The role of clouds in coral bleaching events over the Great Barrier Reef

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Key Points:

- Lagged regional SST is found to be correlated with total cloud cover across the GBR and direct shortwave cloud radiative forcing
- SST over the GBR is more highly correlated with the overhead cloud cover than the large-scale ENSO signal
- Local-scale reduced cloud cover plays a crucial role in the shallow water warming over the GBR and the occurrence of thermal CBEs
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Abstract

Thermal coral bleaching events (CBEs) over the Pacific, including those over the Great Barrier Reef (GBR), have commonly been linked to the El Niño–Southern Oscillation (ENSO), with bleaching reported to be a direct result of sea surface temperature (SST) anomalies driven by El Niño. However, such a relationship cannot explain CBEs that occurred during La Niña or the neutral phase of the ENSO. Here we show that the GBR is characterized by a significant negative correlation between total cloud cover anomaly (TCCA) and lagged SST anomaly (SSTA) whose magnitude and spatial extent are greater than the SSTA-ENSO correlation. This significant negative TCCA-SSTA (lagged) correlation prevails over two-thirds of the study domain even after the ENSO signal is removed, which suggests that local-scale reduced cloud cover is a key component of the regional warm shallow water formation over the GBR and the occurrence of thermal CBEs.

Plain Language Summary

Thermal coral bleaching events (CBEs) over the Pacific, including those over the Great Barrier Reef (GBR), have commonly been linked to the El Niño–Southern Oscillation (ENSO), with bleaching reported to be a direct result of warmer sea surface temperatures (SSTs) driven by El Niño (positive phase of ENSO). However, CBEs have also been reported over the GBR during La Niña and the neutral phase of the ENSO, when large-scale SSTs may be cooler than normal. Here we show that the SST anomaly over the GBR is more highly correlated with local cloud cover than with ENSO. This significant relationship between local cloud cover and SST can be found over two-thirds of the study domain even when the ENSO impact is ignored. Accordingly, we conclude that local-scale reduced cloud cover plays an important role in the regional warm shallow water formation over the GBR, regardless of the large-scale ENSO impact.

1 Introduction

The Great Barrier Reef (GBR) has experienced increasingly frequent coral bleaching events (CBEs) under present day global warming (AIMS, 2017; Hughes et al., 2017; Stuart-Smith et al., 2018). Evidence for a dominant role of sustained elevated water temperature in the bleaching process, specifically thermal CBEs, is unequivocal (Ainsworth et al., 2016; Barnett et al., 2005; Donner et al., 2005; Lough et al., 2018). For the GBR, unusually warm sea temperatures have caused significant thermal CBEs several times in recent decades, particularly in the summers of 1998, 2002, 2006, 2016 and 2017 (AIMS, 2017; Berkelmans et al., 2004; Great Barrier Reef Marine Park Authority, 2006; Hughes et al., 2017; Hughes et al., 2018). For this study, CBEs refer only to thermal coral bleaching events.

Previous studies have shown that reef growth and decline across the Pacific is strongly modulated by El Niño-Southern Oscillation (ENSO) variability (Leonard et al., 2016; Toth et al., 2012). Some of the most devastating mass CBEs, including those reported over the GBR (McGowan and Theobald, 2017), have occurred during El Niño events, where bleaching was reported to be a direct result of increased sea surface temperatures (SSTs) (Baker et al., 2008; Glynn et al., 2001; Kleypas et al., 2015). There are, however, other El Niño events (e.g. 2002-2003) that have not led to reports of significant CBEs across the GBR. Indeed, El Niño itself does not lead to the rise of SSTs in all regions. For example, the Western Pacific typically observes below average SSTs due to the eastward shift of the Walker Circulation during El Niño.

Thus, attributing the CBEs in the western tropical Pacific Ocean directly to the increased regional SSTs caused by El Niño is not consistent with the well-established understanding of ENSO SST variability across the tropical Pacific Ocean (Baker et al., 2008). It is also worth noting that some CBEs (e.g. the 2006 event, Table 1) occurred during the La Niña phase (cool ENSO phase).

At the same time, cloud cover in the equatorial Pacific Ocean is found to be closely linked to ENSO variability (Park and Leovy, 2004; Eastman et al., 2011). For example, El Niño is typically associated with increased cloud cover in the central and eastern tropical Pacific Ocean and reduced cloud cover over the Indonesian and western Pacific regions, and vice versa for La Niña events. Numerous studies have identified the potential of cloud radiative forcing to constrain SSTs at a local scale by governing the incoming solar radiation (e.g. Schneider, 1972; Stephens, 2005, Fischer and Jones, 2012; Tompkins, 2001; Masiri et al., 2008; Fitt et al., 2001) including over the GBR (Leahy et al. 2013). As a result, ENSO presumably affects the local SST change indirectly through cloud cover changes and the associated incoming solar radiation changes.

Evidence that supports this argument has been reported in recent studies. McGowan and Theobald (2017) investigated the role of meteorology in CBEs over the GBR during El Niño years and found that the local meteorology, rather than El Niño-forced SST change itself, has been the primary cause of CBEs over the GBR. In particular, they highlighted the role of reduced cloud cover in the dominant weather conditions associated with the CBEs. Similarly, a more recent study of the 2016 CBE over the GBR (Karnauskas, 2020) revealed that increased radiative heat flux associated with a shift of cloud patterns under El Niño phase was the primary driver of the first ocean warming pulse of the 2016 CBE, highlighting the importance of solar radiation in warming the shallow reef environment.

While the importance of local-scale weather patterns that result in less cloud cover and higher solar radiation associated with El Niño are being recognized, fundamentally lacking is a statistically quantitative analysis of cloud-radiation-SST relationship over the GBR under ENSO regime changes (i.e. El Niño, La Niña and neutral phases). The pioneering studies discussed above, while illuminating, have focused exclusively on CBEs during El Niño year(s), while the broader climatological context has been overlooked. Moreover, their analyses relied heavily on reanalysis datasets whose representations of clouds are prone to large uncertainties. Cloud-related variables are not assimilated into reanalyses but instead predicted by the models, thus their representations are subject to errors related to physical parameterizations (Wu et al., 2012; Xu 2009).

Using a newly published long-term (1996-2018) cloud and radiation satellite dataset, here we analyze the extent that local-scale cloud cover and corresponding solar radiative fluxes relate to regional sea surface temperature change. Our analysis initially focuses on the reported CBEs over the GBR before looking more widely at the cloud cover – SST relationship over the full time period, and the large-scale influence of ENSO. In particular, we seek to address two scientific questions: (1) Is there a natural relationship between local-scale cloud cover, solar radiative flux and SST over the GBR? (2) How and to what extent is such a relationship influenced by ENSO? It is worth noting that our primary objective is to determine the meteorological conditions that could be factors in the occurrence of CBEs over the GBR, rather than detailing the mechanisms and processes that led to CBEs. Nevertheless, addressing these questions aid in establishing the knowledge base that is necessary for developing targeted and effective reef management and restoration strategies.

2 Data and Methods

2.1 Identification of five major thermal CBEs over the GBR

The detailed periods and areas (Figure 1) of five past thermal CBEs across the GBR were identified by the Australia Institute of Marine Science (AIMS) (https://www.aims.gov.au/docs/research/climate-change/coral-bleaching/bleaching-events.html) as shown in Table 1. Bleaching also occurred during the Austral Summer of 2008-2009 and 2010-2011. However, these did not coincide with warm SST during summer season as defined by AIMS. These non-thermal events in 2008 and 2010 were attributed to an influx of freshwater, which are not a focus of this analysis.

Table 1 Summary of time periods and areas of five past thermal CBEs across the GBR

Year	Periods	Areas affected by bleaching	ONI (JFMA average)
1998	Feb. and Mar.	Palm Island Area	+1.63
2002	Jan. to Apr.	Bowen Area	+0.05
2006	Jan. and Feb.	Southern Reef, especially around Keppel Island	-0.58
2016	Feb. to May	Far Northern Area, between Cape York and Port Douglas	+1.85
2017	Austral Summer months	Mid-tropics	0

Note. The positive Oceanic Niño Index (ONI)indicates warm phase of ENSO (El Niño)

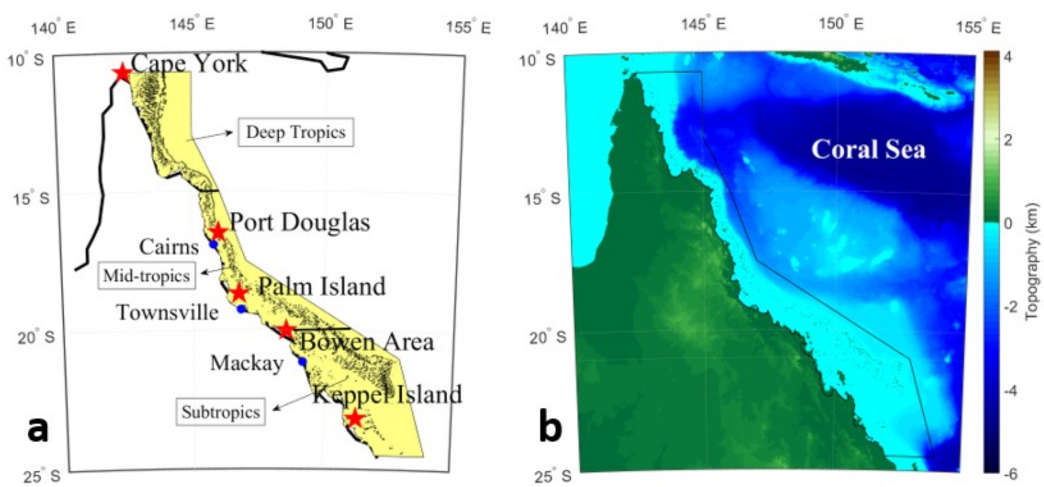

Fig.1 Study domain definition and locations of five thermal CBEs. a Region 140 - 155°E, 10 - 25°S is defined as the study domain. Yellow shading area indicates the GBR general reference map with locations of five past CBEs

(red stars). Three parts of GBR general reference map are defined as Deep Tropics, Mid-tropics and Subtropics. **b** Bathymetric map of the domain.

2.2 Observation data:

Long-term (1996-2018) cloud and radiative properties, including monthly total cloud cover (TCC) and shortwave radiative flux at the bottom of the atmosphere (SWRF), are collected from the Advanced Very High Resolution Radiometer (AVHRR) measurements of European Space Agency's (ESA) Climate Change Initiative (CCI) programme (Hollmann et al., 2013; Finkensieper et al., 2020). In this study we analyze the version 3 of the Cloud_cci AVHRR post meridian (AVHRR-PMv3) dataset, which in many aspects is superior to the precursor version v2 as data quality was improved (Stengel et al., 2020). The Cloud_cci AVHRR-PMv3 dataset contains a comprehensive set of pixel-based cloud and radiative flux retrieved properties on a global scale with a resolution of 0.5° longitude by 0.5° latitude (Sus et al., 2018) (for details see supplementary material Section S1).

In this study, a monthly SST data set is derived from the 5th generation of ECMWF climate reanalysis dataset (ERA5) (Hazewinkel, 2002; Hersbach et al., 2018) with a resolution of 0.25° for the time period of 1996-2018. The monthly anomalies are defined with respect to the average monthly values for the whole 23-year time period (1996-2018).

2.3 Correlation coefficients. All regression analysis in this study is undertaken after applying a 3-month running average to remove high-frequency noise. Unless otherwise stated, the significance of the correlation coefficients throughout the study is estimated by computing empirical probability density functions (EPDFs) for the correlation coefficient of two time series. The correlation is considered to be significant when the confidence level is above 95%.

2.4 Partial Correlation. In addition to total correlations of monthly SWRF anomaly (SWRFA), monthly TCC anomaly (TCCA) and monthly SST anomaly (SSTA), we examine the partial correlation between these variables after removing the ENSO signal, which is represented by the Oceanic Niño Index (ONI). The partial correlation is a measure of the linear dependence between two variables where the influence from possible controlling variables is removed. In the case of three variables, a, b and c, the partial correlation is defined as (Hazewinkel, 2002):

$$r_{ab.c} = \frac{r_{ab} - r_{ac} r_{bc}}{\sqrt{1 - r_{ac}^2}\sqrt{1 - r_{bc}^2}}$$

where r_{ab}, r_{ac} and r_{bc} is the total correlation between each variable pair and $r_{ab.c}$ is the remaining independent correlation between a and b, assuming no controlling variable c. All partial correlations in the text are considered to be significant when the confidence level is above 95%. When considering time-lag partial correlations in this study, the time series of ONI are applied using unlagged and lagged variables, separately.

3 Results

3.1 Cloud-Radiation-SST anomalies during thermal coral bleaching events over the GBR

Consistent with the AIMS (2017) report, the GBR is found to be experiencing local-scale positive SSTA during coral bleaching events, roughly aligned with the location of the CBEs (Fig. 2a), although this positive SSTA does not extend across the entire domain. It is, however, noticeable that the largest positive SSTA values for each bleaching event (up to 1°C above the long-term local average SST) are all located approximately where major CBEs were recorded (shown by open stars).

The SWRFA and TCCA patterns (Fig. 2b & c) show a strong negative correlation, demonstrating the strong physical connection between cloud cover and solar heating over the GBR. All five thermal CBEs are accompanied by reduced cloud cover and positive SWRFA at the surface, especially near where the most intense CBEs were reported. During the CBEs in 2002 and 2006, there was up to 20% less cloud cover than normal with 30 Wm^{-2} more shortwave radiative flux at the surface over the bleaching areas, on average. Overall, the SSTA pattern for each bleaching event is consistent with the overall SWRFA pattern along the GBR, with the local SSTA maximum often observed near the area that experienced the largest shortwave radiation anomaly and, correspondingly, a strong negative TCCA. Turning to the Coral Sea, while a strong negative correlation between the SWRFA and TCCA remains noticeable, there is no evidence of any strong spatial correlation between the SWRFA and the SSTA. It is likely that the much deeper water over the Coral Sea (Figure 1b) makes it less responsive to local solar insolation.

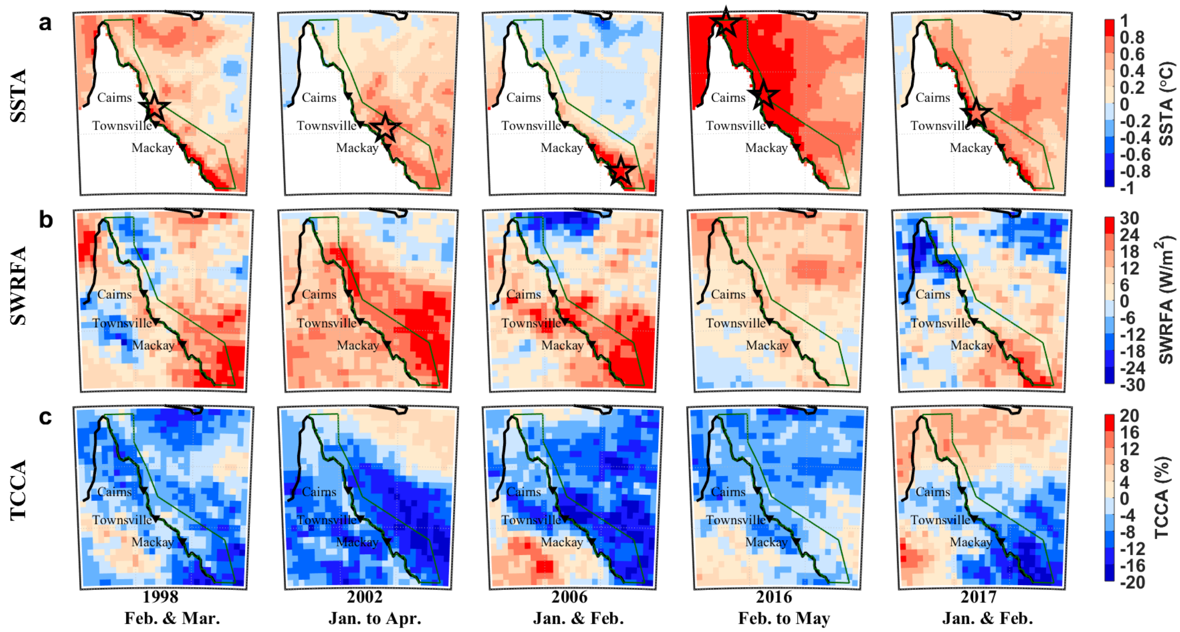

Fig.2 Cloud-Radiation-SST anomalies pattern during CBEs. Geo-distribution of SSTA (**a**), SWRFA (**b**) and TCCA (**c**) for five CBEs. Base period is 1996-2018. Open stars in (**a**) indicate the locations of CBEs in each year. Green lines show the GBR general reference map which covers the main coral reefs of the GBR (same as in Figure 1a).

3.2 Time-lag correlations between cloud cover, radiation and SST anomalies for the coral bleaching season (Jan – Apr)

Given that most thermal CBEs across the GBR occur in Austral warmer months from January to April (Table 1), we define these four months as the coral bleaching season over the GBR. Analysis of the lagged correlations of TCCA, SWRFA and SSTA during the coral bleaching season is examined on a monthly scale using a cross-correlation method based on the 23-year cloud observation record (Fig.S1).

Our results show that SWRFA is most strongly negatively correlated with TCCA with no time lag, which is fully expected. The correlation coefficient between TCCA and SWRFA is up to -0.9 (Fig. S1a) over the full study domain (Fig. 3a), indicating the dominant role of cloud cover in defining the SWRF. Regressing the SWRFA against SSTA produced the strongest positive relationships when the SSTA was lagged by one month (Fig. S1b), which reflects the larger specific heat capacity of the ocean water. This is consistent with earlier research which shows that the lag in SST behind solar radiation (known as the lag of the seasons) is in the range of 30-40 days across the GBR area and 30-60 days for the rest of our domain (Li et al., 2013). Across the GBR, this correlation is statistically significant at the 95% confident level and often in excess of 0.36. The strongest positive correlation between SWRFA and one-month lagged SSTA can be seen in the higher latitudes of the sub-tropics, where the correlation coefficient is around 0.6 (Fig. 3b). Conversely only a very weak, mostly insignificant, correlation is noted over the Coral Sea. Similarly, regressing TCCA against SSTA with a one-month lag produces the strongest statistically significant relationships, especially over the sub-tropics where the correlation coefficient is about -0.5 (Fig. S1c). The TCCA along the GBR in the mid- and sub-tropics is negatively correlated with SSTA with a one-month lag (Fig. 3c), much as it was during the individual CBE events (Fig. 2). Over the deep tropics the negative correlation between TCCA and one-month lagged SSTA is weaker, but still identifiable. The strongest negative correlation over the deep tropics exists with two months lagged SSTA (Fig.S1c). This different SSTA time lag over the deep tropics is not a surprise, given the prevalence of high clouds (Fig. S2), such as cirrus outflows, whose longwave warming effect can commonly exceed their cooling effect.

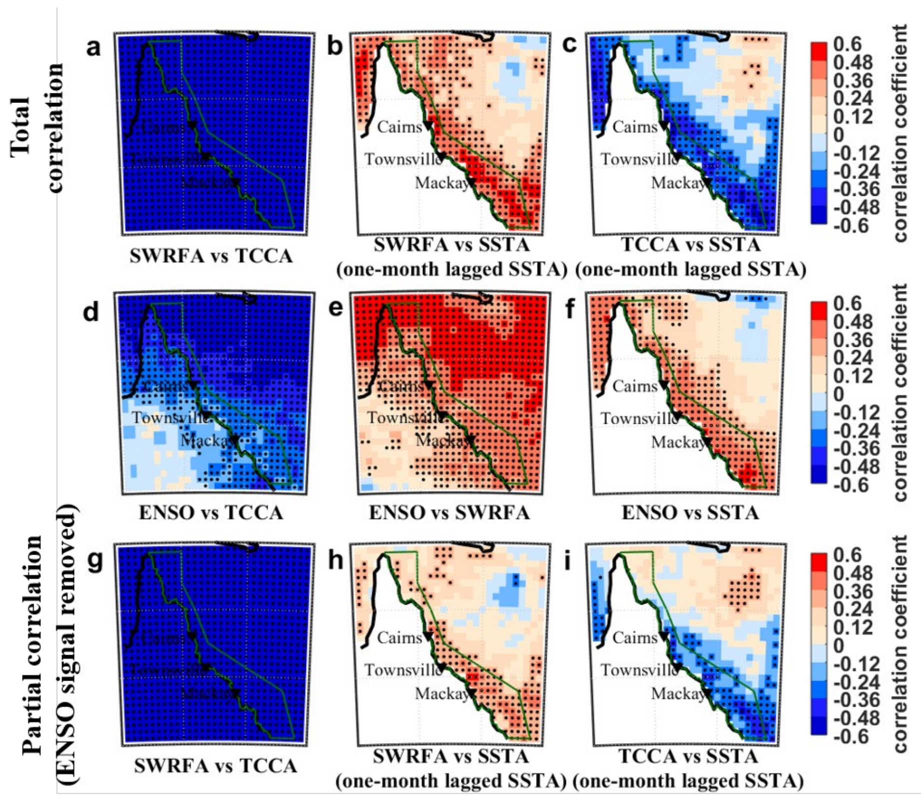

Fig.3 Cloud-Radiation-SST correlations and ENSO impact for coral bleaching months (JFMA). a. Correlation between SWRFA and TCCA with no time lag. **b. c.** Same as **a**. for one-month lagged correlations of between SWRFA and SSTA and between, TCCA and SSTA. **d. e. f.** Correlations of ENSO (ONI index) against SWRFA, TCCA and SSTA on monthly scale. **g. h. i.** Partial correlations of these variable anomalies when ENSO signal is

removed. Note that the correlations are for coral bleaching season (Jan. to Apr.) over the time period of 1996-2018. Black dots indicate the correlations that are statistically significant at a significant level of 95%.

The correlation analysis shows that the SST across the GBR area (yellow shading area shown in the Figure 1a) can respond to cloud cover through the cloud interception of solar radiation. Strong positive cloud-radiation and radiation-lagged SST correlations indicate a rapid radiation response to changes in cloud cover, which then leads to a subsequent SST response with one-month lag across much of the GBR (Fig. 3b & c). In contrast, the north-east corner of the domain (the Coral Sea) stands out with a weak positive TCCA-SSTA (with one month lagged SSTA) correlation and a weak (under 95% significant level) negative correlation between SWRFA and lagged SSTA. Presumably the SST over the Coral Sea is more strongly affected by large-scale ocean currents than over the shallow GBR region (Fig. 1b).

3.3 The role of ENSO in cloud-radiation-SST relationships across the GBR

Linear regression analysis of monthly SWRFA, SSTA and TCCA onto the ONI for the coral bleaching season over the time period of 1996-2018 (Figure 3 d-f) shows a strong negative TCCA-ENSO correlation (in excess of -0.48) across the much of the domain, particularly across the low-latitudes of the deep tropics (Fig. 3d). Such a strong, uniform negative correlation is fully expected: during positive ONI periods (El Niño phase), clouds and deep convection shift eastward across the Pacific. Cloud cover and precipitation is reduced across the Western Pacific including in Coral Sea and much of the northern Queensland (Karnauskas, 2020). Similarly, significant positive correlations can be seen between ENSO and SWRFA (Fig. 3e). The strongest positive ENSO-radiation relationship is again found across the low latitudes of the deep tropics.

While the relationship between the SSTA and the ONI (Fig. 3f) is not uniform across the whole domain, there is a positive correlation along the full extent of the GBR and even beyond this region, extending into the deeper water off the continental shelf. While this positive correlation is statistically significant across much of the GBR, its magnitude is relatively weak (~0.3) compared to the correlation of TCCA against lagged SSTA (Fig. 3c) and SWRFA against lagged SSTA (Fig 3b): the SSTA along the extent of the GBR is more strongly correlated with the TCCA and SWRFA than with ENSO. Looking further offshore and deeper into the Coral Sea region, this correlation weakens and even reverses. The cooler SSTs over the western Pacific (Coral Sea) are more consistent with the expected changes in the equatorial ocean circulation and easterly trade winds driven by ENSO variations.

Given the correlations between ENSO and TCCA and SWRFA (Fig. 3d & e), it is of interest to examine to what extent the cloud-radiation-SST relationship over the GBR can be explained by the variation in ENSO. To this end we construct the partial correlations of the anomalies of these variables where the ENSO signal is excluded (Fig. 3g-i). Focusing first on the relationship between SWRFA and TCCA, the result suggests no significant difference between total and partial correlation, which, once again, indicates the strong physical connection of these variables. Looking at the SWRFA-SSTA (lagged) relationship, the total and partial correlations (Fig. 3b & h) show a similar pattern, although some differences are noted at the low latitudes where the partial correlation shows a weak positive relationship (under the 95% significance level). However, the significant positive correlation between SWRFA and lagged SSTA remains strong across most of the GBR region when ENSO is excluded, especially over the mid- and sub-tropics (Fig. 3h). The same can also be said for the TCCA-SSTA (lagged) correlation. Significant difference between total and partial correlations can only be found across the low-latitude area, where the partial TCCA-SSTA (lagged) correlation shows a positive but insignificant signal across the deep tropics of the GBR. The rest of the GBR domain (mid- and sub-tropics), however, is still marked by significant negative correlation between TCCA and lagged SSTA when the ENSO signal is excluded. These results suggest that there exists a significant natural relationship between local TCC and regional SST across the GBR at a local scale that cannot be explained by the large-scale climate driver effects of ENSO. A significant difference between the total and partial correlations is also identified over the Coral Sea, with more area showing a statistically significant positive TCCA-SSTA (lagged) partial correlation compared to the total correlation. ENSO is masking this positive correlation.

5 Conclusions and Discussion

Our analysis reveals a strong, significant relationship between total cloud cover and the one-month lagged SST across the GBR domain during the coral bleaching season (Jan – Apr), with a correlation coefficient of up to -0.6 over the sub-tropics (Fig. 3c). The cross-correlation analysis of shortwave radiation, SST and cloud cover suggests that the lagged SST changes correspond with total cloud cover changes across the GBR through direct shortwave cloud radiative forcing. This result highlights the potential of clouds to cool the regional shallow ocean water for much of the extent of the GBR along the north-east coast of Australia (Fig. 3c). While elevated SSTs arising from climate change may pose an active threat to coral reefs through more frequent and widespread coral bleaching events, any such threat may be confounded by accompanying changes to the overlying cloud cover, also arising from climate change.

Our analysis also demonstrates that El Niño is associated with reduced cloud cover, more incoming solar radiation and relatively warmer SST along the coast over the GBR during coral bleaching months, where the warmer SST over the GBR (Western Pacific) is not consistent with the long-established ENSO-forced SST pattern. The positive ENSO-SSTA relationship over the shallow water along the coast (Fig. 3f) is considered to be a combined result of ENSO-TCCA and ENSO-SWRFA correlations, in which local clouds play a crucial role in modulating the regional SST change through governing the incoming solar radiation (Fig. 3a-c). This ENSO-SSTA pattern over the GBR suggests that the SST over the shallow water region is more sensitive to local-scale atmosphere-ocean interactions, rather than large-scale ENSO-forced SST variation. While this reduced cloud cover and increased SWRF extends across the domain from the GBR to deeper waters of the Coral Sea, no strong correlation is observed between the TCCA and SSTA over these deeper waters, which is consistent with the well-established understanding of the ENSO-forced ocean circulation. During El Niño, weakened easterly trade winds lead to enhanced upwelling of cooler sea water over the equatorial Western Pacific. Such upwelling of colder waters is expected to be modulated along the shallow and protected waters of the GBR, and hence the SST may warm during an El Niño.

Our results confirm that while the elevated SSTs associated with El Niño (Fig. 3f) may play an important role in the CBEs across the GBR, particularly in the strong events of 1998 and 2016 (Table 1), such a relationship cannot explain CBEs that occurred during La Niña or the neutral phase of ENSO (Table 1). Our analysis reveals that the lagged SSTA is more strongly correlated with TCCA (and SWRFA) than with ENSO. Even when the ENSO signal is removed through a partial correlation, the TCCA is still found to be significantly negatively correlated to the lagged SSTA across the mid-tropics and sub-tropics portion of our domain. The thermal coral bleaching events of 2002, 2006 and 2017 were all found to have negative TCCA and positive SSTA, even though the ONI was weak or even negative. Despite the large-scale influence of ENSO, the important role of local cloud cover in modulating the regional shallow water heat budget at local scale over the GBR needs to be considered. Over the low latitudes of the deep tropics, however, this negative correlation between TCCA and SSTA largely fails, especially when the ENSO signal is removed. We contend that deep convection generated over the deep tropics produces an abundance of high-level clouds that are capable of warming the SST. Such warming is largely negligible for the patchy trade cumulus clouds commonly found over the sub-tropics. Further analysis of the effects of different types of clouds on SST variation across the GBR is needed.

While we have considered ENSO variability, which is one of the important climate drivers in clouds and SST over the tropical Pacific, it must be noted that other forcing mechanisms, such as the Madden-Julian Oscillation, tropical cyclones and Rossby wave breaking along the east coast of Australia (Parker et al. 2014), may also play an important role in SST and TCC variations across the GBR. For example, January 1998 was not part of a coral bleaching event in spite of the strong El Niño event, as category 5 tropical cyclone Katrina spent 23 days off the Queensland coast producing a large positive TCCA for the month. The non-thermal coral bleaching event of 2010-2011 is also noteworthy given that it has the third strongest ENSO event from our 23-year study period. While positive SSTA was observed across the majority of the GBR domain, the anomaly was not statistically significant. The coral bleaching for the year was attributed to an influx of freshwater (AIMS, 2017).

Cloud cover anomaly is by no means the only risk factor for CBEs, but our results demonstrate that it may play a key role in providing optimal bleaching conditions across the GBR. As such, understanding the natural variability of cloud cover across the GBR, in combination of other risk factors, is essential to informed prediction of CBEs. This is also a prerequisite for a more quantitative understanding of the ocean heat budget which would require the consideration of all energy terms including sensible and latent heat fluxes, longwave radiative flux and ocean heat advection, where the incorporation of additional observations and fine-resolution ocean modelling would be essential. Our study reveals the important role of local cloud cover in modulating the regional shallow water heat budget across GBR, particularly the mid and sub-tropics, independent of the large-scale ENSO impact. Understanding its role could help refine the understanding of the local atmosphere-ocean interactions, which may aid in more effective targeting of management solutions of coral bleaching.

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Data Availability Statement

All data sets used in this study are freely and publicly available online and may be accessed directly as follows. The Cloud_cci AVHRR-PM monthly data was downloaded from https://public.satproj.klima.dwd.de/data/ESA_Cloud_CCI/DOIs/v3.0/DOI_ESA_Cloud_cci_AVHRR-PM_V003_landingpage.html. The ERA5 reanalysis data can be downloaded from the website: https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset. The ENSO index (ONI) data is available at the website: https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. The report of time period and locations of CBEs over the GBR is available at the website: https://www.aims.gov.au/docs/research/climate-change/coral-bleaching/bleaching-events.html. Ocean mixed layer depth can be downloaded from the website: http://www.ifremer.fr/cerweb/deboyer/mld/home.php.

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