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Influence of antecedent soil moisture conditions on the synoptic meteorology of the Black Saturday bushfire event in southeast Australia

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The dynamics and large-scale drivers of heat wave (HW) events in Australia are well documented. However, the influence of soil moisture in modulating HWs is largely unexplored. We focus here on a recent significant HW event in southeast Australia that preceded the Black Saturday bushfires (3rd to the 7th of February 2009). During this period, the southeast of Australia experienced unprecedented warm conditions, which, in conjunction with high fuel load and mesoscale weather conditions, led to devastating bushfires. We examine how different initial soil moisture conditions with lead times of 5, 10, and 15 days prior to the event would have altered its overall dynamics at the continental scale. We show that at short lead times (5 days), the influence of perturbing soil moisture is mostly linear. Decreasing (increasing) soil moisture increases (decreases) maximum temperatures, associated with an intensification of the upper-level anticyclone. The effect of increasing soil moisture is more non-linear than decreasing soil moisture with increasing lead time; namely, increasing soil moisture can also lead to an increase in maximum temperature over some parts of the domain, rather than a decrease everywhere. At lead times of up to 15 days, the imposed perturbation in soil moisture, mostly confined to the tropics, is essentially lost such that the impact on maximum temperatures on the day of the event cannot be related to the sign of the imposed perturbation in soil moisture. Our results highlight the importance of accurate soil moisture estimates in capturing the intensity and spatial extent of HW events in southeast Australia, but only at relatively short lead times.
1. Introduction

During the summer of 2008-2009, southeast Australia experienced unprecedented extreme heat conditions with maximum temperatures reaching 46.8°C, culminating with catastrophic bushfires on the 7th of February 2009 (the Black Saturday bushfires), with a maximum temperature anomaly of up to +18°C (Jacobs et al. 2014). These bushfires caused significant damage to infrastructure estimated to be more than $4 billion and resulted in 173 human fatalities (Teague et al. 2010). Heat wave (HW) conditions were observed up to 2 weeks prior to the event, with nine out of the eleven preceding days exceeding 30°C (Engel et al. 2013). This event was largely driven by mesoscale atmospheric dynamics, including complex interactions involving a late-afternoon cold front and propagating nocturnal bores (Engel et al. 2013).

Several studies have attempted to link the occurrence of HWs in Australia to various modes of climate variability and a range of hypotheses have been suggested. Cai et al. (2009) showed that extreme bushfire conditions, such as those experienced during the Black Saturday bushfires, tend to be preceded by positive Indian Ocean Dipole (IOD) events. These tend to produce lower than average rainfall and higher temperatures over eastern Australia, which exacerbate dry conditions. Marshall et al. (2014) focused on intra-seasonal drivers of HWs in Australia and showed that there is skillful predictability of increases in heat extremes with lead times of up to 2-3 weeks with the negative phase of the Southern Annular mode (SAM), the vicinity of the sub-tropical ridge, and the Madden-Julian Oscillation (MJO). Parker et al. (2014b) on the other hand link southeastern Australian HWs to distinct phases of the MJO and the La Nina phases of the El Niño Southern Oscillation (ENSO), but could not link the frequency of HWs to the phases of SAM.

Several studies have also investigated teleconnections which act to reinforce HW-like conditions. Using a tracking scheme, Pezza et al. (2011) showed that a pressure dipole formed by transient cyclones and anticyclones can reinforce HWs in southern Australia. They also show that that HWs over eastern Australia tend to be associated with enhanced monsoon seasons over northern Australia as compared to HWs occurring over Western Australia. Similar teleconnections have been established elsewhere, for example the 2010 Pakistan floods and Russian HWs are thought to have been inter-connected (Lau and Kim 2012). Martius et al. (2013) focussed on the same event and highlighted the role of evapotranspiration from the land surface in increasing atmospheric humidity. A study by Parker et al. (2013) has shown that HWs in southeast Australia, in particular, the Black Saturday event was strongly influenced by the interaction between a tropical cyclone and the large-scale midlatitude flow. A more detailed analysis HWs affecting southeastern Australia by Parker et al. (2014a) further highlights the strong connections between heavy rainfall over the northeast and HWs in southeast Australia.

Few studies have explicitly examined the role of soil moisture on HW dynamics in Australia. Jones and Trewhin (2000) showed that variations in large-scale soil moisture associated with rainfall changes due to the ENSO can enhance the seasonal predictability of land surface temperatures in Australia. Other studies have focussed on the role of soil moisture on climate variability and shown that it is not possible to capture atmospheric variability over Australia without resolving soil moisture variability (Timbal et al. 2002). Nicholls and Larsen (2011) investigated the effect of long-term droughts on temperature extremes in southeast Australia and showed that daily maximum temperatures are typically 1-3 °C higher after droughts, such as the drought affecting southeast Australia prior to the Black Saturday bushfires. More broadly, Hirsch et al. (2014) have shown that realistic initial soil moisture conditions improves the predictability of maximum temperatures over Australia, especially at short lead times of 16-30 days.

The influence of soil moisture on HW dynamics has been examined elsewhere, especially for the 2003 European summer HWs. For example, Ferranti and Viterbo (2006) conducted simulations over this period and showed that the atmospheric response to large perturbations in soil moisture in the root zone lasted up to 2 months, while perturbations to the whole column increased the magnitude of the atmospheric response and lasted up to 3 months. These responses were larger than comparable ocean boundary forcing, and they hence argued that perturbing initial soil moisture conditions is a valuable tool in generating seasonal forecast ensembles. Fischer et al. (2007) examined a similar issue by perturbing soil moisture conditions leading into the
summer of 2003. They found that without imposing soil moisture anomalies, the European summer heat anomalies would have been reduced by up to 40% in some regions, and identified a positive feedback mechanism between soil moisture, continental scale circulation, and temperature. Specifically, drier soils intensify anticyclone circulation anomalies, leading to higher temperatures. Similar mechanisms are reported by Zampieri et al. (2009) who investigated the role of soil moisture on European HWs (including the 2003 event) and showed that drier soils led to higher emissions of sensible heat and favor upper-air anticyclonic circulations.

Several studies have focused on the influence of soil moisture anomalies on the magnitude of HW events. Lorenz et al. (2010) investigated the influence of soil moisture memory on HW persistence and found that simulations with prescribed soil moisture had lower intrinsic HW persistence as compared to simulations with interactive (freely evolving) soil moisture. These modeling results have also been confirmed by observational studies (Hirschi et al. 2010) of soil moisture-atmosphere feedbacks over southeastern Europe using station observations. Hirschi et al. (2010) also noted that while models correctly simulated the soil moisture-atmosphere feedback, they tend to overestimate this feedback over central Europe. A more recent observational study of the 2003 and 2010 European HWs showed that the increased desiccation of the land surface via the advection of heat from large-scale systems acted to progressively accumulate heat within the atmospheric boundary layer over several days, eventually leading to mega-HW events (Miralles et al. 2014).

Finally, Stéfanon et al. (2012) investigated soil moisture-temperature feedbacks over France between 1989 and 2008 using a regional climate model with two different land surface models, one with dynamic hydrology and able to simulate summer dryness, and the other with a constant high soil moisture and no deficit. They found the response of the atmosphere varied with geography. In coastal areas, drier soils enhanced the sea-breeze circulation, which caused a cooling effect. In mountainous regions, drier soils enhanced sensible heating, which increased convection triggering. This led to more precipitation and a reduction in the temperature anomaly. Finally, over low elevation plains, drier soils led to higher sensible heat flux, lower evapotranspiration and a slight increase in shallow clouds, which led to higher temperatures. Hence, unlike previous studies, this study suggests that local effects play an important role in modulating temperature anomalies.

In summary, a large body of literature on the dynamics of HW events, especially for central Europe (e.g., Fischer et al. 2007; Zampieri et al. 2009; Hirschi et al. 2010; Lorenz et al. 2010; Stéfanon et al. 2012; Miralles et al. 2014) shows that soil moisture-atmosphere interactions are important. Whilst the dynamical meteorology of the Black Saturday bushfires event is well documented (Engel et al. 2013) and the overall large-scale drivers of bushfire weather in Australia have been extensively studied (e.g., Cai et al. 2009; Pezza et al. 2011; Parker et al. 2013; Boschat et al. 2014; Cowan et al. 2014; Marshall et al. 2014; Purich et al. 2014; Parker et al. 2014b), there is a clear knowledge gap on the role of soil moisture-atmosphere feedbacks for Australian HWs and associated bushfire events. This paper aims to address this knowledge gap by focusing on the HW conditions during the Black Saturday bushfires as a case study, with emphasis on the role of soil moisture on the synoptic meteorology of the event.

2. Methods

2.1. Simulations

We used the Weather Research and Forecasting system (WRF) Advanced Research WRF (WRF-ARW) Version 3.5 (Skamarock et al. 2008), driven with 6-hourly boundary conditions from ERA-Interim (Dee et al. 2011) over the Australian domain as specified by the Coordinated Regional Downscaling Experiment (CORDEX, Giorgi et al. 2009), shown in Figure 1 (50 km resolution). We used the same WRF physics setting as Evans and McCabe (2010), which produces a reasonable climatology over southeast Australia, with maximum biases in the mean seasonal temperature and precipitation of approximately ±2°C and -50 to +10 mm month⁻¹ respectively, which were mostly confined to regions of complex topography. The model has also been shown to simulate diurnal rainfall variably over southeast Australia reasonably well (Evans and Westra 2012) and similar results have been reported over Western Australia using the same
WRF physics settings (Kala et al. 2015; Andrys et al. 2015). The control (CNTL) simulation was carried out by initialising the model on the 1st of October 2008, providing a 4-month model-spin prior to the event on the 7th of February 2009. All simulations used the NOAH land surface model (Ek 2003).

To investigate the influence of antecedent soil moisture conditions, simulations were conducted that increased and decreased the soil moisture across all model soil levels, by ±5%, 15%, and 25% percent, at 5, 10, and 15 days lead time to the 7th of the February 2009, using restart files from the CNTL experiment. The initial soil moisture fields at each of these lead times (Figure 2) show a clear soil moisture gradient between the northern tropical region and the rest of the continent, which was mostly dry. The imposed changes in soil moisture therefore acted to reduce or intensify that gradient.

The choice of 5, 10, and 15 days lead time was made since weather forecasts are generally made over these timescales. Our experiments therefore indirectly inform how accurate soil moisture initialisation needs to be, to capture HW events such as the Black Saturday event. While previous studies that have investigated the influence of soil moisture on HWs have restricted the perturbation to soil moisture within the wilting point and field capacity range (e.g., Zampieri et al. 2009), we did not apply such a constraint. This is illustrated in Figure 3 showing the percentage difference in surface soil moisture between the experiments with reduced soil moisture and the wilting point soil moisture, and experiments with increased soil moisture and the field capacity soil moisture, at each of the different lead times. Surface soil moisture for the experiments with reduced soil moisture falls below the wilting point over the centre of the continent (±10%) for all experiments, especially when the largest perturbation of -25% percent is applied. This represents a large perturbation; soil moisture below wilting point implies vegetation cannot transpire but this is not an unrealistic situation over a semi-arid continent such as Australia. Similarly, surface soil moisture for the experiments with increased soil moisture exceeds the field capacity over the northern tropical regions (±10%), especially for the experiments with +25% perturbation. This implies that any excess soil moisture would be lost via surface runoff. Again, this is also not an unrealistic assumption over these regions, particularly during the monsoon season.

2.2. Datasets

We used the Australian Water Availability Project (AWAP) (Jones et al. 2009) gridded temperature and precipitation observations to evaluate the control simulation 2-m maximum temperatures (TMAX) and precipitation. The AWAP dataset has a resolution of 0.05° by 0.05° and is an interpolation from a network of weather stations across Australia, and has been previously used for evaluating regional climate simulations over Australia (Evans and McCabe 2010; Evans et al. 2012; Kala et al. 2015; Andrys et al. 2015). The AWAP data was interpolated to the coarser model grid using simple inverse distance weighting prior to comparisons.

Since this study investigates the influence of soil moisture, we also compared the model-simulated surface soil moisture with estimates from the Advanced Microwave Scattering Radiometer - Earth Observing System (AMSR_E) satellite product. The version of AMSR_E used in this study is described in Liu et al. (2009). While the AMSR_E product has inherent uncertainties, it should provide more realistic estimates of the overall spatial distribution of soil moisture as compared to a model-simulated soil moisture, as the latter strongly depends on accuracy of the model-simulated precipitation and evapotranspiration. Therefore we use the AMSR_E data to examine if the model simulates the overall magnitude and spatial distribution of surface soil moisture.

3. Results

3.1. Model evaluation

We first evaluate the control (CNTL) simulation of TMAX on the 7th of February 2009 along with the 5 day period to the peak of the event (3rd to the 7th of February 2009) since HW-like conditions were observed during the week prior to the event. The simulated TMAX are compared against gridded observations from the AWAP dataset, shown in Figure 4 (a) and (b) respectively. On the most extreme day of the event (7th of February 2009) WRF captures the overall spatial pattern of the HW event well (Fig. 4 (a)). There is a large negative bias in TMAX at the southeast coast of -10°C to -12°C, showing that the model-simulated HW did not
extend as close to the coast as observed, as well as a positive bias of +4°C to +6°C in northeastern Australia. This is also reflected in the simulated TMAX over the 5 days to the peak of the event (Fig. 4 (b)). WRF under-estimates TMAX over the southeast and southwest by a smaller magnitude of -4°C to -8°C, but the overestimation over the northern part of the continent remains unchanged. These biases are considerably larger in magnitude as compared to those reported by Evans and McCabe (2010) (±2°C), who used the same WRF configuration over southeast Australia. However, the biases reported by the latter are for the mean seasonal temperature averaged over 24 years, whereas we focus on the bias in TMAX for one of the mostly significant HW events in history and larger errors are therefore to be expected. Finally, the focus of this paper is on the effects of soil moisture at the continental/synoptic scale and although the biases are large, the overall spatial structure of the simulated HW is satisfactory to warrant further simulations with perturbed soil moisture.

The observed (AWAP) and WRF simulated precipitation from the 1st of December 2008 to the 7th of February 2009 (i.e., summer precipitation prior to the event) and the difference between WRF and AWAP (WRF-AWAP) are shown in Figure 5. WRF under-estimates precipitation over the northern tropics by as much as 15 mm day\(^{-1}\), (corresponding to about 40% to 60% in percentage bias) but elsewhere the precipitation is close to observed. Shown in Figure 6 is a comparison of AMSR\(_E\) derived surface soil moisture, and WRF surface soil moisture over the same period. WRF captures the overall spatial patterns and magnitude of AMSR\(_E\) soil moisture well, although there are some distinct features which are not reproduced by the model. WRF simulates lower soil moisture than the AMSR\(_E\) over the
Figure 3. Percentage difference in surface soil moisture between the experiments with -5, -15, and -25% and the wilting point soil moisture, i.e., \( \frac{(\text{experiment} - \text{wilting point})}{\text{experiment}} \times 100 \) (top panels), and +5, +15, and +25% and field capacity, i.e., \( \frac{(\text{experiment} - \text{field capacity})}{\text{experiment}} \times 100 \), (bottom panels) for (a) 5 days, (b) 10 days, and (c) 15 days lead time to the 7th of February 2009. A positive value for the experiments with reduced soil moisture (top panels) indicates that perturbed soil moisture was higher than the wilting point soil moisture and a negative value for the experiments with increased soil moisture (bottom panels) indicates that the perturbed soil moisture was lower than field capacity.

northern tropics, which can be related to WRF under-estimating precipitation over the same region. There are also large negative differences over Tasmania and the southeast and southwestern coasts. However, these areas are densely vegetated and AMSR_E estimates are likely to be less accurate. WRF generally has higher soil moisture over the center of the continent compared to AMSR_E by about 0.025 m$^3$m$^{-3}$ to 0.075 m$^3$m$^{-3}$. This is within the wilting point soil moisture used within the NOAH...
land surface scheme over Australia, which varies between 0.02 m\(^3\) m\(^{-3}\) and 0.1 m\(^3\) m\(^{-3}\). Overall, the general pattern of WRF simulated soil moisture as compared to AMSR\(_E\) is satisfactory to warrant using the model for further simulations with perturbed soil moisture conditions.

### 3.2. Sensitivity to soil moisture

Figure 7 shows the difference in 2-m maximum temperature (TMAX) between each experiment at the different lead times and the CNTL on the 7th of February 2009 (positive values imply that the experiment is warmer than the control and vice-versa). At 5 days lead time to the 7th of February 2009 (Fig. 7 (a)), decreasing (increasing) initial soil moisture by 25% increases (decreases) TMAX by about 2\(^\circ\)C to 3\(^\circ\)C. While the response of the model to decreased soil moisture is broadly consistent, i.e., decreased soil moisture leads to increased TMAX, there are instances when increasing soil moisture leads to an increase in TMAX. This is especially apparent for the ±25% experiment, which shows regions of both increases and reductions in TMAX over parts of the northern tropics and the southeast for the +25% experiment. We explore these dynamics in more detail later in the manuscript.

At 10 and 15 days lead time (Figures 7 (b) and (c)), a noticeable difference compared to 5 days lead time (Figure 7 (a)) is that the response of TMAX is larger with an increase in soil moisture compared to a decrease. The increase in TMAX with decreased soil moisture is approximately 2\(^\circ\)C to 4\(^\circ\)C, whereas the decrease in TMAX with increased soil moisture is approximately -2\(^\circ\)C to -7\(^\circ\)C. This can be expected over a mostly arid continent such as Australia, as the imposed reduction in soil moisture is essentially making an already dry continent drier, i.e., the ratio of sensible to latent heat is unlikely to change drastically. On the other hand, increasing soil moisture provides a mechanism for increased evaporation and hence a larger influence on the partitioning of available energy into latent heat which would reduce the ratio of sensible to latent heat, providing a mechanism for larger changes in TMAX. This is further explored later in the manuscript.

Another noticeable difference at 10 and 15 days lead time (Figures 7 (b) and (c)) as compared to 5 days (Figure 7 (a)), is that the response of the model to different initial soil moisture is increasingly less linear, especially when initial soil moisture is increased. Increasing soil moisture leads to both increases and decreases in TMAX within different regions of the domain. At 10 days lead time, increasing soil moisture by +5% leads to a decrease in TMAX over the west of the domain, which gradually increases in size as the perturbation is increased to +25%. At the same time, a region of increase in TMAX at the southeast corner of the domain gradually intensifies, which corresponds to the region where the CNTL simulation has the largest bias in TMAX (Figure 4). Interestingly, even at +5%, the increase in TMAX...
Figure 5. Comparison between (a) WRF, (b) AWAP total precipitation (mm day$^{-1}$) from the 1st of December 2008 to the 7th of February 2009, and (c) the differences between WRF and AWAP (WRF-AWAP). Inland masked areas in grey are regions whereby AWAP gridded observations are not available.

covers large parts of the continent. The dynamics behind these unexpected results is further explored later in the manuscript.

At 15 days lead time, increasing soil moisture results in an increase in TMAX to the very north of the domain, which intensifies with increasing perturbation of increasing soil moisture from +5% to +25% (Fig. 7(c), bottom panels). At +5%, this extends over most of the domain but the intensification is restricted to the north. At the same time, there are large regions of decrease in TMAX over the southwest of the domain, especially for the +25% experiment. There are also decreases in TMAX to the east of the domain for the +15% and +25% experiments. Additionally, at 10 and 15 days lead time, the effect of decreasing soil moisture is less linear when the perturbation is small (i.e., there are regions of both increase and decrease in TMAX at -5% and -15%, but mostly only increases in TMAX at -25%). As was shown in Figure 3, it is at -25% that the imposed perturbation falls below the wilting point soil moisture, showing that a relatively large negative perturbation (i.e., decrease) in soil moisture needs to be applied to obtain a consistent increase in TMAX across the domain. Additionally we also note that surface soil moisture was slightly lower south of the northern tropics at 15 days lead time as compared to 5 and 10 days lead time for the CNTL (Fig. 2). Hence relatively small reductions in soil moisture of -5% to -15% applied at 15 days lead time are less likely to show a consistent increase in TMAX on the day of the event across the continent.

To determine whether the changes in TMAX on the 7th of February 2009 shown in Figure 7 could be due to internal model variability, we also show the same differences but averaged from the 3rd to the 7th of February (i.e., the preceding 5 days) in Figure 8. Although the magnitude of the differences is smaller compared to differences on the day of the event (Figure 7), the patterns are similar. At 5 days lead time, the influence of decreasing (increasing) soil moisture is largely linear and results in an increase (decrease) in TMAX. At 10 days lead time (Fig. 8(b)), there is an increase in TMAX over the southeast when soil moisture is increased, similar in pattern to Figure 7(b). At 15 days lead time,
lead time the patterns are not as similar as with 10 days, but both
simulations show regions of increase and decrease in TMAX with
increasing initial soil moisture.

As discussed in the introduction, the main dynamical
atmospheric response of reduced soil moisture leading to
increased temperatures near the surface is an intensification of
upper-level anticyclonic systems (Fischer et al. 2007; Zampieri
et al. 2009). The mechanism proposed in the literature is that the
enhanced sensible heat flux and associated reduced latent cooling
leads to higher tropospheric air temperature which increases
the thickness between the surface and 500 hPa. The enhanced
surface heating due to the intensification of the upper-level
anticyclone can therefore result in a positive feedback mechanism.

To investigate this, we show the daily mean 500 hPa geopotential
height (GPH) and the surface latent ($Q_l$) and sensible ($Q_h$) heat
fluxes for the CNTL on the 7th of February 2009 in Fig. 9, and the
difference between each experiment and the CNTL in Figs. 10 to
12.

Figure 9 (a) shows the presence of the upper-level anticyclone
to the east, covering a large part of the center of the continent,
north of the upper-level cyclone south of the Great Australian
Bight. There is also a weak upper-level cyclone near Darwin (Fig.
1). The central interior of the continent was mostly dry with latent
heat fluxes close to 0 W m$^{-2}$ (Fig. 9 (b)) and sensible heat fluxes
between 100 to 150 W m$^{-2}$ (Fig. 9 (c)). Elsewhere, over the
northern tropics, along the southeast Australian coast and central
Western Australia, latent heat fluxes were between 100 to 150
W m$^{-2}$ reflecting the average precipitation pattern (Fig. 5 (a)).

At 5 days lead time, there is a gradual increase in the 500 hPa GPH over the center of the continent as soil moisture is
decreased from -5% to -25% (Fig. 10 (a), top panels), showing an
intensification of the upper-level high. The opposite is true for the
experiments with increased soil moisture and this can explain the
overall increase (decrease) in TMAX with decreased (increased)
soil moisture (Fig. 7 (a)). The increase (decrease) in 500 hPa GPH
over the center of the continent is accompanied by a decrease

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Figure 7. Difference in maximum 2 m temperature (TMAX) on the 7th of February 2009, between each experiment and the control (experiment-CNTL) started at (a) 5 days, (b) 10 days, and (c) 15 days lead time. Positive values indicate that the experiment was warmer than the control (CNTL) simulation.

(increase) in the 500 hPa GPH to the north of the continent near Darwin (Fig. 1) especially noticeable for the -25% experiment (Fig. 10 (a), top right panel (-25%-CNTL)). This can explain the decrease (increase) in TMAX with decreased (increased) soil moisture (Fig. 7 (a)) over this region (Fig. 7). There is also a gradual increase (decrease) in 500 hPa GPH over the ocean to the northeast of the continent and additionally, the experiments with increasing soil moisture also show an increase in 500 hPa GPH south of the Great Australian Bight (Fig. 10 (a), bottom panels).

These changes in 500 hPa GPH over the ocean indicate that perturbing soil moisture over land not only influences the upper-level anticyclone over the continent, but this in turn influences the surrounding upper-level cyclonic systems. This “dipole-like” effect in the 500 hPa GPH has also been found by Fischer et al. (2007), especially when soil moisture in increased (see Fig. 8(c) of Fischer et al. (2007)).

To understand the drivers of the changes in the 500 hPa GPH, we examined the changes in the surface heat fluxes as shown in
Figure 8. Same as in Figure 7, except averaged between the 3rd and the 7th of February 2009 (i.e., mean over the 5 day period to the peak of the event).

Figure 9. (a) Mean 500 hPa geopotential height (GPH, m), (b) surface latent heat flux ($Q_{le}$, W m$^{-2}$), and (c) surface sensible heat flux ($Q_{hs}$, W m$^{-2}$) for the control (CNTL) simulation on the 7th of February 2009.
Figs. 11 (a) and 12 (a). Over the land, decreasing (increasing) soil moisture results in a decrease (increase) in $Q_{le}$ (Fig. 11 (a)) and broadly, an increase (decrease) in $Q_{h}$ (Fig. 12 (a)). We note that there are small regions of decrease (increase) in $Q_{h}$ with decreased (increased) soil moisture, especially when soil moisture is perturbed by a small amount. This can be expected as a relatively small perturbation is less likely to have a persistent effect after 5 days. Overall, the response is consistent and can partly explain the increase (decrease) in 500 hPa GPH over the centre of the continent with decreasing (increasing) soil moisture, consistent with the literature. Over the oceans, there is an increase (decrease) in $Q_{le}$ north of Darwin with decreasing (increasing) soil moisture which corresponds to the intensification (weakening) of the upper-level cyclone over this region (Fig 9), and vice-versa to the northeast of the continent. These changes in $Q_{le}$ over the ocean are driven by, rather than drive the changes in 500 hPa above. This is a result of the “dipole-like” changes in 500 hPa GPH previously discussed.
At 10 days lead time, decreasing initial soil moisture (Fig. 10 (b), top panels) has a similar influence to 5 days lead time (Fig. 10 (a), top panels) with the increase in 500 hPa GPH over the center of the continent and decrease over the Great Australian Bight and northern tropics being more pronounced for 10 days lead time as compared to 5 days lead time. The experiments with increased soil moisture (Fig. 10 (b), bottom panels) also show a similar but stronger increase in 500 hPa GPH over the Great Australian Bight as compared to 5 days lead time (Fig. 10 (a), bottom panels) but the decrease in 500 hPa GPH over the center of the continent is markedly different. Whilst at 5 days lead time, the decrease in 500 hPa GPH is mostly centered over the central southern part of the continent (Fig. 10 (a), bottom panels) at 10 days lead time, the decrease in 500 hPa GPH is almost identical for the +5% and +10% experiments, but markedly intensifies with increasing soil moisture for the +25% experiment from the southwestern part of the continent (Fig. 10 (b), bottom panels). As a result, the increase in 500 hPa GPH over the northern part of the continent is markedly different.
continent (Fig 10 (a), bottom panels) extends further south (Fig 10 (b), bottom panels) at 10 days lead time. This can partly explain the changes in TMAX at 10 days lead time for increasing soil moisture (Fig. 7 (b), bottom panels) which showed the decrease in TMAX gradually intensifying from the west-to-southwestern side of the continent and an increase in TMAX over the southeast and central eastern part of the continent. This pattern of increase in 500 hPa GPH to the east and decrease from the west (Fig 10 (b), bottom panels) enhanced the advection of warm continental air from the northwest towards the southeast with differences in the 10 m wind speed over the southeast corner of up to 3 m s$^{-1}$ for the +25%-CNTL experiment (not shown).

The changes in $Q_{le}$ (Fig. 11 (b)) over the ocean reflect the changes in 500 hPa GPH (Fig. 10 (b)), with regions of decrease (increase) in 500 hPa GPH showing an increase (decrease) in $Q_{le}$ as expected. Over the land the changes in $Q_{le}$ are broadly consistent with the experiments with decreased (increased) soil moisture showing decreased (increased) $Q_{le}$. The changes in $Q_h$
over land however (Fig. 12 (b)), cannot be related to imposed soil moisture perturbation as there are regions of both increases and decreases across the domain, especially for the experiments with increased soil moisture, showing that the imposed perturbation in soil moisture is essentially “lost” after 10 days. The dynamics behind this is explored later in the manuscript.

At 15 days lead time (Fig. 10 (c)), there is no clear pattern in the differences in GPH as compared to 5 and 10 days lead time irrespective of whether soil moisture is increased or decreased, with some patterns being completely opposite. For example, the influence of decreasing soil moisture from -5% to -25% results in a gradual reduction of the increase in GPH over the center of the continent, and a gradual reduction of the decrease in GPH over the Great Australian Bight (Fig. 10 (c), top panels). The experiments with increasing soil moisture show no clear pattern. These changes in GPH are reflected in the changes in $Q_{le}$ (Fig. 11) over the ocean, and similar to the experiments at 10 days lead time, the changes $Q_h$ (Fig. 12) cannot be related to the imposed perturbation in soil moisture.

To better understand these results, we examined the evolution of surface soil moisture for the 15 days lead time experiment as compared to the CNTL, at 5 days, 10 days lead time, and on the day of the event. The imposed increase in soil moisture at 15 days lead time quickly evaporates such that the sign of the change becomes negative over the northern tropics on the day of the event (not shown). Hence, the sign of the imposed perturbation has been lost within 2 weeks. As was shown in Fig. 3, the imposed increase in soil moisture was within ±10% of the field capacity soil moisture over the northern tropics and any excess soil moisture above field capacity would have been lost via surface runoff.

This is further illustrated by an hourly time series of the difference in soil moisture (Fig. 13) between the experiments and the control (EXPT-CNTL) averaged over the northern tropical region (shown by the brown box in Figure 1), at the different lead times. At 5 and 10 days lead time, the imposed change in soil moisture remains almost constant until the 7th of February 2009 (Fig. 13 (a) and (b), top panels). At 15 days lead time (Fig. 13 (c)), there is a convergence of the difference in soil moisture between the 31st of January and 2nd of February 2009, which is reflected in the change in 2-m temperature (T2). At 5 and 10 days lead time the response of T2 to the soil moisture perturbation is largely linear, whereas at 15 days lead time the response converges to nearly zero between the 31st of January and 2nd of February after which the response has no relation to the imposed initial perturbation. Figure 14 shows the same results but averaged over southeast Australia (shown by the second brown box in Figure 1). The response of T2 to perturbed soil moisture does not vary as smoothly as over the northern tropics (Fig. 13), as the perturbation of soil moisture is smaller over the southeast as compared to the tropics (Fig. 2), but the response at 5 days lead time is broadly consistent (Fig. 14 (a)). At 10 and 15 days lead time (Figs. 14 (b) and (c)), the response of T2 shows little predictability from the imposed perturbation after the 5th and 2nd of February respectively.

We further investigated the mechanisms leading to the lack of predictability over the southeast for the 10 days lead time experiment on the 5th of February. This is illustrated in supplementary Figure S1 showing the 500 hPa GPH from the 3rd to the 6th of February and the difference to the CNTL is shown in Figure S2. The upper-level anticyclone gradually covers most of the continent from the 3rd to the 4th (Fig. S1 (a) and (b)) and intensifies on the 5th, moving eastwards (Fig. S1 (c) and (d)), with the region of highest GPH moving east of the continent on the 7th (Fig. 9 (a)). On the 3rd and the 4th, there is little change in GPH over most of the continent (Figs. S2 (a) and (b)). Between the 5th and the 6th, the increase in GPH to the northeast and decrease over the west for the experiments with increased soil moisture intensifies (Figs. S2 (c) and (d)), eventually leading to the strong gradient in GPH on the 7th (Fig. 10 (b), lower panels). Hence the advection of warm air from the northwest can explain the lack of predictability from the 5th for the 10 days lead time experiment.

The dynamics leading to the lack of predictability for the 15 days lead time experiment around the 2nd of February was different. Between the 31st of January and 3rd of February, a ridge of high pressure parallel to the east coast becomes evident and the upper-level cyclone to the northwest moves towards the southwest (Figure S3). On the 31st of January (Figure S4 (a)), the changes in 500 hPa GPH are mostly confined to the southwest, however, from the 1st to the 3rd of February, there are large reductions in GPH around the southeast coast, especially with the experiments.
with increased soil moisture. After the 3rd, these changes in GPH amplify eventually leading to the large differences shown in Figure 10 (c) on the 7th of February. Hence, for both the 10 and 15 day lead time experiments, a gradual amplification of the changes in the upper-level systems with time, means that the resulting changes in surface meteorology cannot be directly related to the sign of the imposed soil moisture perturbation. Also clearly noticeable in Figure S4 are large changes in the location of the upper-level cyclone to the northwest, especially for the experiments with ±25% soil moisture. Decreasing soil moisture changed the location of the cyclone slightly further north whereas increasing soil moisture moved it slightly further south. Given the known teleconnections between tropical cyclone activity and this HW event (Parker et al. 2013), it is likely that this can also partly explain the lack of predictability seen in our results.

4. Discussion

Our study differs from previous studies that have investigated the influence of soil moisture on HWs elsewhere in that the perturbation to soil moisture is applied relatively close to the event (up to two weeks). This was deliberate; previous studies have typically fixed soil moisture to a constant value, or prescribed a seasonal cycle (Lorenz et al. 2010); perturbed soil moisture up to 2 months prior to the event (Fischer et al. 2007; Zampieri et al. 2009); used different land surface schemes which either resolve hydrology or prescribe consistently high soil moisture (Stéfanon
et al. 2012); or, initialised soil moisture to fixed values across the domain, ranging from very dry to very wet (Ferranti and Viterbo 2006). For our study, we wanted the soil moisture to still have a realistic spatial pattern; so we choose not to use fixed values. The choice of 15 days was to broadly reflect the time frames usually used in numerical weather prediction.

Our results show that WRF is able to reproduce the HW event reasonably well, although the simulated spatial extent of the HW did not reach as close to the southeast coast as observed with large biases of up to -10°C to -12°C over Victoria. There was a relatively large bias in precipitation over the tropics during the summer months preceding the event. However, comparisons of the simulated surface soil moisture with remotely sensed estimates showed reasonably good spatial agreement facilitating further experiments with perturbed initial soil moisture from the control experiment at varying lead times.

At short lead times of 5 days, decreasing (increasing) soil moisture led to an increase (decrease) in maximum temperature, due to an intensification of upper-level highs. This is consistent with earlier literature (Fischer et al. 2007; Zampieri et al. 2009). At longer lead times of 10 and 15 days, the influence of perturbing soil moisture becomes more non-linear, especially when soil moisture is increased rather than reduced. Over a semi-arid continent such as Australia, a reduction in soil moisture essentially makes a dry continent slightly drier, and an increase in soil moisture is likely to be quickly lost via surface evaporation. As a result, over relatively long lead times, the response on the day cannot be easily related to the imposed perturbation 10 to 15 days prior. Nonetheless, we further explored the dynamical reasons leading to the lack of predictability.

At 10 days lead time, we showed that the unexpected increase in TMAX over the center of the continent and the southeast with increase in soil moisture was due to the patterns of 500 hPa GPH leading to the advection of warm continental air from the northwest to the southeast. Hence, even small changes in soil moisture have an influence on upper-level anticyclone and the resulting interactions with surrounding cyclones can result in large changes in the spatial extent of TMAX over the continent. The control simulation showed a negative bias in TMAX over the southeast and an under-estimation of precipitation over the tropics when compared with gridded observations. This translated into an under-estimation of soil moisture over the tropics when compared with remotely sensed estimates. The experiments with higher soil moisture can therefore be regarded as having soil moisture closer to reality. These experiments showed increases in TMAX over southeast, where the CNTL had a large negative bias. Hence, the experiments with increased soil moisture provide a plausible explanation (increased continental warm air advection) for the large under-estimation of TMAX by WRF (CNTL) over the southeast.

For the 15 days lead time experiment, we showed that between the 31st of January and 3rd of February, changes in GPH were large enough to alter a ridge of high pressure on the east coast. These changes amplified such that it was not possible to relate them to the imposed sign of the perturbation in soil moisture. Hence, beyond 10 days lead time, perturbing soil moisture has little impact on the predictability of the event as the changes in the upper-level systems become too large and essentially override the imposed change in soil moisture. This is an important result as it shows that accurate surface soil moisture is critical in the simulating of HW events such as the Black Saturday bushfires, but the predictability of the effect of soil moisture is only possible up to 5 to 10 days prior to the event. Parker et al. (2013) showed strong links between tropical cyclone activity to the northwest and the Black Saturday bushfires, and our results at the 15 day lead time showed a slight shift in the position of the tropical cyclone to the northwest with soil moisture perturbations. Hence this is also likely a contributing factor to the lack of predictability.

The role of soil moisture in determining the predictability of maximum temperatures over Australia has been documented elsewhere. For example, Timbal et al. (2002) ran simulations over Australia with freely evolving soil moisture versus a prescribed climatology, and showed that it is not possible to capture atmospheric variability over Australia without resolving soil moisture variability. Similarly, Hirsch et al. (2014) have shown that realistic initial soil moisture conditions improves the predictability of maximum temperatures over Australia, especially at short lead times of up to 16-30 days. This is consistent with the results presented here. We showed that even slightly different initial (± 5%, ±15%) conditions 15 days in advance of an event...
led to differences in maximum temperatures exceeding 1°C to 2°C. The event considered here was one of the most significant HW events in Australian history; hence our results show higher sensitivity than other studies that have typically focused on seasonal means (Hirsch et al. 2014).

5. Conclusions

The climatology and large-scale drivers of HW events in Australia is well documented, as are future climate projections of HWs over Australia. However, the role of soil moisture on HW dynamics in Australia remains largely unexplored and a large body of literature on HW events elsewhere suggests it plays a key role. We addressed this gap by conducting a series of experiments with perturbed initial soil moisture up to ± 5%, ± 15%, and ± 25%, at 5, 10, and 15 days lead time to one of the most significant bushfires/HW events in southeast Australia, the Black Saturday bushfires. The focus of the paper was on the influence soil moisture perturbations at the synoptic/continental scale.

Our results show that soil moisture has an important role in modulating the intensity of HW events in southeast Australia. We show that the impact of perturbing soil moisture is strongly dependent on lead time to the event. At 5 days lead time, decreasing (increasing) soil moisture, increases (decreases) maximum temperature over most of the continent, via an intensification of upper-level highs. At longer lead times of 10 to 15 days, the imposed perturbation is essentially lost, and the resulting impact on maximum temperature on the day of the event has no predictability as the changes in the upper-level systems become too large. This highlights that accurate initial soil moisture profiles are essential to capturing the severity and spatial occurrence of HWs in southeast Australia. More importantly, soil moisture in the tropics is shown to have a strong influence on HW dynamics in southeast Australia. Hence, whilst HW events in southeast Australia are largely driven at the large scale, soil moisture is critical in modulating their spatial extent and magnitude, but this relationship only predictable at relatively short lead times.

6. Supplementary information

**Figure S1:** Mean daily 500 hPa geopotential height (GPH) from the CNTL experiment, from the 3rd to the 6th of February 2009.

**Figure S2:** Difference in 500 hPa geopotential height between each experiment and the CNTL for the experiment at 10 days lead time, from the 3rd to the 6th of February 2009.

**Figure S3:** Mean daily 500 hPa geopotential height (GPH) from the CNTL experiment, from the 31st of January to the 3rd of February 2009.

**Figure S4:** Difference in 500 hPa geopotential height between each experiment and the CNTL for the experiment at 15 days lead time, from the 31st of January to the 3rd of February 2009.

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