Diurnal Preconditioning of Subtropical Coastal Convective Storm Environments

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ABSTRACT

Boundary layer evolution in response to diurnal forcing is manifested at the mesobeta and smaller scales of the atmosphere. Because this variability resides on subsynoptic scales, the potential influence upon convective storm environments is often not captured in coarse observational and modeling datasets, particularly for complex physical settings such as coastal regions. A detailed observational analysis of diurnally forced preconditioning for convective storm environments of South East Queensland, Australia (SEQ), during the Coastal Convective Interactions Experiment (2013–15) is presented. The observations used include surface-based measurements, aerological soundings, and dual-polarization Doppler radar. The sea-breeze circulation was found to be the dominant influence; however, profile modification by the coastward advection of the continental boundary layer was found to be an essential mechanism for favorable preconditioning of deep convection. This includes 1) enhanced moisture in the city of Brisbane, potentially due to an urban heat island–enhanced land–sea thermal contrast, 2) significant afternoon warming and moistening above the sea breeze resulting from the advection of the inland convective boundary layer coastward under prevailing westerly flow coupled with the sea-breeze return flow, and 3) substantial variations in near-surface moisture likely associated with topography and land use. For the 27 November 2014 Brisbane hailstorm, which caused damages exceeding $1.5 billion Australian dollars (AUD), the three introduced diurnal preconditioning processes are shown to favor a mesoscale convective environment supportive of large hailstone growth. The hybrid high-precipitation supercell storm mode noted for this event and previous similar events in SEQ is hypothesized to be more sensitive to variations in near-surface and boundary layer instability in contrast to contemporary supercell storms.

1. Introduction

Diurnal forcing of the planetary boundary layer (PBL) air mass is manifested at mesobeta (≤200 km) and smaller spatial scales (Fujita 1986). Radiative heating, cooling, and

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quantifying the influence of CBL processes upon convective storms is a significant challenge and remains the focus of both numerical modeling (e.g., Clark et al. 2012; Sun et al. 2014; Weisman et al. 2015) and observational efforts (e.g., Weckwerth et al. 2004; Wurman et al. 2012).

Under weak synoptic gradients, coastal CBL development is strongly influenced by the prevailing sea-breeze circulation. A coastal setting with substantial relief can induce thermotopographic circulations that influence the inland propagation of the sea breeze (Banta 1995; De Wekker et al. 2012; Muppa et al. 2012). Furthermore, approximately 44% of the global population resides within 150 km of the coastline as urbanization of coastal landscapes continues to increase (United Nations 2010), leading to extensive modification of the environment through land clearing and urban sprawl. High-density metropolitan regions experience significantly warmer surface temperatures than the surrounding rural areas in response to lower albedo, reduced evapotranspiration, and the larger heat storage capacity of the urban landscape (Gartland 2011). Urban heat islands have been documented to interact with numerous atmospheric processes. This includes the sea breeze through earlier onset and stagnation (e.g., Melas et al. 1998; Lemonsu et al. 2006; Freitas et al. 2007), cloud formation (e.g., Tsunematsu and Kai 2004; Schatz and Kucharik 2014), precipitation (e.g., Dixon and Mote 2003; Ryu et al. 2016), and convective initiation (e.g., Rozoff et al. 2003; Shem and Shepherd 2009). Finescale variations in boundary layer moisture and temperature shaped partly by diurnally forced near-surface and PBL variability are also considered important factors for both convective initiation (e.g., Weckwerth 2000; Frye and Mote 2010; Haberlie et al. 2015a) and intensification (e.g., Smith et al. 2000). Quantifying diurnal variability on this scale remains difficult without extensive instrumentation (Weckwerth et al. 2004) or specialized techniques [e.g., radar refractivity gradients; Feng et al. (2016)]. The availability of this information for understanding near-surface thermodynamic conditions benefits both the nowcasting of convective initiation (Koch and Ray 1997; Wilson et al. 1998; Wakimoto and Murphey 2009) and initialization of numerical weather prediction models (Gasperoni et al. 2013; Weisman et al. 2015). In spite of this wealth of observational and numerical studies, further research is required to address the role of boundary layer thermodynamics for convective storms in coastal settings given the sensitivity of the convection to parcel stability.

In this study we present an investigation of the effects of diurnally forced near-surface and PBL variability upon convective storms in South East Queensland (SEQ), Australia (Fig. 1). Land use across SEQ consists of irrigated and dry agriculture in the western inland region, and a rapidly growing urban area that stretches for almost 200 km along the coast with a population of approximately 3.4 million, centered on the capital city of Brisbane (shown in Fig. 1; Queensland Statistician Government’s Office 2015). Bordering the western and southern limits of SEQ are mountain ranges with sub-tropical rain forest above an altitude of 750 m, while a complex coastline of large sand islands and bays extends along the eastern periphery. The diverse physical setting of SEQ is impacted by an average of 22 severe storm days per year (Soderholm et al. 2017), where individual events have resulted in insured losses exceeding $1 billion Australian dollars (AUD; Insurance Council of Australia 2015). The socioeconomic impact of frequent storm activity in SEQ is recognized through ongoing efforts to understand the drivers of deep convective activity (Callaghan 1996; Richter et al. 2014; Peter et al. 2015) and through the Coastal Convective Interaction Experiment (CCIE; Soderholm et al. 2016). As part of the CCIE, climatological investigations by Soderholm et al. (2017) identified an increased frequency of hailstorm development in proximity to the sea-breeze circulation; however, the atmospheric processes by which this intensification occurs remains unresolved.

Observational datasets collected during the CCIE across two warm seasons (November 2013–January 2014 and November 2014–January 2015) are explored by this study to understand and quantify the critical processes that favor frequent convective storms across SEQ. Observational platforms and datasets from CCIE are discussed in section 2. A conceptual model of near-surface and PBL processes is developed through the investigation of multiseason datasets in sections 3 and 4, respectively. These concepts are applied to explore the storm evolution for the 27 November 2014 case study in section 5. A summary and concluding remarks are presented in section 6.

2. Methodology

The Australian Bureau of Meteorology (BoM) maintains a variety of observational platforms across SEQ, including automatic weather stations (AWSs), weather radars, and the Brisbane Airport aerological sounding site. Near-surface observations are obtained from a network of 20 AWSs (see Fig. 1 for locations) situated to minimize local influences (e.g., urban effects, tall vegetation). Out of the 20 AWSs, only 3 are located in proximity to the southwest region of frequent convective initiation and hailstorm development (Soderholm et al. 2017). To fill this observational gap, two additional AWSs were deployed by the University of Queensland for the duration of CCIE (November 2013–January 2015). The Kalbar (KBR) and Grandchester (GCH)
sites (see Fig. 1 for locations) were located adjacent to irrigated and dry pastoral agriculture, respectively, potentially measuring associated local effects. Furthermore, the CCIE wind sensors were positioned at a nonstandard height of 2.5 m, and their measurements are more strongly influenced by surface friction in contrast to BoM wind sensors at 10 m. A further 14 AWSs maintained by the Queensland Government Department of Environmental and Heritage Protection (EHP) were also incorporated into this study to increase spatial resolution. EHP AWSs are operated to monitor local pollution levels within urban, industrial, and mining environments and therefore are more influenced by anthropogenic local effects (e.g., paved surfaces and buildings) in contrast to the BoM sites. Santamouris (2015) proposes that the nonstandard EHP configuration is more suitable for observing the urban heat island due to the dominant thermal contribution of the localized environment.

To assist the spatial interpretation of thermodynamic observations from the BoM, EHP, and CCIE networks (36 sites in total), these datasets were interpolated onto a 0.1° grid at a 6-min interval to provide an automated mesoanalysis. This type of analysis is an important tool for both forecasters and researchers, particularly when identifying the spatial positioning of airmass boundaries (Atkins and Wakimoto 1997; Koch and Ray 1997). Given the sparseness of observations across large areas of SEQ, the bivariate thin-plate spline interpolation technique was implemented to ensure physically realistic near-surface fields (Boer et al. 2001; Tait and Woods 2007). Grid points above 300 m in elevation and those located offshore of SEQ were removed from the interpolated fields because of insufficient observations across these differing surfaces.

Automatic weather stations were also used to identify sea-breeze days across the CCIE using an automated, filter-based approach adapted from Azorin-Molina et al. (2011) for analysis in section 3. Azorin-Molina et al. (2011) noted that this automated method is biased toward true sea breezes and complete diurnal sea–land breeze cycles (opposed to more diffuse sea breezes embedded in stronger gradient flow) and, therefore, produce more conservative results than manual detection. Given the suppression of diurnal processes during stronger synoptic advection, this bias is considered to have a negligible impact upon the analysis of diurnal preconditioning.

To ensure the sea breeze had propagated at least 25 km inland, and to the west of Brisbane, detection was performed at the Archerfield (ACH) AWS (Fig. 1). Information regarding the instrumentation, quality control, and reliability of this site is documented by the Australian Bureau of Meteorology (2015). Furthermore, onshore flow at this site is less affected by topographical forcing in contrast to sites to the west of the Teviot and D’Aguilar coastal ranges. A series of filters was selected and calibrated to detect changes characteristic
of the sea-breeze boundary (associated with wind speed, wind direction, and relative humidity changes) through the analysis of 100 manually identified sea-breeze days between July 1997 and June 2015 [see Soderholm et al. (2016) for algorithm]. Verification of the sea-breeze detection algorithm showed an 80.9% probability of detection and a false alarm rate of 19.4%, using manually identified sea breezes as truth (see section 1 of the electronic supplement to Soderholm et al. 2016). For a subset of sea-breeze events analyzed in section 4, automated detection results were manually verified through the identification of sea-breeze boundary finelines (e.g., Wilson et al. 1994; Sills et al. 2011) observed by the Mount Stapylton weather surveillance radar (Fig. 1).

Aerological sounding datasets were obtained using fixed and mobile instrumentation during CCIE. Daily operational soundings from Brisbane Airport (YBBN) at 0900 Australian eastern standard time (AEST = UTC + 10h) were provided by the BoM in addition to adaptive afternoon releases on anticipated storms days as part of the CCIE on 26 days (15 sea breeze and 11 non–sea breeze). Adaptive soundings were released between 1200 and 1600 AEST, depending on the expected time of storm development. Mobile soundings were conducted during CCIE field days by the University of Queensland at 1200 AEST from KBR in southwest SEQ. In contrast to the coastal location of the Brisbane Airport profiles, soundings at Kalbar provide the opportunity to sample the developing continental CBL in the absence of a sea breeze. Sounding datasets were processed using the Sounding/Hodograph Analysis and Research Program in Python (SHARPpy) package (Halbert et al. 2015).

Radar coverage across the CCIE domain was provided by the Australian Bureau of Meteorology’s CP-2 research radar (Fig. 1). This radar provided dual-frequency (X and S bands) polarimetric capabilities in addition to excellent clear-air sensitivity characteristics (Keenan et al. 2007). CP-2 was operated on a 6-min volume cycle that included two adaptive range–height indicator (RHI) scans on 10 campaign days, 6 of which were sea-breeze days. CP-2 was not operated on all campaign days because of equipment failures and staffing requirements. Prior to storm development, RHIs were collected perpendicular to the sea-breeze boundary (70° azimuth determined from climatological investigation) to observe clear-air reflectivity and Doppler velocity vertical cross sections. Winds within the sea-breeze circulation are mostly perpendicular to the boundary, implying that boundary-normal Doppler radial winds at low-elevation angles approximate the true wind velocity (Wakimoto 1982). Radar datasets were processed using the Python Atmospheric Radiation Measurement (ARM) Radar Toolkit (py-ART) package (Helmus and Collis 2016).

3. Near-surface environment

a. Transect analysis

To compare the cross-coastline environment during sea-breeze and non-sea-breeze conditions, transects of warm season mean temperature, dewpoint, and wind speed were constructed. Both CCIE and BoM AWSs are utilized to cover a geodesic distance of 133 km (dash–dot line in Fig. 1). This transect extends from the southwest region of frequent hailstorm initiation (KBR and GCH sites), through to the densely populated coastal plains [Amberley (AMB), ACH, and Brisbane City (BNE) sites] and across the coastline to the maritime climate of an offshore sand island [Brisbane Airport (YBBN) and Cape Moreton Lighthouse (CML)], providing a comparison of the diverse near-surface environments of SEQ.

Temperature, dewpoint, and wind speed values at 1200 AEST were obtained for sites along the transect during warm season months (October–March) between November 2013 and January 2015. Mean values for days when the sea breeze (northeast flow) was detected and not detected are shown in Figs. 2a and 2b, respectively. Lower wind speeds and higher mean 2-m temperature across the inland portion of the transect are more apparent for sea-breeze days, which is indicative of a stronger land–sea thermal contrast. This thermal contrast is strongest between YBBN and BNE, particularly for sea-breeze days when weaker synoptic flow permits warming of air over land to remain closer to the coast. The dewpoint gradient between Brisbane Airport and Brisbane remained comparable regardless of sea-breeze presence.

The most common arrival time for the sea breeze at Archerfield was 1330 AEST (Soderholm et al. 2017), indicating that most of the inland section of the 1200 AEST transect represents a warming continental air mass. For this inland segment, the Amberley site recorded both the warmest mean temperature and the lowest mean dewpoint (<16°C) regardless of sea-breeze presence. Comparison with the nearest rural BoM site [Gatton (GAT)] shows that near-surface moisture at Amberley mixes out earlier (Fig. 3), contributing to the lower dewpoint observations at 1200 AEST. This earlier mixing of near-surface moisture may be a result of enhanced local heating from dry pastoral land and a large air force base in proximity to the Amberley AWS. Farther inland, mean near-surface moisture increases to levels comparable with Brisbane Airport (~18°C), particularly for Kalbar on sea-breeze days, while the mean temperature decreases. Extensive irrigated agriculture
surrounding the Kalbar site (Fig. 1) likely favors latent over sensible heat fluxes in comparison to nonirrigated sites (Clark and Arritt 1995), leading to higher dewpoints throughout the diurnal cycle (Fig. 3). Kalbar also experiences the lowest 1200 AEST wind speeds for the transect, possibly as a result of elevated topography surrounding the region to the west (800–1200 m), south (600–1200 m), and east (300–500 m). This topographical “block” may contribute to the enhanced dewpoints through reduced advection of near-surface moisture away from the area. Low wind speeds are also observed at Brisbane despite its exposure to onshore flow, presumably because of the higher surface friction of the city landscape (Dandou et al. 2009).

b. Urban heat island intensity

City landscapes modify the local atmosphere through the UHI effect, where the intensity of the temperature anomaly varies as a function of the urban landscape, physical setting, and meteorological environment (Santamouris 2015). To quantify the UHI intensity for Brisbane, the temperature difference of four AWS sites situated in the city from the mean of three AWSs in nearby rural settings (at a comparable distance from the coastline) were calculated using 0900 AEST observations, prior to sea-breeze onset (Fig. 4). City AWSs consisted of one BoM site (Brisbane) located in a lower-density suburban environment and three EHP sites—South Brisbane (SBNE), Woolloongabba (WLG), and Central Brisbane (CBNE)—located in higher-density urban settings (e.g., major highways and inner city). The proximity of the EHP sites to local urban effects leads to significantly (two-sample $t$ test at 99% level) warmer temperatures (median difference of 1.5°C–2.7°C) than the BoM city site. The three baseline rural sites of Nambour (NMB), Beerburrum (BER), and Logan (LGN) were selected to be approximately the same distance from the coastline as Brisbane City (15–20 km), thus minimizing the differences due to the land–sea boundary. Temperature distributions among the three rural sites are consistent, with no significant difference (two-sample $t$ test...
at 99% level) between their median 0900 AEST values (~25°C, not shown), thus providing a robust measure of the ambient environment. The rural baseline temperature was found to be 0.7°C cooler than the BoM city site and 2.1°–2.9°C cooler than the EHP city sites (median difference), which we take to signify the intensity of the Brisbane UHI prior to sea-breeze modification. The highest median difference and variability occurred at the central Brisbane site, likely a result of the dense urban environment of the inner city.

The intensity of the 0900 AEST warm season Brisbane UHI is comparable to the average daily UHI intensity (difference between city and nearby rural temperature) for the Australian coastal cities (Melbourne, ~2.7°C; Sydney, ~3.5°C) and internationally [e.g., Osaka, Japan, ~3.1°C; Incheon, South Korea, ~2.5°C; Santamouris (2015)]. Simulations of the Brisbane UHI by Khan and Simpson (2001) showed that anthropogenic heat flux contributed approximately 1.1°C during midmorning (0900 AEST) and up to 4.5°C at night. The authors also noted that the simulated Brisbane UHI can substantially modify the local wind field in mesoscale model simulations. In addition to increased surface friction and enhanced aerosol release, the effect of the Brisbane city UHI must be considered a potential influence upon convective preconditioning of the city PBL through increased near-surface parcel buoyancy.

c. Spatial mesoanalysis

To explore the spatial extent of characteristics identified by the transect and UHI analyses, mesoanalysis of mean warm season (October–March) conditions during the CCIE (November 2013–January 2015) at 1200 and 1500 AEST on sea-breeze (Figs. 5a,c) and non-sea-breeze days (Figs. 5b,d) are shown. Additionally, derived equivalent potential temperature $\theta_e$ is included for comparison of near-surface parcel stability. In agreement with the transect analysis, sea-breeze days are clearly the highest-energy environments, with a southwest SEQ $\theta_e$ maximum exceeding 336 K at 1200 AEST (Fig. 5a). A secondary $\theta_e$ maximum centered over Brisbane appears to be a result of maritime moisture (16°C dewpoint contour) displaced an additional 15–25 km inland compared to other coastal locations, and particularly warm near-surface temperatures (29°C) over the city. Previous modeling studies have shown that this increased maritime flow is attributed to UHI modification of sea-breeze forcing in locations including Brisbane (Khan and Simpson 2001), Tokyo, Japan (Kusaka et al. 2000), and São Paulo, Brazil (Freitas et al. 2007). The UHI-enhanced land–sea temperature gradient leads to a faster propagation speed and therefore the earlier arrival of the sea breeze, increasing moisture levels across the city environment. Alternatively, increased moisture levels may be attributed to increased irrigation within the urban environment, or the close proximity of the city stations to the Brisbane River (700 m or less).

Between 1200 and 1500 AEST (Fig. 5c), moisture (16°C dewpoint contour) builds more rapidly over rural coastal areas in contrast to areas west of Brisbane. Modeling studies suggest this may be related to increased friction from the urban canopy (Gedzelman et al. 2003; Dandou et al. 2009) or interactions with the UHI circulation (Freitas et al. 2007), stagnating the flow of the sea breeze inland of the city and possibly displacing the UHI downwind. Evidence of these processes in the mesoanalysis is less apparent because of sparse observations west of the city. The arrival of the sea breeze also appears to suppress further warming (and $\theta_e$ increase) over Brisbane between 1200 and 1500 AEST in contrast to rural areas, where $\theta_e$ increased notably in response to the afternoon arrival of the sea breeze. On non-sea-breeze days the cross-coastal surface temperature gradient is weaker, leading to comparatively low $\theta_e$ values across the coastal environment. Inland of the coast, an axis of warmer, comparatively drier air resides to the west of the D’Aguilar and Teviot ranges on both sea-breeze and non-sea-breeze days at 1200 AEST (see Fig. 1 for locations). Dry pastoral agriculture through this region may promote early and deep CBL development through increased sensible heating in contrast to irrigated areas (cf. Amberley
observations discussed in section 3a). In southwest SEQ, a region of enhanced $\theta_e$ is evident on sea-breeze days in response to near-surface moisture, most likely because of stronger latent heat fluxes from the irrigated land surrounding the Kalbar site (Figs. 5a,c). Cooler temperatures on non-sea-breeze days account for a reduced $\theta_e$ maximum in this area (Figs. 5b,d). For northwest SEQ, analysis is limited by a lack of AWS observations across the region.

4. Planetary boundary layer

Small-scale changes in near-surface and CBL conditions have been shown to significantly influence both the initiation (e.g., Weckwerth 2000; Wakimoto and Murphey 2009) and development of existing convective storms (Smith et al. 2000). However, the representativeness of near-surface observations is limited in the absence of a well-mixed boundary layer (Mueller et al. 1993; Weckwerth et al. 1996). Furthermore, even for storms that are considered surface based, the inflow layer may extend well above the surface (Thompson et al. 2007). Therefore, the careful consideration of the entire PBL depth is required for understanding the influence of near-surface conditions on deep moist convection, particularly in the presence of a sea breeze.

a. Sea-breeze structure

Six sea-breeze days were observed by CP-2 radar during the 2014–15 CCIE campaign, providing an opportunity to

![Figure 5](image-url)
explore the clear-air structure (Fig. 6). A fixed azimuth of 70° was used for all RHI scans (dashed line segment in Fig. 1), with onshore east-northeast flow shown as negative radial velocities (blue shading) and the west-southwest flow aloft as positive radial velocities (red shading). Vertical cross sections were selected at times after the passage of the sea-breeze boundary at the radar site to sample an approximately steady state of the circulation. Despite these efforts, Kelvin–Helmholtz waves between the onshore and elevated offshore flow can be seen in half of the cases (Figs. 6a,c,e), likely resulting from shear at this interface and insolation-forced thermodynamic instability (Simpson et al. 1977; Atkins et al. 1995; Chiba et al. 1999; Plant and Keith 2007).

The depth of the onshore flow varied between ~500 m in case e (Fig. 6e) to ~1.5 km AGL in case c (Fig. 6c), while maximum onshore wind speeds were often located close to the surface and ranged from 9 m s⁻¹ (Fig. 6b) to less than 2.5 m s⁻¹ (Figs. 6a,f). Westerly flow aloft was typically of greater depth (500 m–2.5 km AGL) and intensity (5–10 m s⁻¹) than the sea breeze, suggesting a disproportionate mass flux within the return limb of the circulation. Reflectivity of this layer ranges from 0 to 25 dBZ (not shown) across the six cases, which is supportive of particulate scattering (e.g., insects) being responsible for the clear-air returns (Wilson et al. 1994). Particulates are generally an indicator of a well-mixed air mass; therefore, it is hypothesized that the sea-breeze return flow is coupled with an eastward advected inland CBL above the sea breeze. Synoptic winds with a westerly component are typical of SEQ storm environments above the PBL (Callaghan 1996; Peter et al. 2015; Soderholm et al. 2017); thus, an advected CBL is likely to be of continental origin.

b. Boundary layer variability

Although the sea breeze is relatively shallow, the hypothesized advection of an inland CBL aloft could provide a significantly deeper layer of conditionally unstable air for convective storm development. To further investigate the thermodynamic evolution of the coastal PBL, morning (0900 AEST) and afternoon (adaptive) Brisbane Airport soundings were collected for 15 warm season days on which sea breezes occurred, and storms were anticipated as part of the CCIE (Fig. 7). Figures 7a–f correspond to the same days as the cross sections in Figs. 6a–f. Despite the small sample size, these profiles provide a unique opportunity to explore the diurnal boundary layer evolution of SEQ thunderstorm days. In a majority of cases, except for Figs. 7c,e,f,k,j, morning profiles exhibit a well-mixed CBL to a depth of approximately 1–1.5 km AGL. Mean winds through the morning CBL were light on sea-breeze days (2.5–5 m s⁻¹), backing from the north to northwest (thin barbs in Fig. 8c). Above the CBL, conditions during the morning were considerably more varied, ranging from...
dry, continental air masses (Figs. 7l,n) to moist, well-mixed flow (Figs. 7b,c) from the southwest (Fig. 7l) to northwest (Fig. 7d). By afternoon, the distinctive shallow, surface-bound intrusion of maritime sea-breeze air from the northeast can be seen in a majority of the profiles (Fig. 7). The depth of the onshore flow varied between 300 and 600 m within a total CBL depth of 1.5–3.5 km, comparable with afternoon CP-2 observations (cf. Fig. 6) and international studies of warm season sea breezes (Atkins and Wakimoto 1997; Chiba et al. 1999; Simpson et al. 1977). Thermodynamic changes associated with the sea breeze were diverse, with some cases showing low-level warming (Figs. 7c,e,j,l,m,o) and moistening (Figs. 7a,d,h–l) relative to morning conditions, while others (Figs. 7b,f,g,n) showed marginal temperature change and moistening. Conceptually, sea-breeze air, which originates from more northerly directions, may have a trajectory closer to the coastline and possibly entrain air that has been warmed over land; however, in this small sample no relationship can be seen between the wind direction and thermodynamic trends.

Above the sea-breeze current (approximately 750 m; cf. Fig. 6), the transition from the return flow to the free atmosphere is indistinct, except for an increasing westerly wind component. Warming ranging from 2°C for (Fig. 7g) to 9°C (Fig. 7l) is also observed above the sea-breeze current for a majority of cases. As a result, the mean temperature difference between afternoon and morning profiles reaches a maximum of 2.8°C at 800 m (Fig. 8a), while at the surface and above 1.5 km AGL, 0.5°C (or less) of warming occurs. Mean dewpoints also show a consistent region of moistening above this warming layer, with a dewpoint increase of more than 4°C at 1.5 km AGL (Fig. 8b). Figure 7d most clearly represents the mean changes observed in Fig. 8. Examination of the afternoon profile for this case shows two well-mixed layers are present: the lowest within the north-northeast sea breeze in the lowest 500 m AGL and a second elevated mixed layer within 7.5–10 ms⁻¹.
northwest flow to a depth of 1.8 km AGL (≈810 hPa). Elevated westerly flow implies the advection of the inland continental boundary layer toward the coast, which would continue to deepen and warm throughout the afternoon separate from the sea breeze. Muppa et al. (2016) showed a comparable case of an elevated well-mixed layer entrained into a developing continental CBL.

A conceptual model summarizing the diurnal evolution of the coastal PBL developed from Fig. 7d is shown in Fig. 9. The advection of the continental CBL above the sea breeze results in warming, particularly for the layer that contained the cooler, morning CBL. Notable moistening occurs above the morning CBL, where the drier free atmosphere of the morning is replaced by the deeper afternoon continental boundary layer. This moisture results from thermals within the deep continental CBL vertically transporting near-surface moisture while adiabatically cooling, increasing relative humidity with height (e.g., Bennett et al. 2010). Cases of deep return flow (>2.5 km AGL) in CP-2 RHI scans (Figs. 6b,e) corresponds with exceptionally well-mixed profiles (Figs. 7b,e) above the sea-breeze inversion. Anticipated warming of the sea-breeze air mass (e.g., Abbs 1986; Finkele et al. 1995; Chiba et al. 1999) as it propagates inland from the coastal Brisbane Airport site is also shown, leading to the partial erosion of the maritime inversion and, in some cases, deepening of the elevated mixed layer downward to the surface (cf. Figs. 7b,c,g).

Convective storm parcels in Fig. 9 are sourced from the sea-breeze circulation and advected CBL, depending on airmass characteristics (e.g., conditional stability and moisture depth) and the strength of any capping inversion. For three of the four active cases in Figs. 7b,c,j, parcels sourced from the sea-breeze air mass (lowest 50 hPa) were most unstable (≥1250 J kg⁻¹ of convective available potential energy (CAPE)) and had less inhibition (<70 J kg⁻¹ of convective inhibition (CIN)) than elevated CBL parcels. For the remaining active case (Fig. 7m), elevated CBL parcels (approximately 890 hPa) were most favorable for convection as a result of a capped sea breeze. In addition, lifting of continental CBL parcels along the sea-breeze front would have likely contributed to updraft development in active cases in Fig. 7 (e.g., Sills et al. 2004).

Application of the concepts developed in Fig. 9 to the remaining cases in Fig. 7 highlights an elevated CBL air mass associated with warming and moistening above the sea breeze for all cases, excluding (Figs. 7b,l,n), where warming was accompanied by limited, or no, moisture advection. This may be explained by the presence of a strong inversion for the cases in Fig. 7l and Fig. 7n, which act to cap deep inland CBL development. For the case in Fig. 7b, the morning free atmosphere above the CBL was considered well mixed and humid through to 3 km AGL, limiting the contribution of moisture by the advected continental CBL.

To ascertain whether the eastward afternoon advection of a deep continental CBL is unique to the sea-breeze days, an examination of 11 cases for which storms were anticipated but no sea breeze was detected is presented in Fig. 10. The mean wind profiles show limited diurnal variability through the first 1 km AGL in contrast to the afternoon veering seen on sea-breeze days (Fig. 8c). Westerly advection starts from a higher altitude (1.5 km AGL) for non-sea-breeze cases, resulting in an elevated but marginal mean afternoon warming maximum of 1.2°C at 1.1 km AGL (Fig. 8a). Mean moisture advection in the north-to-northwesterly flow was also minimal (1.1°C increase) and shallower (replaced by drying above 1.7 km AGL), suggesting the continental CBL was less developed than on sea-breeze days. Analysis of the individual cases (Fig. 10) indicates the presence of cloud layers (Figs. 7a,b,f,g,h,k) and strong synoptic flow (Figs. 7g,h), which may contribute to a less developed CBL inland. Furthermore, the absence of sea-breeze return flow likely reduces the continental CBL mass flux for the cases in Fig. 10.

c. Static stability

Adaptive afternoon soundings from YBBN were released on 26 separate days during the CCIE when storms were forecast for SEQ; however, storms only developed on 14 days (53%), 10 (71%) of which had a sea breeze and 4 (29%) were without a sea breeze. The higher occurrence of SEQ storm days during sea-breeze conditions
is consistent with Soderholm et al. (2017). Furthermore, convective storm activity varied markedly when it was present, with rapid intensification occurring for some cases over coastal plains (e.g., Brisbane), while other cases saw rapid dissipation when storms crossed the sea-breeze front area. This variability is summarized through the shaded backgrounds in Figs. 7 and 10.

To assess the stability characteristics of sea-breeze convective environments, mean profiles of morning and afternoon $u_e$ are shown in Fig. 11. The stability of individual profiles appears related to the level of storm activity, with null modes occurring in the lowest-energy environments, and convective modes in the highest-energy environments. While the small sample sizes for these modes limit any conclusions being drawn, numerical results from McCaul and Cohen (2002) likewise show that increases in $\theta_e$ within the updraft inflow layer increase the thunderstorm updraft strength. On sea-breeze days, a shallow near-surface stable layer (increasing $\theta_e$ with height) is present for weakening and convective modes, while the lower-$\theta_e$ profile for null modes may limit the energy difference to maritime air. Above approximately 750 m AGL (sea-breeze depth; cf. Fig. 6), the decrease in $\theta_e$ with height apparent in the morning profiles is replaced with an afternoon layer of near-constant $\theta_e$ from the well-mixed continental CBL, resulting in steeper $\theta_e$ lapse rates (indicating stronger buoyancy) for all storm modes. The depth and magnitude of this warming also relate to storm activity, with the low-energy shallow ($\sim 800$ m), cooler (335 K) CBL for null cases, and the high-energy deep ($\sim 1.8$ km AGL), warmer (345 K) mixed layer for convective days. Although the afternoon convective mode profile is the highest-$\theta_e$ environment, it is also the only profile with a substantial stable layer below 1 km AGL, whereby afternoon $\theta_e$ is briefly lower than morning values around 450 m (7-K reduction).

To diagnose the thermal and moisture-driven contributions of the mean $\theta_e$ profile for convective cases, the mean difference between the afternoon and morning

Fig. 9. Conceptual schematic of diurnally forced preconditioning processes for deep moist convection in SEQ based on the soundings from Fig. 7. Idealized temperature (black) and dewpoint (gray) profiles are shown for the inland agricultural/forested region and the coastal urban region with solid lines. The 0900 AEST profile is superimposed onto the 1500 AEST urban coastal profile with thin dashed lines for comparison. Hypothesized warming due to inland trajectories of the sea breeze over the coastal UHI and land are shown by a boldface dotted line. Horizontal (vertical) flow is shown with black dashed (dotted) lines. Idealized wind profiles are also provided on the rhs.
profiles of temperature and dewpoint are shown in Fig. 12. The near-surface $u_e$ maximum of the convective mode profile in Fig. 11 is driven by both warming and moisture increases by afternoon, while the elevated $u_e$ maximum is mostly attributed to an increase in moisture. Maximum warming between 300 and 800 m is offset by substantial drying, leading to the noted stable $u_e$ layer. Analysis of individual cases (Figs. 7b,c,j,m) shows a reduction in afternoon dewpoint through a shallow layer at approximately 975–950 hPa, associated with subsidence of westerly return/synoptic flow above the sea breeze (Finkele et al. 1995; Chiba et al. 1999). Mixing of this drier air into storm inflow would likely reduce the parcel buoyancy; however, the effect would be marginal because of the moisture aloft and its proximity to the surface (Fig. 12).

5. 27 November 2014 case study

This section presents a severe thunderstorm event that illustrates how the boundary layer preconditioning concepts introduced above can influence the evolution of deep convection. On 27 November 2014, a hailstorm producing 70–80-mm hailstones and a maximum wind gust of 39.2 m s$^{-1}$ impacted Brisbane and the surrounding suburbs, resulting in insured losses exceeding $1.4 billion AUD (Insurance Council of Australia 2015). The synoptic environment was unremarkable, with a weak upper-level trough positioned over southeast Australia, a shallow southeasterly airmass change (southeasterly change) propagating into the region, and a continental dryline to the west (not shown). As a result, the 0900 AEST Brisbane Airport sounding (Fig. 7b) lacks the steep lapse rates and deep-layer wind shear commonly associated with high-impact, organized convective storms (Weisman and Klemp 1982). A CCIE IOP was conducted during this event, providing the opportunity for an in-depth analysis of environmental preconditioning and storm evolution.

a. Radar and environmental analysis

Surface mesoanalyses were generated at four instances (1200, 1500, 1612, and 1624 AEST) prior to the storm’s passage over Brisbane at 1642 AEST using the
BoM, EHP, and CCIE AWS networks (Fig. 13). Characteristic features of the mean sea-breeze mesoanalysis (Fig. 5) can be seen prior to the development of convection at 1200 AEST (Fig. 13a), including the enhancement of moisture over Brisbane and the southwest region, and an axis of comparatively drier, warmer air running north-northwest to south-southeast through Amberley. Overall, near-surface temperature and dewpoint fields were 2°–4°C higher than the mean conditions (cf. Fig. 5a), increasing θe by approximately 10 K across SEQ. A 1200 AEST sounding at Kalbar (Fig. 14) suggests that the developing continental CBL was advected toward Brisbane under weak southwesterly flow. The moisture depth (~850 hPa) and content of the CBL observed at Kalbar is comparable to the elevated CBL observed in the 1400 AEST Brisbane Airport profile, 2 h later (Fig. 14), which therefore supports the hypothesized mechanism for the observed warming and moistening over the coastal plains by the afternoon (Fig. 9).

As the afternoon progresses, the near-surface dewpoint gradient (12°–19°C) sharpened as the continental dryline propagated into western SEQ at 1500 AEST (Fig. 13b), decreasing the near-surface θe over western SEQ due to lower surface moisture. Developing storms (reflectivity >35 dBZ) were also present at this time, triggered near the elevated topography of the southern ranges and the approaching southeasterly change. At 1541 AEST, an hour prior to impact on Brisbane, a CP-2 RHI scan aligned with the sea-breeze flow (south-southwest) observed the sea-breeze air mass lifted above its level of free convection (LFC) by a denser multicell cold pool, as it continued to rise through the midlevels of the storm (Fig. 15). At this time, radar reflectivity also showed a bounded weak-echo region (BWER) had developed at 3 km in altitude in proximity to the updraft, indicating the lifted sea-breeze parcels were supporting a strong updraft. Intensification of the sea breeze was observed as the multicell storms continued to track toward Brisbane, with 1600 AEST Brisbane Airport 10-m winds reaching 8 m s⁻¹ from the north-northeast (10 min) and a 1551 AEST Aircraft Meteorological Data Relay (AMDAR) observations of 11 m s⁻¹ (northeast) at 600 m above Brisbane (not shown), increasing the favorable storm-relative inflow.

By 1612 AEST, storms in the southeast region had organized into an east–west-oriented multicell, while southwestern storms had dissipated following a period
of strong outflow, despite interacting with a potentially favorable sea-breeze triple point (Fig. 13c). In contrast to the dry, weakly sheared environment of central SEQ, the eastern multicell was developing in a deep well-mixed CBL, with rich near-surface moisture and favorable storm-relative inflow from the sea breeze as it approached Brisbane. To estimate the convective potential of the sea-breeze air mass, the 1630 AEST Brisbane AWS (BoM) observations of 28°C and 20°C for temperature and dewpoint, respectively, were inserted into the lowest level of the 1400 AEST Brisbane Airport sounding. This sea-breeze–UHI influenced parcel was the most unstable in the profile (including the advected CBL), with 2120 J kg⁻¹ of surface-based CAPE (SBCAPE), only 30 J kg⁻¹ of CIN, and an LFC of 2090 m. The environmental wind profile at 1400 AEST was nevertheless marginal for organized storms; with 0–3-km storm-relative helicity (using a storm motion toward 14° at 14 m s⁻¹) of –23 m² s⁻² and 7.7 m s⁻¹ of 0–6-km bulk shear. The proximity of the southeasterly change to the developing multicell storm would likely have further increased the shear, particularly in the low levels.

As the eastern storm propagated into the high-θₑ near-surface environment around Brisbane, multiple concurrent BWERs (Phillips 1973; Markowski 2002) were observed on radar from 1554 AEST, followed by a pronounced three-body scatter spike (TBSS; Wilson and Reum 1988) associated with an elevated hail core from 1618 AEST onward. Velocity couplets associated with midlevel mesocyclone activity were also present (e.g., Fig. 16d shows a moderate-strength mesocyclone over
the Archerfield marker with rotational velocity of 19.5 m s$^{-1}$ at 24 km from CP-2); however, they exhibited short duration (6–12 min). A set of CP-2 PPI scans providing low (~500 m) and midlevel (~3.5 km) coverage of the storm is shown in Fig. 16, revealing the complex structure of the multicell, including the presence of concurrent BWERs. At 1624 AEST, two midlevel BWERs can be identified in the 12.8$^\circ$ PPI scan (Fig. 16c) on the leading northern edge of the multicell, while 5 min later low-level outflow along the western flank produced a 39.2 m s$^{-1}$ gust at Archerfield (1629 AEST). By 1642 AEST, the two previous BWERs were replaced with a single larger BWER, as the system tracked north. A new BWER collocated with a broad midlevel mesocyclone (Fig. 16d) is also present above a surface inflow notch (Fig. 16b), indicating that an updraft was intensifying as the storm propagated over Brisbane. The presence of large BWERs from 1554 AEST onward is indicative of the storms’ potential to grow large hail. A broad region of high reflectivity >65 dBZ (Figs. 16b,d) and low differential reflectivity (ZDR) (~1 to 0 dB; not shown) aloft and at the surface was associated with 70–80-mm hailstones reported southwest of Brisbane.

b. Environmental drivers of storm characteristics

The presence of intermittent high-precipitation (HP) supercell features (e.g., large BWERs, >65-dBZ reflectivity, and brief midlevel mesocyclones) within a predominantly multicell storm system (concurrent updrafts, transience of the mesocyclones, and lack of organization) suggests the 27 November 2014 event was a hybrid HP supercell (Moller et al. 1990). This mode was also observed by Richter et al. (2014) for a windstorm that impacted northwest Brisbane on 16 November 2008. The convective environments from the 27 November 2014 and 16 November 2008 events are remarkably similar; including low 0–6-km bulk shear (~10 m s$^{-1}$), 2000 J kg$^{-1}$ of afternoon surface-based (SBCAPE), an approaching southeasterly change, and a sea breeze. Weisman and Klemp (1982) showed that for a given amount of buoyancy, a low-to-moderate shear noted for these events favors multicellular, rather than supercellular, growth. The strong vorticity required to build a mesocyclone can potentially be sourced from the lifting and tilting of horizontal vorticity within the inflow layer along the boundaries [e.g., southeasterly change, sea-breeze boundary; Markowski et al. (1998); Atkins et al. (1999)]. Sills et al. 2004 found that low-level boundaries
were central to the enhancement and mesocyclone development of storms that produced tornadoes in Sydney under weak synoptic-scale forcing. Furthermore, without the sustained dynamical lifting promoted by a long-lived mesocyclone (Doswell 1996; Ziegler et al. 2010), hybrid HP supercells are consequently more sensitive to the stability of the inflow layer.

For the 27 November 2014 case where the storm’s inflow layer included a deep well-mixed CBL, the heterogeneous near-surface moisture supply (e.g., sea-breeze advection, irrigated areas) and heating (e.g., UHI, inland regions) likely influenced the ultimate buoyancy of inflow parcels, and thus updraft intensity. The importance of land surface properties for storm evolution is widely recognized, including for urban settings (Chen et al. 2007; Haberlie et al. 2015b; Ryu et al. 2016), reservoirs (Haberlie et al. 2015a), sea breezes, and irrigation/agriculture (Pielke and Zeng 1989; Carleton et al. 2001; DeAngelis et al. 2010). Within the PBL, the availability of moisture also influences the updraft intensity through the entrainment and drying of lifted parcels (James and Markowski 2010). The deep moisture from the advected CBL shown in Fig. 14 suggests reduced potential for the entrainment of dry ambient air and consequent buoyancy loss of updraft parcels. Furthermore, findings by Coniglio et al. (2011) and analysis by Richter et al. (2014) suggest that deep moisture, substantial hydrometeor loading, and the associated melting of hailstones may have contributed significantly toward the destructive surface gusts observed at Archerfield.

The weak deep-layer shear, high-CAPE synoptic-scale storm environments of the 2014 and 2008 Brisbane events are symptomatic of the subtropical climate in SEQ due to the poleward shift of the jet stream during

![Fig. 16. PPI imagery of the 27 Nov 2014 hailstorm from the CP-2 radar (location marked in bottom-left corner). PPI scans are shown at (a), (c) 1624 and (b), (d) 1642 AEST for (a), (c) 1.7°, (b) 12.8°, and (d) 9.1° tilts. Approximate heights where the PPI surface cuts through the storm updraft are (a) 300 m, (b) 500 m, (c) 3.3 km, and (d) 3.6 km. Doppler velocity is color shaded and contours of smoothed reflectivity are shown in steps of 10 dBZ from 35 dBZ, with a thick contour for 35 dBZ to show BWERs and a thick dashed contour for 65 dBZ to show likely hail. The location of Brisbane is marked with a white circle and Archerfield with a white triangle.](image)
the warm season. Synoptic-scale convective parameters therefore provide limited diagnostic skill for forecasting hybrid-HP supporting environments. On the mesoscale, the southeasterly change and sea breeze noted in the 2008 and 2014 cases represent the dominant boundaries for SEQ hailstorms (Soderholm et al. 2017), including for the Brisbane region. Given both the synoptic conditions and mesoscale forcing of the 2008 and 2014 cases are not outliers within the climatology, it is not unexpected to find that these environmental conditions repeatedly occur for historical high-impact storm cases. This includes the 18 January 1985 hailstorm (Callaghan 1996), which incurred the largest single insured losses of any natural disaster for Brisbane ($2 billion AUD; Insurance Council of Australia (2015)).

6. Discussion and conclusions

An improved understanding of diurnal processes that favor severe thunderstorms in the typically maritime coastal atmosphere has clear benefits for storm prediction. A diverse range of diurnally forced planetary boundary layer (PBL) processes occur within the coastal settings (e.g., sea breezes, urban effects, terrain winds); yet, further research is required to understand their influence upon the convective storm environment. Observations from the Convective Coastal Interactions Experiment (CCIE) were analyzed to identify and understand processes that provide favorable PBL preconditioning for convective storms in South East Queensland (SEQ), Australia.

The observational datasets were divided according to the presence or absence of the sea breeze, which is recognized as an important influence on coastal environments. The sea breeze and prevailing synoptic conditions were found to be associated with increased inland warming and coastal moisture (Fig. 2); however, modification by the near-surface and PBL processes was essential for favorable convective preconditioning. Increased moisture was observed for Brisbane in contrast to the adjacent coastal rural environments, possibly because of the urban heat island (UHI)–enhanced sea-breeze flow, increased urban irrigation, and the Brisbane River. Previous documentation of this interaction is limited to modeling studies (Khan and Simpson 2001; Ohashi and Kida 2002; Freitas et al. 2007). Furthermore, the enhanced moisture coupled with the UHI thermal contribution (Fig. 4) creates a notable near-surface instability maximum over the Brisbane region (Fig. 5), which may influence convective updraft intensity (e.g., Smith et al. 2000; Kunz et al. 2009; Mona et al. 2016).

Above the sea breeze, coastal advection of the inland convective boundary layer (CBL; Fig. 6) led to substantial afternoon warming and moistening of the vertical profile (Figs. 7 and 8). Coupled with the moisture-rich sea breeze, the elevated continental boundary layer adds an additional layer of substantially buoyant air for deep convective updrafts (Fig. 9; Thompson et al. 2007). An elevated CBL was also noted by Muppa et al. (2016) for continental western Germany, suggesting this processes is not restricted to coastal settings. To the best of our knowledge, the concept of an elevated continental CBL above the sea breeze contributing to moistening and warming is absent from the previous literature.

The importance of diurnally forced changes to the near-surface and PBL atmosphere was highlighted in the 27 November 2014 case study. The storm intensified as it approached an equivalent potential temperature maximum centered on Brisbane, induced by enhanced moisture and warming within the urban environment (Fig. 13). Furthermore, an inland sounding confirmed the coastward advection of a deep inland CBL (Fig. 14), supporting the hypothesized mechanism for regular moistening and warming above the sea breeze. A vertical cross section from the CP-2 radar indicates that sea-breeze parcels were lifted above their LFCs by the storm cold pool, contributing toward the deep convective updraft (Fig. 15). Although the broad-scale shear profile was unfavorable for storm organization, intermittent supercell features were noted during the event (Fig. 16), potentially because of low-level vorticity ingested from nearby surface boundaries and associated lifting/tilting, as suggested by Atkins et al. (1999). The predominantly multicellular features with occasional transient mesocyclones indicate a hybrid HP supercell mode (Moller et al. 1990), comparable to the 16 November 2008 windstorm event (Richter et al. 2014). Lacking the sustained dynamical lifting of a long-lived supercell, this mode is hypothesized to be more susceptible to the thermodynamic properties of the inflow. Numerous studies have identified the importance of heterogeneous surface features such as cities (Niyogi et al. 2011; Haberlie et al. 2015b; Ryu et al. 2016), reservoirs (Haberlie et al. 2015b), terrain (Banta and Schaaf 1987; Weckwerth et al. 2011; Nisi et al. 2016), and irrigated land (Pielke and Zeng 1989; Deangelis et al. 2010) for understanding the convective response to the land surface properties.

Comparable storm-prone coastal environments can be found globally throughout the subtropical regions, including southern and southeastern United States (Blanchard and López 1985), Taiwan (Lin et al. 2011), and Brazil–Argentina (Pinto et al. 2013), as well as for warmer, more temperate climates including Spain (Azorín-Molina et al. 2015), Italy (Baldi et al. 2014), New Zealand (Steiner 1989), and the eastern United States.
(Cintineo et al. 2012). The findings of this study are applicable across these regions, particularly for coastal cities and synoptic conditions supporting the coastward advection of an inland CBL profile. From a technical perspective, this study would be impracticable without the use of adaptive afternoon soundings and an extensive AWS network. Adopting a similar observational strategy for coastal convective storm environments would greatly benefit operational convection forecasters when assessing diurnal preconditioning. Further research is required to quantify the UHI modification of the coastal CBL and determine the contribution of different CBL air masses (e.g., sea breeze, UHI, advection inland CBL) toward convective storm updraft evolution. A detailed investigation of the hybrid HP supercell event is also encouraged to further our understanding of the boundary layer influence upon their storm attributes.

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