Changes in the Risk of Cool-Season Tornadoes over Southern Australia due to Model Projections of Anthropogenic Warming

B. Timbal
Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Victoria, Australia

R. Kounkou
Météo-France, Paris, France

G. A. Mills
Centre for Australian Weather and Climate Research, Bureau of Meteorology, Melbourne, Victoria, Australia

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ABSTRACT

Anthropogenic climate change is likely to be felt most acutely through changes in the frequency of extreme meteorological events. However, quantifying the impact of climate change on these events is a challenge because the core of the climate change science relies on general circulation models to detail future climate projections, and many of these extreme events occur on small scales that are not resolved by climate models. This note describes an attempt to infer the impact of climate change on one particular type of extreme meteorological event—the cool-season tornadoes of southern Australia. The Australian Bureau of Meteorology predicts threat areas for cool-season tornadoes using fine-resolution numerical weather prediction model output to define areas where the buoyancy of a near-surface air parcel and the vertical wind shear each exceed specified thresholds. The diagnostic has been successfully adapted to coarser-resolution climate models and applied to simulations of the current climate, as well as future projections of the climate over southern Australia. Simulations of the late twentieth century are used to validate the models’ ability to reproduce the climatology of the risk of cool-season tornado formation by comparing these with similar computations based on historical reanalyses. Model biases are overcome by setting model specific thresholds to define the cool-season tornado risk. The diagnostic, applied to simulations of the twenty-first century, is then used to quantify the impact of the projected climate change on cool-season tornado risk. The sign of the response is consistent across all models: a decrease of the risk of formation during the twenty-first century is projected, driven by the thermodynamical response. The thermal response is modulated by the dynamical response, which varies between models. The projected decrease in tornadoes risk during the cool season is consistent with the projection of positive southern annular mode trends and the known influence of this mode of variability on interannual to intraseasonal time-scale variations in cool-season tornado occurrence.

1. Introduction

Extreme weather events are often the most important aspect of the climate system felt by society and the natural environment; understanding the impact of any modification of the climate system on extreme events is therefore of the utmost importance. The Fourth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC; Solomon et al. 2007) has put a critical emphasis on the modification of the extreme climate events resulting from anthropogenic forcings. In that context, it is important to keep in mind that the cornerstones of climate change science are general circulation models (GCMs). GCMs are integrated over time to generate future projections of the climate in response to external radiative forcings resulting from the emissions of anthropogenic greenhouse gases, aerosols, and stratospheric ozone-depleting agents. The global nature of GCMs, their computational requirements, and the challenges in dynamically solving the complexity of
the interactions affecting the climate system are such that these models are run with coarse resolution (between 100- and 500-km grid spacing) and do not capture the small spatial scales at which many extreme meteorological events occur.

One such class of extreme events are the tornadoes (which typically are of the order of 10–100 m wide) associated with supercell thunderstorms (typically of the order of 1–10 km). The possible impact of climate change on tornadoes and recent trends in occurrence, at least for Northern Hemisphere summer tornadoes, have been discussed and shown to be unanswered and challenging issues (Deffenbaugh et al. 2008, and references therein). In Australia, more than 700 tornadoes have been recorded since the beginning of European settlement, leading to the loss of over 40 lives. The real number of tornadoes is likely to be much higher because many thunderstorms occur over sparsely populated inland regions and remain unnoticed. Almost half of these tornadoes (a dozen a year) occur during the winter months from May to September, and are known locally as cool-season tornadoes (CSTs). Although associated with large thunderstorms or deep convective clouds, Hanstrum et al. (2002) showed that CSTs occurred in a large-scale environment, which differs from that for summer tornadoes; they form in a combination of less (but still) positively buoyant and high low-level vertical wind shear environments.

While individual events remain nearly impossible to forecast at any scale outside short nowcasting time scales, these subsynoptic environments in which they may form can be well predicted. On short (24–48 h) time scales the cool-season tornado threat area forecasts are generated by the Australian Bureau of Meteorology using high-resolution regional numerical weather prediction (NWP) model output based on a diagnostic of the environment that is favorable for tornadic formations developed by Hanstrum et al. (2002). The threat areas are defined by those points for which the NWP model forecasts show both the surface lifted index (SLI) to 700 hPa being more negative (unstable) than a specified threshold, and the vertical wind shear to 1500 m exceeding another threshold value. This forecast has been proven to be skillful over several years (Mills 2004).

Recently, the application of this diagnostic to reanalysis datasets with coarse resolution similar to those of state-of-the-art GCMs was demonstrated (Kounkou et al. 2009, hereafter KA09) for southern Australia. The study used two sets of reanalyses: the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40; Uppala et al. 2005) and joint National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (NNR; Kalnay et al. 1996). KA09 found surprisingly large differences between the threat area climatologies from the two sets of reanalyses and argued that this difference provides a measure of the uncertainties attached with the estimation of the “observed” climatology of the CST risk, since both reanalysis sets are equally plausible. These reanalysis climatologies of CST risk provide a framework for validating a GCM’s ability to reproduce these extreme conditions for the current climate, using the differences between the reanalyses as a measure of the uncertainties attached to the climatology of the risk of CST formation.

In this note, we detail the application of the CST diagnostic to a limited set of GCM simulations of the twentieth-century climate and evaluate their ability to reproduce the recent climate of CST risk in light of KA09. Then, the diagnostic is applied to simulations of the twenty-first-century climate forced by anthropogenic greenhouse gas emissions and the impact of climate change on CST risk is quantified. The future projections of CST risk are evaluated in light of the ability of the GCM to produce a realistic climatology of CST risk for the current climate, and also in terms of projected changes to the most relevant planetary scale mode of variability—the southern annular mode (SAM).

2. Data and method

a. Data

In conjunction with the IPCC Fourth Assessment Report (Solomon et al. 2007), a set of global climate model experiments has been produced: the World Climate Research Program (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel dataset. Twenty-five GCMs contributed to the CMIP3 dataset; however, our diagnostic relies on daily outputs of atmospheric variables that are not included in the list of requested daily outputs. Additional data had to be sourced from individual modeling groups; this was done for four GCMs (Table 1). The model resolutions vary, but in general they are slightly coarser than the reanalyses data (2.5°) that are used to evaluate the applicability of the CST diagnostic by KA09. In Table 1 the models are ranked according to a measure of their sensitivity to anthropogenic forcing (ΔT; last column), which is calculated using the global warming produced by the model using the A1B scenario when approximated by linear regression over the twenty-first century (CSIRO and the Bureau of Meteorology 2007). Daily data were analyzed for three time slices: 40 yr from 1961 to 2000 for the simulation of the late twentieth century, and two 20-yr periods, from 2046 to 2065 and from 2081 to 2100, in the
TABLE 1. Global climate models from the CMIP3 database used in this study; the name of the originating group, the acronym used, and the official model name as per the CMIP3 database and the approximate size of the model horizontal grid box are shown. Models are ranked according to a measure of their climate sensitivity (ΔT, last column) from the least sensitive at the top to the most sensitive at the bottom (see text for details).

<table>
<thead>
<tr>
<th>Originating group</th>
<th>Acronym</th>
<th>CMIP3 database official name</th>
<th>Grid size (°)</th>
<th>ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadian Centre for Climate Modelling and Analysis</td>
<td>CCCma</td>
<td>CCCma Coupled General Circulation Model, version 3.1CGCM3.1(T47)</td>
<td>3.75 × 3.75</td>
<td>2.47</td>
</tr>
<tr>
<td>Météo-France</td>
<td>CNRM</td>
<td>Centre National de Recherches Météorologiques Coupled Global Climate Model, version 3CM3</td>
<td>2.8 × 2.8</td>
<td>2.81</td>
</tr>
<tr>
<td>L’Institut Pierre-Simon Laplace</td>
<td>IPSL</td>
<td>L’Institut Pierre-Simon Laplace Coupled Model, version 4IPSL-CM4</td>
<td>2.5 × 3.75</td>
<td>3.19</td>
</tr>
<tr>
<td>Max Planck Institute for Meteorology</td>
<td>MPI</td>
<td>ECHAM5/Max Planck Institute Ocean Model MPI-OM</td>
<td>2.8 × 2.8</td>
<td>3.69</td>
</tr>
</tbody>
</table>

twenty-first century. Among the six future emission scenarios that are available in the CMIP3 database, only one emission scenario for the twenty-first century was considered: a high emission scenario (A2). This scenario was chosen because observations of greenhouse gases have consistently superseded all of the emission scenarios noted in the Special Report on Emissions Scenarios (SRES; Canadell et al. 2007), and so a more severe scenario, such as A2, therefore looks increasingly more realistic. Furthermore, it was anticipated that a large forcing would aid the identification of a robust climate change signal.

b. Method

KA09 characterized the CST environment in ERA-40 and NNR using only two parameters, which is a simplification of the original methodology (Hanstrum et al. 2002). The first parameter is an instability threshold computed as the difference between the temperature at 700 hPa and the temperature of a surface (2 m) air parcel (with a known temperature and dewpoint) that is lifted adiabatically to saturation, and then pseudoadiabatically saturated to 700 hPa—the SLI to 700 hPa. The second parameter is a measure of low-level vertical wind shear (VWS) between the surface (10 m) and 850 hPa, computed as

\[
VWS = \sqrt{(u_{500hPa} - u_{surf})^2 + (v_{500hPa} - v_{surf})^2}.
\]

KA09 found that for most of southern Australia [the southern half of the state of western Australia (WA) and the southern part of the state of south Australia (SA); Fig. 1], meaningful thresholds (i.e., not too low to lead to too many false detection cases) could be estimated for both reanalyses based on 24 known cases in WA and SA. The two regions as well as the locations of 20 reported occurrences of CST during the 1999–2002 period (Mills 2004) are shown in Fig. 1.

To adapt the CST diagnostic tool to the climate models, taking into account model biases, probability density functions (PDFs) of SLI and VWS of daily data from 1961 to 2000 for a 5-month period corresponding to the cool season (May–September) are calculated at each individual grid point at 0000 UTC (the most relevant time of the day for CSTs formation, according to KA09). The models’ PDFs are then evaluated compared to similar PDFs obtained from the reanalyses across all continental points in the area of interest in WA and SA. To perform this comparison, the area below the PDF curve between the extreme values of each parameter (low in the case of SLI, high in the case of VWS) and the threshold values set in KA09 was computed for each reanalysis point. A spatial average is then generated from all land gridpoint values in the area of interest (for WA and SA separately), and then by taking the mean of the two reanalyses. Thereafter, for each grid point for each model the individual thresholds are calculated such that the same areas lie under the PDF curve for that model grid point and parameter as the average areas calculated from the reanalysis PDFs. In general, for any one GCM, the thresholds were found to be very similar from one grid point to another in the same region. Finally, all gridpoint thresholds were averaged separately for WA and SA and presented in the results section as a single southern Australia average (the mean of WA and SA values).

This methodology provides SLI and VWS thresholds tuned to each GCM, taking into account its resolution and biases (both for the mean and the distribution). This methodology is appropriate because the CST risk is defined as a joint probability between two parameters: SLI and VWS. However, it is not expected to provide an identical mean climatology of the CST risk environment among the models. Instead, the focus is to ensure that the definition of the thresholds is consistent with the model simulations, including its biases, to ensure the robustness of the application of the diagnostic to model.
simulations, and hence its direct applicability to a simulation of a different climate. When the diagnostic is applied to simulations of the twentieth century, it is an opportunity to critically assess the model performances. When the diagnostic is applied to future climate projections, keeping individual model thresholds unchanged, it provides a tool to quantify the impact of climate change on the CST risk relative to that of the modeled late-twentieth-century climate.

3. Evaluation of the twentieth-century simulations

Figure 2 illustrates the application of the diagnostic to four GCMs across southern Australia, showing PDFs of SLI and VWS for two grid points (located with gray stars in Fig. 1) corresponding to the regions of the largest occurrence of CST environments from the two reanalyses in WA and SA. GCM values are given for the nearest grid point to the reanalysis location; exact locations for each model are listed in Table 2. Differences in location can be offset by up to 2.5° in longitude and 1° in latitude, but in all cases the GCM grid box is similar to that of the reanalyses in terms of physical geography; that is, each captures the edge of the Australian continent (in WA or SA) at the appropriate latitude as represented by each GCM land–sea mask.

The two reanalyses exhibit rather different PDFs for SLI and VWS (Fig. 2). The NNR PDF is narrower and shifted to lower SLI values than that of ERA-40, while the PDF of VWS for NNR is shifted toward higher values than that of ERA-40. In most instances, the GCMs’ PDFs do not depart significantly from one of the two reanalyses, and therefore are within the range of uncertainties arising from the differences between the two reanalyses that are treated as equally plausible representations of the real unobserved climate system. A notable outlier is the L’Institut Pierre-Simon Laplace (IPSL) model: the PDF of its VWS is broader (the consequence of this shift on the CST climatology for the IPSL model will be discussed later). Most of the differences in climatologies are likely to be due to a complex mix of dynamical calculations and physical parameterizations within an individual model.

The ability of each GCM to reproduce the reanalysis PDFs for the two parameters were evaluated using simple correlations between the PDFs of the GCM and the two sets of reanalyses using the methodology described by Perkins et al. (2007). Correlations for each GCM with both reanalyses were calculated, and the largest value of the two was selected; values above 0.75 were considered satisfactory. The selection of the largest correlation is based on the hypothesis that each reanalysis is an equally likely proxy for the real climate. Therefore, a model was considered satisfactory if it produces a PDF that correlates above the set threshold for at least one of the two reanalyses. For SLI, correlations in general are high at
most grid points (e.g., above 0.95 for the SA example shown in Fig. 2 and above 0.75 for the WA case). No model appears to be consistently underperforming. For the VWS parameter, only two models have correlations that are consistently above the 0.75 threshold: the Canadian Centre for Climate Modelling and Analysis (CCCma) and Max Planck Institute (MPI) models. The Centre National de Recherches Météorologiques (CNRM) and IPSL models have VWS PDFs that are not suitably close to one or the other reanalyses [a correlation of 0.68 (0.71) for the CNRM (IPSL) model for the SA case and 0.57 for the IPSL model for the WA case]. In light of these findings, model results are considered in two phases—first for the best-performing models (CCCma and MPI), and second for the entire ensemble that is available (including the CNRM and IPSL models). It should be noted that this notion of a best-performing model is solely focused on the problem at hand and should not be interpreted as valid for other aspects of the climate system.

Values of individual model thresholds (calculated as per the methodology described in the previous section) that are averaged (for each grid point) for southern Australia are comparable to the range obtained from the two sets of reanalyses (Table 3). All of the models have the same SLI threshold, which is higher than for both reanalyses. VWS thresholds are less homogeneous and range from 7 m s\(^{-1}\) for the CNRM model to 15 m s\(^{-1}\) for the IPSL model (as expected from the broader PDF shifted toward higher values). Despite the impact of the model resolution on individual gridbox PDFs illustrated earlier (Fig. 2), the thresholds do not appear to be dependent on the model resolution (Table 1). This is apparent from the lack of difference for SLI and for VWS; the model with the lowest resolution (CCCma) has the same threshold as the model with the highest resolution (MPI).

The inferred climatology of CST risk from each GCM based on these thresholds is compared to similar climatologies from the two reanalyses in Table 3. The comparison is limited to the period of 1979–2000 because of

![PDFs of SLI (115-32.5)](image1)

![PDFs of VWS (115-32.5)](image2)

**TABLE 2.** Gridpoint locations at which the PDFs of SLI and VWS are calculated for each model.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>WA grid point</th>
<th>SA grid point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reanalyses</td>
<td>32.5°S, 115.0°E</td>
<td>35.0°S, 140.0°E</td>
</tr>
<tr>
<td>CCCma</td>
<td>31.5°S, 116.3°E</td>
<td>35.3°S, 142.5°E</td>
</tr>
<tr>
<td>CNRM</td>
<td>32.1°S, 115.3°E</td>
<td>34.9°S, 140.6°E</td>
</tr>
<tr>
<td>IPSL</td>
<td>31.7°S, 116.2°E</td>
<td>34.2°S, 142.5°E</td>
</tr>
<tr>
<td>MPI</td>
<td>32.6°S, 114.4°E</td>
<td>34.5°S, 140.6°E</td>
</tr>
</tbody>
</table>
concerns with the reanalyses in the presatellite era prior to 1978. KA09 highlighted that while a strong trend was evident in the entire period from 1958 to 2000, this was mostly due to a discontinuity in the late 1970s following the availability of polar-orbiting satellite sounding data. The average number of cases with risk of CST formation varies by nearly a factor of 2 between the GCMs. This range is large but is chiefly due to the IPSL model, which is a clear outlier (the other three models exhibit a difference of less than 15%). This is the consequence of the very broad PDF for VWS with the IPSL model (Fig. 2). Differences between CST risk climatology were expected because of the chosen methodology described earlier. A poor-man’s ensemble mean using all four models shows a climatological mean within the range of the reanalyses (as does an average based on the two best-performing models). The interannual variability (shown in Table 3 as standard deviation computed on annual mean during the 1979–2000 period) for the ensemble mean is lower than either of the reanalyses. Only the CCCma model shows a larger interannual signal, and thus the average of the best two models matches the reanalyses. Finally, linear trends from 1979 to 2000 show only a very small and nonsignificant increase of the CST risk with time in both reanalyses. There is no consistent signal among the four climate models. If only the two best-performing models are considered (MPI and CCCma), then a similar small positive trend is obtained. However, the IPSL model shows a negative trend. All of these trends from reanalyses and GCMs are very small and are not statistically significant at any meaningful level. Overall, on the limited set of data available, climate models forced with realistic external forcings confirm earlier findings (KA09) and do not suggest a significant trend of CST risk during the last two decades of the twentieth century.

4. Change of CST risk due to climate change signal

Having defined the twentieth-century climatology of CST risk for four climate models, the diagnostic can now be applied to simulations of the twenty-first century and differences between the models’ current and future climatologies of the risk evaluated. Because the methodology did not tune the diagnostic to obtain identical climatological means for the current climate, but rather to define thresholds consistent with each model’s representation of the two environmental parameters, these thresholds are equally applicable to the same climate models for a different climate and the difference in CST risk can be computed for individual models.

PDFs for the two environment parameters (SLI and VWS) are shown for each individual GCM (Fig. 3) for the two twenty-first-century time slices (2046–65 and 2081–2100) compared with the reference period of 1961–2000 for a single location (the WA grid box shown in Fig. 1). This is illustrative of the overall response of the climate models across southern Australia (a similar figure for SA is not shown). Not surprisingly, the PDFs are very similar in the three time slices; that is, the differences for an individual model resulting from the projected global warming are small compared to intermodel differences. This demonstrates the strong influence of each model’s background climatology and emphasizes the need to define model-based thresholds in order to infer a meaningful uncertainty range from the models’ projections.

Subtle differences exist in the PDFs of the environmental parameters as time evolves. In particular, some consistent changes in the distribution of SLI and VWS values can be observed at this location and are consistent across most of southern Australia (not shown). The GCMs show a shift of the SLI PDFs toward higher values, that is, a more stable and less buoyant large-scale environment. It is more pronounced at the higher end of the distribution (with no impact on the CST risk), but it is also true at the lower end of the distribution, hence reducing the number of occurrences when the SLI is less stable (more negative) than the threshold at which a risk of CST formation can be triggered. This thermal response is consistent across models and increases as the external forcing increases by the end of the twenty-first century.

<table>
<thead>
<tr>
<th>Model</th>
<th>SLI (°C)</th>
<th>VWS (m s⁻¹)</th>
<th>Mean</th>
<th>Std dev</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA-40</td>
<td>0</td>
<td>8</td>
<td>161</td>
<td>39</td>
<td>0.58</td>
</tr>
<tr>
<td>NNR</td>
<td>-2</td>
<td>10</td>
<td>111</td>
<td>38</td>
<td>0.88</td>
</tr>
<tr>
<td>CCCma</td>
<td>2</td>
<td>9</td>
<td>141</td>
<td>43</td>
<td>0.16</td>
</tr>
<tr>
<td>MPI</td>
<td>2</td>
<td>9</td>
<td>127</td>
<td>32</td>
<td>1.42</td>
</tr>
<tr>
<td>CNRM</td>
<td>2</td>
<td>7</td>
<td>125</td>
<td>31</td>
<td>-0.01</td>
</tr>
<tr>
<td>IPSL</td>
<td>2</td>
<td>15</td>
<td>226</td>
<td>37</td>
<td>-0.71</td>
</tr>
<tr>
<td>Full ensemble mean (CCM and MPI only)</td>
<td></td>
<td></td>
<td>155 (134)</td>
<td>36 (38)</td>
<td>0.21 (0.79)</td>
</tr>
</tbody>
</table>

Table 3. Individual SLI and VWS thresholds used for each reanalyses and GCMs and inferred CST risk climatology from 1979 to 2000 (mean standard deviation and trends in total number of cases per year).
century; the changes are roughly twice as large in the second period.

Unlike the thermal response, the dynamic responses, which are expressed as changes in VWS, are smaller in magnitude and are not consistent among the models. Both the CCCma and the IPSL models indicate a decrease of VWS, opening the possibility of a compounding effect toward reducing the CST risk. The MPI model has no such signal, while the CNRM model indicates an opposite trend with a shift toward higher values of VWS over WA, particularly in the second time slice. This finding, in conjunction with the large differences among the models in reproducing a twentieth-century PDF for VWS, shows that it is the more uncertain of the two large-scale parameters.

Overall, this analysis indicates that the SLI is expected to increase during the next century, following the SRES A2 scenarios, and that the increase is a function of the amount of greenhouse gases emitted in the atmosphere. The effect on VWS is not as clear among the models, and therefore should modulate the overall model response in term of CST risk. It is important to remember that both environmental parameters contribute to the CST risk and it is not a simple additive effect: the change for each parameter is not necessarily reflected in changes in CST risk. However, differences for each parameter shed light on the overall changes in CST risk provided by each model.

These results described above for a single grid point are fairly consistent across the entire domain and explain the differences in trend of future projections of CST risk in southern Australia (Table 4). All of the models demonstrate an overall decrease in CST risk by the end of the twenty-first century for southern Australia, and all but one in the middle of the century. The consistency among the models, as explained earlier, is driven by the same thermal response (increase of SLI values) in all models. It is interesting to point out that the outlier is the CNRM model, which was shown to have a dynamic response favorable to CST formation, thus opposing the thermal response. The differences among the other models are very small and are consistent with shifts in the PDFs of the two parameters described earlier for a single grid box. Overall, the thermal response (SLI) is modulated by the dynamical response (VWS). The intensity of the reduction is controlled by the response to SLI (i.e., relatively homogeneous among the models and growing with the increased forcings). The dynamical response, which shows opposite behavior between the models, is the main contributor to the fourfold
uncertainty range in the projection. Finally, over time it appears that the intensity of the response is related to the amount of external forcing; the reduction in the CST’s risk is larger by the end of the century when the magnitude of the thermal response reduction starts to dominate the uncertainties driven by the dynamical response. It is interesting to note that the agreement between the two best-performing models is very high: a reduction of 5%–9% by 2050 and 20%–21% by 2090. The range however becomes much larger when all models are considered (Table 4). Despite the two models responsible for this broader range having being assessed as less satisfactory during the evaluation of the model climatology, this large range is worth considering when evaluating these projections. It is, for example, not possible to rule out that the range provided here is an underestimation of the full range of the uncertainty attached to the projections because only a limited number of CMIP3 GCMs are considered here, and model responses were only analyzed for a single, but likely conservative, emission scenario.

5. Discussion

An application of a diagnostic of the tornado formation risk during the cool months of the year to GCM simulations of twenty-first-century climates shows that the risk of occurrence of these extreme weather events is very likely to decrease across southern Australia because of projected global warming. The reduction appears primarily due to changes in large-scale thermal variables, suggesting a stabilization of the atmosphere. The three variables used in the SLI calculation were analyzed further for the two best-performing models (CCCma and MPI). The mean values (Table 5) of surface (2 m) temperature, 700-hPa temperature, and surface specific humidity for all grid points over southern Australia for the three periods of interest (1961–2000, 2046–65, and 2081–2100) were calculated. Results indicate a stronger warming of the atmosphere at 700 hPa compared with the surface. The surface also shows a steady increase in mixing ratio through to 2090, but that low-level humidity increase is roughly consistent with the increase of surface temperature. The principal factor for the stabilization in the region of interest is the increase of 700-hPa temperature. These thermodynamical changes are consistent with the general theory and model results concerning greenhouse gas--induced warming of the climate system (Solomon et al. 2007), and they can be summarized on a thermodynamic diagram (Fig. 4) where the increasing SLI for the end of the twenty-first-century time slice are compared with the 20C3M experiment using values from the CCCma model. It is interesting to note that the CCCma model displays a larger thermal signal in the vicinity of southern Australia than the MPI model despite being the model with a lower global sensitivity (defined in Table 1) of the two. In the case of the CCCma model, the thermal stabilization (difference between the warming at 700 hPa and the surface) is greater than with the MPI model; the difference is 1.3° versus 0.5° C by 2050, but is reduced by 2090 (to 1.7° versus 1.2°C). In agreement with these numbers, the CCCma model suggests a larger reduction of the risk of CST formation than the MPI model by 2050, but no more by 2090. However, one has to remember that the risk for CST is defined as the result of a joint probability between two parameters, and therefore the fact that the CCCma but not the MPI model showed a dynamical response (a reduction of the number of cases with high VWS values) is also relevant.

KA09 showed that the most significant relationship between CST risk and several large-scale modes of variability known to influence the climate of southern Australia was a negative correlation between the dominant mode in the Southern Hemisphere, the southern annular mode (SAM) index. Projected changes in the SAM index based on the current IPCC models, including the ones used in this study (Miller et al. 2006), show an increase of the SAM index in winter throughout the twenty-first century, which is stronger when ozone forcing is considered in addition to greenhouse gas emissions. This result is consistent with our findings: with global warming,
the SAM index rises and the risk of CST formation declines. It suggests that the link between SAM and the CST risk in southern Australia, which has been identified in the current climate, is maintained in the future, and hence as the SAM index rises, the CST risk is also reduced. A further analysis would be required to clarify how the SAM impacts on the CST risk formation: it can either be through dynamical factors (surface winds and vertical wind shear) or thermal changes. Mills (2004) did show that there were higher numbers of CST per season over the southwest of WA when the mean winter pressure was lower in that region, which are conditions in which the SAM index tends to be lower. SAM has also been documented to have an influence on wind in the lower troposphere as well as surface temperature over the Australian continent (Hendon et al. 2007).

This study contributes to our ability to tackle the difficult issue of the impact of global warming on extreme weather events as it illustrates the application of a NWP-derived methodology to climate model simulations of the current and future climate. It suggests the potential of using similar methods to quantify the impact of climate change for other extreme weather events. However, it is worth noting that this study specifically deals with the risk of formation of tornadoes during the cooler months of the year across southern Australia. These results should not be extrapolated to other weather extremes and other regions. In particular, the finding that cool-season tornadoes are less likely to form in the future because of a stabilization of the lower troposphere during the winter month does not necessarily translate to a similar conclusion for summer thunderstorms, and associated supercells and summer tornadoes, where different environments may be at play (Deffenbaugh et al. 2008). On the other hand, the consistent signal across all of the climate models considered here regarding the cool-season tornadoes’ risk of decreasing because of thermal stabilization of the lower troposphere appears robust and is likely to be a contributor for CST risk anywhere. Albeit an important caveat noted earlier, it must be kept in mind that change to vertical wind shear can significantly modulate the risk reduction resulting from thermal stabilization.

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