The Australian Wind Profiler Network

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Introduction

In 2011 the Australian Government Bureau of Meteorology commenced the installation of nine new wind profiling radars (WPRs) across Australia. The aim of this project is to provide data for routine forecasting and data ingestion into NWP models. Four of the radars are the more powerful stratospheric tropospheric (ST) class, and are intended to also contribute to the long term upper atmosphere climate record. There are currently eight systems installed. These are in Ceduna, Tennant Creek, Carnarvon, Mildura, Cairns, Coffs Harbour, Halls Creek and Mackay. The final profiler is pending installation in Longreach. These systems complement an existing Bureau network of five profilers installed at Sydney, Launceston, Canberra, Broadmeadows and East Sale, which underwent software and minor hardware upgrades as part of the project. In addition to desktop use by Australian forecasters, data from the Bureau profilers are available on the GTS (see e.g., http://www.eumetnet.eu/radar-wind-profilers), and are currently being ingested into both Australian and global NWP models.

In addition to the operational Bureau network, ATRAD Pty Ltd, the University of Adelaide, the Australian Antarctic Division and Mt Isa Mines also operate profilers in Adelaide, Davis station in Antarctica and Mt Isa, respectively, which combined create a network of 18 instruments across Australia. While Australia has had multiple research and operational profilers in the past, we believe the profiler coverage is now sufficiently dense as to call it the Australian Wind Profiler Network.

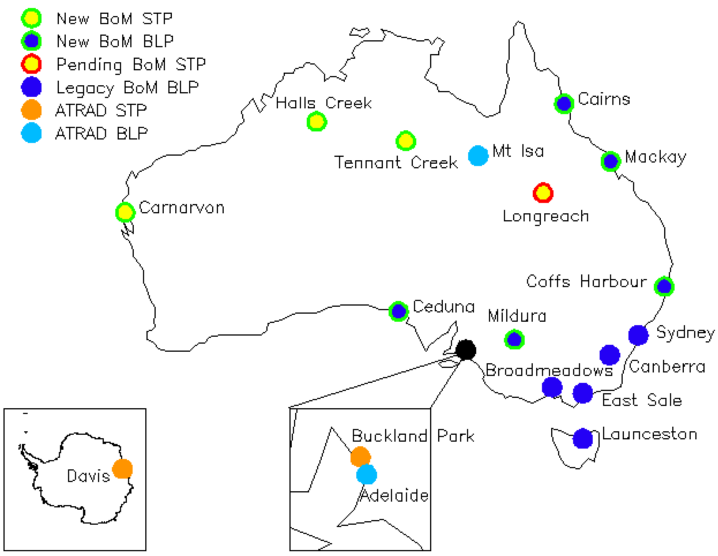

Figure 1 Australian Wind Profiler Network

All Profilers operate at a frequency of 55 MHz, and the network consists of Stratospheric Tropospheric (ST) Profilers, intended to provide winds in the region from 500-m to 20-km, and Boundary Layer (BL) Profilers, intended to provide winds from 300-m to 7-km. The ST radars utilize the Doppler Beam Swinging (DBS) technique, which is commonly used by other weather agencies. In contrast, the BL radars utilize the Spaced Antenna approach and the Full Correlation Analysis (FCA). The Australian Wind Profiler network is shown in Figure 1.

In addition to routine forecasting, model ingestion and research, the Australian Wind Profiler Network has revealed both greater information gains on previously known phenomena, such as the frequency of low level jets at Tennant Creek, and also previously unknown phenomena, such as a small temporal scale wave pattern at Ceduna, associated with the formation of the convective boundary layer. The network is described and discussed in the following paper.

Operational Wind Profilers

The Australian Wind Profiler Network consists of both BL and ST Profilers. The BL systems operate at 12 kW, and utilise 27 Yagi antennas, arranged in three subgroups of 9 antennas. These nine antennas are arranged equi-distantly on a square grid, with $\lambda/\sqrt{2}$ spacing. The center of each square grid forms the vertices of an equilateral triangle, as shown in Figure 2.

The BLP estimates horizontal winds using the Spaced Antenna (SA) Full Correlation Analysis (FCA) technique Briggs [1984]. This technique involves transmission with a vertical beam using the entire array, and independent reception on the three sub-arrays. The sub-arrays sample the diffraction pattern formed by partially reflected or backscattered radiation from irregularities in the refractive index of the atmosphere. This pattern moves across the ground with a motion corresponding to that of the irregularities themselves, and so the magnitude and direction of the horizontal wind can be estimated from the correlation between receiver pairs. Corrections are made for random changes in the pattern, and for pattern anisotropy. Vertical winds are estimated from the zero lag of the mean auto-correlation function measured from the three sub-groups, although this parameter is regarded as providing a coarse measure unless additional corrections are made for the angle of arrival.

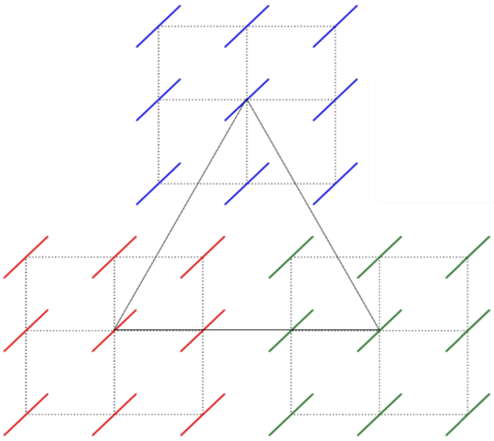

Figure 2 Antenna layout of a BL Profiler. 27 antennas are arranged in 3 groups of 9, and the center of each group forms the vertices of a triangle.

The ST systems operate at 80 kW and are comprised of 144 antennas arranged in a 12x12 square grid. These profilers are Doppler beam-swinging (DBS) systems, and measure horizontal winds through beam steering and measuring the line of sight Doppler shift. The ST systems can operate in up to five-beam directions, with beams selected from 15° off-zenith in the cardinal directions and vertical. Typically, and in the interests of temporal resolution, two orthogonal directions, plus the vertical, are used to resolve the three-dimensional wind field.

Both system types utilize the same hardware, although they differ in their peak powers, number of receiver channels, and in antenna arrangements. Basic technical specifications for both systems are given in Table 1.

Parameter	ATRAD BLP	ATRAD STP
Power	12 kW (three 4 kW modules)	80 kW (24 4 kW modules)
Operating Frequency	55 MHz	55 MHz
Antenna Configuration	27 Yagi antennas, arranged in 3 square grids of 9. The center of each square forms the vertex of an equilateral triangle.	144 Yagi antennas, arranged in a 12 x 12 square grid.
Radar Receiver	Three coherent (complex) radar receiver channels	One coherent (complex) radar receiver channel
Data Acquisition	Virtex-4 FPGA; 16-bit native digitization	Virtex-4 FPGA; 16-bit native digitization
Analysis Modes	FCA	Doppler
Remote Control	Remote monitoring and control via internet, Ethernet or dialup	Remote monitoring and control via internet, Ethernet or dialup
Data Output	ATRAD data format (raw and analyzed) and BUFR format (as individual or averaged profiles)	ATRAD data format (raw and analyzed) and BUFR format (as individual or averaged profiles)
Sampling Range	User configurable, suggested settings are from 0.2 – 20 km	User configurable, suggested settings are from 0.2 – 20 km
Range Resolution	User configurable from 100 m to 1200 m. Standard settings are 100 m (low mode) and 250 m (high mode)	User configurable from 100 m to 1200 m. Standard settings are 250 m (low mode) and 500 m (high mode)

Table 1 BL and ST technical specifications

BL and ST systems typically operate with interleaved low and high modes, with the low mode at a lower power and a finer resolution to capture boundary layer phenomena, and the high mode with a higher power at the sacrifice of resolution, attempting to sample as high into the atmosphere as possible. Typical operating parameters for low and high mode experiments are given in Table 2.

	BLP low mode	BLP high mode	STP low mode	STP high mode
Pulse width	100 m	500 m	250 m	500 m
PRF	20 000 Hz	10 000 Hz	14 000 Hz	6 000 Hz
Range	0 – 7 km	0 – 14 km	0 – 8 km	1 – 20 km
Sampling Interval	100 m	250 m	100 m	500 m
Dwell time	55 s	55 s	55 s (per beam)	55 s (per beam)
Coherent integrations	1000	500	700	150
No. Spectral points	1100	1100	1100	2200

Table 2 Typical BLP and STP low and high mode experiment parameters.

Quality Control

BL and ST profilers produce a wind estimate every 2 – 6 minutes, depending on mode of operation. In an operational setting, these data are then quality controlled and averaged to produce wind estimates every 30 minutes. The wind profile is then converted to BUFR and output to operational users. In most cases, Australian Wind Profiler data are available on the GTS.

The operational profilers utilize a technique following Weber and Wuertz [1991], and the technique for a BL profiler is described in detail in Dolman & Reid [2014]. Briefly, the algorithm considers a time-height block of data across which it wishes to perform an average. In the case of profilers using the FCA technique, magnitude and direction are considered. In the case of Doppler systems, the algorithm will operate on either the magnitude and direction, or the radial data from each beam. The latter method offers greater performance in terms of height coverage over the approach of averaging in the wind domain. This particular operation mode was tailored to user requirements, but the algorithm is generic and operation could be modified to run on a continuous data set.

Low and high mode data are considered independently, and thus each time-height data block consists of as many profiles as were collected in the 30-minute period in each mode, at all acquisition heights for that mode. The algorithm considers each data point (say, point x) within a local neighborhood which includes, at maximum, two time-stamps either side of point x, and two heights above and below point x. Depending on the location of the data point in the time-height grid, point x will have a minimum of 8 and a maximum of 24 neighbors. Within the local neighborhood the 'similarity' between point x and each of its neighbors is calculated, and only points which are considered 'similar' are retained for further analysis. The neighborhood of similar points is then used in a planar interpolation, and an interpolated value of point x is calculated. The similarity of point x to the interpolated value of x is then calculated, and point x is considered 'good' if the similarity check is passed.

When this process has been completed for each data point, the time-height block of good data is considered, and the median and standard deviation is calculated at each height. In a windowing procedure, points which lie within the median $\pm$ 1 standard deviation bound are re-included as good data. This can occur when a good point falls within a neighborhood of outliers. It is assigned a bad status due to its lack of similarity with its neighbors, where in reality it fits well with other points at that height.

For radial data, the median profile is then calculated from the good data. In the case of magnitude and direction data, the algorithm considers data separately (including some extra tests for direction wrap around), and only those data deemed to be good in both components are used to generate the final median profile. As a final test, coarse outliers are rejected by removing points more than 4 standard deviations from the final profile. This can occur in the presence of persistent external interference.

These profiles are then converted to BUFR format, and output to forecasters in real time, as separate low and high mode data. All processing, including conversion to BUFR, is performed on site on the radar PC, utilizing ATRAD proprietary software.

Data Validation

To validate each new operational installation in the Australian network, a testing protocol comparing averaged data from the wind profiler to radiosondes was developed. To develop the protocol, a long term data set from a BL Profiler located at Buckland Park (BP), was compared to Australian Government Bureau of Meteorology routine radiosonde flights from the closest station at Adelaide

Airport (AAP). AAP is approximately due South of BP, and the two sites are separated by approximately 40 km. Data from 2009 and 2010 were compared, encapsulating various seasons and meteorological conditions. A total of 233 days of data were available, 69 from 2009 and 164 from 2010. Seasonally, there are 28 days of summer data, 77 days in autumn, 1 day in spring, and 127 days in winter. Through these 233 days of BLP data, 826 sonde flights were available for comparison.

Radiosonde data reporting methods are variable. AAP sondes report pressure, temperature and humidity data at 5 second intervals, and calculate wind magnitude and direction through change in position. Position data are collected through a radar tracking the sonde package. As a result of the high spatial resolution of the sonde in comparison to the profiler, the sonde data were averaged to the profiler range gate spacing, centered on the gate. That is, for the 500 m data point, sonde data from 450 to 549 m were averaged.

The profiler data were averaged temporally, to generate a single profile to match the sonde. The optimal time interval and the starting point of the average were investigated. Using the same data set, profiler data were averaged for 30 and 60 minutes, beginning from sonde launch time, and centered on sonde launch time. This generated 4 averaged profiles, which could be compared to the spatially averaged sonde profile. To determine the optimal averaging method, a 'goodness factor' was determined. A least-squares line of best fit was fitted to each data set, and for a data set to be deemed 'good', the slope of the line of best fit was required to lie within +/- 0.03 of unity, with a y-intercept within +/- 0.5 of 0. More than 50% of the data also had to be available; that is a data set could not be considered 'good' if there were just a few points that happened to agree well. The percentage occurrence of 'good' data for the 4 data sets was then compared, and no significant differences were shown. The 'goodness factor' was examined in relation to particular atmospheric conditions, with the same result. The conclusion can therefore be drawn that the averaging method bears little effect on the end result. An alternate method would be to track the sonde through the profiler data. Given the results of the initial study, this was not deemed important. Thus, testing protocol chosen is a 30-minute average, beginning from sonde launch time.

Bias Correction

In addition to the quality control described above, some additional data analysis is applied to the BL profilers. The Spaced Antenna (SA) Full Correlation Analysis (FCA) technique is known to produce excellent agreement in direction, but underestimate the wind magnitude by up to 10%, when compared to an independent data source such as radiosondes. The underestimation has been observed in all regions of the atmosphere, and in comparison to different instruments. This underestimation in magnitude results from any effect that suppresses the correct value of the cross-correlation functions of the fading time series calculated between the antenna pairs. A full discussion on the underestimation can be found in Holdsworth [1999], and further discussed in Dolman and Reid [2014].

The bias must be accounted for in an operational environment, and the procedure followed to correct for it is described in some detail in Dolman & Reid [2014], and here we only provide a brief summary as follows. All available FCA data sets with an available sonde comparison were examined. Variations in the underestimation with direction, magnitude and height were investigated. A dependence on magnitude was found, with the percentage underestimation decreasing with increasing magnitude. This implies a non-linear correction. After investigation of several different forms, a power law was derived, given by:

$$correction = {M_0}^{0.32} - 1.23$$

where M_0 is the magnitude originally measured. An example of the underestimation is shown in Figure 3, where data from a field campaign are compared to 48 co-located sonde launches. The empirical correction is shown in Figure 4 which demonstrates excellent agreement.

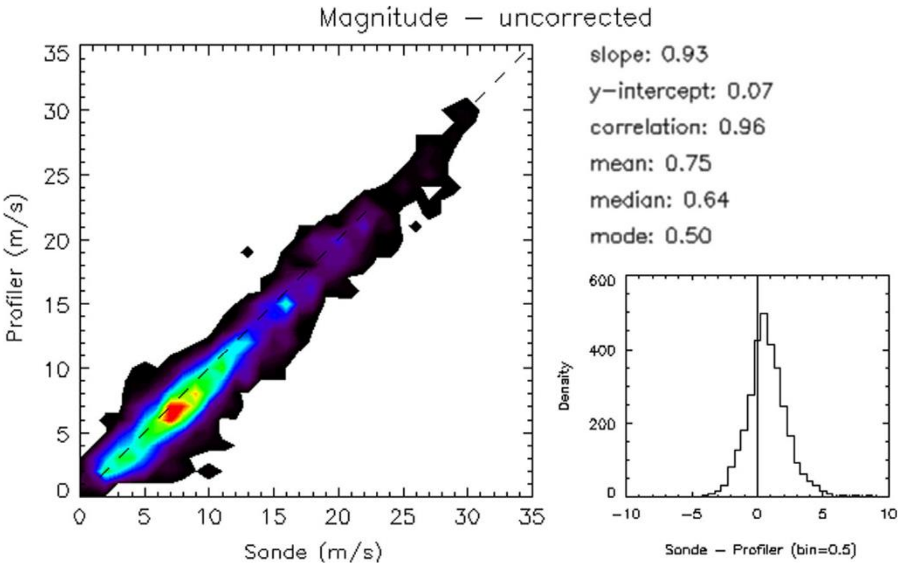

Figure 3 48 GPS sonde flights measured magnitude against uncorrected BL magnitude

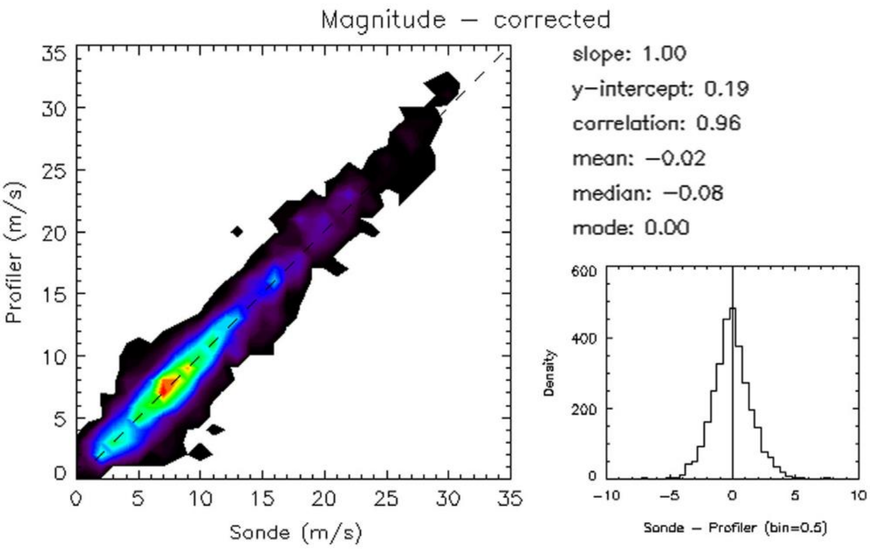

Figure 4 48 GPS sonde flights measured magnitude against corrected BL magnitude

Using the data validation data technique, quality controlled and in the case of BL systems, bias corrected profiler data were compared to nearby sondes for all operational installs. Zonal and meridional line of best fit statistics are given in Table 3, which shows excellent agreement for both profiler types, and demonstrates the correction holds across all locations. It should be noted that correlations typically decrease with increasing height, as the sonde potentially drifts further away from the profiler sampled air space. The statistics listed in Table 3 can be improved with techniques attributing error to the sonde if desired.

Location	Type	Mode	Zonal	Meridional
Ceduna	BL	Low	1.02	1.01
Mildura	BL	Low	1.00	1.05
Mackay	BL	Low	0.99	1.03
Coffs Harbour	BL	Low	0.99	1.00
Cairns	BL	Low	0.96	1.01
Tennant Creek	ST	Low	1.00	0.97
		High	0.96	0.93
Carnarvon	ST	Low	1.00	1.00
		High	0.97	0.93
Halls Creek	ST	Low	0.97	0.93
		High	0.97	0.93

Table 3 Summary of Bureau of Meteorology Operational Wind Profiler to sonde intercomparisons

Height Coverage

Height coverage and data availability are areas of great importance to users of operational profiler data. The following plots show typical height coverage for the first installation of a BL at Ceduna, and ST at Tennant Creek. Each day of profiler data was divided into 30 minute blocks, and an average, quality controlled wind estimate produced. The percentage data availability at each height was then calculated, that is the percentage of useable winds across a 24-hour period, at each height. A summary plot, showing the percentages for each day, is shown in Figure 5 for Ceduna in low mode, and Figure 6 and Figure 7 for Tennant Creek in low and high modes respectively. Cells colored green indicate 90% or more data was available at that height. Blue cells show 80-90%, yellow 70-80%, orange 60-70% and red less than 60%. Black cells indicate 48 half-hourly averages were not available on that day.

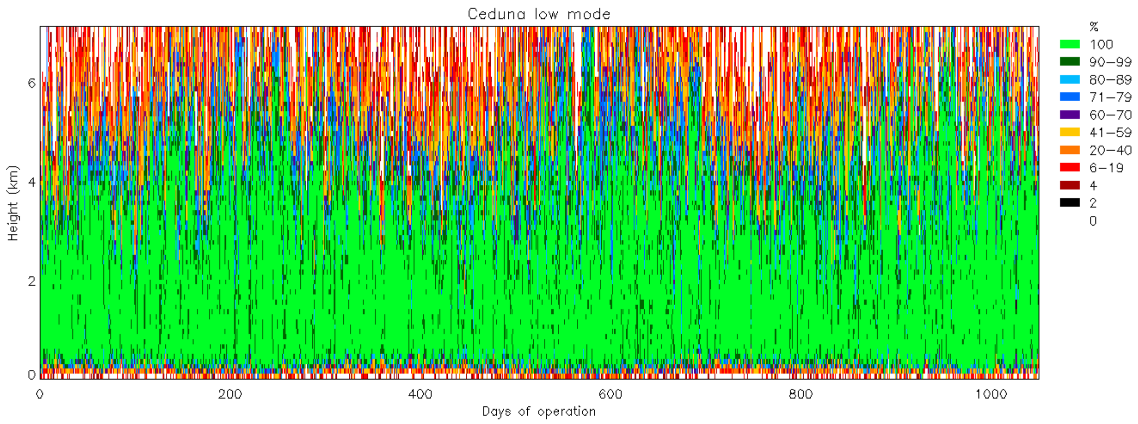

Figure 5 Ceduna low mode daily 90% acceptance summary plot. The x axis shows days beginning from 14 June 2011.

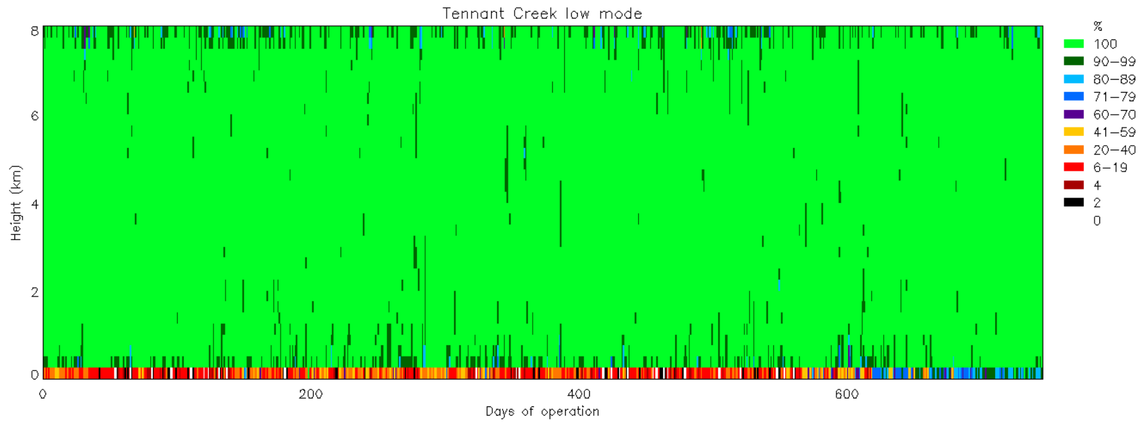

Figure 6 Tennant Creek low mode daily 90% acceptance summary plot. The x axis shows days beginning from 13 December 2011.

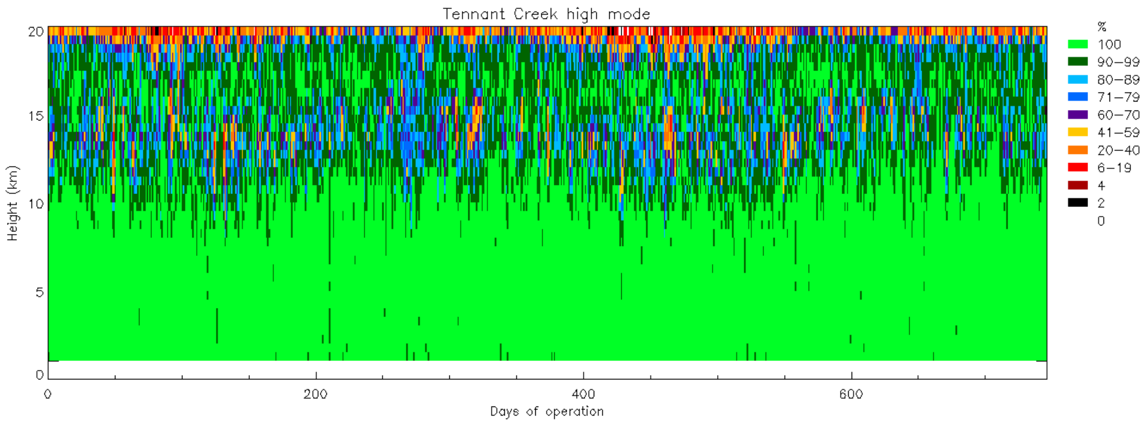

Figure 7 Tennant Creek high mode daily 90% acceptance summary plot. The x axis shows days beginning from 13 December 2011.

Operational Data Use

As stated above, operational data from the Australian Profiler Network is averaged to 30 minute intervals, quality controlled and converted to BUFR. These data are then available to local forecasters, local models, and available to the global community on the GTS.

Australian Forecasters

Australia runs a regional forecasting center in each capital city, and relevant profiler data is available to forecasters. Profiler data use is dependent on location, availability of other similar data such as radiosondes, expertise and individual preference. Applications of Profiler data across Australia include:

- Gradient winds for sea breeze and fog forecasting
- Steering winds in thunderstorms
- Aviation forecasts, particularly for ground-truthing models when deciding whether to issue a SIGMET
- Fire weather
- Convective analyses, steering winds in mid-levels are analysed as to direction developing convection will take
- Forecast verification of low level jet onset time and strength

Australian NWP

The Australian Community Climate and Earth System Simulator (ACCESS) ingests BUFR data into the model observation processing system at 6 hour intervals, although higher temporal intervals are available for higher spatial resolution models. Data are then quality controlled including background and sanity checks and then go into variational analysis with all other data.

Non-operational Data Use

In addition to their operational use, the Australian Profiler Network, including the non-operational instruments, can be used for additional data analysis and research, and have highlighted previously unknown phenomena. An example of this is a short temporal scale (approximately 5 minutes) wave discovered at Ceduna. The wave initially presented as a gap in the wind data, associated with a region of high signal to noise ratio (SNR) where winds would otherwise be expected. An example of the 'Ceduna wave' can be seen in Figure 8, which shows the 30-minute averaged wind barb field, overlaid on the SNR. From approximately 00 to 06 hours the SNR is high, but no winds have been retrieved.

During the 2011/12 Australian summer more than 40 events of up to 6 hours of data drop out were observed. Investigations revealed the profiler was measuring winds of an oscillatory nature within the 30-minute average period, which were subsequently rejected by the quality control algorithm. Events are synoptically predictable typically occurring during a dry northerly wind regime ahead of a south westerly change. The wave appears to be associated with the formation of the convective boundary layer, and ceases when the wind takes on a southerly component, most likely associated with the introduction of moisture from the Southern Ocean. Once the wave was understood, modifications to the quality control routines were made such that data drop outs ceased to occur.

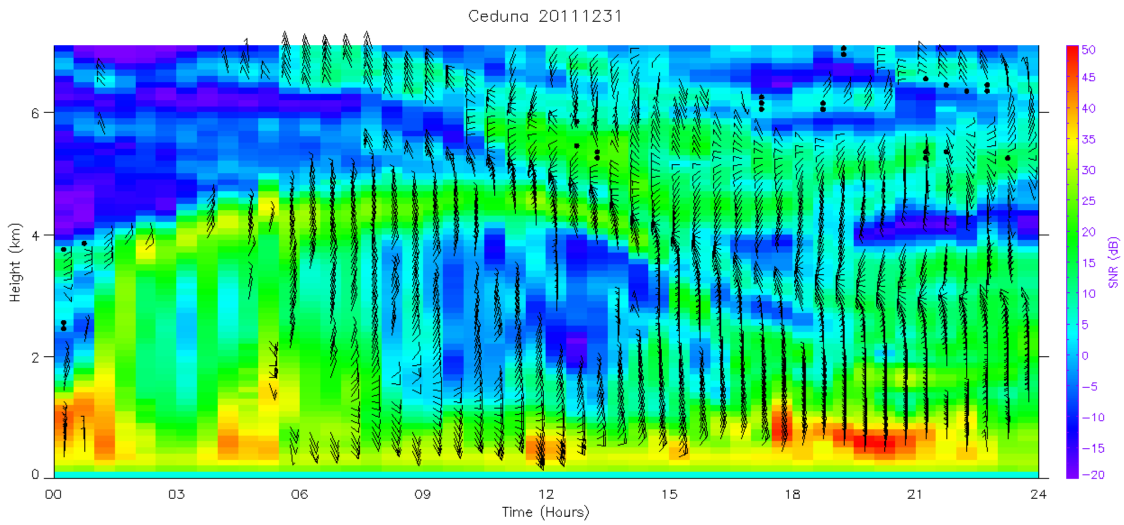

Figure 8 Wind data from Ceduna, overlaid on the SNR. A data gap associated with the Ceduna wave can be seen from approximately 00 to 06 hours.

Wind Profiler data can also be used to routinely detect the tropopause, which was most recently demonstrated by Alexander et. al. [2013]. Consider Figure 9, which shows a typical wet season high mode wind field from the Tennant Creek ST Profiler, overlaid on the SNR. While winds were retrieved through most heights, there is a region of lower SNR between approximately 10 and 15 km at all times, above which signal increases again. The increase in signal is the radar tropopause. The radar tropopause, and the associated change in height with season can also be seen in Figure 7.

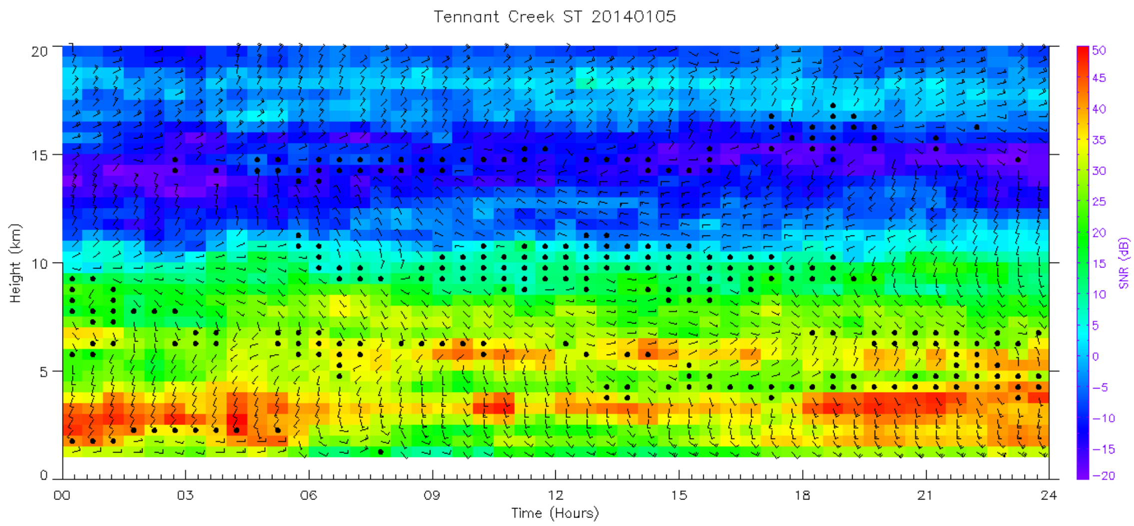

Figure 9 High mode wind data from Tennant Creek, overlaid on the SNR.

The vertical component of profiler data can be used to examine rainfall, and through a de-convolution process retrieve the rainfall drop size distribution (DSD) and associated integral parameters such as rain-rate and liquid water content. Profiler retrievals of the DSD have typically been performed on a campaign basis as the retrieval process is typically requires extensive manual input. We are currently working on routines to allow DSD retrievals to be performed in near real time. Initially planned for roll out at Adelaide Airport, real-time DSD retrievals will allow both real time and post event analysis of the vertical column above the profiler. DSD data can then potentially be available as an additional data product, and with further research it is possible profiler DSD data can be used a calibration tool for weather watch radars.

Conclusion

The Australian Wind Profiler Network consists of a mix of 18 operational and research 55 MHz systems. The network is a mix of boundary layer systems utilising spaced antenna techniques to measure the three-dimensional wind field, and larger stratospheric tropospheric systems using Doppler techniques. All systems produce quality controlled winds to an average interval of user choosing, including a correction for the known spaced antenna full correlation analysis wind magnitude underestimation. A systematic approach to compare radiosonde to wind profiler data has been developed for profiler validation, and is employed as standard practice when a new operational system is commissioned. Once approved, data is available globally on the GTS. Within Australia, wind profiler data is used by forecasters on the bench, ingested into NWP models and utilised in research such as tropopause height and precipitation studies.

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