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Assessing the potential for tropical cyclone induced sea surface cooling to reduce thermal stress on the world's coral reefs

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Abstract

Coral reefs face an uncertain future as rising sea surface temperature (SST) continues to lead to increasingly frequent and intense mass bleaching. At broad spatial scales, tropical cyclone (TC) induced cooling of the upper ocean (SST drops up to 6° C persisting for weeks) reduces thermal stress and accelerates recovery of bleached corals - yet the global prevalence and spatial distribution of this effect remains undocumented and unquantified. A global dataset (1985–2009) of TC wind exposure was constructed and examined against existing thermal stress data to address this. Significant correlations were found between TC activity and the severity of thermal stress at various spatial scales, particularly for Caribbean reefs. From this, it is apparent that TCs play a role in bleaching dynamics at a global scale. However, the prevalence and distribution of this interaction varies by region and requires further examination at finer spatial and temporal scales using actual SST data.

Keywords

reefs, stress, coral, thermal, reduce, cooling, surface, sea, induced, cyclone, tropical, potential, assessing, world

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

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Assessing the potential for tropical cyclone induced sea surface cooling to reduce thermal stress on the world's coral reefs

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[1] Coral reefs face an uncertain future as rising sea surface temperature (SST) continues to lead to increasingly frequent and intense mass bleaching. At broad spatial scales, tropical cyclone (TC) induced cooling of the upper ocean (SST drops up to 6° C persisting for weeks) reduces thermal stress and accelerates recovery of bleached corals - yet the global prevalence and spatial distribution of this effect remains undocumented and unquantified. A global dataset (1985–2009) of TC wind exposure was constructed and examined against existing thermal stress data to address this. Significant correlations were found between TC activity and the severity of thermal stress at various spatial scales, particularly for Caribbean reefs. From this, it is apparent that TCs play a role in bleaching dynamics at a global scale. However, the prevalence and distribution of this interaction varies by region and requires further examination at finer spatial and temporal scales using actual SST data. **Citation:** Carrigan, A. D., and M. L. Puotinen (2011), Assessing the potential for tropical cyclone induced sea surface cooling to reduce thermal stress on the world's coral reefs, *Geophys. Res. Lett.*, *38*, L23604, doi:10.1029/2011GL049722.

1. Introduction

[2] Increasing incidence of mass bleaching across the tropics over the last three decades is cause for major concern [e.g., *Hoegh-Guldberg*, 1999; *Baker et al.*, 2008]. Coral bleaching, a stress response whereby the coral host expels its endosymbiotic microalgae (zooxanthellae), can be triggered by a range of localized stressors and can ultimately result in coral mortality. Large-scale (100s of km) coral bleaching is a recent phenomenon that was first observed in the late 20th century and is associated with anomalously high sea surface temperature (SST; typically 1–2°C beyond climatological maximum [e.g., *Hoegh-Guldberg*, 1999]). If SST continues to rise over the next century as projected [*Intergovernmental Panel on Climate Change*, 2007], more frequent and intense mass bleaching is expected to follow [*Hoegh-Guldberg*, 1999; *Donner et al.*, 2005]. Yet not all reefs are equally affected during mass bleaching, which is often observed in clusters on the order of 1000s of meters [*Berkelmans et al.*, 2004]. This patchiness occurs due to locally varying environmental and physical factors that alter the coral response to thermal stress [*West and Salm*, 2003; *Baker et al.*, 2008]. For example, a number of natural mechanisms (e.g., currents, upwelling) can periodically bring deeper, cold water to the surface via vertical mixing of the water column [*Skirving et al.*, 2006]. Depending on their regularity and intensity, these hydrodynamic processes can create scattered refugia in which severe bleaching of corals is less likely. Knowledge of the frequency and location of vertical mixing agents can thus augment the success of marine reserve designs [*West and Salm*, 2003]. Tropical cyclones (TCs) cool the sea surface at broad spatial scales (100s of km) and, likely due to their episodic nature, have been largely overlooked as a mitigating factor in coral bleaching.

[3] Meteorologists have long observed that TCs cool the upper ocean layer via entrainment and upwelling of cold subsurface water [*Price*, 1981]. Satellite and in situ observations of the pre- and post-storm SST field have revealed cool anomalies (up to 6°C) which can persist for days to weeks [*Price et al.*, 2008] and extend 100s of kilometers from the TC center [*Stramma et al.*, 1986]. While it is widely known that TCs generate damaging waves that can cause lasting impacts on coral communities [*Harmelin-Vivien*, 1994], there is evidence that TC sea surface cooling in reef areas can reduce the severity and duration of bleaching [*Manzello et al.*, 2007]. In the Caribbean summer of 2005, the passage of nearby TCs reduced bleaching severity and duration around corals in the Florida Keys, with notable cooling present well beyond (~400 km) the expected area of damage (typically 30–90 km [*Done*, 1992; *Fabricius et al.*, 2008]). Conversely, coral communities in the U.S. Virgin Islands unexposed to TC cool wakes exhibited more severe bleaching and slower recovery times.

[4] Unlike other vertical mixing agents that occur with some regularity (e.g., currents, local upwelling), TC-induced mixing occurs episodically and both its timing and precise location are difficult to predict. Nonetheless, TCs are highly efficient cooling agents that presumably could create temporary refugia for thermally stressed reefs. Yet, it remains unclear whether reef areas frequently exposed to TCs sustain less overall thermal stress. Here, we utilize historic global TC track data in combination with reef locations and retrospective thermal stress data to determine how TC activity near reefs varies spatially and temporally, and whether TC cooling is likely to affect reefs when thermal stress is high. Given the large extent of a cool wake (100s of km), a TC could benefit a much larger area of thermally stressed corals than it would damage, resulting in a 'net cooling benefit.' As tropical oceans continue to warm [*Intergovernment Panel on Climate Change*, 2007; *Deser et al.*, 2010], TC-induced

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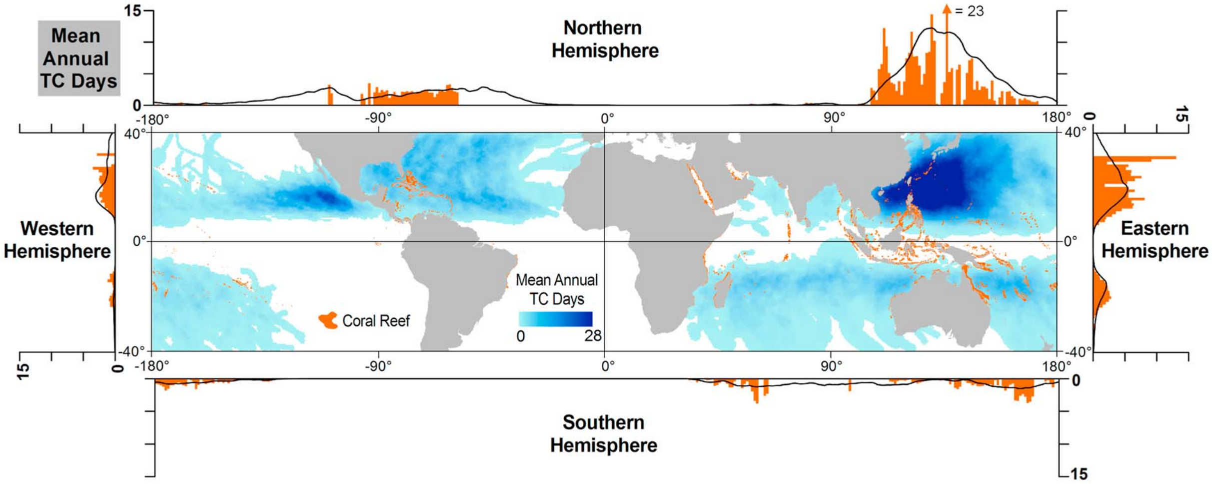

Figure 1. Mean annual tropical cyclone (TC) days across the tropics, 1985–2009, with the most active areas shown in dark blue. Graphs present the mean annual TC days for all study area pixels (black line) and for all reef locations (orange bars) binned by 1° latitude and longitude in each hemisphere.

cooling in some regions could play a vital role in the distribution of coral bleaching.

2. Data and Methodology

2.1. TC Cooling Zone Estimation

[5] Historic TC data was sourced from the International Best Track Archive for Climate Stewardship (IBTRACS) TC dataset [*Knapp et al.*, 2010]. For the study period (1985–2009), only those TCs that generated winds of at least gale force (34 knots) were included. As a conservative estimate of the extent of potential cooling, cooling is assumed to be constrained within the radius of gale force winds (typically 200–400 km). Prior to the last decade, most TC bureaus did not record gale radius information, therefore missing data were filled according to storm intensity using average gale radii determined by *Moyer et al.* [2007] from a ten-year climatology of North Atlantic TCs. To account for regional TC size variation, the estimated gale values were adjusted using basin averages derived from a ten year global climatology of TC sizes [*Chavas and Emanuel*, 2010]. Finally, daily gale zones were constructed from the 6-hourly data for each TC and combined globally to produce a TC-day grid (50-km resolution) for each day of the study period.

2.2. Coral Reef and Thermal Stress Data

[6] Reef-building coral locations were obtained from the Global Distribution of Coral Reefs Dataset (2010) produced by UNEP-WCMC (www.unep-wcmc.org). From this, a data layer was created by designating any 50 km grid cell that contained a portion of reef as a 'reef cell', and reef cells were grouped into eight regions adapted from meteorologically defined TC basins.

[7] For beneficial cooling to occur, it is assumed that thermal stress must be present in a given season. Thermal stress levels were assessed using the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program's degree heating week (DHW) thermal stress index [*Liu et al.*, 2006]. The DHW metric measures the accumulation of thermal stress (based on a maximum monthly mean climatology) over a rolling 12-week time period, where DHW values of 4 or more and values of 8 or more indicate likely and severe bleaching, respectively. A retrospective annual maximum DHW dataset for the study period was provided by CRW.

2.3. Spatio-temporal Analysis of TCs During Thermal Stress

[8] Mean annual TC days were spatially binned by 1° latitude and longitude in each hemisphere across both the entire study area (40°N to 40°S) and for reef cells alone. Based on these data, the annual temporal distribution of TC activity by region (i.e., TC basin) was quantified and annually contrasted with CRW's maximum DHW metric at all reef areas over the study period.

3. Results

3.1. Spatial Distribution of TCs Near Reefs

[9] As expected, clear differences in exposure to TCs are evident (Figure 1). TCs rarely, if ever, tracked near a notable number of reefs located ± 5° of the equator and in the Middle East. In contrast, reefs in the east and west North Pacific basins were the most frequently exposed to TCs, though few reefs exist where activity peaks. Since the occurrence of beneficial cooling depends on local thermal stress levels at the time of TC passage, the timing of TC exposure was critical, particularly for the remainder of reefs which were intermittently exposed to TCs.

3.2. Temporal Variability of TCs and Thermal Stress Near Reefs

[10] TC activity at reefs in all regions varies considerably over time (Figure 2), most notably over the second half of the study period where activity increased in the North Atlantic (Figure 2b) and declined in the Northwest and Southwest Pacific (Figures 2d and 2h, respectively). The recent active period in the North Atlantic corresponds to a transition to the warm phase of the Atlantic Multidecadal Oscillation (AMO) beginning in 1995 [*Bell and Chelliah*,

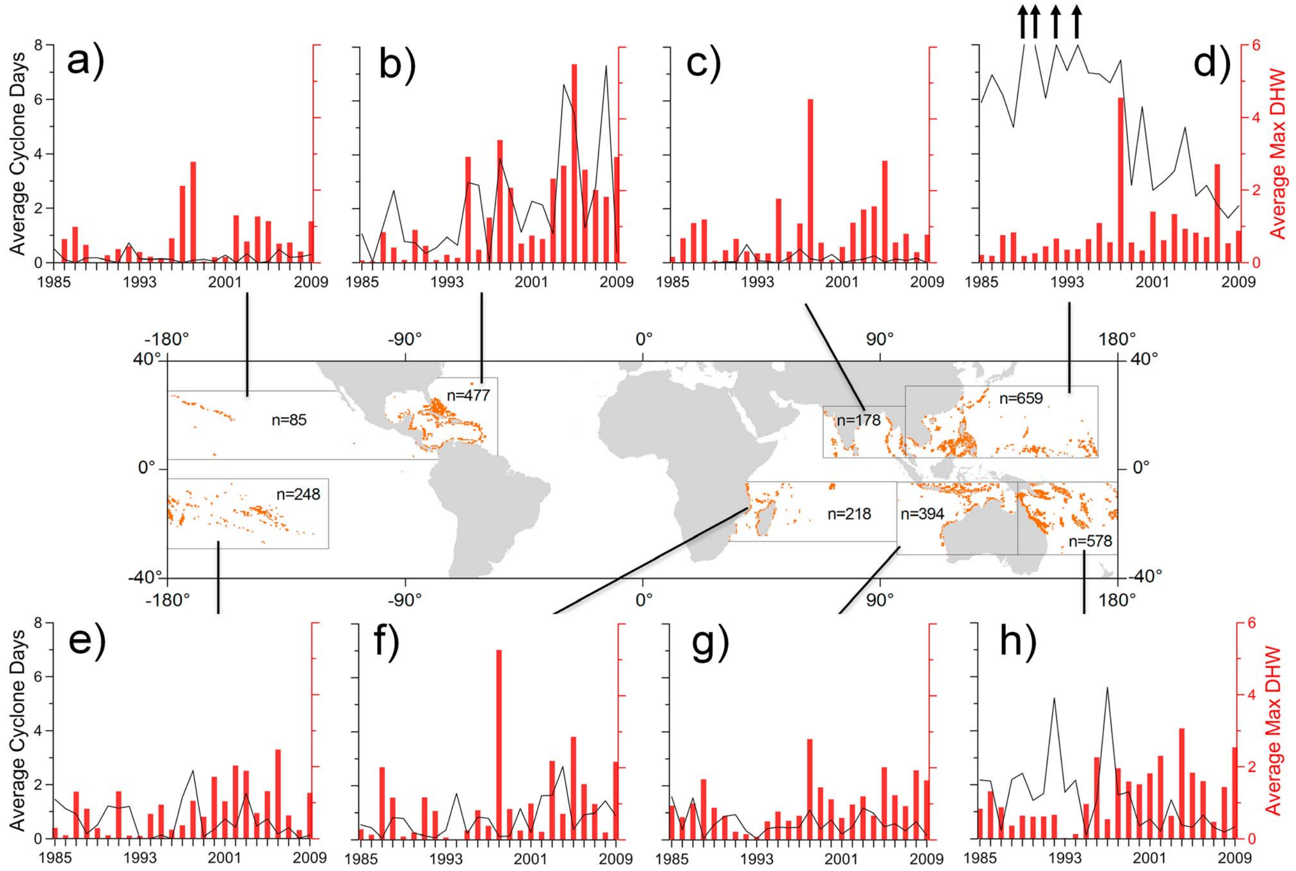

Figure 2. Temporal distribution of tropical cyclone (TC) activity and maximum accumulated thermal stress near reefs split into 8 TC basins: (a) East/Central North Pacific, (b) North Atlantic, (c) North Indian, (d) Northwest Pacific, (e) South central Pacific, (f) Southwest Indian, (g) Southeast Indian, and (h) Southwest Pacific. On the graphs, the black line represents the annual cyclone days averaged across all 50 km reef cells (orange pixels). Red bars represent maximum accumulated thermal stress (red y-axis) averaged across all reef cells. Black arrows on Figure 2d indicate TC activity beyond graph scale (max = ~15 TC days in 1990).

2006]. In the Northwest Pacific, observed decreases in TC activity have been associated with fluctuations in the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) that are not yet fully understood [*Maue*, 2011]. Despite a recent decrease (2007–present), overall global TC activity shows no significant trends with observed interannual and decadal fluctuations in the spatial distribution of TCs between basins attributed to large-scale climatic patterns [*Maue*, 2011].

[11] It is clear that high thermal stress has not always been accompanied by frequent TC activity and vice versa, which is reasonable given high SST is only one of numerous environmental conditions required for TC genesis [*Gray*, 1979]. Therefore, whether or not a reef benefits from TC cooling depends largely on the timing of individual TCs with respect to thermal stress. At the scale of an entire basin over multiple seasons, a strong link between thermal stress and TC activity will only be apparent if most TCs occur when and where thermal stress is high across the region. For example, the 2005 Caribbean bleaching event coincided with an extremely active TC season (Figure 2b). Likewise, numerous basins show a relative spike in TC activity during the 1998 global bleaching event (Figure 2). When the level of TC activity and thermal stress are not both high, the likelihood of a strong relationship (across large areas) between the two variables presumably decreases.

3.3. Correlation Between TC Days and Thermal Stress at Reef Cells

[12] For all basins, a noticeable overall increase in thermal stress was apparent over the latter half of the study period (1998–2009; Figure 2). Thus, tests for a relationship between annual TC days and maximum thermal stress at reef

Table 1. Correlations Between Mean Annual TC Days and Maximum Thermal Stress at Reef Cells for All 8 TC Basins[a]

Region	Correlation	
	1985–1997	1998–2009
North Atlantic	**−0.231**	**−0.463**
North Indian	**0.263**	0.01
North east/central Pacific	*0.267*	−0.022
Northwest Pacific	**0.208**	**0.559**
Southeast Indian	**0.255**	**0.176**
Southwest Indian	0.076	**0.207**
South central Pacific	**0.251**	**0.661**
Southwest Pacific	0.068	0.065

[a] Bold font and italicised font depict correlations significant at the 99% and 95% levels, respectively, based on a two-tailed Student's t-test.

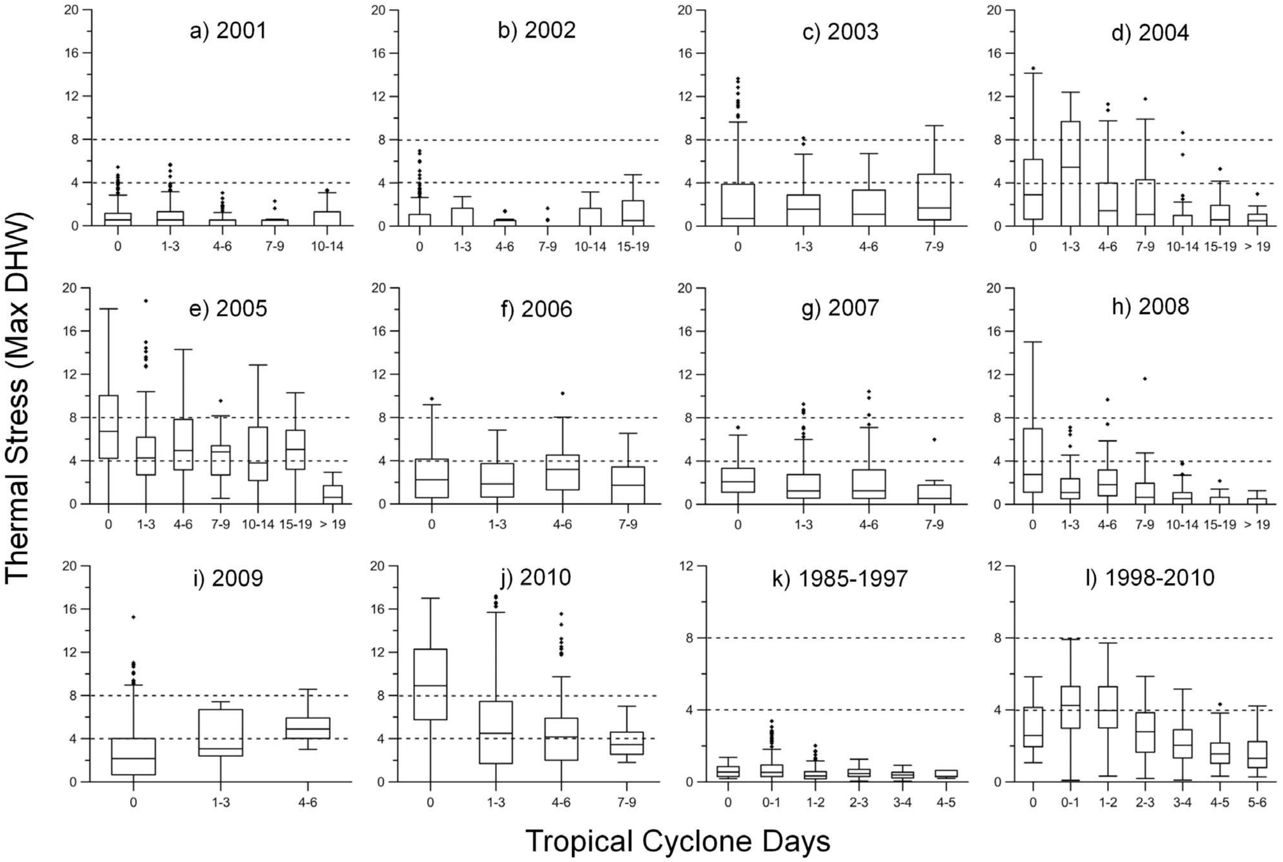

Figure 3. Boxplots showing the relationship between thermal stress (y axis – maximum degree heating weeks) and the number of tropical cyclone days (x axis) at reef cells (n=477) across the Caribbean. The plots show individual seasons over: (a–j) a 10-year period (2001 to 2010) and two time series grouped subjectively into (k) inactive (1985–1997) and (l) active (1998–2010) TC/thermal stress years. Dashed lines at y-values of 4 and 8 indicate thermal thresholds for coral bleaching and severe coral bleaching, respectively.

cells (Table 1) were conducted separately for low thermal stress (1985–1997) and high thermal stress (1998–2009) periods. The North Atlantic basin was the only region to exhibit a significant (99% level based on the t-test) negative correlation (i.e., thermal stress decreases as TC activity increases) which indicates that TC activity may have resulted in cooling appropriately timed to reduce thermal stress. That this relationship was found across a broad spatial (basin-wide) and temporal (multiple seasons) scale implies that TC cooling during times of thermal stress is pervasive in the region. On the other hand, other basins displayed a significant positive correlation. This can be partially explained by the fact that the magnitude of cooling within the wake of a TC is highly variable [*Stramma et al.*, 1986]. For example, TC cooling can be inhibited due to a deep oceanic mixed layer [*Price*, 1981], which has been shown to vary seasonally and geographically on a global basis [*de Boyer Montégut et al.*, 2004]. Thus, it is possible for high TC activity and thermal stress to coincide without the added benefit of cooling. Further, high variability in TC exposure among reef cells within some basins can mask the potential for beneficial cooling as tests show that the relationship between thermal stress and TC activity is sensitive to the placement of basin boundaries (modifiable area unit problem). For example, sub-setting the Northwest Pacific (n=659) to include only those reefs surrounding Japan (n=65) yielded an insignificant negative correlation for both the low (−.058) and high (−.186) thermal stress periods (compared to the significant positive one found for the entire basin – Table 1). Similarly, sub-setting the Southeast Indian Ocean to include only Western Australia reefs (n=79), which are known to be frequently exposed to TCs, yields significant negative correlations for the low (−.365) and high (−.606) thermal stress periods, respectively. Further, sub-setting the Southwest Pacific, which shows no significant correlations over the study period, to include only the Great Barrier Reef (n=199) during the 1998 bleaching event yields a significant negative correlation (−.364). From this, it is evident that beneficial cooling may occur in other basins besides the Caribbean. Detecting these effects requires examining TC activity and thermal stress at finer spatial and temporal scales.

3.4. Widespread Effect in the North Atlantic

[13] Given the strong correlations found in the North Atlantic, the seasonal relationship between TC days and thermal stress over a 10-year period (Figures 3a–3j) was examined along with the overall relationship grouped by the low (Figure 3k) and high (Figure 3l) thermal stress periods. During years of high thermal stress and frequent TCs (Figures 3d, 3e, 3h, and 3j) thermal stress at reef areas generally was low when TC activity was high. The strength of this relationship in those seasons, despite the occurrence

of other seasons where it does not hold, is sufficient to create a similar trend for the active period overall (Figure 3l), which mirrors that found for the entire time period. In other basins, where such active seasons do not occur as often (Figure 2), beneficial cooling is still possible but may only be detected on a seasonal or event-by-event basis.

4. Discussion

[14] While TCs are potentially damaging, the associated cool wakes can provide temporary refuge for reefs during heat-induced stress events. This study used the extent of TC-generated gale force winds as a proxy for upper ocean cooling near reefs to assess the potential prevalence and spatial distribution of this effect. The results indicate that TCs likely play a role in coral bleaching dynamics on a global scale, which has implications for the response of reefs to climate change. TCs and mass bleaching are episodic events that can intersect spatially and temporally, and although high SST is required for both, their coincidence in space and time is far from certain. Yet favorably timed and located TCs can mitigate coral bleaching across broad areas. Our results clearly demonstrate that the likelihood of beneficial TC cooling is widespread across the Caribbean, where the recent active period of TC activity coincided with an upswing in thermal stress levels (Figure 2b). This enabled appropriately timed TC cooling to lower thermal stress at specific reefs. Beneficial cooling is possible in other basins, justifying further research effort to explore historic data for past interactions to inform future conservation management decisions and ecological response model projections. Finally, this study assumed that thermal stress must be present for beneficial cooling to occur even though it is plausible that a TC could disrupt a SST warming cycle before thermal thresholds are exceeded, further adding to the potential for TC benefits to reefs. Further examination of this phenomenon at finer spatial and temporal scales by measuring actual temperature drops rather than using TC activity as a proxy for cooling is warranted.

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