Diurnal cycles of cloud and rainfall over North–East Queensland during the coral bleaching season

Alanah Chapman[1,2,3,4], Yi Huang[1,2], and Claire Vincent[1,2]

[1]School of Geography, Earth and Atmospheric Sciences, The University of Melbourne
[2]ARC Centre of Excellence for 21st Century Weather, Melbourne, VIC, Australia
[3]CSIRO Environment, Melbourne, Australia
[4]Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, AU, Australia

Correspondence: Yi Huang (yi.huang4@unimelb.edu.au)

Abstract. Mass coral bleaching events are becoming increasingly frequent over the Great Barrier Reef (GBR), posing a critical risk to Australia's marine ecosystems and the broader global ocean environment. These events are primarily driven by anomalously warm water temperatures, but their severity is strongly influenced by local cloud cover, which controls the amount of solar radiation reaching the ocean surface (including ultra–violet radiation which exacerbates bleaching). This study presents a characterization of the cloud and rainfall diurnal cycles over north–east Queensland during the coral bleaching season, providing a foundational step to untangling the complex relationships between clouds, rainfall, local–scale processes and the surface energy budget for this climate–sensitive region. Leveraging high–resolution Himawari–8 satellite brightness temperature data, C–band radar observations, and BARRA–R2 regional reanalysis, a multi–year analysis is conducted across three representative zones: coastal land, coastal ocean and open ocean. Results show that diurnal cycles vary distinctly by region and are strongly modulated by prevailing wind regimes. In general, westerly regimes are associated with clear skies and stronger daytime heating over the coastal ocean with enhanced convection over coastal land. In contrast, the frequently observed southeasterlies lead to relatively weaker development over the land and ocean. Cloud and rainfall maxima exhibit out–of–phase behavior between land and ocean, with rainfall often preceding cold cloud tops, indicative that cold brightness temperatures frequently correspond to decaying anvils rather than active convection. Latitudinal and topographic differences contribute to more intense convection near Cairns than Townsville. Variations in inland versus offshore propagation speeds further highlight regional complexity. Our findings emphasize the necessity for high–resolution simulations to advance understanding of need for high-resolution simulations to better understand the convection initiation and propagation mechanismsprocesses that shape cloud cover and rainfall variability over the GBR during the coral bleaching season, when cloud-radiation interactions may influence reef heat stress.

1 Introduction

Variations in the diurnal cycles of clouds over tropical regions significantly influencesrainfall variability and regional heat and energy budgets. The Over the Great Barrier Reef (GBR), the relationship between local–scale cloud cover and radiation is a key factor modulating the ~~Sea Surface Temperatures~~ sea surface temperatures (SSTs) ~~over the Great Barrier Reef (GBR)(Huang et al., 2024; McGowan and Theobald, 2023; Richards et al., 2024; Zhao et al., 2022). With~~ (Huang et al., 2024; Leahy et al., 2013; McGowan and Theobald, 2023; Richards et al., 2024, 2026; Zhao et al., 2022). Through its modulation of incoming solar radiation and outgoing longwave radiation, cloudiness can influence the timing and magnitude of upper-ocean warming, which is a key factor in the development of thermal stress conditions associated with coral bleaching events (CBEs). Given that anomalously warm SSTs ~~recognized as~~ are the main driver of ~~thermal coral bleaching events (CBEs), understanding the multi–scale variability in cloud cover over~~ mass CBEs, improved understanding of the spatial and temporal variability of cloud systems in this region is a ~~crucial step towards a quantitative~~ critical step toward improving our understanding of the ~~ocean heat budget.~~ atmospheric contribution to reef-scale thermal conditions. In particular, characterizing the formation, propagation, and dissipation of cloud systems provides important context for interpreting atmospheric variability experienced by the GBR during the austral warm season.

Driven by the daily cycle of solar heating, diurnal cycles not only impact local and regional weather, but can also contribute to non–linear upscale processes which can influence the global climate (Masson et al., 2012; Slingo et al., 2003). This effect is particularly pronounced in the deep tropics where diurnally forced convection and rainfall accounts for roughly 50% of mean rainfall and strongly interacts with the Madden–Julian Oscillation (MJO) (Birch et al., 2016; Love et al., 2011; Rauniyar and Walsh, 2011). Global transport of moisture and energy is intricately linked to tropical variability, prompting extensive research on diurnal cycles, particularly over the Maritime Continent (MC) (Lopez-Bravo et al., 2023b; Mori et al., 2004; Neale and Slingo, 2003; Sakaeda et al., 2017; Yamanaka et al., 2018). However, climate models continue to systematically underestimate mean convection and rainfall in the tropics, often due to ~~misrepresentation of~~ deficiencies in how they represent key processes controlling the diurnal cycle. In particular, many models have difficulty capturing the timing, amplitude, and propagation of convection because of limited spatial resolution and parameterized convection schemes that cannot fully resolve the interaction between boundary-layer evolution, surface heating, moisture convergence, and cloud–precipitation feedbacks (Christopoulos and Schneider, 2021; Covey et al., 2016; Tang et al., 2021; Xie et al., 2019). Recent advances in convection-permitting modeling, including emerging regional and a small number of global-scale simulations, have demonstrated substantial improvements in representing the diurnal cycle of convection and its propagation, although such approaches remain at the frontier of computational capability and are not yet widely available for long-term or ensemble climate applications (Clark et al., 2016; Hohenegger et al., 2008; Huang et al., 2026; Kendon et al., 2019; Pearson et al., 2014; Stevens et al., 2019 . This underscores the ~~diurnal cycle. These persistent shortcomings underscore the~~ critical need to understand local–scale convective processes, particularly in under–studied regions such as northeast Queensland, Australia (Birch et al., 2016; Love et al., 2011; Neale and Slingo, 2003).

Diurnal cycles of clouds and rainfall over tropical coastal land regions, particularly in the nearby MC, typically peak during the afternoon–~~to early evening (Hassim et al., 2016; Mori et al., 2004; Vincent and Lane, 2016; Yang and Slingo, 2001; Lopez-Bravo et al.~~ to-early evening (Lopez-Bravo et al., 2023b; Hassim et al., 2016; Mori et al., 2004; Vincent and Lane, 2016; Yang and Slingo, 2001). These patterns are shaped by local–scale processes such as sea and valley breezes, and boundary layer mixing, which are further influenced by local topography and large–scale background wind fields (Bui et al., 2023; Dao et al., 2025b; Pereira and Rutledge, 2006; Short et al., 2019). Convection that develops over land during the day often propagates offshore during the evening and night, leading to peak cloudiness and rainfall over adjacent ocean areas during the late evening to early morning hours (Yang and Slingo, 2001; Lopez-Bravo et al., 2023b) (Lopez-Bravo et al., 2023b; Yang and Slingo, 2001). High–resolution simulations show that offshore propagation can extend up to 700 km from the coastline (Vincent and Lane, 2016), and is associated with two distinct mechanisms: slow–moving density currents associated with the land and mountain breezes near–shore, and faster–traveling gravity waves beyond 200 km from the coastline (Mapes et al., 2003). While these patterns represent typical diurnal behavior in tropical coastal and marine environments, significant regional variations exist (Lopez-Bravo et al., 2023b; Peatman et al., 2023; Yokoi et al., 2017). Therefore, it is essential to characterize the diurnal cycles of clouds and rainfall specific to the GBR region, which spans both tropical and subtropical zones. Such characterization is important for improving our understanding of the local heat and energy budgets, particularly during the periods relevant to coral bleaching, and is subject to strong gradients in large-scale circulation, thermodynamic conditions, and coastal–oceanic interactions.

Understanding the diurnal variability of local cloud and rainfall cycles is crucial for uncovering how cloudiness interacts with surface energy fluxes, and for identifying the processes that govern these exchanges. Vincent and Huang (2022) examined the relationship between local morning insolation and the diurnal rainfall cycle for three forested sites in the MC. They found that higher morning insolation is associated with increased afternoon rainfall over land, and that this was poorly captured in convection–permitting model simulations. Beyond the MC, relatively few studies have explored how diurnal cycles of clouds and rainfall interact with the boundary layer and surface fluxes. May et al. (2012) used data from the international Tropical Warm Pool International Cloud Experiment (TWP–ICE) and weather radar (among other instruments) to investigate the effects of convective rainfall on surface radiation in a coastal monsoon setting. Their findings showed that the shortwave (SW) cloud effects dominated net surface radiation fluxes, with up to three times more energy reaching the surface during periods of large–scale suppressed conditions. In contrast, during the monsoonal period, increased cloud optical thicknesses and persistent high–level clouds significantly reduced net surface radiation by blocking incoming SW radiation. Direct in situ measurements of the surface energy balance are far more common over land than ocean, largely due to the logistical challenges of instrument setup and maintenance in marine environments. In the southern GBR, a case study by McGowan et al. (2010) examined the surface energy balance using in situ measurements. They found that 80–98% of net daytime radiation reaching the ocean surface contributed to heating of shallow reef flats. Although their observations were limited to spring and winter, the study highlighted the critical role of cloud cover in modulating the ocean heat budget.

In the context of clouds and rainfall over the GBR, Zhao et al. (2022) provided a broad characterization of seasonal cloud properties which are influenced by local-scale forcings across large spatial scales. However, fineMore recently, Dao et al. (2025a) investigated wet-season rainfall propagation over northeast Queensland using a 180-day convection-permitting regional model simulation complemented by radar observations around Townsville. Their results demonstrated that interactions between land–scale diurnal variability — poorly captured by both Numerical Weather Prediction and climate models — remains largely unexamined. This gap is critical, given the significant effects of diurnal radiative cloud

~~forcings on surface radiative fluxes in the tropics, and the recognized role of cloud cover in driving shallow warm water formation linked to coral bleaching. This study aims to address two~~ sea breezes and large-scale background winds play a key role in regulating coastal rainfall patterns, particularly the offshore and onshore propagation of heavy rainfall systems. These studies highlight the importance of multiscale interactions in shaping coastal convection in the region. However, a more integrated understanding of diurnal cloud and rainfall evolution across coastal and marine environments remains needed to better characterize regional variability and its implications for coral bleaching risk. Building on this scope, we examine the diurnal variability of both clouds and rainfall during the Coral Bleaching Season (CBS) using multi-year Himawari-8 observations, BARRA-R2 regional reanalysis, and rainfall observations from three coastal radars. Unlike Dao et al. (2025a) which focused primarily on rainfall propagation, we consider the coupled evolution of cloud and rainfall systems across coastal land, coastal ocean, and open ocean environments under different prevailing wind regimes, with a particular emphasis on the spatial and temporal variability of cloud-top characteristics, rainfall timing, and cloud–rainfall relationships associated with convection across northeast Queensland including the GBR.

This study therefore addresses two primary scientific questions: (1) What are the characteristics of the diurnal cloud and rainfall cycles over coastal and open ocean regions of north–east Queensland? (2) How do the background wind fields interact with local–scale processes to shape these diurnal patterns? Focusing on the ~~Coral Bleaching Season (CBS ;~~ CBS period (January–April), when most CBEs in the GBR occur, we ~~use a multi–year dataset combining high–resolution geostationary satelliteobservations (Himawari–8), C–band radardata, and BARRA–R2 regional reanalysis . Through this integrated approach, we characterize diurnal cycles~~ combine satellite, radar, and regional reanalysis datasets to characterize the diurnal variability of cloud and rainfall ~~,~~ and examine the thermodynamic and dynamical factors that modulate them. ~~Drawing on the observed patterns~~Through this integrated analysis, we propose plausible mechanisms underlying ~~these interactions, offering~~ the observed cloud and precipitation variability, providing a foundation for future targeted process studies~~in future work~~.

2 Data and Methods

2.1 Observational and Reanalysis Datasets

Cloud diurnal cycles were analyzed using the Channel 13 Brightness Temperature (BT; infrared wavelength band 10.4 μm) from the Himawari–8 satellite Level 1 atmospheric and cloud property dataset, which covers the Australian region at an hourly temporal and 2 km spatial resolution (Lopez-Bravo et al., 2021a, b). The BT data was regridded for the study domain at 2 km spatial resolution, spanning 21.5°–14° S and 143°–152° E, encompassing a region of north–east Queensland, the central GBR and the Coral Sea, including the coverage areas of three weather radars (Fig. 1). Diurnal cloud characteristics were analyzed for the January to March period — including small convective clouds observable with the high resolution Advanced Himawari Imager (AHI). A shortened Coral Bleaching Season (CBS) was analyzed due to data availability (Jan–Mar rather than the defined CBS Jan–Apr). Previous studies of the same Level–1 dataset have provided detailed insights on diurnal cycles of convection in the tropical Maritime Continent (Lopez-Bravo et al., 2023a, b).

Rainfall estimates were obtained from Level–2 ~~rain rate~~ historical ground reflectivity retrievals derived from C–band Doppler radar data. This study uses data from the Townsville, Cairns and Willis Island operational weather radars operated by the Australian Bureau of Meteorology, archived on the National Computational Infrastructure (Soderholm et al., 2022). ~~Rain rate estimates have a~~ Historical ground reflectivity data has spatial resolution of 1 km, extending horizontally from the radar site up to a range of 150 km in all directions (360°), with a temporal resolution between 5–10 min (increasing in frequency towards the end of the analysis period). The analysis focuses on the full CBS (Jan–Apr), for the years when data from for all three radars are available (2012–2022).

Surface wind data from the Australian Bureau of Meteorology's automated weather stations (AWS) in Townsville and Cairns are used to highlight the complex local–scale influences on surface conditions. AWS data was analyzed for the full CBS for the period of 1990 to 2020, with a temporal resolution of 30 min. The location of both stations is shown in Fig. 1, with height above sea level of 4.34 m for Townsville and 2 m for Cairns (with wind measurements 10 m above ground level). Hourly averaged wind direction was calculated using the circular mean, which is used for averaging angular data (i.e. taking the average of 350° and 10° to result in 0°).

The Australian Bureau of Meteorology Atmospheric high–resolution Regional Reanalysis for Australia (BARRA–R2) was used to provide meteorological context for the radar rainfall and satellite cloud observations. BARRA–R2 covers the Australian region from 1979 to the present, with a horizontal grid resolution of 12 km and a temporal resolution ranging from hourly to monthly; this study focuses on variables at hourly resolution. Full documentation can be found in Su et al. (2022). Previous studies have used the BARRA–R2 reanalysis to examine diurnal cycles of temperature and humidity over northern Australia (May et al., 2022). The higher horizontal resolution of BARRA–R2 compared to global reanalyses enables improved representation of local features such as coastal and topographic circulations, though fine–scale processes (such as convection) remain parametrized.

2.2 Methods

In this study, BARRA–R2 was used primarily for defining the background wind and local environmental conditions through composite analysis~~, as described in Section 2.2.~~ Large-scale meteorological conditions were characterized ~~using hourly~~ by 850 hPa level winds, whose direction and strength relative to the coastline have been shown to influence the diurnal cycle of coastal precipitation (Aoki and Shige, 2024; Dao et al., 2025a). The mean 850 hPa wind direction at 12 Local solar Time (LT) from BARRA–R2 was calculated across each radar domain for the full CBS from 2012 to 2022. For each day within the temporal domain the 12 LT mean wind direction was computed (by first averaging zonal and meridional components separately before computing wind direction), and each hour of that day (00-23 LT) assigned to the resultant wind regime. In this way composite results are reflective of a full diurnal cycle. Wind regimes at 850 hPa were categorized as north–easterly (0°–90°), south–easterly (90°–180°), south–westerly (180°–270°) and north–westerly (270°–360°). This classification was designed to establish a clear northerly–southerly distinction, effectively separating tropical air masses (typically warmer and more humid) from those of mid–latitude origin (typically cooler and drier). Due to the variation in coastline orientation across the radar

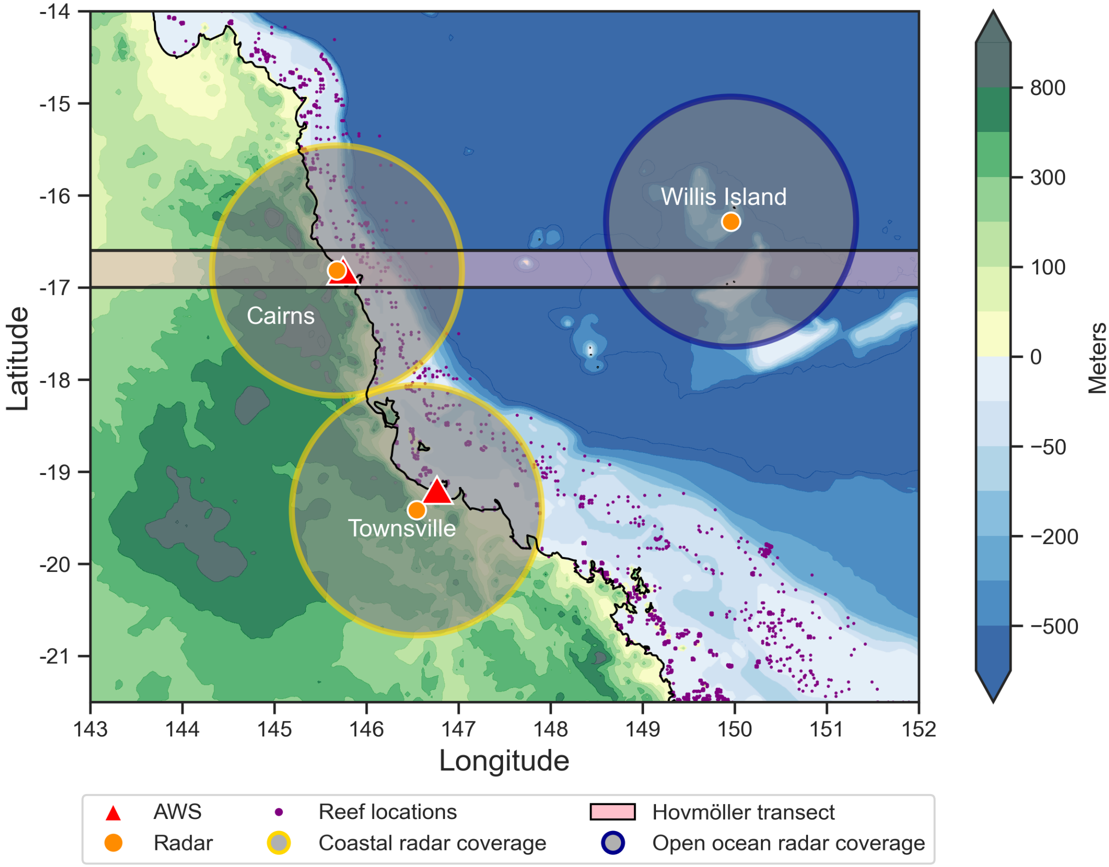

Figure 1. ~~Map of the study domain, including elevation above and below sea level for north–east Queensland produced using the NOAA ETOPO2 dataset. Shown is the complex coastal topography, shallow coastal oceans of the GBR, with reef locations (purple markers), and the deep bathymetry of the open ocean. The three large circles show the spatial coverage of the Townsville, Cairns and Willis Island radars, with orange markers indicating the radar site location. Townsville and Cairns Automated Weather Station (AWS) locations are marked by red triangles. Defined coastal and open ocean regions are indicated by the light blue and navy radar domain colours respectively (the coastline in black divides coastal land and ocean regions). Hovmöller analyses (see 2.2) is conducted over the horizontal transect shaded in pink.~~ Map of the study domain, including elevation above and below sea level for north–east Queensland produced using the NOAA ETOPO2 dataset (NOAA National Geophysical Data Center, 2006). Shown is the complex coastal topography, shallow coastal oceans of the GBR with reef locations (Lawrey and Stewart, 2016), and the deep bathymetry of the open ocean. Townsville and Cairns Automated Weather Station (AWS) locations are marked by red triangles. The three large gray circles show the spatial coverage of the Townsville, Cairns and Willis Island radars, with orange markers indicating the radar site location. Defined coastal and open ocean regions are indicated by the yellow and navy radar domain colours respectively (the coastline in black divides coastal land and ocean regions). Hovmöller analyses (see Section 2.2) were conducted over the horizontal transect shaded in pink.

domains, a simple easterly–westerly division was also adopted to ensure consistency and interpretability in the analysis. Further characterization of meteorological conditions were performed by calculating

To better understand the convective environments associated with each wind regime, the thermodynamic structure of the atmosphere was examined using vertical profiles of equivalent potential temperature (θ_e)using BARRA–R2 . Profiles were constructed at the BARRA-R2 grid point nearest to each radar site (Townsville, Cairns, and Willis Island), using temperature and specific humidity over the Townsville, Cairns and Willis Island radar domains for each wind regimefields across all pressure levels, calculated using the open-source MetPy Python package. θ_e is a combined measure of temperature and moisture, and it provides a useful indicator of an air parcel's convective potential. Higher values of θ_e suggest warmer or more moisture–rich conditions, whereas lower values are associated with colder or drier conditions. The vertical structure of θ_e also reveals information about boundary layer depth and stability, taking into account latent heat release from condensation of the moisture in the air. Analysis of θ_e anomalies associated with each wind regime was done by constructing a smoothed rolling mean climatology (for the period 1979-2024 Jan-Apr) to remove seasonal signals.

Instantaneous rain rate (R mm h^{-1}) was derived from the radar historical ground radar reflectivity factor (Z mm^6 m^{-3}) using the Z-R relationship, $Z = aR^b$. Further detail on a and b coefficients used are outlined in Appendix A Table A1. Prior to the diurnal analysis, the rain rate data required pre–processing to remove regions with erroneous data caused by the partial radar beam blockage from complex topography around the Townsville and Cairns radar sites. To identify regions with erroneous rain rate data, the climatological mean rain intensity over 2012–2022 was calculated, and a lower threshold was applied to exclude affected data from the diurnal analysis: 0.8 mm h^{-1} for Townsville and 1.2 mm h^{-1} for Cairns. No lower threshold was applied to the Willis Island radar data, as the highest elevation on the island is 20 m above sea level and topographic blockage is absent. However, the Willis Island radar exhibited the highest proportion of missing temporal data — 6.65% of periods analyzed — and also carries greater uncertainty in its rain rate retrievals due to the absence of co–located in situ rain gauges for calibration (Bowden et al., 2024).

Diurnal cloud and rainfall analyses focused on three distinct regions: coastal land, coastal ocean and open ocean, as indicated in Fig. 1. Coastal land is defined as land areas within the Cairns and Townsville radar domains, while coastal ocean encompasses the oceanic portions of these radar domains. These regions were delineated using land–sea masks derived from the National Oceanic and Atmospheric Administration (NOAA) 2–minute Gridded Global Relief Data (ETOPO2) v2 dataset, which provides high–resolution topography, bathymetry and shoreline information (NOAA National Geophysical Data Center, 2006). In this classification, coastal ocean areas are defined by surface elevation below 0 m ($z < 0$) and coastal land by elevation above 0 m ($z \geq 0$). The open ocean is defined as the area within the Willis Island radar domain. Given that Willis Island lies about 450 km from the Queensland coastline, and measures only about 500 m in length and 150 m in width, it is considered to have little to no land–surface influences on local convection and rainfall processes.

The diurnal mean hourly values of cloud BT, rain intensity and rainfall frequency across the CBS were computed for each of the three regions — coastal land, coastal ocean and open ocean — under the defined wind regimes. Rain intensity and frequency were calculated using a ±30–minute window around each hour to match the hourly temporal resolution of the cloud BT dataset. Rain intensity calculations include all time periods (i.e. raining and non–raining) to maintain consistency with BT diurnal cycles. Rain frequency was defined as the percentage of points in a given time step where rain rate was greater than 0.001 mm h^{-1}. An example of satellite–derived channel 13 BT and corresponding radar rain rate retrievals at a single time step over the Cairns radar domain is provided in Fig. 2.

The diurnal evolution of cloud and rainfall was examined through a Hovmöller analysis. A longitudinal transect was chosen which spans the coastal land, coastal ocean and open ocean regions (shown in pink in Fig. 1). This transect crosses both the Cairns and Willis Island radar domains, offering simultaneous data on cloud and rainfall characteristics for coastal land, coastal ocean and open ocean regions. Mean hourly values of BT and rain intensity were calculated for each longitude point along the transect using a narrow latitude range (16.6°–17° S), to minimize radar–induced noise. These data were used to generate Hovmöller diagrams that represent the mean diurnal cycle of each variable and reveal patterns in the spatiotemporal propagation of cloud and rainfall features across the domain.

3 Results

3.1 Background wind regimes

The large–scale wind regimes during the CBS period play a crucial role in shaping local thermodynamic environments and convective behavior. This section examines the characteristics of the four wind regimes (850 hPa winds) defined in Section 2.2. Figure 3a shows ~~the composite~~ histograms of the 850 hPa winds for each regime at the three study sites, while the monthly frequency distribution is presented in Fig. 3b–d. Additional statistical summaries are provided in ~~Table A2 in Appendix A~~ Appendix A Table A2.

The south–easterly wind regime, representing the trade winds, dominated across all three sites, accounting for ~~60–70~~57-67% of the CBS period. At Townsville, south–easterly winds were least frequent in January (about 50%) but increased steadily to ~~nearly 80~~75% by April. Cairns and Willis Island ~~showed a more delayed transition, with relatively stable~~ show relatively similar frequencies in January–February followed by a marked increase in March and April. This north–south contrast may reflect stronger tropical influences at the lower–latitude sites early in the season, and a progressive strengthening of the trade wind belt as the Inter–Tropical Convergence Zone (ITCZ) shifts northward.

The north–easterly wind regime was ~~on average~~ the second most common regime across all three sites during the CBS, occurring ~~14–24~~15-23% of the time~~on a seasonal mean basis~~. It was most commonly observed in January and February over Townsville (~~33.7% and 28.3~~31.5% and 27.6% respectively). Cairns and Willis Island exhibit less month–to–month variation in north–easterly frequencies (~~18.6~~19.1–~~20.2~~20.3%) during the same period of time, with a similar drop–off from March onward (Fig. 3~~b, c~~c, d). This regime's seasonal decline coincides with the strengthening south–easterlies, indicating ~~a shift in dominant flow as the tropical influence weakens~~weakening of tropical influences.

North–westerly and south–westerly regimes were relatively infrequent, each occurring in ~~6–12~~6-13% of CBS periods, with peak frequencies during January–February and a marked decline by April. South–westerlies became especially rare at Willis Island in April (~~3.5~~3.3%). While the northwesterly regime is likely associated with transient tropical lows, monsoonal flow, or monsoon burst events (Wheeler and McBride, 2012), the south–westerly regime is likely more closely linked to the passage of

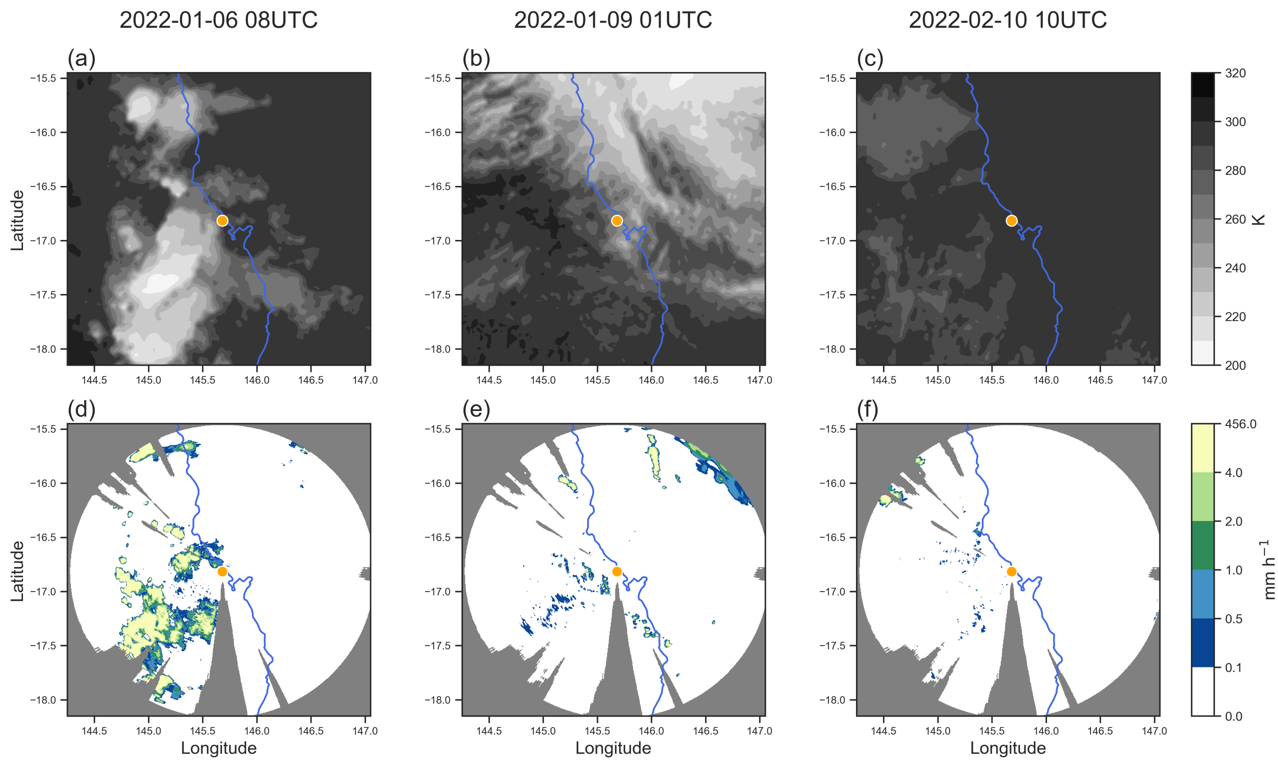

Figure 2. Snapshots of the cloud fields from satellite channel 13 BT and Cairns radar rain rate fields in UTC for: (a,d) 2022-01-06 0800~~06–01–2022~~; (b,e) 2022-01-09 0100~~09–01–2022~~; and (c,f) ~~1000 10–02–2022.~~ 2022-02-10 1000. All plots show the Cairns radar domain, with the Queensland coastline marked in blue (land on left). ~~In (a,b,c) orange~~ Orange markers indicate the Cairns radar site location~~, with a larger gray circle showing the radar range~~. Cloud BT is shown in filled gray–scale ~~shading~~ contours where white indicates colder BTs, and black indicates warmer BTs. Rain rate in (d,e,f) is shaded in color, with dark gray ~~hatching~~ shading indicating regions where no observations are taken (i.e. the corners of the Constant Altitude Plan Position Indicator radar retrieval grid) or masked (due to radar beam blockage).

cold fronts driven by deep mid–latitude troughs along the east coast (Kong and Zhao, 2010). The enhanced westerly flow and deep convection typical of north–westerlies are also consistent with active MJO phases influencing northern Australia (Dao et al., 2023).

In summary, south–easterly trades dominate the CBS period, with a clear seasonal transition replacing early–season tropical and cyclonic regimes — which drive the higher frequency of northerlies (Richards et al., 2026). Latitudinal differences suggest stronger tropical influence at Cairns and Willis Island, particularly early in the season, likely modulated by MJO activity, monsoon flows and ITCZ positioning.

3.2 Thermodynamic environment

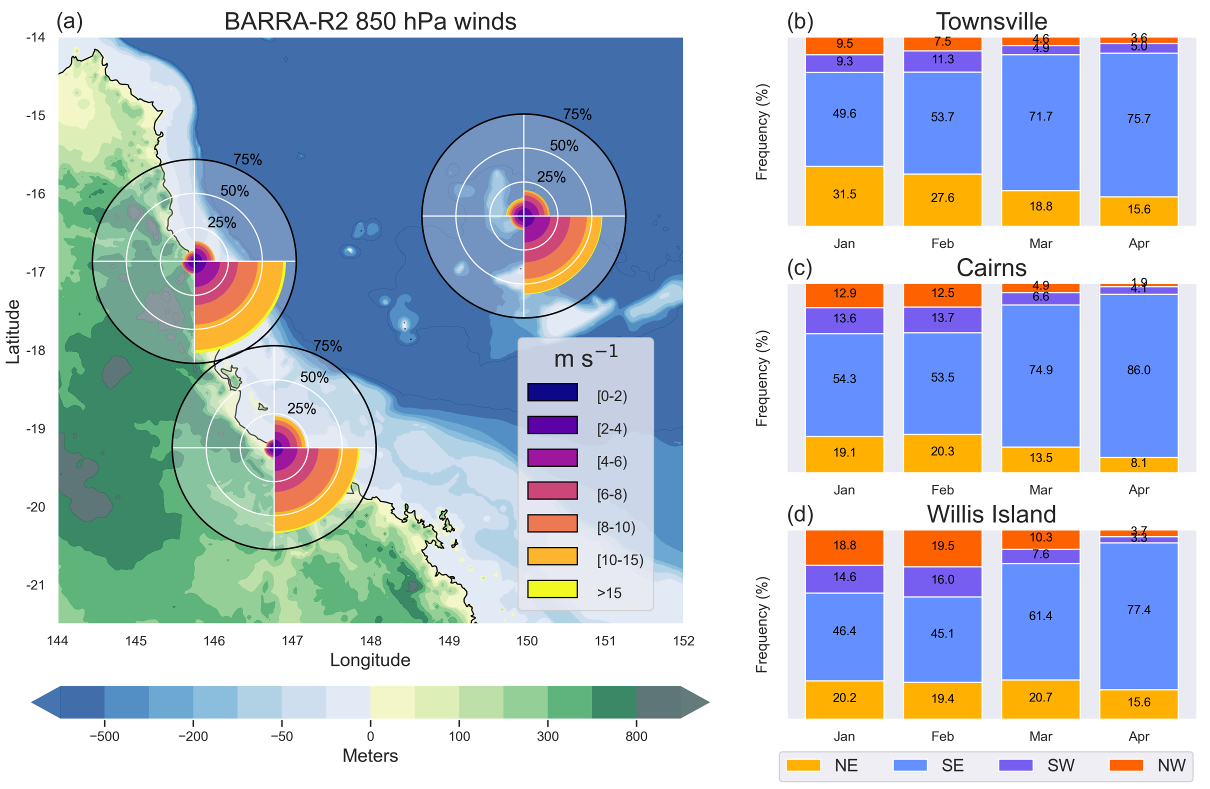

Figure 3. (a) Polar histograms over the CBS for BARRA–R2 850 hPa wind regimes defined in Section 2.2for the CBS. Bar length indicates wind direction frequency, and with colours indicating corresponding wind speeds in m s^{-1}. (b,c,d) shows the monthly regime frequency each month for Willis IslandTownsville, Cairns and TownsvilleWillis Island. BARRA–R2 850 hPa winds are averaged over each site's radar domain (see Fig. 1) for the CBS over the period 1979–2024.

To better understand the convective environments associated with each wind regime, we examine the thermodynamic structure of the atmosphere using vertical profiles of equivalent potential temperature (θ_e) from BARRA–R2. θ_e is a combined measure of temperature and moisture, and it provides a useful indicator of an air parcel's convective potential. Higher values of θ_e typically signify warmer, moister air masses, while lower values suggest drier or cooler air masses. The vertical structure of θ_e also reveals information about boundary layer depth and stability, taking into account latent heat release from condensation of the moisture in the air. The The CBS mean and wind–regime–averaged θ_e profiles for the three sites are shown in Fig. 4a, c, e, with anomalies relative to a smoothed rolling mean climatology shown in Fig. 4b, d, f.

The four large–scale wind regimes exhibit distinct thermodynamic signatures, as reflected in their The four large-scale wind regimes can be interpreted in terms of two key controls on convective potential: (i) the moisture and temperature characteristics of the air mass (θ_e anomaly profiles relative to the seasonal composite mean. The southmagnitude), and (ii) the vertical stability structure (θ_e gradient and inversion strength). To complement the θ_e analysis, corresponding Convective Available Potential

Energy (CAPE) and vertical velocity cross-sections from the BARRA-R2 reanalysis are presented in Appendix A (Figs. A1–~~easterly regime is characterized by the strongest~~ A2), providing additional insight into the spatial patterns of instability and large-scale vertical motion associated with each regime.

The four wind regimes represent fundamentally different thermodynamic and dynamical environments for convection. The south-easterly regime represents a cool, dry, and highly stable environment, with persistent negative θ_e anomalies ~~throughout the atmospheric column, indicating cooler and drier conditions likely originating from the subtropical Pacific. This regime is also marked by enhanced~~ through the column. Stronger warming aloft relative to the boundary layer enhances stability above the 600 hPa inversion~~(θ_e anomaly increasing with height), strongly suppressing deep convection.~~. This suppression is reflected in uniformly low CAPE, generally below 1000 J kg^{-1} over land and below 1500 J kg^{-1} over the adjacent ocean (Fig. A1d, h). The absence of large-scale ascent over the marine sector further limits opportunities for convective development (Fig. A2d). In contrast, the ~~north–easterly regime displays persistent positive~~ north-easterly regime is characterized by a warm and moist lower and mid-troposphere, but weak vertical θ_e ~~anomalies in the lower and mid~~gradients hence only moderate instability. Despite the moderate CAPE (2000–~~troposphere, reflecting the influence of warm, moist air masses from lower latitudes. However, the relatively weak vertical~~ 2500 J kg^{-1}) over the ocean, a pronounced band of deep ascent along the coastal ranges highlights the importance of orographic lifting in triggering convection (Fig. A2b). The interaction of moist north-easterly flow with the steep coastal terrain appears to locally release the available instability, focusing convection along the windward slopes. The south-westerly regime exhibits a more heterogeneous structure, with weak positive θ_e ~~gradient below the inversion suggests limited buoyancy and somewhat suppressed convective development despite the elevated total energy. South–westerly regimes reveal a~~ anomalies over land suggesting some surface-driven destabilization, while open ocean conditions remain close to climatology. CAPE shows a marked land–~~ocean contrast: over land, it shows modest positive θ_e anomalies and signs of surface–driven instability, while at Willis Island, θ_e remains closest to the climatological mean, implying minimal thermodynamic departure from baseline maritime conditions. North–westerly regimes exhibit the most pronounced~~ sea contrast, exceeding 3000 J kg^{-1} over the coastal ocean but remaining substantially lower further inland (Fig. A1c, g). Localized ascent along the windward coastal ranges highlights the importance of orographic forcing (Fig. A2c). However, the ascent is weaker than in the north-easterly regime, likely because the south-westerly flow encounters less abrupt upwind terrain. As a result, convection is likely influenced more by land surface heating and boundary-layer growth than by orographic lifting alone. By contrast, the north-westerly regime stands out as the most convectively favorable, with strong positive θ_e anomalies ~~, particularly~~ in the lower and ~~mid~~mid-levels and enhanced vertical gradients indicative of an unstable air mass. CAPE exceeds 2000–~~levels, alongside steep vertical gradients that signal strong instability and high convective potential. These patterns are~~ 3000 J kg^{-1} across much of the domain and is accompanied by deep, widespread ascent ($>$0.02 m s^{-1}), demonstrating that both thermodynamic instability and large-scale dynamical forcing support convection. This structure is consistent with monsoonal or tropical intrusions that inject warm ~~, moist , and energetically favorable air into the region~~and moist air masses, providing both moisture supply and reduced stability (Berry and Reeder, 2016). Together, these characteristics highlight how large–scale flow direction modulates both the source characteristics of air masses and the vertical thermodynamic structure that governs convective potential across the study region.

The diurnal evolution of θ_e ~~(~~under each wind regime is shown in Fig. 5 ~~) across the three sites highlights the combined influence of synoptic wind regimes and surface characteristics on the boundary layer structureand convective potential. At the two~~ as anomalies relative to a smoothed rolling mean climatology over the CBS. Consistent with Fig. 4, the wind regimes primarily define the background thermodynamic state, setting the moist static energy and stability structure. In particular, north-westerly flow associated with the highest θ_e and weakest stability, north-easterly flow showing intermediate moistening, and south-easterly flow characterized by persistently low θ_e and enhanced stability. Figure 5 further shows how this background state is modulated by the diurnal cycle. A clear contrast emerges between the coastal land sites ~~—~~(Townsville and Cairns~~—~~) and the marine site (Willis Island). Over land, θ_e profiles ~~show stronger diurnal modulation~~ exhibit strong diurnal modulation of the lower troposphere, especially under ~~south~~north–westerly regimes ~~, reflecting land~~ (Fig. 5a, f). Positive θ_e anomalies larger than 6 K occur during the afternoon and early evening, reflecting daytime surface heating and ~~boundary layer deepeningduring the day. Townsville exhibits the most pronounced diurnal growth in θ_e under south~~boundary-layer deepening, which enhance near-surface moist static energy and convective potential. Townsville shows the strongest response under north–westerly ~~flow, pointing to enhanced surface~~flows, consistent with more intense land–~~driven convection. Cairns shows similar patterns, albeit more subdued, with notable θ_e enhancement below 600 hPa under south–westerly conditions.~~ surface forcing under this regime. Cairns exhibits a similar but slightly more muted behavior except under south-easterly conditions, where the diurnal signal is substantially suppressed (Fig. 5f, g, h). In contrast, Willis Island shows ~~minimal~~ little systematic diurnal variability across all regimes, ~~reflecting the stabilizing influence of the ocean surface . Regime–wise, north–westerly flow at all sites generally brings high~~ indicating that the absence of strong land surface forcing limits sub-daily modulation of θ_e ~~values and weaker stability, favoring convection, while north~~in the marine boundary layer (Fig. 5k, l, m, n). This sharp land–~~easterly flow produces moist but capped profiles with limited diurnal evolution. South–easterly regimes consistently feature the lowest θ_e values and most stable conditions across all sites, indicating suppressed convective potential~~sea contrast highlights the dominant role of surface heating in driving diurnal thermodynamic variability. Overall, these features underscore the interplay between large–scale flow direction and surface type in shaping diurnal thermodynamic evolution and the likelihood of convective activity.

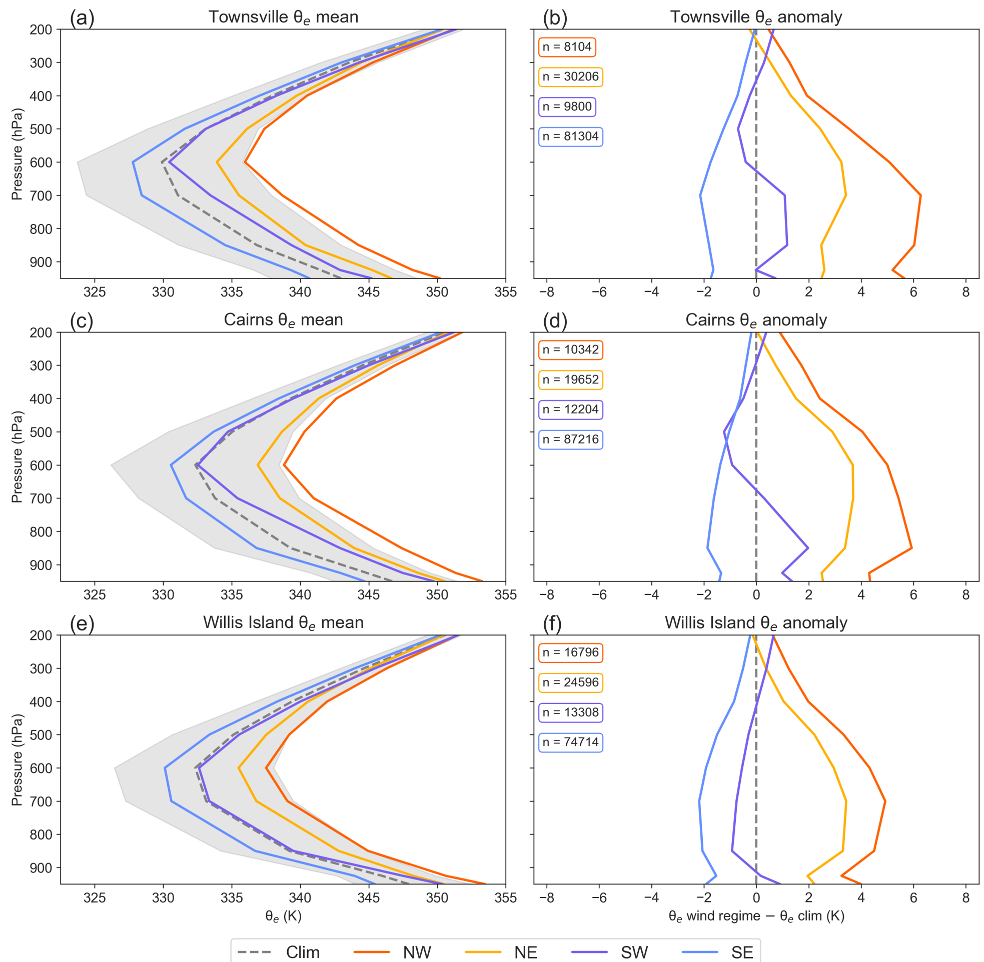

Figure 4. ~~Mean and anomaly θ_e profiles for Townsville (a,b), Cairns (c,d) and Willis Island (e,f) domains under each wind regime (north–easterly: NE, south–easterly: SE, south–westerly: SW, and north–westerly: NW) for the CBS over the period 1979–2024 from BARRA–R2. Sample sizes for each site across all times and pressure levels are provided for each regime. Grey shading indicates the interquartile range of the θ_e profile.~~Mean and anomaly θ_e profiles for Townsville (a,b), Cairns (c,d) and Willis Island (e,f) radar sites under each wind regime (north–easterly: NE, south–easterly: SE, south–westerly: SW, and north–westerly: NW) for the CBS over the period 1979–2024 from BARRA–R2. Anomaly plots are calculated by subtracting a smoothed rolling mean climatology from each timestep within the wind regime-classified periods, then averaging across all time steps within each regime to remove seasonal signals. Sample sizes for each site across all times are provided for each regime. Grey shading indicates the inter-quartile range of the θ_e profile.

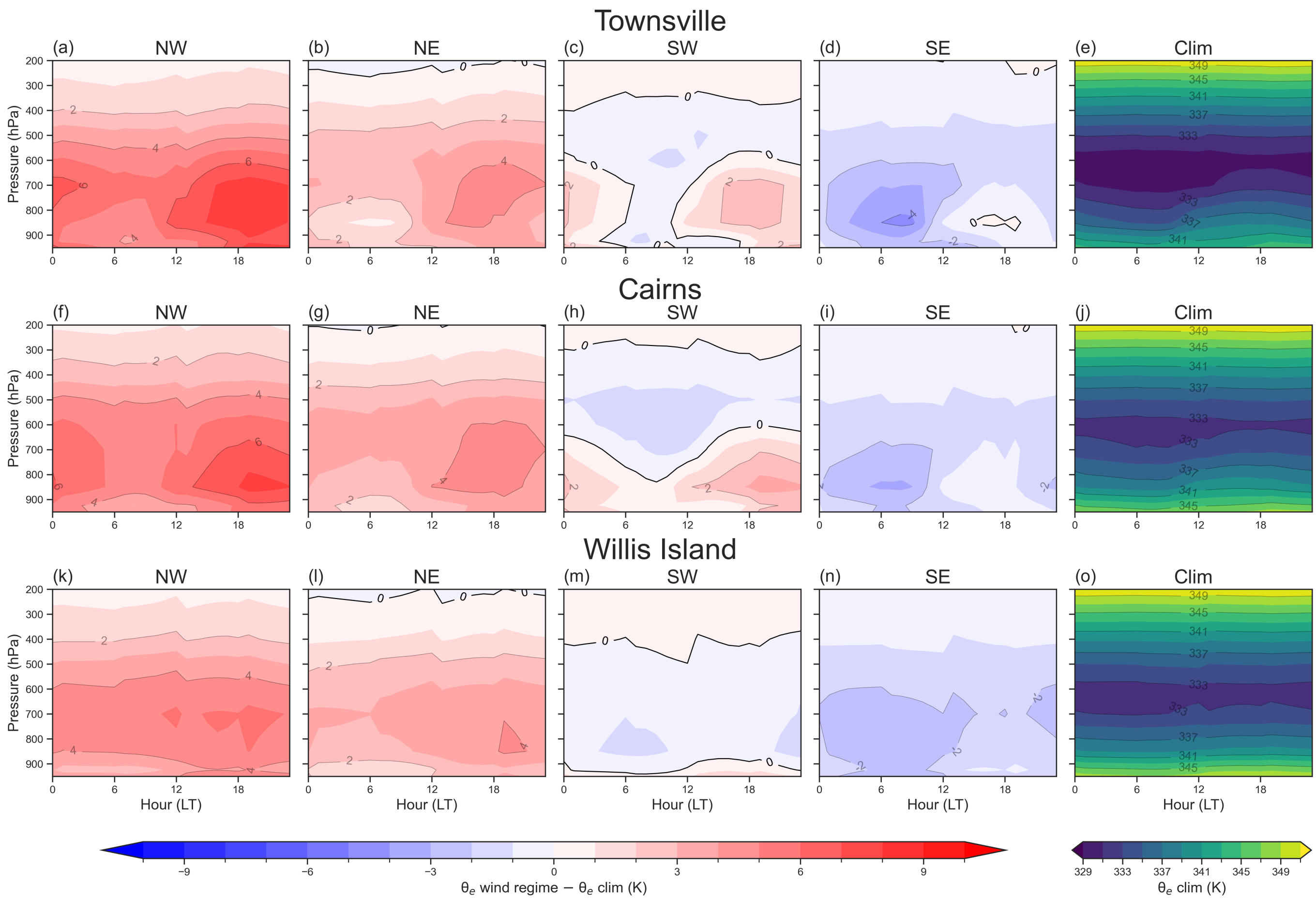

Figure 5. ~~Hourly mean equivalent potential temperature profiles for (a,b,c,d) Townsville, (e,f,g,h) Cairns and (i,j,k,l) Willis Island radar domains under each wind regime (north–westerly: NW, north–easterly: NE, south–westerly: SW, and south–easterly: SE) for the CBS over the period 1979–2024 from BARRA–R2.~~ Diurnal θ_e profile difference plots between wind regimes and a smoothed rolling mean climatology over the CBS for (a,b,c,d) Townsville, (f,g,h,i) Cairns, and (k,l,m,n) Willis Island. (e,j,o) show the CBS mean θ_e diurnal profiles over the period 1979–2024 (Jan-Apr). Note that the 'Clim' panels for each site (e, j, o) represent the CBS climatological mean for reference, and are not equivalent to the smoothed rolling mean used in the difference plots (which varies at daily time resolution).

3.3 Diurnal cloud and rainfall characteristics

Next we examine how these thermodynamic conditions influence the diurnal evolution of cloud and rainfall patterns. Differences In general, differences in vertical stability and moisture content across wind regimes are expected to influence not only the likelihood of convection but also its timing and intensity throughout the day. The mean diurnal cycles of satellite–derived Brightness Temperature (BT) from the 10.4 μm infrared wavelength band (channel 13) and radar–derived rainfall frequency and intensity under different wind regimes are presented in Fig. 6. The , with the seasonal mean conditions are provided in the Supplementary Material (Fig. ??). BT serves shown in Fig. 6 m, n, o. BT is used as a proxy for cloud heightand type — colder BTs indicate cloud-top height, with colder BTs indicating higher, deeper clouds often associated with convection , while warmer BTs suggest fewer or lower level clouds. and warmer BTs suggesting shallow cloud or clearer conditions.

A first-order feature across all regimes is again a strong land-sea contrast in the diurnal cycle. Over land, BT typically increases through the morning and decreases sharply in the afternoon to evening, consistent with boundary-layer growth and the development of deep convection, accompanied by a corresponding increase in rainfall frequency and intensity. Over the coastal ocean, this signal is phase-shifted, with rainfall and colder BTs generally occurring from evening to early morning. In contrast, Willis Island exhibits minimal diurnal variability in both BT and rainfall, reflecting weak surface forcing in a more homogeneous marine environment.

NorthSuperimposed on this common structure are regime-dependent modulations that primarily affect amplitude, timing, and convective characteristics. The north–easterly regime is characterized by relatively colder BTs , and more frequent, intense rainfall than and enhanced rainfall compared to the seasonal mean, especially over land. Cairns , in particular, experiences the strongest diurnal signals among all three sites, with BTs over land warming through the morning (peaking around 12 LT at reaching 277 K) and sharply cooling at 11 LT) and cooling rapidly into evening (250 K by at 19 253 K by 18 LT), indicative of deepening vigorous deep convection. Townsville shows a similar warming trend (approximately 1 K per hour) but with more gradual cooling, about half of the rate at Cairns, likely reflecting the reduced influence of orographic uplift and elevated terrain heating compared to Cairnsweaker orographic enhancement. Rainfall frequency and intensity at both land sites mirror these BT patternsclosely follow this evolution, peaking in the afternoon–evening, especially at Cairns, with moderate amplitudes of 6.25% and 0.34 6.65% and 0.61 mm h^{-1}. Notably, peak rainfall A notable feature is that peak rainfall at 16 LT precedes the coldest BTs by several 3 hours, suggesting that the coldest minimum BTs likely reflect the later anvil-dominated stage of convection rather than the peak rainfall phase.expansion of convective anvil clouds following the main rainfall event. Over the coastal oceans, rainfall follows the BT cycles which are present but with weaker amplitudes, with both rainfall peaks and minimum BTs occurring in the evening. Willis Island shows minimal diurnal variation in either field, consistent with weaker surface forcing. Overall, the diurnal variations in cloud and rainfall across these sites and the land–ocean contrastalign with thermodynamic conditions marked by high total energy but somewhat constrained buoyancy, which limits the potential for deep convective development.

The In contrast, the south–easterly regime , dominated by trade–wind conditions, exhibits is characterized by the warmest BTs and the lowest rainfall frequencies and intensities weakest rainfall across all land regions— with the exception of the south–westerly regime during the day. These patterns suggest shallow, low–topped , consistent with shallow, low-topped cumulus clouds and reduced convective activitysuppressed deep convection. Unlike the north–easterly regime, BT and rainfall diurnal cycles in the south-easterly regime over Cairns and Townsville are more synchronized and subdued, though rainfall intensity over Cairns is slightly enhanced in the afternoon — likely due to orographic lifting/elevated heating. Cloud and rainfall variability over again likely linked to localized orographic lifting and elevated terrain heating, which can partially overcome the otherwise stable background conditions. Over the coastal and open ocean remains limited, with minimal diurnal amplitudeoceans, both BT and rainfall variability remain weak throughout the day, consistent with the more stable marine boundary layers and low–level trade wind cumulus . These characteristics are broadly consistent with the thermodynamic constraints described above. dominated by shallow trade-wind cumulus and limited diurnal destabilization.

South–westerly regimes display regime exhibits very strong diurnal modulation in both BT and rainfall, suggesting enhanced surface–driven convection. Over Cairns and Townsville, BTs peak around midday 11–13 LT (295 K land, BTs peaks around midday (296 K at Cairns and 298 K at Townsville), indicating minimal cloud cover, and drop before dropping sharply in the afternoon. Correspondingly, rainfall frequency and intensity are minimal around midday but increase later in the day, with rapidly in the early afternoon, reaching maxima in the late afternoon over land and shifting to early morning over the coastal ocean. Cairns generally exhibits more experiences more frequent and intense rainfall than Townsville, particularly in the afternoon–evening . Oceanic domains period. Oceanic regions show comparable rainfall magnitude across both coastal sitesnear the coast, while Willis Island again shows little diurnal variability, reflecting its open–ocean character. These patterns align with the south–westerly regime fostering deeper, more organized convection through localized surface heating and atmospheric destabilization.

The north–westerly regime is associated stands out as the most convectively active, with the coldest BTs and the most frequent and intense rainfall , particularly during the peak phase of the diurnal cycleshighest rainfall frequency and intensity. Over land, convection deepens through the afternoon, accompanied by cooling BTs and increased rainfall. Again, the rate of change in cold BTs lags the increase in rainfall by several hours, likely reflecting the typical progression of convective development: rainfall intensifies during the early to mature stages of convection , while significant BT cooling (marking the development of deep cloud tops) peaks later, during the mature to stratiform transition phase. Notably, with progressively colder BTs and increasing rainfall. The most intense rainfall over land peaks at 17 LT, whereas peak rainfall frequency and cold BTs lag by 3 hours, again reflecting a transition from active convection to mature and stratiform/anvil-dominated cloud. Over the coastal oceandomains show strong diurnal cycles, strong diurnal structure is evident, with daytime (11–14 LT) BT warming and suppressed rainfall , followed by nocturnal intensification. The large amplitudes of cloud and rainfall signals over the coastal ocean highlight the strong diurnal forcing under the north–westerly this regime. In contrast, over the open ocean (Willis Island) the cloud BT and rainfall cycle is weak with no clear signals . The north–westerly observed cloud and rainfall characteristics correspond to strong instability from Willis Island shows only weak signals in both fields, consistent with the open-ocean environment. These features are consistent with enhanced instability associated with elevated θ_e and steep gradients , strong vertical gradients fueled by moist north–westerly inflow. Diurnal patterns over land and coastal ocean reflect surface heating and boundary–layer dynamics.

Overall, the diurnal ~~variations in~~ evolution of brightness temperature and rainfall ~~are strongly influenced by prevailing wind regimes , which control the depth and intensity of convection through their thermodynamic characteristics. North~~reflects a consistent interaction between large-scale wind regimes and surface forcing. The wind regimes control the background thermodynamic environment and convective potential, while land–~~westerly flows promote deeper, more intense convection and rainfall, while southeasterly trades favor shallower, weaker cloud systems with limited rainfall. Surface heating and boundary–layer processes drive pronounced diurnal cycles over land and coastal regions, particularly under south–westerlies, but these effects diminish over the open ocean~~sea contrasts regulate the timing, propagation, and amplitude of the diurnal cycle, with the strongest organization occurring under south-westerly and north-westerly regimes and the weakest under south-easterly trade conditions.

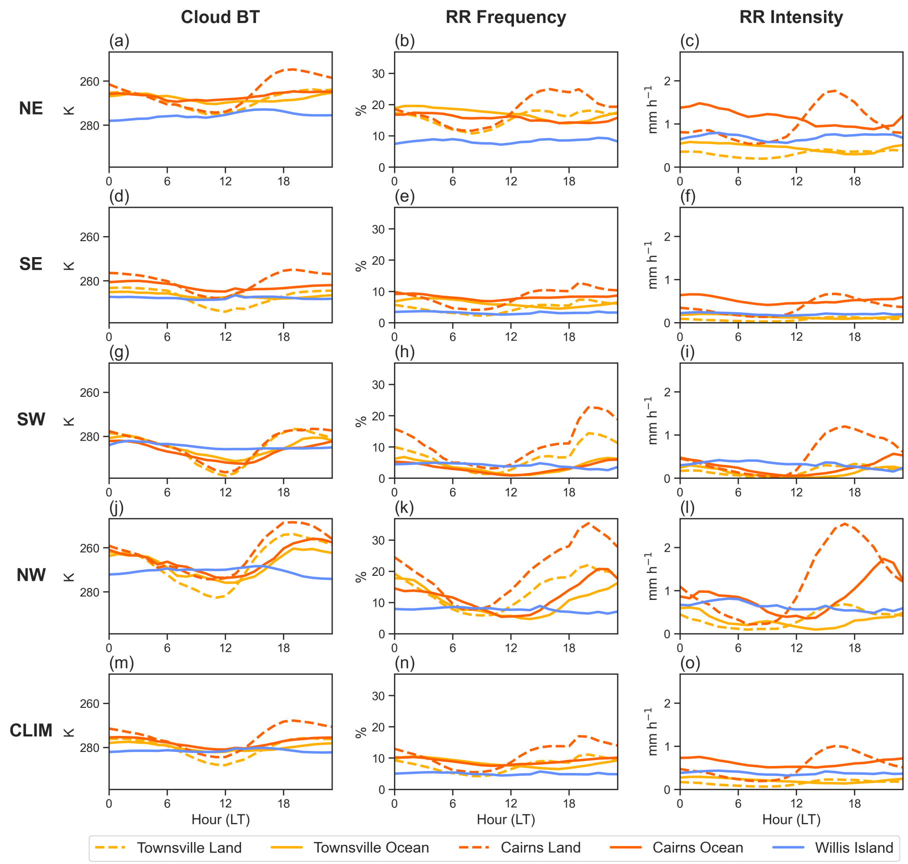

Figure 6. Diurnal cycle ~~hourly means~~ of Himawari–8 satellite channel 13 BT (10.4 μm infrared wavelength band), radar retrieved rainfall frequency (percentage of points greater than 0.001 mm h^{-1}) and intensity (mean rain rate) calculated over the CBS for each wind regime and site. Each row ~~(a, b, c)~~ shows the corresponding BT, rainfall frequency and rainfall intensity with consistent y-axes for each ~~site~~wind regime– with different colored lines for each site. Townsville and Cairns are separated into land (dashed) and ocean (solid) domains, associated with their radar coverage. The BT y–axis is inverted, so that peaks in the diurnal cycle indicate colder BTs. Rain intensity is calculated for all periods of valid data (not just raining periods).

3.4 Spatial structure and propagation

Building on the discussion of diurnal BT and rainfall cycles, Hovmöller diagrams were produced to examine ~~evolution over~~ the spatial evolution and propagation of convection through time. Using the method ~~discussed~~ described in Section 2.2, Fig. 7 shows BT and rain intensity (averaged across both raining and non–raining periods) under each wind regime defined by the Cairns domain ~~.~~ with terrain elevation in Fig. 7e, f (for reference).

A consistent feature across all regimes is the strong influence of coastal geometry and topography on convective initiation and propagation. Convection typically develops over or near the coastal ranges during the afternoon before propagating either inland or offshore depending on the prevailing background flow. The extent, speed, timing, and organization of this propagation vary substantially between regimes, indicating strong modulation by the large-scale thermodynamic and kinematic environment identified in the previous sections.

The clearest offshore propagation occurs under the north-westerly regime. In this regimes, BTs below 253 K develop by 16 LT over coastal land, particularly near regions of elevated terrain (Fig. 7a, e). Nighttime propagation of convection is evident over the coastal and open oceans, with BTs below 263 K reaching 200–300 km offshore, and rainfall extending to the eastern edge of the Cairns radar domain. Inland propagation is comparatively weak in this regime. The coldest BTs are largely confined to near–coastal waters (within 100 km of the coastline) and are associated with relatively slow-moving rainfall features (2–5 m s^{-1}). In contrast, warmer BTs propagate farther offshore more rapidly, at speeds of 12–15 m s^{-1}. In this regime, the coldest BTs correspond closely with the most intense rainfall.

Under the north–easterly regime (Fig. 7b), widespread moderate coastal rainfall persists throughout the day, consistent with a moist environment~~. BTs over the coastal ocean region remain colder than 273 K throughout the diurnal cycle. The coldest~~, while colder BTs (below 263 K) ~~are observed~~ develop over land and ~~the adjacent coastal ocean in~~ adjacent coastal waters during the evening to early morning period. From around 12 LT, BTs below 273 K ~~begin to propagate across coastal areas,~~ propagate both inland and offshore~~. Inland convection advances westward at speed of~~ , although the inland signal is more coherent and appears more directly linked to coastal convective development. Inland propagation speeds reach approximately 30 m s^{-1}, ~~reaching the western boundary of the study domain, over~~ extending more than 300 km westward from the coastline. ~~Apparent eastward propagation over the domain also occurs at similar speeds, crossing the westward edge of the Willis Island domain, about 300–400 km offshore. However, this offshore signal may reflect a broader open–ocean feature rather than true propagation, since colder BTs can also be seen over the open ocean under other regimes with no clear link to coastal activity. BTs below 263 K first appear over coastal land around 16 LT and then propagate inland at similar speeds and distances.~~ The coldest BTs are typically found on the leeward side of the mountain ranges between ~~18~~19–22 LT, traveling westward — suggesting convection enhanced by mountain effects that produce strong thunderstorms propagating westward into the evening.

~~Under south–easterly regimes, light–to–moderate coastal rainfall is again present but confined to a more limited area. Cold BTs start propagating inland from the coast by 13 LT, penetrating more than 200 km inland at speeds of 12–15 m s^{-1}, with the coldest BTs emerging about 250 km from the coast in the late evening between 22–01 LT, suggesting storm enhancement during inland propagation. Rainfall follows a similar westward propagation, though slightly slower (10–15 m s^{-1}), and generally tracks the BT contours. Notably, a spike in afternoon rain intensity is observed over elevated terrain, which may reflect orographic enhancement rather than a propagating disturbance, though potential radar artefacts cannot be ruled out. Over the coastal ocean, convection is less clearly defined, and no consistent signal of offshore propagation is observed~~Offshore propagation is also apparent in the BT field, though this signal is less clearly tied to coastal convection and may partly reflect broader open-ocean cloud variability. Compared to the north-westerly regime, convection appears less organized offshore but more effective at penetrating inland.

For south–westerly regimes (Fig. 7c), coastal rainfall exhibits a pronounced diurnal cycle, with little to no rainfall occurring from early morning through to midday before convection rapidly intensifies during the afternoon. ~~Hovmöller analysis indicates~~

BTs below 273 K forming over land , particularly on the windward side of the topography. This convection then propagates BTs below 283 K form over land during the afternoon before propagating both inland and offshore, with the coldest BTs occurring between 20. The coldest BTs occur between 18–23 00 LT over land. Relatively cooler bands of convection can be seen moving offshore reaching distances of approximately 200 Early morning convection moves offshore by approximately 100 km, associated with light rainfall. In general, rainfall contours track closely with cloud BTsRainfall contours generally track the BT evolution closely, although peak rainfall (orange and red contoursblue) often occurs prior to the appearance of the coldest BTs — again suggesting these may correspond to high–level anvil clouds decoupled from topographic influence. This regime is also the only one to show rainfall possibly aligned with BT propagation over Willis Island (03–09 LT), although the low rainfall frequency means there is considerable uncertainty.

Under northUnder south–westerly regime, BTs below 263 Kdevelop by 17 LTover coastal land, especially on the windward side of the topography. Nighttime propagation of convection is evident over the coastal and open oceans, with BTs below 273 K reaching 200easterly regimes, light–300 km offshore, and extending to the eastern edge of the study domain. Inland propagationis less well defined. The coldest BTs are largely confined to nearto–coastal waters (within 100 km of the coastline) and are associated with rainfall moving at slower speeds (2moderate coastal rainfall is present (similar to north-easterly regimes) but confined to a narrower coastal region. Cooler BTs (283 K) start propagating inland from the coast by 15 LT, penetrating more than 200 km inland at speeds of 12–15 m s^{-1}). In contrast, warmer BTs propagate farther offshore more rapidly, at speeds of 12^{-1}, with the coldest BTs emerging about 250 km from the coast in the late evening between 20–03 LT, suggesting storm enhancement during inland propagation. Rainfall follows a similar westward propagation, though slightly slower (10–15 m s^{-1}). In this regime, the coldest BTs correspond closely with the most intense rainfall ., and generally tracks the BT contours. Compared with the other regimes, convection remains weaker and less spatially extensive, consistent with the more stable trade-wind environment discussed earlier. Localized regions of enhanced afternoon rainfall over elevated terrain further indicate an important role for orographic forcing under otherwise suppressed convective conditions. Over the coastal ocean, convection is less coherent and no strong offshore propagation signal is evident.

The spatial patterns and propagation characteristics of the BTs and rainfall suggest that land–sea breeze circulations play a variable but important role in shaping the diurnal development of convection over north–east Queensland, depending on the prevailing wind regime. Figure 8 presents surface wind roses at 07 :00 and 15 :00 local timeLT, alongside the diurnal evolution of hourly average wind speed and direction at Cairns and Townsville stations. weather stations. We use station-based surface wind observations here rather than the BARRA–R2 reanalysis as the 12 km horizontal resolution of the reanalysis may be too coarse to reliably resolve these coastal circulations. While a classic wind reversal pattern is not observed (likely due to the region's complex coastal geometry and orographic influences), distinct afternoon landward winds indicative of sea–breeze influence are observed at both stations. Similarly, evening seaward winds consistent with land–breeze activity are also evident, supporting the presence of thermally driven circulations despite terrain–induced variability.

Further detail on the variable influence of land–sea breeze circulations can be seen in the contrasting diurnal convection surface wind patterns observed across different wind regimes at Cairns (Supplementary Fig. ??A3). Afternoon landward winds are evident across all regimes, though with varying strength, which is a reflection of the modulating effect of background winds and possibly the topographic flows. This variation helps explain the differing speeds and inland reach of the convective propagation seen in Fig. 7, where convection initiates near the coast in the early afternoon and moves inland at speeds characteristic of sea–breeze dynamics. In contrast, seaward winds are most pronounced under the two westerly regimes, aligning with the offshore–propagating convection that peaks in the evening shown in Fig. ~~??~~7. This suggests a potential role for nocturnal land breezes in triggering marine convection, though the extent of offshore propagation also depends on ambient moisture availability and background wind strength, which influence the distances over which colder BTs are observed.

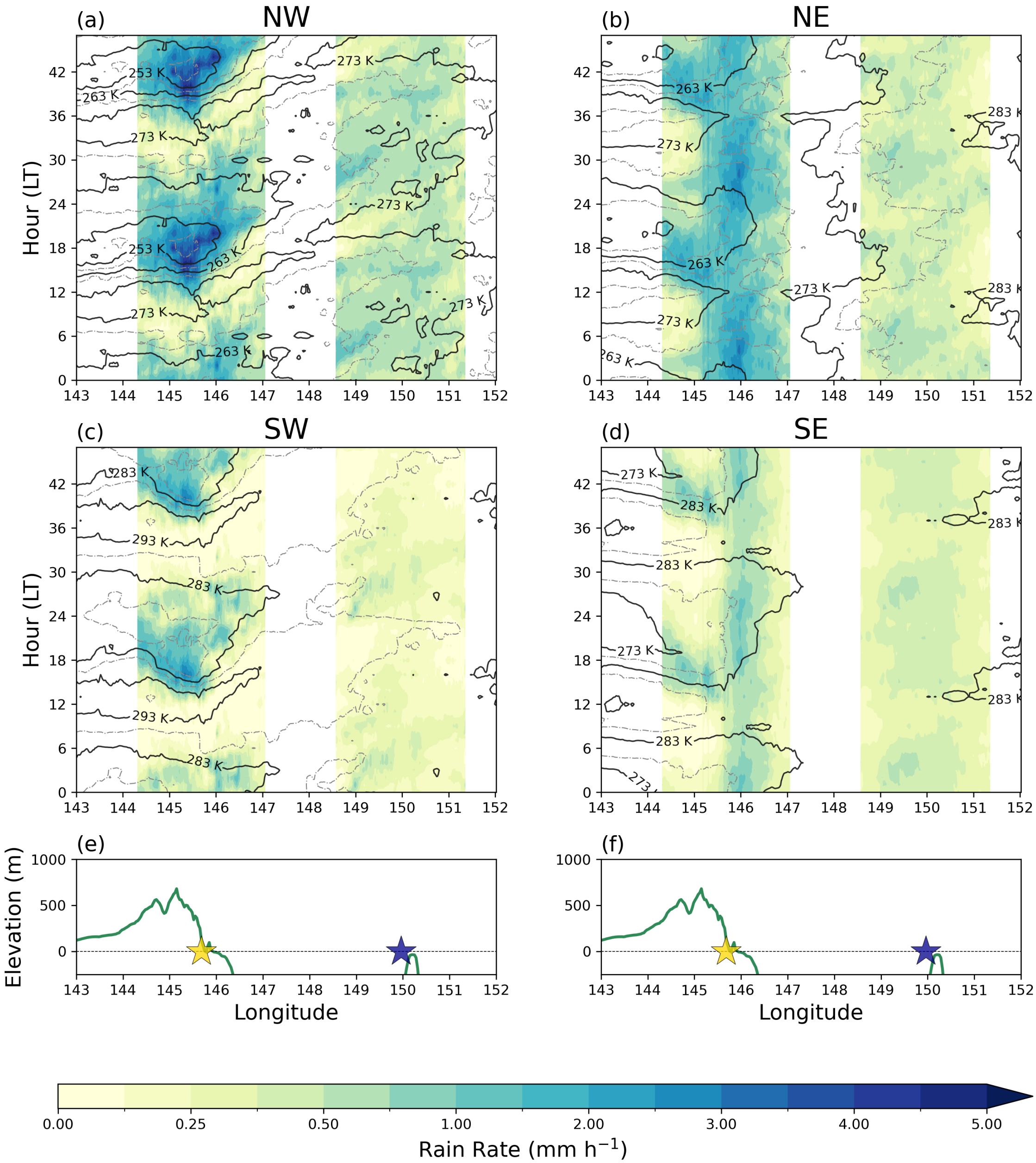

Figure 7. Hovmöller ~~diagram~~ diagrams of ~~mean daily~~ cloud BT and rain intensity (including non–raining periods) for the longitudinal transect shown in Fig. 1~~under each regime~~. (a,b,c,d) show labeled cloud BT contours for 253 K, 263 K, 273 K, 283 K and 293 K (with dashed gray contours every 5 K), along with rainfall data from the Cairns (left ~~colored contour column~~filled contours in each panel) and Willis Island radars (right ~~colored contour column in each plot~~filled contours) under each wind regime. The ~~vertical black dashed line marks the coastline (land on left), the solid black contour lines indicate 273 K BT, and dashed black contour lines indicate 263 K BT. Estimates of inland and offshore convection and rainfall propagation are indicated on the plots through solid black and dashed black lines respectively. The~~ y axis (in ~~Local Time;~~ LT) is repeated to show clear propagation of cloud BT and rainfall between the evening and morning. (e) shows elevation from NOAA National Geophysical Data Center (2006) averaged over the longitudinal transect, with this plot repeated in (f) for referral to the above panels. Yellow and blue stars indicate the longitude of the Cairns and Willis Island radar site respectively, with a black dashed line at 0 m elevation.

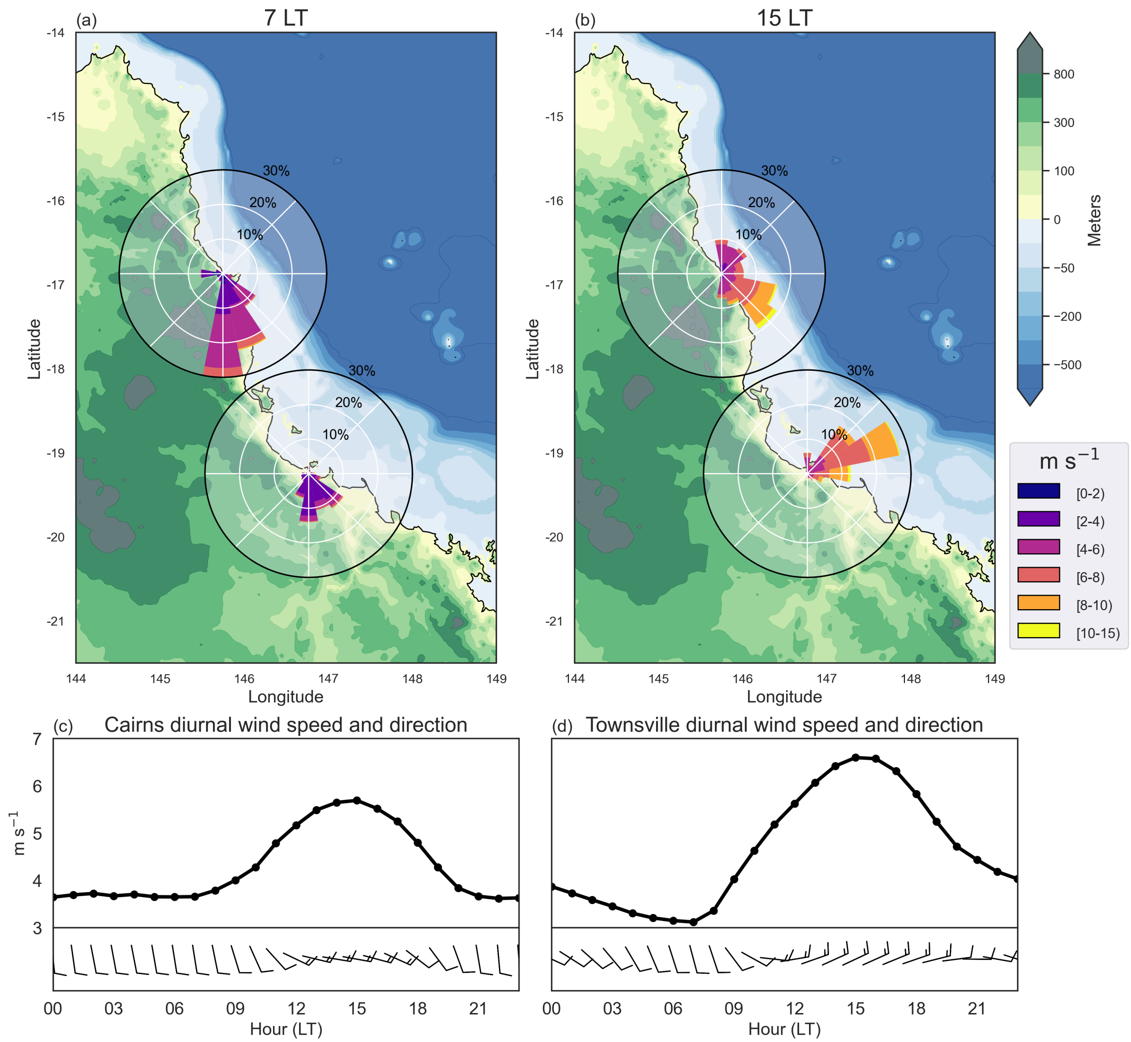

Figure 8. (a,b) Cairns and Townsville AWS surface winds. Wind roses show the surface wind frequency and magnitude at 07 and 15 LT. (c,d) show hourly averaged wind speed and direction (wind barbs; calculated using a circular mean) for each station.

4 Discussion

Our analysis reveals distinct diurnal patterns of convection and rainfall across the Greater GBR region in northeast Queensland Australia, shaped by background wind regimes, geographic features, and atmospheric conditions. Consistent with prior tropical studies (As-syakur et al., 2019; Lopez-Bravo et al., 2023b, 2025; Mori et al., 2004), the coldest cloud tops — indicative of deep convection — are primarily observed over land in the evening, coinciding with the timing of upslope winds from daytime heating and sea–breeze convergence. In contrast, convection over the adjacent coastal ocean peaks later, typically overnight to early morning, propagating offshore at speeds consistent with density currents near the coast and gravity waves further offshore (Dipankar et al., 2019; Lopez-Bravo et al., 2023a; Vincent and Lane, 2016). Notably, the influence of land–sea breeze circulations varies across different background wind regimes, modulating the extent, timing, and propagation of convection.

Figure 9 provides a conceptual summary of the contrasting diurnal cycles of cloud and rainfall, along with the ~~hypothetical~~ proposed mechanisms of convection initiation and propagation. It is intended as a framework for interpreting the observed diurnal cloud and rainfall behavior, rather than a complete or definitive description of all underlying processes. Some elements are necessarily interpretative, particularly where direct observational constraints are limited, and are therefore presented as hypotheses consistent with the observed patterns and existing literature. The schematic spans five key time periods — nighttime, early morning, ~~midday, late afternoon, evening, and nighttime~~ morning, afternoon, and evening — and outlines the general evolution of convection and rainfall across the three sites. ~~While some elements are necessarily speculative, given the limitations of observations alone, the diagrams synthesize evidence presented in this study and highlight key processes that warrant~~ We also include gravity waves within Fig. 9 which are not fully evidenced in our analysis given the limitation of observations — instead inferred from our estimated convection propagation speeds which are consistent with gravity waves as a mechanism for offshore convection in previous literature (Mapes et al., 2003; Yokoi et al., 2017). These diagrams synthesize well-supported findings from this study with more tentative, literature-informed mechanisms to identify key processes warranting further investigation in future work.

Under the southeasterly regime, weak large–scale forcing and minimal atmospheric instability limit the development of deep convection. As a result, precipitation is dominated by shallow trade wind cumulus producing light, widespread rainfall. Coastal enhancement of convection is persistent, driven by the combined effects of sea breeze convergence and orographic uplift. Diurnal variability is weak, with rainfall occurring sporadically throughout the day.

In the northeasterly regime, warm, humid air masses advected from lower latitudes contribute to elevated equivalent potential temperature. However, despite the abundant moisture, relatively ~~weak~~ moderate instability and limited buoyancy inhibit the formation of deep convection. Precipitation primarily consists of ~~light to~~ moderate coastal rainfall, with ~~inland propagation driven by the~~ convection strongly influenced by orographic lifting, as moist north-easterly flow interacting with the steep coastal ranges locally releases the available instability and focuses ascent along the windward slopes. Inland propagation is driven by diurnal cycle through combined effects of sea breeze circulations and orographic lifting, and offshore propagation likely influenced by gravity wave activity. North–easterly regimes show the largest inland propagation of deep convection, reaching the up wind (western) side of the coastal mountain ranges. The offshore signal, however, is partially obscured by the widespread moisture associated with this regime.

The southwesterly regime promotes deeper and more organized convection, primarily driven by strong localized surface heating and enhanced atmospheric destabilization. This occurs despite the relatively moderate equivalent potential temperature associated with the cooler air masses linked to passing mid–latitude systems. Pronounced diurnal cycles of cloud and rainfall are observed over both coastal land and adjacent ocean, with the sunniest conditions typically occurring from early morning fostering surface heating that initiates afternoon convection.

The northwesterly regime is characterized by the most intense convection, supported by the highest levels of equivalent potential temperature. It exhibits the strongest diurnal variability and produces the heaviest rainfall among the four regimes. Intense precipitation occurs over both coastal land and adjacent ocean, while widespread, persistent moderate rainfall extends across the open ocean. Although inland propagation is less clearly defined, pronounced offshore propagation is evident and appears consistent with a transition from density current outflow to gravity wave–driven processes.

Together, these four regimes highlight the diverse atmospheric conditions influencing clouds and sub–daily rainfall along the Queensland coast. The contrasting roles of large–scale moisture availability, thermodynamic instability, and local forcing mechanisms—such as sea breeze circulations and orographic effects — shape not only the intensity and spatial distribution of clouds and rainfall, but also its diurnal variability ~~.~~ and propagation characteristics. Importantly, our results suggest that cloudiness over the GBR cannot be considered solely as a local marine phenomenon. Instead, cloud cover over reef environments is closely linked to the evolution of nearby coastal convection and its subsequent inland or offshore propagation. The differing propagation characteristics among wind regimes imply that the timing, extent, and persistence of cloud cover over the GBR may vary substantially depending on the prevailing large-scale circulation. Given the recognized influence of cloud cover on solar radiation reaching the ocean surface and the links between cloudiness, upper-ocean warming, and coral bleaching risk, these findings provide important context for understanding environmental conditions associated with reef shading during the coral bleaching season.

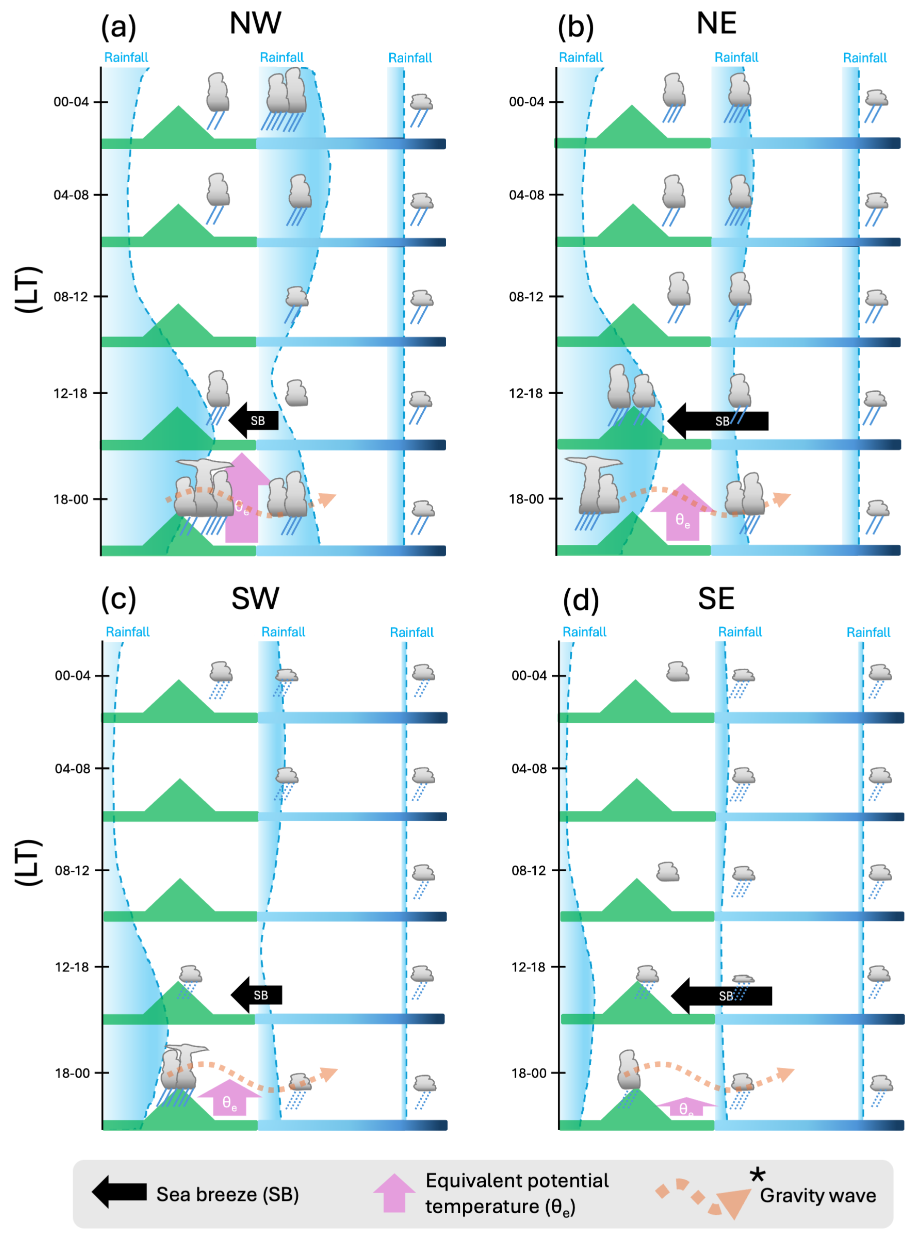

Figure 9. Hypothesized mechanisms for each wind regime (a,b,c,d) cloud BT and rainfall observations. Each panel shows time (Local Time) along the left column, corresponding to mean rainfall changes throughout the day (blue shading). Five distinct stages are shown, with land and topographical features on the left (a general feature of the north–east Queensland coastline), the coastal ocean in the center, and the open ocean on the right. Upward pink arrows indicate the relative size of peak equivalent potential temperatures for each wind regime. The afternoon land sea breeze is shown by black arrows with relative maximum wind speeds indicated by arrow ~~size~~ length (see supplementary Fig. ~~??~~A3). ~~Orange~~ *Mechanism inferred from estimated propagation speeds consistent with gravity wave propagation in literature - dashed orange oscillating arrows indicate the nighttime offshore propagation of convection induced by gravity waves.

5 Conclusions

This study characterizes cloud and rainfall diurnal cycles over north–east Queensland during the coral bleaching season, offering a foundation for understanding links between clouds, rainfall, local processes, and surface energy in this climate–sensitive region. Using Himawari–8 data, C–band radar, and BARRA–R2 reanalysis, a multi–year analysis is conducted across coastal land, coastal ocean, and open ocean zones. Key findings are summarized below:

- Background wind regimes significantly modulate diurnal cloud and rainfall cycles by modulating thermodynamic structure and convective dynamics.
- Strongest diurnal cycles occur under westerly regimes over coastal land, with cloud and rainfall variability significantly reduced over the coastal ocean and minimal over the open ocean.
- The southeasterly regime tends to support shallower and weaker convective systems, resulting in reduced cloud development, limited rainfall and little diurnal variability.
- Cloud and rainfall diurnal cycles are out of phase between land and ocean, with peak cloudiness and rainfall occurring in the evening over land and early morning over the ocean.
- Rainfall peaks precede coldest cloud tops over land, suggesting colder cloud tops often reflect anvil cloud remnants rather than active convective cores.
- Latitudinal and topographic influences are substantial, where Cairns experiences more frequent and intense convection than Townsville.
- Convection propagates more quickly inland but more slowly offshore, highlighting the contrasting dynamics across the region.
- Land–sea breeze circulations and coastal winds exert a variable influence on the spatial patterns and propagation of convection, modulated by ambient moisture availability and background wind strength.

The distinct diurnal patterns of clouds and rainfall identified in this study under different background wind regimes have important implications for the understanding ~~and anticipating coral bleaching risk~~ environmental conditions associated with coral bleaching across the GBR. ~~In particular, the timing and spatial distribution of clouds and rainfall influence the sea surface energy balance and solar radiation exposure, both of which are key drivers of thermal stress on coral reefs. Under westerly~~ Previous studies have demonstrated strong links between cloud cover, surface radiative fluxes, SST variability, and coral bleaching. Within this broader context, our results show that propagation of cloud systems vary substantially between wind regimes, ~~clear skies and stronger daytime heating over the coastal zone followed by intense inland convection and reduced cloudiness over the adjacent reef waters may lead to increased SSTs and higher shortwave radiation loads, elevating bleaching risk during heatwaves. Conversely, under easterly regimes , more persistent but less intense cloud cover and~~

rainfall over the coastal ocean may help moderate daytime warming and limit radiation extremes, offering partial thermal protection. Additionally, the offshore propagation of rainfall and cloud anvils during the night may play a role in delaying nighttime cooling or maintaining elevated humidity, further modulating the reef's thermal balanceimplying that the atmospheric conditions influencing reef environments can differ markedly depending on the prevailing large-scale circulation. In particular, the extensive late afternoon offshore propagation of convective cloud systems under north-westerly regimes suggests greater potential for cloud cover to extend over offshore reef areas, whereas the predominantly inland propagation observed under north-easterly and south-easterly regimes may reduce the influence of coastal convection on reef cloudiness. Because cloud cover is known to influence the radiative environment experienced by coral reefs, these contrasting cloud regimes may contribute to differences in environmental conditions conducive to bleaching. While our study did not explicitly examine sensible and latent heat fluxes, does not directly quantify radiative fluxes, ocean heat budgets, or bleaching impacts, these processes are likely modulated by the observed wind regimes and atmospheric structure, and may further influence SST variability. Together, these findings highlight the importance of incorporating diurnally evolving mesoscale weather processes, especially those linked to background wind regimes and coastal convection, into assessments and forecasts of coral bleaching risk across the GBRduring the austral warm season.

Code and data availability. The code for this project is hosted on GitHub: alanah-chapman. Data from the Level 1 Himawari–8 dataset (Lopez-Bravo et al., 2021a) is available at NCI. The Level 2 Australian Operational Weather Radar dataset (Soderholm et al., 2022) is available at NCI. BARRA–R2 regional reanalysis data (Su et al., 2022) is found on NCI Gadi.

Appendix A

A1

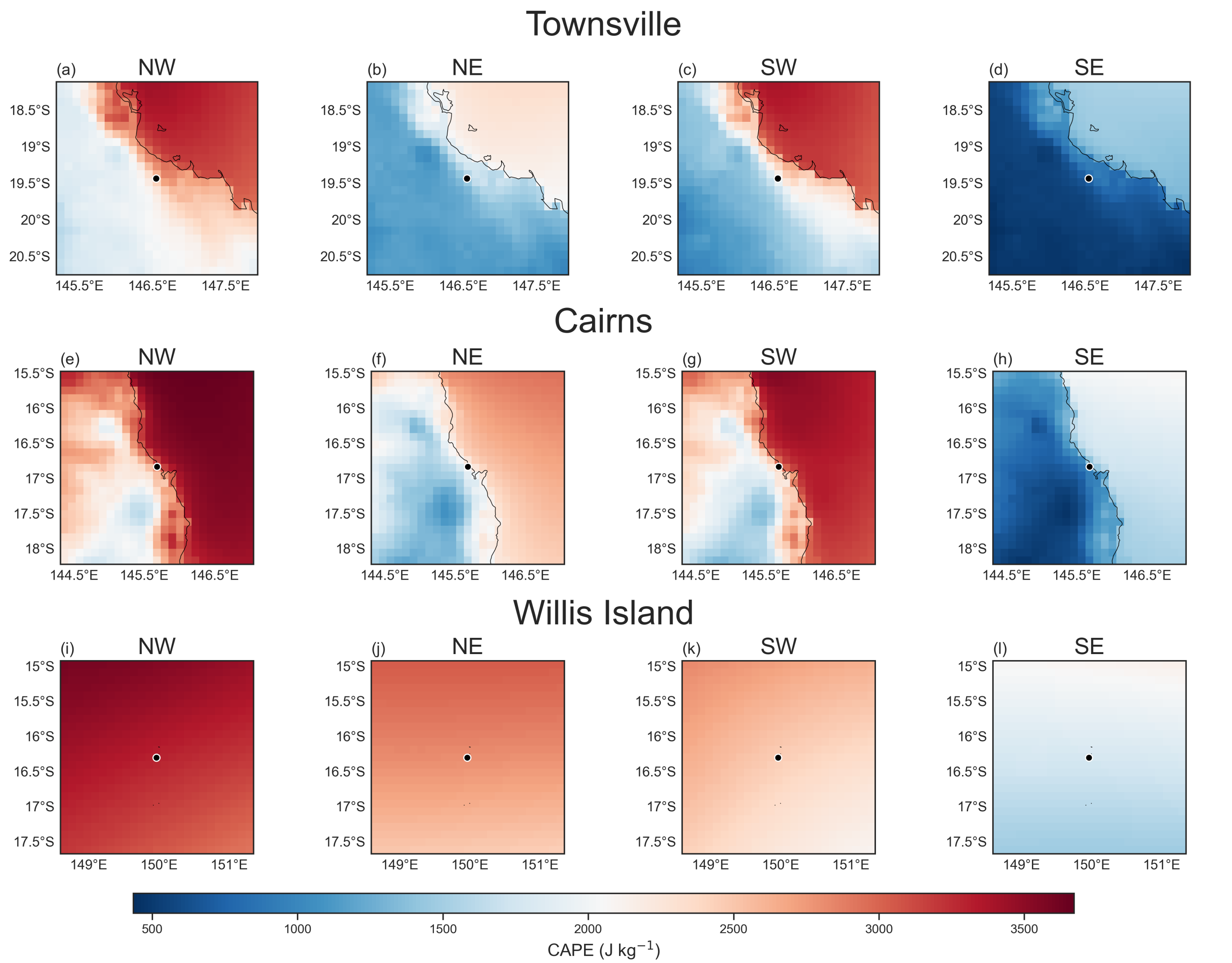

Figure A1. Diurnal cycle plots of (a, b) Himawari–8 satellite channel 13 BT, (c, d) radar retrieved rain rate frequency and (e, f) rate rate intensity calculated from hourly means over the CBS. The cloud BT axis is inverted, so that peaks in the diurnal cycle indicate colder BTs. Townsville (green), Cairns (pink) and Willis Island (blue) diurnal cycles are shown. The subplots in the left column show the cycles of the cloud proxy and rain rate variables for the coastal land, whereas the right column show Townsville and Cairns coastal oceans and the Willis Island open ocean region. Rain rate intensity is calculated for all periods of valid data (not just raining periods).Townsville (a, b), Cairns (c, d), (e, f, g, h) and Willis Island (i, j, k, l) BARRA-R2 Convective Available Potential Energy (J kg^{-1}) under each wind regime during the CBS between 1979 and 2025. Black markers indicates the radar locations for each site.

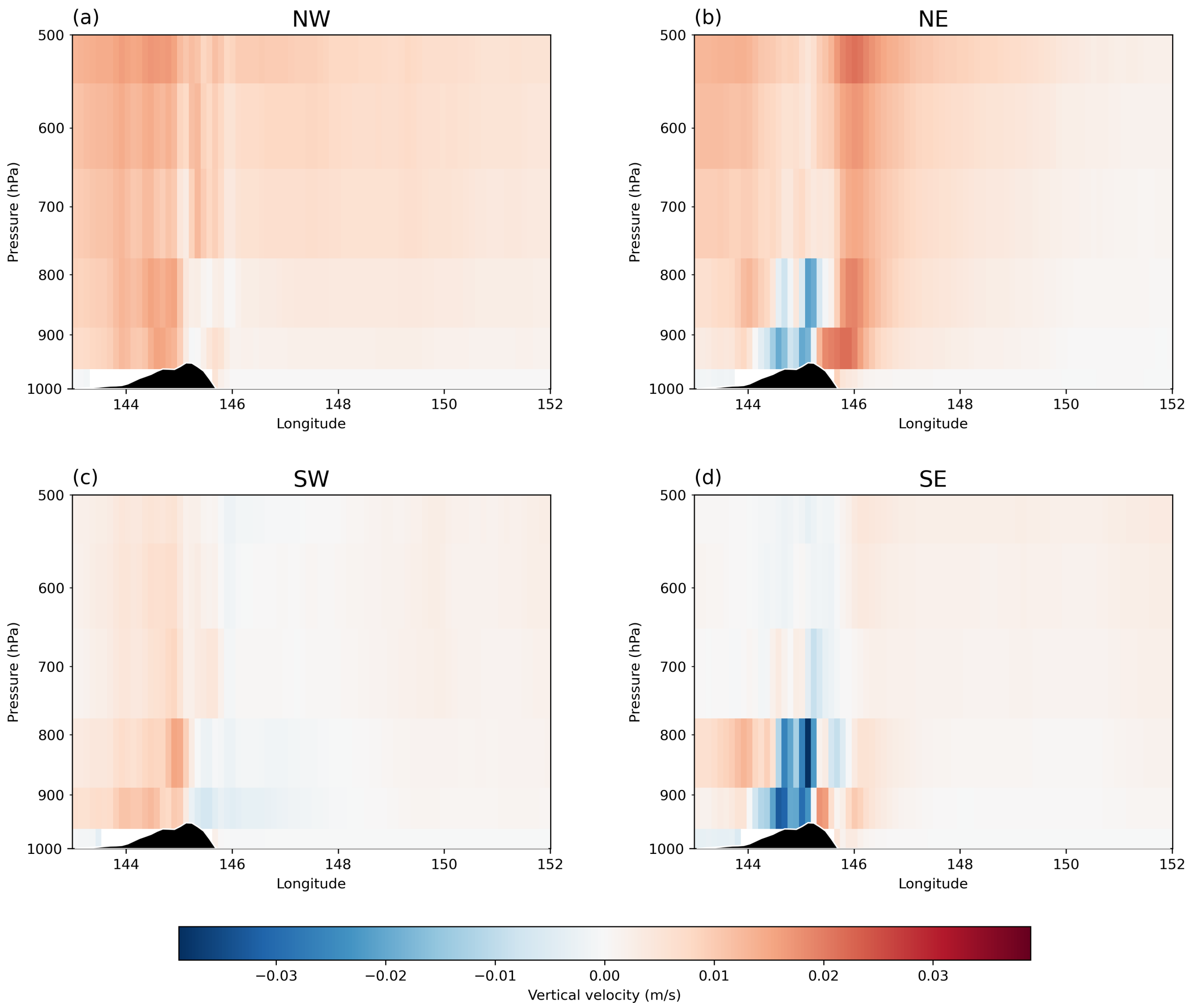

Figure A2. Vertical velocity (m s^{-1}) over the Hovmöller transect shown in Fig. 1. For each wind regime, the CBS mean (between years 1979–2025) is computed across the small latitude band. Mean topography from BARRA-R2 (16.6°S–17°S) is shaded in black, with elevation converted to pressure coordinates assuming a standard atmosphere.

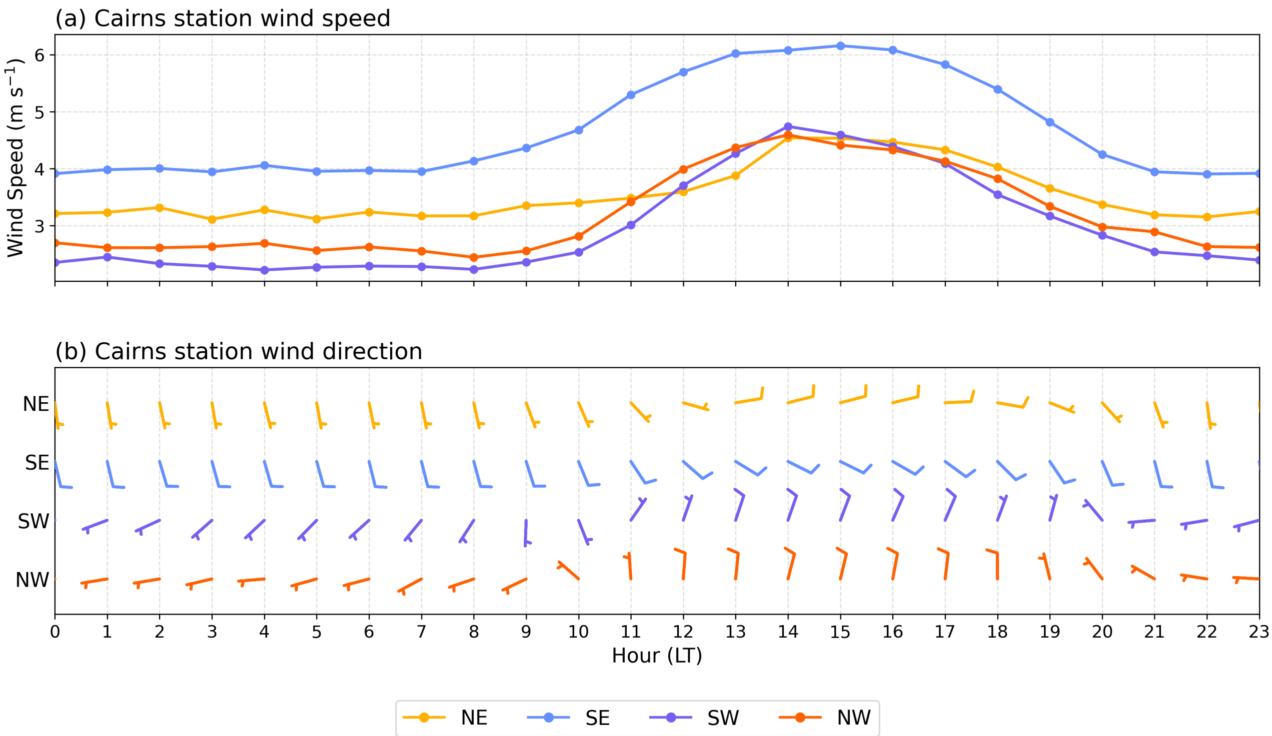

Figure A3. (a) Cairns station surface wind speeds and (b) wind direction (wind barbs) over the full CBS under each wind regime for the period 1990–2020.

Table A1. Coefficients used for the Z-R relation for each radar site. *Note the Z-R fit for Cairns was also used for Willis Island (which lacks rain gauges for calibration).

Site	**a**	**b**
Townsville	125	1.3
Cairns	85	1.35
*Willis Island	85	1.35

Table A2. Statistics on the 850 hPa winds averaged across each radar domain site for the four wind regimes. Note that sample sizes (N) shows the percentage of time periods under each regime for each site. These values were calculated for the CBS from BARRA–R2 wind fields between 1979–2023.

	Mean (m s^{-1})	Median (m s^{-1})	Maximum (m s^{-1})	Minimum (m s^{-1})	Standard Deviation (m s^{-1})	N (%)
NE Regimes						
Townsville	~~6.37~~6.29	~~6.02~~5.91	~~38.57~~38.21	~~0.07~~0.04	~~3.35~~3.28	~~23.3~~23.43
Cairns	~~5.33~~5.25	~~4.88~~4.76	~~20.07~~20.60	0.07	~~2.96~~3.00	~~14.4~~15.25
Willis Island	~~5.35~~5.65	~~4.90~~5.24	34.94	~~0.08~~0.02	3.07	~~17.6~~19.13
SE Regimes						
Townsville	~~7.83~~7.95	~~7.73~~7.85	40.05	~~0.07~~0.08	~~3.26~~3.21	~~64.2~~62.54
Cairns	~~8.28~~8.23	~~8.25~~8.21	~~27.81~~27.89	~~0.06~~0.05	~~3.56~~3.59	~~67.2~~67.01
Willis Island	~~7.35~~7.40	~~7.22~~7.27	~~33.56~~30.99	~~0.01~~0.09	~~3.21~~3.17	~~61~~57.36
SW Regimes						
Townsville	~~4.42~~4.35	~~3.97~~3.86	22.21	~~0.03~~0.07	~~2.68~~2.75	~~6.4~~7.49
Cairns	~~4.31~~4.32	~~3.80~~3.83	~~27.89~~18.82	~~0.08~~0.04	~~2.69~~2.60	~~9.6~~9.34
Willis Island	~~5.26~~5.18	~~4.57~~4.44	~~30.27~~30.92	0.01	~~3.40~~3.54	~~9.5~~10.22
NW Regimes						
Townsville	~~4.68~~4.63	~~3.93~~3.83	~~21.56~~21.57	~~0.08~~0.03	~~3.26~~3.23	~~6~~6.19
Cairns	~~5.68~~6.03	~~4.86~~5.27	26.65	~~0.04~~0.06	~~3.78~~3.76	~~8.8~~8.06
Willis Island	~~6.42~~6.20	~~5.51~~5.08	~~30.52~~25.92	~~0.02~~0.01	4.31	~~11.9~~12.94

Author contributions. AC performed data analyses and contributed to writing the manuscript. YH contributed to project conception, results interpretation, and manuscript writing. CV contributed to results interpretation and research direction.

Competing interests. The authors declare that they have no conflict of interest.

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