The end-to-end convective hazard risk forecast process developed by the Australian Extreme Weather Desk for the South Australian 28 September 2016 tornado outbreak

Australian Government
Bureau of Meteorology

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Introduction

During the afternoon and evening of 28 September 2016, one of the most significant severe thunderstorm outbreaks in recent decades impacted central and eastern parts of the Australian state of South Australia. Multiple supercell thunderstorms produced damaging to destructive wind gusts, including at least seven tornadoes, very large hailstones and locally intense rainfall. These supercell thunderstorms and tornadoes impacted the South Australian power network, contributing to a **state-wide power outage** leaving approximately **1.7 million people without electricity**.

Five faults led to the 'black system event', with four of these faults occurring on three transmission lines that were caused by the impact of tornadic supercell thunderstorms; **two of the damaged transmission lines spaced over 100 km apart were damaged by two separate tornadoes within 88 seconds of each other**. Damage surveys were conducted for four of the seven identified tornadoes, three of which were assessed to have caused damage consistent with an F2 intensity rating (181–253 km/h), and one with an estimated F1 (117–180 km/h) intensity rating.

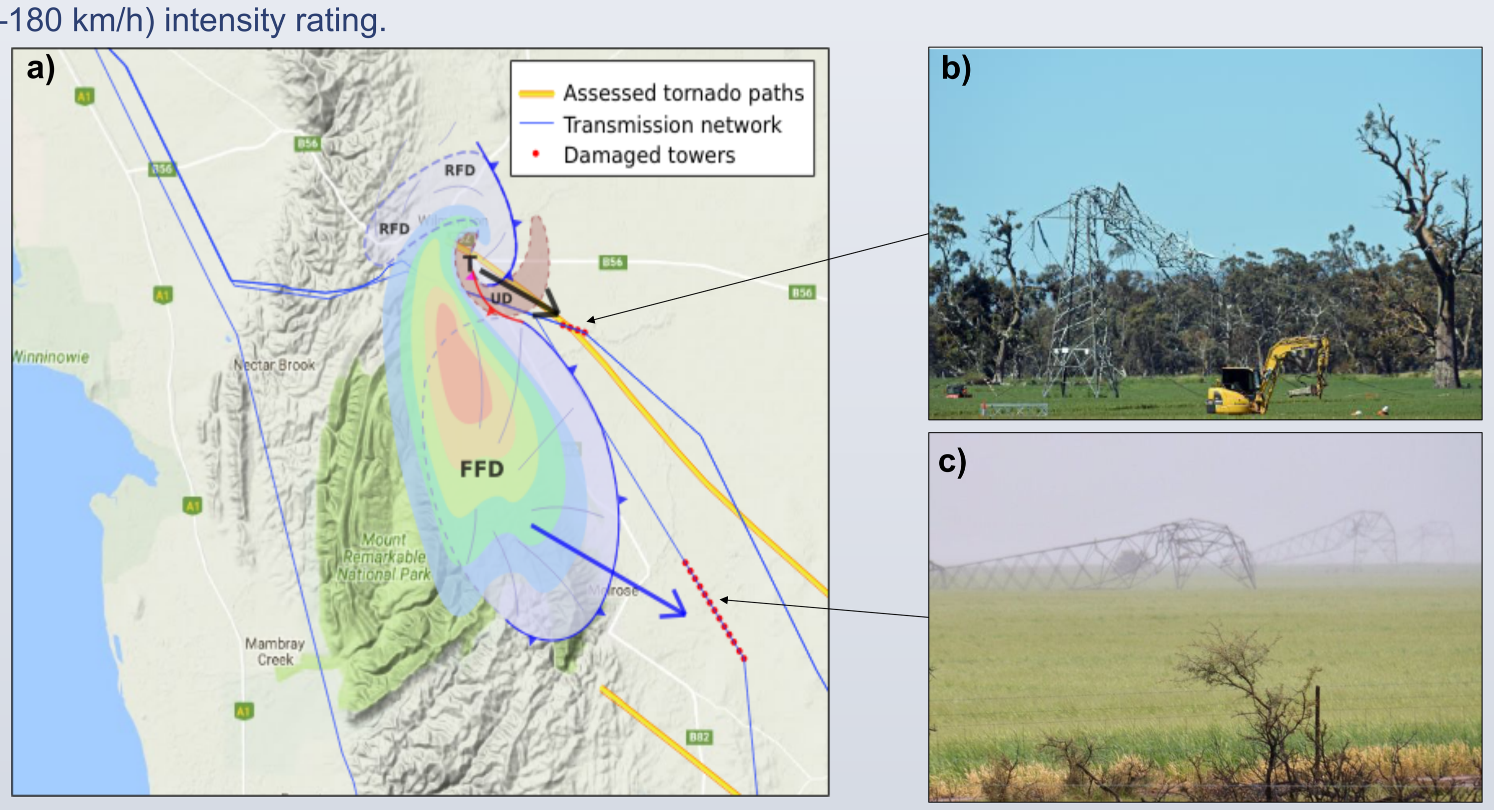

*Figure 1. **a)** Idealised Wilmington, SA supercell thunderstorm, depicting the position of the tornado (T), forward flank downdraught (FFD), rear flank downdraught (RFD) and updraught (UD), and the impact on the **b)** Davenport-Belalie/Davenport-Mt Lock transmission line from the tornado; and **c)** Davenport-Brinkworth transmission line from the FFD.*

EWD Convective Hazard Risk Forecast Process

The Australian Bureau of Meteorology National Operations Centre's Extreme Weather Desk (EWD) provides "a national focus for extreme weather intelligence" and "enhanced severe weather capacity during periods of sustained demand", and has developed a complete end-to-end forecast process for convection hazard risk forecasting which included the development of guidance systems that inform national hazard risk forecasts of thunder, large hail, damaging wind gusts, heavy rainfall and tornado.

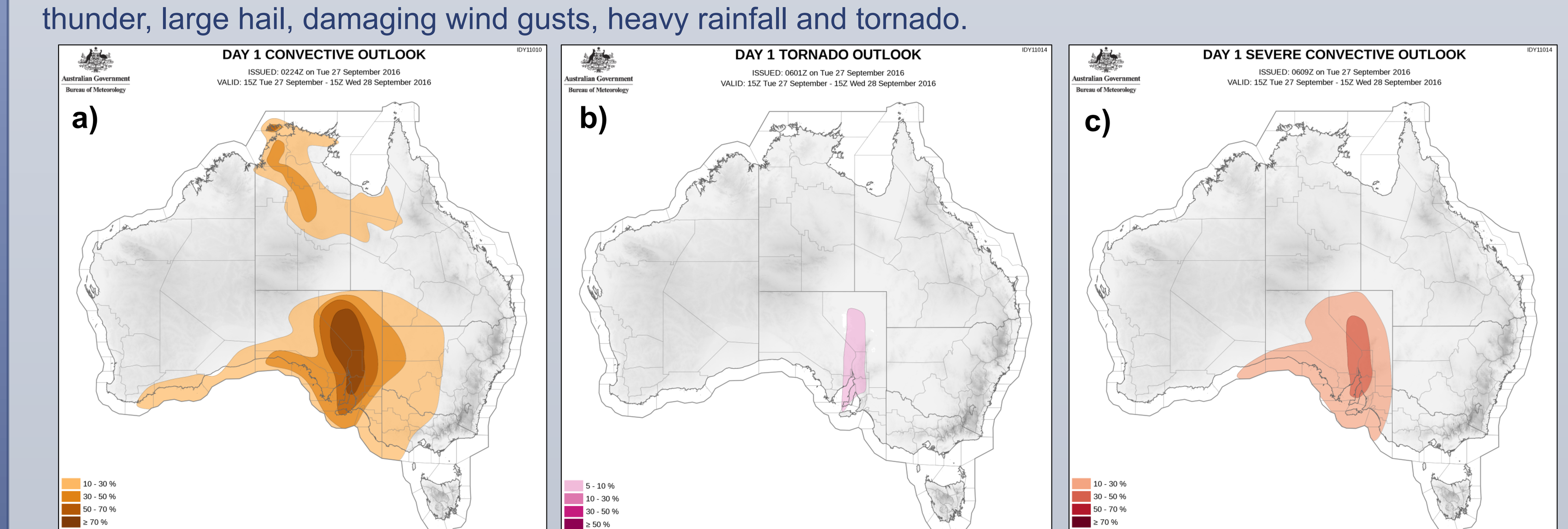

*Figure 2. EWD Convective Outlook products issued 02:24 UTC 27 September 2016, valid 15 27 – 15 UTC 28 September 2016 depicting the probability within 10 km of a point of **a)** lightning; **b)** tornado conditional upon lightning and; **c)** severe convective phenomenon conditional upon lightning.*

The primary guidance sources used for the forecast products in Figure 2 were the 12 UTC 26 September 2016 runs of the Bureau of Meteorology's ACCESS-R model, and the ECMWF deterministic model. This guidance suggested an environment favourable for organised convection in the warm and humid sector ahead of the cold front with deep layer bulk shear in excess of 50 kt and ML-CAPE in excess of 1000 J kg^{-1}. Relatively straight line winds through middle and upper levels with a backing low-level hodograph resulted in a convective mode forecast (described in the National Convective Outlook Discussion) of "Discrete supercell potential in pre-frontal convergence and squall line potential with embedded rotation or book ends along the front." United States National Weather Service (NWS) Storm Prediction Centre (SPC) normalised convective parameters of Supercell Composite Parameter (SCP), Derecho Composite and Significant Tornado Parameter (STP), along with favourable Tornado Critical Angles, provided increased confidence of the environmental conditions for these threats which was reflected in the graphical conditional probability forecasts presented in Figure 2.

Antecedent Conditions

Australia experienced its **second wettest winter on record** in 2016 and the wettest winter for the state of South Australia since 2001 thanks to the combination of **positive Southern Oscillation Index** (SOI) and the **strongest negative Indian Ocean Dipole (IOD) in the preceding 15 years** and associated **record high SSTs off the northwest Australian coast**. Negative IOD events provide increased available moisture to weather systems traversing the continent which promoted well above average rainfall over Australia during winter and spring. Consequently, the continuation of rainfall events into September resulted in increased soil moisture (**highest on record root zone soil moisture deviation from average** for 27 September 2016) allowed for enhanced and unseasonable atmospheric moisture availability.

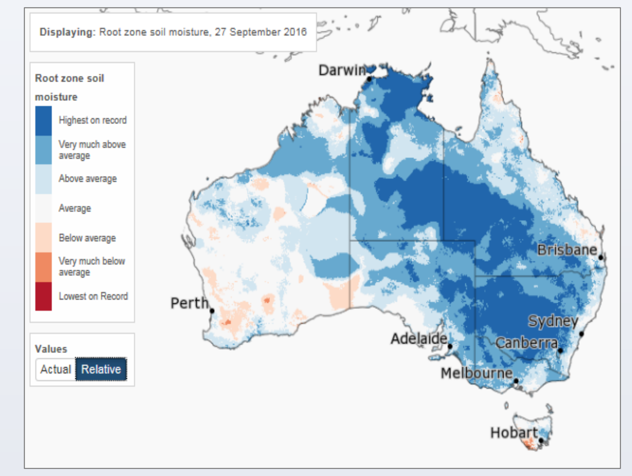

Figure 3. Root zone soil moisture anomalies for 27 September, 2016.

Synoptic-scale Forcing

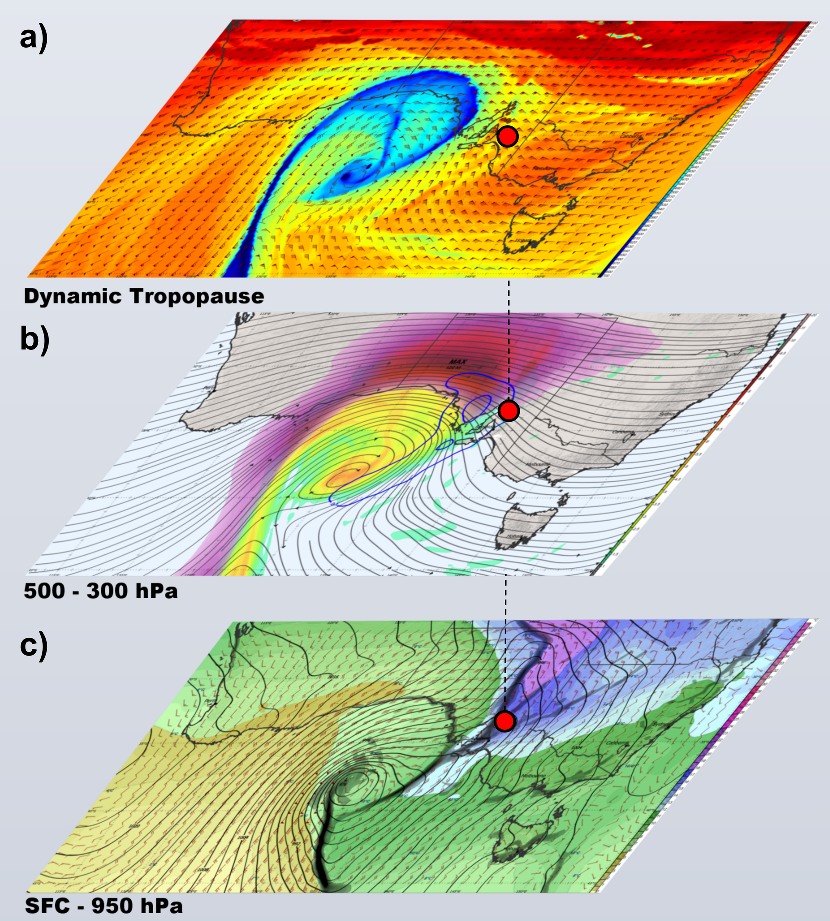

*Figure 4. Bureau of Meteorology APS3 ACCESS-R 00 UTC 28 September 2016 run valid 06 UTC **a)** -1.5 PVU Dynamic Tropopause pressure and wind barbs; **b)** 500-300 hPa layer mean PV (yellow-green shading), streamlines, CVA (blue contours) and isotachs (purple/red shading); and **c)** SFC-950hPa layer mean wind barbs, Instantaneous Contraction Rate, WBPT, and MSLP. Red dot indicates broad position of tornado reports.*

Active tropics over southeast Asia in conjunction with an active Madden-Julian Oscillation (MJO) over the eastern Indian Ocean lead to strong ridging over the southern Indian Ocean (via anticyclonic potential vorticity advection) which, in turn increased baroclinicity and subsequent strengthening of the polar front jet stream. Coupled with highly mobile synoptic-scale Rossby waves, the approaching wave amplified rapidly south of Western Australia on 27 September before becoming negatively tilted and subsequently over-turning and "breaking" on the 28 September. **Explosive cyclogenesis** ensued, with the developing low south of the Great Australian Bight deepening by 23 hPa in 24 hours to be 973 hPa during the afternoon of 28 September; Adelaide (South Australia's capital city) recorded its **lowest barometric pressure on record** (977.3 hPa) as the low centre passed to the south of Adelaide during the morning of 29 September. **Strong frontogenesis** of the fast moving front extending ahead of the parent low resulted in response to the vertical coupling with **strong Cyclonic Vorticity Advection** (CVA) and the poleward exit region of the sub-tropical jet stream aloft. The front traversed central and eastern South Australia during the afternoon and evening of 28 September, providing the primary lifting mechanism, the axis of which acted as the focus point of highly convergent winds stemming from strong pressure and thermodynamic gradients and resultant pre-frontal isallobaric east to northeasterly wind.

Convective Environment

Severe thunderstorms primarily formed in the warm and humid airmass between the frontogenetic cold front, and warm front to the east that joined to form a triple point within the vicinity of tornado reports. Based on the 00 UTC 28 September 2016 ACCESS-R model run valid at 06 UTC (nearest forecast time to observed tornado occurrences), the convective environment was characterised by strong pre-frontal moisture advection with **WBPTs of 16-18°C** leading to strong moisture convergence and the sharpening of the density gradient across the front (mixing ratio gradient of 4-5 g kg^{-1}) assisting density related uplift. ML-LCLs typically ranged between 700 and 900 m AGL, with **ML-CAPE** values rather low ranging between **500 and 1200 J kg^{-1}** and ML-CIN values of 20-50 J kg^{-1}. The deep layer shear profile was favourable for storm organisation consisting of a backing wind profile with height and **deep layer bulk wind difference of 50 to 60 kt**. Forecast SFC-1 km and SFC-3 km AGL SRH values were generally -150 and -400 m^2 s^{-2} respectively for an unmodified storm motion vector ~340°/35 kt, and **-250 and -500 m^2 s^{-2}** respectively for Bunkers left storm motion vector ~320°/35 kt suggesting ample streamwise vorticity to support cyclonic supercell organisation. This was further supported by **SCP values of 3-4**. **STP** (using mixed layer parcel) values were broadly **around 1** suggesting **an environment conducive to significant (EF2+) tornadoes.**

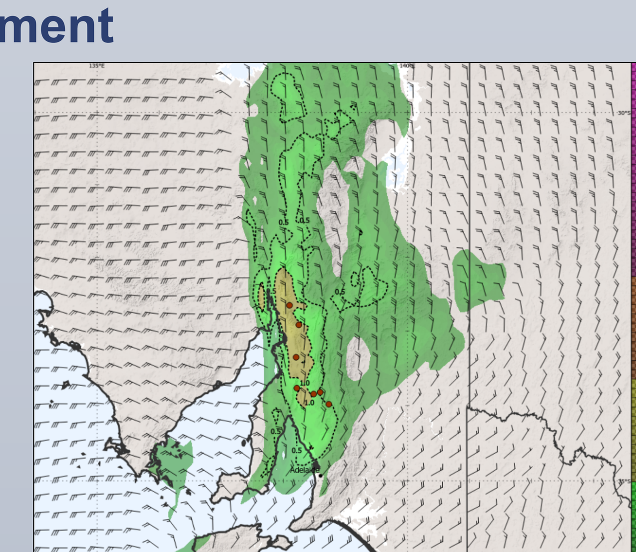

Figure 5. 00 UTC 28 September 2016 ACCESS-R run valid 06 UTC Significant Tornado Parameter and 10 m AGL wind barbs. Red dots show tornado reports.

Mesoscale Environment

Convective Allowing Model (CAM) output was not available to operational meteorologists at the time of forecast preparation but is presented here to demonstrate how CAM output can be used to confirm the convective environmental assessment obtained from parameterised NWP.

CAM derived maximum absolute **Updraught Helicity** for the period 05-07 UTC suggested vigorous rotating updraughts with absolute values reaching **>300 m^2 s^{-2}** consistent with supercell organisation and confirming the assessment that the environment was conducive to rotating thunderstorms. Furthermore, the 1 km AGL 05-07 UTC **maximum simulated RADAR reflectivity** also suggested intense precipitation echoes reaching **60-70 dBZ** indicating the existence of strong convective storms, while confirming the operational meteorologist's assessment of QLCS convective mode.

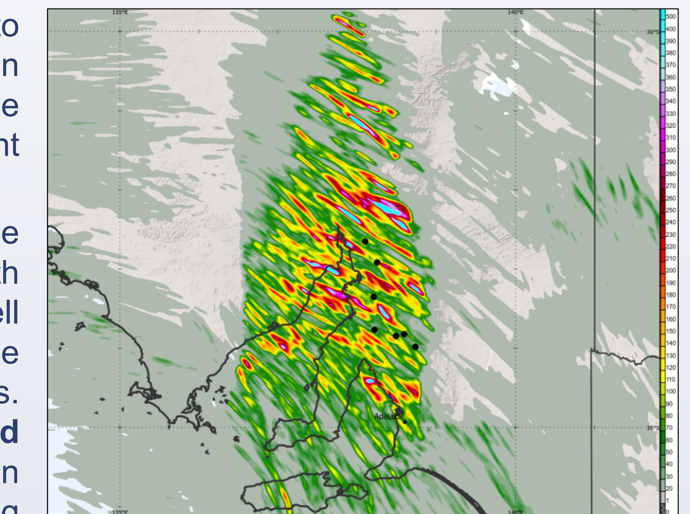

Figure 6. 00 UTC 28 September 2016 ACCESS-C run maximum Updraught Helicity for the period 05-07 UTC. Black dots show tornado reports.

Verification

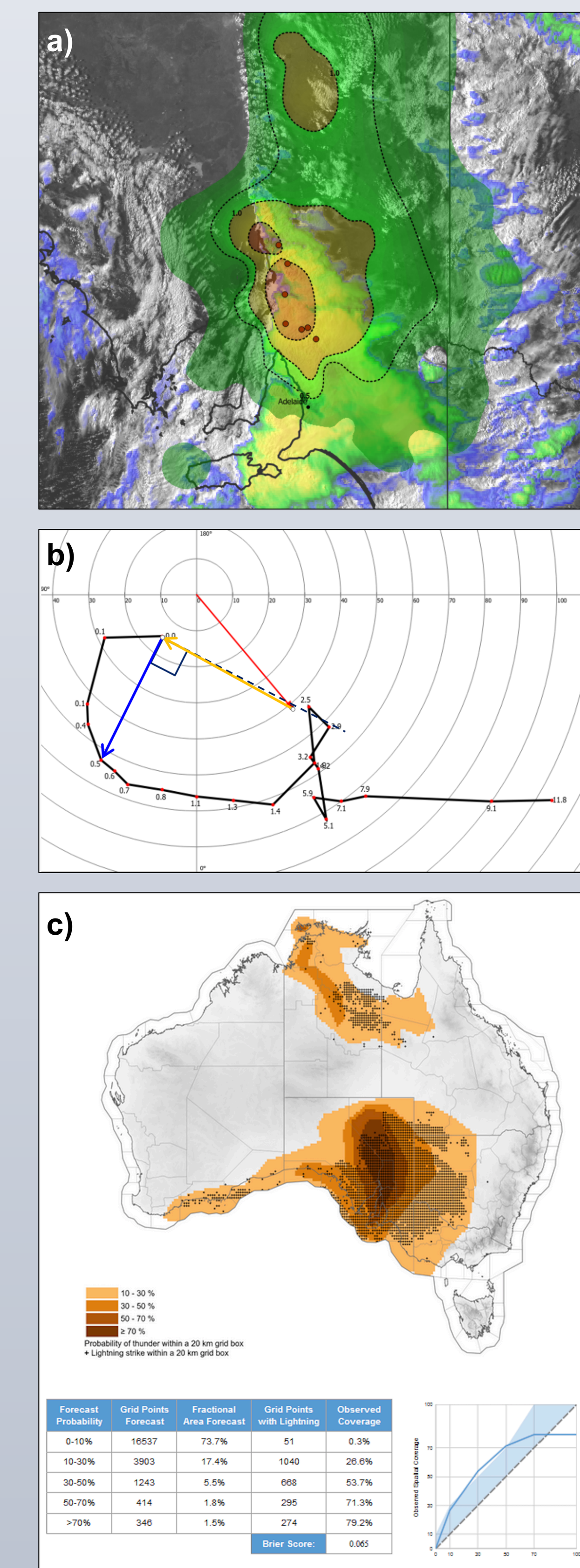

*Figure 7. 06 UTC 28 September 2016 **a)** STP mesoanalysis with red dots showing tornado reports; **b)** Adelaide Airport 04:40 UTC hodograph with observed storm motion vector (red), storm relative inflow vector (orange) and 10-500 m AGL shear vector (blue); **c)** EWD objective spatial verification of the Day 1 (next day) probability convective outlook valid 28 September 2016.*

The Extreme Weather Desk's non-operational mesoanalysis system suggested **SCP values of 5-10** and **STP values of 2-3** within the area of reported tornadoes at 06 UTC that provided supportive evidence that the environment was conducive to supercell organisation and significant tornadoes.

An analysis of the Blyth tornado (situated ~100 km north of Adelaide's Buckland Park RADAR) revealed a 0.5° elevation Doppler **maximum rotational velocity of 62 kt** at ~1400 m AGL in the vicinity of the reflectivity hook echo signature at 06:01 UTC. When combined with a maximum (analysis within 80 km) **STP value of 2.7**, the **unconditional probability of a tornado** after Smith et al (2015) was **~70%**, whilst the combined **conditional probability of an EF2+ tornado rating was 40-50%** which is consistent with the **estimated F2 tornado intensity damage rating** for the Blyth tornado obtained via onsite damage assessment (Bureau of Meteorology uses the Fujita scale).

Hodograph analysis of the Adelaide Airport 04:40 UTC atmospheric profile with observed 0615 UTC pre-storm winds substituted from Clare (situated 11 km southeast of Blyth) of 040°/15 kt and an observed storm motion vector of 320°/41 kt (closely approximated by NWP derived Bunkers left storm motion vector) resulted in **SFC-1 km and SFC-3 km AGL SRH values of -845 m^2 s^{-2} and -1094 m^2 s^{-2}** respectively. With 10 m - 500 m AGL shear of 38 kt and 10 m AGL storm relative inflow of 119°/41 kt, the **Tornado Critical Angle**, which has been shown to be a strong discriminator between tornadic and non-tornadic supercells by Esterheld and Giuliano (2008), **was found to be 87°**, suggesting the **ingestion of purely streamwise vorticity concentrated in the near-surface storm inflow layer**.

As part of the end-to-end convective forecast process, the EWD calculates daily and seasonal objective verification, although this was not available to operational meteorologists at the time. The probabilistic forecast verified well with observed spatial coverages close to or within forecast spatial coverages. Routine daily objective, quantitative and subjective verification in the EWD facilitates the continual improvement and bias correction of individual operational meteorologists and the broader EWD team.

Conclusions

NWS SPC normalised convective parameters were useful in diagnosing and highlighting environments conducive to tornadic supercell thunderstorms and demonstrated their **application in the Southern Hemisphere**. CAM guidance and mesoanalysis, if utilised operationally for short-term forecasts and warnings, can be used to confirm the convective environmental assessment and increase confidence in convective mode and spatial forecasts, allowing for refined probabilities to be forecast for convective threats and improve the communication of high-impact convective hazards.

Note: Please refer to the conference extended abstract for further information and references.