Investigating the Mechanisms of Diurnal Rainfall Variability Using a Regional Climate Model

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ABSTRACT

This study investigates the ability of a regional climate model (RCM) to simulate the diurnal cycle of precipitation over southeast Australia, to provide a basis for understanding the mechanisms that drive diurnal variability. When compared with 195 observation gauges, the RCM tends to simulate too many occurrences and too little intensity for precipitation events at the 3-hourly time scale. However, the overall precipitation amounts are well simulated and the diurnal variability in occurrences and intensities are generally well reproduced, particularly in spring and summer. In terms of precipitation amounts, the RCM overestimated the diurnal cycle during the warmer months but was reasonably accurate during winter. The timing of the maxima and minima was found to match the observed timings well. The spatial pattern of diurnal variability in the Weather Research and Forecasting model outputs was remarkably similar to the observed record, capturing many features of regional variability. The RCM diurnal cycle was dominated by the convective (subgrid scale) precipitation. In the RCM the diurnal cycle of convective precipitation over land corresponds well to atmospheric instability and thermally triggered convection over large areas, and also to the large-scale moisture convergence at 700 hPa along the east coast, with the strongest diurnal cycles present where these three mechanisms are in phase.

1. Introduction

Understanding the nature of precipitation is of significant interest to a variety of stakeholders, who are becoming increasingly reliant on model-derived precipitation data as a supplement to—or substitute for—gauge-based records as the basis for evaluating how precipitation might change under a future climate. Although a combination of data availability and climate model resolution has meant that most of the research emphasis on likely future precipitation patterns has been at aggregated daily or longer (e.g., seasonal/annual) time scales, there is also significant interest in better modeling likely changes at finer temporal and spatial resolutions, down to the time scale of individual storm systems and spatial scale of small- to medium-sized catchments.

The use of climate model-derived projections of sub-daily precipitation requires, in the first instance, a demonstration that the selected modeling system is capable of simulating the relevant physical processes. One set of measures for model evaluation at this time scale is the diurnal cycle, represented in terms of the timing of the daily maximum and minimum average rainfall intensity, the diurnal range, the frequency of precipitation occurrences at various times of the day, and a number of related measures. These measures typically have been reproduced poorly by general circulation models (Collier and Bowman 2004; Dai 2006; Dai and Trenberth 2004; Jeong et al. 2011; Yang and Slingo 2001), with the modeled onset of convective precipitation usually occurring too early in the day and the amplitude of the cycle usually being too high. Shin et al. (2007) furthermore found that the convective scheme and the horizontal resolution of the model had a significant role (see also Lee et al. 2007; Liang et al. 2004; Wang et al. 2007), potentially providing a pathway to model improvement. Recently, several studies examined the capacity of finer resolution models—including...
regional climate models (RCM), cloud-resolving models, and multiscale models—to simulate the diurnal cycle (Pritchard and Somerville 2009; Sato et al. 2009; Wang et al. 2007), with the results typically showing that finer resolution modeling combined with judicious selection of a convective scheme did, indeed, allow for significant improvements in the timing, amplitude, and spatial variability of the diurnal cycle.

As the use of the diurnal cycle as a metric for model evaluation is increasing, so too is our understanding of the complexity of the diurnal cycle itself, with recent studies suggesting that diurnal variability is produced as the interaction of a diversity of precipitation mechanisms, and with observational work also finding significant variability in both space and time. For example, one of the early studies of diurnal rainfall variability at the global scale used 3-hourly weather reports from about 15,000 stations around the globe from 1975 to 1997 (Dai 2001), and found that over most land areas, drizzle and nonshowery precipitation occurs most frequently in the morning around 0600 local solar time (LST), whereas showery precipitation and thunderstorms occur most frequently in the late afternoon. The proposed mechanism for this was a peak in relative humidity (due to a trough in atmospheric temperature and an approximately constant specific humidity) contributing to an early-morning peak in low-intensity precipitation events, whereas solar heating on the ground produces a late-afternoon maximum in convective available potential energy (CAPE) in the atmosphere, which in turn produces concurrent moist convection and showery precipitation. Furthermore, when considering latitudinal variations in the diurnal cycle, it was found that in tropical regions for which convective precipitation represents the dominant precipitation-inducing mechanism, the amplitude of the diurnal cycle is at a maximum, whereas in the higher-latitude regions the diurnal cycle is weaker.

A more recent study using satellite-derived tropical precipitation data from the Tropical Rainfall Measuring Mission (TRMM) dataset (Kikuchi and Wang 2008) from 1998–2006 identified three distinct diurnal cycle regimes—oceanic, continental, and coastal—which were distinguished according to the amplitude, peak time, and phase propagation of the cycle. Consistent with the study by Dai (2001), the continental regime features a large amplitude and an afternoon peak around 1500–1800 LST, whereas the landside coastal regime featured peaks distributed over the period from 1200 to 2100 LST. Although emphasizing that a significant mechanism for the diurnal cycle is solar insolation, thereby accounting for the observed latitudinal and seasonal variability, the study also acknowledged that significant uncertainties remain as to the exact mechanism of the diurnal cycle across continental and coastal regimes. A number of studies (e.g. Garreaud and Wallace 1997; Sorooshian et al. 2002; Takayabu and Kimoto 2008) also noted a propagation of the diurnal cycle of rainfall over land areas (referred to as “diurnal marches”), with daily rainfall maxima usually commencing in coastal regions and propagating inland. Finally, a study by Dai et al. (1999) in the United States using a 31-yr hourly gridded precipitation product from approximately 2500 stations found significant interannual variability in the winter diurnal cycle, which was linked to the influence of the El Niño–Southern Oscillation (ENSO) phenomenon (Dai et al. 1999), suggesting that the strength of the diurnal cycle may itself exhibit substantial variability in time.

This complexity of the diurnal cycle, as described in the aforementioned studies, implies that it would be difficult for a climate model to correctly represent this process without correctly representing a range of key precipitation mechanisms. With this in mind, the study described in this paper commences by examining the capacity of a regional climate model, the Weather Research and Forecasting (WRF) model, to simulate diurnal rainfall variability in a domain located in the southeast of Australia, using a range of measures of the diurnal cycle. The basis for this comparison is a large dataset of gauged subdaily rainfall, which is available at sufficient spatial resolution to provide insights into the role of coastal, orographic, and other geographic factors in determining the nature of diurnal rainfall variability. As we will show, the WRF model reproduces observed diurnal variability reasonably well, enabling us to use the WRF analysis as the basis for a more detailed examination of the possible mechanisms that drive diurnal variability. Specifically, we examine the role of a range of precipitation triggering mechanisms including wind convergence induced by heating over the elevated topography, topographic lifting, land–sea breezes, and tidal variations in pressure, with each of these mechanisms having been postulated previously as potentially influencing diurnal variability (Dai and Deser 1999; Dai and Wang 1999; Liu et al. 2009; Yin et al. 2009; Zaitchik et al. 2007).

The remainder of this paper is structured as follows. In the next section, we provide an overview of the regional climate model that is used for evaluating the possible mechanisms of diurnal rainfall variability. This is followed in section 3 by a description of the gauge-based rainfall data used to evaluate model performance. In section 4, a detailed review of the capacity of the regional climate model to simulate diurnal rainfall variability is provided, commencing with a comparison of the mean diurnal cycle and then moving to an assessment of the spatial signature of diurnal variability. In section 5, a number of potential mechanisms are postulated, with evidence
2. Regional climate model

The Weather Research and Forecasting (WRF) modeling system is developed as a collaborative partnership among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration National Centers for Environmental Prediction (NCEP) and Forecast Systems Laboratory, the U.S. Air Force Weather Agency, the Naval Research Laboratory, the University of Oklahoma, and the U.S. Federal Aviation Administration, as well as the wider research community. The version used in this study is the Advanced Research WRF (ARW), version 3, maintained at NCAR (Skamarock et al. 2008).

WRF was run over southeastern Australia from 1985 through 2008, excluding the first two months of the simulation, which were discarded as model spinup. The model used the following physics schemes: the WRF Single Moment 5-class microphysics scheme, the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme, the Dudhia shortwave radiation scheme, the Monin–Obukhov surface layer similarity, the Noah land surface scheme, the Yonsei University boundary layer scheme, and the Kain–Fritsch cumulus physics scheme. Many combinations of physics parameterizations have been tested over this region (Evans et al. 2012), with this combination being among the better performing. The deep soil temperature was allowed to vary slowly with a 150-day lagged averaging period, while the atmospheric CO2 concentration changed monthly following measurements taken at Baring Head, New Zealand.

The model simulation uses 6-hourly boundary conditions from the NCEP–NCAR reanalysis project (NNRP) (Kalnay et al. 1996) with an outer 50-km-resolution nest and an inner 10-km-resolution nest that covers southeastern Australia (Fig. 1). Both nests used 30 vertical levels spaced closer together in the planetary boundary layer. The sea surface temperature field is derived from the reanalysis and does not contain a diurnal cycle. This simulation has been evaluated extensively at daily and longer time scales and was found to perform well (Evans and McCabe 2010). Further detail on the climatology (including seasonal precipitation and temperature) in this study region can also be found in that paper.

3. Observational data

The observational dataset used in this study comprises a subset of the Australian subdaily precipitation record provided by the Australian Bureau of Meteorology, which has formed the basis of a number of previous studies examining the fine time-scale behavior of Australian precipitation (e.g. Hardwick-Jones et al. 2010; Jakob et al. 2011; Westra and Sisson 2011; Westra et al. 2012). Precipitation data was collected using a combination of Dines pluviographs and tipping-bucket rain gauges (TBRGs), with all data having been digitized and made available at a 6-min time step. More details on the full Australia-wide subdaily record can be found in the aforementioned references.

In total, 195 gauges were selected for this analysis and are shown as black dots in Fig. 1. To ensure consistency with the WRF output, only those stations with records spanning the period from 1985–2008 were used. Furthermore, each of the stations were selected to have less than 15% of the record listed as either “missing” or as an accumulated total over some previous time period, such that the influence of gauging errors is expected to be minimal. Finally, the 6-min data was converted into 3-h rainfall amounts, using the same time step as was used in WRF (i.e., 0100–0400, 0400–0700, ..., 2200–0100 local time).

For consistency with previous studies, the approach to measuring the diurnal cycle described in Dai et al. (1999) was adopted and is summarized briefly here. All analyses were conducted separately for each season with the seasons defined as summer [December–February (DJF)], autumn [March–May (MAM)], winter [June–August (JJA)], and spring [September–November (SON)]. We define a rainfall “occurrence” as a depth of rainfall exceeding 0.1 mm during any given 3-h period,
with results given in subsequent sections representing the seasonally averaged number of occurrences for each 3-h time step. The rainfall intensity was calculated as the average rainfall intensity over each of the 3-h time steps, and once again the seasonally averaged intensity was selected for presentation. Finally, the rainfall amount represents the product of the number of occurrences and average rainfall intensity during each occurrence.

4. Results

Here we compare the diurnal cycle of rainfall recorded at each of the 195 gauges (henceforth referred to as the “observed” record) with the diurnal cycle of WRF modeled outputs (henceforth referred to as the “modeled” record), using the data from the 10 km × 10 km grid box in which the gauge resides. In the following section, we compare the various attributes of the mean diurnal cycle at each of the 195 gauges, whereas in section 4b we focus on the spatial pattern of diurnal rainfall variability.

a. Seasonal-mean diurnal cycle in east Australia

1) RAINFALL OCCURRENCES

The seasonally averaged number of rainfall occurrences for each 3-h period is presented in Fig. 2 for each season of the year. Here, as well as for the results of Figs. 3–5 described below, the WRF averages were calculated using the data only from grid cells directly overlying the rainfall gauging stations to ensure that the observational and modeled results were comparable.

![Figure 2: Comparison of rainfall occurrence statistics between observations (black) and WRF model output (gray). The results are presented as the seasonal average number of occurrences in each 3-h block, using a simple arithmetic mean over the 195 gauge locations.](image-url)
point measurements for the observed record, it is unlikely that this would wholly account for this discrepancy. Indeed, previous studies of climate models (Stephens et al. 2010; Sun et al. 2006) have consistently found that they overestimate the frequency and underestimate the intensity of rainfall events. Sun et al. (2006), in particular, attributes much of this discrepancy to the convective parameterizations being too easily triggered, and this appears to be the case with the Kain–Fritsch convection scheme (Kain 2004; Kain and Fritsch 1990) used here.

In this paper we are more interested in the diurnal variability of observed and modeled rainfall, rather than the absolute number of occurrences. We therefore rescaled the data as a fraction of the total number of occurrences, with the situation in which the rainfall is distributed evenly throughout each of the time steps (i.e., no diurnal cycle) expected to show a constant fraction of $\frac{1}{8} = 0.125$ for each of the eight periods. The results, presented in Fig. 3, enable the diurnal cycle to be distinguished much more clearly compared to Fig. 2. Considering first the observed record, it is apparent that the strongest diurnal cycle occurs in spring and summer with the wettest period (1600–1900) in both seasons having approximately 50% more occurrences than the driest period (0700–1000). Although the amplitude of the diurnal cycle is somewhat lower for autumn and winter with only about 27% more occurrences during the maximum compared to the minimum period, the general pattern is the same, except now the period with the lowest number of occurrences is slightly later in the day (1000–1300). Note that, here and in the remainder of this paper, all times are given as the local time.

Comparing these results with the output from WRF, it can be seen that the model performs well in simulating the
diurnal cycle for spring and summer except for a slight overestimation of rainfall occurrences in the morning when the observed diurnal cycle is at its minima. The diurnal range is slightly lower than the observed record, with the maxima being about 40% greater than the minima during both seasons. In contrast, WRF does a less satisfactory job at simulating the diurnal cycle for autumn and winter with the amplitude of the cycle significantly undersimulated. Nevertheless WRF still captures the correct timing of the peak at 1600–1900, although the modeled record only has 17% more occurrences in the wettest period compared to the driest period.

Another approach for comparing the observed and WRF diurnal cycle is to evaluate the percentage of locations for which the peak and trough of the diurnal cycle occurred at the same time. This was achieved by extracting the time of day for the maximum and minimum number of occurrences for each of the 195 stations, and then repeating for the WRF results at the grid box overlaying the rain gauge location. Considering first the maxima in summer, we found that for 45% of the stations the maxima occurred in the same time period, whereas for a further 35% of the stations the maxima occurred within one time period either side of the observed maxima. Interestingly, of the remaining 20% of locations where the maxima of the observed and modeled record were more than a single time period apart, the vast majority were within about 50 km of the coast, suggesting potential difficulties in simulating coastal precipitation. In contrast, only 26% of stations had the minima occur in the same time increment, with a further 36% of stations having the minima occur within one time period either side of the observed minima. Considering the remaining seasons, the performance of the WRF results for spring was almost identical to the summer results, whereas for the autumn and winter fewer stations had the maxima or minima occur at the same time for the observed and modeled records. This is most likely due to the smaller amplitude of the cycle for autumn and winter.

2) RAINFALL INTENSITY

We next consider the mean intensity of rainfall, with results presented in Fig. 4. In contrast to the occurrence statistics for which WRF oversimulates the probability of rainfall occurrence, here the results show that WRF is undersimulating the rainfall intensity. This might once again be partially attributed to the difference between point observed data and gridded modeled data, but this does not fully account for the discrepancy. Previous studies found this to be a common problem with climate models (e.g. Jeong et al. 2011; Stephens et al. 2010; Sun et al. 2006). As with occurrences, however, our interest is not with the absolute values of precipitation intensity but with its diurnal variability, and comparing point-based observations and gridded modeled output at the 10 km × 10 km resolution is not expected to have a significant bearing on such an analysis.

Examining the diurnal features of rainfall intensity, it can be seen that the observational record peaks at 1300–1600 or 1600–1900, with the greatest amplitude being for the spring and summer and substantially lower amplitude for autumn and winter. The WRF results show a similar pattern, except that typically the maximum intensity is more apparent for the 1600–1900 period suggesting a simulated diurnal maximum slightly later in the day. The minima for the observed and modeled record generally occur in the 0700–1000 period.

In this case the amplitude of the diurnal cycle for the modeled record is greater than for the observed record, with the maxima in summer being 80% and 51% greater than the minima for the modeled and observed record, respectively. Similar results were found for spring, whereas in winter the maxima were only about 20% greater for both the modeled and observed records.

When comparing the timing of the maxima between the observations and modeled outputs, it was found that 30% of the gauge locations had the maxima occur during the same 3-h period, with a further 44% of stations having the modeled maxima occurring within one time period from the observed maxima. Similarly, it was found that 26% of the gauge locations had the minima occur in the same 3-h period, with a further 45% of stations having the modeled minima occur within one period from the observed minima.

3) RAINFALL AMOUNT

Finally, we evaluate the total amounts of rainfall for each season, being the product of the number of rainfall occurrences and the average rainfall intensity per occurrence. These results are presented in Fig. 5. It is apparent that the significant overestimation in occurrences and underestimation in intensity cancels out to a large extent for the total rainfall amounts, with only a slight overestimation of the WRF outputs compared to observations. There is a clear diurnal cycle apparent for both the observations and WRF outputs, with a distinct maxima occurring for both observed and modeled records at 1600–1900.

The amplitude of the rainfall amount is much higher compared with either occurrences or intensity, reflecting the fact that rainfall occurs more often, with higher intensity, in the late afternoon. In fact, the maximum rainfall amount during summer are 139% and 201% greater than the minimum amount for the observed and modeled record, respectively, while for winter the
differences are 35% and 38%. The amplitude of the remaining seasons was found to be between these extremes with WRF generally having stronger diurnal variability compared to the observations.

The timing of the maxima for amounts is found to be much better than the timing for occurrences and intensity, with 55% of locations having the maxima occur in the same time period, and a further 34% of stations having the WRF modeled maxima being within one time period from the observed maxima. The timing of the minima was generally worse, with 34% of locations having the minima occur at the same time, and a further 39% of locations having the minima occur within a single time step. This is likely due to the fact that the timing of the minima is less distinct than the timing of the maxima in Fig. 5.

b. Diurnal cycle in the regional climate model

The seasonal diurnal cycle produced by the RCM is shown in Figs. 6 and 7. The diurnal time of the precipitation maxima and its strength relative to the precipitation produced throughout the day is shown in Fig. 6. The timing of the maxima is given by the hue of the color such that dark blue indicates that the maximum 3-hourly rain fell between 1300 and 1600. The strength of this maximum is indicated by the saturation/intensity of the color such that the darkest colors indicate that more than 40% of the daily rain fell in the maximum 3-h period while

### Fig. 4. Comparison of rainfall intensity statistics between observations (black) and WRF model output (gray). The histogram depicts the mean intensity (mm h⁻¹) over the 3-h period, averaged over each season.
gray indicates that less than 15% fell in the maximum 3-h period. Note that a uniform distribution through the day would mean 12.5% falls in every 3-h period.

Several features of the diurnal cycle are clear in the model simulation from this figure. The diurnal maximum is stronger in summer (DJF) than winter (JJA). The land generally has a stronger diurnal maximum than the ocean, which may be related to the sea surface temperature having no explicit diurnal cycle in the model. The high country along the Great Dividing Range and land near the coast tends to have a stronger diurnal maximum compared to farther inland or right at the coast. For most of the land, in summer and in the transition seasons the diurnal maximum occurs in the early afternoon (1300–1600) with some areas having maxima just before or after this period. In winter the maxima are much smaller and tend to be scattered throughout the day.

The oceans present a very different diurnal cycle with little to no maximum occurring during spring and winter, while in autumn and summer the maxima tend to occur during the night and early morning. This different timing of the diurnal cycle over the ocean has been found in observational studies using the Tropical Rainfall Measuring Mission satellite (e.g. Biasutti et al. 2012; Hirose et al. 2008; Nesbitt and Zipser 2003). It is also worth noting that a small section of the coast in the southwest of the domain (around Adelaide) tends to have an early morning maximum in summer and the transition seasons, which is unlike the rest of the domain.

**FIG. 5.** Comparison of rainfall amount statistics between observations (black) and WRF model output (gray). The histogram depicts the average total rainfall amount (mm) over each 3-h period for each season.
The colored circles in Figs. 6 and 7 indicate the maximum and minimum 3-hourly precipitation observed at rainfall gauging stations. Figure 6 shows that the RCM tends to agree well with observations when a strong maximum is present. In summer the spatial distribution of the timing and intensity of the maximum is captured quite well, even capturing the unique diurnal timing present around Adelaide. In spring the RCM performs almost as well as summer though it consistently places the maximum slightly later in the day than is observed around Melbourne. In autumn and winter, when the maximums become weaker, the correspondence in timing between the RCM and the observations also weakens.

Figure 7 shows the corresponding information for the timing and size of the 3-hourly precipitation minima. Some similar features to those identified for the maxima are also present for the minima. The summer has the strongest minima and winter has the weakest. The land and ocean display distinctly different behavior in terms of the timing of the minima. The minima on land tends to occur late at night or in the early morning, while over the ocean it tends to occur from the middle of the day through to the early evening. The timing of the minimum over land is more variable than the timing of the maximum. The RCM tends to do a good job capturing the observed timing when the minimum is strong (summer) and has more difficulty when the minimum is weak (winter). Again, it is worth noting that the RCM is able to simulate the unique timing around Adelaide in summer.
5. Diurnal cycle in precipitation triggering mechanisms

A number of physical mechanisms have been investigated to explain the diurnal cycles found in precipitation in various locations around the world. These include wind convergence induced by heating over the elevated topography, topographic lifting, land–sea breezes, and tidal variations in pressure (Dai and Deser 1999; Dai and Wang 1999; Liu et al. 2009; Yin et al. 2009; Zaitchik et al. 2007). Using the output from our RCM allows investigation of the diurnal nature of a number of precipitation triggering mechanisms that may relate to the diurnal precipitation. While this analysis cannot determine cause and effect, it does highlight the likely mechanisms involved in the diurnal nature of the precipitation.

In the RCM, precipitation is produced either by the cumulus parameterization, hereafter referred to as convective, or by the microphysics scheme, referred to as nonconvective. The following discussion focuses on summer, as this is when the strongest diurnal effects are present in both observations and model. Figure 8a shows the diurnal maximum in the nonconvective precipitation. Strong similarities can be seen between this figure and the DJF part of Fig. 6. Over land the convective
precipitation maximum tends to occur in the afternoon with some locations occurring just before or after this period. A large stretch of the east coast has a maximum around midday which is confined to the coastal low-lands. As noted for Fig. 6 the strongest diurnal maxima exist in the high country along the Great Dividing Range and the coastal land to the east. The timing of the convective maxima over the ocean is very different, tending to occur at night or in the early morning, though off the southeast coast it occurs consistently in the early evening.

Comparing DJF in Figs. 8a,b with Fig. 6, it can be seen that the convective precipitation dominates the total precipitation diurnal maximum timing and intensity. This does not imply that most of the precipitation that falls is convective in nature, as shown in Fig. 8c. Figure 8c shows the proportion of the total 3-hourly maximum precipitation that is convective in nature. Over the eastern part of the land and most of the ocean less than 30% of the total precipitation is convective in nature, while to the west as much as 90% is convective. Comparing Figs. 8b and 8c shows that, where convection dominates the precipitation, it has only a weak diurnal cycle and, where the convection has a strong diurnal cycle, it accounts for only a small proportion of the total precipitation. The regions with the strongest diurnal maxima seen in DJF in Fig. 6 have most of the precipitation produced through nonconvective means and a relatively small amount of precipitation produced through convective means. Thus, it is the strength of the diurnal cycle of convective precipitation, not the proportion of the day’s rainfall that is convective, which appears to be most important in determining the strength of the diurnal cycle. To understand the causes of the observed diurnal variations, it is therefore necessary to understand mechanisms driving this convective precipitation diurnal variation.

**a. Precipitation triggering mechanism definitions**

The cumulus scheme used in this simulation is the Kain–Fritsch scheme (Kain 2004; Kain and Fritsch 1990). It is triggered when low-level air parcels are buoyant at their lifting condensation level. This can be caused by a wide variety of processes, some of which are investigated here through diurnal variations in related indices. The indices, some of which have been used in previous investigations (Evans 2010; Evans et al. 2004), are defined below. In each case the mechanism indicator is calculated every 3 h and then combined to produce mean seasonal diurnal cycles. It is worth noting that these are not necessarily independent processes and may, in fact, work in unison to trigger diurnal precipitation.

1) **Atmospheric Instability (MCAPE)**

This can be caused in a number of ways including thermally (heating of surface) and the mixing of air masses. It can be measured using the (maximum) convective available potential energy (MCAPE), calculated for the air parcel with the maximum equivalent potential temperature (Colman 1990). MCAPE is a measure of the amount of energy this parcel of air would have if lifted a certain distance vertically through the atmosphere. The higher MCAPE is, the more energy is available to be used in convection. While atmospheric instability and the buoyancy of low-level air parcels are related, it is often the cause of this instability that is of most interest.

2) **Thermal Convection ($\varphi$)**

The buoyancy of air parcels can be increased by adding energy (heat) to the lowest atmospheric levels. This can be due to direct heating of the air due to a hot land (or sea) surface, or energy may also be transferred as water vapor evaporated from the surface. To capture this effect an index is calculated as the difference between the
equivalent potential temperature of a near-surface (lowest sigma level) air parcel $\theta^e$, and the equivalent potential temperature of an air parcel at 500 hPa $\theta^e_{500}$:

$$\varphi = \theta^e - \theta^e_{500}.$$  \hspace{1cm} (1)

Here $\varphi$ is zero when the near-surface potential convective energy, as indicated by $\theta^e$, is equal to the potential convective energy aloft, indicated by $\theta^e_{500}$. If $\varphi$ is positive, then more potential convective energy exists at lower levels indicating potential instability of the atmosphere.

3) **TOPOGRAPHIC LIFTING ($\psi$)**

Adverting an air mass up over topography may allow it to overcome low-level negative buoyancy and trigger convection. This mechanism is quantified using the topographic index $\psi$, defined as

$$\psi = \lambda_{wv} \cdot \nabla h,$$  \hspace{1cm} (2)

where $\lambda_{wv}$ is the flux of water vapor below 100 m, $h$ is the topographic elevation, and $\nabla$ is the gradient function. That is, it is directly related to the vertical distance over which the horizontal vapor flux is forced to flow. The higher this vertical distance or stronger the vapor flux, the more likely a parcel of air is to reach positive buoyancy and begin convecting.

4) **SEA BREEZE**

Coastal contrasts between water (ocean and/or lake) and land surfaces can generate local circulations due to differential heating. These thermally driven systems can produce precipitation if air parcels are forced to rise, perhaps due to incident terrain or instabilities at the sea-breeze front. Sea breezes are a quasi-regular diurnal feature of coastal environments. They characterize have low-level onshore flow with a depth scale of $\sim$500 m, above which a diffuse return flow is found at around 900 hPa (Crosman and Horel 2010; Miller et al. 2003). In this study a sea (or land) breeze is defined when the lowest model atmospheric level ($0.9975 \times$ surface pressure) flows in the opposite direction to the air $\sim$1 km above it ($0.905 \times$ surface pressure). The strength of the sea breeze is given by the magnitude of the low-level wind. The sea breeze is accumulated for each of eight wind directions (north, northeast, . . . ) and the timing of the maximum sea breeze is reported. It is worth noting that the genesis of a sea breeze relies on little to no background wind being present.

5) **LARGE-SCALE MOISTURE CONVERGENCE (CONV700)**

The large-scale circulation may cause regions of moisture convergence that leads to condensation. This causes the release of latent heat that warms the air parcel, creating buoyancy and potentially convection leading to precipitation. While there is no a priori reason to expect this mechanism to vary diurnally, it is explicitly tested by examining the characteristics of convergence at the 700-hPa level.

6) **FRONTAL SYSTEMS ($\delta T$)**

The large-scale motions can also create frontal systems. These are regions of moisture convergence, but they may also trigger convection by lifting one air mass up over another. So frontal system precipitation is likely to be a combination of both convective and nonconvective conditions. We do not expect a diurnal signal in the timing of frontal systems, and weather fronts move across the landscape at all times of day. The presence of a frontal system is diagnosed using the change in the thickness of the 1000–500-hPa layer through time. This gradient is increased in the presence of a weather front.

7) **TIDAL VARIATIONS IN PRESSURE ($\delta P$)**

Diurnal variations in surface pressure are also investigated, as they were found to play an important role in diurnal precipitation elsewhere in the world (e.g. United States; Li and Smith 2010). The seasonally averaged diurnal cycle is calculated and the timing of the minima is investigated as lower surface pressure is more likely to be associated with precipitation.

b. **Mechanism results**

The strength of the diurnal cycle in the various precipitation triggering mechanisms during summer (DJF) is shown in Fig. 9. MCAPE and $\varphi$ both have a preference for an afternoon maximum toward the coast, in agreement with both timing of the convective precipitation maximum and the observed overall precipitation maximum. The thermally driven mechanism ($\varphi$) tends to have a larger diurnal cycle in the western portion of the domain where generally hotter conditions prevail, while the MCAPE diurnal cycle tends to be larger along most of the coastal areas. These differences may be due to the fact that MCAPE is sensitive to the vertical structure of the atmosphere, which can differ substantially between the inland and coastal regions, while $\varphi$ is not. In both cases the diurnal cycle at the coastline itself often has a midday/early afternoon peak, while the peak occurs later in the afternoon farther inland.

On the east coast a similar pattern can be seen in the convergence at 700 hPa. Overall the diurnal cycle is relatively weak in the convergence; however, there is a clear midday/early afternoon peak along much of the east coast, with a later peak farther inland. That this
region of afternoon maxima in convergence is confined to the coastal land east of the Great Dividing Range suggests that it may be related to the diurnally regular movement of a sea-breeze front through the area. Focusing on the sea breeze measure, the same section of coast has a midday/early afternoon peak that is associated with low-level easterly to northeasterly winds. Some of the strongest midday sea breeze winds are found on the southeast coast. These sea breezes tend to have a strong easterly component in the low-level wind, limiting the inland movement of any sea-breeze front, and hence any signature in the convergence at 700 hPa. The southwest coast sea breeze is dominantly southeasterly to southerly low-level winds, though the coast near Adelaide experiences the strongest sea breezes during southwesterly flow. Some quite strong sea-breeze-type circulations are also found at night in the mountains. These appear to be associated with the development of low-level cold-air drainage with only weak flow aloft. In this case the low-level wind direction is determined by the downslope direction of the topography.

The measure of frontal systems (\(\delta T\)) and the upslope flow (\(\psi\)) show no or a very weak diurnal cycle, making them unlikely to play any significant role in the observed precipitation diurnal cycle. The diurnal pressure variation is only 1–3 hPa, similar to the observed variation reported in Kong (1995). While such small variations are not likely to trigger precipitation, the minimum pressure over land does consistently occur in the late afternoon. Thus, it may assist other mechanisms that are active at this time.

The presence of a diurnal cycle does not imply a relationship with precipitation. To test for a potential relationship with precipitation the correlation between the mean monthly diurnal cycles of convective precipitation and the precipitation triggering mechanisms was calculated. The three mechanisms that had significant correlations are shown in Fig. 10. Note that this is not testing the general correlation between triggering mechanisms and convective precipitation, but rather the proportion of the diurnal cycles that correlate. For example, the general time series correlation of MCAPE and convective precipitation is significant throughout the domain (not shown), while the diurnal correlation is mostly significant over land and toward the coast. The convergence at 700 hPa also has significant diurnal correlation along the thin coastal strip. Inland the correlations often remain significant but have lower magnitudes.

The diurnal correlation is dominated by the thermal convection index \(\varphi\). This is not surprising as the diurnal cycle is fundamentally driven by the input of thermal...
energy. The region with the largest diurnal cycle in the convective precipitation (Fig. 8b) is the region where these three mechanisms have their highest diurnal correlation and the same afternoon timing for the maximum. Where only one mechanism is significantly correlated or the mechanisms have different timings, only weak diurnal cycles are present.

We note that, while the sea breeze had a relatively strong diurnal cycle, it did not produce a significant diurnal correlation with precipitation. At the coast this can be understood as the strongest sea breezes occur on sunny days when the thermal gradient between land and ocean is the greatest and precipitation is unlikely. In contrast, in the mountains a weak negative correlation exists indicating that precipitation is less likely during periods of cold-air drainage.

6. Conclusions

The objectives of this study are to add to the body of knowledge on the nature of finescale precipitation variability and to evaluate the capacity of WRF in simulating the diurnal variability observed in the historical precipitation record. Like many regional climate modeling projects, one of the intended applications of WRF as applied to southeast Australia is to develop future climate projections of subdaily rainfall, and this study represents a necessary precursor by providing an improved understanding into the key processes that drive such fine time-scale rainfall variability.

The comparison of various metrics of the diurnal cycle between the 195 subdaily rainfall gauges and the WRF modeled outputs showed—with some notable exceptions—that WRF generally did a reasonable job capturing a range of features of diurnal variability. In particular, the following results were found:

1) Although WRF oversimulated the probability of rainfall occurrence, the diurnal variability of occurrences was generally similar to that of the observed records. In particular the diurnal variability of spring and summer rainfall occurrences were found to be similar, whereas WRF undersimulated the amplitude of the diurnal cycle for autumn and winter.

2) The intensity of rainfall per occurrence was found to be undersimulated by WRF, although once again the pattern of diurnal variability was found to be much better than the absolute value of rainfall intensity. The timing of the maximum intensity was found to be in early or late afternoon for both observed and modeled data and was fairly pronounced, whereas the minima was found to occur in the morning and was less pronounced. The amplitude of the modeled data was generally fairly similar to the observed data except in summer where the modeled amplitude was higher.

3) The diurnal cycle was most pronounced for rainfall amounts statistics, with the maxima in summer being 139% and 201% greater than the minima for the observed and modeled records, respectively. Generally WRF oversimulated the amplitude of the diurnal cycle for the warmer seasons but was reasonably...
accurate for the winter season, whereas the timing of the maxima and minima was found to closely approximate the observed records.

4) The spatial pattern of diurnal variability in the WRF outputs was remarkably similar to the observed record, capturing many features of regional variability, such as the increase in the strength of the diurnal cycle along the Great Dividing Range, compared with closer to the coast, and the near-reversal in the diurnal cycle near Adelaide.

The various discrepancies between observational and modeled results are similar to those found in previous studies of climate models (Jeong et al. 2011; Stephens et al. 2010; Sun et al. 2006). In agreement with those studies it is found that the simulation of diurnal variability would be improved if the convective parameterization was more difficult to trigger, allowing the accumulation of potential convective energy that would produce more intense precipitation once released. However, the deficiencies present in the simulation of precipitation occurrences and intensities are compensatory and the strong performance in simulating rainfall amounts allowed us to consider the mechanisms by which the WRF simulated diurnal variability more closely.

The RCM diurnal cycle is dominated by the convective (subgrid scale) precipitation with the large-scale precipitation contributing little to diurnal variability. A sharp distinction is seen between the land and ocean diurnal cycle with the ocean generally having a relatively weak diurnal cycle, with a maximum at night, and the land having a relatively strong diurnal cycle peaking in the afternoon. The RCM simulated diurnal cycle of precipitation over land corresponds well with atmospheric instability (MCAPE) and thermal convection (φ) over large areas, but also with the large-scale moisture convergence at 700 hPa along the east coast. The strongest diurnal cycles are present where these three mechanisms are in phase. The diurnal cycle itself is driven by strong variations in solar energy, so it is not surprising that it is the thermal convection (φ) that has the highest correlations with diurnal precipitation and is likely the dominant forcing mechanism.

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