Future Australian Severe Thunderstorm Environments. Part II: The Influence of a Strongly Warming Climate on Convective Environments

JOHN T. ALLEN
School of Earth Sciences, University of Melbourne, Victoria, Australia, and International Research Institute for Climate and Society, The Earth Institute, Columbia University, Palisades, New York

DAVID J. KAROLY AND KEVIN J. WALSH
School of Earth Sciences, University of Melbourne, Victoria, Australia

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ABSTRACT

The influence of a warming climate on the occurrence of severe thunderstorm environments in Australia was explored using two global climate models: Commonwealth Scientific and Industrial Research Organisation Mark, version 3.6 (CSIRO Mk3.6), and the Cubic-Conformal Atmospheric Model (CCAM). These models have previously been evaluated and found to be capable of reproducing a useful climatology for the twentieth-century period (1980–2000). Analyzing the changes between the historical period and high warming climate scenarios for the period 2079–99 has allowed estimation of the potential convective future for the continent. Based on these simulations, significant increases to the frequency of severe thunderstorm environments will likely occur for northern and eastern Australia in a warmed climate. This change is a response to increasing convective available potential energy from higher continental moisture, particularly in proximity to warm sea surface temperatures. Despite decreases to the frequency of environments with high vertical wind shear, it appears unlikely that this will offset increases to thermodynamic energy. The change is most pronounced during the peak of the convective season, increasing its length and the frequency of severe thunderstorm environments therein, particularly over the eastern parts of the continent. The implications of this potential increase are significant, with the overall frequency of potential severe thunderstorm days per year likely to rise over the major population centers of the east coast by 14% for Brisbane, 22% for Melbourne, and 30% for Sydney. The limitations of this approach are then discussed in the context of ways to increase the confidence of predictions of future severe convection.

1. Introduction

It is well established that the climate system is warming, and this has implications for the occurrence of severe thunderstorms (Meehl et al. 2007; Trenberth et al. 2007). It is also very likely that most of the observed increase in global temperatures since 1950 has resulted from rising greenhouse gas concentration attributable to anthropogenic sources (Bindoff et al. 2013). Despite this and the perception that the frequency and intensity of severe thunderstorm events may be increasing (Bouwer 2011; Brooks 2013), few studies exist that quantify the potential changes that result in severe thunderstorms (defined as hail exceeding 2 cm, wind gusts in excess of 90 km h⁻¹, or any tornado) in a warmed world, particularly over Australia (Cubasch et al. 2001; Trenberth et al. 2007). Climate simulations using global climate models (GCMs) are commonly used to provide a picture of large-scale climate changes in temperature and moisture. However, resolution limitations in both the horizontal and vertical for GCMs have presented issues with resolving the occurrence of severe storms (Brooks 2013). By exploring larger-scale environmental conditions favorable to the occurrence of severe thunderstorms, estimates of changes can be made from global and regional models, with research to date focusing on the United States and Europe (Trapp et al. 2007a; Del Genio et al. 2007; Marsh et al. 2009; Trapp et al. 2009; Van Klooster and Roebber 2009; Gensini et al. 2014; Diffenbaugh et al. 2013).
Under future anthropogenic high warming scenarios, the potential for severe thunderstorm environments over the United States increases (Trapp et al. 2007a, 2009; Del Genio et al. 2007; Van Klooster and Roebber 2009; Diffenbaugh et al. 2013). This originates from changing surface specific humidity and low-level water vapor responding to rising temperatures resulting in an increasing frequency of high convective available potential energy (CAPE) environments (Gettelman et al. 2002; Marsh et al. 2009; Trapp et al. 2009; Brooks 2013; Diffenbaugh et al. 2013). Temperature-driven increases in vertical instability between the surface and midtroposphere also may contribute; however, this assumes no future increase in midtropospheric temperatures relative to the surface (Peterson et al. 2011). While the increase in temperatures are likely global, on smaller spatial scales modest reductions to relative humidity may occur, particularly over land areas that are water limited. The contributions of these factors suggest that more energy may be available for convective processes; however, these only include two of the four ingredients necessary for severe thunderstorms (moisture and instability), while a source of lift to initiate storms and wind shear remains unaddressed.

Two relatively unknown quantities under a warming climate are the changes to convective inhibition (CIN) and the occurrence of synoptic systems associated with both initiation and deep-layer shear. As CIN describes a relatively thin layer of warm temperature, the vertical resolution needed to capture this process is almost always unavailable in GCMs. This makes anticipating changes to CIN difficult (Brooks 2009, 2013); given that the existence of severe convection is intrinsically tied to the overcoming of CIN, anything more than an analysis of environmental occurrence becomes impossible without the use of a convection-resolving model (e.g., Trapp et al. 2007b, 2011). Recently, Diffenbaugh et al. (2013) suggested that the increase to days with high CAPE coincided with low CIN, promoting more intense storms, though there remains the potential that this is not well represented in many models because of poor handling of mesoscale processes (Trapp et al. 2007a; Del Genio et al. 2007). In contrast, the modeled poleward shift of synoptic patterns and decreased thermal gradient between the midlatitudes and poles has been used to argue that fewer high 0–6-km bulk vertical wind shear (S06) and low CAPE severe thunderstorm environments will occur over both the United States and Europe (Del Genio et al. 2007; Marsh et al. 2009; Brooks 2013; Diffenbaugh et al. 2013). Despite the decrease in S06, little change outside of natural variability is apparent in the occurrences of initiating features such as fronts, troughs, and dry lines, when combined with increasing CAPE, leads to a greater frequency of days with moderate to strong S06 that also have high CAPE (Trapp et al. 2009; Diffenbaugh et al. 2013; Gensini et al. 2014). The interplay between the deep-layer shear and CAPE, when combined with the out-of-phase annual cycle of these quantities, is a problem for estimating changes in climate, as the greatest increase in CAPE may not necessarily correspond to the largest decrease in deep-layer shear (Brooks et al. 2007; Brooks 2013; Diffenbaugh et al. 2013). This implies that the overall change in the severe storm threat may be small or alternatively suggests a seasonal shift rather than a definite increase or decrease. This codependence leaves the results of an analysis of either CAPE or S06 individually incapable of truly estimating the impact of climate change on the frequency of favorable severe thunderstorm environments.

In comparison to the Northern Hemisphere, changes to severe convective parameters have received less attention in the Southern Hemisphere. On a regional scale, the implications of a warming climate for Australian severe storms relate to two main factors: the availability of moisture and the response of the jet stream to a warming climate. Decreasing trends in extratropical cyclone numbers accompanied by increases in their intensities have been suggested for the Southern Hemisphere, with sensitivity to the modeling or observational datasets used (Meehl et al. 2007; Simmonds and Keay 2000; Simmonds et al. 2003; Wang et al. 2006; Kidston and Gerber 2010). Recent indications are that, despite model differences, the midlatitude jet stream over the Southern Hemisphere will shift poleward, suggesting that the spatial distribution of cyclones critical to both deep-layer shear environments and initiating systems may shift southward away from Australia (Barnes and Polvani 2013). Difficulties in modeling relevant quantities also extend to moisture, with decreasing trends in observed specific humidity for southern Australia identified between 1948 and 2004 (Drost and England 2008), while climate models indicate positive trends in the recent period, and hence future model scenarios may be a significant departure from reality (Willett et al. 2010). The corresponding changes to severe thunderstorm environments over Australia are projected to be similar to both Europe and the United States, with a lower frequency of severe convection but a higher incidence of the most severe thunderstorms (Abbs et al. 2007; Nicholls 2008). However, the influence of a warming climate on severe convection in Australia has yet to be established, with projections limited to small geographical areas. Regional results have shown instability-driven decreases in the number of hail days but increases in intensity for a small number of southeast Australian stations and locations (Niall and Walsh 2005; Leslie et al.
Simulations using a GCM from phase 3 of the Coupled Model Intercomparison Project (CMIP3) under a strong warming scenario suggested a doubling in the frequency of days over the east coast with environments favorable to severe hail [Commonwealth Scientific and Industrial Research Organisation Mark, version 3.5 (CSIRO Mk3.5); Abbs et al. 2007], contrasting with regional results for the Sydney basin (Leslie et al. 2008). The spatial extent of changes indicates significant impacts over the areas with greatest population density, emphasizing the need for additional study of the influence of a warming climate on severe thunderstorm environments.

Previously, Allen et al. (2014, hereafter Part I) have shown that two climate models [Cubic-Conformal Atmospheric Model (CCAM) and CSIRO Mk3.6] have utility in simulating the occurrence of convective environments over Australia when compared with reanalysis data, albeit with a number of limitations (Part I). Both models have their positive and negative qualities, with the interior of the continent being too dry in CCAM despite a better representation of the climatology and CSIRO Mk3.6 having comparatively higher values of CAPE over an extended area of the continent. Despite these limitations, CSIRO Mk3.6 is one of the two Australian climate models contributed to the recent phase 5 of CMIP (CMIP5) multimodel evaluation, while CCAM offers a potentially better atmospheric model. As GCMs are typically better at representing differences between mean climate states, such as changes between the early and late twentieth century, than the long term, both models are used to explore changes to the warmed climate state and differences in how this is simulated. In the current paper, the simulated impact on convective ingredients due to a strongly warmed climate for the period 2079–99 is examined. A CMIP5 model (CSIRO Mk3.6) and an enhanced higher-resolution atmospheric model (CCAM) with similar forcing over the region are used to look at differences between projections of future severe convection and assess the limitations of the CMIP5 model. Because of the uncertainties in the extent that severe thunderstorm environments may be affected by warming, high emissions scenarios that test the effect of a large perturbation are considered.

The paper is structured as follows: Section 2 describes the model datasets and characteristics used for examining future changes to Australia’s climate. Section 3 explores how the respective models simulate variables including temperature, moisture, and sea surface temperature in a strongly warmed climate. In section 4, the implications of these changes on convective ingredients and their distribution over the continent resulting from changes to the troposphere are examined. Section 5 considers the impact of warming on severe thunderstorm environments for the highly populated areas of the east Australian region (EAReg; bounded by 39°–20°S and 144°–154.5°E), while section 6 examines how the environments and their contributing parameters will change during the seasonal cycle. Finally, in section 7 the findings of this research are discussed, along with future directions to address the limitations of projecting severe thunderstorm occurrence under warming.

2. Data and model characteristics

In Part 1, the two models applied here and their twentieth-century climatologies relevant to severe thunderstorm environments were described. CSIRO Mk3.6 is a CMIP5 fully coupled atmosphere–ocean global climate model (AOGCM), providing a 1.875° grid resolution with 18 vertical levels (Rotstayn et al. 2010). In contrast, CCAM is a cubic-conformal global atmospheric model, with a stretched domain to provide 50-km resolution over the Australian region with 18 vertical levels with sea surface temperature (SST) and sea ice forcing applied from a parent CSIRO Mk3.5 (pre-CMIP5) GCM simulation (McGregor 2005; McGregor and Dix 2008). Two different but similar high warming scenarios were chosen based on the findings of Rogelj et al. (2012). For CSIRO Mk3.6, this was the representative concentration pathway 8.5 (RCP8.5) scenario, where global radiative forcing attributable to changing anthropogenic influence reaches 8.5 W m\(^{-2}\) by 2100, resulting from the quadrupling of the preindustrial CO\(_2\) concentration (Moss et al. 2010; van Vuuren et al. 2011). The equivalent high-end warming simulation from CCAM chosen was the Special Report on Emissions Scenarios (SRES) A2 scenario, as, because of availability, the parent forcing CSIRO Mk3.5 GCM was a CMIP3 model developed using an SRES framework (Corney et al. 2010). The similarity of these scenarios can be determined by considering the likely range in temperature increase above preindustrial levels by the period 2090–99 using a simple model (Rogelj et al. 2012). The RCP8.5 scenario has range of global mean warming between 3.8° and 5.7°C, while the SRES A2 scenario leads to slightly less warming (3.2°–4.8°C) but with a range overlapping that of the RCP8.5. This suggests that both scenarios lead to a high rate of warming in the period of investigation and thus are likely directly comparable.

2.1. 

CSIRO Mk3.6

A historical CMIP5 run spanning the period 1980–2000 (referred to as the twentieth-century period) was used as the reference climatology for convective warm seasons (September–April), for 0600 UTC soundings
over the Australian domain (48°–8°S, 105°–160°E) to correspond with a midafternoon sounding for a large majority of the continent. The future run chosen was the fully coupled RCP8.5 scenario from 2005 to 2099 (Rotstayn et al. 2010; Jeffrey et al. 2013), with the specific period of interest 2079–99 (referred to as the twenty-first-century period). Full details of the model configuration for both the historical and future runs are found in Table 1.

For both periods, thermodynamic and kinematic parameters were calculated using daily 0600 UTC model soundings of temperature, wind, and moisture. CAPE was calculated using a 50-hPa mixed-layer parcel (MLCAPE) with a most unstable equivalent potential temperature condition for parcels above the mixed layer and with the virtual temperature correction applied (Doswell and Rasmussen 1994). This choice of parcel was found to be the closest to rawinsonde observations for Australia (Allen and Karoly 2014). S06 was calculated using the standard bulk vector difference between the model surface layer and 6 km. Mean values of near-surface (2 m) temperature and moisture, along with 500-hPa wind fields, were also calculated, with the seasonal spatial differences then calculated between the twentieth and twenty-first centuries. Finally, mean monthly SST fields for the convective warm season were used to calculate mean values and changes between the periods.

### 3. Changes to climate over Australia

#### a. Temperature

Increases to near-surface temperature have the potential to increase the warmth of a surface parcel relative to the upper atmosphere and consequently the magnitude of instability. However, this assumption is tempered by the relative stability being also dependent on the comparative increases in tropospheric temperature. The twenty-first-century temperature distribution has large differences between the models, with the mean area-average (September–April) change over the continent being 4.3°C for CCAM, as compared to 5.2°C for CSIRO Mk3.6 (Fig. 1). During the austral spring, the warming magnitude in both CCAM and CSIRO Mk3.6 is similar, with the main differences relating to a southward
displacement in CCAM, primarily over the southeast [September–November (SON); Figs. 1a,b]. During both summer [December–February (DJF); Figs. 1c,d] and early autumn [March–April (MA); not shown], increases in CCAM are smaller over the east coast, reflecting the relatively coarse spatial scale of CSIRO Mk3.6 that leads to smoothing of the complex east coast topography and increased warming magnitude over the coast. Over the northwest of Australia during DJF and MA, CSIRO Mk3.6 simulates large increases in surface temperature between 7° and 8°C, exceeding CCAM over the same area by 3°–4°C. These large changes in temperature for CSIRO Mk3.6 suggest the potential for large increases in the frequency of convective environments where moisture is available in the model projections.

b. Moisture

Given the dependence of the suspension of water in the atmosphere on temperature (increasing at an expected rate of $\sim 7\% \, K^{-1}$; Willett et al. 2010), it is unsurprising that where moisture is available for evaporative processes, both CSIRO Mk3.6 and CCAM indicate an increase in the water vapor mixing ratio $q$. During SON, CSIRO Mk3.6 simulates a drier continental interior, with small decreases to surface moisture despite substantial increases to temperature and increases in moisture over the northern coastline, the east coast, and coastal Western Australia (Figs. 2a,b). In comparison, CCAM indicates large increases to moisture, particularly over the northern portions of the EAReg. In both DJF and MA, CSIRO Mk3.6 simulates decreases to moisture over the north central parts of the continent, with the spatial change corresponding to large model temperature increases (Fig. 2c). This change is related to the positive feedback of enhanced surface drying over this area with increasing surface temperatures. In contrast, little change is simulated over the northern interior by CCAM, though smaller increases are found over Western Australia. Increases to moisture occur for both models over coastal areas and inland, where advection from the surrounding moist ocean air mass occurs. CCAM simulates larger increases to moisture over the inland and southern parts of the EAReg. These differences also appear to be related to different handling of topography for the Great
Dividing Range, which blocks the near-surface flow from the east for the southern half of the continent, and is poorly resolved in CSIRO Mk3.6 (Part I).

c. Sea surface temperatures

Another source of differences in modeled moisture relates to differences in the SST fields. However, as discussed in section 2, CCAM is an atmosphere-only climate model, with warming forcing for oceanic temperature derived from CSIRO Mk3.5 SST fields for the A2B scenario. Differences in the twentieth century are notable between the two models, with the bias-corrected CSIRO Mk3.5 SSTs cooling the western Pacific warm pool relative to CSIRO Mk3.6 (Figs. 3a,c). Changes for the twenty-first century have larger SST increases farther south in the CSIRO Mk3.5 simulation. Near the southeast coast, increases to SSTs are 0.5°–1°C greater in CSIRO Mk3.5 as compared to CSIRO Mk3.6, which has similar differences north of the continent. This disparity appears to explain two of the differences between moisture in CCAM and CSIRO Mk3.6: the inland extent and greater magnitude of moisture increase over the east coast and the reduced increases to moisture over the north of the continent.

4. Changes in ingredients

a. CAPE

Increases to both near-surface temperature and moisture in the twenty-first century are likely to increase the frequency of occurrence of nonzero CAPE environments, provided the upper troposphere warms less than the change in the moist adiabat resulting from surface warming (Trapp et al. 2007a; Leslie et al. 2008; Diffenbaugh et al. 2013). Relative distributions of CAPE magnitude and frequency normalized by the number of land grid points were considered over the entire Australian landmass, as well as the EAReg (Fig. 4). Small decreases occur by the late twenty-first century for CSIRO Mk3.6, in both low (between 10 and 400 J kg\textsuperscript{-1}) and extreme (greater than 2000 J kg\textsuperscript{-1}) CAPE. The net change to nonzero CAPE is a large decrease; however, there is also a marginal increase to environments above 3600 J kg\textsuperscript{-1} (Tables 2, 3). Decreases correspond to 11% for low CAPE relative to the twentieth century and 20% for extreme CAPE environments. In CCAM, large decreases of 16% occur for low CAPE (Fig. 4b). In contrast, moderate CAPE (400–1000 J kg\textsuperscript{-1}) increases by
21% and high CAPE (1000–2000 J kg$^{-1}$) increases by 27%, while increases to extreme CAPE are slightly smaller, at 9%. The CCAM simulation indicates that not only does the frequency of nonzero CAPE increase but also the available energy increases in a warming climate, contrasting the results for CSIRO Mk3.6.

Over the EAReg, the frequency of nonzero CAPE environments decreases for CSIRO Mk3.6, with the frequency of low CAPE falling by 21%, while moderate CAPE also decreases (Fig. 4c). High and extreme CAPE environments increase, with the largest increase in extreme CAPE (26%). This suggests that the strongest CAPE environments may become more frequent, while the overall frequency decreases. Decreases in low CAPE are smaller over the EAReg (2%) for CCAM as compared to the continental frequency. However, moderate to high CAPE events are simulated to increase by 51% relative to the twentieth century, while extreme CAPE events also increase by 15% (Fig. 4d and Table 3). Over the EAReg, both models indicate that a warmer climate will increase the frequency of CAPE environments in excess of 1000 J kg$^{-1}$, despite a decrease in the overall frequency of nonzero CAPE environments particularly for low shear as noted by earlier studies (Abbs et al. 2007; Trapp et al. 2007a; Leslie et al. 2008; Diffenbaugh et al. 2013).

Large differences in the spatial distribution of mean CAPE were identified in CSIRO Mk3.6 for SON, while relatively smaller changes were simulated by CCAM (Fig. 5). CSIRO Mk3.6 decreases up to 100 J kg$^{-1}$ over much of the continent, particularly over the north and east coasts (Fig. 5a), a response to increasing temperature with slightly decreasing moisture (Figs. 1, 2a). This culminates in a drier boundary layer and has a decreasing precipitation feedback, leading to less CAPE because of intense warming of the tropospheric temperature profile (Fig. 6a). In both models, CAPE increases occur over the northern coast and surrounding sea, responding to moisture (Figs. 6a,e); however, CCAM shows smaller increases, consistent with reduced increases.
to moisture and tropospheric in this model (Figs. 3b, 5b, 6d) Over the west of the continent, CCAM simulates decreases of less than 50 J kg\(^{-1}\), while increases of up to 75 J kg\(^{-1}\) are found over the east coast.

CSIRO Mk3.6 simulates large decreases (up to 500 J kg\(^{-1}\)) in mean CAPE over the continental interior, northwest, and northeast for DJF (Figs. 5c,d). Over eastern Australia, increasing moisture yields a response of increases to mean CAPE of 200–300 J kg\(^{-1}\), while there are also large CAPE increases (500 J kg\(^{-1}\)) over coastal northern Australia (Figs. 2c, 6h). In contrast, CCAM simulates smaller increases (100–200 J kg\(^{-1}\)) that extend farther inland with the moisture over the east and across the north for DJF (Figs. 5d, 6l). No significant decreases to mean CAPE are identified over the continent for CCAM during DJF. In MA, CSIRO Mk3.6 has large spatial gradients in the changes to mean CAPE, contrasting the relatively weak CAPE variations in CCAM (Figs. 5e,f). Decreases to CAPE are reduced in extent for CSIRO Mk3.6, while increases over the north coast (\(\geq 1000\) J kg\(^{-1}\)) correspond to the large increases to

![Fig. 4](image-url). Comparison of the frequency distribution of the twenty-first-century climatology and the twentieth-century climatology of nonzero MLCAPE environments as a fraction of the total occurrences of nonzero MLCAPE for CSIRO Mk3.6 and CCAM including all grid points over (a),(b) Australia and (c),(d) the EAReg.

<table>
<thead>
<tr>
<th>Grid point</th>
<th>SEV environment</th>
<th>Twentieth century</th>
<th>Twenty-first century</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Australia</td>
<td>EAREg</td>
<td>Australia</td>
</tr>
<tr>
<td>CSIRO Mk3.6</td>
<td>2000</td>
<td>2197</td>
<td>1785</td>
</tr>
<tr>
<td>CCAM</td>
<td>1362</td>
<td>1248</td>
<td>1472</td>
</tr>
</tbody>
</table>

**TABLE 2.** Total occurrences of nonzero MLCAPE environments over both Australia and the EAReg as determined from the twentieth- and twenty-first-century climatologies for CSIRO Mk3.6 and CCAM normalized by grid resolution over land for the respective regions [Australia: CSIRO Mk3.6 (221) and CCAM (3038); EAReg: CSIRO Mk3.6 (56) and CCAM (795)].

<table>
<thead>
<tr>
<th>CAPE (J kg(^{-1}))</th>
<th>10–400</th>
<th>400–1000</th>
<th>1000–2000</th>
<th>&gt;2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional change relative to twentieth century (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSIRO Mk3.6</td>
<td>-11.54</td>
<td>-7.26</td>
<td>-14.40</td>
<td>-20.59</td>
</tr>
<tr>
<td>CCAM</td>
<td>-16.46</td>
<td>21.34</td>
<td>27.61</td>
<td>8.70</td>
</tr>
<tr>
<td>EAReg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSIRO Mk3.6</td>
<td>-20.92</td>
<td>-8.54</td>
<td>5.59</td>
<td>26.62</td>
</tr>
<tr>
<td>CCAM</td>
<td>-2.05</td>
<td>51.85</td>
<td>51.14</td>
<td>14.97</td>
</tr>
</tbody>
</table>
moisture induced by the SST peak with a less warmed upper troposphere (not shown). CCAM also indicates this pattern of change; however, the magnitude over the north is reduced (≈100 J kg^{-1}), reflecting differences in tropospheric moisture (Figs. 6h, l). Over Western Australia, CSIRO Mk3.6 simulates increases of up to 200 J kg^{-1}, contrasting decreases of less than 25 J kg^{-1} in CCAM. Over the east coast, CSIRO Mk3.6 produces the strongest increase of any part of the season, with increases approaching 400 J kg^{-1} over most of the EAReg, reflecting SST changes, available moisture, and the less warmed troposphere (Fig. 6k). CCAM for MA simulates a smaller coastally confined increase, further highlighting this sensitivity of CAPE changes to the SST distribution.

b. S06

Changes to S06 are sensitive to how the respective models shift the subtropical jet in a warmed climate. Both CCAM and CSIRO Mk3.6 indicate only small increases to S06 in the presence of nonzero CAPE, mainly for moderate shear between 10 and 20 m s^{-1} (Fig. 7b). However, in contrast to CCAM, CSIRO
FIG. 6. Seasonal changes in the mean vertical structure of the atmosphere for the twenty-first-century period as compared to the twentieth century for CSIRO Mk3.6 and CCAM. (left) Longitudinal mean temperature between 1000 and 50 hPa over the domain from 5° to 55°S for the (a),(d) SON and (g),(k) DJF periods respectively. (center) Changes to mixing ratio for the same domain. (right) Changes to the zonal (eastward) wind. CSIRO Mk3.6 contours are based on 14 vertical levels, while CCAM contours correspond to 16 vertical levels that are more concentrated in the lower atmosphere.
Mk3.6 also decreases in the frequency of environments with S06 less than 7.5 m s$^{-1}$. These changes are most likely a distortion of the S06 distribution attributable to decreases in the frequency of nonzero CAPE rather than changes to the S06 parameter (Table 2). This effect is present for all values of S06, though is smallest between 10 and 20 m s$^{-1}$ (Table 4). In both models, large decreases are found for strong S06 (>20 m s$^{-1}$), contrasting the results for the Northern Hemisphere that simulate increases for this quantity (Diffenbaugh et al. 2013). Over the EAReg, decreases in strong S06 are present for both models, while increases in both weak and moderate values of S06 for CCAM contrast with decreases in CSIRO Mk3.6. The large differences primarily result from changes to the frequency of nonzero CAPE environments with weak S06 environments in CCAM increasing by 38% (Tables 3, 4). Both models indicate that poleward migration of the subtropical jet at 500 hPa is the likely cause for this change, particularly during SON (Fig. 9), with corresponding decreases in the frequency of cyclonic waves and greater variations in jet speed over the continent further contributing to this decrease in the future (Kidston and Gerber 2010; Barnes and Polvani 2013).

Spatial modifications to mean S06 reflect this change to the displacement of the subtropical jet (Figs. 8, 9). During SON, both models indicate a decrease in S06 magnitude over the north and center of the continent, while increases occur over the south. CSIRO Mk3.6 decreases are confined north of 25°S, while increases (≥2 m s$^{-1}$) occur over the south and near the jet exit over the east coast (≥3.5 m s$^{-1}$; Fig. 8a). In contrast, larger decreases in CCAM extend farther south with greater magnitude (≥3 m s$^{-1}$ over Western Australia), while small increases (≥1.5 m s$^{-1}$) are confined to the far southwest of Western Australia and Tasmania, where the flow has migrated (Fig. 8b). During DJF, the subtropical jet is displaced farther southward, with decreases of ≥3 m s$^{-1}$ in the mean in CSIRO Mk3.6 and

<table>
<thead>
<tr>
<th>S06 (m s$^{-1}$)</th>
<th>0–10</th>
<th>10–20</th>
<th>&gt;20</th>
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<tr>
<td>Fractional change relative to twentieth century (%)</td>
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<tr>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSIRO Mk3.6</td>
<td>−15.57</td>
<td>−1.07</td>
<td>−13.35</td>
</tr>
<tr>
<td>CCAM</td>
<td>9.01</td>
<td>8.31</td>
<td>−20.60</td>
</tr>
<tr>
<td>EAReg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSIRO Mk3.6</td>
<td>−15.38</td>
<td>−0.51</td>
<td>−12.01</td>
</tr>
<tr>
<td>CCAM</td>
<td>37.59</td>
<td>6.68</td>
<td>−21.92</td>
</tr>
</tbody>
</table>
1.5 m s\(^{-2}\) in CCAM. Both models simulate increases of less than 1.5 m s\(^{-1}\) over parts of the southwest, consistent with a weak jet, and the northern coast in CSIRO Mk3.6 (Figs. 9c,d). Decreases over the southeast, are up to 1 m s\(^{-1}\) in CCAM, particularly over the east coast and continental interior. In MA, both models simulate continentwide decreases in mean S06, with the pattern and magnitude for CSIRO Mk3.6 similar to that of SON in CCAM (Figs. 8b,e). Decreases in CSIRO Mk3.6 extend farther over the southeast while, in contrast, CCAM simulates decreases in shear (\(\leq 1\) m s\(^{-1}\)) over the entire continent (Fig. 8f).

5. Changes over the EAReg

The distribution of Australia’s population means that any potential change to the occurrence of severe thunderstorm (SEV) environments (Allen and Karoly 2014) over the EAReg is likely to have the greatest impact. SEV here refers to the covariate relationship

\[
\text{CAPE} \times S06^{1.67} \geq 25\,000\,\text{m}^3\text{s}^{-3}
\]

This discriminant relationship between severe and nonsevere thunderstorm environments was determined...
via proximity sounding analysis for Australia (Allen et al. 2011). The discriminant has been shown to be climatologically useful in both reanalysis (Brooks 2013; Allen and Karoly 2014) and in twentieth-century climate model simulations (Part I). To estimate the significance of changes to SEV, a two-tailed 95% confidence test was performed for the change in environments based on bootstrap resampling of the 40-yr difference distribution at each respective grid point (Wilks 2006). If a grid point has the mean difference exceeding the 97.5th percentile, this is referred to as a significant increase; if a gridpoint mean difference is below the 2.5th percentile, this is referred to as a significant decrease.

CSIRO Mk3.6 simulates increases of 4 or greater SEV environments per season east of 147°E and between 23° and 35°S. Significant increases in frequency (10%–16%) are found over the areas known to have the highest observed frequency of severe thunderstorms: along the east coastal plain to the western side of the Great Dividing Range (Fig. 10a). CCAM simulates smaller changes than the CSIRO Mk3.6, with the increases displaced inland and southward of the coarser model. Significant increases to frequency (15%–30%) are simulated for CCAM over the southern east coast, with inland increases west of the Great Dividing Range between 30% and 60%, decreasing farther southward. These areas of increase appear to follow the displaced CAPE and moisture fields of CCAM closely and when combined with synoptic advection over warmer SSTs and more extensive topographic features within CCAM explain much of the difference between the model simulations.

To quantify the risk for changes in the frequency of SEV environments over the major east coast population centers (Melbourne, Sydney, and Brisbane) the occurrence of environments for the nearest land grid points were considered (Table 5). For Brisbane, CSIRO Mk3.6 simulates a 17% increase to mean environment frequency with little change to interannual variability. In contrast, CCAM simulates a 14% change in the mean, with increases to both the interannual variability and maximum frequency. CSIRO Mk3.6 SEV environments over Sydney are also simulated to increase 14%, with increasing interannual variability. CCAM, however, suggests a larger relative increase of 30% to the mean, with little change to the interannual variability outside of large changes to the minimum frequency. For
Melbourne and each of the east coast centers in the twentieth century, CSIRO Mk3.6 identifies an overly high frequency of SEV environments in the mean. This problem has previously been identified in earlier versions of CSIRO Mk3.6 (e.g., CSIRO Mk3.5; Abbs et al. 2007). Simulations for the twenty-first century indicate a 28% decrease in mean SEV environments for Melbourne, with a decrease to the interannual variability. This contrasts with CCAM, which simulates a 22% increase in frequency with little change to the interannual variability.

### 6. Changes to the seasonal cycle

#### a. Mean monthly cycle

A warming climate may shift the mean seasonal cycle of SEV environments by virtue of the intersection of the changes to both S06 and MLCAPE. In evaluation for the twentieth-century climate, CCAM showed promise in reflecting the environmental distribution, while CSIRO Mk3.6 had a number of deficiencies (Part I). CSIRO Mk3.6 for the twenty-first century indicates decreases in both mean and maximum environmental occurrence for September through December (Fig. 11). This change reflects the model’s simulation of decreases to mean CAPE over the inland areas of the EAReg during this period. In contrast, CCAM has little change to the mean for SON, while increases are found for maximum frequency, particularly in October. CCAM also simulates increases to the mean during DJF, with the maximum also changing substantially in January. In MA, both CSIRO Mk3.6 and CCAM simulate increases to the mean over the EAReg, though the increases in the former are much larger, corresponding to the period in which this model overestimated the spatially normalized frequency (Part I).

#### b. Spatial distribution

CSIRO Mk3.6 simulates widespread significant decreases in SEV environments during SON, particularly over the east coast and center of the continent (Fig. 12a). These changes are a response to decreases in moisture along with tropospheric warming decreasing CAPE and reductions in S06 from southward migration of the jet stream. Over the EAReg, the decrease in environments corresponds to the decreasing CAPE and the frequency of nonzero CAPE environments. Changes in CCAM are smaller than in SON, with nonsignificant decreases of

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<th>TABLE 5. Mean frequency of SEV environments from land grid points proximal to the major east coast capitals based on the twentieth- and twenty-first-century climatologies, along with standard deviation, maximum, and minimum for the 20 warm seasons in the respective periods. Grid points chosen correspond to the nearest to the population centers, and where no grid point was available means and statistics were calculated based on an average between the closest grid points.</th>
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<td>Mean severe environments per season</td>
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1–2 SEV environments per season over the west and the coastal fringe of the east coast (Fig. 12b). These reductions are found where decreases in S06 occur without increases to CAPE.

During DJF, CSIRO Mk3.6 simulates significant increases to SEV environments (8–12 per season) over the northern coast and widespread along the east coast in response to increasing moisture over areas of high climatological frequency in the twentieth century (Fig. 12c). This contrasts with the significant decreases over the central and inland portions of the continent, reducing the twentieth-century frequency of environments to zero over these areas. In comparison, CCAM indicates large areas of significant increases over much of continental Australia, with a small but significant decrease over the west coast, where few environments occur (Fig. 12d). Increases are largest over northern Australia, with greater inland extent as compared to CSIRO Mk3.6. This change is a response to the inland penetration of moisture in CCAM during DJF, potentially with the monsoon pattern (Figs. 2d, 6l). Significant increases of 3–4 SEV environments are also simulated west of the Great Dividing Range, where moisture-driven CAPE increases are largest.

In MA, CSIRO Mk3.6 has a similar distribution to DJF, with a decreased change in magnitude, despite larger decreases to moisture and increases to temperature (Fig. 12e). Significant increases also occur farther inland over the EAReg, and the frequency of severe thunderstorm environments over Western Australia doubles. Decreases over the inland parts of the continent cover a smaller northeasterly displaced area with reduced significance. CCAM also indicates this decrease, albeit with smaller magnitude. While similarities exist between the patterns of CSIRO Mk3.6 and CCAM, the magnitude of the latter is noticeably reduced, reflecting smaller changes to CAPE over the continent (Fig. 12f). Of greatest contrast to CCAM is the small but significant decrease over Western Australia (1–2 SEV per season), compared to the significant increases of 4–6 SEV environments per season in CSIRO Mk3.6.

c. Conditional environments

To explore the dependence of changes in SEV on the covariate parameters, the conditional occurrence of environments for high values of the two components is examined. The approach considers changes to the seasonal occurrence of CAPE environments exceeding at least 1000 J kg\(^{-1}\) in the presence of at least 5 m s\(^{-1}\) for S06 and the converse 15 m s\(^{-1}\) for S06 in the presence of at least 10 J kg\(^{-1}\) for CAPE. During SON, CSIRO Mk3.6 SEV environments decrease in response to reduced high CAPE for the northern parts of the continent, and to a lesser extent over the east coast (Fig. 13a). However, this change is relatively small compared to the changes in SEV environments; if high shear environments are considered (Fig. 14a), the largest changes over eastern Australia are attributable to changes in this parameter. For CCAM, the decreasing frequency of SEV environments is a response to decreases in high S06 without a coincident increase in CAPE, particularly over the southeast coast (Figs. 13b, 14b).

During DJF, CSIRO Mk3.6 SEV changes are increasingly dependent on the frequency of high CAPE environments rather than the decreases in the frequency of high S06 environments (Fig. 13c). While some dependence does remain on CAPE because of the conditional criteria
used, S06 also contributes to increases in SEV environments over the east coast, where increases were found in the S06 distribution (Fig. 7d). In contrast, high S06 environments in CCAM mainly contribute a negative change to the overall frequency of SEV for all seasons over much of the east coast (Figs. 14b,d,f). This negative change however is outweighed during DJF by the increases to the frequency of high CAPE environments, particularly over the eastern and north parts of the continent (Fig. 13d).

In MA, there are large increases in the occurrence of high CAPE environments for CSIRO Mk3.6 over the east of the continent. Modest increases are also found for S06 over both the east and southwest of the continent, reflecting the increases to 500-hPa winds over this area (Figs. 13, 14e). This contrasts weak contribution of CAPE for this period in CCAM, with only a small region of significant increases over New South Wales (NSW; Fig. 13f). Small decreases in both CAPE and S06 are found over the southwest of Australia and combine for the significant decreases in the climatologically infrequent SEV environments over the west coast.

**FIG. 12.** Differences between the mean seasonal frequency of SEV environments for the twenty-first-century period and the twentieth-century period over the Australian continent for (left) CSIRO Mk3.6 and (right) CCAM. Periods correspond to (a),(b) SON; (c),(d) DJF; and (e),(f) MA. Stippling and hatching is as in Fig. 10.
7. Discussion and conclusions

The implications of a strongly warming climate for severe convective environments were explored using the CSIRO Mk3.6 and CCAM climate models over Australia. The origins of changes to convective environments were investigated by analyzing the component ingredients of the models (temperature, moisture, SSTs, and wind fields) and the sources of change. The occurrence of low CAPE environments (10–400 J kg\(^{-1}\)) over Australia was found to decrease for both models, while the occurrence of higher CAPE environments (greater than 1000 J kg\(^{-1}\)) increased. These changes resulted from simulated increases in surface temperature where a nearby source of moisture was available, presenting similar conclusions to those found in the United States (Diffenbaugh et al. 2013). These changes have a high degree of sensitivity to proximity to high sea surface temperatures, with large increases in this quantity for northern and eastern Australia and the model’s relative responses to the warming climate particularly in terms of inland drying for CSIRO Mk3.6. Minimal changes to the frequency of low and moderate S06 environments are found, contrasting decreasing frequency of high S06 environments (greater

FIG. 13. As in Fig. 12, but for changes to the mean seasonal frequency of conditional MLCAPE environments exceeding 1000 J kg\(^{-1}\) in the presence of at least 5 m s\(^{-1}\) for S06.
than 20 m s$^{-1}$) in both models. This change relates to the poleward shift of the subtropical jet stream, likely decreasing the frequency of cyclogenesis events favorable to the development of thunderstorms over the continent. Despite this decrease, increases to CAPE lead to a higher frequency of severe thunderstorm environments in areas where moisture is available.

Significant increases to SEV environments over the east coast of the continent ranging between 14% and 60% in the mean including over the major populations centers of Melbourne, Brisbane, and Sydney were found in both model simulations. While climatologically the frequency over this area is the largest for the continent, this change corresponded to an increase in the frequency of high CAPE environments, with the relative small decrease to S06 unlikely to offset the increases in CAPE. Despite the sensitivity of changes to the model chosen, it appears likely that a warmed climate will yield a trend of increasing severe thunderstorm environments and hence severe thunderstorms over both northern and eastern Australia. These results agree with the limited existing research for the response of convective environments to a warming climate over the east coast (Abbs et al. 2007; Leslie et al. 2008). The seasonal cycle
of severe thunderstorm environments is also simulated to change, with an extension over the peak of the season between December and January over eastern Australia.

The influence of model characteristics on the simulated convective future is an unsurprising result given the sensitivity of changes in CAPE to model convective parameterization schemes (Ye et al. 1998; Marsh et al. 2007; Leslie et al. 2008; Diffenbaugh et al. 2013). In the simulations analyzed here, the CSIRO Mk3.6 uses a development of the Gregory and Rowntree (1990) mass-flux scheme, whereas CCAM employs the scheme of McGregor (2003). In the McGregor (2003) scheme, it is assumed that within each grid square, there is an upward mass flux in a saturated plume, with surrounding subsidence. The parameterization is formulated using the dry static energy, with convection being exhausted during the model time step, with the addition of a convective adjustment relaxation time scale of 20 min. With a relatively short convective time scale, there is less potential for CAPE buildup in this scheme, which may explain some of the differences in CAPE between the two model simulations.

Other contributions to the sensitivity shown here include the distribution of SST changes and handling of changes to the moisture distribution. The small spatial scale of convective environments relative to climate model grid spacing also contributes, with topographic smoothing in GCMs important for spatial changes to moisture (e.g., Iorio et al. 2004; Abbs et al. 2007; Gensini et al. 2014). Despite similar sensitivity to warming in this study, model biases and different model responses can clearly lead to a large spread of potential convective futures. However, while considering a large ensemble of models may help limit the influence of model sensitivity on convective ingredients, the ensemble projection may only be as good as its worst members [e.g., CSIRO Mk3.6 used by Diffenbaugh et al. (2013)].

Another limitation of the methodology shown here is ascertaining whether increases to environments over the northwest coast and inland north are in any way realistic or examining changes where actual observations of severe thunderstorms are limited (Allen et al. 2011; Allen and Karoly 2014). This is compounded by the relationship of an environment to a severe storm not being one to one, as not all favorable environments produce severe thunderstorms, most noticeably over the lower mid-latitudes and subtropical regions (Allen and Karoly 2014; Brooks 2013). Another limitation may be in the environmental relationship considered, as only relatively small observational relationships have been examined to date, which could entail that some environments producing severe thunderstorms are uncaptured by the current discriminant or require separate discriminants for different phenomena produced by severe thunderstorms (Brooks et al. 2003; Allen et al. 2011; Brooks 2013; Diffenbaugh et al. 2013).

The changes found over the east coast are similar to those previously identified (Abbs et al. 2007), as well as other findings worldwide (e.g., Trapp et al. 2007a; Marsh et al. 2009; Diffenbaugh et al. 2013). However, the hypothesis that events will be more intense but less frequent relies on processes that climate models have a limited capability to resolve, particularly convective inhibition (Brooks et al. 2003; Marsh et al. 2007; Diffenbaugh et al. 2013). Approaches that address these issues could include combining convective environments with initialization processes using nested high-resolution downscaled models or dynamic downscaling, which may offer a better picture than an environmental approach (e.g., Trapp et al. 2007b, 2011). Other solutions may involve developing models with higher vertical resolution to better handle convective inhibition, greater or dynamic horizontal resolution to better handle topographic contributions, or even directly approaching the cloud-resolving processes to better handle convection (e.g., Kharoutdinov et al. 2005; Oouchi et al. 2006; Randall et al. 2007). Alternatively, considering use of large-scale synoptic features or gradients as suggested by Griffiths et al. (1993) in conjunction with an environmental climatology may be another way forward. A combination of these steps or at the very least consideration of a greater number of climate models similar to Diffenbaugh et al. (2013) is needed to give further certainty to the influence of a warming world on severe thunderstorms over Australia and other geographical regions.

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