indicators of the state of oscillation, and the areal extent of useful rainfall correlations. Recently the Darwin Regional Office has attempted to operationally monitor the oscillation using time-selections of spatially averaged fields of digital infrared satellite imagery, and 200 hPa velocity potential in the equatorial zone. However, the level of predictability attributed to the 30 to 60-day oscillation in Fig. 8 is quite speculative. It seems probable that the development of coupled ocean-atmosphere general circulation models will have a positive impact on intra-seasonal and seasonal forecasts within several years.

Current developments and future possibilities in two key service areas are now discussed.

**Public weather services**

As the result of recent work in BMRC and the National Meteorological Centre the stochastic Markov model now automatically provides short-range guidance for principal cities throughout Australia. Stochastic models lend themselves to the provision of rainfall probability forecasts which would be particularly apt in the convective tropics. Rainfall probability forecasts are being trialled in Canberra city, and the question of extending this service is under consideration within the BOM.

Figure 8 suggests a two-stage approach to forecasts and warnings of significant convective events, the first being a short-range mesoscale forecast of conditions conducive to severe convection, the second being an extrapolation forecast, or nowcast, of observed phenomena. In the tropics, where NWP is less reliable, the short-range forecast leans heavily on such techniques as stochastic and diagnostic models, and decision ladders (cf. Colquhoun 1987), aimed particularly at the skillful discrimination of situations calling for a severe weather 'watch'. The second, or 'warning' stage, requires a nowcasting system directed to efficient detection and quick response. The nowcasting system needs to be automated to a level that avert's delays in the provision of advisories. A basic system may apply simple linear models to outputs from radars, lightning location systems, and automatic weather stations to project threat areas about 1-2 hours ahead. The automated system would need to be carefully monitored by experienced forecasters who will have to translate graphical outputs into text messages, providing expert commentary and extending the forecast interval where possible when, for example, features such as line squalls, super cells or mesoscale convective complexes likely to give rise to flash floods are diagnosed.

Current developments within the Bureau of Meteorology will provide forecasters with access to an interactive graphics workstation capable of accessing several kinds of raw and processed data as well as outputs from the numerical weather analysis and prediction program and other forecast guidance. The scenario painted by Holland et
al. (1987), which envisages forecasters at the hub of an interactive work station supported in routine tasks by expert systems and automatically prepared forecasts, should start evolving during the next decade.

An important area of planning in Queensland is directed towards upgrading coastal marine weather services and the tropical cyclone warning service to meet the needs of rapidly expanding tourism and development along some 2000 km of the Queensland coast and Great Barrier Reef. Recent surveys of marine users confirm a strong requirement for representative real-time data, reflecting the sensitivity of marine operations to variations in winds and sea state. Service improvements will be partly constrained by forecaster workload given the very large area to be monitored. Bearing in mind simple linear forecast models are difficult to better for the first hour or two efforts will be directed to expanding the network of automatic weather stations monitoring surface conditions, and to the efficient delivery of real-time wind, wave, pressure and radar data in suitable formats to users for evaluation within the context of the current short to medium-range forecasts.

Turning to long-range forecasts, it is reasonable to believe that there is predictive information in the 30 to 60-day oscillation. Future work might focus on the spatial variability of the effects of the oscillation, and the development of both statistical and dynamical model outputs applicable to forecasts over the areas affected. Predictive implications of the intuitive relationship between tropical cyclone formation and the oscillation, and the intra-seasonal effects of interaction between the oscillation and ENSO, need to be studied. The efficacy of the seasonal forecast service, based on ENSO, that commenced during 1989, should be gradually improved by the insights provided from statistical, diagnostic and dynamical model developments.

**Tropical cyclone warnings**

A scientific breakthrough that will dramatically improve the predictability of cyclones appears unlikely. However, there is considerable scope for improving the accuracy of cyclone predictions in Australia through improved monitoring technology and the further development of statistical and dynamical forecasting models. For example, if the technology to nearly eliminate operational errors in tropical cyclone centre locations was available, Fig. 3(a) suggests that a 37 per cent reduction in 12-hour forecast errors to match the best track persistence forecast might be achievable. To closely approach this ideal it will be necessary to overcome the problems of eye wobble and determine the centre of the inertially stable high speed wind circulation rather than the centre of the clear eye as determined by current satellite and radar observations (Sheets 1985a).

Aircraft reconnaissance could provide the required measurements, but efforts to pursue this in Australia have been unproductive. There are a number of likely improvements in remote sensing of the 4-dimensional cyclone volume and its surroundings that may provide better measurements and lead to more skillful predictions (Sheets 1985b). In the future, remote sensing of the sea surface by skywave radars (Keenan and Anderson 1987) or active satellite sensors may provide substantial improvements in cyclone tracking and intensity determinations beyond our land-based radar and automatic weather station (AWS) networks. In Queensland, it would be cost-effective to develop a more extensive offshore AWS network over the Great Barrier Reef in order to provide a better definition of cyclones threatening the coast and islands.

There is scope for the implementation of improved statistical-synoptic models supporting cyclone movement predictions; for example models drawing predictors from the automated tropical analysis scheme, and models employing stratifications of the movement classes that reduce the forecast error variance (e.g. Keenan 1986). Additionally, there is evidence that NWP can provide skillful forecasts of tropical cyclone motion at medium range (e.g. Neumann 1981), though this has yet to be convincingly demonstrated in the Australian region. Friedrich and Leslie (1989) have recently suggested a limitation to deterministic cyclone track predictability of about 24 hours resulting from the degree of chaos exhibited by Australian region cyclone tracks.

An important challenge confronting the Bureau and cyclone warning centres world-wide is the development of a system of public advices that results in levels of preparedness properly attuned to the probabilistic levels of threat, while keeping the message sufficiently clear and simple. There is a need to contain both the preparedness costs and credibility problems associated with over-conservative warnings.

**Conclusions**

The contention of Holland et al. (1987), that there is too much concentration on medium-range forecasts in tropical Australia, is supported. The technology is becoming available in the BOM to monitor weather events in real-time as never before. New communications and information systems are becoming available to deliver such perishable information as current data and very short-range forecasts to users with unprecedented timeliness. At the longer time-scales, intra-seasonal and seasonal forecasts can be expected to become more prominent. However, the evolution of our public weather services may involve streamlining some of the traditional medium-range products in order to accommodate the new opportunities.
The tropical cyclone warning system will be placed under ever increasing pressure by the expanding coastal community. The author believes the warning system can respond with continuing improvements in its technical performance and socio-economic effectiveness.

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