A Review of Severe Thunderstorms in Australia

John T. Allen^{a,*}, Edwina R. Allen^{b,*}

^a*International Research Institute for Climate and Society, The Earth Institute of
Columbia University, Palisades, New York, USA.*

^b*No Affiliation, Nanuet, New York, USA.*

Abstract

1 Severe thunderstorms are a common occurrence in Australia, and have been
2 documented since the first European settlement in 1788. These events are
3 characterized by large damaging hail in excess of 2cm, convective wind gusts
4 greater than 90kmh⁻¹ and tornadoes, and contribute a quarter of all natural
5 hazard related losses in the country. This impact has lead to a growing body
6 of research and insight into these events. In this article, the state of knowl-
7 edge regarding their incidence, distribution, and the resulting hail, tornado,
8 convective wind risk and lightning will be reviewed. Applying this assess-
9 ment of knowledge, the implications for forecasting, the warning process and
10 how these events may respond to climate change and variability will also be
11 discussed. Based on this review, several potential avenues for future research
12 and exploration are suggested, and ongoing work in the field outlined. Most
13 notably, the need for improved observational or proxy climatologies, fore-
14 casting guidelines for tornadoes and a greater understanding of how severe
15 thunderstorms respond to climate variability are highlighted.

Keywords: Severe Thunderstorms, Hail, Tornado, Wind, Australia

1. Introduction

16 Thunderstorms present a significant threat to life and property in Aus-
17 tralia, and have been regularly recorded in written accounts from the period
18 as early as five days after the arrival of the first European settlers in 1788
19 (Day, 2007). These storms have resulted in fatalities, destruction of homes
20 and property, and in some cases changed the course of the settlement in
21 terms of local population. Verbal records from the pre-European settlement
22 of the aboriginal population suggest that such events have been the norm

*Corresponding Author: Monell Building, Lamont-Doherty Earth Observatory, 61
Rte 9W, Palisades, NY, 10964, USA
Email address: JohnTerrAllen@gmail.com (John T. Allen)
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23 for an extended period. Thunderstorm events have influenced nearly the
24 entire continent and with greater frequency than any other natural hazard
25 (Australian Bureau of Statistics, 2008). Thunderstorms can produce light-
26 ning, extreme rainfall, hailstones in excess of 2cm, wind gusts greater than
27 90kmh^{-1} and tornadoes. The production of any one or more of hail, dam-
28 aging convective winds and tornadoes leads an event to be referred to as
29 severe by the Bureau of Meteorology (BOM). Any of these phenomena are
30 capable of producing high impact events on small spatial scales on the order
31 of tens of meters to hundreds of kilometers. Examples of such events with
32 high financial impact approaching or exceeding one billion Australian dollars
33 (AUD) in losses include hailstorms in Sydney (Yeo et al., 1999; Harper et al.,
34 2000), Melbourne (Buckley et al., 2010; Allen, 2012), Brisbane (Munich RE,
35 2015) and Perth (Buckley et al., 2010). Despite the relatively high frequency
36 of such events, understanding their characteristics and climatology has been
37 limited by the distribution of Australia’s population, with 85% living within
38 50 kilometers of the coastline (Australian Bureau of Statistics, 2001). This
39 has led to difficulties in determining the frequency of thunderstorm events
40 over inland areas, which encompass economically crucial agricultural regions
41 sensitive to the impacts of hail (Cremer, 1984a,b; McMaster, 1999, 2001). As
42 of 2008, it was estimated that severe storms in Australia cost the country on
43 average 284 million AUD per year in damage, a quarter of the total cost due
44 to natural hazards for the continent (Middlemann et al., 2007; Crompton
45 and McAneney, 2008). This contribution is exceeded by many single thun-
46 derstorm events that have affected metropolitan areas (e.g. the 2010 events
47 in both Melbourne and Perth exceeded 1 billion AUD in losses; Buckley et al.
48 (2010), while the November 2014 Brisbane hailstorm was associated with a
49 1.35 billion AUD insured loss; Munich RE (2015)). Since 1824, over 770 peo-
50 ple have lost their lives to thunderstorm related phenomena in Australia, and
51 this has the potential to greatly increase if a single high impact event over
52 a metropolitan area occurs in the future (Blong, 2005; Middlemann et al.,
53 2007; Crompton and McAneney, 2008).

54 The risks posed to the population and built environment by severe thun-
55 derstorms have spurred a body of research exploring the various impacts
56 of these events through a range of case studies, climatology, modeling and
57 development of forecasting procedures. Nevertheless, many aspects of se-
58 vere thunderstorms in Australia are far from well understood, particularly
59 in the context of observational and environmental climatology and climate
60 variability. It is also important to realize that not all international advances

in thunderstorms are necessarily representative of a continent that spans the tropics, sub-tropics and the mid-latitudes. As there has been no formal national review of the literature on severe thunderstorms in Australia to the authors' knowledge, in this paper we review the existing research that has been conducted to date, place this work into context in terms of advances from international efforts, and discuss areas which present opportunities for further research.

The structure of this review is as follows: Section 2 discusses the definition of a severe thunderstorm and the information currently available to explore severe thunderstorm characteristics and climatology. Section 3 investigates the lightning climatology for Australia and the derivative thunderstorm climatology to understand the spatial occurrence of these events and places severe thunderstorms into context. Section 4 details the existing research into severe thunderstorm climatology and phenomena such as hail, tornadoes and damaging convective winds. Extending from the climatological information, we explore the context of the forecast procedures developed for the continent in section 5. In section 6 we discuss existing research on climate variability and change relationships to thunderstorms in Australia. Finally in section 7, we discuss the limitations of the existing studies, ongoing research that will contribute to the knowledge of Australian severe weather in the future, and directions of inquiry that would ultimately benefit our understanding in the next decade.

2. Definitions and Available Data

2.1. Severe Thunderstorms

Thunderstorms are moist deep convective systems that arise from the local instability of warm moist air relative to the overlying air mass. The processes associated with releasing this instability result in the occurrence of atmospheric convection (Doswell et al., 1996). Three key factors are necessary to produce favorable environments for the development of deep convection: (i) an unstable environmental lapse rate; (ii) sufficient moisture such that there exists buoyancy; and (iii) a process to lift a parcel to the point at which it is buoyant (Doswell, 1987). For the purpose of this discussion, only deep convective storms that produce either hail, tornadoes or damaging convective winds with or without lightning are considered. Assuming that the atmosphere is unstable or is brought to a state of instability, and that deep convection initiates, a thunderstorm updraft may form when the air reaches

97 the level of free convection. If sufficient moisture exists such that the atmo-
98 sphere becomes saturated, cloud will form and a thunderstorm may initiate
99 (Byers and Braham, 1949). In condensing water vapor at the lifted conden-
100 sation level, the release of latent heat warms the air, further contributing to
101 the process and generating additional buoyancy for the parcel. In deep con-
102 vection, freezing can also occur, with energy released in this process driving
103 the air within the thunderstorm high into the troposphere. Ascent continues
104 until such time that the air is neutrally buoyant, which may be in the lower
105 stratosphere.

106 Given sufficient instability and the necessary environment, deep moist
107 convection can generate hazardous phenomena (hail, damaging convective
108 winds, and tornadoes). Such storms may be categorized as severe thunder-
109 storms. In Australia, the BOM classifies thunderstorms associated with any
110 one or more of extreme rainfall causing flash flooding, hail greater than 2cm,
111 wind gusts in excess of 90kmh^{-1} and any tornadic event as severe (Mills and
112 Colquhoun, 1998; Harper et al., 2000). These thresholds are comparable
113 to those used in the United States (U.S.) and Europe (Hales, 1993; Brooks
114 et al., 2003; Doswell et al., 2005; Dotzek et al., 2009), although extreme
115 rainfall causing flash flooding is not considered in the same category in the
116 U.S. This exclusion can partly be explained by the existence of other non-
117 deep convective processes that can result in extreme rainfall and subsequent
118 flooding, including the dependence on topography and local surface condi-
119 tions. Consequently there is the potential for such events to be produced by
120 either convective or non-convective clouds that are not severe in any other
121 sense, and which may be persistently regenerating over a location or exist
122 in a very moist environment (Doswell et al., 1996). For the context of this
123 discussion, we refer the reader to the numerous articles on extreme rainfall
124 over Australia. Despite these classifications, it is important to recognize that
125 little physical difference exists between a storm that produces near-severe,
126 and severe thunderstorms (e.g. 1.9cm vs 2.0cm hail; Doswell (2001)).

127 Two-tier classifications of severe phenomena have also considered signif-
128 icant severe thunderstorms (Hales, 1993), requiring higher thresholds than
129 those for severe phenomena and are based on report climatologies over the
130 U.S. This second stratification is used to isolate events with an increased
131 potential for damage to human habitation (Kelly et al., 1985; Brooks et al.,
132 2003). Significant severe thunderstorms are defined as those producing 5cm
133 or greater hail, winds exceeding 120kmh^{-1} and tornadoes exceeding F2 inten-
134 sity (Hales, 1993; Doswell, 2001). Such conditions have been observed rela-

135 tively infrequently in Australia compared to the U.S. (Tucker, 2002; Schuster
136 et al., 2005b; Allen et al., 2011), but do produce significant damage when
137 the storms interact with populated areas. Nonetheless, severe hail less than
138 5cm in Australia still causes substantial damage, particularly to agriculture
139 (Kuhnel, 1998; McMaster, 1999; Harper et al., 2000; McMaster, 2001; Yeo,
140 2005).

141 It should also be noted that despite the threat lightning poses to hu-
142 man life (Coates et al., 1993), a storm need not produce any of the other
143 severe phenomena in order to produce lightning, nor need produce lightning
144 in order to produce other phenomena (Doswell, 2001). However, lightning
145 occurrence is a useful proxy to estimate the occurrence of thunderstorms,
146 which are requisite for each of the other severe phenomena, and thus mea-
147 sures of thunderdays can provide an independent spatial picture of thunder-
148 storm occurrence (Kuleshov et al., 2002, 2006; Dowdy and Kuleshov, 2014).
149 Thus instead of focusing explicitly on whether a study considers severe or
150 non-severe thunderstorms, here we review literature concerning the following
151 four phenomena associated with thunderstorms: lightning in the context of
152 informing our understanding of severe thunderstorm occurrence, hail, dam-
153 aging convective winds and tornadoes.

154 2.2. Severe Thunderstorm Reports and Remotely Sensed Observations

155 Reports of severe thunderstorms are sourced by *in situ* observations,
156 where an observer is needed to identify a tornado, measure a fallen hailstone,
157 or assess damaging convective winds. This can lead to a number of incon-
158 sistencies related to non-standard measurement techniques including the use
159 of reference objects rather than analytic measurement for hail, issues with
160 presence or lack of an observer, and perception-based intensity assessments of
161 damage from tornadoes and damaging convective winds (Brooks et al., 2003;
162 Trapp et al., 2006; Allen et al., 2011; Tippett et al., 2015; Allen and Tip-
163 pett, 2015). In Australia, these reports are currently collated as part of the
164 publicly available BOM Severe Thunderstorm Archive (STA; BOM, 2015),
165 that contains data on hail, tornadoes and damaging convective winds from
166 1795 and is updated on an ongoing basis. Exploring these records in both
167 Australia and in other parts of the world, observations of severe thunder-
168 storms producing hail, damaging convective winds and tornadoes are iden-
169 tified to have the highest frequency of occurrence near population centers,
170 or along road networks (Schuster et al., 2005b; Allen et al., 2011; Tippett
171 et al., 2015; Allen and Tippett, 2015). This effect results from the sparse

172 distribution of observers in less-populated rural regions, which has a signifi-
173 cant impact on the knowledge of severe thunderstorms in these areas (Hales,
174 1993; Griffiths et al., 1993; Doswell, 2001). The extensive areas with a lower
175 density population, combined with the relatively small scale across which
176 severe thunderstorms do their damage can mean many events go unreported,
177 and thus the understanding of the climatology for thunderstorm-related phe-
178 nomena is often limited (Kelly et al., 1985; Griffiths et al., 1993; Geerts and
179 Noke-Raico, 1995; Mills and Colquhoun, 1998). In contrast, over-reporting
180 of events also occurs over the dense areas of population associated with cities
181 and urban sprawl. A significant limitation encountered in Australia is that
182 the severe weather section of the BOM was not established until 1987, and
183 hence there was no formal collection mechanism prior to this date, leading
184 to temporal inconsistencies which must be carefully considered (Hales, 1993;
185 Griffiths et al., 1993). The strong tendency for existing events to be clustered
186 towards highly populated areas is emphasized by considering a population
187 chloropleth compared to reports (Figure 1). When combined, for example,
188 with the noticeable increase in the number of hailstorms over this period due
189 to changes in the monitoring network, the population clustering results in a
190 record that has a spurious positive trend and produces questionable spatial
191 distributions of a phenomena’s occurrence. Thus it can be assessed that the
192 STA provides a short and inconsistent observational record prior to this pe-
193 riod, making an extensive report-based climatology challenging to produce
194 for periods longer than a couple of decades using existing data.

195 For Australia there are currently two alternate potential sources of re-
196 motely sensed severe thunderstorm observations. These are derivable from
197 the national network of rain and single-polarized Doppler radar sites (Matthews
198 and Geerts, 1995; SREP, 2015), and from the limited satellite observations
199 that are available over the continent (e.g. Bhaskaran et al., 2001; Cecil and
200 Blankenship, 2012; Punge et al., 2014; Ferraro et al., 2015). The relatively
201 short temporal records and spatial coverage available for these sources of
202 proxy observations preclude a substantial climatological analysis. However,
203 it is likely that these resources will prove an important contribution to the
204 understanding of severe thunderstorms in Australia in the future, as sug-
205 gested by Matthews and Geerts (1995), Geerts and Noke-Raico (1995) and
206 Tippet et al. (2015).

2.3. *Environmental Conditions*

The limitations of observations for severe thunderstorms and lack of remotely-sensed data to reveal information regarding the occurrence and intensity of severe thunderstorms has led to alternate approaches. The severity of a thunderstorm is governed primarily by the environmental conditions in which it develops (Brooks et al., 2003; Allen et al., 2011), however the potential for severity can be influenced by the convective mode (organization) of a thunderstorm (Thompson et al., 2012). Little physical difference exists between a storm that produces near-severe, and severe weather (Doswell, 2001), but severe storms are more commonly recognized due to their impact on the day-to-day lives of the population. The convective mode plays an important role in the generation of severe weather, with stronger and more persistent updrafts leading to a longer convective lifetime, and in sufficient steering flow, to an extension of the potential spatial impact of severe phenomena (Thompson et al., 2012). This is particularly the case for high-end severe events in the U.S., with greater than 95% of hail in excess of 5cm being associated with supercell type thunderstorms (Blair et al., 2011; Thompson et al., 2012; Brooks, 2013), along with the majority of tornadic occurrences (Doswell, 2001; Thompson et al., 2012).

Extensive research has been undertaken in the U.S. and to a lesser extent Europe (Brooks et al., 2003; Brooks, 2009; Grams et al., 2011; Thompson et al., 2012) to explore the conditions favorable to severe storm development using the ingredients-based methodology adapted from Doswell et al. (1996). Primarily these investigations have revealed that the greatest controls on thunderstorm severity can be extrapolated back to the combination of vertical wind shear (VWS) over various depths of the atmosphere, and thermodynamic instability, with other important parameters specific to individual phenomena, and in some cases, the necessary ingredients are not fully understood. As a detailed assessment has yet to explore many of alternative parameters used operationally and for climatology in the U.S. in application to Australian conditions (Ryan, 1992; Hanstrum et al., 2002; Allen et al., 2011), here we focus on a common measure of atmospheric instability, Convective Available Potential Energy (CAPE), and an equally common measure of VWS, the bulk magnitude of the wind vector difference between the surface and 6 kilometers (S06). A discriminant fixed value of the product of these two parameters, and cross-validated using a set of observed Australian severe thunderstorms (Allen et al., 2011; Allen and Karoly, 2014) has been shown to perform well in identifying favorable environments for severe thunderstorm

formation (Figure 2; though such environments will not necessarily produce a thunderstorm). As the magnitude of this product increases, through either its respective components or through joint increases, the probability of larger hail, stronger tornadoes, and more intense damaging convective winds rises. On this basis, discriminant thresholds (Figure 2) based around this product from Allen et al. (2011) are used to approximate the overall occurrence of severe thunderstorm events where few observations are available using reanalysis or model data, a situation common to most of the Australian continent (Figure 1).

3. Lightning and Thunderstorm Climatology

To gain a greater understanding of the climatology of severe thunderstorms for Australia, an appreciation of what is known about the spatial distribution of thunderstorms is a useful indicator of their potential climatology. A simple approach to estimate the frequency of thunderstorm occurrence is to use the concept of thunderdays, the days on which thunder was observed at an observing station. Using 300 observation stations nationally, Kuleshov et al. (2002) identified thunderdays as being most prevalent across the tropics, with secondary maxima in the interior (likely associated with the northern Monsoon across WA, NT and QLD), and in southeast Australia. Subsequent and progressive updates to this climatology using an 18-year record of automatically identified lightning flashes from a national detection network have explored both frequency of occurrence and seasonality independent of observer biases (Figure 3, Kuleshov and Jayaratne, 2004; Kuleshov, 2004; Kuleshov et al., 2006, 2009; Dowdy and Kuleshov, 2014). Most notably a bi-modal behavior was identified, with the expected spring and summer peak, along with a secondary peak over the east coast associated with intense extratropical cyclone development during the winter months. The peak occurrence through the southeast occurred during spring through early autumn, while in the tropics generally this was during the summer and into early autumn corresponding to the development of the monsoon.

Unlike STA reports, there are few spatial biases to this technique owing to the remote-sensing of lightning observations using nationwide network. However, the production of lightning does not necessarily reflect the intensity of thunderstorms or require surface based or deep convection, and as little as 400 Jkg^{-1} of CAPE or even less can produce lightning, far below the values commonly associated with other thunderstorm-related phenomena (Doswell,

2001; Brooks et al., 2003). Thus, while lightning data and thunderdays can be useful for obtaining a picture of thunderstorm occurrence over regions of lower population density and can be a feature of severe thunderstorms (Rasmussen and Blanchard, 1998; Kuleshov and Jayaratne, 2004; Kuleshov, 2004), they have little bearing on the distribution of other thunderstorm effects such as hail, tornadoes and damaging convective winds. In addition, low CAPE environments such as those encountered in cool-season tornado environments (Hanstrum et al., 2002) and tropical cyclone tornado environments (Edwards, 2012) rarely produce lightning, and thus lightning provides little information on the areas in which these events occur. Despite these disconnects, lightning is likely the most deadly of all phenomena associated with severe thunderstorms, accounting for approximately 85% of all fatalities in Australia associated with these events (Coates et al., 1993; Blong, 2005). Other potential impacts associated with lightning mainly relate to initiation of wildfire events, a large proportion of which result from cloud-to-ground strikes (Dowdy and Mills, 2012).

While thunderdays suggest that the greatest occurrence of thunderstorms is in the tropical regions of Darwin and the Kimberly, the Australian tropics typically do not have adequate VWS to promote strong and long-lived thunderstorms that produce the largest fraction of severe phenomena (Barnes, 2001). The short convective life-cycle, weakly organized updrafts, and an elevated freezing level result in few hail events in tropical regions. High relative humidities in the lower layers also inhibit the production of damaging convective winds. The lack of VWS to organize updrafts also reduces the possibility of supercellular tornado events. In contrast, strong cumulus updrafts and relatively weak surface flow are supportive of non-supercellular tornadoes, particularly waterspouts over near-coastal regions. The dynamic conditions being less favorable in the tropics suggests that like other locations worldwide (e.g. Brooks et al., 2003), Australian thunderstorms producing phenomena other than lightning predominantly occur in the mid-latitude regions of the continent (Barnes, 2001; Allen and Karoly, 2014).

4. Severe Thunderstorm Phenomena: Hail, Tornadoes, Convective Wind

4.1. Climatology and Overview

The majority of analyses of severe thunderstorm occurrence to date have focused on the southeast and east coast of the continent (Schuster et al.,

2005a; Yeo, 2005), with a particular bias towards NSW given the relatively widespread population and history of significant thunderstorm events (Yeo et al., 1999; Buckley et al., 2001; Leigh and Kuhnel, 2001). This does not necessarily mean that, given the required conditions, severe thunderstorms do not occur in other parts of the continent (Hanstrum and Foley, 1990; Allen, 2012; Richter et al., 2014). Instead, it suggests that the spatial distribution of frequency elsewhere is such that the probability of a population center being hit is comparatively low. In a short duration global climatology Brooks et al. (2003) and later Brooks and Dotzek (2007) estimated severe thunderstorm favorable environment frequency using a U.S. derived discriminant for reanalysis data, showing a peak frequency over eastern Australia (QLD, NSW, VIC) and across the north of the continent (NT, WA). Refining this approach and extending the climatology over the full continent independent of observations, Allen and Karoly (2014) used an environmental discriminant to develop a 32-year climatology using a different reanalysis (Figure 4). These higher resolution results identified high frequencies extending along the Great Dividing Range, across northern Australia (QLD, NT, WA) and down into southern WA. Environments in southeast QLD and northeast NSW were identified to have a greater dependence on CAPE for most of the convective warm season, while environments further south (SA, VIC, TAS, WA, southern NSW) typically depended more on S06, as would be expected given the typical southerly displaced Australian mid-latitude storm track. A limitation of this environmental approach was noted to be the excessive identification of favorable environments over the northern subtropics and tropics, which have few severe thunderstorm observations in the existing record (Figure 1). As there is little population to speak of in the northwest of Australia, the peak frequency here suggests the need for further investigation to explore severe thunderstorm occurrence in this region.

Severe thunderstorms and favorable environments for their occurrence in Australia are most frequent between midday and 7pm local time (Figure 5a), with the peak occurrence falling between 3 and 7 pm (Griffiths et al., 1993; Schuster et al., 2005a; Allen et al., 2011; Allen and Karoly, 2014). This is consistent with the occurrence of both non-severe and severe thunderstorms worldwide, which are generally found to peak with the diurnal cycle of surface temperature and the maximum availability of heating, and hence potential updraft strength and CAPE (Kelly et al., 1985).

Seasonally, Australian severe thunderstorms can be broken into two groups; the predominant warm season severe thunderstorms typically occurring be-

355 tween September and April (Figure 5b, Harper et al., 2000; Tucker, 2002;
 356 Niall and Walsh, 2005; Schuster et al., 2005a; Allen et al., 2011; Allen and
 357 Karoly, 2014)), and cool-season thunderstorms that typically produce low-
 358 instability tornadoes over the south of the continent in WA, SA, VIC and
 359 NSW (Griffiths et al., 1993; Hanstrum et al., 2002; Mills, 2004; Kounkou
 360 et al., 2009). As would be expected given the range of latitudes that the
 361 continent spans, there are geographic variations in the seasonal distribu-
 362 tion between QLD and the more mid-latitude states (NSW, VIC) due to
 363 the regularity of passage of synoptic systems, with QLD tending to peak
 364 earlier (October to January and a second peak in March; Yeo, 2005) than
 365 further south, where the peak of severe thunderstorm season coincides with
 366 the spring and summer (Allen and Karoly, 2014). While many of the most
 367 severe thunderstorms are typically confined to the warmer months, there is a
 368 high degree of inter-annual variability within the occurrence both temporally
 369 and spatially.

370 Interannual variability has proven difficult to quantify for Australia, as
 371 much of the observed data experiences a strong increasing trend after the
 372 establishment of the severe storms sections of the BOM and growth of the
 373 storm spotters network after 1989 (Schuster et al., 2005a). Analysis using
 374 environmental proxy counts over the whole continent and the eastern half of
 375 the continent suggests considerable variability associated with the El Niño
 376 Southern Oscillation (ENSO Rasmusson and Wallace, 1983) signal (discussed
 377 in Section 6), but no apparent trend in the occurrence of favorable environ-
 378 ments over the same period as illustrated in Figure 6.

379 In summary, while there is a useful appreciation for the overall aspects
 380 of the seasonal and diurnal cycle, significant limitations exist for the spatial
 381 and temporal climatology of severe thunderstorms and their associated envi-
 382 ronments, making understanding risk, variability and potential trends over
 383 the last few decades challenging.

384 4.2. *Hail*

385 Large hail is one of the most common features of Australian severe thun-
 386 derstorms, occurring in 30% of events (Griffiths et al., 1993; Harper et al.,
 387 2000). However, comparatively little is known about the distribution of larger
 388 hail diameters, as such events are uncommon in the STA (Tucker, 2002;
 389 Schuster et al., 2005a). Nonetheless, as the Sydney hailstorm and other re-
 390 cent events in other capital cities have illustrated, more extreme hail sizes
 391 are certainly possible in Australia (Yeo et al., 1999; Leigh and Kuhnel, 2001;

392 Allen, 2012). The largest record in the existing archive suggests a maximum
393 hail diameter of 16cm, though uncorroborated reports suggest historically
394 that events have produced hail as large as 20cm or larger.

395 Spatially, reports of severe hail in excess of 2cm are most frequent toward
396 the coastal regions and show heavy clustering characteristics toward the heav-
397 ily populated urban centers (Figure 7a). However, the reports also reflect the
398 national highways and accompanying town centers. The highest frequencies
399 outside of the respective state capitals are found along the Great Dividing
400 Range, stretching from western VIC, throughout eastern NSW and north
401 to central QLD. Reports also stretch inland east of Perth, and surrounding
402 Adelaide. Intriguingly there is a surprising number of observations over the
403 limited road network through northwestern WA and central Australia, and in
404 and around Darwin (12.45°S) in the NT, which suggests that estimates from
405 the environmental climatology may be less far-fetched than first thought.
406 These are accompanied by several hail reports of 5cm or greater, suggesting
407 a propensity for organized thunderstorms such as supercells as well (Figure
408 7b). The majority of these larger hail reports occur over the east coast and
409 nearer to capital cities, and are found further north reflecting the increased
410 moisture and instability found in the subtropics. The increased bias towards
411 the capital cities reflects the smaller swath width of the larger hail diameters,
412 as noted for the U.S. (Blair et al., 2011).

413 Hailstorms have been appreciated as a relatively common occurrence for
414 much of Australia’s history (Newman, 1947; Hanstrum and Foley, 1990; An-
415 drews and Blong, 1997; Eyre, 1992; Doswell and Brooks, 1993; Colquhoun,
416 1995; Crompton and McAneney, 2008). Yet it was only relatively recently
417 that such events became a major research focus, particularly following a
418 spate of hailstorms around the Sydney area, culminating in the record Syd-
419 ney Hailstorm of 1999 (Yeo et al., 1999; Leigh and Kuhnel, 2001; Buckley
420 et al., 2001; Schuster et al., 2005b). Characterized by extensive swathes of
421 hail of 7.5cm diameter (cricket ball), verified reports to 11cm and more iso-
422 lated reports as large as 13.1cm, the storm moved from south to north over
423 a 5.5 hour period, tracking over eastern Sydney causing a record 1.74 billion
424 AUD insured loss (2015 adjusted loss 4.3 billion AUD). The event occurred
425 outside the typically perceived severe thunderstorm season, but more than
426 ample instability and strong VWS combined to produce a highly favorable
427 environment along the coastal plain. In recent years, similar events have
428 impacted Brisbane, Melbourne and Perth, highlighting the need for a better
429 understanding of climatology (Buckley et al., 2010; Allen, 2012; Munich RE,

430 2015).

431 The Sydney storm also prompted a greater interest in hailstorm clima-
432 tology over NSW and southeastern Australia in an attempt to assess the
433 overall profile of risk (McMaster, 2001; Tucker, 2002; Schuster et al., 2005a,
434 2006). Notable to each of the studies was the population and spotter biases
435 in hail observations towards the populated centers, and an increasing trend
436 toward the end of the record associated with increased reporting (McMaster,
437 2001; Tucker, 2002; Schuster et al., 2005a), though verification of hail events
438 poses challenges even on the east coast (Mills and Colquhoun, 1998). Con-
439 sidering rural NSW hailfall from crop insurance data and two observational
440 records, McMaster (2001) noted a greater dependency on the frequency and
441 intensity of hail, rather than simply absolute magnitude. This combined ap-
442 proach revealed that hailstorms were most frequent in the elevated areas of
443 the Great Dividing Range in NSW and most severe in the north of the state
444 where there is summer-dominant hailfall. This analysis is consistent with
445 the analyzed environments (Tucker, 2002; Allen and Karoly, 2014), which
446 have larger CAPE and more precipitable water available to form stronger
447 updrafts in this region. Considering the east coast as a whole, Tucker (2002)
448 noted larger mean hail sizes for the northern urban centers as compared to
449 Melbourne, which was expected given the atmospheric differences. Some-
450 what surprisingly, both Sydney and Brisbane had similar mean diameters
451 over the period 1982-2001. Controversially, Tucker (2002) also suggested
452 that environments for hailstorms in Australia appeared to be more similar
453 to Europe than the U.S., with lower instability but modest VWS, though
454 based on a larger proximity climatology (Allen et al., 2011) these results
455 seem to be unrepresentative and are perhaps related to the use of poorly
456 timed proximity soundings from rawinsonde data. In an effort to extend the
457 observational record, Schuster et al. (2005a) used newspaper and insurance
458 archives together with the STA to produce a climatology from 1791 to 2003
459 over NSW. These results largely agreed with the work of McMaster (2001),
460 placing large frequencies over the Great Dividing Range and its margins,
461 and comparatively low frequencies across the lightly populated inland areas.
462 In the Sydney region ten severe hailstorms per year were identified, though
463 the observation evidence pointing toward a recent decrease in frequency ap-
464 peared to be questionable (Figure 6), and potentially could be explained by
465 a drought period and recent natural variability (Allen and Karoly, 2014).
466 Schuster et al. (2005a) also analyzed maximum hailstone sizes based on 1081
467 storms and found similar mean maximum diameters to Tucker (2002) for Syd-

468 ney (3.8cm), and that 22% of all reports were over 5cm in diameter, though
469 few exceeded 10cm. In all three climatological studies, the peak for severe
470 hail occurrence was found to closely match the spring and summer seasonal
471 peak for severe thunderstorms as a whole between October and January (Mc-
472 Master, 2001; Tucker, 2002; Schuster et al., 2005a). In addition to studies
473 conducted locally, a 5-year global environment-based analysis explored hail
474 over NSW (Hand and Cappelluti, 2011), and identified a similar spatial pat-
475 tern, though this may have overestimated the frequency in comparison to
476 Schuster et al. (2005a). These observational results are further supported
477 by the continental frequency of severe thunderstorm favorable environments
478 (Brooks et al., 2003; Brooks and Dotzek, 2007) for which large hail is a
479 primary contributor to the conditions that determine the discriminant.

480 In attempts to decouple observations from the climatological estimates,
481 progress toward remotely sensed climatologies has also been made in recent
482 years using satellite microwave sensors to detect overshooting tops or hail
483 signatures (Cecil and Blankenship, 2012; Ferraro et al., 2015). These cli-
484 matologies provide a useful and independent analysis of hail risk, solidifying
485 the picture offered by environments and observations. However both of two
486 analyses were limited by short temporal availability (eight and one year re-
487 spectively), and over-estimate hail risk in the tropics (Allen et al., 2015a;
488 Ferraro et al., 2015). Nonetheless, these estimates are consistent with the
489 observational and environmental records available, and reliably highlight the
490 seasonal peak and general spatial characteristics of hail over 2.5cm in diam-
491 eter over the mid-latitudes.

492 The potential of impact of damaging hailstones is clearly related to more
493 than just their diameter (Schuster et al., 2006), and the frequency of hail-
494 storm occurrence, as volume of hailfall is also important, particularly for
495 agriculture (McMaster, 2001). While impacts of hailstorms on heavily pop-
496 ulated urban environments can produce the largest insured losses (Andrews
497 and Blong, 1997; Crompton and McAneney, 2008) such storms can also have
498 significant impacts on the natural environment, forestry and other horticul-
499 ture processes (Cremer, 1984b,a; Myers, 1984; Houston, 1999). Alternative
500 approaches to estimate the climatology are underway using hail occurrence
501 derived from radar, and these will likely provide further insight over the
502 major urban areas (e.g. Figure 8 Soderholm et al., 2016). In light of the
503 widespread potential for hail to damage the human environment, consider-
504 able research is needed to better understand hail occurrence, the risk posed
505 by both magnitude and volume, and how these events can potentially influ-

ence natural and human environments by way of a better understanding of hailstorm climatology.

4.3. *Tornadoes*

Tornadoes in Australia occur in a wide range of meteorological settings (Southern, 1960; Phillips, 1965; Plukss, 1979; Minor et al., 1980; McRae et al., 2013), and can cause considerable damage to property, particularly when interacting with the major urban centers (Holcombe and Moynihan, 1978; Sills et al., 2004). A commonly held perception in Australia has been that few tornadoes are experienced, and those few that do occur are weak compared to their counterparts in the U.S. (Fujita, 1973; Minor et al., 1980; Allen, 1980; Geerts and Noke-Raico, 1995). However, while the perception of frequency appears to be a reasonable estimate (Fujita, 1973; Goliger and Milford, 1998; Allen et al., 2016), intensity assessments are not consistent with reality, as has been noted for Europe and globally (Brooks and Doswell, 2001), and is evidenced by a number of strong and damaging tornadoes in the Australian record (Holcombe and Moynihan, 1978; Plukss, 1979; Minor et al., 1980). The first documented tornado in Australia occurred in 1795 in the suburbs of Sydney, doing extreme damage to several properties over a narrow path. While numerous tornadoes were subsequently observed, the first scientific documentation of an event did not occur until the late 1800s, though events were commonly discussed in the media with varying degrees of understanding (Russell, 1889, 1891, 1893). Subsequent case studies of tornadic events were periodically undertaken, particularly between 1950 and 1980, and especially where these events impacted populated areas or drew considerable media attention (e.g. Abbe, 1906; Hunt and W.J., 1927; Phillips, 1965; Plukss, 1979; Minor et al., 1980). For a more detailed list of historical case studies we direct readers to lists that appear in Minor et al. (1980) and Allen (1980).

In comparison to the array of case studies, climatologies of tornadoes in Australia have been relatively sparse and generally temporally limited (Clarke, 1962; Evesson, 1970; Minor et al., 1980; Allen, 1980; Geerts and Noke-Raico, 1995). As with all severe thunderstorm climatologies, each of these efforts were hampered by clustering toward population centers and the coastal fringes. Particularly notable to tornadoes however were terminology changes, narrow tornado damage paths and confusion early in the record as to how an event could be defined from eyewitness reports of varying quality (Clarke, 1962; Evesson, 1970; Allen, 1980; Geerts and Noke-Raico, 1995).

543 In the earliest effort, Clarke (1962) focused on 'severe local windstorms',
544 characterized by strong winds on a lateral scale of a few miles that caused
545 noteworthy damage to buildings and trees. This approach identified 167
546 tornado events from January 1950 to June 1961 using documentary records
547 and newspapers (Figure 9a). Based on this record, Clarke (1962) assessed
548 that the frequency of tornadoes for QLD and WA was similar to the states
549 with the highest rate of occurrence in the U.S., but that the tornadoes were
550 generally less intense. This initial foray prompted greater interest in case
551 studies over the next decade, and further efforts to determine the climatology,
552 particularly over NSW.

553 Evesson (1970) expanded the NSW tornado record for the period 1805-
554 1966 using newspaper archival records, and a defined set of criteria that
555 excluded events where evidence was uncertain. An intriguing result from
556 this analysis was rather than reports of tornadoes increasing with time, there
557 appeared to be a greater interest in tornado events in the past prompting
558 multiple newspaper articles, whereas in the 1950s and 1960s damage to an
559 urban center was necessary to generate a news article of public interest.
560 To overcome issues with estimating the frequency over the state, Evesson
561 (1970) extrapolated the frequency over the highly populated coastal fringe to
562 suggest 15 tornadoes per year occurred over NSW. This contrasted the earlier
563 estimate of 14.6 occurring per year for the entire country made by Clarke
564 (1962) and later repeated by Fujita (1973). Like Clarke (1962), Evesson
565 (1970) suggested that NSW also was comparable to the U.S. states with the
566 highest tornado frequency. Both of these assertions were later challenged
567 by Fujita (1973), who in post-analyzing Clarke's data suggested that the
568 frequency of Australian tornadoes was at least order of magnitude smaller
569 than that found in the U.S.

570 The growth of the record continued with Minor et al. (1980), who were
571 surprised to find that tornadoes in Australia were perceived as more of a
572 curiosity than a concern compared to the U.S., and were generally misunder-
573 stood by the public. Assessing a large number of case studies in addition the
574 climatology of Evesson (1970), they identified that tornadoes in Australia ex-
575 hibited many of the classic characteristics of American tornadoes, including
576 appearance and intensity (Peterson et al., 1979; Minor et al., 1980). Their es-
577 timated rate of occurrence adjusting for population density suggested events
578 may occur as frequently in parts of Australia as in some parts of the U.S.
579 (Figure 9b). Taking this frequency, combined with the rare occurrence rate
580 of strong tornadoes noted for the U.S. (approx. 1%, Minor et al., 1980;

581 Brooks and Doswell, 2001) they suggested little difference in the potential
582 strength of tornadoes between the two continents. Further extension to the
583 climatology followed (Allen, 1980) to build on the work of Clarke (1962) and
584 Evesson (1970). This led to the continuation of the assumption that derived
585 statistics were representative for the major population centers, but a gross
586 underestimation otherwise (Figure 9c). Despite these limitations, tornadoes
587 were arguably identified to be the source of 41 fatalities, however this cli-
588 matology suggested it was rare for more than one tornado to be found in
589 the Australian record on a given day, contrasting outbreak events commonly
590 found in the U.S. (Fujita, 1973), though this result has since been found to
591 be simply a function of limited data (Allen et al., 2016).

592 The need for an improved tornado observational record was again raised
593 by Geerts and Noke-Raico (1995), who used the early STA archive of 700
594 tornadoes and performed a reanalysis of information regarding tornadoes oc-
595 ccurring between 1960 and 1992, reflecting the most validated period of the
596 record (Allen, 1980). Contrasting earlier studies, Geerts and Noke-Raico
597 (1995) identified an average of 29 tornadoes per year over the continent (348
598 events; Figure 9d), with the frequency of tornadoes per year per 26,000 km²
599 over Sydney around half the frequency for central Oklahoma. The urban
600 results also prompted discussion as to whether solely population density pro-
601 vided the best explanation, as other factors such as detection saturation, the
602 spread of structures to function as a detection network and allocation of an
603 observation to the nearest urban population appeared to contribute to the
604 distribution. Despite these issues, Geerts and Noke-Raico (1995) suggested
605 that outside of the coastal fringe, tornadoes were rare over the continent.

606 Subsequent assessments with global context used limited data from 1985-
607 1995 (Goliger and Milford, 1998), and noted that the estimates by Minor
608 et al. (1980) were overstated, and the frequency of tornado occurrence closer
609 to Fujita (1973)’s assessment. Despite indicating lower frequency than Geerts
610 and Noke-Raico (1995), these results were suggested to be complementary,
611 owing to the localized regional scales considered in the Australia only study.
612 Assessing global tornado frequency using an environment proxy for a short
613 period, Brooks et al. (2003); Brooks and Dotzek (2007) and later updated by
614 Tippet et al. (2015) identified modest frequencies of environments favorable
615 to the development of tornadoes over eastern Australia, but non-zero proba-
616 bilities over much of the continent. This result was consistent with estimates
617 derived from observations, suggesting that like most of the world, the fre-
618 quency of tornadoes is considerably rarer than for the U.S. This suggestion

619 was further supported by Allen et al. (2016), exploring the media-alleged
620 'record' 2013 tornado season of 63 events in the context of the digitized STA.
621 This identified that the significant under-reporting of tornadoes continues
622 into the present, despite a spatial distribution similar to those of earlier
623 studies.

624 The seasonal cycle of tornado frequency was also revealing in addition to
625 the climatology of frequency (Griffiths et al., 1993; Geerts and Noke-Raico,
626 1995). This suggested a bi-modal seasonal cycle that was unlike the pat-
627 tern in the U.S. with an early spring/summer peak and a secondary peak
628 in the early winter months. The variations over the length of the record
629 also appeared to suggest a weakening seasonal cycle, with contributions from
630 either large interannual or decadal variability or the increasing detection of
631 tornadoes occurring in alternate environmental conditions over the continent
632 (Geerts and Noke-Raico, 1995). Subsequently, tornadoes such as the event
633 described by Southern (1960) were identified as cool-season events, char-
634 acterized by low but surface based instability environments ($200\text{--}400\text{ Jkg}^{-1}$
635 CAPE) accompanied by high low-layer VWS (Geerts and Noke-Raico, 1995;
636 Hanstrum et al., 2002; Mills, 2004; Kouunkou et al., 2009). These cool-season
637 tornadoes were identified to comprise a large fraction of the overall clima-
638 tology, and were commonly found over southwestern WA, southern SA and
639 western VIC. Based on environment derived proxies, Hanstrum et al. (2002)
640 suggested that approximately 8 days per year were associated with conditions
641 favorable to cool-season tornado development over both regions, highlight-
642 ing a substantial risk. Another contribution in relatively low instability also
643 was identified to originate from tropical cyclone tornadoes (Edwards, 2012),
644 which have been identified in isolated cases such as Tropical Cyclone Joan
645 (Minor et al., 1980; Geerts and Noke-Raico, 1995) and more recently in Ex-
646 tropical Cyclone Oswald (H. Ramsay, pers. comm.). Perhaps uniquely to
647 Australia, a wildfire in 2003 also induced a strong tornado beneath the base
648 of a pyro-cumulonimbus, causing significant damage and rapid spread of the
649 fire (Fromm et al., 2006; Cunningham and Reeder, 2009; McRae et al., 2013).

650 The analysis of tornadoes in 2013 (Allen et al., 2016) further illustrated
651 the wide range of formative environments of tornadoes in Australia that
652 included many of the environments commonly encountered worldwide. This
653 suggests a higher risk of tornadoes for Australia than applying a single criteria
654 from the U.S. may reveal (e.g. Brooks et al., 2003).

655 Common to each of these climatological studies has been insufficient ob-
656 servations to assess the overall risk of tornadoes to the continent. Yet despite

657 this limitation, the risk assessed from these observational studies has influ-
 658 enced engineering assessments over parts of the continent (e.g. Melaragno,
 659 1976). This, combined with the apparent risk to heavily populated urban
 660 areas (Geerts and Noke-Raico, 1995; Allen et al., 2016), suggests a need to
 661 better understand the intensity and occurrence of tornadoes for the continent
 662 as such events are rarely assessed in the field. Further efforts are necessary
 663 to update the climatology to document and improve the existing STA record
 664 of 1273 tornadoes (Figure 9e), and to expand this record using historical
 665 archives similar to the efforts of (Grazulis, 1993) for the U.S. Preliminary
 666 work towards this goal has doubled the number of confirmable tornado obser-
 667 vations over the period 1795-1910, greatly improving the spatial distribution
 668 (Figure 9f), while providing further metadata to the existing STA archive.
 669 There also appears to be a significant need to explore applications of envi-
 670 ronmental proxies similar to Brooks et al. (2003) to assess the climatological
 671 risk for at least the last three decades, and develop proximity climatologies of
 672 tornado favorable environments to assess alternate formative environments
 673 and develop local forecasting guidelines.

674 *4.4. Damaging Convective Winds*

675 Damaging convective winds produced by thunderstorms can pose a widespread
 676 hazard, leading to wind gusts up to and over 200 kmh^{-1} that can destroy
 677 homes, snap trees and impact areas of a greater spatial extent than torna-
 678 does (Geerts, 2001; Richter et al., 2014). Combined hazards can also arise
 679 when such winds occur in tandem with large damaging hail in supercell thun-
 680 derstorms, propelling them horizontally against structures, a situation com-
 681 monly experienced in southeast QLD and along the east coast (Eyre, 1992;
 682 Doswell and Brooks, 1993; Colquhoun, 1995; Richter et al., 2014; Munich RE,
 683 2015). Often damaging convective wind events can be challenging to differen-
 684 tiate from weak tornadoes, leading to a tendency for the two to be considered
 685 jointly in some cases (Clarke, 1962; Evesson, 1970). The vast range of en-
 686 vironments that promote the formation of wet, hybrid and dry microbursts
 687 that typically produce damaging convective wind events (Wakimoto, 2001)
 688 also make it difficult to proxy their occurrence using environments, as do lim-
 689 itations of the observed record (Geerts, 2001). The most challenging element
 690 of the observed record is isolating the winds associated with thunderstorm
 691 gusts, rather than synoptic scale events, and this issue is particularly pro-
 692 nounced for anemometer data (Wang et al., 2013), and to a lesser extent
 693 in the STA. This distinction is important, as damaging convective winds

694 and non-convective (synoptic) wind gusts have different probability curves,
 695 suggesting that they need to be considered independently (Holmes, 2002).
 696 Further to this issue, without anemometer data, damaging convective winds
 697 are notoriously poorly estimated, leading to issues with classification and ex-
 698 aggeration (Trapp et al., 2006). Thus predominantly, studies for damaging
 699 convective winds over Australia have focused on anemometer records, and
 700 performed manual exclusion of non-convective events (Geerts, 2001). Geerts
 701 (2001) developed a climatology for NSW from 9 anemometers, and illus-
 702 trated that damaging convective wind gusts were more prevalent on or west
 703 of the Great Dividing Range during November to December, though not in
 704 the western plains where lightning climatology also reveals thunderstorms to
 705 be infrequent. Dry microbursts were found to be the most common source of
 706 damaging convective winds in this record, while the distribution of wind gust
 707 magnitudes was exponentially decreasing with increasing intensity. These re-
 708 sults highlighting dry microbursts are not reflective over southeast QLD or
 709 east of the Great Dividing Range, where hybrid microbursts are more com-
 710 mon, particularly with high precipitation supercells (Eyre, 1992; Colquhoun,
 711 1995; Richter et al., 2014).

712 An alternate application for anemometer data is to consider the distri-
 713 bution of damaging convective wind occurrences statistically using extreme
 714 value theory. Holmes (2002) used a peaks-over-threshold extreme value ap-
 715 proach from recorded anemometer measurements to designate the 500-year
 716 wind standards return level for Australia, identifying that for each of the
 717 state capitals, damaging convective winds were the most important factor,
 718 excluding Perth where synoptic winds were generally stronger, and neces-
 719 sitated the building standard requirement of resistance to 162kmh^{-1} gusts.
 720 More recently, approaches using reanalysis environment data downscaled to
 721 14km resolution have been explored to spatially extend this approach over
 722 Tasmania and approximate the 500-year return levels for wind magnitude
 723 from thunderstorms from extreme value theory (Sanabria and Cechet, 2010;
 724 Cechet et al., 2012). These results suggest that the overall hazard from
 725 these events was less than from synoptic winds, but still returned values of
 726 133.2kmh^{-1} for the north, and 122.4kmh^{-1} for the south. These methods
 727 provide a way to assess risk for damaging convective winds, though do not
 728 provide information regarding its occurrence, and are subject to limitations
 729 arising from the problems of the observational record and the assumptions
 730 of extreme value theory (Sanabria and Cechet, 2010).

731 Particular gaps arise concerning the occurrence of widespread damaging

convective wind events caused by squall lines or derechos (Corfidi et al., 2015) and other observed damaging convective wind events outside of NSW and southeast QLD. Exploring other approaches to leverage and extend observations (e.g. Foley and Hanstrum, 1990) from the Bureau STA is another approach to improve our understanding of these events. Given the wide array of environments favorable to damaging convective winds, this also suggests the need to explore environmental climatology of these conditions over the continent to understand the risk.

5. Forecasting

To describe the full responsibilities of the meteorologists that staff Australian regional severe weather desks would be cumbersome in the context of this review, so hence here we focus on the research conducted to build tools to inform this system and refer readers to Deslandes et al. (2008) for further details, while discussing the limitations in our understanding for forecast guidelines and the current warning process.

Guidance at the outlook period for severe thunderstorm forecasters in Australia (Deslandes et al., 2008) was developed using a decision tree algorithm that has been extended from its initial inception in 1987 to be applied as an automated severe thunderstorm threat assessment from regional numerical weather prediction (Colquhoun, 1987; Mills and Colquhoun, 1998). The algorithm relies on a set of derived environmental relationships used to discriminate at each level of the decision tree, primarily based on instability and VWS, applying the latest parameters identified as useful for forecasting in the U.S. and locally. This approach provides an automated analysis that is equivalent to severe thunderstorm watch guidance (Mills and Colquhoun, 1998; Mills, 2004). One limitation of this approach however, were the relatively small samples (e.g. of supercell thunderstorms) used to determine some of the decision criteria in subsequent iterations (e.g. Treloar and Hanstrum, 2002), and a limited testing period prior to implementation (Mills and Colquhoun, 1998). These limitations suggest a need for more extensive climatology and larger samples to develop forecasting guidelines, particularly for events which do not conform to the existing forecasting decision tree.

In addition to the need to explore and revise guidelines for the various elements of severe thunderstorm environment applications and sub-cases, there are also limitations to the existing warning and nowcasting processes (Deslandes et al., 2008; Allen et al., 2016). Despite operationally now having

the Doppler radar network along with tools and radar-algorithms to issue cell-based warnings (Fox et al., 2004; Joe et al., 2004; Wilson et al., 2004; SREP, 2015) outside of the state capitals, public warnings similar to watches are issued for several hours on a state-wide basis (Figure 10). Following this step, little to no guidance is provided to the rural public to warn of particularly intense or dangerous cells such as supercells, in contrast to the major centers. This problem is further exacerbated by few verifications of forecasts and evaluations of the warning process, and compounded by insufficient severe thunderstorms observations to perform an appropriate analysis. Even over the major centers, there are some elements of public confusion regarding the implications of the issued warnings, for example if they are referring to a rainfall hazard or severe thunderstorm phenomena such as hail, or damaging convective wind gusts. A further ongoing issue is the lack of flexibility to issue tornado warnings without visual confirmation, despite the recent availability of a considerable network of 19 S or C-band Doppler radar sites (Sills et al., 2004; SREP, 2015; Allen et al., 2016).

6. Climate Change and Natural Variability

6.1. Climate Variability

There are a number of climate signals that contribute to natural variability in severe thunderstorm occurrence around the globe (Tippett et al., 2015). It is important to note however that establishing such relationships is made challenging by the limitations of observed records, and often requires the use of environmental proxies to establish a robust signal (e.g. Allen et al., 2015b). The largest contribution to interannual variability worldwide comes from ENSO, which also has a significant impact on the moisture available over southeast Australia. This leads to strong relationships with severe thunderstorm activity, though there are regional variations in the observed signal. Over the Sydney region, hailstorm activity is strongly enhanced during La Niña, or rising Southern Oscillation Index (SOI) between July to November (Kuhnel, 1998; Leigh and Kuhnel, 2001). In contrast, neutral ENSO conditions are considerably more active for severe thunderstorm days over southeast QLD, while El Niño provides the second most favorable scenario (Yeo, 2005). Analyzing proxy severe thunderstorm environments, Allen and Karoly (2014) identified that neutral ENSO conditions produced the greatest number of favorable severe thunderstorm environments across the continent and east coast (Figure 6). The largest spatial changes however were instigated by

the available moisture during La Niña, which produces a larger area of favorable environments south and inland over the east coast (Figure 11a). During El Niño, there is an increase in frequency over the southwest of the continent, and a northward shift over the east coast related to differences in moisture availability (Figure 11b). However, this simple analysis of the influence of the ENSO signal reveals that this climate signal explains only part of the variability of severe thunderstorm events over Australia. This suggests the need for further study to explore other locally relevant potential contributions to variability such as local sea-surface temperatures (Allen and Karoly, 2014), land cover changes (Gero and Pitman, 2006), the Madden-Julian Oscillation (Barrett and Gensini, 2013), the Indian Ocean Dipole (Webster et al., 1999) and contributions from decadal variability (Mantua et al., 1997).

6.2. Climatic Change

Investigations over the U.S. and Europe have established that despite insufficient observational or proxy evidence to identify conclusive trends in 20th century severe thunderstorm occurrence, a warming climate is simulated to lead to an increased frequency of severe thunderstorm favorable environments, primarily driven by an increase in CAPE (Trapp et al., 2007; Brooks, 2013; Tippet et al., 2015; Diffenbaugh et al., 2013). On this basis we direct the reader to consider a global analysis of this question for a more general discussion (Brooks, 2013; Tippet et al., 2015), and here we focus on the regional implications for Australia, given that a similar lack of trend outside of natural variability is seen in both the frequency of thunderdays and environmental climatology (Figure 6) for the past three decades (Davis and Walsh, 2008; Allen and Karoly, 2014).

Early analysis of primitive and coarse resolution global climate model simulations for Australia suggested decreases in the frequency of hail (McMaster, 1999). These results were supported by later projections using the CSIRO Mk3 model which suggested decreases in the number of days with sufficient CAPE for severe hail, and an increase in the intensity of hail events when they do occur for two stations in southeast Australia (Niall and Walsh, 2005). Over the Sydney basin, high resolution simulations identified that favorable CAPE pre-storm environments were expected to increase in association with rising surface temperatures and dewpoints, leading to increasing severity in large hail events despite reduced frequency (Leslie et al., 2008). These results were consistent with a simulation over the continent Abbs et al.

(2007), which suggested a doubling in the frequency of days with environments favorable to severe hail over NSW, despite the model overestimating frequency over the remainder of the southeast.

In the most recent analysis of the impacts of climate change on Australian severe thunderstorms Allen et al. (2014a) assessed the performance of two global climate models (CSIRO Mk3.6 and the Cubic-Conformal Atmospheric Model or CCAM) to represent convective parameters in the present climate by comparing with reanalysis climatology. This analysis revealed a strong degree of sensitivity in severe thunderstorm environments to model physics, particularly relating to moisture advection and convective parameterizations. Contributing to these issues were considerable differences in the height of east coast topography as a result of horizontal resolution, with peak terrain heights in CSIRO Mk3.6 limited to 400m, contrasting 1200m for CCAM, leading to large differences in moisture advection from the Tasman and Coral Seas. CSIRO Mk3.6 also struggled in resolving the diurnal cycle of occurrence, and, in each aspect the higher resolution CCAM was found to be conservative but offer a more accurate representation of the actual climatology. Taking into account these model limitations, Allen et al. (2014b) explored future projections for 2079-2099 under highly warmed future climate scenarios. In a warming climate, severe thunderstorm environments increased in frequency, particularly over the east coast (Figure 12). Statistically significant increases in occurrence for Brisbane, Sydney and Melbourne were 15%, 30% and 22% respectively of 20th century values. Changes were found to be strongly sensitive to the model considered, particularly as a function of topography and its resulting influence on advection, but in both cases proximity to higher sea-surface temperatures and advected moisture increased the frequency of high CAPE environments in a warmed world. In contrast, high S06 frequency decreased with poleward shift of the jetstream, but did not outweigh the contribution of increases to the thermodynamic energy available to the atmosphere, consistent with the international and prior regional results (e.g. Diffenbaugh et al., 2013).

A consideration that has not been explored globally concerns the influence of warming on cool-season tornadoes which form in low-instability environments (Kouunkou et al., 2007). These events, unlike their warm season counterparts, have been suggested to be less likely because of thermal stabilization of the lower troposphere during the winter months (Timbal et al., 2010), however further research is needed to explore these potential signals in more detail.

878 Despite recent work that better quantifies the influence of a warming cli-
879 mate on severe thunderstorms in Australia, the body of research remains
880 limited. A number of questions remain unanswered relating to the need to
881 consider a larger suite of model output for analyzing the potential change
882 given large differences between models, how to interpret estimations of initi-
883 ation of these events in the future, and the importance of model physics and
884 topographical features to the severe thunderstorm environment in Australia.
885 Several options also exist to explore dynamical downscaling approaches such
886 as those applied by Gensini and Mote (2015) over the U.S. to directly simu-
887 late storm occurrence rather than favorable environments. Also unaddressed,
888 and spurred by the lack of observations or proxy climatologies, are estimates
889 of how hail, tornadoes and damaging convective winds respectively may re-
890 spond to a warming climate.

891 **7. Discussion and Future Directions**

892 Based on the literature reviewed, it would appear that no capital city of
893 Australia is immune to the risk severe thunderstorm impacts, and much of
894 the continent has a relatively high rate of exposure. The formation mech-
895 anisms can widely vary for each of the phenomena over the continent, and
896 in doing so can mean that their occurrence may be unexpected. As noted
897 by Middlemann et al. (2007) insufficient observational records for each of the
898 primary hazards associated with severe thunderstorms are a primary limiting
899 factor in determining risk, though alternate approaches using environmental
900 proxies, satellite-derived climatologies and radar-derived records are becom-
901 ing available to compensate for these limitations. This is accompanied by
902 a disconnect to the resulting vulnerability in communities and the natural
903 environment. Thus even with an adequate profile of risk, further research is
904 necessary to understand the impacts of near-surface damaging winds from
905 convective storm events or tornadoes, and the impacts of hail on agriculture
906 and the built environment (Middlemann et al., 2007).

907 The relative infrequency of recent case studies and evaluation of forecasts
908 for verification also highlights the need increased scrutiny of recent events to
909 identify characteristics that can improve the nowcasting and forecast knowl-
910 edge for the continent. This can partly be explained by the relatively small
911 severe storm community in Australia at the current juncture, which results
912 in relatively few active research projects in the subject area. Examples of
913 ongoing work include exploring the climatology of hail using radar data sim-

ilar to the approach of Cintineo et al. (2012) (H. Ramsay, pers. comm.), the use of portable and fixed radars to study the climatology of thunderstorm initiation and structure of storms in the Brisbane region (Soderholm et al., 2016), efforts to extend the observational database of hail and tornadoes (Allen and Allen, 2014; Allen et al., 2016) as well as ongoing case studies and efforts to extending forecasting guidance by operational/support meteorologists (Richter, 2014a,b). The recent expansion of the Doppler radar network (SREP, 2015) to 19 Doppler capable S- or C-band sites across the country will play a critical role in the near future, as it allows an enhanced ability to warn the general public, along with promoting increased remotely-sensed observations from which to explore the characteristics and climatology of severe storms in Australia.

Specific directions that present opportunity for future research include:

- A greater utilization of the implemented Doppler radar network and potentially satellite data to provide a basis for case studies for significant events, to improve the warning process and for post-event climatological identification similar to the efforts of Cintineo et al. (2012) and expanding the work of Soderholm et al. (2016).
- A need for observational climatology to be revisited and extended by leveraging both local knowledge and digitized written records. One such example currently underway is the Australian Tornado Project (Allen and Allen, 2014) which applies National Library Archive data to identify historical tornadoes, and has been incredibly successful in extending this dataset (Figure 9).
- A greater application of numerical model and reanalysis data to understand the environmental conditions leading to severe thunderstorms in Australia. This direction acts to both enhance the knowledge of climatology, but also provide forecasting guidelines to operational meteorologists to improve the overall hazard detection process.
- A need to pursue a greater understanding of the impacts of climate variability and change on severe thunderstorms and their climatology. While several of the above noted directions suggest that producing a climatology of occurrence will require considerable effort, there is a need to take this step and understand what the changes to risk are as a response to either a warming climate, or climate signals such as ENSO.

- 949 • Consideration of a cell-based warning system outside of the major cap-
 950 ital cities to improve the efficacy of warning for severe thunderstorms,
 951 and whether a separate category for tornado warnings similar to those
 952 applied in the U.S. (Brotzge and Donner, 2013) may be appropriate
 953 given increasing understanding of the risk.
- 954 • Improved understanding of the vulnerability and losses due to severe
 955 thunderstorm hazards. This includes using these insights for the built
 956 and natural environments to inform enhancements to subsequent cli-
 957 matological risk assessments and thereby increase resilience of the pop-
 958 ulation to the impacts of these events.

959 8. Conclusions

960 There remain a number of significant gaps in our understanding of severe
 961 thunderstorms over Australia, and the risks they entail for the general pub-
 962 lic and the built environment. A groundwork has been laid in many of the
 963 relevant areas to begin to better understand the hazard, stretching from ob-
 964 servational climatologies to proxy-derived frequency assessments, numerous
 965 case studies, and applications to climate change and variability. The exist-
 966 ing work however has numerous limitations that are ripe to be addressed
 967 using modern resources and techniques to extend our understanding of the
 968 climatology and improve forecasting of these events. Numerous opportuni-
 969 ties also exist to better understand why one year may be more active for
 970 severe thunderstorms than another, and assess how this may change into
 971 the future. Along with the relatively small research community, the limited
 972 research resources available for this topic further exacerbates the gaps in ex-
 973 isting knowledge. This suggests that an opportunity is present to support
 974 further fundamental research into understanding the damaging potential of
 975 severe thunderstorms over the continent.

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Figure 1: Hail and tornado reports from the Bureau STA for the period 1795-2014, and gridded non-adjusted population density choropleth as of the year 2000 from the Center for International Earth Science Information Network Gridded Population of the World, Version 3, at 2.5 arc-minute resolution. States are indicated by their respective boundaries and common abbreviations, QLD: Queensland, NSW: New South Wales, VIC: Victoria, TAS: Tasmania, SA: South Australia, NT: Northern Territory, WA: Western Australia.

Figure 2: $\log(\text{CAPE})$ - $\log(\text{S06})$ phase space for 1550 unique severe and significant severe Australian model-derived proximity soundings. Discriminant lines shown correspond to the discriminant determined (left to right) for severe thunderstorms from non-severe thunderstorms based on POD (Eq. 7 from Allen et al. (2011) marked S), potentially significant severe thunderstorms (P) from severe thunderstorms which corresponds to a line drawn between the maximum and minimum variation lines (Eq. 6 from Allen et al. (2011) marked P), and significant severe thunderstorms from severe thunderstorms (Eq. 4 from Allen et al. (2011) marked Sig). Used with permission from Allen et al. (2011).

Figure 3: Remotely-sensed ground-flash lightning observation density (flashes $\text{km}^{-2}\text{yr}^{-1}$) for the period 2005-2012, with major population centers indicated. Used with permission from Dowdy and Kuleshov (2014).

Figure 4: Annual mean distribution of favorable severe thunderstorm environments for the period September 1979 to April 2011. Frequency is the number of days where SEV environments exceed the severe discriminant of Allen et al. (2011) at each grid point of the ERA-Interim reanalysis for Australia. Favorable environments must also satisfy the conditions: $MLCIN < 25 \text{ Jkg}^{-1}$, $S06 > 7.5 \text{ ms}^{-1}$, 700 to 500 hPa Lapse rate $> 6.5 \text{ Kkm}^{-1}$, and occur over land. Adapted from Figure 8a. of Allen and Karoly (2014)

Figure 5: a) Seasonal and b) diurnal cycles of hail and tornado events for Australia based on Bureau of Meteorology STA reports for the period 1900-2014. The annual cycle is fitted with a periodic 15-day Gaussian kernel smoothing procedure to preserve the structure of the cycle at the end of year boundaries. Diurnal timing of reports is in local time, and represented at the fraction of reports over the 24 hourly blocks.

Figure 6: Time series of the total number of environment days 1979-2011. (a) Total number of environments in Australia exceeding the severe discriminant (top line), and number of environments exceeding the significant severe discriminant (bottom line). Significant ENSO events (El Niño, La Niña, Neutral) over the period are shown in color. (b) As for (a) except total number of environments over eastern Australia. Adapted from Figure 10 of Allen and Karoly (2014)

Figure 7: a) Total density of Bureau STA sourced Hail reports from 1979-2014, aggregated on a 75x75km grid and overlaid with point report locations, b) As for a) except >5cm hail reports.

Figure 8: Cumulative mean annual incidence of radar-derived hail in excess of 21mm detected using the Maximum Expected Size of Hail (MESH) algorithm. MESH is calculated on a 1km grid for every 10min scan using volumetric data from the Marburg radar (July 1997 to June 2015) and the nearest Brisbane airport soundings in time. Figure 2a of Soderholm et al. (2016), used with the authors permission.

Figure 9: Evolution of the spatial climatologies of tornadoes in Australia through time. a) 167 tornadoes from 1950-1961, adapted from Clarke (1962) b) Areas with tornado frequency comparable to the active states of the U.S., adapted from Minor et al. (1980), c) Gridded 2x2 degree density of tornadoes from 1950-1959, adapted from Allen (1980), d) Distribution of the Bureau STA record of 348 tornadoes reported during 1960-1992. The triangles were used to denote summer events (22/9 - 21/3) and the circles winter events (22/3 - 21/9). Adapted from Geerts and Noke-Raico (1995), e) Total density of Bureau STA sourced tornado reports from 1795-2014, aggregated on a 75x75km grid and overlaid with point report locations, and f) Reanalysis of observed Australian tornadoes from historical archives gridded analogously to e) for the period 1795-1910 (Allen and Allen, 2014).

Figure 10: A typical areal state based warning from 23rd November 2013 for severe thunderstorms over the southeast part of QLD. Courtesy H. Richter, Australian Bureau of Meteorology.

Figure 11: a) Composite anomaly number of severe thunderstorm environments for three El Niño warm seasons determined for Southern Oscillation Index < 8 (1982/1983, 1991/1992, 1994/1995). b) As for a) except for three La Niña warm seasons determined for Southern Oscillation Index $> +8$ (1988/1999, 1998/1999, 2010/2011). Adapted from Fig 11 Allen and Karoly (2014)

Figure 12: Mean frequency anomaly for severe thunderstorm environments between 2079-2099 and 1980-2000 over eastern Australia for a) CSIRO Mk3.6 and b) CCAM. Stippling illustrates significant increases to the twenty-first-century mean above the 97.5th percentile, while hatching indicates significant decreases below the 2.5th percentile as determined using a bootstrapping procedure. Units are changes to the number of environments per season. Used with permission (their Figure 10) from Allen et al. (2014b)