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Special issue of Climatic Change

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**Natural hazards in Australia: storms, wind and hail**

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25 **Abstract**

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3 26 Current and potential future storm-related wind and hail hazard in Australia is reviewed.  
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5 27 Confidence in the current incidence of wind hazard depends upon the type of storm producing the  
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8 28 hazard. Current hail hazard is poorly quantified in most regions of Australia. Future projections of  
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10 29 wind hazard indicate decreases in wind hazard in northern Australia, increases along the east coast  
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13 30 and decreases in the south, although such projections are considerably uncertain and are more  
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15 31 uncertain for small-scale storms than for larger storms. A number of research gaps are identified  
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17 32 and recommendations made.

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## 34 **1. Introduction**

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3 35 Natural hazards associated with storms, such as severe wind and large hail, cause significant  
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5 36 economic damage and social dislocation across Australia. For example, the high winds from  
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8 37 Cyclone Tracy (1974) caused an estimated A\$2 billion dollars in damage (1999 dollars; BTE 2001).  
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10 38 Similarly, the insured cost of the 1999 Sydney hailstorm was estimated to be A\$1.7 billion in 1999  
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13 39 dollars (RMS 2009).

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16 40 Despite the severity of the impacts wrought by storms, there are limited reliable observed data for  
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19 41 some types of storms and associated hazards, particularly for the estimation of current wind hazard  
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21 42 from thunderstorms (section 2.2) and hail (section 2.3). Moreover, projections of future storm  
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23 43 characteristics have important uncertainties associated with them (section 4), while for hail,  
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26 44 projection studies have been few (section 4.2). Nevertheless, important progress has been made. To  
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28 45 summarise the latest knowledge and understanding of Australian storms, this paper reviews the  
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31 46 current scientific literature on the assessment, causes, observed trends and future projected changes  
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33 47 of storm hazard in Australia, with a specific focus on severe wind and hail hazard. The  
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36 48 meteorological causes of severe wind and hail are first outlined, including their geographical  
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38 49 distribution and methods of measurement, followed by observed trends. Future projections of these  
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41 50 hazards are then detailed, along with the uncertainties in these projections, concluding with  
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43 51 principal findings and some key open knowledge gaps and recommendations on future research  
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45 52 priorities.

## 49 53 **2. Understanding wind and hail hazards**

### 57 55 **2.1 Storms that produce severe wind and hail**

56 “Storms” are here defined as weather systems that produce severe wind and hail but their  
 157 occurrence varies from region to region in Australia. In the mid-latitude regions of Australia’s  
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 3 58 south, extreme winds are produced by severe thunderstorms and intense extra-tropical cyclones  
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 6 59 (ETCs), including their cold fronts. In the tropical regions of Australia, the largest contribution to  
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 8 60 wind hazard is from tropical cyclones (TCs), with wind hazard from these systems occasionally  
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 11 61 extending as far south as northern New South Wales (NSW) on the east coast and the Perth region  
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 13 62 in the west. In addition to wind hazard, TCs can cause storm surge (which is discussed in the  
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 15 63 companion coastal extremes paper, McInnes *et al.* (this issue)), flooding (which is similarly  
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 18 64 discussed in Johnson *et al.* (this issue)), landslide damage and tornadoes. The east coast of Australia  
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 21 65 from eastern Victoria (VIC) to southeastern Queensland (QLD) is subject to heavy rain, strong  
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 23 66 winds and large waves resulting from coastal low pressure systems that develop from a variety of  
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 25 67 weather systems (Speer *et al.* 2009). Generally referred to as East Coast Lows (ECLs), they cause a  
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 28 68 significant amount of damage along the east coast each year. In the alpine areas, mountain wave  
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 30 69 activity can lead to destructive winds on the downwind side of a ridge line under specific  
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 33 70 meteorological conditions (Reinecke and Durran 2009), for example, at Thredbo valley in 2014  
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 35 71 (pers. comm. including site inspection; <http://www.abc.net.au/catalyst/stories/4117934.htm>).

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 38 72 Severe thunderstorms are convective systems defined by the Australian Bureau of Meteorology to  
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 41 73 be accompanied at least one of the following:

- 44 74 • Hailstones with a diameter of 2 cm or more
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48 75 • Wind gusts of 90 km/h or greater
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51 76 • Flash flooding
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55 77 • Tornadoes

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 58 78 Storms that produce large hail and/or damaging winds (including tornadoes) typically form in  
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 61 79 environments with significant thermodynamic instability and strong vertical wind shear (large  
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80 changes in wind speed and direction with height). In Australia, the highest incidence of these  
 181 systems is reported along the central and southern portions of the east coast (e.g. Allen et al. 2011,  
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 3 their Fig. 1a).  
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## 783 **2.2. Assessing current wind hazard**

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 1184 The strongest wind hazard is in the tropical regions of the country, where TCs occur. For the design  
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 1385 and assessment of buildings and structures, the region of influence of TCs is deemed to be coastal  
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 1586 strips as far south as 27°S on both the Western Australia (WA) coastline, and on the east QLD coast  
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 1887 (Standards Australia 2011). Based on the predicted effects of global warming (see section 4), these  
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 2188 boundaries may need to be extended further south (Holmes 2008, 2011; Kossin *et al.* 2014)  
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2489 Since the 1960s, the ‘standard’ method of making estimates of return periods for high wind speeds  
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 2690 (i.e. for low annual probabilities of exceedence) has been based on recorded or ‘historical’ data, to  
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 2991 which the Type I Extreme, or Gumbel, probability distribution has been fitted (e.g. Coles *et al.*  
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 3192 2001). This distribution suffers from the disadvantage that it produces extreme values with no upper  
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 3493 limit: that is, continually increasing values of wind speed are generated as the return period  
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 3694 increases. From the 1990s onward, the less conservative Type III Extreme Value Distribution has  
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 3995 been used in Australia (Standards Australia 2011). This distribution produces predictions that  
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 4196 slowly asymptote to a (very) high upper limit, which is physically more realistic.  
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 4597 In Australia, the only recorded wind data that can realistically be used to assess extreme wind  
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 4798 speeds is the daily maximum gust that has been recorded by the Bureau of Meteorology since the  
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 4999 1940s, mostly at the standard height of 10 metres above flat, open country. These data are not  
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 5200 temporally homogeneous. In the 1990s, the conversion from the Dines anemometer (approximately  
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 55101 0.2 second gusts) to Automatic Weather Stations (AWS) with cup anemometers (digitally filtered to  
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 57102 3-second gusts) resulted in a discontinuity in the database, with the later AWS extreme gusts being  
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 59103 on average 10-20% lower than the earlier values, although conversion factors between the two have  
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104 been established (Holmes and Ginger 2012; Miller *et al.* 2013). These issues have affected efforts to  
 105 develop high quality surface wind data sets (Jakob 2010).

106 In many parts of Australia, high gusts are generated by more than one storm type – for example, in  
 107 the Sydney area both short duration thunderstorms and longer duration, synoptic-scale events, such  
 108 as ECLs, can produce high gusts. It is advisable, and good practice, for gusts produced by different  
 109 storm types to be separately analysed when carrying out extreme value analysis for a site.

110 Clearly, making estimates of extreme wind speeds at return periods of the order of hundreds of  
 111 years (which is usual for the design of structures against collapse or overturning – the so-called  
 112 ‘ultimate limit states’) will result in significant sampling errors, when data for an individual  
 113 recording station is only available for 30-40 years. This can be partially alleviated in practice by  
 114 combining data from several stations in the same general location into a single ‘super-station’ (but  
 115 see Palutikof *et al.* 1999 for a discussion of the limitations of this method).

116 Nevertheless, at locations where the occurrence of storms of a certain type are infrequent – for  
 117 example TCs at Cairns, QLD – the use of recorded gust data to make long-term return period  
 118 estimates will give very unreliable results. An alternative approach has been developed since the  
 119 1970s, based on simulating thousands of storms with the characteristics of those in the general area,  
 120 for example the Coral Sea in the case of Cairns. These methods generally consist of a combination  
 121 of probabilistic components (e.g. for the central pressure of TCs) and deterministic components  
 122 (e.g. for the wind field model associated with a tropical storm) (e.g. Harper 1999). A similar  
 123 approach is adopted for the impact of smaller storms such as thunderstorm downbursts or tornadoes  
 124 on physically large systems such as a transmission line several hundred kilometres in length (e.g.  
 125 Oliver *et al.* 2000).

126 The ability to estimate the current hazard accurately varies between storm types. Wind and hail  
 127 hazard from severe thunderstorms can be difficult to estimate over a large region. The main source

128 of data for severe thunderstorm incidence is reports provided by a network of observers, many of  
129 whom are members of the general public. This record is spatially and temporally inhomogeneous  
130 (Allen *et al.* 2011). The size of severe thunderstorms, typically less than 50 km in diameter, means  
131 that they are not well observed in the sparsely populated regions of Australia. Meaningful  
132 climatologies based on severe thunderstorm reports have been constructed in other parts of the  
133 globe but these are typically in regions of higher population and data density (e.g. Doswell *et al.*  
134 2005). Allen and Karoly (2014) circumvented this underreporting problem by instead examining the  
135 incidence of larger-scale meteorological conditions conducive to the generation of severe  
136 thunderstorms (that is, favourable “storm environments”), based on previous similar approaches  
137 such as that of Brooks *et al.* (2003). They calibrated their severe thunderstorm thresholds with  
138 available reports of severe thunderstorms in densely populated regions. A limitation of this  
139 technique is that it estimates only the potential for formation of severe thunderstorms and is not an  
140 accurate estimate, since their technique relies on probability assessment based on sparse data.

141 Observations of lightning can also provide insight into the occurrence of hazardous convective  
142 weather, including damaging winds. Studies from the USA have demonstrated a clear link between  
143 an increase in lightning flash count (so-called lightning “jumps”) and the onset of severe weather  
144 (e.g. Schultz *et al.* 2011). However, to date, lightning data in Australia have only been used to  
145 examine the distribution of all thunderstorms (Dowdy and Kuleshov 2014) and not specifically  
146 severe storms.

147 Tornadoes are a particularly violent form of severe winds that are produced mostly by supercell  
148 thunderstorms, long-lived thunderstorms that have their own small cyclonic circulation  
149 (“mesocyclone”). Supercell tornadoes have been studied extensively in U.S. through two dedicated  
150 field campaigns (VORTEX1; Rasmussen *et al.* 1994; VORTEX2; Wurman *et al.* 2012) and many  
151 observational and numerical studies. In Australia, some tornado case studies have been published  
152 (e.g., Hanstrum *et al.* 2002; Richter 2007), but the composition of a meaningful tornado climatology

153 is still a work in progress, as it involves the painstaking collection and evaluation of disparate  
154 information sources such as newspaper articles (Allen and Allen 2016).  
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5 155 ECLs are phenomena with relatively small spatial scales (often smaller than TCs) and short  
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7 156 lifetimes (Holland *et al.* 1987), and their pressure centres may develop or intensify offshore making  
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9 157 them difficult to study using standard *in situ* observations. It has been known for some time that  
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12 158 ECLs produce large precipitation and wind events on the east coast of Australia (e.g. Holland *et al.*  
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14 159 1987; McInnes *et al.* 1992; Hopkins and Holland 1997; Mills *et al.* 2010). Moreover, ECLs have  
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17 160 the capacity for rapid intensification (Holland *et al.* 1987), and thus have been found to satisfy the  
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19 161 “Bomb” or rapid intensification criterion (a central pressure fall of 24 hPa in 24 hours) of Sanders  
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22 162 and Gyakum (1980).  
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25 163 The specific way in which ECLs are defined and the methodology used to identify and track these  
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28 164 cyclones varies considerably. The earlier work of Hopkins and Holland (1997) employed an  
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30 165 objective technique that combined wind and rain signatures typical of ECLs, as verified by  
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33 166 comparison with surface charts. Recent studies have used approaches based on expert judgment  
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35 167 (Speer *et al.* 2009), and various automated techniques that either track low pressure systems (Pepler  
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38 168 and Coutts-Smith 2013; Browning and Goodwin 2013; Di Luca *et al.* 2015) or identify favourable  
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40 169 conditions for their formation (Dowdy *et al.* 2013b). Pepler *et al.* (2014) investigated the  
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42 170 differences in ECL characteristics obtained using three different identification methods, finding that  
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45 171 the methods concur for relatively large and strong ECL events (including those producing high  
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47 172 winds) but diverge for smaller ECLs. While few studies have focused specifically on the wind  
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50 173 hazard associated with ECLs, the various measures used to characterize the intensity of ECLs, such  
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52 174 as the pressure gradient around the centre or the maximum cyclonic vorticity, are related to the  
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55 175 wind and hence changes in these intensity measures are expected to reflect changes in the wind.  
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176 At higher latitudes, for ETCs and their associated cold fronts, wind hazard can be estimated  
 177 reasonably well from Bureau of Meteorology wind data, as ETCs are more common than TCs.  
 178 Higher return period winds from ETCs have considerably lower accuracy, however.

### 179 **2.3 Assessing current hail hazard**

180 Current estimates of the hail hazard in Australia are available only from the Bureau of  
 181 Meteorology's severe-storm archive (SSA; <http://www.bom.gov.au/australia/stormarchive/>). As  
 182 previously discussed, this dataset suffers from large uncertainties associated with population bias  
 183 and changing reporting practices, making it unsuitable for assessing the climatology of hail storms  
 184 on a national scale. However, for local regions with high population density, valuable information  
 185 can be extracted. Using an expanded dataset for NSW, Schuster *et al.* (2005) were able to assess  
 186 various characteristics of hail occurrence in the eastern part of the state, including seasonal and  
 187 diurnal cycles, geographical variability, and the distribution of maximum hailstone size. Soderholm  
 188 *et al.* (2015) identified preferred regions for hailstorm occurrence in southeast QLD based on a 17-  
 189 year radar-based climatological study.

190 Meteorological radars provide a three-dimensional view of storms within a few hundred kilometres  
 191 of their location at high spatial and temporal resolution. Numerous methods have been proposed for  
 192 diagnosing hail occurrence at the surface based on the reflectivity measured aloft by single-  
 193 polarization radars (e.g. Amburn and Wolf 1997, Schuster *et al.* 2006). The hail detection algorithm  
 194 (HDA) currently employed by the National Weather Service (NWS) in the USA uses the method of  
 195 Witt *et al.* (1998) to provide real-time estimates of the probability of severe hail (POSH) and the  
 196 maximum expected size of hail (MESH). This approach was also used by Cintineo *et al.* (2012) to  
 197 generate a multi-year radar-based climatology of severe hail for the contiguous United States. A  
 198 similar effort is currently being undertaken for the Brisbane region by one of the authors (R.  
 199 Warren). Future upgrades to the operational radar network in Australia – in particular, the

200 incorporation of dual-polarization measurements – should allow for a more accurate assessment of  
 201 the hail hazard (e.g. Heinselman and Ryzhkov 2006).  
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 203 While radars offer the most direct method of identifying hail remotely, their coverage in many  
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 204 countries, including Australia, is limited to major population centres. Thus, assessment of the hail  
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 205 hazard over larger geographic domains demands alternative methods. Two which have shown  
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 206 promise in other countries are the detection of overshooting cloud tops (OTs) using satellite-derived  
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 207 brightness temperatures (e.g. Bedka 2011) and the observation of rapid increases in lightning  
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 208 activity from ground-based sensors (e.g. Schultz *et al.* 2009). Both features are proxies for a  
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 209 strong/strengthening convective updraught and have been found to frequently precede the  
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### 3. Observed trends

#### 3.1 Observed trends in severe wind – large-scale storms

To date, much of the analysis of observed trends in extreme wind hazard has been focused on trends  
 in individual meteorological phenomena rather than wind *per se*. Trend analyses that have been

224 performed on winds in the Australian region have given inconclusive results. McVicar *et al.* (2008)  
 225 showed positive trends in maximum winds for an average of a limited number of Australian stations  
 2 over the period 1975-2006. The later study of Troccoli *et al.* (2012) indicated some trends in the  
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230 To understand the causes and uncertainties of future projections of extreme wind changes, it is  
 231 important to understand the causes and trends of the storms producing them. Trends in TC winds  
 232 are often difficult to estimate due to the rather short reliable record of TC numbers and intensities.  
 233 For example, in remote ocean areas, many TCs were simply undetected before the satellite era  
 234 (before about 1970) and it was not until the advent of routine geostationary satellite monitoring  
 235 around 1980 that a systematic estimation of TC intensity could be obtained. One way to address this  
 236 issue is to analyse only land-based data. Callaghan and Power (2011) constructed a database of  
 237 eastern Australian landfalling TC data, and found a substantial decrease in the incidence of severe  
 238 TCs making landfall in this region since the late nineteenth century. Dowdy (2014) show a similar  
 239 decrease in TC numbers, based on analysis of satellite observations and after removing the effects  
 240 of ENSO variations on TC numbers.

241 For ECLs, there is large inter-annual and inter-decadal variability in their frequency (e.g. Hopkins  
 242 and Holland 1997; Di Luca *et al.* 2015; Ji *et al.* 2015) and a lack of any statistically significant trend  
 243 in recent decades (Pepler *et al.* 2014). In the mid-latitudes during the late 20th century, the Southern  
 244 Hemisphere (SH) midlatitude jet and associated ETC storm track moved polewards and intensified  
 245 (Fyfe 2003). This is consistent with Australian-focused studies that find a reduction in rainfall-  
 246 producing systems over southwestern Australia since 1975 (Hope *et al.* 2006) and a reduction in  
 247 storm numbers in southeastern Australia (Alexander and Power 2009) since the mid-19<sup>th</sup> century.  
 248 Another mid-latitude wind hazard is caused by TCs that have moved into the mid-latitudes and

249 become ETCs (e.g. Sinclair 2002; Ramsay et al. 2012). These storms can affect southern Australia  
 250 and New Zealand, causing large rainfall events and storm surge.

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### 252 **3.2 Observed trends in severe thunderstorm winds and hail**

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 1253 Analysis of trends in severe thunderstorm incidence from reports is highly problematic due to the  
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 15254 sparse and inhomogeneous nature of these records (e.g. Kuleshov *et al.* 2002). As a result,  
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 17255 environment-based studies, similar to those described above, have been used as a basis for trend  
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 19256 estimation and projections. The recent reviews of Kunkel *et al.* (2013) and Brooks (2013) discuss  
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 22257 this issue in detail for the United States and elsewhere, finding no significant current trends in  
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 24258 severe thunderstorm environments.

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 28259 Trend analysis has been performed in Europe using networks of hail measuring devices (“hailpads”  
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 30260 e.g. Hermida *et al.* 2013) but such long-term records do not exist in Australia. Therefore reliable  
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 33261 trend analysis has not been performed and remains a significant gap in our knowledge.

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## 37 38 39 40263 **4. Future projections**

### 41 42 43 44264 **4.1 Projections of severe wind – large-scale storms**

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 48265 Projections of future wind hazard have primarily focused on projections of different storm types.  
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 50266 Current issues for global predictions of TCs are summarized in (for example) Walsh *et al.* (2015).  
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 53267 This section briefly summarizes the current state-of-the-art of these methods but focuses more on  
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 55268 the predictions of changes of these hazards in the Australian region.

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 59269 In a warmer world, theoretical and modeling results suggest an expansion of the tropical regions,  
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 61270 which in principle suggests weaker wind shear in the subtropical region and thereby poleward

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271 expansion in the region influenced by tropical cyclones, of the typical latitudes of formation of  
 272 ECLs, and of the latitudes where TCs typically become extratropical (e.g. Kossin et al. 2014). A  
 273 similar poleward movement in the main extratropical storm track is suggested (Chang et al. 2012),  
 274 although consensus on the precise mechanism for this is lacking at present.

275 The main tool for the prediction of future TC wind hazard is the climate model. The main limitation  
 276 of this tool for TC prediction is that studies have shown that to simulate realistic numbers of TCs,  
 277 climate models typically require resolutions usually higher than 25 km, finer than are routinely used  
 278 (Strachan *et al.* 2013). Even finer resolutions are often required to generate a realistic distribution  
 279 of TC wind speeds. This limitation has spurred the development of regional climate modelling  
 280 approaches, whereby finer resolution is only applied over a restricted region of the globe (Knutson  
 281 *et al.* 2015). The best such models typically are run at horizontal resolutions finer than 10 km and  
 282 are now able to generate a realistic TC wind distribution.

283 A consistent prediction of such modelling approaches is an increase in the maximum intensity of  
 284 TCs combined with a decrease in their total numbers (Christensen *et al.* 2013). The recent results of  
 285 Knutson *et al.* (2015) indicate substantial decreases in total TC numbers in the Australian region,  
 286 typically around 30% or more towards the end of the 21st century, especially off the northeast coast.  
 287 Even larger declines in the Australian region are projected in numbers of the most intense Saffir-  
 288 Simpson category 4 and 5 storms, typically around 50%. A projected decrease in future numbers of  
 289 very intense TCs is important because one of the uncertainties in previous work has been whether  
 290 the combination of predicted decreased numbers of TCs, combined with an increase in their  
 291 maximum intensities, would lead to a decrease or an increase in future intense TC numbers in the  
 292 Australian and adjacent South Pacific regions. The results of Knutson *et al.* (2015) suggest future  
 293 decreases in extreme TC wind hazard in a warmer world in these regions, but this result will need to  
 294 be made more robust through further improvements in modelling and theoretical techniques, due in  
 295 part to the large basin-to-basin variability in this result in their study (their Table 3). For instance,

296 based on analytical techniques, Holland and Bruyere (2014) suggested that there is unlikely that a  
 297 decrease in numbers of intense storms will occur in this basin.

298 The main limitations of climate model projections of TC incidence are twofold. First, due to the  
 299 infrequent and sometimes unpredictable formation and track of TCs, a very lengthy climate record  
 300 is required to produce a statistically stable incidence of TC climatology, typically thousands of  
 301 years (e.g. McInnes *et al.* 2003). Thus estimates of the likely changes in incidence need to be  
 302 averaged over regions to construct climate change scenarios, rather than being extracted directly  
 303 from the output of climate models. Secondly, the same uncertainties that plague all climate model  
 304 projections affect our confidence in the future projections of TCs: uncertainty regarding future  
 305 projections of the atmospheric concentration of greenhouse gases (due to wide variations in  
 306 predictions of future economic conditions) and uncertainties regarding the accuracy of the climate  
 307 models themselves.

308 As for TCs, ECL projections are generally based on results from climate model simulations.

309 However, an additional issue associated with ECLs is related to their identification, which has been  
 310 shown to be strongly sensitive to the horizontal resolution of the input data in both reanalysis (Di  
 311 Luca *et al.* 2015) and GCMs (Dowdy *et al.* 2013c). Dowdy *et al.* (2013a) and Dowdy *et al.* (2013c)  
 312 used a vorticity measure based on a small number of GCM projections and found a 30% decrease in  
 313 future ECL frequency by the end of the 21st century. They associated this change with a decrease of  
 314 8 to 25% in heavy rainfall events on the eastern seaboard.

315 Some studies have used finer resolution dynamical downscaling of GCMs to better capture the full  
 316 distribution of ECLs (Hemer *et al.* 2011; Ji *et al.* 2015). Hemer *et al.* (2011; 2013) used a regional  
 317 climate model to downscale three GCMs to 60km resolution. They found that mean wind speeds  
 318 tend to decrease between latitudes 30S and 40S, with little change in the 99th percentile of wind  
 319 speed. Ji *et al.* (2015) applied the vorticity measure proposed by Dowdy *et al.* (2013b) to a 12  
 320 member ensemble of 50-km resolution regional climate projections created by downscaling four

321 GCMs with three RCMs within the NARcliM project (Evans *et al.* 2014). They found an overall  
 322 decrease in ECL frequency by 2070, particularly in winter.

323 While this collection of studies does not represent a comprehensive analysis of projected future  
 324 changes in ECLs, they do consistently predict a decrease in storm activity, particularly in winter.  
 325 However, previous studies have not explicitly examined wind speed changes produced by the most  
 326 intense ECLs. Figure 1 shows the composite wind fields derived from ECLs developing near the  
 327 east coast of Australia (see the white rectangle in Figure SM1 in the Supplementary Material) that  
 328 produce maximum wind speeds of at least  $20\text{ms}^{-1}$  according to the NARcliM ensemble (12 50-km  
 329 resolution RCM simulations). In both present and future climates, seasonal differences in the wind  
 330 fields are clear, with summer ECLs tending to produce higher wind speed maxima compared to  
 331 winter ECLs which produce a broader area of high wind speeds further from the low centre. While  
 332 these results agree with previous studies in terms of projecting an overall decrease in the frequency  
 333 of winter ECLs, they suggest no change in the frequency of the most intense and highest wind  
 334 producing ECLs in winter and an increase in the frequency in summer. Hence the wind hazard  
 335 associated with these intense events is likely to increase in the future (see the Supplementary  
 336 Material).

337 Further south, the overall effect of greenhouse gas forcing on ETCs during the 21st century is  
 338 complex because climate models indicate changes that would have opposing effects on ETC  
 339 activity including, for example, a reduction of the equator-to-pole temperature gradient near the  
 340 surface but enhanced gradients aloft (Lim and Simmonds 2009). Grieger *et al.* (2014) find a  
 341 reduction in the total number of Southern Hemisphere ETCs but an increase in the number of strong  
 342 ETCs particularly over the southeastern Australian region, in a multimodel ensemble of CMIP3  
 343 climate models. These changes are consistent with findings of a general reduction in future extreme  
 344 wind speed along much of the southern coastline except for Tasmania in the winter months

345 (McInnes *et al.* 2011). For extratropically-transitioning TCs, studies in this region of the effect of  
 346 climate change are currently lacking.  
 2  
 3  
 4  
 347 Studies have constructed scenarios of the effect of climate change on wind hazard and then applied  
 5  
 6  
 348 these scenarios for the estimation of future wind hazard in Australia. Wang *et al.* (2013) construct  
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 9  
 349 current climate estimates of both cyclone and non-cyclone wind gust hazard in the Australian region  
 10  
 11  
 350 by fitting a statistical model to wind speed observations from anemometers. They then applied  
 12  
 13  
 351 climate change scenarios, encompassing a wide range of uncertainty and including scenarios of both  
 14  
 15  
 352 increases and decreases in TC intensities and frequencies, to estimate the changes in these statistical  
 16  
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 18  
 353 distributions. For some of the scenarios that they examined, changes in wind speed return periods  
 19  
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 21  
 354 would occur that would exceed current design standards in a number of coastal tropical locations in  
 22  
 23  
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 355 Australia. It is noted that because of the wide range in predictions of future cyclone incidence in this  
 25  
 26  
 356 region, this is a highly uncertain outcome.

## 3057 **4.2 Projections of severe thunderstorm wind and hail**

31  
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 358 Projections of severe thunderstorm occurrence are limited: Brooks (2013) states in his recent review  
 35  
 36  
 359 that this question remains open. Recently, Allen *et al.* (2014) used an environments-based  
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 39  
 360 approached to suggest an increase in severe thunderstorm incidence in south-east Australia,  
 40  
 41  
 361 although with a wide range of uncertainty. For hail, Braganza *et al.* (2013) reviewed this topic and  
 42  
 43  
 362 noted that the few available studies indicate increases in hail frequency in the southeastern regions  
 44  
 45  
 363 and near Sydney.

## 50364 **5. Conclusions and research gaps**

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 365 Current hazard for various storm types has not been reliably estimated, due to either inadequate  
 55  
 56  
 366 length of data record or spatial gaps. These issues are particularly pronounced for hail records but  
 57  
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 367 satellite observations have considerable potential to address these issues. The projections of future  
 60  
 368 wind hazard in the Australian region differ from region to region. For example, in the tropics, recent  
 62  
 63  
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369 evidence suggests that extreme wind hazard may decrease, although confidence in this prediction is  
 370 low, whereas increases are possible in the east coast region subject to ECLs. Further south, a  
 371 general reduction in extreme wind speed return periods may occur. All of these projections are  
 372 accompanied by considerable uncertainty but such uncertainty has the potential to decrease with  
 373 improvements in modelling techniques.

374 Identifiable research gaps vary between storm type. For TCs, while improvements have been made  
 375 in the confidence of projections of future wind hazard, further improvements in climate model  
 376 simulations of TCs are needed, through increased resolution and better representation of model  
 377 physics. Similar arguments can be made for ECLs. The effect of a warmer climate on extratropical  
 378 former TCs is a potential area of research. ETCs are better simulated because of their larger size, so  
 379 there the main research issue is whether the large-scale climate itself is well simulated. This issue is  
 380 of course important as well for all types of storms.

381 For severe thunderstorms, remote-sensing platforms offer the potential to greatly improve our  
 382 understanding of the associated hail and wind hazard in Australia. These include the GPATS  
 383 lightning-detection network ([www.gpats.com.au](http://www.gpats.com.au)), the new Himawari-8 satellite, and the Bureau of  
 384 Meteorology's radar network, which will soon begin an upgrade to dual-polarisation. Work is  
 385 needed to investigate the applicability to Australian storms of existing methods of severe-weather  
 386 detection based on these technologies (e.g. Heinselman and Ryzhkov 2006, Schultz *et al.* 2009,  
 387 Bedka 2011). Validation of these techniques will require a large number of high-quality direct  
 388 observations of hail and damaging winds. Based on the success of the mPING citizen scientist  
 389 project in the US (Elmore *et al.* 2014), it is suggested that a mobile-phone application for reporting  
 390 severe weather would be an excellent way of obtaining these data while simultaneously engaging  
 391 the general public with the atmospheric science community. Reports could additionally be solicited  
 392 directly from the public (Ortega *et al.* 2009) or collected in targeted field campaigns (Heymsfield *et*  
 393 *al.* 2014).

394

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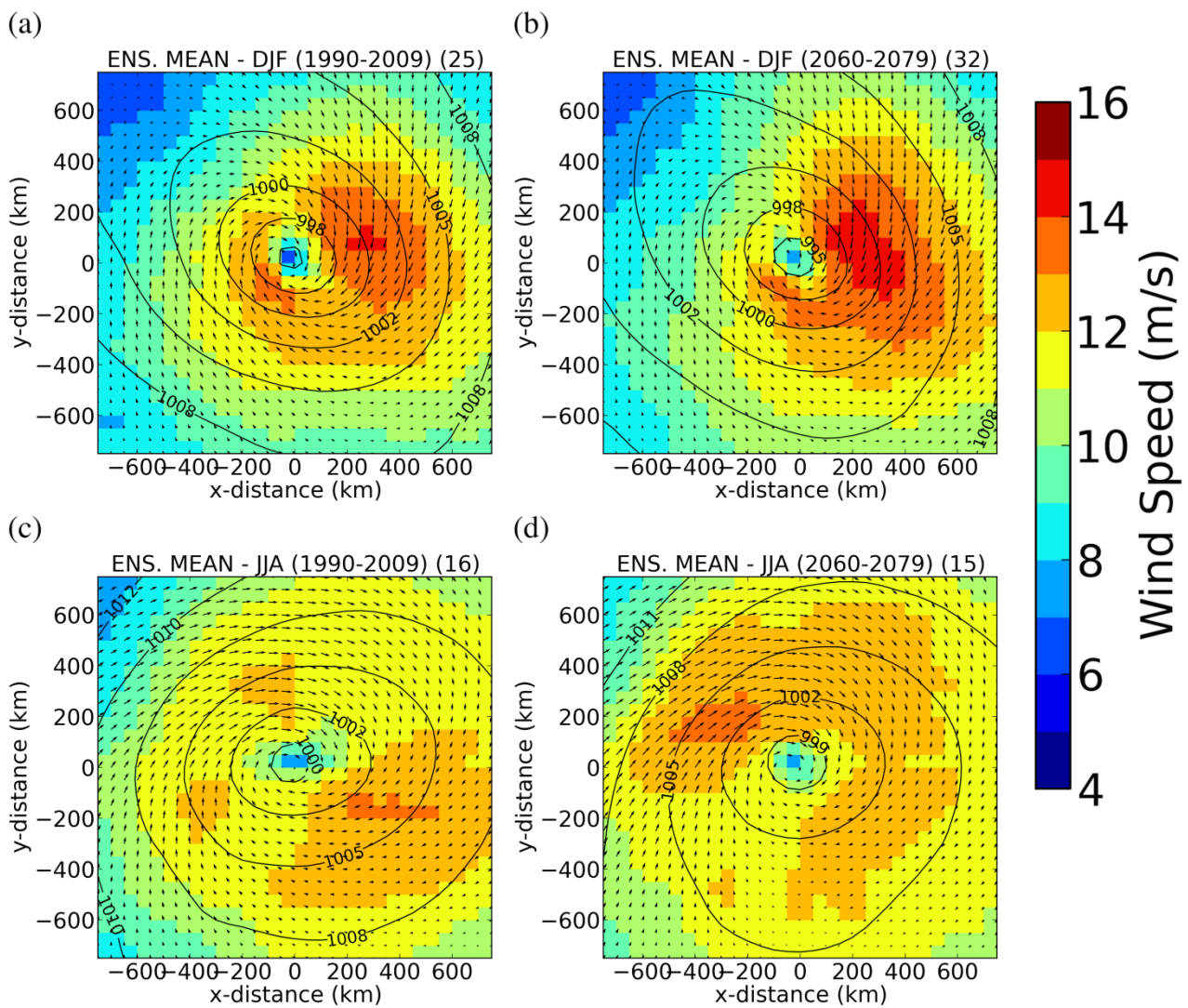
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2 **Figure 1:** Ensemble composites of summer (DJF: top row) and winter (JJA: bottom row) ECLs  
 3 with a maximum wind speed greater than  $20\text{ms}^{-1}$  from the NARcliM ensemble for the recent past  
 4 (1990-2010: left column) and the future (2060-2079: right column). Coloured contours and vectors  
 5 indicate wind speed while solid line contours indicate the sea level pressure. The ensemble-mean  
 6 number of events within the composite is indicated to the top-right of each panel.

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