



Trade wind regimes during the Great Barrier Reef coral bleaching season

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Abstract. The trade winds over the Great Barrier Reef (GBR) dominate the local weather in the region, bringing cooler and drier air over the Reef, which promotes ocean cooling. The absence of the trade winds is often marked by periods of weaker winds and higher humidity, known as the doldrums, which cause ocean temperatures to spike and can develop into marine heatwaves that lead to coral bleaching. As the shallow waters of the GBR are strongly tied to the local meteorology, studying the evolution and structure of the trade winds during the austral warmer months is essential for understanding the development of thermal bleaching events. Through a *K*-Means cluster analysis on reanalysis soundings at Davies Reef from December–April 1996–2024, we find the formation of the doldrums is linked to the passage of a Rossby-wave train over eastern Australia. Years with mass thermal bleaching are linked with more doldrums days and weakened trade winds during December and April which can promote early-summer warming and allow warmer temperatures to persist later into the season.

Merrifield, 2011; Takahashi and Watanabe, 2016), typically cooling them as the strong surface winds enhance the latent heat flux (LHF) promoting evaporational cooling and ocean mixing (Skirving et al., 2006). The trades also enhance surface convection, as the strong winds promote the formation of trade cumulus (Malkus, 1958; Nuijens and Stevens, 2012) which reduces the amount of short-wave flux (SWF) reaching the ocean's surface.

While the trade winds are typically sustained in the winter hemisphere (Wyrski and Meyers, 1976), they can frequently weaken or collapse in the summer hemisphere as tropical disturbances, such as monsoon troughs and tropical cyclones/storms, progress through the region (Holland, 1986; Pope et al., 2009; Murphy et al., 2016). As the presence of the trade winds promotes ocean cooling, when they weaken or collapse local ocean temperatures can spike. This collapse can result in what is known as the doldrums, creating areas of weak winds and high surface humidity which dampen the LHF (Karnauskas, 2020; Richards et al., 2024). At the same time, the lack of boundary layer convection limits cloud formation allowing more SWF into the ocean promoting ocean heating. While the doldrums have more explicitly been studied over the tropical Atlantic (Klocke et al., 2017; Windmiller, 2024), reports of “calm and clear” conditions appearing in trade wind regions can be traced back to the 1950's (Crowe, 1950) and are a common feature of thermal coral bleaching studies (Glynn, 1968; Smith, 2001; Jokiel and Brown, 2004; Bainbridge, 2017; Baird et al., 2018; Richards et al., 2024).

1 Introduction

Covering almost half of the Earth's surface, the trade winds carry colder air from higher latitudes into the tropics, while their strength and location vary annually following the position of the inter-tropical convergence zone as it migrates with the seasons (Crowe, 1950; Malkus, 1958; Wyrski and Meyers, 1976). The trades play an essential role in regulating subtropical ocean temperatures (Liu and Philander, 1995;

The majority of the world's coral reefs lie in trade wind zones, including the Great Barrier Reef (GBR), located in the Coral Sea on the Australian eastern coast, which hosts the world's largest coral reef ecosystem of tremendous biological, cultural, and economic value. One of the many pressures facing the Reef is the increasing frequency of mass coral bleaching events (CBEs), with nine recorded since 1998, six of which occurring since 2016 (Australian Institute of Marine Science (AIMS), 2025). These events are increasing due to the background warming of ocean temperatures from climate change (Henley et al., 2024). The shallow waters of the GBR are particularly sensitive to changes in weather patterns and cloud cover (Harrison et al., 2019; Zhao et al., 2021), where shifts from the trade winds to doldrums conditions can cause ocean temperature spikes and potentially coral bleaching (Karnauskas, 2020; Richards et al., 2024). Connections between the local and synoptic meteorology were explored by Richards et al. (2024), who followed the local and synoptic meteorological evolution at Davies Reef during the 2022 CBE. The initial spike in ocean temperatures was linked to the weakening and eventual breakdown of the trade winds. As the trade winds collapsed, wind speeds decreased and surface humidity rose, dampening the LHF. Following the event's peak, ocean temperatures rapidly fell as the trade winds re-established bringing cooler, drier air and stronger surface winds over the site, allowing the LHF to triple. The collapse and re-establishment of the trades can be traced to the extra-tropics, where a string of Rossby-wave breaking events and continual cut-off low formation was thought to initiate the trade's breakdown, while the trade's re-establishment was attributed to a strong coastal ridging event that surged up the Australian east coast.

While other synoptic typing studies have provided valuable insights into the northern Australian wet season (Lyons and Bonell, 1992; Pope et al., 2009), a climatology of GBR weather patterns and a more detailed understanding of the trade-wind “cycle” during thermal bleaching periods is missing from the literature. Thus, we aim to characterise the trade wind regimes over the GBR during the Australian coral bleaching season (December–April) and answer the following questions:

1. What weather regimes are conducive to heating and cooling on the GBR?
2. Are all recent GBR CBEs preceded by a trade wind breakdown?

Using *K*-Means clustering of reanalysis data on a central GBR site, we construct our clusters from the thermodynamics of the trade-wind layer of the lower free troposphere. Designating our clusters into trade wind and non-trade wind regimes, we use our clusters to show the synoptic differences between bleaching and non-bleaching years and their evolution throughout recent bleaching events.

2 Data and Methodology

2.1 Cluster analysis

To categorise the dominant weather patterns during the GBR coral bleaching season, *K*-Means clustering is performed on atmospheric profiles at Davies Reef (Fig. 1 first column) to determine regional weather types based on the thermodynamic structure of the boundary layer and middle atmosphere where the trade wind layers persist. As the GBR covers a large latitudinal range (10–24° S), we chose Davies Reef (18.83° S, 147.63° E, mid-shelf lagoonal reef) as the clustering location, as it is both in the central GBR, with more frequent CBEs recorded, and has a highly consistent observational record of both atmospheric and oceanic parameters through the Australian Institute of Marine Science (AIMS) Davies Reef Automatic Weather Station (AWS) placed within the lagoon (Bainbridge, 2017). Due to an absence of observational soundings over the GBR, atmospheric reanalysis data from the European Centre for Medium-Range Weather Forecasts' fifth reanalysis (ERA5) (Hersbach et al., 2020), produced on hourly intervals at 0.25° resolution, taken at the closest grid point to Davies Reef (18.75° S, 147.75° E), is used to construct the clusters. We cluster on air temperature, dew point temperature, and the horizontal wind components at the surface, 925, 850, 700, 600, and 500 hPa, using only the 00:00 UTC (10:00 LST) time step to avoid complications with diurnal cycles and remain closest to the sounding release time at the neighbouring Townsville and Willis Island stations. The profiles are restricted to 500 hPa to focus on the diversity in the trade wind layer, providing a daily snapshot of the atmosphere from the surface to the mid-troposphere, well above the trade inversion. Despite the large latitudinal extent of the GBR, the clusters produced at Davies Reef also largely capture the diversity of the northern and southern sectors, where a clustering analysis performed at Lizard Island and Heron Island found similar weather regimes (Figs. S1 and S2 in the Supplement).

To capture the recent GBR CBEs, the analysis period covers from December to April for the years 1996–2024. As this manuscript was prepared before the 2025 CBE was declared, we only include the eight events from 1998 to 2024. While the GBR coral bleaching season was originally defined as January–April by Zhao et al. (2021), this study expands the definition to include December to fully capture the period of warmest ocean temperatures.

2.2 Synoptic analysis

After each day in the clustering period is assigned, the daily average surface synoptic conditions are calculated for each cluster followed by their anomalies. The synoptic analysis combines ERA5 mean sea-level pressure (MSLP) and 10 m horizontal winds with the satellite derived National Oceanic and Atmospheric Administration's (NOAA) Daily Optimum

Interpolation Sea Surface Temperature (DOISST) version 2.1 (Huang et al., 2021). Day-of-year based anomalies are calculated using a daily mean climatology for the 1996–2024 period to remove the cluster’s underlying seasonal cycle. The sea surface temperature anomalies (SSTA) have been linearly detrended to remove the long-term warming signal, after which the SSTA tendency or $dSSTA/dt$ is calculated. All anomalies have then undergone a simple one sided t test to show that the mean anomalies are significantly different from zero where only the anomalies with a p value < 0.01 (0.05 for SSTA tendency and horizontal wind anomalies) are considered. Lastly, to understand the origin of the boundary layer air masses, back trajectories are produced for each cluster using the Lagrangian analysis tool Lagranto version 2.0 (Sprenger and Wernli, 2015), which utilises ERA5 data on 6-hourly intervals. The daily back trajectories each start at 00:00 UTC running for 72 h from Davies Reef at 925 hPa.

2.3 Davies Reef observations

Daily averages of atmospheric and oceanic observations from the Davies Reef AWS are used throughout the clustering period, noting that observations from 23–30 April 2024 were unavailable and therefore omitted from all analysis. The Davies Reef daily averaged 4 m ocean temperature (T_{4m}) is considered our primary ocean temperature record as many other AIMS GBR AWS sites contain frequent missing observations. For rare occasions when the Davies Reef T_{4m} is not available, missing data is filled by interpolating the T_{2m} and T_{8m} records (0.59 % of data). When this interpolation over depth was not possible, the daily T_{4m} was estimated by averaging the daily T_{4m} from the nearest available days (0.07 % of data). For periods when the Davies Reef AWS wind and air temperature observations were not available, missing data was filled using ERA5 data (2.06 % of data) or by averaging the nearest available days (0.08 %). We note ERA5 was previously found to have a high correlation with the AIMS Davies Reef atmospheric observations (Richards et al., 2024). As the rain accumulation and relative humidity are only available from 2008 onwards, no gap filling was performed where the reduced cluster sizes are stated in Table 3.

Due to the lack of in-situ fluxes, a local net surface energy budget is produced at Davies Reef using a daily average of ERA5’s mean net surface flux products, analysing the contribution of the radiative fluxes (short-wave (Q_{SW}) and long-wave (Q_{LW})) and the turbulent fluxes (latent heat (Q_E) and sensible heat (Q_H)) to the total net flux (Q^*) (Eq. 1).

$$Q^* = Q_{SW} + Q_{LW} + Q_H + Q_E. \quad (1)$$

2.4 Cloud cover

The satellite imagery from the Japan Aerospace Exploration Agency’s (JAXA) Himawari-8/9 satellite are used to investigate the cloud fields that are associated with clusters at Davies Reef. Himawari-8/9 uses the International Satellite

Cloud Climatology Project (ISCCP) cloud classification system which uses cloud top pressure and cloud optical thickness to determine the cloud type (Nakajima and Nakajima, 1995; Kawamoto et al., 2001). The cloud types are sorted into low clouds (cumulus, stratocumulus, and stratus), mid-level clouds (altocumulus, altostratus, and nimbostratus), and high clouds (cirrus, cirrostratus, and deep convection). It should be noted that as Himawari-8/9 is a passive sensor, meaning it cannot detect multi-layer clouds, low cloud may be underrepresented when upper-level clouds are optically thick (Marchand and Ackerman, 2010), thus higher clouds may be overrepresented in cloud fraction calculations. Here we consider only a 1° box centred on Davies Reef taking only the 00:00 UTC observations. Note that this analysis is limited to time period of December 2015 to April 2024, as Himawari-8/9 was launched in 2015.

2.5 MJO indices

Lastly, as the Madden-Julien Oscillation (MJO) is known to influence tropical winds and convection in the Australian tropics, and potential links have been noted between the MJO and Australian marine heatwaves (Holbrook et al., 2019), we analyse the phase distribution between our clusters. Here we utilise the Bureau of Meteorology’s Real-time Multivariate MJO index (Wheeler and Hendon, 2004) to analyse the MJO phase and amplitude and how they differ between our clusters.

3 Cluster climatology

3.1 Cluster identification

In the cluster analysis at Davies Reef, we found five clusters were able to best represent the diversity in the atmospheric profiles. To help characterise each cluster, composite soundings from the surface to the mid-troposphere were produced (Fig. 1) with their monthly frequency (Fig. 2). The five clusters are split into three “trade wind” clusters (classic trades, summer trades, and wet trades) and two “non-trade wind” clusters (doldrums and northerlies) and are ordered based on the direction and the strength of the surface winds. The classic trades display a common trade wind structure, where surface south-easterlies weaken and turn to westerlies at upper levels (Fig. 1a). The frequency of classic trade wind days is small during December–March however become the dominant cluster ($\sim 60\%$) in April (Fig. 2) as the Australian monsoon retreats and the subtropical ridge moves north (Fig. 1b). In the boundary layer, the thermodynamic profile of the summer trades is similar to the classic trades, whilst above it, the summer trades lack an upper-level wind reversal also becoming warmer and drier aloft (Fig. 1d). The omega profiles are also similar between the classic and summer trades, with on average only slightly weaker surface ascent separating the summer trades (Fig. 3a). The monthly

proportion of summer trade days remain similar across all months, averaging around 20 % frequency in each month (Fig. 2). The wet trades differ significantly from the other trade clusters, with a warmer and more moist profile and a larger easterly component to the lower-level winds becoming calm aloft (Fig. 1g). The wet trades omega profile shows on average net ascent throughout the column with the strongest average surface ascent of the five clusters (Fig. 3a). As the wet trades are more frequent between January and March ($\sim 30\%$) (Fig. 2), when the monsoon is active, the higher atmospheric moisture is not surprising. Moving to the non-trades clusters, the doldrums are characterised by their weak lower-level winds and a weakening of the boundary layer temperature lapse rate (Fig. 1j). Along with having comparatively weaker ascent near the surface, above this inversion the air is typically descending (Fig. 3b). The doldrums are most frequent between December and February, becoming scarce by April (Fig. 2). Lastly, the northerlies cluster is dominated by northerly winds with warm and moist air throughout its profile (Fig. 1m). Similar to the wet trades, the northerlies display strong ascending motion throughout the profile (Fig. 3b). The northerlies are most frequent in January–February, which is the active monsoon period, though only occurring around 20 % of the time. From December to February, the monthly proportion of trade and non-trade cluster days remains almost constant with the trade wind clusters present for 56 % of each month. By March this proportion shifts to 77 % trades and to 92 % in April (Fig. 2).

When comparing each cluster's mean synoptic environment, a key difference is the location of the eastern high-pressure ridge. In the three trade wind clusters, the high is located over south-east Australia or the Tasman Sea, forming a ridge along the Australian east coast (Fig. 1b, e, h), which triggers the typical southeasterly trade winds. While in the non-trade clusters, the anticyclone is centred east of New Zealand, allowing a trough to develop over the Australian east coast. Additionally, there is also a polewards shift in the low-pressure region over northern Australia (Fig. 1k, n), which is likely explained as our non-trade clusters tend to form under the Australian monsoon active months.

In the classic trades, the high is the strongest of the three trade clusters and centred over south-eastern Australia, while in the summer trades, the high is now weaker and centred over the Tasman Sea. In the wet trades, the Tasman high is larger than in the summer trades, creating a more zonally orientated ridge along the east coast, forcing the easterly component to the wet trades' winds. The east coast ridging is strongest in the classic trades and extends furthest north with trade winds covering the entire GBR. The ridging extent and therefore latitudinal range of the trade winds decreases within the summer and wet trades. The general poleward shift and weaker tropical pressure gradients in the wet trades shows westerlies forming in the Arafura Sea north of Australia, indicating a monsoonal shift. In the doldrums, weak pressure gradients now cover the GBR and northern

Australia, while the westerlies in the Arafura Sea strengthen. Finally, the northerlies depict a classic monsoon set-up, with surface westerlies over Darwin brought by the deepening of the low-pressure area over northern Australia (Troup, 1961). In turn, this this low-pressure area also turns the GBR winds to northerlies.

Moving from the surface wind fields, we next considered the origin of these boundary layer air masses. We find the cluster back trajectories largely follow the surface wind fields, where the trade wind clusters have minimal continental influence to the Davies Reef air masses, aside from a small portion in the classic trades that move anticyclonically from the continent to Davies Reef (Fig. 1c, f, i). Air masses in the classic trades also come from the furthest south, with many trajectories extending into the Tasman Sea. The continental influence is larger in the non-trade clusters, where both clusters show more variability in their trajectories, particularly the doldrums, which have no strong preference in trajectory direction. Most trajectories originate from the neighbouring Coral Sea, with occasional continental influence from far north-eastern Australia (Fig. 1l). The northerlies indicate two main trajectory paths, which are a monsoonal path coming from the northwest via the Maritime Continent and an easterly to north-easterly path from the Coral Sea (Fig. 1o). When considering the pressure levels the air masses originate from (Fig. 3c–d), the classic and summer trades show almost identical distributions originating from around 800 hPa. However, the wet trades tend to pull air masses from the lower atmosphere (875 hPa) with many trajectories originating near the surface (Fig. 3c). In the doldrums, parcels are often weakly descending and originate closer to the starting pressure with trajectories on average originating from 860 hPa. Conversely, the northerlies have the largest surface influence with many trajectories originating from below 950 hPa and on average from 915 hPa (Fig. 3d).

To examine cluster relationships, we use a transition matrix (Table 1) showing how the clusters evolve on average. The transition matrix highlights the common pathways between the trade winds and non-trade clusters, including what transitions seldom occur. Each cluster strongly biases transitioning to itself, particularly the classic trades. The three trade wind clusters have a secondary preference for another trade cluster, with the classic trades and wet trades moving to the summer trades which in turn moves to the wet trades. To move into the non-trade clusters, the most likely path is from the summer trades to doldrums (9 %) or from the wet trades to northerlies (8 %). Once in the doldrums, there is a similar preference for transitioning to the wet trades or northerlies. However, the transition back to the trade clusters is most frequently from the northerlies to wet trades (20 %), noting that the northerlies seldom transition to the other trade clusters.

Along with the cluster transitions, we analyse the persistence frequency in each cluster by counting individual consecutive events and the proportion of days captured within those events to normalise the data between the clusters (Ta-

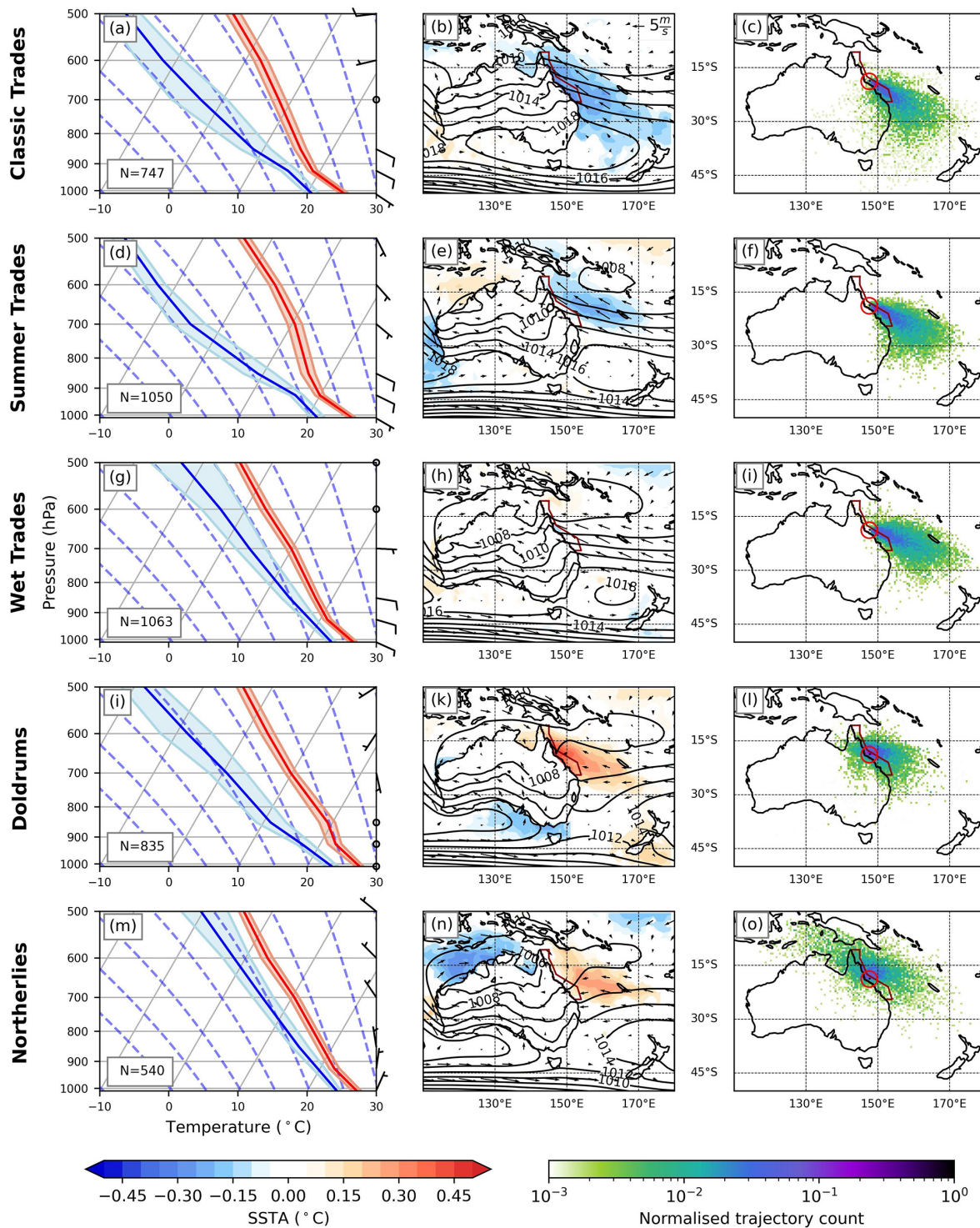
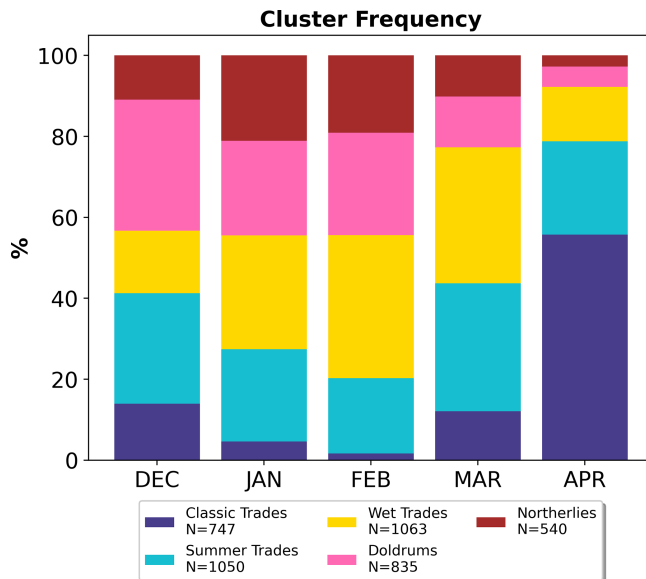


Figure 1. The left column shows a Skew-T plot of the ERA5 cluster composite soundings for Davies Reef (18.75°S , 147.75°E , red circle) with N representing the number of days in each cluster. Here the air temperature (red) and dew point temperature (blue) are shown with solid lines marking the mean and shading the upper and lower quartiles. The middle column shows the cluster daily average synoptic surface means. MSLP (black contours, 2 hPa spacing) and horizontal winds (quivers, m s^{-1} , quiver key found in panel b) are taken from ERA5, while NOAA's DOISST is used for the SSTAs (filled contours) with a mask showing where the composite anomalies are statistically significantly different from zero at the 99 % confidence level is applied. The right column shows the 72 h back trajectory composites launched from 925 hPa. The composites are normalised and placed on a log scale. The maroon outline marks the boundaries of the Great Barrier Reef.

Table 1. Cluster transition matrix showing the transition percentage from the starting cluster (first column) to the final cluster (first row).

		Final cluster				
		Classic Trades	Summer Trades	Wet Trades	Doldrums	Northerlies
Initial cluster	Classic Trades	76.3 %	14.2 %	5.4 %	3.4 %	0.7 %
	Summer Trades	8.4 %	68.2 %	13.6 %	9.3 %	0.6 %
	Wet Trades	6.1 %	14.7 %	64.6 %	6.4 %	8.2 %
	Doldrums	3 %	8.5 %	10.8 %	67.4 %	10.3 %
	Northerlies	1.5 %	0 %	19.5 %	13.5 %	65.5 %

**Figure 2.** Cluster frequency for each month based on the 1996–2024 period with N representing the number of days in each cluster.

ble 2). The trades generally persist longer than the non-trades, with the classic trades having the longest duration, at 37 d, being the only cluster to exceed 20 d, noting that all > 20 d events occur in April. The summer and wet trades have similar persistence rates, but with more 1–2 d events in the wet trades. The doldrums have the highest proportion of days in 6–10 d events, with only three events lasting > 10 d, while the northerlies have the shortest maximum duration (13 d) with more events lasting 3–5 d.

3.2 Synoptic anomalies

To extend our understanding each cluster's typical meteorology, we examine day-of-year anomalies at 500 hPa and the surface. Over the GBR and Coral Sea, our classic and summer trades produce cooler SSTAs (Fig. 1b, e), while our non-trades, particularly the doldrums, show warmer SSTAs (Fig. 1k, n). Despite the wet trade's weak SSTAs (Fig. 1h), when we consider the SSTA tendency the wet trades have the strongest GBR cooling rate, while the largest heating rate is again found in the doldrums (Fig. 4e, g).

The SSTAs are well connected to the overlying meteorology through the MSLP and 500 hPa geopotential height anomalies. In the doldrums, the warmest SSTAs and heating rates spread from the central GBR through the Coral Sea to New Zealand, aligned with a surface cyclonic anomaly (Fig. 4g), while cooler SSTAs appear over south eastern Australia (Fig. 1k). Consistent with typical summer patterns over Australia (Ndarana and Waugh, 2011; O'Brien and Reeder, 2017), many clusters indicate Rossby-wave breaking. This surface cyclonic anomaly connects to an upper-level cut-off low extending to at least 250 hPa (not shown) resultant of wave breaking on a previous day. Interestingly, the cyclonic anomaly also sits at the end of a Rossby-wave train that extends to South America (Fig. 4g–h). In the northerlies, the SSTAs are weaker and centred further east in the Coral Sea (Fig. 1n) matching the only area of significant heating (Fig. 4i). The southern GBR shows only weak positive SSTAs, while cooler SSTAs extend up to the Maritime Continent Fig. 4i), following the strong westerlies which intensify the wind-evaporation feedback (Sekizawa et al., 2018, 2023). However, a significant cooling pattern is not found here (Fig. 4i). Over the GBR, north-westerly winds arise from the equatorward extension of a cyclonic anomaly over south-eastern Australia combined with a weak upper-level anticyclone over the Coral Sea, producing strong cyclonic flow down to the surface (Fig. 4i–j).

The classic trades show the coldest SSTAs over the GBR, extending south to the Tasman Sea (Fig. 1b), though significant cooling is limited to the Coral Sea and northern/southern GBR (Fig. 4a). In the summer trades, the cool SSTAs are confined to the Coral Sea with little GBR impact (Fig. 4c), while wet trades produce the strongest GBR cooling, radiating into the Coral Sea (Fig. 4e). The cooling rate is strongest in the wet trades as they more frequently transition from the warmer non-trades, thus having the greatest potential to cool. All trade clusters feature surface anticyclones over south eastern Australia (Fig. 4a, c, e); in the classic and summer trades these extend to 500 hPa (Fig. 4b, d), with the classic trades showing the strongest anticyclone over Tasmania. In the classic trades, a cyclonic anomaly tongue extends over the GBR creating the westerly wind reversal seen in the cluster soundings (Fig. 1a). This tongue becomes more defined at 250 hPa (not shown) signalling the presence of wave break-

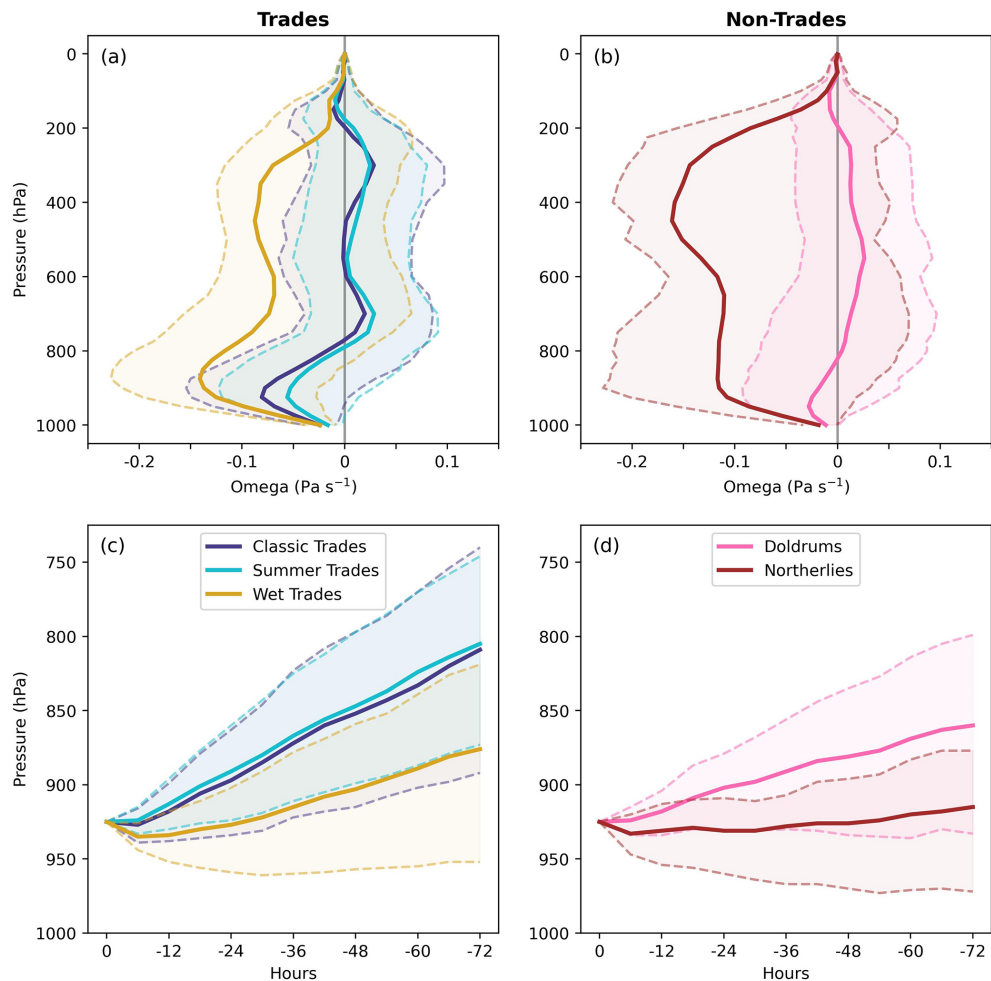


Figure 3. The means (solid) and lower-upper quartile ranges (dashed and shaded) are shown for both the ERA5 omega profiles at 00:00 UTC at Davies Reef (a–b) and the pressure changes throughout the 72 h back trajectories launched from 925 hPa at Davies Reef at 00:00 UTC (c–d).

Table 2. Cluster duration event counts with the percentage of days captured within each duration period.

Cluster durations					
	Classic Trades	Summer Trades	Wet Trades	Doldrums	Northerlies
1–2 d	102 (17.4 %)	183 (23.9 %)	228 (29.8 %)	155 (27.1 %)	109 (28.9 %)
3–5 d	50 (26.1 %)	111 (40.6 %)	111 (38.8 %)	78 (34.6 %)	59 (40.4 %)
6–10 d	30 (30.4 %)	38 (26 %)	34 (23.1 %)	40 (33.7 %)	16 (21.2 %)
11–20 d	8 (14.1 %)	7 (9.3 %)	7 (8.3 %)	3 (4.7 %)	4 (8.9 %)
> 20 d	3 (12 %)	0	0	0	0
Maximum duration	37 d	16 d	17 d	15 d	13 d

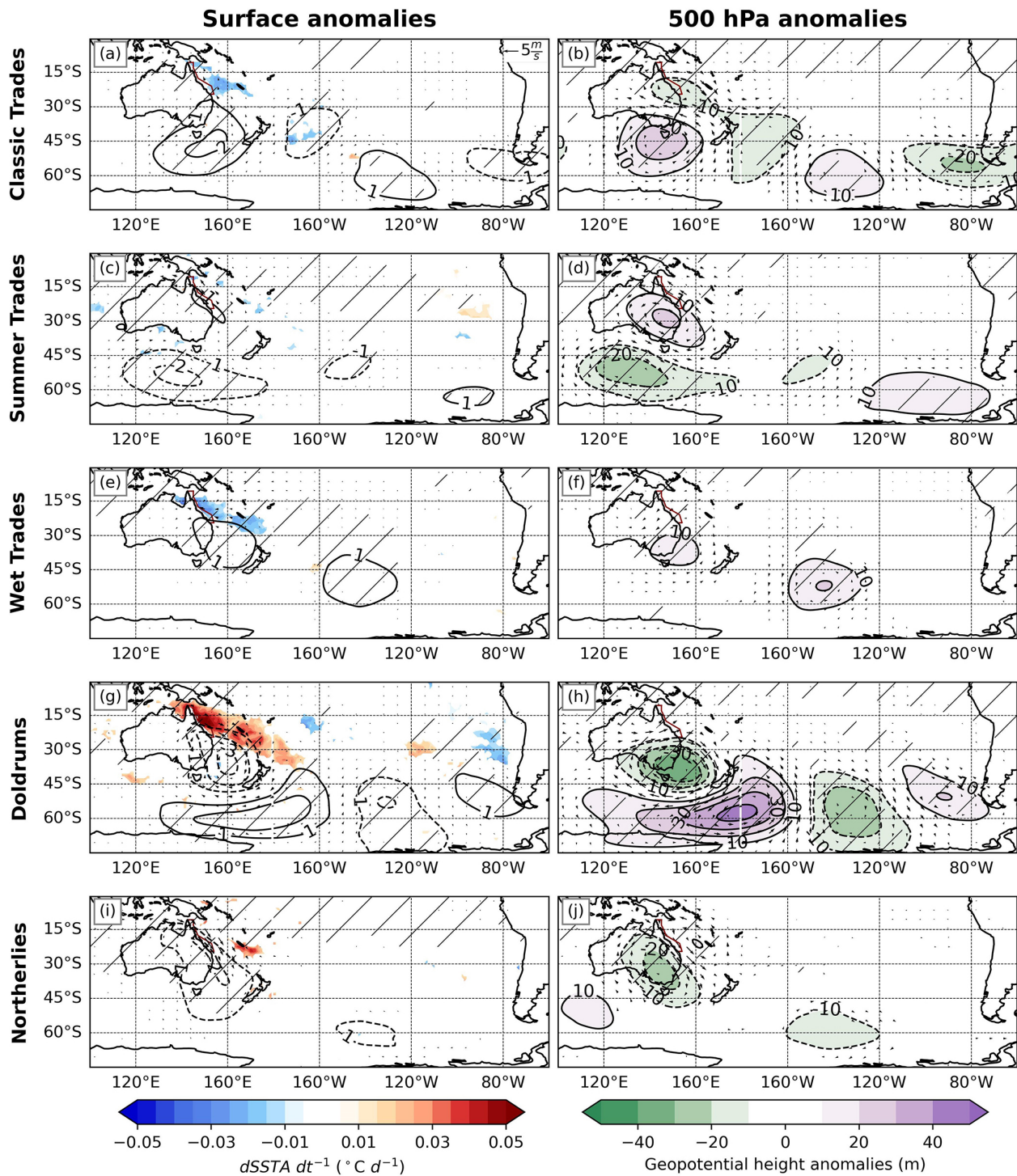


Figure 4. Day-of-year based cluster anomalies for the surface (left) and 500 hPa (right). The surface anomalies show ERA5 MSLP (contours, 1 hPa intervals) and 10 m horizontal winds (quivers, $m s^{-1}$) with the SSTA tendency (filled contours, $^{\circ}C$), while at 500 hPa, only the ERA5 geopotential height (filled contours, 10 m intervals) and horizontal winds (quivers, $m s^{-1}$) are shown. Masks have been applied to both the SSTA tendency and horizontal winds where only mean anomalies that are statistically significantly different from zero at the 95th % confidence level are shown. For the MSLP and geopotential height contours, hatching represents where the composite anomalies are statistically significantly different from zero at the 99 % confidence level.

ing found at a higher level compared to the doldrums. In contrast, the wet trades have few synoptic anomalies (Fig. 4f), potentially from enhanced convection in the GBR region.

3.3 Davies Reef observations

Moving next to the local analysis at Davies Reef, we connect the observations from the Davies Reef AWS (Table 3) and Himawari-8/9 satellite imagery (Fig. 5) to the cluster surface energy budget (Fig. 6) at the same site. The trade wind clusters feature strong south-easterly winds that produce a large LHF and overall negative net flux (ocean cooling). The strongest average cooling is found in the classic trades (-62 W m^{-2}), followed by the wet trades (-27 W m^{-2}), then summer trades (-10 W m^{-2}) (Fig. 6). While both the average 4 m ocean and air temperatures increase when moving from the classic to wet trades, the trade clusters differentiate mainly through their cloud profiles. The summer trades exhibit a reduced cloud fraction (44 %) compared to the classic trades (59 %), due to a reduction in high cloud (mainly cirrus) (Fig. 5), thus increasing the SWF (Fig. 6). The wet trades feature the strongest surface winds and highest relative humidity and rainfall of the trade clusters (Table 3). Here, the cloud fraction is also the highest (77 %) with substantial high cloud (38 %), and the second largest deep convection (6 %) (Fig. 5). Despite the stronger surface winds, the higher humidity in the wet trades has weakened the cluster's LHF, however, it is still within a normal range (Fig. 6).

The non-trade clusters are set apart by their warm ocean and air temperatures, weaker surface winds, and reduced LHF creating a positive net flux (ocean heating). The doldrums cluster captures the calm and clear conditions often described in the literature (Klocke et al., 2017), producing the warmest ocean and air temperatures, weakest winds (Table 3), and lowest cloud fraction (41 %) (Fig. 5). Expectantly, the doldrums produce the highest SWF and lowest turbulent fluxes (Fig. 6). Despite the “clear sky” connotation the doldrums also capture the passage of infrequent storms through the small increase in deep convection (Fig. 5). The northerlies are considerably more humid than the doldrums, with the highest rainfall (Table 3) and cloud fraction (81 %) comprised mainly of high cloud (57 %), with large proportions of deep convection (17 %) (Fig. 5). This increased cloud fraction weakens the northerlies SWF and net flux (47 W m^{-2}), making the doldrums the strongest heating regime (132 W m^{-2}) (Fig. 6).

3.4 MJO

As the MJO is a key driver of tropical convection and wind patterns, thus we analyse the MJO phase distribution between the clusters. In this study, the MJO is divided into its eight standard phases along with corresponding weak (amplitude < 1) phases (Fig. 7). Typically over the Australia region, phases 4–7 enhance convection and phases 8–3 suppress

convection (Wheeler and Hendon, 2004). Although Davies Reef sits outside of the classic MJO definition ($15^\circ \text{ N}–15^\circ \text{ S}$), MJO-related influences remain relevant. Specifically, phases 5–6 (1–2) could enhance (suppress) convection over the northern GBR.

Moving from the classic trades to the northerlies, the proportion of days under suppressed convection decreases and days under active convection increases. The classic trades are the only cluster with more days under the suppressed phases (36 %) and the most days considered weak (39 %). The summer and wet trades have slightly higher proportions of enhanced convective phases (35 % and 39 %) with the wet trades having the largest proportion of days in phases 3–5 indicating an active MJO over the western-central Australian tropics. The non-trade clusters show a higher proportion of days in phases 6–7, particularly phase 7 which denotes an active MJO in the western Pacific. The northerlies show the largest frequency in phase 7 (17 %) with also the largest proportion of convectively active days (47 %), closely followed by the doldrums with 14 % days in phase 7 and 41 % of days convectively active. Overall the non-trade clusters align more with active MJO conditions over the central-eastern Australian tropics and GBR region.

4 Thermal stress

The doldrums cluster captures weather conditions strongly conducive to mass coral bleaching, being weak winds and clear skies, thus unsurprisingly produces the warmest ocean temperatures on average. Therefore, we now analyse the proportion of days in each cluster that exceed normal temperature ranges for our site Davies Reef. Using the local “bleaching threshold” (29.8° C) for Davies Reef (Berkelmans, 2002), marking the point where heat stress begins to accumulate, and the maximum +1 standard deviation temperature (29.4° C) (Richards et al., 2024) for Davies Reef, we can indicate the potential for heat stress accumulation in each cluster (Table 4). Unsurprisingly, the non-trades, especially the doldrums most frequently exceed both thresholds, far beyond the minimal occurrences of the trade clusters. The doldrums, compared to the northerlies, have over double the total days > 29.4° C and 11 more days > 29.8° C .

As the doldrums cluster captures the weather associated with coral bleaching and most frequently exceeds the local bleaching threshold at Davies Reef, it would be reasonable to suggest that mass coral bleaching years result from more frequent doldrums. After separating the cluster days into bleaching ('98, '02, '06, '16, '17, '20, '22, '24) (Australian Institute of Marine Science (AIMS), 2025) and non-bleaching years (Fig. 8), bleaching years have on average nine more doldrums days per year ($p = 0.16$) (Fig. 8a). By removing the fringe months and focusing on the warmest months of the bleaching season (January–March), the doldrums show the only significant difference between bleaching and non-bleaching years ($p < 0.05$) (Fig. 8b). However,

Table 3. AIMS Davies Reef AWS daily averages. The atmospheric variables are taken at 12 m. Relative humidity data is only available from 2008–2022, and rainfall 2008–2024. The amount of d captured by the reduced data sets is shown for each cluster.

	Classic Trades	Summer Trades	Wet Trades	Doldrums	Northerlies
Cluster days	747 d	1050 d	1063 d	835 d	540 d
4 m Ocean temperature (°C)	27.2	28.1	28.3	28.7	28.6
Air temperature (°C)	26.1	27.2	27.3	28.2	27.6
Wind speed (m s ^{−1})	8.3	7.7	9	4.4	6
Wind direction (°)	107	100	103	27	31
Relative humidity (%)	68.8 (311 d)	68.3 (539 d)	76.4 (539 d)	74 (442 d)	80 (280 d)
Rainfall accumulation (mm d ^{−1})	2.4 (339 d)	1.5 (598 d)	12.8 (630 d)	1.7 (520 d)	26.5 (333 d)

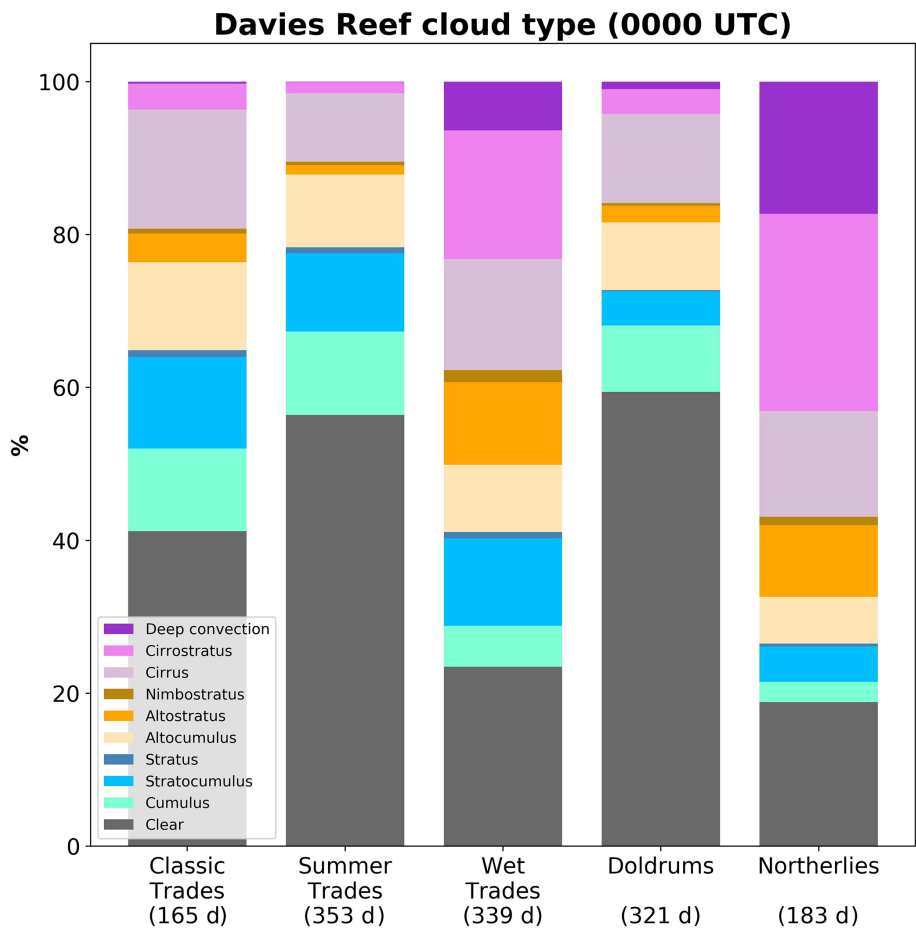


Figure 5. December to April cluster average cloud type using JAXA Himawari-8/9 cloud typing for a 1° box centred on Davies Reef at 00:00 UTC (10:00 LST). Cloud typing is based on the ISCCP cloud classification system. The high clouds are represented by the purples, mid-level clouds the oranges, and low clouds the blues/greens. Note data is only available from December 2015 to April 2024.

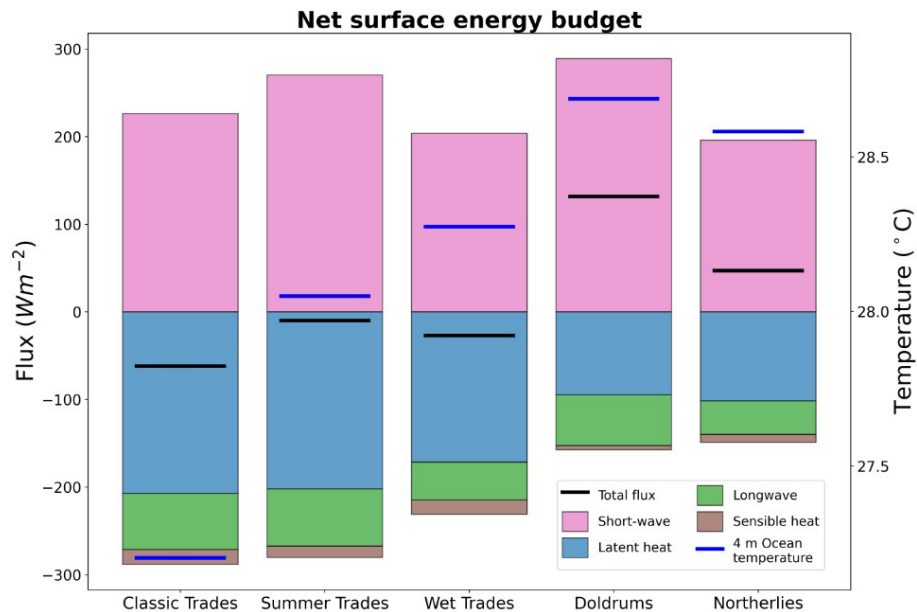


Figure 6. Cluster averages of daily averaged net surface fluxes (bars) with the total net flux (black) and AIMS Davies Reef AWS 4 m ocean temperature (blue). Note here positive (negative) flux values represent incoming (outgoing) radiation.

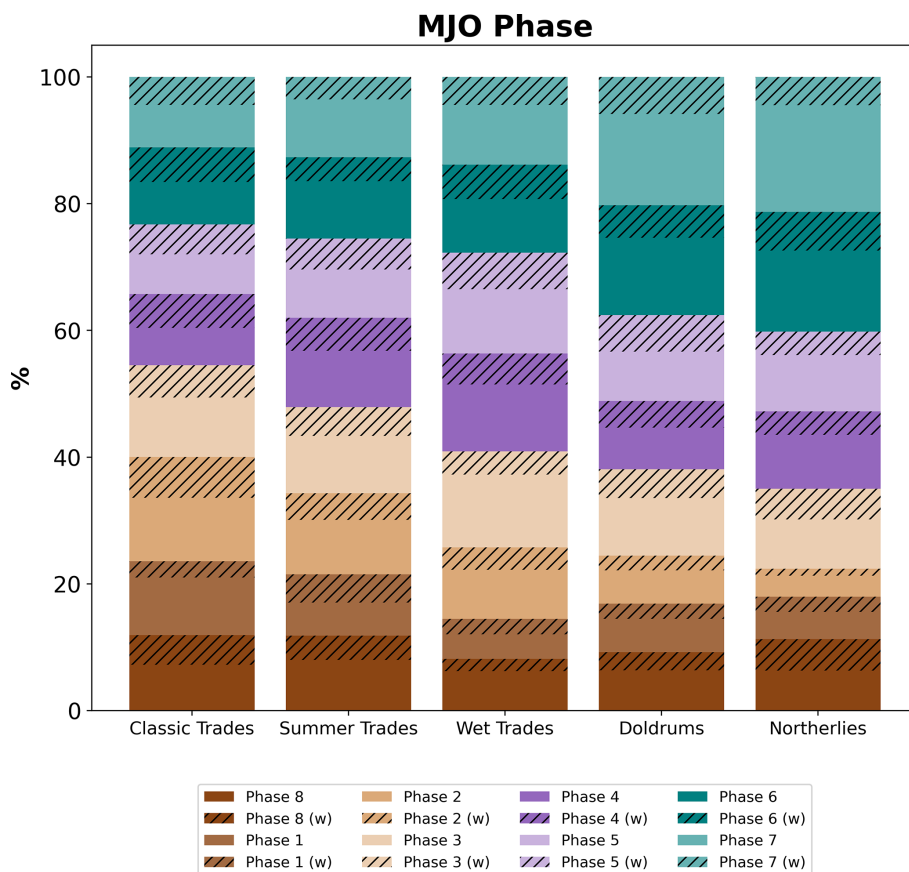


Figure 7. MJO phase breakdown for the December–April 1996–2024 period separated into active phases (solid) and weak phases (hashed). Based on the Australian region, the suppressed convective phases 8–3 (browns) and the enhanced convective phases 4–7 (purples/blues) are grouped.

Table 4. Number of days the Davies Reef daily averaged 4 m ocean temperatures exceeds the maximum +1 standard deviation temperature (29.4 °C) and local bleaching threshold (29.8 °C) during the 1996–2024 December–April period for each cluster.

	Classic Trades	Summer Trades	Wet Trades	Doldrums	Northerlies
Total days	747	1050	1063	835	540
Days > 29.4 °C	0	15	37	119	56
% of cluster	0 %	1.4 %	3.5 %	14.3 %	10.4 %
Days > 29.8 °C	0	0	7	29	18
% of cluster	0 %	0 %	0.7 %	3.5 %	3.3 %

there is only small shift towards longer doldrums in bleaching years (Fig. 9d). Interestingly, while the northerlies show minimal frequency differences, bleaching years tend to have no > 10 d events and more 3–5 d events (Fig. 9e).

Along with an increase in the doldrums, there is a more notable absence of the strongest cooling cluster, the classic trades, during mass bleaching years which have instead been replaced with the weaker summer trades cluster (Fig. 8a). For the classic trades, these shifts are statistically significant in both the December–April ($p < 0.01$) and April ($p < 0.01$), while the summer trades has significant shifts in December ($p < 0.05$) and April ($p < 0.01$) (Fig. 8a, c–d). While the classic trades are normally relatively infrequent from December–March, in December, five out of eight bleaching years had no classic trades form. Although there are years that also had no classic trades form in December that did not bleach (2011, 2019), these years had strong cooling in April with 26 and 18 classic trades forming respectively. Comparatively, all eight bleaching years did not exceed 14 classic trades in April. This reduced frequency aligns with a general loss of the long duration (> 10 d) events in bleaching year towards more ≤ 5 d events (Fig. 9a). As the classic trades on average make up 56 % of the April cluster, bleaching years may be experiencing an unusual extension of the warm season in conjunction with an earlier weakening of the trade winds in December.

While we do see evidence of more doldrums and fewer classic trades in bleaching years, it is important to note that given the number of recorded CBE cases is relatively limited (eight CBEs between 1996 and 2024), this does constrain the statistical robustness we can produce from our comparison between bleaching and non-bleaching years.

5 Case Studies

While on average the non-trade clusters, in particular the doldrums, show the highest risk for thermal spikes, it is important to understand the cluster evolution during CBEs. Here we analyse the clusters across three separate GBR mass bleaching events during the three El Niño Southern Oscillation (ENSO) phases; 2016 (El Niño), 2022 (La Niña), and 2024 (Neutral), where the phase distinction is based on the

December–February average Southern Oscillation Index. We analyse daily averages of the ERA5 surface net flux and its four components with 4 m ocean temperature and surface wind observations from the AIMS Davies Reef AWS (Fig. 10). As it is difficult to determine the exact start/end dates for individual CBEs, we instead analyse a 91 d period centred on the warmest day in the 4 m ocean temperature record for each CBE.

In general, all three bleaching events show the same well-documented meteorological pattern where periods of ocean temperature spikes coincide with a change in wind direction away from the south-easterly trades and a drop in the LHF forced by weakened surface winds and/or increased surface humidity, regardless of the phase of ENSO. These heating periods are followed by relatively rapid cooling driven by a return to the stronger trade south-easterlies and subsequent enhancement of the LHF. However, the timing and duration of these heating periods differ across the events.

In all three events, the longest heating spikes line up with sustained non-trade conditions of at least 15 d. In 2016, there were three distinct temperature spikes with gradual warming during periods of calm winds and rapid cooling as strong easterly winds re-established on 8 and 21 February, and 2 March (Fig. 10a–b). These events clearly illustrate the inverse relationship between wind speed and the LHF. Each warming spike was dominated by the non-trade clusters (primarily the doldrums), followed by a shift to wet or summer trade clusters during the subsequent rapid cooling phase. The first heating spike in particular saw a large consecutive non-trade period lasting 15 d (6 doldrums, 9 northerlies), where the ocean temperature rose 0.9 °C. Conversely, the 2022 CBE featured a single major heating spike that hit a maximum on 10 March (Fig. 10c–d). This heating period also coincided with a stretch of 15 consecutive non-trade wind days (12 doldrums, 3 northerlies) resulting in a 1.2 °C temperature increase before transitioning into the wet trades and then the classic trades as temperatures plummeted. Unlike 2016 and 2022, the 2024 heating appeared earlier in the season, with a first spike on 19 December and a second spike on 27 January (Fig. 10e–f). The December spike was particularly intense, corresponding to the longest consecutive non-trade period

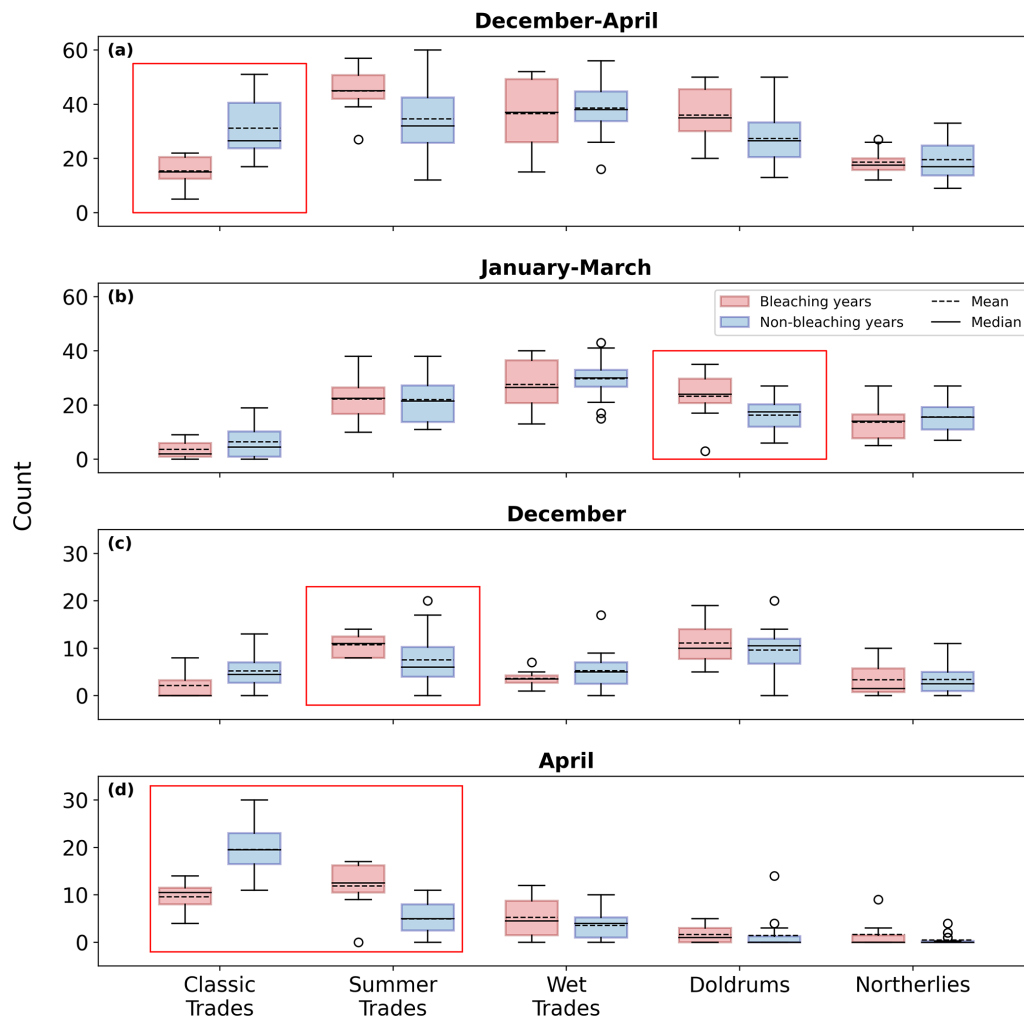


Figure 8. Cluster frequency box plots splitting the 1996–2024 data into mass bleaching ('98, '02, '06, '16, '17, '20, '22, '24) and normal years. The distribution is split into the full GBR coral bleaching season (December–April) (a), isolating the warmest months (January–March) (b) and the fringe months; December (c) and April (d). Red boxes highlight samples where $p < 0.05$ based on Kolmogorov–Smirnov testing.

(18 d, 13 doldrums and 5 northerlies), during which ocean temperatures rose by 2.4°C .

The cluster distribution across the three time series shows that the doldrums are the most frequent (32 %), while the wet trades follow closely (30 %) with the summer trades (17 %), northerlies (16 %), and classic trades (5 %). The absence of the classic trades is unsurprising as they are typically missing until April (Fig. 2). While the doldrums and wet trades have similar frequencies across the three periods, the doldrums generally persist the longest with an average duration of 3.7 d with 30 % of events ≥ 6 d and 42 % ≤ 2 d. Conversely, the wet trades is skewed more to shorter events with average duration of 2.6 d with only 13 % events ≥ 6 d and 62 % ≤ 2 d.

6 Discussion

Our trade and non-trade regimes presented show clear differences in both their heating/cooling tendency and frequency during mass bleaching periods. The largest ocean heating periods aligns with sustained non-trade conditions, particularly long stretches of doldrums periods. Conversely, the most pronounced temperature drops occur during the wet trades often following transitions from doldrums or northerlies (Table 1). Bleaching years feature significantly more doldrums forming in the warmest months (January–March), with often no classic trades in December and significantly less in April which generally bring ocean cooling. A lack of stronger trades in December could allow ocean heat to build up early in the season (Spady et al., 2022), which would be amplified in the warmer January–March period as the trades break down more frequently into the doldrums. Likewise, the lack of clas-

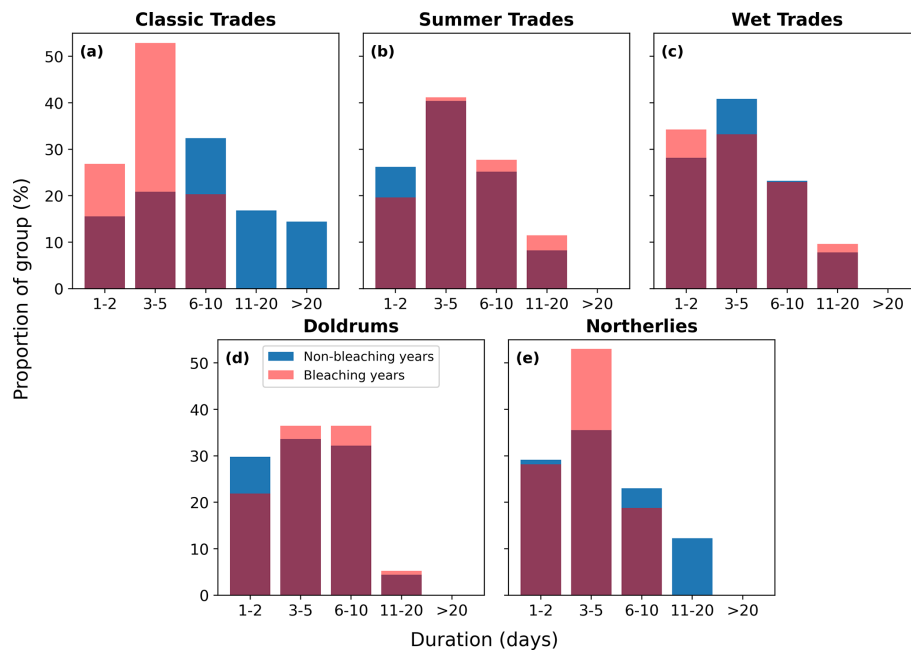


Figure 9. Cluster durations split the 1996–2024 data into mass bleaching ('98, '02, '06, '16, '17, '20, '22, '24) and non-bleaching years. As the total days in each cluster are different, each bleaching and non-bleaching duration frequency is normalised by dividing through the amount of days in the respective group.

sic trades in April may allow the warmer ocean temperatures to persist for longer causing late-season bleaching (Smith and Trewin, 2024). The drivers of increased doldrums and fewer classic trades is not currently obvious, however they suggest a general weakening of the trade winds over the GBR during bleaching years despite the observed strengthening of the western equatorial Pacific trades (Li et al., 2019).

While it is clear non-trade conditions provide the ideal environment for ocean heating, what causes the initial breakdown and duration of the non-trade clusters is more complex. Given that trade winds represent the climatological baseline for the region's meteorology (Malkus, 1958), their breakdown requires the introduction of a synoptic-scale disturbance capable of disrupting the subtropical ridge pattern that sustains them. For the doldrums, this disturbance needs to flatten the pressure gradients over the GBR region. One potential mechanism is Rossby-wave breaking over eastern Australia, where the associated potential vorticity mixing can weaken surface pressure gradients and suppress trade wind flow (Hoskins et al., 1985). Our synoptic anomalies do indicate Rossby-wave activity through the presence of a wave train that has just passed over eastern Australia (Fig. 4h). Consecutive anticyclonic Rossby-wave breaking events were noted during the 2022 bleaching event and thought to drive the breakdown of the trade winds in this event (Richards et al., 2024) while Rossby waves have also been connected to marine heatwaves in the North Pacific (Di Lorenzo and Mantua, 2016) and western Indian Ocean (Chambers et al., 1999; Spencer et al., 2000). Interestingly, our wave chain is almost

identical to the work of Lee et al. (2010), who attributed a central South Pacific marine heatwave in 2009–2010 to the overlying anticyclones in a Rossby-wave chain. While the wave in Lee et al. (2010) was associated with strong central Pacific warming, this wave could also be generated by cyclonic Rossby-wave breaking as described by Barnes et al. (2025). This process may also be similar to the doldrums in the North Atlantic trade region where the location of Rossby-wave breaking has also been found to alter the typical trade wind flow during boreal winter when the trades are usually more stable (Aemisegger et al., 2021). The passage of African Easterly Waves is also thought to weaken the trade winds in the tropical east Atlantic, allowing for the formation of the doldrums and ocean heating (Thiam et al., 2025). While these interactions with Rossby-waves provide valuable insight into the synoptic patterns over the GBR, further research is needed to fully understand their influence on the trade wind regions.

Both non-trade clusters showed larger proportion of the MJO in phases 6–7. While it has been argued that a faster propagating MJO in phases 6–7 can disrupt these doldrums periods (Gregory et al., 2024), that is not obvious in our analysis. The MJO's passage over the northern GBR may at times contribute to trade wind breakdown, but it is not the sole driver, as while there is enhanced convection and rainfall in the northerlies, we find the opposite in the doldrums. Given the MJO's tropical definition (15° N–15° S) we cannot expect the same phase relationship with sites outside of this region (Wheeler et al., 2009). For example, Dao et al.

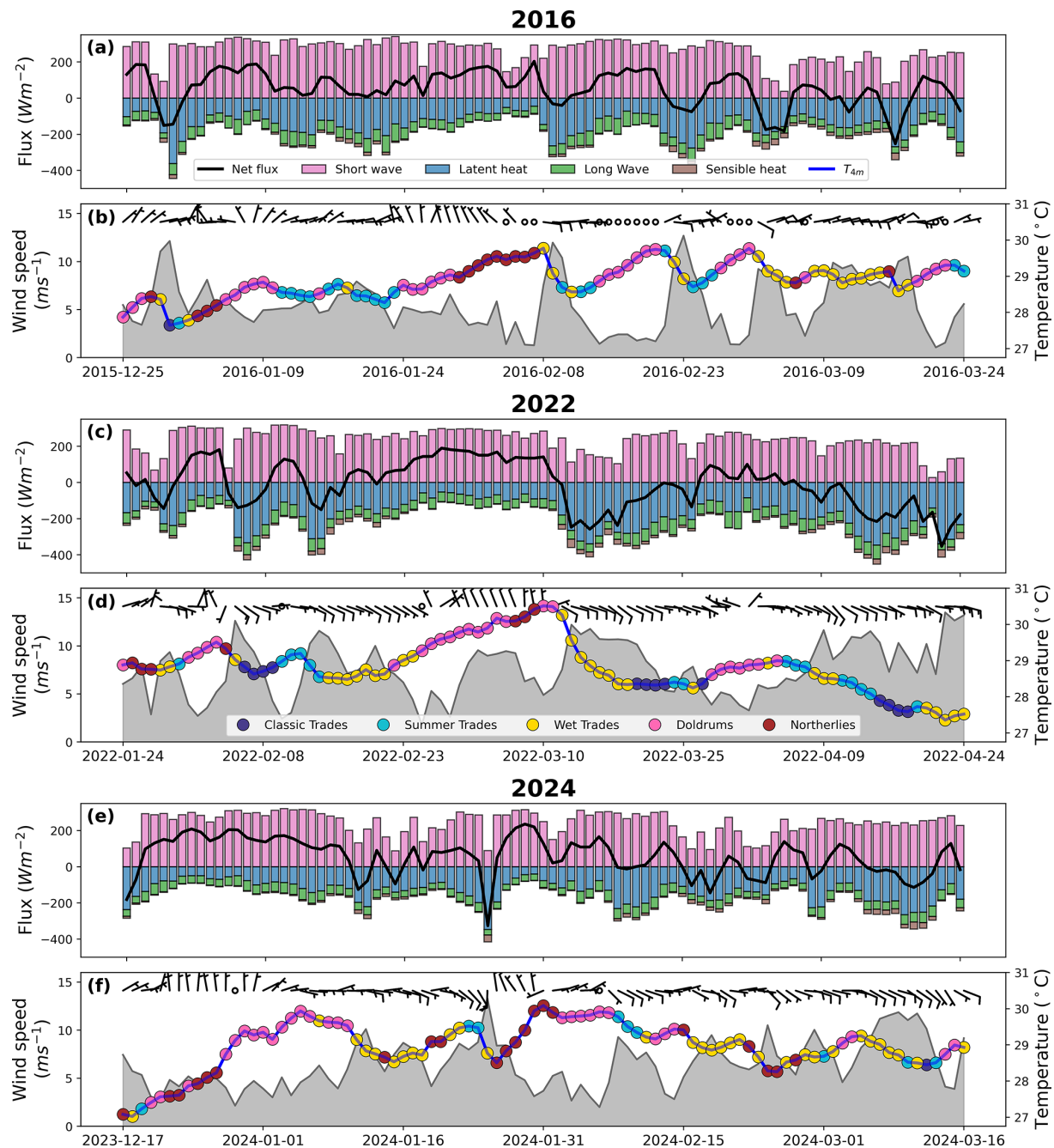


Figure 10. Case studies during the 2016, 2022 and 2024 GBR CBEs taken at Davies Reef on a daily average time frame. Panels (a), (c), (e) show ERA5 flux data, with net short-wave (pink), net long-wave (green), latent heat (blue), sensible heat (brown) and the net flux (black). Here positive (negative) values represent incoming (outgoing) radiation. Panels (b), (d), (f) show surface wind speeds (grey, m s^{-1}) and directions (barbs, m s^{-1}) and 4 m ocean temperatures (blue, $^{\circ}\text{C}$) from the Davies Reef AIMS AWS. The daily cluster is plotted along the temperature.

(2025) showed how the local environment can enhance precipitation over the Townsville region (100 km southwest of Davies Reef) even during the suppressed convection phases of the MJO. At Davies Reef, the existing local circulation and lower tropospheric winds likely determines how the environment interacts with the MJO, where primarily the northerlies

have the strong northerly flow needed to transport moist air from the tropics. This is also evident in the back trajectories, as the northerlies predominantly contains air masses from either the Maritime Continent or neighbouring Coral Sea that are found closer to the surface, while in the doldrums, air masses rarely originate equatorwards of 15°S (Fig. 11) and

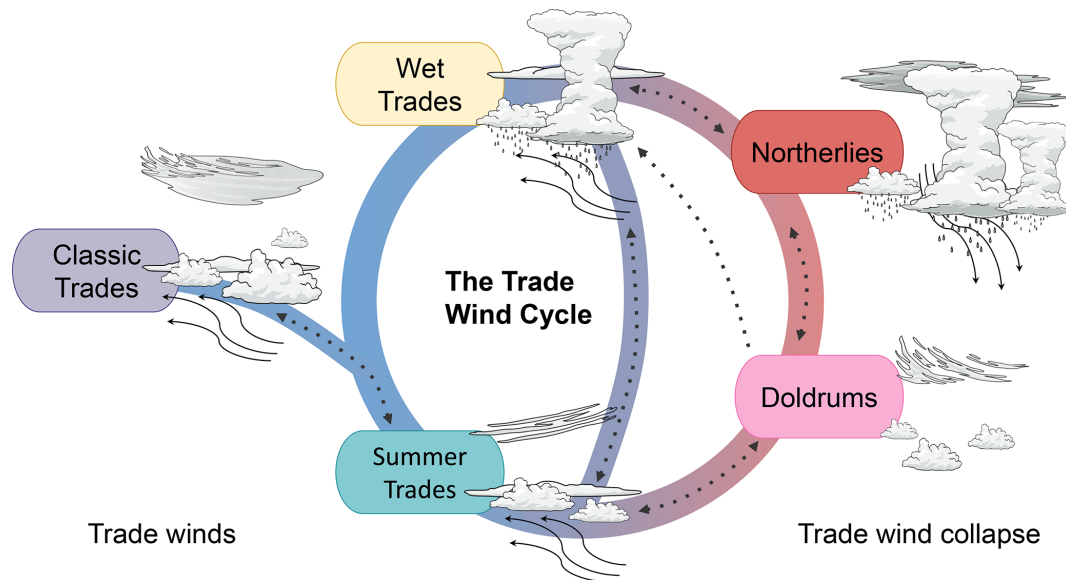


Figure 11. Schematic of the proposed trade wind cycle.

are generally subsiding (Fig. 3), as was proposed by Windmiller (2024).

The transitions between the trade wind and non-trades regimes is a complicated process, however, we propose a basic “trade wind cycle” to provide meaningful insight into the processes underlying ocean heat and atmosphere variability (Fig. 11). This framework offers valuable potential for improving the prediction of particular wind regime, as well as informing long-term strategies for mitigation of CBEs. Trade winds represent the basic state of the regional atmosphere, making them more resistant to disruption and easier to re-establish once perturbed. Over December–April the trade wind clusters generally transition between the summer and wet trades until the system is disturbed and shifts into the non-trade regime, typically from the summer trades to the doldrums via a cyclonic anomaly. Here the low cloud fraction drops as the winds weaken, while the air and ocean temperatures increase. If the cyclonic anomaly moves equatorwards, the doldrums transition to the northerlies where high cloud and deep convection dominate the region, however the high surface humidity continues to suppress the LHF and maintain high ocean temperatures. Re-establishment of trade winds generally occurs through the wet trades cluster as a ridge re-develops over eastern Australia aiding the return of easterly winds that reduces humidity and increases the LHF, promoting rapid cooling. However, high cloud and deep convection from the preceding northerly phase often remain.

As the shallow waters of coral reefs are particularly sensitive to changes in the daily meteorology, the ability to forecast these events is again dependent on how well these weather-scale processes are represented in subseasonal prediction models. Over the GBR, while there is skill in forecasting the start of the marine heatwave, there is less predic-

tive skill in determining the marine heatwave’s end due to the under representation of weather scale processes like tropical cyclones (Benthuisen et al., 2021). While our study has begun to explore the relationship between the trade winds and ocean temperature, there is a clear need for better process-level understanding of ocean-atmosphere interactions to improve the prediction of the events’ end or the duration of the thermal stress period would provide essential information for reef management and regional climate adaptation strategies. In turn, influencing the continued survival and health of the GBR and the countless stakeholders dependent on it.

7 Conclusions

Through our clustering climatology of the GBR coral bleaching season, our study has shown how the dominant synoptic patterns can be separated into a trade wind and non-trade wind regimes. The three identified trade wind clusters, which typically bring stronger winds and more extensive cloud cover, are associated with ocean cooling while the non-trades, particularly the doldrums, have weak LHF brought by weaker winds and higher humidity, that cause ocean heating.

The doldrums capture not only the warmest GBR ocean temperatures, but also the calm and clear conditions reported amongst bleaching events for many decades. While bleaching years do have more frequent doldrums, especially during the warmest months, the development of more longer duration doldrums and non-trade periods combines to elevate the risk of thermal spikes and coral bleaching. In conjunction, mass bleaching years more often have no classic trades

forming in December with low numbers in April meaning where the loss of long (> 10 d) duration classic trades is most prevalent. Losing the classic trades means less ocean cooling during these months and could contribute to a build-up of early summer heat stress and/or the persistence of heat later into the season. Thus, while it was already apparent that periods of calm and clear conditions during the doldrums cause ocean heating, the absence of cooling events on the edges of the coral bleaching season may be more important in turning a normal year into a bleaching year.

To transition into the doldrums the trade winds over the GBR need to be disrupted. This could be achieved by Rossby-wave breaking which can weaken the pressure gradients forming areas of weak winds, clear skies, and subsiding air. However, there are other mechanisms likely to break down the trade winds such as the passage of tropical cyclones or jumps in the monsoon trough which should be investigated further.

This work provides a framework for understanding the evolution of the trade winds over the GBR, whose presence is important for ocean cooling and preventing marine heat-waves. As the local weather conditions are essential drivers of GBR ocean temperatures, furthering our understanding of the trade wind structure and how they break down is crucial for the continued monitoring and forecasting of marine heat-waves and thermal bleaching events.

Data availability. All datasets used in this study are publicly available online. The Australian Institute of Marine Science Davies Reef data is available at <https://doi.org/10.25845/5c09bf93f315d> ((AIMS), 2020). The ERA5 reanalysis data is available from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS), with single level data found at <https://doi.org/10.24381/cds.adbb2d47> (Hersbach et al., 2023b) and pressure level data at <https://doi.org/10.24381/cds.bd0915c6> (Hersbach et al., 2023a). The Himawari-8/9 cloud categorisation data is available from the Japan Aerospace Exploration Agency (JAXA) P-Tree System (<https://www.eorc.jaxa.jp/ptree/>, last access: 12 June 2025). The Bureau of Meteorology SOI data is available at <http://www.bom.gov.au/climate/enso/soi/> (last access: 3 June 2024) and the MJO RMM index from <http://www.bom.gov.au/climate/mjo/> (last access: 5 September 2024). Lastly, NOAA's OISST data can be found at <https://www.ncei.noaa.gov/products/optimum-interpolation-sst> (Huang et al., 2021).

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