Impact of drought on temperature extremes in Melbourne, Australia

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Melbourne, Australia, experienced a large increase in its maximum daily temperature on 7 February 2009. This new record was set after an extended period of drought. We test whether droughts tend to lead to increased daily maximum temperatures in Melbourne, relative to temperatures experienced after wet periods, separating this drought effect from the effect of synoptic-scale wind-flow on maximum temperatures. Data from 1957–2008 indicate that the daily maximum temperature is typically 1–3 °C higher after drought, relative to a similar synoptic situation after a wet period, in situations typically associated with high maximum temperatures (i.e. with winds from the north). When the wind is from the south (i.e. from over the sea) there is typically little or no difference between daily maximum temperatures after droughts or wet periods.

Introduction

The severe bushfire weather that impacted southeast Australia on ‘Black Saturday’, 7 February 2009, was the result of a synoptic event that led to a new record maximum temperature for Melbourne, Australia of 46.4 °C (Bureau of Meteorology 2009). This was substantially hotter than the previous record high temperature (45.6 °C, 13 January 1939) in the previous 154 years of data, and was 3.2 °C hotter than the previous record February temperature (set in 1983). This large jump in record maximum temperature occurred in the context of a long-term upward trend in temperature, with temperatures in southeastern Australia increasing about 0.7 °C since 1910 (http://www.bom.gov.au/climate/change/). This warming trend should be leading to an increased likelihood of new record maximum temperatures (and a decline in the frequency of the setting of new cold records). However, the gradual increase cannot explain, by itself, the large jump in the record February temperature seen on Black Saturday.

In recent years similarly unprecedented high temperatures have been observed in other parts of the world, including Western Europe in 2003 (Fischer et al. 2007a, 2007b) and Eastern Europe and Russia in 2010 (Barriopedro et al. 2011). Several studies have concluded that low soil moisture associated with a drought was likely contributing to these very high temperatures (Seneviratne et al. 2006, 2010; Fischer et al. 2007a,b; Dole et al. 2011). More generally, Durre et al. (2000) demonstrated that low soil moisture shifted the entire frequency distribution of daily maximum temperatures towards warmer values in the contiguous United States of America, with the effect being more pronounced at the high end of the distribution.

In the lead-up to Black Saturday, southeast Australia had been subjected to an extended drought. Melbourne had experienced twelve years in a row with rainfall less than the long-term average, and much of southeast Australia had experienced record-low twelve-year rainfalls (Bureau of Meteorology 2008). Almost no rain fell in the first five weeks of 2009. It seems feasible therefore, based on the studies noted above, that the dry conditions may have exacerbated the very hot temperatures associated with Black Saturday, leading to a large increase in record daily maximum temperatures. This study uses data prior to 2009 to examine whether dry soil conditions lead to increased daily maximum temperatures in Melbourne.

One advantage of examining this question for southeast Australia is the geographical situation. High daily maximum temperatures in this region are generally associated with northerly winds in summer which advect warm air from inland Australia across Melbourne and its surrounds. In dry years, northerly winds might be expected to be warmer than in ‘wet’ years when the soil has higher moisture content and the partitioning of the available energy may include a larger latent heat component at the expense of sensible heating. In contrast, southerly winds reaching Melbourne typically...
have travelled over the ocean, and so may experience little or no change in moisture availability between years classified as ‘wet’ or ‘dry’ on the basis of soil moisture conditions. Thus the geographical situation provides us with a ‘fingerprint’ for our hypothesis, as we would expect the warming effect in ‘dry’ years relative to ‘wet’ years to be clearer and stronger on days with winds from the north.

We use an estimate of the strength of the northerly wind component to determine if days in ‘dry’ years typically exhibit hotter maximum temperatures than days during ‘wet’ years, after taking account of the direction and strength of the meridional wind. We estimate soil moisture using only data in months (July to December) leading up to the period for which we examine the effects of northerly winds and soil moisture (the immediately following January and February), to avoid possible confounding from concurrent events. So, we calculate soil moisture content using a simple soil moisture model, up to the end of December. We then stratify the years into ‘dry’ and ‘wet’ years and then examine the relationship between the strength of the northerly wind and maximum daily temperatures in the immediately subsequent January and February. We compare these relationships in dry and wet years (determined from data up to the end of the previous December), to see if there is an effect of soil moisture on daily maximum temperatures, separate from the influence of the strength of the northerly winds on temperature. We also look for the ‘fingerprint’ noted above, namely that any warming effect associated with the dry conditions should be evident only when the winds are from the north.

Data and method

Daily temperature data from the Melbourne Regional Office (station number: 086071; latitude: 37.81°S; longitude: 144.97°E; elevation: 31 m) were used in the analysis of January and February daily maximum temperature. Locations of the stations used in this study are shown in Fig. 1.

In order to categorize the period leading up to summer according to the dryness of the soil, a soil water balance model was constructed using data obtained from the Australian Bureau of Meteorology. Following Allen et al. (1998) daily actual evapotranspiration was estimated for Warburton (station number: 086090; latitude: 37.71°S; longitude: 145.79°E; elevation: 240 m) on the eastern outskirts of Melbourne, for the period January 1955 to February 2008. This was used together with daily precipitation data for Warburton to drive a ‘bucket type’ soil water balance model, with an available soil water capacity set to 100 mm. Warburton was chosen (instead of modelling soil water for Melbourne city) to allow the validation of the soil moisture model from other observations, and because an estimate of soil water for a forested region was considered more likely to be representative of the surrounds of Melbourne than a city-based estimate would have provided. Daily temperature data from the Melbourne Regional Office were used in the soil water balance model, because daily temperature data were not available for Warburton. The model was initialised each year on the first day of July with the soil saturated. In dry years, the available soil moisture typically reduced to zero over the spring (September-November), and remained at zero until the next rainfall, following which it dried again at the actual evapotranspiration rate. The number of days for which soil moisture was at zero (Dry Soil Days, DSD) over the period July–December were summed and used as an index of dryness. Any year with twenty or more DSDs in the preceding July–December was considered a ‘dry’ lead up to the summer months of January and February. Years with fewer than five DSDs were taken to indicate a ‘wet’ year lead up to January and February. Table 1 lists the sixteen ‘dry’ and seventeen ‘wet’ years identified from this analysis.

Daily mean sea-level pressure (MSLP) data for the Cape Otway Lighthouse (station number: 090015; latitude: 38.86°S; longitude: 143.51°E; elevation: 82 m) and the Wilsons Promontory Lighthouse (station number: 085096; latitude: 39.13°S; longitude: 146.42°E; elevation: 95 m) were used to drive a ‘bucket type’ soil water balance model, with an available soil water capacity set to 100 mm.

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Table 1. Years categorised as either ‘wet’ (fewer than five dry soil days July-December) or ‘dry’ (more than twenty dry soil days July-December), based on Warburton modelling/data. Years shown in italics are those excluded based on modelling/data for Echuca. Years shown bold are the additional years excluded, based on the analysis of area-averaged July-December rainfall total.

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<th>Wet’ years</th>
<th>‘Dry’ years</th>
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determine the geostrophic meridional wind component over Melbourne. The equation used to derive the geostrophic wind is equation 2.23 in Holton (2004).

In the cases where there were missing data, the average of the day before and after the ‘target’ day was used, and in the (rare) case where several days were missing, data from Melbourne Regional Office were substituted.

For each January and February day for the 50-year period 1958–2007 we calculated the strength of the northerly gradient, as described above, and plotted the observed daily maximum temperature at the Melbourne Regional Office against the strength of this gradient (Fig. 2). The data were stratified into years when the lead–up to the season (up to the end of December) had been categorised as ‘dry’ or ‘wet’ as described above.

The results of the above exercise were tested in two ways for their sensitivity to the method used for the categorisation of years as either ‘wet’ or ‘dry’, and to the selection of Warburton as the site for estimating soil moisture balance for the categorisation. Firstly, the above analysis was repeated using data from Echuca (station number: 080015; latitude: 36.16°S; longitude: 144.76°E; elevation: 96 m) located about 200 km north of Melbourne, to confirm the stratification of years into ‘dry’ or ‘wet’ at Warburton. This process identified three years (1981, 1987, 2003) that had been identified as ‘wet’ or ‘dry’ from the Warburton modelling that could not be correspondingly categorised using the Echuca modelling. However, repeating the following analysis excluding these three years did not affect the following results significantly. A second sensitivity test was conducted by simply using the total July–December rainfall, averaged over the region 143 – 146°E, 36 – 38°S (calculated from the Bureau of Meteorology web site using its Data Portal) to delete further years that had been categorised as ‘wet’ or ‘dry’ using the Warburton modelling/data and had been retained after examining the Echuca modelling/data. Using this areal average rainfall, a further three years were deleted (1957, 1979, 1991), as well as the three years that were deleted based on the Echuca modelling/data. Deletion of these six years means that all years categorised as ‘dry’ had less than 350 mm for the area-averaged July–December rainfall whereas all years categorised as ‘wet’ received more than 350 mm rainfall.

Repeating the fit of the daily maximum temperature data, after deletion of these six years, produced very similar results to those discussed below. Thus, the two sensitivity checks indicate that the results were insensitive to the exact method used to categorise years as ‘wet’ or ‘dry’.

**Results**

Figure 2 shows that daily maximum temperatures, in both ‘dry’ and ‘wet’ years, are related to the meridional wind component, with a strong tendency for warmer temperatures when the wind had a northerly component (i.e. meridional wind < 0). The figure also shows a tendency for warmer daily maximum temperatures after ‘dry’ years, compared to ‘wet’ years. This difference between the two sets of years tends to increase as the northerly component strengthens (i.e. as the meridional component becomes more negative). This is illustrated by the nonlinear regression lines fitted to the two sets of data, which tend to diverge as the northerly component strengthens, although the effect is also discernable in the linear regressions shown in the figure (which diverge as the northerly component increases).

There appears to be a tendency for temperatures to drop when the meridional component is a very strong northerly. This may be a statistical artefact, because the number of data points is quite small at the extremes of the distribution, or could be due to errors in the data. An alternative explanation might be that days with very strong northerly winds might also be days with a strong change to a southerly component after the passage of a cold front—such a synoptic situation might result in relatively cool daily maximum temperatures.

The statistical significance of the difference in daily maximum temperatures between ‘dry’ years and ‘wet’ years was calculated by restricting the data only to those days on which the meridional component was northerly (i.e. < 0). The median daily maximum temperature for the 310 northerly days following ‘wet’ years was 30.20 °C while the median temperature for the 229 northerly days following ‘dry’ years was 32.00 °C. The difference between the two means for these two sets (30.06 °C for ‘wet’ years versus 31.66 °C for ‘dry’ years) was highly statistically significant (based on a conventional t-test for differences in two means).

As was noted earlier, because of the location of Melbourne
at the south edge of the continent, one would not expect that dry years would lead to an enhancement of daily maximum temperatures over those in wet years, when the wind was from the south (and thus from over the ocean rather than over land). Figure 2 suggests that this is the case, since the linear and non-linear fits show less difference between the dry and wet year temperatures, at larger positive values of the meridional wind (i.e. southerly winds). This has been confirmed by comparing the temperatures following the wet and dry years, only using those days when there was a strong southerly component (specifically, when the meridional wind exceeded 15 m s⁻¹ from the south). The mean daily maximum temperature in the 135 days exceeding this threshold wind following wet years was 20.37 °C, whereas the mean daily maximum temperature on the 133 days following dry years was 20.17 °C.

Discussion

Figure 2, and the comparison of mean daily maximum temperatures following wet and dry years, confirms the expectation that, at Melbourne, winds reaching Melbourne from the inland lead to higher daily maximum temperatures after an extended dry period, relative to when the countryside is wet. The ability to stratify data to avoid the possibility that this apparent effect was due to synoptic activity (by separating the effect of meridional wind direction and strength on daily maximum temperature) strengthens our confidence that this is due to soil moisture – air temperature interaction. The existence of a stronger effect of dry years relative to wet years, when the wind was from the north compared to the situation when the wind had a southerly component (i.e. from over the ocean) tends to confirm that the warming effect is related to partitioning of the available energy. This result supports other studies in Europe and the USA that have demonstrated that dry soil conditions lead to an enhancement of daily maximum temperature. It seems likely, based on these other studies and on the results of this study, that the very dry conditions leading into Black Saturday were a contributor to the large jump in record maximum temperature seen on that day.

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References