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Widespread local chronic stressors in Caribbean coastal habitats

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Financial Disclosure Please describe all sources of funding that have supported your work. **This information is required for submission and will be published with your article, should it be accepted.** A complete funding statement should do the following: Include **grant numbers and the URLs** of any funder's website. Use the full name, not acronyms, of funding institutions, and use initials to identify authors who received the funding. **Describe the role** of any sponsors or funders in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. If the funders had **no role** in any of the above, include this sentence at the end of your statement: "*The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.*" However, if the study was **unfunded**, please provide a statement that clearly indicates this, for example: "*The author(s) received no specific funding for this work.*" * typeset	Through the years the CARICOMP program was supported by the MacArthur Foundation, the Coral Reef Initiative of the US Department of State, UNESCO’s Environment and Development in Coastal Regions and Small Islands and the US National Science Foundation. Each participating institution and national agency from each CARICOMP country have also provided individual financial and logistical support. IC was supported by the Summit Foundation. JC thanks the Vicerrectoría de Investigación, Universidad de Costa Rica and UNEP for funding the monitoring in Costa Rica. FRR, EEM and EJD thank the Universidad Nacional Autónoma de México for funding the monitoring in México.
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Additional data availability information:	

Cover Letter

Smithsonian
Institution

Davis, California, 4th of October 2017

PLOS ONE Editorial Office

Dear Dr. Patterson,

Thank you for your time and effort revising our manuscript, *Widespread local chronic stressors in Caribbean coastal habitats*.

We have found the review process very constructive and we have tackled each of the issues raised by the reviewers and yourself. While none of the edits have changed the results or the fundamental message of the manuscript, they have made the paper stronger by giving it a sturdier methodological base and a clearer *so what* aspect.

We have included a large amount of additional information in the manuscript to clarify the methods, expand the discussion and make our conclusions more transparent. As suggested, we have edited three figures to improve their readability. The text has been thoroughly revised for errors, formatting and style, and to improve readability. We believe that with your input and our adjustments is ready for publication in PLOS ONE.

We have clarified a few methodological choices and misunderstandings and amended the manuscript to include clarifications whenever needed (e.g. explained the reviewer why the way we summarized the data is appropriate given the focus of the paper).

We agreed to most changes suggested by the reviewers with a few exceptions: (1) we did not change the objectives to relate this dataset to the state of coastal ecosystems in the Caribbean basin as suggested: we believe we are asking an interesting research question that is self-contained and warrants a paper by itself; (2) we did not include a table highlighting the relevance of each monitoring site because we didn't do a full assessment that could allow doing this unequivocally (we expanded the discussion on this issue instead); (3) we kept figure 6 in the discussion given that this analysis is not related to any objective and is truly a tool to better discussing our results; (4) we did not replace the boxplots by multipanel figures showing seasonality, given that this is not associated to any objective and it would involve a large amount of space.

Overall, we believe the manuscript has greatly improved after this round of comments, and we hope you will continue giving it your consideration. Sincerely,

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Widespread local chronic stressors in Caribbean coastal habitats

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Abstract

Coastal ecosystems and the livelihoods they support are threatened by stressors acting at global and local scales. Here we used the data produced by the Caribbean Coastal Marine Productivity program (CARICOMP), the longest, largest monitoring program in the wider Caribbean, to evidence local-scale (decreases in water quality) and global-scale (increases in temperature) stressors across the basin. Trend analyses showed that visibility decreased at 42% of the stations, indicating that local-scale chronic stressors are widespread. On the other hand, only 18% of the stations showed increases in water temperature that would be expected from global warming, partially reflecting the limits in detecting trends due to inherent natural variability of temperature data. Decreases in visibility were associated to increased human density. However, this link can be decoupled by environmental factors, with conditions that increase the flush of water dampening the effects of human influence. Besides documenting environmental stressors throughout the basin, our results can be used to inform future monitoring programs, if the desire is to identify stations that provide early warning signals of anthropogenic impacts. All CARICOMP environmental data are now available, providing an invaluable baseline that can be used to strengthen research, conservation, and management of coastal ecosystems in the Caribbean basin.

Key words: Monitoring; climate change; pollution; mangrove; seagrass meadow; coral reef

Introduction

Changes at local and global scales are influencing our oceans, altering their health and the benefits we receive from them. Here we use the terms global and local to define scales of action of anthropogenic stressors, ranging from disturbances acting on broad spatial scales, such as ocean warming, to those acting at very localized scales, such as dredging [1,2]. These changes have affected the health of marine ecosystems and the services they provide [3] and may threaten coastal livelihoods and food security [4]. Long-term measurements of environmental parameters over wide geographic regions are necessary to understand the rate of change at global and local scales. Such a strategy provides information that informs identification of threatened areas and provides potential explanations for and predictions of ecosystem responses. A long-term approach also allows the assessment of progress towards management objectives and planning for mitigation or adaptation accordingly [5].

Increases in temperature and decreases in water quality are common indicators of changes in the oceans at global and local scales, respectively [1,6]. Increases in greenhouse gases released by human activities have altered ocean temperature, generally by warming [7]. In the Caribbean, analyses of remote sensing data indicate that most areas have warmed at rates that range from 0.2 to 0.5°C dec^{-1} during the last three decades [8]. These increases in temperature have been positively correlated with increases in the frequency and prevalence of coral bleaching and, in some cases, diseases affecting coral reef species across the region [9–11]. The localized influence of human stressors, on the other hand, has been manifested as decreases in water quality driven by increased pollution resulting from rapid development and habitat conversion [1]. Decreases in water quality have also been mapped using satellite information but only at regional scales, showing increases in turbidity in several localized areas in the Caribbean [e.g. 12,13].

Optical remote sensing has been a pivotal tool in quantifying changes in the oceans at global and regional scales [14], however, this tool is not well suited to study patterns and processes at the land-sea interface [15]. While this technology can sample the globe cheaply and repeatedly over a large area, it can be inaccurate in coastal areas. The inaccuracy of optical remotely-sensed data close to the coast is related to two main issues: high cloud coverage in coastal areas that blocks the view from satellites, and the presence of land that contaminates the signal received by the sensor [15,16]. Additionally, the complex optical signal of coastal waters hinders the quantification of water quality along the coast; the complex mixture of components in coastal waters makes the quantification of the separate constituents very difficult, and shallow bottoms can look very similar to heavily turbid regions. As a result, water quality can be measured using remote sensing only in particular locations using algorithms that are heavily reliant on *in situ* data [15,16]. Thus *in situ* measurements from monitoring programs may play an important role in quantifying patterns in coastal areas.

Long-term *in situ* datasets documenting temporal changes in the environment of coastal areas, where most economically valuable ecosystems are located, are limited [17,18]. Most *in situ* datasets that record ocean conditions focus on open-ocean areas [e.g. SeaBASS: 19], and do not provide repeated measurements that allow for the quantification of changes at fine spatial scales [e.g. the World Ocean Database: 20]. First of its kind in the wider Caribbean, the international Caribbean Coastal Marine Productivity program (CARICOMP) was established almost 30 years ago to fill this gap [21]. The CARICOMP long-term program was developed to study processes at the land-sea interface and understand productivity, structure and function of the three main coastal habitats (mangroves, seagrass meadows, and coral reefs) across the region [21,22]. Together with biological monitoring, the

CARICOMP network has collected environmental data since 1992 using simple, standardized methods [21–23].

Here we used the environmental data collected by CARICOMP's monitoring network to quantify long-term changes in oceanographic conditions in coastal habitats in the wider Caribbean. We focused our analyses on temperature and visibility, two proxies of global and local chronic stressors in marine environments. We had two aims. First, quantifying significant changes in these environmental variables over time. Second, understanding if these stressors are influencing the entire basin in a homogeneous way, and if not, what factors (i.e. water movement, rainfall, and human influence) could explain differences among sites. In this study we not only synthesize the information in this an unparalleled dataset (which is made available with this publication), but provide guidelines for the better selection of monitoring sites if future aims include identifying early warning signals of change.

Materials and methods

CARICOMP Dataset

Beginning in 1992, CARICOMP established permanent monitoring stations in mangrove, seagrass, and coral reef habitats. Effort was made to select stations that specifically avoided anthropogenic sources of disturbance, particularly coastal development and pollution [21]. Weekly (whenever possible) physical measurements were taken at each station between 10:00 and 12:00 local standard time. Measurements consisted of water temperature (°C), salinity, and visibility (m). Temperature and salinity were measured with a field thermometer and a refractometer at 0.5 m depth at all habitats. Visibility was measured with a Secchi disk in seagrass (measured horizontally 0.5 m below the surface, as these habitats are often too shallow for a standard vertical measurement) and reef habitats (typically measured vertically over the drop-off), and can be assumed to indicate water quality at the surface. Secchi depth is strongly correlated to the amount of particulate material in the water column and it has been used as a cheap, fast, and simple proxy for visibility and water quality [24]. We are aware, however, that this is only one of the multiple environmental variables that characterize water quality at a site, and that a full assessment of this component would require also the measurement of other variables (e.g. concentration of nutrients, pollutants, dissolved matter).

Data from previously published CARICOMP databases and updates provided directly from individual researchers at CARICOMP stations were compiled into a uniform format. All environmental CARICOMP data are available in the Supporting Information (a description of all stations is in Tables S1-A and S1-B and the data are in S2 Appendix). Although information from all three variables is included in the appendix, to address the aims of this research only temperature and secchi data were analyzed.

Simple mixed effect models for the assessment of differences among habitats (fixed factor) including all stations (as random factor) were fitted with the R package *lmerTest* [25], which provides additional F statistics and p-values for factors calculated based on Satterthwaite's approximations. Satterthwaite’s method allows calculating the denominator degrees of freedom as a function of the variance of the parameter estimate [26], and therefore estimating significance in mixed effect models which is generally problematic [27].

Monthly averages were calculated from the weekly data for each station. To ensure meaningful quantification of a linear trend, only stations with data for at least three years and a minimum of 30 monthly records were included in subsequent analyses (60% of the sites: Table 1, Fig 1).

Table 1. Description of sites. CARICOMP stations with long-term data (at least three years and 30 monthly records).

Country	Site	Habitat	Station acronym	Latitude	Longitude	Year range
Barbados	Bellairs	Coral Reef	BARr	13.192	-59.642	11/1992-12/1999
Barbados	Bellairs	Seagrass Beds	BARs	13.068	-59.578	11/1992-09/1996
Belize	Carrie Bow Cay	Coral Reef	BELr	16.800	-88.067	01-1993/07-2015
Belize	Carrie Bow Cay	Seagrass Beds	BELs	16.825	-88.099	01-1993/07-2015
Bermuda	Hog Breaker Reef	Coral Reef	BERr	32.344	-64.865	09-1992/12-2002
Bermuda	North Seagrass	Seagrass Beds	BERs	32.401	-64.799	09-1992/12-2002
Bonaire, N.A.	Barcadera Reef	Coral Reef	BONr	12.195	-68.301	08/1994-12/1997
Colombia	Chengue Bay	Coral Reef	COLr	11.328	-74.128	09-1992/06-2011
Colombia	Chengue Bay	Mangrove	COLm	11.317	-74.128	09-1992/06-2011
Colombia	Chengue Bay	Seagrass Beds	COLs	11.321	-74.127	09-1992/06-2011
Costa Rica	Rio Perezoso	Seagrass Beds	CRIs	9.737	-82.807	03-1999/05-2015
Jamaica	Discovery Bay	Coral Reef	JAMr	18.472	-77.414	09-1992/02-2002
Jamaica	Discovery Bay	Mangrove	JAMm	18.469	-77.415	09-1992/02-2002
Jamaica	Discovery Bay	Seagrass Beds	JAMs	18.471	-77.414	09-1992/02-2002
Mexico	Puerto Morelos	Coral Reef	MEXr	20.878	-86.845	10-1992/10-2005
Mexico	Puerto Morelos	Seagrass Beds	MEXs	20.868	-86.867	09-1992/10-2005
Panama	STRI_colo	Coral Reef	PANr	9.349	-82.266	06-1999/05-2015
Panama	STRI_colo	Mangrove	PANm	9.352	-82.259	02-1999/05-2015
Panama	STRI_colo	Seagrass Beds	PANs	9.352	-82.258	06-1999/05-2015
Puerto Rico	La Parguera	Coral Reef	PURr	17.935	-67.049	01-1993/12-2014
Puerto Rico	La Parguera	Seagrass Beds	PURs	17.955	-67.043	01-1993/12-2014
Saba, N.A.	Ladder Labyrinth	Coral Reef	SABr	17.626	-63.260	09-1992/04-1997
USA	Long Key	Seagrass Beds	USAs	24.800	-80.717	07-1996/06-2004
Venezuela	P.N. Morrocoy –Caiman	Coral Reef	VENr1	10.852	-68.232	09-1992/11-1999
Venezuela	P.N. Morrocoy - Cayo Sombrero	Coral Reef	VENr2	10.881	-68.213	02-2000/11-2012
Venezuela	P.N. Morrocoy	Mangrove	VENm	10.836	-68.261	01-1993/11-2012
Venezuela	P.N. Morrocoy	Seagrass Beds	VENs	10.858	-68.291	09-1992/11-2012
Venezuela	Punta de Mangle	Mangrove	VEN2m	10.864	-64.058	01-1993/12-2003

Venezuela	Punta de Mangle	Seagrass Beds	VEN2s	10.864	-64.058	01-1993/12-2003

Fig 1. Changes in temperature and visibility throughout the CARICOMP network. Map of CARICOMP stations showing significant increases, decreases, or non-significant trends for temperature (A) and visibility (B). Labels as in Table 1, with upper case letters indicating the location and lower case the habitat.

Global and local-scale changes across the Caribbean

To assess global and local-scale changes across the Caribbean, we focused our analyses on changes in temperature and visibility, which as previously noted, are common proxies for change at each scale. Long-term trends and significance were calculated considering serial correlation, an characteristic of the data that, if not taken into account, violates the assumption of independence of most regression analyses and influences the magnitude and significance of trends [27].

Following Weatherhead et al. [27], for temperature (*T*), we fitted a non-linear model with the form:

$$T = \mu + S_t + \frac{\omega t}{12} + N_t \text{ (1)}$$

Where the temperature at time *t* in months is a function of a constant term μ, a seasonal component with sinusoidal form S_t, a linear trend ω of rate °C $year^{-1}$, and residuals N_t.. In this model, the seasonal component is allowed to include up to two cycles, and is described by the formula:

$$S_t = \sum_{j=1}^{4} \beta_{1,j} \sin \tfrac{2\pi jt}{12} + \beta_{2,j} \cos \tfrac{2\pi jt}{12} \quad (2)$$

Where t is the number of months, and β are parameters to be estimated. And the residuals have an AR-1 autocorrelation form, the simplest form of autocorrelation (aka, the similarity between a time series and a lagged version of itself). That is, the residuals at time t are a function of the residuals at time $t-1$ (i.e. the temporal "memory" of the time series has a one month lag), depending on the station-specific autocorrelation parameter Φ, along with the noise [$\epsilon_{t,}$ 27]:

$$N_t = \phi N_{t-1} + \epsilon_t \quad (3)$$

For visibility (V), we fitted a non-linear model that follows the approach described above but without the seasonal component:

$$V = \mu + \tfrac{\omega t}{12} + N_t \quad (4)$$

In this model, V at a given time t in months is a function of a constant term μ, a linear trend ω of rate m year^{-1}, and residuals, N_t also assumed to have a AR-1 autocorrelation form (Eq. 3)

The models were fitted using generalized squares and the package *nlme* in *R* [28]. Initial estimates for μ and ω were obtained through simple linear regression, and initial values of 1 were used for all β's.

Correlates of global and local-scale changes

Global and local-scale stressors can be exacerbated or dampened by local conditions related to water movement, with circumstances that increase the flush of water potentially less conducive to warming and decreases in visibility [29,30]. We examined the effects of water movement through the inclusion of two variables: wave exposure and current speed. Additionally, trends in visibility can be driven by human influence (with areas of rapid population increases expected to lose visibility), and could also be influenced by trends in rainfall (with stations that are getting wetter anticipated to show increased turbidity); therefore these two variables were also included to explain trends for this response variable. This way, we characterized each station with the explanatory variables: (1) average wave exposure; (2) average current speed; (3) changes in human population density; (4) trend in rainfall. Due to the lack of consistent *in situ* datasets for all stations, modelled or remote sensing sources were used to derive explanatory variables. Below we briefly describe each dataset.

Wind-driven wave exposure for each station is dependent on the wind patterns and the configuration of the coastline, which defines the *fetch*, or the length of water over which a given wind has blown to generate waves. To calculate wave exposure, wind speed and direction data at each location were acquired from the QuickSCAT (NASA) satellite scatterometer from 1999 to 2008 at 25 km spatial resolution [31]. Coastline data were obtained from the Global Self-consistent, Hierarchical, High-resolution, Shoreline (GSHHS v 2.2) database which provides global coastline at 1:250,000 scale [32]. From these datasets wave exposure was calculated using the methods based on wave theory described in Chollett et al. [33] for 32 fetch directions and the coastline data at full resolution. Average wave exposure at each station was calculated in *R* with the aid of the packages *maptools, raster, rgeos,* and *sp* [34–37].

Average surface current speed was extracted from the ocean model HYCOM [38]. We used global data-assimilative runs at 1/12˚ of spatial resolution for the period 2008-2011. The HYCOM model is forced by wind stress, wind speed, heat flux, and precipitation and the system uses *in situ* temperature and salinity profiles to improve estimates, providing the most detailed and comprehensive global dataset of ocean currents available to date [39].

Gridded human population density data for the years 1990 and 2000 (the most recent dataset available at that spatial detail) were obtained from the Global Rural-Urban Mapping Project, Version 1 [GRUMPv1: 40]. These years coincide with most of CARICOMP sampling took place between those decades, with time series beginning on average in February 1994 and finishing on average in September 2007 (Table 1). We used the adjusted population density grids as inputs, which provide population density in persons per square kilometre using census information but also observations of night lights to delineate the extent of urban areas. From these datasets we extracted the number of people within a buffer of 1-degree diameter around each station, and then calculated the difference in population between the years 2000 and 1990, which captures a proxy for broad impacts of human population expansion on coastal ecosystems. A one degree buffer was considered as a reasonable range at which many human impacts might affect coastal ecosystems, as it has been shown before [41].

Satellite rainfall data were extracted from the GPCP v2.2 combined precipitation dataset, which merges satellite and gauge precipitation values in monthly estimates of total precipitation from 1986 to 2016 (i.e. 37 years of data) at 2.5° spatial resolution. This is the longest, most accurate global dataset of rainfall available to date [42,43]). For each station trends were calculated from these monthly means taking into account the temporal autocorrelation of the data (Eq. 4).

When trends are non-significant their value is uninformative (e.g. a trend in temperature of 2°C year^{-1} with a p value of 0.8 is meaningless), hindering the use of the actual trend values as a response variable in quantitative analyses. We therefore transformed the continuous data (i.e. trend values in temperature and visibility) into nominal data (i.e. trend categories) by classifying trends as non-significant, significantly increasing or significantly decreasing. We then used multinomial regression models to identify what factors were relevant at explaining the observed trend categories in temperature and visibility. Multinomial regression is a method used to generalize logistic regression where the response variable is nominal and has more than two classes, in which the log odds of the outcomes are modelled as a linear combination of predictor variables. Here, we modelled trends in temperature as a function of wave exposure and currents, and trends in visibility as a function of wave exposure, currents, changes in human population, and trends in rainfall. Multinomial regression was carried out using the package *nnet* in R [44]. All figures were produced using the package *ggplot2* in R [45].

Results

CARICOMP Dataset

CARICOMP collected data at 48 stations in 18 countries/territories across the wider Caribbean (Tables S1-A and S1-B). Participants in the network have sampled environmental data from 20 reefs, 19 seagrass meadows, and 9 mangrove forests since 1992. Data collection is ongoing at some stations.

Water temperature and visibility were variable throughout the region (Figs 2 and 3). Average temperature ranged from about 22˚C in Bermuda (BER) to almost 30˚C in Cuba (CUB), but many stations showed relatively similar values (Fig 2). There were no clear differences in temperature among seagrass, mangroves, and coral reefs (mixed effect model with location as random effect, F = 0.74, p = 0.48). Visibility, only measured in reef and seagrass habitats, also showed large variability among stations, with a minimum of about 3 m at the seagrass meadow off eastern Venezuela (VEN2), and a maximum of 37 m at the reef in the Bahamas (BAH, Fig 3). Locations with lower values of visibility also showed the greatest variability. As expected, there were clear differences in visibility between habitats, with higher values in coral reefs (mixed effect model with location as random effect, F = 18.22, p < 0.001). Sixty percent of the CARICOMP stations (described in Table 1) included long-term records and were therefore suitable candidates for the estimation of long-term trends in subsequent analyses.

Fig 2. Sea temperature throughout the CARICOMP network. Sea temperature in each site and habitat in the CARICOMP network, all data are presented, including all years (i.e. since 1992) and all stations, with and without long-term (> 3 years) data: (A) Coral reefs; (B) Seagrass meadows; and (C) Mangroves. In boxplots, lines represent means, boxes 25 and 75% quantiles, whiskers 1.5 inter-quartile ranges and dots outliers. Sites are: Costa Rica (CRI), Panama (PAN), western Venezuela (VEN), eastern Venezuela (VEN2), Colombia (COL), Trinidad y Tobago (TAT), Bonaire (BON), northern Colombia (COL2), Curaçao (CUR), Barbados (BAR), Belize (BEL), Puerto Rico (PUR), Saba (SAB), Dominican Republic (DRE), Jamaica (JAM), Mexico (MEX), Cuba (CUB), the Bahamas (BAH), United States (USA), and Bermuda (BER). Sites with an asterisk were included in subsequent analyses.

Fig 3. Visibility throughout the CARICOMP network. Visibility in each site and habitat in the CARICOMP network, all data are presented, including all years (i.e. since 1992) and all stations, with and without long-term (> 3 years) data: (A) Coral reefs; and (B) Seagrass meadows. In boxplots, lines represent means, boxes 25 and 75% quantiles, whiskers 1.5 inter-quartile ranges and dots outliers. Sites are: Costa Rica (CRI), Panama (PAN), western Venezuela (VEN), eastern Venezuela (VEN2), Colombia (COL), Trinidad y Tobago (TAT), Bonaire (BON), northern Colombia (COL2), Curaçao (CUR), Barbados (BAR), Belize (BEL), Puerto Rico (PUR), Saba (SAB), Dominican Republic (DRE), Jamaica (JAM), Mexico (MEX), Cuba (CUB), the Bahamas (BAH), United States (USA), and Bermuda (BER). Sites with an asterisk were included in subsequent analyses.

Global and local-scale changes across the Caribbean

Data collected by the CARICOMP network offered evidence of widespread local, but not global-scale changes across the wider Caribbean using visibility and sea temperature as proxies. While a few stations showed evidence of warming, about half the stations showed evidence of decreased visibility (Fig 1). The mixed effects models represented the temporal variability in the oceanographic variables well, capturing both the seasonality (for temperature) and long-term linear trends (Fig 4, Tables S3-A and S3-B).

Fig 4. Time series example. Time series for sea temperature (A) and visibility (B) for the reef at Chengue Bay (Colombia), showing significant increases in temperature and significant decreases in visibility. For temperature, the model fit takes into account both seasonality (sinusoidal line) and a linear trend (straight line).

There was large spatial variability in temperature and visibility trends across the CARICOMP network (Fig 1). Of the 28 reef, seagrass, and mangrove stations, 18% (1 mangrove, 2 seagrass meadow, and 2 coral reef stations) showed a significant increasing trend in temperature, and only one (Bonaire reef) showed a significant decrease (Fig 1A, Table S3-A). On the other hand, of the 24 reef and seagrass stations, 42% (4 seagrass meadows and 6 reefs) showed a significant decreasing trend in visibility, and two stations (Jamaica seagrass and Bermuda reef) showed a positive trend (Fig 1B, Table S3-B). Neither warming nor decreases in visibility were observed to be more common in any of the three habitats monitored (Chi-squared tests, $p > 0.05$).

Correlates of global and local-scale changes

The presence of negative, positive, or non-significant trends in temperature was not explained by either of the two local factors assessed (wave exposure and currents, multinomial regression, $p > 0.05$ for both variables).Trends in visibility were explained by all variables, that is, changes in human population, wave exposure, current speed, and trend in rainfall (multinomial regression, $p < 0.01$). Decreases in visibility were more likely to occur in areas where human population (and associated coastal development) has increased the most (Fig 5A). Oceanographic and atmospheric variables have the ability to modulate changes in visibility (Figs 5B-D). Long-term decreases in visibility were more likely to occur at stations with slow water motion, characterized either by low exposure (Fig 5B, top panel) or low current speed (Fig 5C, top panel). Conversely, long-term increases in visibility were more likely at stations with high wave exposure and current speed, although these variables had a very small effect in driving significant long-term increases in visibility (Figs 5B and 5C, bottom panels). Finally, decreases in visibility were also more likely to occur in areas that were getting wetter, and increases were more likely in areas that were getting drier (Fig 5D). The functional responses to these explanatory variables were similar no matter the habitat (Fig 5).

Fig 5. Explaining trends in visibility. Predicted probability of decreases and increases in visibility (as per right-hand labels of the top and bottom panels respectively) against changes in human population (A), wave exposure (B), current speed (C), and trend in rainfall (D).

Discussion

The longest and most spatially comprehensive *in situ* monitoring effort in the wider Caribbean provides evidence of widespread local changes within the basin. This is a relatively unexpected result, given that CARICOMP stations were intended to be established in pristine areas under minimal local impacts that could serve as a baseline against which to measure degradation [21]. However, 15 years ago it was already suggested that some stations were under the influence of human activities [22]. Results presented here support this statement, agree with results of localized studies in some of these locations [e.g. 46-50], and indicate that human impacts on coastal habitats are ongoing and pervasive within the Caribbean basin.

CARICOMP’s time series do not show widespread evidence of long-term warming at coastal stations in the wider Caribbean. These findings contrast with a global study that showed prevalent warming along the world’s coasts using 30 years of satellite data [30], and a regional study which showed significant warming throughout most of the Caribbean basin using 25 years of satellite temperatures [8]. The lack of signal in the CARICOMP time series can be attributed to two related issues: the larger variability of *in situ* temperature data and the need for longer time series to detect significant trends. Satellites measure temperature at the ‘skin’ of the ocean surface, which is more stable [51], and ignores subsurface temperature patterns that are more variable at multiple temporal scales [52]. Therefore *in situ* temperature data are more variable making trend estimation more difficult. Low precision of *in situ* measurements due to external influences [such as changes in sampling methodology, observers, instrumentation, or gaps in the time series: 27, 53] could also increase variability and limit the ability to detect trends. Besides the issue of increased variability, the inability to detect trends might be related to the length of the CARICOMP time-series (from 3 to 22 years). This timeframe may provide insufficient statistical power to assess long-term changes in temperature due to intrinsic characteristics of the location, particularly in stations where the magnitude of the trend is small, the memory (i.e. temporal autocorrelation) is high, or temperature is especially variable [27].

Site-specific information on the inherent characteristics of the time-series can be used to aid in the identification of monitoring sites that are cost-effective in the sense that they have the power to detect trends earlier [27], if the detection of early changes is the main objective of the monitoring. Significant trends will be detected faster at sites characterized by low variability and temporal autocorrelation of the noise, which is a measure of the ‘memory’ or inertia of the time-series. For example, within the CARICOMP network, the time period to detect an expected change varies greatly among stations (Fig 6, Table S3-A). Within this dataset, given the variability and memory of the time-series, Puerto Morelos in Mexico would need the shortest sampling to identify changes in temperature, and it might be a good location to identify trends in temperature early. On the other hand the seagrass meadow and mangrove stations in Eastern Venezuela might need the longest time series to detect a significant trend (Fig 6, Table S3-A). This result is not rare: research in atmospheric [27] and oceanographic [54, 55] science has shown that for most expected environmental changes, several decades of high-quality data may be needed to detect significant trends. For example, many years of continuous data were needed to distinguish a climate change trend in pH and sea surface temperature (about 15 years), chlorophyll concentration and primary production (between 30 and 40 years) from the background natural variability

[54, 55]. The process of deciding which site can be useful for future detection of trends is very similar to conducting power analysis to estimate the number of samples needed to detect a particular effect. This type of analysis can be done if the data has already been collected (as in the example in Fig 6) or before collecting the data assuming a range of effect sizes, autocorrelation, and noise [27] and taking into account any external forces that might be affecting the accuracy of the data [see previous paragraph: 53]. This information can be used to set realistic expectations on trend detectability at different sites. It could also help select sites for further monitoring of chronic impacts [56], where trends can be detected sooner, after taking other considerations into account such as the relevance of the site to answer the focal scientific question, or logistic factors such as accessibility and maintenance of the monitoring site, which are also important.

Fig 6. Explaining the lack of trends in temperature. Number of years needed to detect a trend in temperature of 0.05°C year^{-1} as a function of the autocorrelation of the noise (ϕ) and the residuals of each station [27]. Also shown in color the actual number of years of data available for each station. Note that to identify trends of different magnitudes, different number of years might be required.

Decreases in visibility were related to changes in human density, which increased in all but one (Bonaire) of the CARICOMP stations assessed. The effects of local anthropogenic impacts can be modulated, however, by local hydrodynamic and weather conditions. Areas with high flush of marine water and/or drier weather are less vulnerable to deteriorating visibility. Waves and currents flush sediments, nutrients, and pollutants and determine the spatial variability in visibility patterns [29,57]. Decreased rainfall, on the other hand, diminishes runoff reaching the stations, thus improving visibility

[58]. The Caribbean basin is getting drier [59] due to the intensification of the Caribbean Low Level Jet [60] and warming in the Atlantic [61]. Because rainfall is predicted to decrease further [60], we expect that rainfall and runoff will play diminished roles in exacerbating local stressors in the basin in the near future. Knowledge of the factors that modulate the detection of trends in visibility can also assist in the identification of the best monitoring sites for early warning signal detection. In this sense, sites with vigorous water movement should be avoided if the desire is the early detection of water quality degradation in coastal areas.

Chronic decreases in coastal water quality can be linked to the increase in marine diseases [62] and the demise of seagrass [63] and coral reef ecosystems [57]. Furthermore, declines in water quality have been linked to economic losses such as decreases in property value and tourism revenues [reviewed in 64]. Results presented here pinpoint areas that might require management interventions. Such interventions may include identifying the cause of decreased water quality, and implementing changes in management practices and long-term commitments towards change. Improving water quality could also have the added benefit of improving resilience of coastal ecosystems to other disturbances, such as climate change [65,66].

CARICOMP's environmental dataset provides an invaluable baseline that can be used to strengthen research, conservation, and management of coastal ecosystems in the Caribbean basin. In the first place, the dataset provides context for other local studies, aiding comparisons and understanding of observations at single locations [67]. CARICOMP's environmental measurements also provide a powerful *in situ* dataset to help improve satellite observations in coastal areas, where accuracy is currently limited [15]. In addition, *in situ* CARICOMP datasets can help ground truth environmental reconstructions of coastal ecosystems based on geochemical analyses of natural archives (e.g. massive corals). Particularly, calibrations of temperature and salinity proxies can be achieved using CARICOMP data. Such calibrations and reconstructions are indispensable to extend time scales prior to monitoring and instrumental records [68-69] and to infer the magnitude of human-induced impacts within the context of natural variability. Because CARICOMP sites are located in areas with contrasting setting (not only in terms of oceanography but also human influence) the dataset could be used to assess the impact of these potential controls in key physicochemical variables. For example, the CARICOMP data can be useful in identifying and assessing indicators of the long-term effects of Marine Protected Areas (MPA), by comparing sites outside an inside MPAs [e.g. Costa Rica, Colombia, Venezuela: 46, 49,70]. Furthermore, CARICOMP data can be used to assess the impact of disturbances. For example, the dataset has been used to show a relationship between high sea surface temperatures and coral bleaching [e.g. 71]. Finally, CARICOMP environmental data may support models of marine ecosystem dynamics in the Caribbean region which can be translated into applicable inputs for science-based decision-making of recovery, restoration or conservation of these ecosystems.

The CARICOMP program aimed to relate environmental data to observed changes in mangrove, seagrass meadow and coral reef communities over time [22], and this study has contributed as a first step towards that goal. Long-term changes in seagrass biomass and productivity were reported by van Tussenbroek et al [72] and the documentation of the changes in mangrove and reef communities are currently under preparation. Large heterogeneity in environmental signals reported here could explain, for example, the variability in responses showed by seagrass meadows in the region [72], a hypothesis that could be tested now that both datasets are available. CARICOMP represented the longest, broadest international effort to manually collect data in coastal ecosystems using standard methodologies. By leveraging efforts of a large group of collaborators from multiple institutions across large spatial scales, CARICOMP’s *in situ* monitoring provides an invaluable source to document the spatial distribution of anthropogenic impacts in the coastal Caribbean. Results from this unparalleled effort highlight limitations of highly variable coastal *in situ* data, but also potential for documenting change at regional scales.

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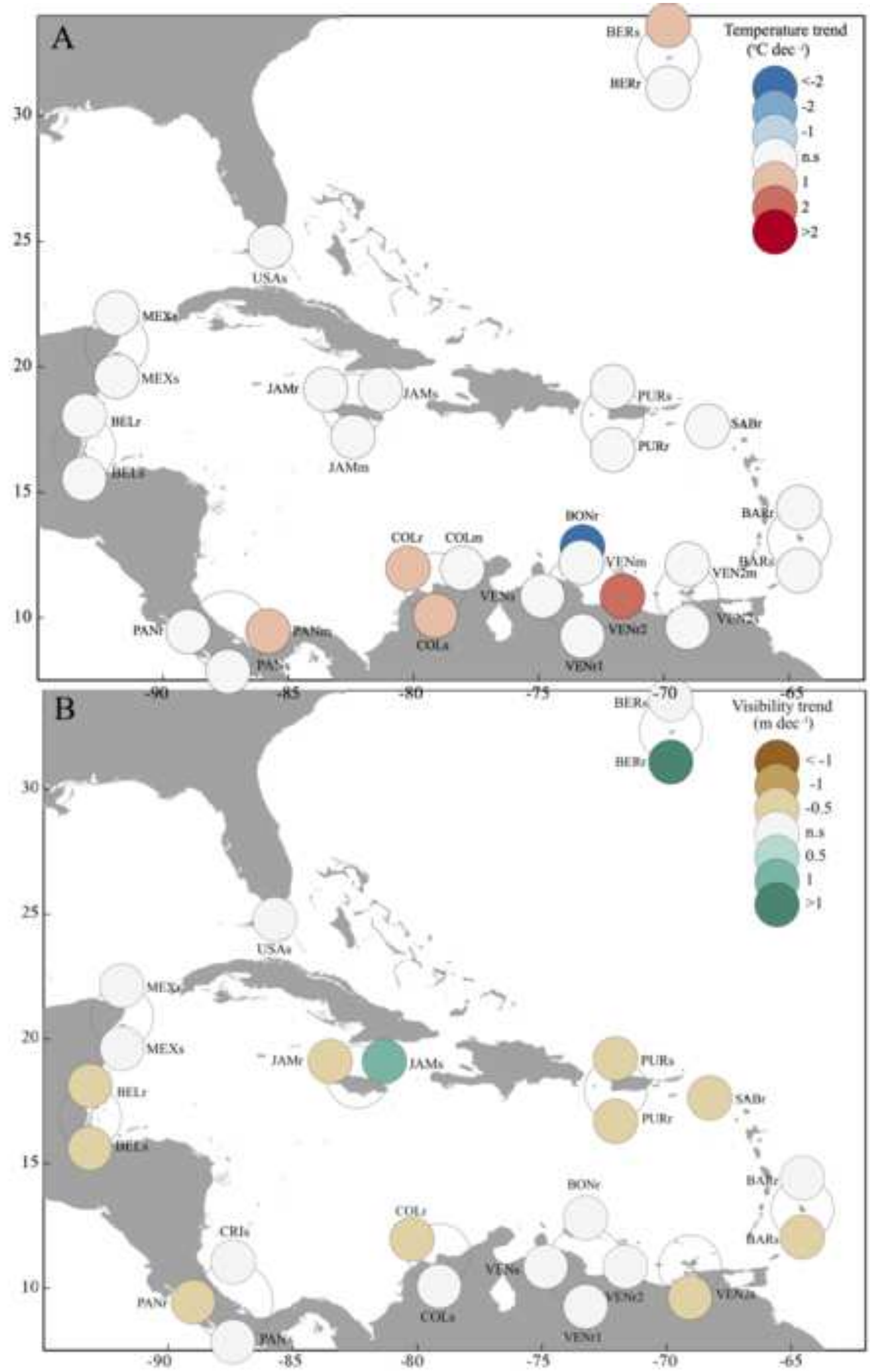
Supporting information

S1 Appendix. Site metadata. Word file including metadata for all CARICOMP stations included in the database and mixed effect model fits for temperature and visibility

S2 Appendix. CARICOMP environmental database. Text file including all CARICOMP’s weekly environmental data

S3 Appendix. Mixed effect models results. Word file including non-linear mixed effect model fits for temperature and visibility

Figure 1


A
Temperature trend
(°C dec⁻¹)
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MEXs
MEXs
BELr
BELs
JAMr
JAMs
JAMm
PURs
PURr
SABr
BARr
BARs
BONr
VENm
VEN2m
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VENr2
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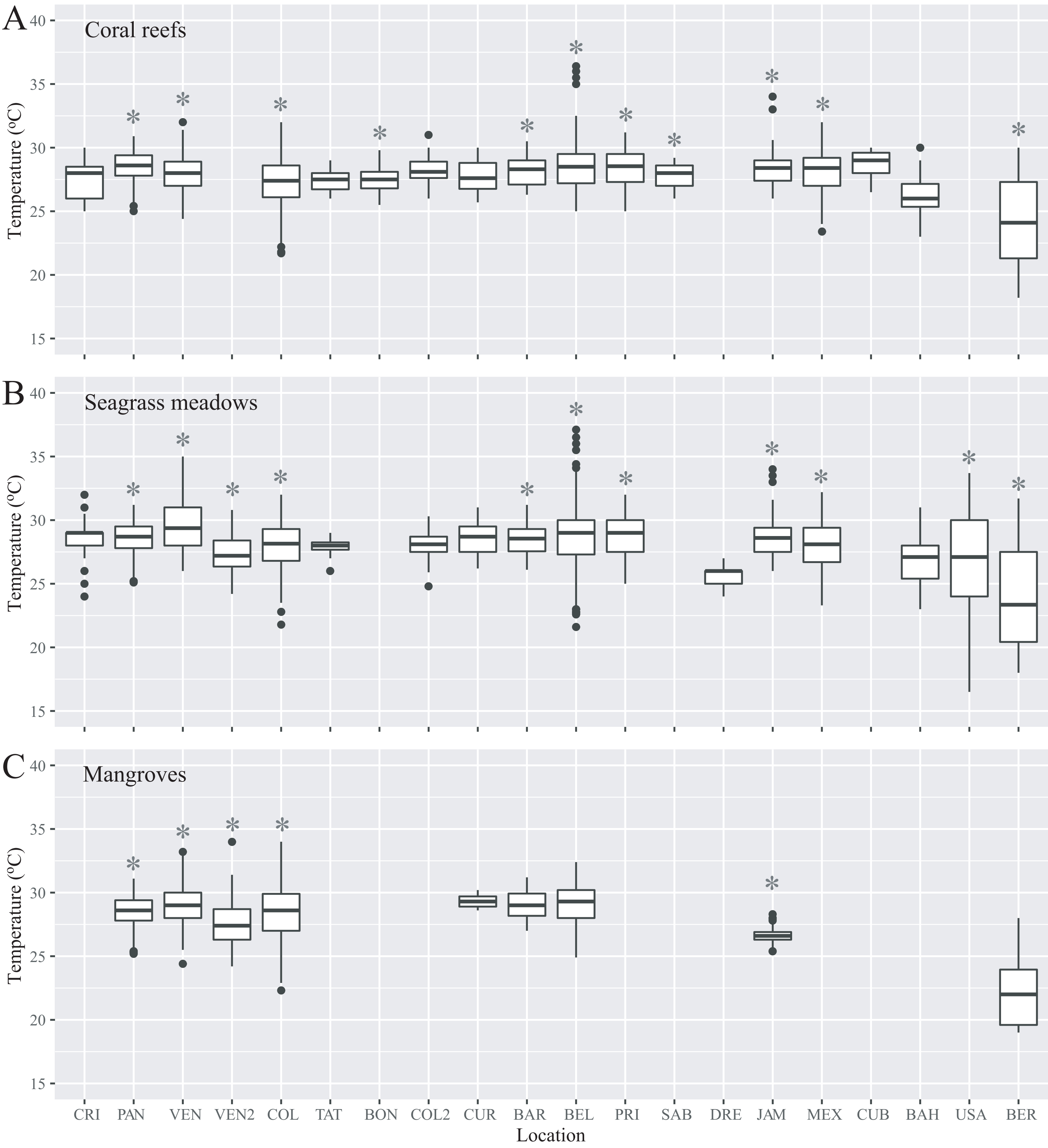
20
15
10
-90
-85
-80
-75
-70
-65
B
Visibility trend
(m dec⁻¹)
< -1
-1
-0.5
n.s
0.5
1
>1
BERs
BERr
USAs
MEXs
MEXs
BELr
BELs
JAMr
JAMs
PURs
PURr
SABr
BARr
BARs
BONr
CRIs
COLr
COLs
VENs
VENr2
VENr1
VEN2s
PANr
PANs
30
25
20
15
10
-90
-85
-80
-75
-70
-65


A
Coral reefs
B
Seagrass meadows
C
Mangroves
Temperature (ºC)
40
35
30
25
20
15
CRI
PAN
VEN
VEN2
COL
TAT
BON
COL2
CUR
BAR
BEL
PRI
SAB
DRE
JAM
MEX
CUB
BAH
USA
BER
Location

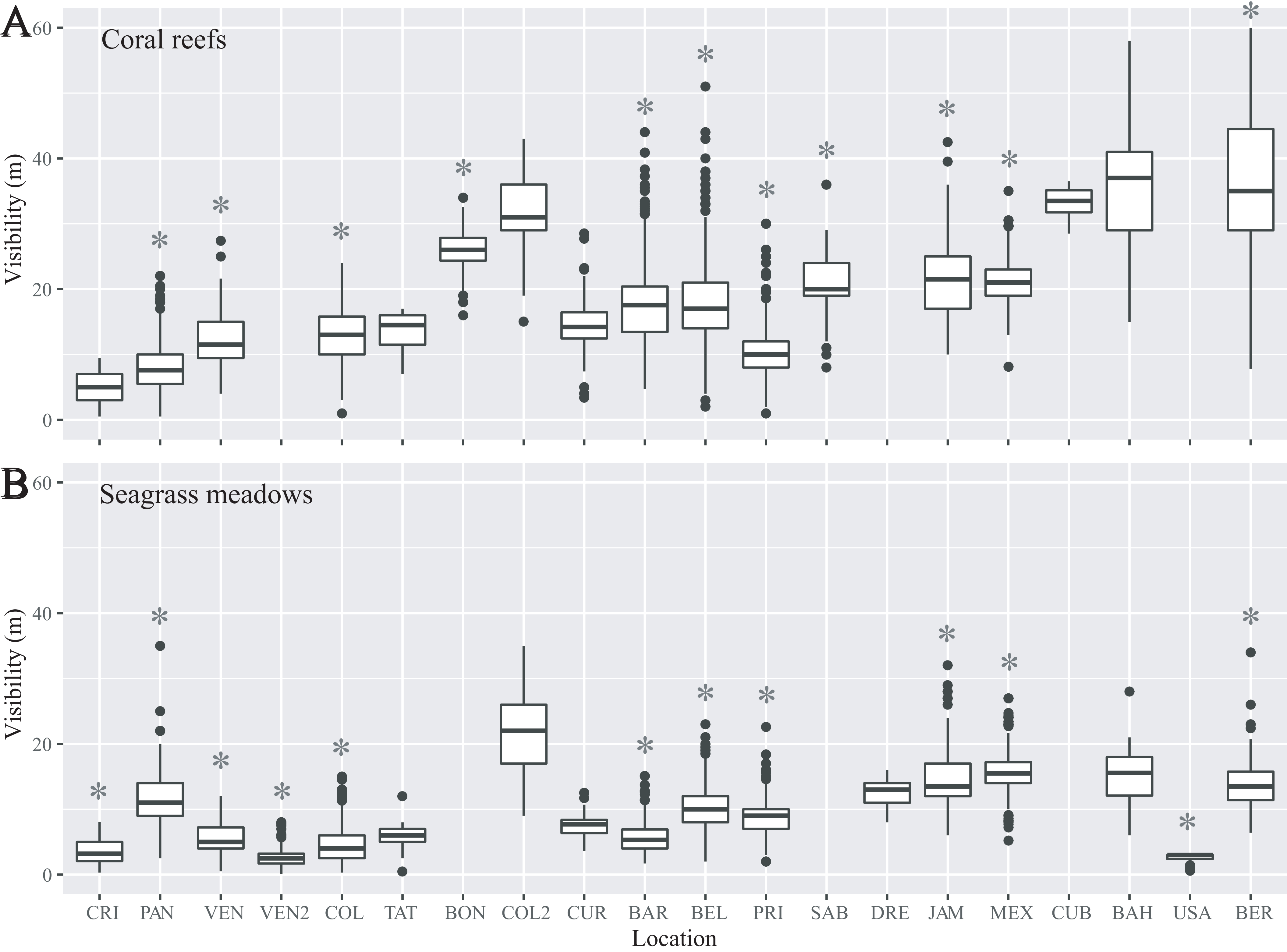

A
Coral reefs
B
Seagrass meadows
Visibility (m)
0
20
40
60
Location
CRI
PAN
VEN
VEN2
COL
TAT
BON
COL2
CUR
BAR
BEL
PRI
SAB
DRE
JAM
MEX
CUB
BAH
USA
BER
*

Figure 4

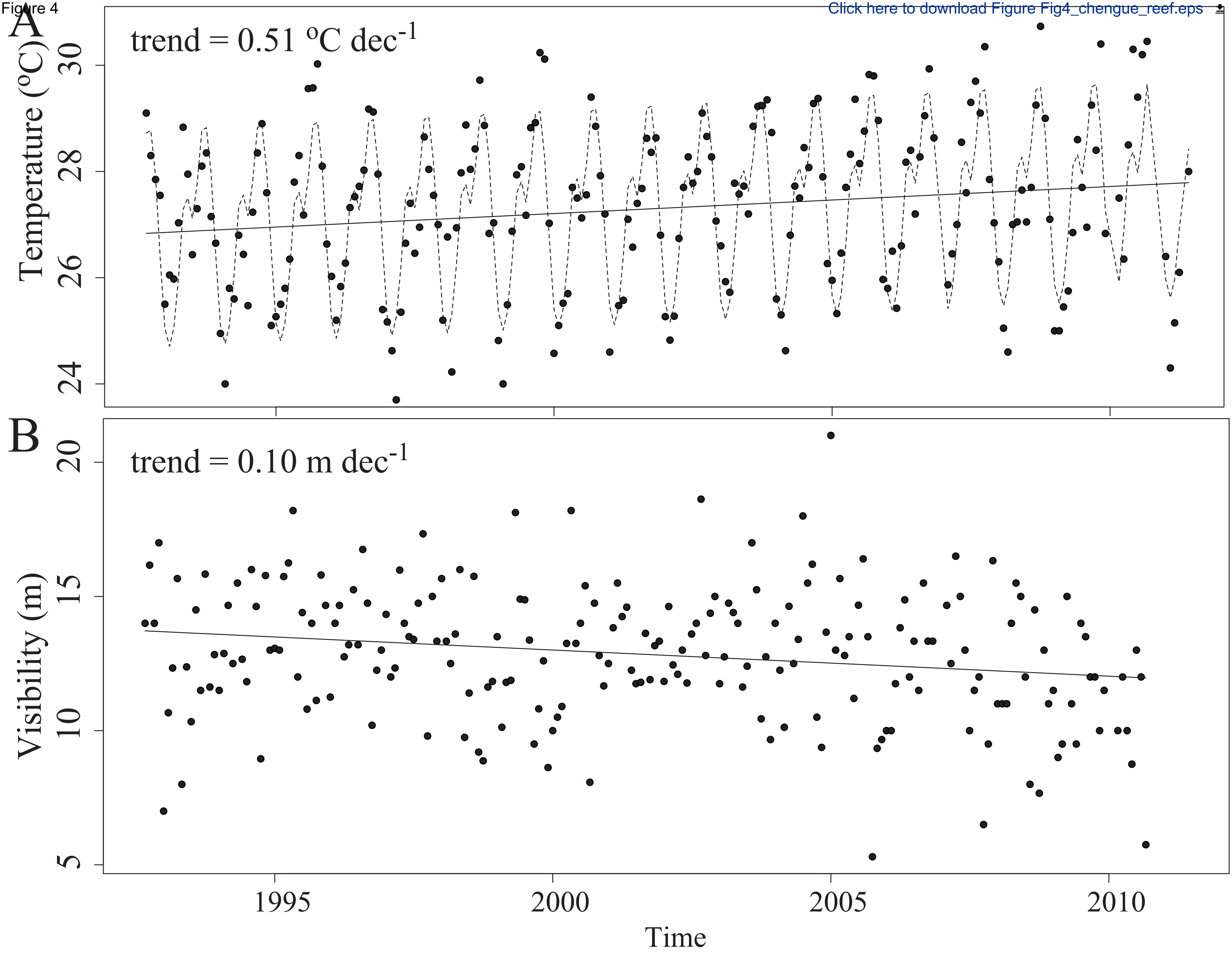

A
trend = 0.51 ºC dec-1
Temperature (ºC)
24
26
28
30
B
trend = 0.10 m dec-1
Visibility (m)
5
10
15
20
1995
2000
2005
2010
Time

Figure 5

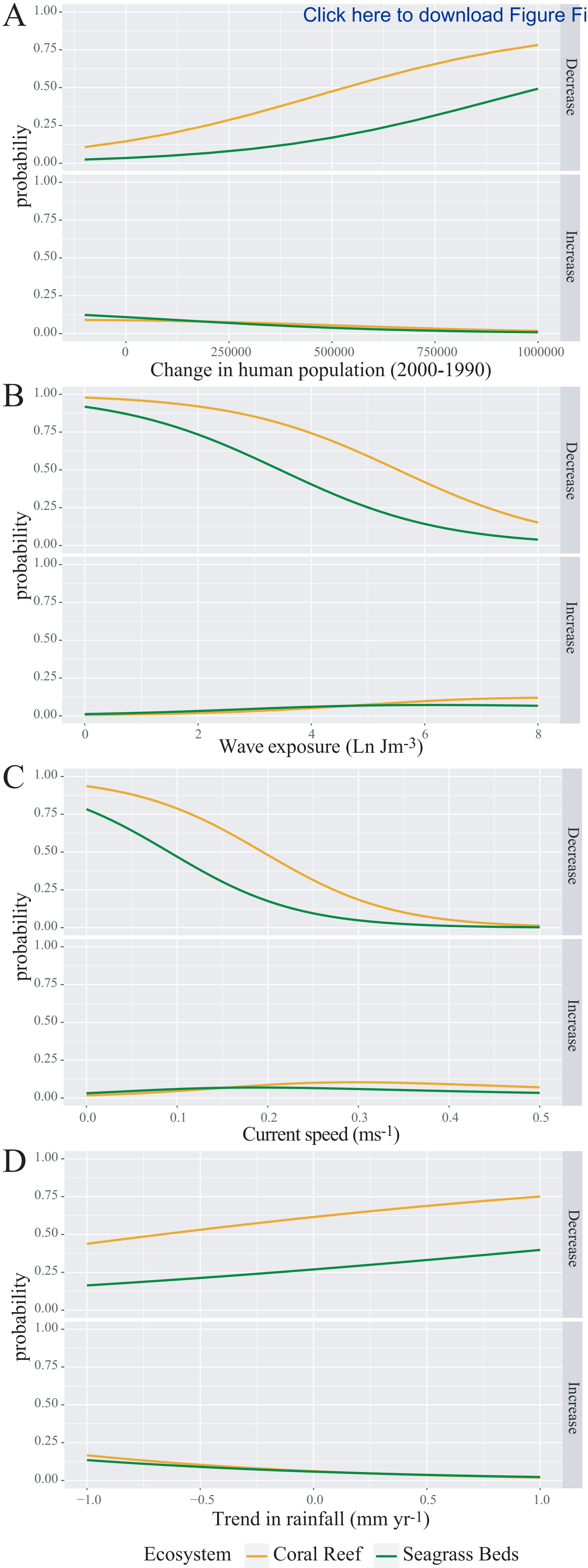
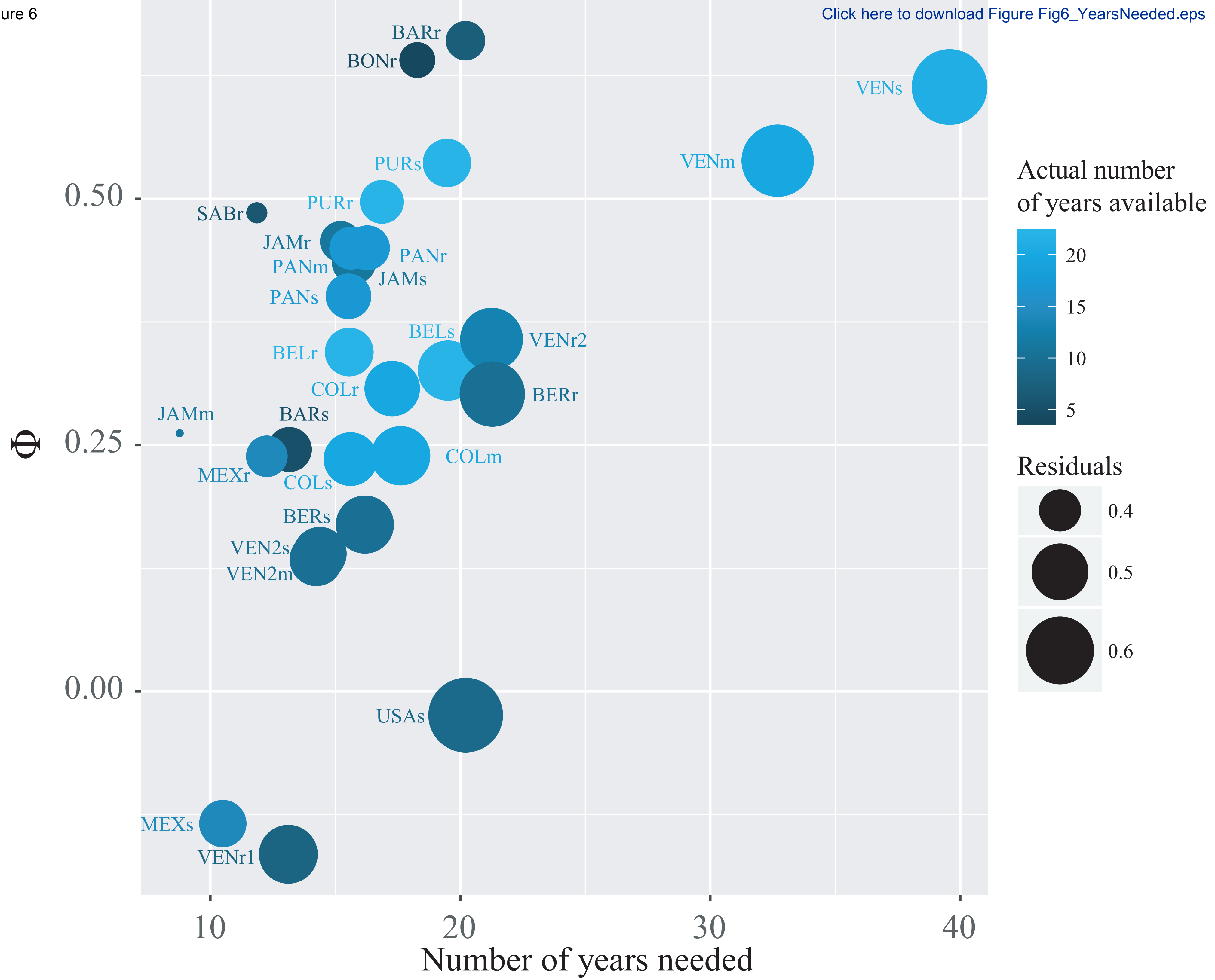

A
probabiliy
Decrease
Increase
1.00
0.75
0.50
0.25
0.00
0
250000
500000
750000
1000000
Change in human population (2000-1990)
B
probability
Decrease
Increase
0
2
4
6
8
Wave exposure (Ln Jm-3)
C
probability
Decrease
Increase
0.0
0.1
0.2
0.3
0.4
0.5
Current speed (ms-1)
D
probability
Decrease
Increase
−1.0
−0.5
0.0
0.5
1.0
Trend in rainfall (mm yr-1)
Ecosystem
Coral Reef
Seagrass Beds

Figure 6


BARr
BONr
VENs
PURs
VENm
PURr
SABr
JAMr
PANr
PANm
JAMs
PANs
BELs
VENr2
BELr
COLr
BERr
JAMm
BARs
COLm
MEXr
COLs
BERs
VEN2s
VEN2m
USAs
MEXs
VENr1
0.50
0.25
0.00
Φ
10
20
30
40
Number of years needed
Actual number of years available
20
15
10
5
Residuals
0.4
0.5
0.6

Widespread local chronic stressors in Caribbean coastal habitats

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Abstract

Coastal ecosystems and the livelihoods they support are threatened by stressors acting at global and local scales. Here we used the data produced by the Caribbean Coastal Marine Productivity program (CARICOMP), the longest, largest monitoring program in the wider Caribbean, to evidence local-scale (decreases in water quality) and global-scale (increases in temperature) stressors ~~in~~ across the basin. Trend analyses showed that visibility decreased at 42% of the stations, indicating that local-scale chronic stressors are widespread. On the other hand, only 18% of the stations showed increases in water temperature that would be expected from global warming, partially reflecting the limits in detecting trends due to ~~limited evidence of global-scale chronic stress due partly to~~ inherent natural variability of ~~CARICOMP's *in situ* measurements~~ temperature data. Decreases in visibility were associated to increased human density. However, this link can be decoupled by environmental factors, with conditions that increase the flush of water dampening the effects of human influence. Besides documenting environmental stressors throughout the basin, our results can be used to inform future monitoring programs, if the desire is to identify stations that provide early warning signals of anthropogenic impacts. All CARICOMP environmental data are~~is~~ now available, providing an invaluable baseline that can be used to strengthen research, conservation, and management of coastal ecosystems in the Caribbean basin.

Key words: Monitoring; climate change; pollution; mangrove; seagrass meadow; coral reef

Introduction

Changes at local and global scales are influencing our oceans, altering their health and the benefits we receive from them. Here we use the terms global and local to define scales of action of anthropogenic stressors, ~~Marine systems are affected by a plethora of stressors~~, ranging from disturbances acting on broad spatial scales, such as ocean warming, to those acting at very localized scales, such as dredging [~~(~~1,2]~~)~~. These changes have affected the health of marine ecosystems and the services they provide [~~(~~3]~~)~~ and may threaten coastal livelihoods and food security [~~(~~4]~~)~~. Long-term measurements of environmental parameters over wide geographic regions are necessary to understand the rate of change at global and local scales. Such a strategy provides information that informs ~~allows identifying~~ identification of threatened areas and~~,~~ ~~providing~~ provides potential explanations for and predictions of ecosystem responses. A long-term approach also allows~~, monitoring~~ the assessment of progress towards management objectives and planning for mitigation or adaptation accordingly [~~(~~5]~~)~~.

Increases in temperature and decreases in water quality are common indicators of changes in the oceans at global and local scales, respectively [~~(~~1,6]~~)~~. Increases in greenhouse gases released by human activities have altered ocean temperature, generally by warming [~~(~~7]~~)~~. I~~i~~n the Caribbean, analyses of remote sensing data indicate that most areas have warmed at rates that range from 0.2 to 0.5°C dec^{-1} during the last three decades [~~(~~8]~~)~~. These increases in temperature have been positively correlated with increases in the frequency and prevalence of coral bleaching and, in some cases, diseases affecting coral reef species across the region [~~(~~9–11]~~)~~. The localized influence of human stressors, on the other hand, has been manifested as decreases in water quality driven by increased pollution resulting from rapid development and habitat conversion [~~(~~1]~~)~~. Decreases in water quality have also been mapped using satellite information but only at regional scales, showing increases in turbidity in several localized areas in the Caribbean [~~(~~e.g. 12,13]~~)~~.

Optical remote sensing has been a pivotal tool in quantifying changes in the oceans at global and regional scales [~~(~~14]~~)~~, however, this tool is not well suited to study patterns and processes at the land-sea interface [~~(~~15]~~)~~. While this technology can sample the globe cheaply and repeatedly over a large area, it can be inaccurate in coastal areas. The inaccuracy of optical remotely-sensed data close to the coast is related to two main issues: high cloud coverage in coastal areas that blocks the view from satellites, and the presence of land that contaminates the signal received by the sensor [~~(~~15,16]~~)~~. Additionally, the complex optical signal of coastal waters hinders the quantification of water quality along the coast;~~:~~ the complex mixture of components in coastal waters makes the quantification of the separate constituents very difficult, and shallow bottoms can look very similar to heavily turbid regions. As a result, water quality can be measured using remote sensing only in particular locations using algorithms that are heavily reliant on *in situ* data [~~(~~15,16]~~)~~. Thus *in situ* measurements from monitoring programs may play an important role in quantifying patterns in coastal areas.

Long-term *in situ* datasets documenting temporal changes in the environment of coastal areas, where most economically valuable ecosystems are located, are limited [~~(~~17,18]~~)~~. Most *in situ* datasets that record ocean conditions focus on open-ocean areas [~~(~~e.g. SeaBASS: 19]~~)~~, and do not provide repeated measurements that allow for the quantification of changes at fine spatial scales [~~(~~e.g. the World Ocean Database: 20]~~)~~. First of its kind in the wider Caribbean, the international Caribbean Coastal Marine Productivity program (CARICOMP) was established almost 30 years ago to fill this gap [~~(~~21]~~)~~. The CARICOMP long-term program was developed to study processes at the land-sea interface and understand productivity, structure and function of the three main coastal habitats (mangroves, seagrass meadows, and coral reefs) across the region [~~(~~21,22]~~)~~. Together with biological monitoring, the CARICOMP network has collected environmental data since 1992 using simple, standardized methods [~~(~~21–23]~~)~~.

Here we used the environmental data collected by CARICOMP's monitoring network to quantify ~~chronic~~ long-term changes in oceanographic conditions in coastal habitats in the wider Caribbean. We focused our analyses on temperature and visibility, two proxies of global and local chronic stressors in marine environments. We ~~were interested in~~had two ~~issues~~aims. First, quantifying significant changes in these ~~*in situ*~~ environmental variables over time. Second, understanding if these stressors are influencing the entire basin in a homogeneous way, and if not, what factors (i.e. water movement, rainfall, and human influence) could explain~~ the~~ differences among sites. In this ~~manuscript~~ study we not only synthes~~t~~ize the information in this~~produced by~~ an unparalleled dataset (which is made available with this publication), but provide guidelines for the better selection of monitoring sites if ~~the desire is to~~future aims include identifying early warning signals of change~~ in the future~~.

Materials and methods

CARICOMP Dataset

Beginning in 1992, CARICOMP established permanent monitoring stations in mangrove, seagrass, and coral reef habitats. Effort was made to select stations that specifically avoided anthropogenic sources of disturbance, particularly coastal development and pollution- [~~(~~21]~~)~~. Weekly (whenever possible) physical measurements were taken at each station between 10:00 and 12:00 local standard time. Measurements consisted of water temperature (°C), salinity~~ (psu)~~, and visibility (m). Temperature and salinity were measured with a field thermometer and a refractometer at 0.5 m depth at all habitats. Visibility was measured with a Secchi disk in seagrass (measured horizontally 0.5 m below the surface, as these habitats are often too shallow for a standard vertical measurement) and reef habitats (typically measured vertically over the drop-off), and can be assumed to indicate water quality at the surface. Secchi depth is strongly correlated to the amount of particulate material in the water column and it has been used as a cheap, fast, and simple proxy for visibility and water quality [~~(~~24]~~)~~. We are aware, however, that this is only one of the multiple environmental variables that characterize water quality at a site, and that a full assessment of this component would require also the measurement of other variables (e.g. concentration of nutrients, pollutants, dissolved matter).

Data from previously published~~existing~~ CARICOMP databases and ~~data~~ updates provided directly from individual researchers at CARICOMP stations were compiled into a uniform format. All environmental CARICOMP data are available in the Supporting Information (a description of all stations is in Tables S1-A and S1-B ~~in S1 File~~ and the data are in S2 ~~file~~Appendix). Although information from all three variables is included in the appendix, to address the aims of this research only temperature and secchi data were analyzed.

Simple mixed effect models for the assessment of differences among habitats (fixed factor) including all stations (as random factor) were fitted with the R package *lmerTest* [~~(~~25]~~)~~, which provides additional F statistics and p-values for factors calculated based on Satterthwaite's approximations. Satterthwaite's method allows calculating the denominator degrees of freedom as a function of the variance of the parameter estimate [26], and therefore estimating significance in mixed effect models which is generally problematic [27~~(26)~~].

Monthly averages were calculated from the weekly data for each station. To ensure meaningful quantification of a linear trend, o~~O~~nly stations with data for at least three years and ~~at least~~a minimum of 30 monthly records ~~that could allow the meaningful quantification of a linear trend~~ were included in subsequent analyses (60% of the sites: Table 1~~I~~, Fig 1).

Table 1~~I~~. Description of sites. CARICOMP stations with long-term data (at least three years and 30 monthly records).

Country	Site	Habitat	Station acronym	Latitude	Longitude	Year range
Barbados	Bellairs	Coral Reef	BARr	13.192	-59.642	11/1992-12/1999
Barbados	Bellairs	Seagrass Beds	BARs	13.068	-59.578	11/1992-09/1996
Belize	Carrie Bow Cay	Coral Reef	BELr	16.800	-88.067	01-1993/07-2015
Belize	Carrie Bow Cay	Seagrass Beds	BELs	16.825	-88.099	01-1993/07-2015
Bermuda	Hog Breaker Reef	Coral Reef	BERr	32.344	-64.865	09-1992/12-2002
Bermuda	North Seagrass	Seagrass Beds	BERs	32.401	-64.799	09-1992/12-2002
Bonaire, N.A.	Barcadera Reef	Coral Reef	BONr	12.195	-68.301	08/1994-12/1997
Colombia	Chengue Bay	Coral Reef	COLr	11.328	-74.128	09-1992/06-2011
Colombia	Chengue Bay	Mangrove	COLm	11.317	-74.128	09-1992/06-2011
Colombia	Chengue Bay	Seagrass Beds	COLs	11.321	-74.127	09-1992/06-2011
Costa Rica	Rio Perezoso	Seagrass Beds	CRIs	9.737	-82.807	03-1999/05-2015
Jamaica	Discovery Bay	Coral Reef	JAMr	18.472	-77.414	09-1992/02-2002
Jamaica	Discovery Bay	Mangrove	JAMm	18.469	-77.415	09-1992/02-2002
Jamaica	Discovery Bay	Seagrass Beds	JAMs	18.471	-77.414	09-1992/02-2002
Mexico	Puerto Morelos	Coral Reef	MEXr	20.878	-86.845	10-1992/10-2005
Mexico	Puerto Morelos	Seagrass Beds	MEXs	20.868	-86.867	09-1992/10-2005
Panama	STRI_colo	Coral Reef	PANr	9.349	-82.266	06-1999/05-2015
Panama	STRI_colo	Mangrove	PANm	9.352	-82.259	02-1999/05-2015
Panama	STRI_colo	Seagrass Beds	PANs	9.352	-82.258	06-1999/05-2015
Puerto Rico	La Parguera	Coral Reef	PURr	17.935	-67.049	01-1993/12-2014
Puerto Rico	La Parguera	Seagrass Beds	PURs	17.955	-67.043	01-1993/12-2014
Saba, N.A.	Ladder Labyrinth	Coral Reef	SABr	17.626	-63.260	09-1992/04-1997
USA	Long Key	Seagrass Beds	USAs	24.800	-80.717	07-1996/06-2004
Venezuela	P.N. Morrocoy –Caiman	Coral Reef	VENr1	10.852	-68.232	09-1992/11-1999

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Venezuela	P.N. Morrocoy - Cayo Sombrero	Coral Reef	VENr2	10.881	-68.213	02-2000/11-2012
Venezuela	P.N. Morrocoy	Mangrove	VENm	10.836	-68.261	01-1993/11-2012
Venezuela	P.N. Morrocoy	Seagrass Beds	VENs	10.858	-68.291	09-1992/11-2012
Venezuela	Punta de Mangle	Mangrove	VEN2m	10.864	-64.058	01-1993/12-2003
Venezuela	Punta de Mangle	Seagrass Beds	VEN2s	10.864	-64.058	01-1993/12-2003

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Fig 1. Changes in temperature and visibility throughout the CARICOMP network. Map of CARICOMP stations showing ~~and~~ significant increases, decreases, or non-significant trends for temperature (A) and visibility (B). Labels as in Table 1~~I~~, with upper case letters indicating the location and lower case the habitat.

Global and local-scale changes across the Caribbean

To assess global and local-scale changes across the Caribbean, we focused our analyses on changes in temperature and visibility, which as previously noted, are common proxies for change~~s~~ at each~~both~~ scale~~s~~. Long-term trends and significance were calculated considering serial correlation, an ~~issue~~ characteristic of the data that, if not taken into account, violates the assumption of independence of most regression analyses and influences the magnitude and significance of trends [~~(~~27]~~)(26)~~.

Following Weatherhead et al. [~~(~~27]~~)(26)~~, for temperature (T), we fitted a non-linear model with the form:

$$T = \mu + S_t + \frac{\omega t}{12} + N_t \quad (1)$$

Where the temperature at time *t* in months is a function of a constant term μ, a seasonal component with sinusoidal form~~,~~ S_t, a linear trend ω of rate °C year^{-1}, and residuals N_t.. In this model, the seasonal component is allowed to include up to two cycles, and is described by the formula:

$$S_t = \sum_{j=1}^{4} \beta_{1,j} \sin \frac{2\pi j t}{12} + \beta_{2,j} \cos \frac{2\pi j t}{12} \quad (2)$$

Where *t* is the number of months, and β are parameters to be estimated. And the residuals have an AR-1 autocorrelation form, the simplest form of autocorrelation (aka, the similarity between a time series and a lagged version of itself). That is, the residuals at time *t* are a function of the residuals at time *t-1* (i.e. the temporal "memory" of the time series has a one month lag), depending on the station-specific autocorrelation parameter Φ, along with the noise [~~(~~ϵ_t, 27]~~)~~:

$$N_t = \phi N_{t-1} + \epsilon_t \quad (3)$$

For visibility (*V*), we fitted a non-linear model that follows the approach described above but without the seasonal component:

$$V = \mu + \frac{\omega t}{12} + N_t \ (4)$$

In this model, *V* at a given time *t* in months is a function of a constant term μ, a linear trend ω of rate m year^{-1}, and residuals, N_t also assumed to have a AR-1 autocorrelation form (Eq. 3)

The models were fitted using generalized squares and the package *nlme* in *R* [~~(~~28]~~7)~~. Initial estimates for μ and ω were obtained through simple linear regression, and initial values of 1 were used for all β's.

~~Explaining trends~~Correlates of global and local-scale changes

Global and local-scale stressors can be exacerbated or dampened by local conditions related to water movement, with circumstances that increase the flush of water potentially less conducive to warming and decreases in visibility [~~(28,~~29,30]~~)~~. We examined the effects of water movement through the inclusion of two variables: wave exposure and current speed. Additionally, trends in visibility can be driven by human influence (with areas of rapid population increases expected to lose visibility), and could also be influenced by trends in rainfall (with stations that are getting wetter anticipated to ~~get more~~show increased turbidity); therefore these two variables were also included to explain trends for this response variable. This way, we characterized each station with the explanatory variables: (1) average wave exposure; (2) average current speed; (3) changes in human population density; (4) trend in rainfall. Due to the lack of consistent *in situ* datasets for all stations, modelled or remote sensing sources were used to derive explanatory variables. Below we briefly describe each dataset.

Wind-driven wave exposure for each station is dependent on the wind patterns and the configuration of the coastline, which defines the *fetch*, or the length of water over which a given wind has blown to generate waves. To calculate wave exposure, wind speed and direction data at each location were acquired from the QuickSCAT (NASA) satellite scatterometer from 1999 to 2008 at 25 km spatial resolution [~~(~~31~~0~~]~~)~~. Coastline data were obtained from the Global Self-consistent, Hierarchical, High-resolution, Shoreline (GSHHS v 2.2) database which provides global coastline at 1:250,000 scale [~~(~~32~~1~~]~~)~~. From these datasets wave exposure was calculated using the methods based on wave theory described in Chollett et al. [~~(~~33~~2~~]~~)~~ for 32 fetch directions and the coastline data at full resolution. Average wave exposure at each station was calculated in *R* with the aid of the packages *maptools, raster*, *rgeos*, and *sp* [~~(~~34~~3~~–37~~6~~]~~)~~.

Average surface current speed was extracted from the ocean model HYCOM [~~(~~38~~7~~]~~)~~. We used global data-assimilative runs at 1/12° of spatial resolution for the period 2008-2011. The HYCOM model is forced by wind stress, wind speed, heat flux, and precipitation and the system uses *in situ* temperature and salinity profiles to improve estimates, providing the most detailed and comprehensive global dataset of ocean currents available to date [~~(~~39~~8~~]~~)~~.

Gridded human population density data for the years 1990 and 2000 (the most recent dataset available at that spatial detail) were obtained from the Global Rural-Urban Mapping Project, Version 1 [~~(~~GRUMPv1: ~~39)~~40]. These years coincide with most of CARICOMP sampling took place between those decades, with time series beginning on average in February 1994 and finishing on average in September 2007 (Table 1). We used the adjusted population density grids as inputs, which provide population density in persons per square kilometre using census information but also observations of night lights to delineate the extent of urban areas. From these datasets we extracted the number of people within a buffer of 1-degree diameter around each station, and then calculated the difference in population between the years 2000 and 1990, which captures a proxy for broad impacts of human population expansion on coastal ecosystems. A one degree buffer was considered as a reasonable range at which many human impacts might affect coastal ecosystems, as it has been shown before [41].

Satellite rainfall data were extracted from the GPCP v2.2 combined precipitation dataset, which merges satellite and gauge precipitation values in monthly estimates of total precipitation from 1986 to 2016 (i.e. 37 years of data) at 2.5° spatial resolution. This is the longest, most accurate global dataset of rainfall available to date [~~(~~42~~0~~,43]~~1~~). For each station trends were calculated from these monthly means taking into account the temporal autocorrelation of the data (Eq. 4).

When trends are non-significant their value is uninformative (e.g. a trend in temperature of 2°C year^{-1} with a p value of 0.8 is meaningless), hindering the use of the actual trend values as a response variable in quantitative analyses. We therefore transformed the continuous data (i.e. trend values in temperature and visibility) into nominal data (i.e. trend categories) by classifying trends as non-significant, significantly increasing or significantly decreasing. We then used multinomial regression models to identify what factors were relevant at explaining the observed trend categories in temperature and visibility. Multinomial regression is a method used to generalize logistic regression where the response variable is nominal and has more than two classes, in which the log odds of the outcomes are modelled as a linear combination of predictor variables. Here, we modelled trends in temperature as a function of wave exposure and currents, and trends in visibility as a function of wave exposure, currents, changes in human population, and trends in rainfall. Multinomial regression was carried out using the package *nnet* in R [~~(~~44~~2~~]~~)~~. All figures were produced using the package *ggplot2* in R [~~(~~45~~3~~]~~)~~.

Results

CARICOMP Dataset

CARICOMP collected data at 48 stations in 18 countries/territories across the wider Caribbean (Tables S1-A and S1-B~~ in S1 File~~). Participants in the~~The~~ network have~~s~~ sampled environmental data from 20 reefs, 19 seagrass meadows, and 9 mangrove forests since 1992. Data collection is ongoing at some ~~are still being collected at some~~ stations~~ today~~.

Water temperature and visibility were variable throughout the region (Figs 2 and 3). ~~Median~~ Average temperature ranged from about 22˚C in Bermuda (BER) to almost 30˚C in Cuba (CUB), but many stations showed relatively similar values (Fig 2). There were no clear differences in ~~median~~ temperature among seagrass, mangroves, and coral reefs (mixed effect model with location as random effect, $F = 0.74$, $p = 0.48$). Visibility, only measured in reef and seagrass habitats, also showed large variability among stations, with a minimum of about 3 m at the seagrass meadow off eastern Venezuela (VEN2), and a maximum of 37 m at the reef in the Bahamas (BAH, Fig 3). Locations with lower ~~median~~ values of visibility also showed the greatest variability. As expected, there were clear differences in visibility between habitats, with higher values in coral reefs (mixed effect model with location as random effect, $F = 18.22$, $p < 0.001$). Sixty percent of the CARICOMP stations (described in Table ~~I~~1) included long-term records and were therefore suitable candidates for the estimation of long-term trends in subsequent analyses.

Fig 2. Sea temperature throughout the CARICOMP network. Sea temperature in each site and habitat in the CARICOMP network, all data are presented, including all years (i.e. since 1992) and all stations, with and without long-term (> 3 years) data: (A) Coral reefs; (B) Seagrass meadows; and (C) Mangroves. In boxplots, lines represent me~~di~~ans, boxes 25 and 75% quantiles, whiskers 1.5 inter-quartile ranges and dots outliers. Sites are: Costa Rica (CRI), Panama (PAN), western Venezuela (VEN), eastern Venezuela (VEN2), Colombia (COL), Trinidad y Tobago (TAT), Bonaire (BON), northern Colombia (COL2), Curaçao (CUR), Barbados (BAR), Belize (BEL), Puerto Rico (PUR), Saba (SAB), Dominican Republic (DRE), Jamaica (JAM), Mexico (MEX), Cuba (CUB), the Bahamas (BAH), United States (USA), and Bermuda (BER). Sites with an asterisk were included in subsequent analyses.

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Fig 3. Visibility throughout the CARICOMP network. Visibility in each site and habitat in the CARICOMP network, all data are presented, including all years (i.e. since 1992) and all stations, with and without long-term (> 3 years) data: (A) Coral reefs; and (B) Seagrass meadows. In boxplots, lines represent me~~di~~ans, boxes 25 and 75% quantiles, whiskers 1.5 inter-quartile ranges and dots outliers. Sites are: Costa Rica (CRI), Panama (PAN), western Venezuela (VEN), eastern Venezuela (VEN2), Colombia (COL), Trinidad y Tobago (TAT), Bonaire (BON), northern Colombia (COL2), Curaçao (CUR), Barbados (BAR), Belize (BEL), Puerto Rico (PUR), Saba (SAB), Dominican Republic (DRE), Jamaica (JAM), Mexico (MEX), Cuba (CUB), the Bahamas (BAH), United States (USA), and Bermuda (BER). Sites with an asterisk were included in subsequent analyses.

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~~Sixty percent of the CARICOMP stations (described in Table I) included long-term records and were therefore suitable candidates for the estimation of long-term trends in subsequent analyses.~~

Global and local-scale changes across the Caribbean

Data collected by the CARICOMP network offered evidence of widespread local, but not global-scale changes across the wider Caribbean using visibility and sea temperature as proxies. While a few stations showed evidence of warming, about half the stations showed evidence of decreased visibility (Fig 1). The mixed effects models represented the temporal variability in the oceanographic variables well, capturing both the seasonality (for temperature) and long-term linear trends (Fig 4, Tables S3-A and S3-B~~ in S3 File~~).

Fig 4. Time series example. Time series for sea temperature (A) and visibility (B) for the reef at Chengue Bay (Colombia), showing significant increases in temperature and significant decreases in visibility. For temperature, the model fit takes into account both seasonality (sinusoidal line) and a linear trend (straight line).

There was large spatial variability in temperature and visibility trends across the CARICOMP network (Fig 1). Of the 28 reef, seagrass, and mangrove stations, 18% (1 mangrove, 2 seagrass meadow, and 2 coral reef stations) showed a significant increasing trend in temperature, and only one (Bonaire reef) showed a significant decrease (Fig 1A, Table S3-A~~ in S3 File~~). On the other hand, of the 24 reef and seagrass stations, 42% (4 seagrass meadows and 6 reefs) showed a significant decreasing trend in visibility, and two stations (Jamaica seagrass and Bermuda reef) showed a positive trend (Fig 1B, Table S3-B~~ in S3 File~~). Neither warming nor decreases in visibility were observed to be more common in any of the three habitats monitored (Chi-squared tests, p > 0.05).

Correlates of global and local-scale changes ~~Explaining trends~~

The presence of negative, positive, or non-significant trends in temperature was not explained by either~~any~~ of the two local factors assessed (wave exposure and currents, multinomial regression, p > 0.05 for both variables).

Trends in visibility were explained by all variables, that is, changes in human population, wave exposure, current speed, and trend in rainfall (multinomial regression, $p < 0.01$). Decreases in visibility were more likely to occur in areas where human population (and associated coastal development) has increased the most (Fig 5A). Oceanographic and atmospheric variables have the ability to modulate changes in visibility (Figs 5B-D). Long-term decreases in visibility ~~a~~were more likely to occur at stations with slow water motion, characterized either by low exposure (Fig 5B, top panel) or low current speed (Fig 5C, top panel). Conversely, long-term increases in visibility we~~a~~re more likely at stations with high wave exposure and current speed, although these variables had~~ve~~ a very small effect in driving significant long-term increases in visibility (Figs 5B and 5C, bottom panels). Finally, decreases in visibility we~~a~~re also more likely to occur in areas that we~~a~~re getting wetter, and increases were more likely in areas that we~~a~~re getting drier (Fig 5D). The functional responses to these explanatory variables we~~a~~re similar no matter the habitat (Fig 5).

Fig 5. Explaining trends in visibility. Predicted probability of decreases and increases in visibility (as per right-hand labels of the top and bottom panels respectively) against changes in human population (A), wave exposure (B), current speed (C), and trend in rainfall (D).

Discussion

The longest and most spatially comprehensive *in situ* monitoring effort in the wider Caribbean provides evidence of widespread local changes within the basin. This is a relatively unexpected result, given that CARICOMP stations were intended to be established in pristine areas under minimal local impacts ~~(21).~~

~~Trends in visibility indicate that many CARICOMP stations, originally situated in relatively pristine areas, are now under the influence of anthropogenic stressors. The intention of CARICOMP was to collect information in undisturbed locations~~ that could serve as a baseline against which to measure degradation [~~(~~21]~~)~~. However, ~~already~~ 15 years ago it was already suggested that some stations were under the influence of human activities [~~(~~22]~~)~~. Results presented here support this statement, agree with results of localized studies in some of these locations [~~(~~e.g. 46-50~~4,45–48~~]~~)~~, and indicate that human impacts on coastal habitats are ongoing and pervasive within the Caribbean basin.

CARICOMP's time series do not show widespread evidence of long-term ~~temperature increases~~warming at ~~in~~ coastal stations ~~along~~ in the wider Caribbean. These findings contrast with a global study that showed prevalent warming along the world's coasts using 30 years of satellite data ~~(29)~~[30], and a regional study which showed significant warming ~~along~~ throughout most of the Caribbean basin using 25 years of satellite temperatures ~~(~~[8]~~)~~. The lack of signal in the CARICOMP time series can be attributed to two related issues: the larger variability of *in situ* temperature data and the need ~~of~~ for longer time series to detect significant trends. Satellites measure temperature at the 'skin' of the ocean surface, which is more stable ~~(49)~~[51], and ignores subsurface temperature patterns that are more variable at multiple temporal scales ~~(50)~~[52]. Therefore *in situ* temperature data ~~will be~~are more variable making trend estimation more difficult. Low precision of *in situ* measurements due to external influences [such as changes in sampling methodology, observers, instrumentation, or gaps in the time series: 27, 53] ~~introduced human error~~ could also increase variability and limit the ability to detect trends. Besides the issue of increased variability, the inability to detect trends might be related to the length of the CARICOMP time-series (from 3~~three~~ to 22 years). This timeframe may provide ~~can be~~ insufficient ~~to provide enough~~ statistical power to assess long-term changes in temperature due to intrinsic characteristics of the location, particularly in stations where the magnitude of the trend is small, the memory (i.e. temporal autocorrelation) is high, or temperature is especially variable [~~(~~27~~6~~]~~)~~.

Site-specific information on the inherent characteristics of the time-series can be used to aid in the identification of monitoring sites that are cost-effective in the sense that they ~~are able~~have the power to detect trends earlier [~~(~~27~~6~~]~~)~~, if the detection of early changes is the main objective of the monitoring. Significant trends will be detected faster ~~to detect in~~at sites characterized by low variability and temporal autocorrelation of the noise, which is a measure of the ‘memory’ or inertia of the time-series. For example, within~~ in~~ the CARICOMP network, the time period to detect an expected change varies greatly among stations (Fig 6, Table S3-A). Within this dataset, given the variability and memory of the time-series, Puerto Morelos in Mexico would need the shortest sampling to identify changes in temperature, and it might be a good location to identify trends in temperature early.~~,~~ On the other hand ~~while~~ the seagrass meadow and mangrove stations in Eastern Venezuela might need the longest time series to detect a significant trend~~sampling~~ (Fig 6, Table S3-A). This result is not rare: research in atmospheric [27] and oceanographic [54, 55] science has shown that for most expected environmental changes, several decades of high-quality data may be needed to detect significant trends. For example, many years of continuous data were needed to distinguish a climate change trend in pH and sea surface temperature (about 15 years), chlorophyll concentration and primary production (between 30 and 40 years) from the background natural variability [54, 55]. The process of deciding which site can be useful for future detection of trends is very similar to conducting power analysis to estimate the number of samples needed to detect a particular effect. This type of analysis can be done if the data has already been collected (as in the example in Fig 6) or before collecting the data assuming a range of effect sizes, autocorrelation, and noise [27] and taking into account any external forces that might be affecting the accuracy of the data [see previous paragraph: 53]. This information can be used to set realistic expectations on trend detectability ~~in~~ at different sites. It could also~~, and~~ help select ~~best~~ sites for further monitoring of chronic impacts ~~(51)~~[56], where trends can be detected sooner, after taking other considerations into account such as the relevance of the site to answer the focal scientific question, or logistic factors such as accessibility and maintenance of the monitoring site, which are also important.

Fig 6. Explaining the lack of trends in temperature. Number of years needed to detect a trend in temperature of 0.05°C year^{-1} as a function of the autocorrelation of the noise (ϕ) and the residuals of each station ~~(26)~~[27]. Also shown in color the actual number of years of data available for each station. Note that to identify trends of different magnitudes, different number of years might be required.

~~Contrary to previous reports our analyses indicate that changes in temperature are not modulated by water mixing (e.g. 29). This result might be related to the high variability in the time-series and the lack of significance of the trends in temperature at most stations, together with the dependence of warming patterns on processes affecting at meso-scales (7).~~

Decreases in visibility were related to changes in human density, which increased in all but one (Bonaire) of the CARICOMP stations assessed. The effects of local anthropogenic impacts can be modulated, however, by local hydrodynamic and weather conditions. Areas with high flush of marine water and/or drier weather are less vulnerable to deteriorating visibility. Waves and currents flush sediments, nutrients, and pollutants and determine the spatial variability in visibility patterns [~~(~~29~~8~~,5~~2)~~7]. Decreased rainfall, on the other hand, diminishes runoff reaching the stations, thus improving visibility [~~(~~5~~3)~~8]. The Caribbean basin is getting drier [~~(~~59]~~4)~~ due to the intensification of the

Caribbean Low Level Jet ~~(55)~~[60] and warming in the Atlantic ~~(56)~~[61]. Because rainfall is predicted to decrease further ~~(55)~~[60], we expect that rainfall and runoff will play diminished roles in exacerbating local stressors in the basin in the near future. Knowledge of the factors that modulate the detection of trends in visibility can also assist in~~also provide advice for~~ the identification of the best monitoring sites for early warning signal detection. In this sense, sites with vigorous water movement should be avoided if the desire is the early detection of water quality degradation in coastal areas.

Chronic decreases in coastal water quality can be linked to the increase in marine diseases [62] and the demise of seagrass [63] and coral reef ecosystems [57]. Furthermore, declines in water quality have been linked to economic losses such as decreases in property value and tourism revenues [reviewed in 64]. Results presented here pinpoint areas that might require management interventions. Such interventions may include identifying the cause of decreased water quality, and implementing changes in management practices and long-term commitments towards change. Improving water quality could also have the added benefit of improving resilience of coastal ecosystems to other disturbances, such as climate change ~~(Wooldridge and Done 2009, Kennedy et al. 2013)~~[65,66].

CARICOMP's environmental dataset provides an invaluable baseline that can be used to strengthen research, conservation, and management of coastal ecosystems in the Caribbean basin. In the first place, the dataset provides context for other local studies, aiding comparisons and understanding of observations at single locations [67]. CARICOMP's environmental measurements also provide a powerful *in situ* dataset to help improve satellite observations in coastal areas, where accuracy is currently limited [15]. In addition, *in situ* CARICOMP datasets can help ground truth environmental reconstructions of coastal ecosystems based on geochemical analyses of natural archives (e.g. massive corals). Particularly, calibrations of temperature and salinity proxies can be achieved using CARICOMP data. Such calibrations and reconstructions are indispensable to extend time scales prior to monitoring and instrumental records [68-69] and to infer the magnitude of human-induced impacts within the context of natural variability. Because CARICOMP sites are located in areas with contrasting setting (not only in terms of oceanography but also human influence) the dataset could be used to assess the impact of these potential controls in key physicochemical variables. For example, the CARICOMP data can be useful in identifying and assessing indicators of the long-term effects of Marine Protected Areas (MPA), by comparing sites outside an inside MPAs [e.g. Costa Rica, Colombia, Venezuela: 46, 49,70]. Furthermore, CARICOMP data can be used to assess the impact of disturbances. For example, the dataset has been used to show a relationship between high sea surface temperatures and coral bleaching [e.g. 71]. Finally, CARICOMP environmental data may support models of marine ecosystem dynamics in the Caribbean region which can be translated into applicable inputs for science-based decision-making of recovery, restoration or conservation of these ecosystems.

The CARICOMP program aimed to relate environmental data to observed changes in mangrove, seagrass meadow and coral reef communities over time [~~(~~22]~~)~~, and this study has contributed as a first step towards that goal. ~~The l~~Long-term changes in seagrass biomass and productivity were reported by van Tussenbroek et al ~~(57)~~[72] and the documentation of the changes in mangrove and reef communities are currently under preparation. Large heterogeneity in environmental signals reported here could explain, for example, the variability in responses showed by seagrass meadows in the region ~~(57)~~[72], a hypothesis that could be tested now that both datasets are available. CARICOMP represented the longest, broadest international effort to manually collect data in coastal ecosystems using standard methodologies. By leveraging efforts of a large group of collaborators from multiple institutions across large spatial scales, CARICOMP's *in situ* monitoring provides an invaluable source to document the spatial distribution of anthropogenic impacts in the coastal Caribbean. Results from this unparalleled effort highlight limitations of highly variable coastal *in situ* data, but also potential for documenting change at regional scales.

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Supporting information

S1 ~~File~~Appendix. Site metadata. Word file including metadata for all CARICOMP stations included in the database and ~~Mixed ~~mixed effect model fits for temperature and visibility

S2 Appendix~~File~~. CARICOMP environmental database. Text file including all CARICOMP’s weekly environmental data

S3 Appendix~~File~~. Mixed effect models results. Word file including non~~p~~-linear mixed effect model fits for temperature and visibility

Thanks so much for your time and effort revising this manuscript. Please find our responses to the reviewers (and you!) below in blue Arial font. We highlighted in yellow the rare cases when we disagreed or were unable to address the comment raised by the reviewer.

PONE-D-17-03684
Widespread local chronic stressors in Caribbean coastal habitats
PLOS ONE

Dear Mrs Chollett,

Thank you for submitting your manuscript to PLOS ONE. After careful consideration, we feel that it has merit but does not fully meet PLOS ONE's publication criteria as it currently stands. Therefore, we invite you to submit a revised version of the manuscript that addresses the points raised during the review process.

I thought this was an interesting manuscript with quite an impressive data set. However, there was disagreement among all three reviewers with recommendations for minor revision, major revision and rejection. I think there are some substantial issues with the manuscript as written, including how the data were summarised and the general lack of detail in the paper. There is also not a clear link between the conclusions and data as presented. In addition, there are numerous errors in the manuscript.

I think with some careful and rigorous revision the manuscript may be acceptable for publication. Certainly the data are there. But the authors need to restructure the manuscript so all the appropriate detail is there for readers. In addition, the authors need to think about how they summarised the data and the conclusions drawn. All the reviewers have provided detailed comments on the manuscript, as have I (see attached), to assist the authors in their revision. I strongly encourage the authors to consider all the comments provided.

We look forward to receiving your revised manuscript.

Kind regards,

Heather M. Patterson, Ph.D.
Academic Editor
PLOS ONE

Thanks so much for considering our paper. We have made a substantial revision to the manuscript which has improved greatly the paper. We have explained the reviewer why the way we summarized the data is appropriate given that this paper is focused on long-term trends and not on pulse events (which, in fact, we want to avoid capturing!). This type of approach (using temporal summaries) is followed by central research on climate change detection, including work by the IPCC.

We have included a lot of extra information in the manuscript to clarify the methods, expand the discussion and make our conclusions more transparent. All these adjustments made the manuscript stronger but they did not imply changes in the analyses, results or modified the message of the paper. The text has been thoroughly revised for errors, formatting and style and we believe that with your input and our adjustments is ready for publication in PLOS ONE.

Reviewers’ comments

Reviewer #1: The manuscript uses 23 years of data from the largest monitoring program ‘the Caribbean Coastal Marine Productivity program’ (CARICOMP) implemented to quantify chronic long-term changes in oceanographic conditions in coastal habitats (coral reefs, seagrass, mangroves) of the wider Caribbean such as local (water quality decline) and global (increase in seawater temperature due to climate change) stressors. While data supports a decline in water quality variables such as visibility due to local stressors (mainly correlated to an increase in local human population), evidence for an impact of global stressors (increase in seawater temperature) is less clear. The latter is mainly explained by the lack of a consistent measuring method of in situ seawater temperature throughout the Caribbean (if I understood this correctly). The major advantage of using this dataset to inform on the state of Caribbean coastal habitats is that it is long-term. On the other hand, only visibility and seawater temperature have been recorded which the authors use to infer on local and global stressors but don’t compare these data to the actual state of corals, seagrass and mangroves. Salinity has been recorded and is included in the data supplementing the manuscript but no analyses have been undertaken. The manuscript will be much stronger if these physical variables measured would be set in context to the state of the ecosystems e.g. decrease in benthic cover through time.

We understand the reviewer is curious about linking this data with the state of coastal ecosystems in the Caribbean but tackling that question would represent a totally different manuscript. We believe we are asking an interesting research question that is self-contained and warrants a paper by itself. Furthermore, the trajectories of coastal ecosystems in the basin would not only be influenced by long-term trends in temperature and turbidity (variables measured here), but also by short term disturbances, and more importantly, other variables not measured by the CARICOMP network, such as management interventions, which have shown to have a disproportionate influence in the health and resilience of local systems in the basin (e.g. Jackson et al. 2014).

> Jackson JBC, MK Donovan, KL Cramer, VYY Lam, RPM Bak, I Chollett, SR Connolly, J Cortés, P Dustan, CM Eakin, AM Friedlander, BJ Greenstein, SF Heron, T Hughes, J Miller, PJ Mumby, JM Pandolfi, CS Rogers, R Steneck, E Weil, JB Alemu I, WS Alevizon, JE Arias-González, A Atkinson, DL Ballantine, C Bastidas, C Bouchon, Y Bouchon-Navaro, S Box, A Brathwaite, JF Bruno, C Caldow, RC Carpenter, BH Charpentier, B Causey, M Chiappone, R Claro, A Cróquer, AO Debrot, P Edmunds, D Fenner, A Fonseca, MC Ford, K Forman, GE Forrester, JR Garza-Pérez, PMH Gayle, GD Grimsditch, HM Guzmán, AR Harborne, MJ Hardt, M Hixon, J Idjadi, W Jaap, CFG Jeffrey, AE Johnson, E Jordán-Dahlgren, K Koltes, JC Lang, Y Loya, I Majil, C Manfrino, J-P Maréchal, CMR McCoy, MD McField, T Murdoch, I Nagelkerken, R Nemeth, MM Nugues, HA Oxenford, G Paredes, JM Pitt, NVC Polunin, P Portillo, H Bonilla-Reyes, RE Rodríguez-Martínez, A Rodriguez-Ramirez, BI Ruttenberg, R Ruzicka, S Sandin, MJ Shulman, SR Smith, TB Smith, B Sommer, C Stallings, RE Torres, JW Tunnell, Jr., MJA Vermeij, ID Williams, JD Witman (2014) Part I: Overview and synthesis for the wider Caribbean region. Pp. 55-114 In: Jackson JBC, MK Donovan, KL Cramer, VV Lam (editors) Status and Trends of Caribbean Coral Reefs: 1970-2012. Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland.

I can’t comment on whether the statistical analyses are valid but would recommend the authors to do a better job explaining these for the unspecialised reader.

We have expanded the methods section to explain the methods in more detail. Please see some of the relevant sections below, new text in italics:

On mixed effects models and Satterthwaite’s approximations:

> “Simple mixed effect models for the assessment of differences among habitats *(fixed factor)* including all stations *(as random factor)* were fitted with the R package lmerTest [25], which provides additional F statistics and p-values for factors calculated based on Satterthwaite's approximations. *Satterthwaite’s method allows calculating the denominator degrees of freedom as a function of the variance of the parameter estimate [26], and therefore estimating significance in mixed effect models which is generally problematic [27].”*

On seasonality in the nonlinear model:

> “Where the temperature at time t in months is a function of a constant term μ, a seasonal component *with sinusoidal form* S_t, a linear trend ω of rate °C year^{-1}, and residuals N_t. In this model, the seasonal component *is allowed to include up to two cycles, and* is described by the formula: …”

On temporal autocorrelation in the nonlinear model:

> “And the residuals have an AR-1 autocorrelation form*, the simplest form of autocorrelation (aka, the similarity between a time series and a lagged version of itself).* That is, the residuals at time t are a function of the residuals at time t*-1 (i.e. the temporal “memory” of the time series has a one month lag)*, depending on the station-specific autocorrelation parameter Φ, along with the noise (ϵ_t):”

In addition, I think, rather than to state that these data are available now, the authors should explain how the CARICOMP data can be used to improve conservation and management of these ecosystems

We included a paragraph with this information (copied below) which makes an excellent addition to the discussion (thanks!)

> “CARICOMP’s environmental dataset provides an invaluable baseline that can be used to strengthen research, conservation, and management of coastal ecosystems in the Caribbean basin. In the first place, the dataset provides context for other local studies, aiding comparisons and understanding of observations at single locations [67]. CARICOMP’s environmental measurements also provide a powerful in situ dataset to help improve satellite observations in coastal areas, where accuracy is currently limited [15]. In addition, in situ CARICOMP datasets can help ground truth environmental reconstructions of coastal ecosystems based on geochemical analyses of natural archives (e.g. massive corals). Particularly, calibrations of temperature and salinity proxies can be achieved using CARICOMP data. Such calibrations and reconstructions are indispensable to extend time scales prior to monitoring and instrumental records [68-69] and to infer the magnitude of human-induced impacts within the context of natural variability. Because CARICOMP sites are located in areas with contrasting setting (not only in terms of oceanography but also human influence) the dataset could be used to assess the impact of these potential controls in key physicochemical variables. For example, the CARICOMP data can be useful in identifying and assessing indicators of the long-term effects of Marine Protected Areas (MPA), by comparing sites outside an inside MPAs [e.g. Costa Rica, Colombia, Venezuela: 46, 49,70]. Furthermore, CARICOMP data can be used to assess the impact of disturbances. For example, the dataset has been used to show a relationship between high sea surface temperatures and coral bleaching [e.g. 71]. Finally, CARICOMP environmental data may support models of marine ecosystem dynamics in the Caribbean region which can be translated into applicable inputs for science-based decision-making of recovery, restoration or conservation of these ecosystems.”

– also I am not convinced how this manuscript provides guidelines for a better selection of monitoring sites to detect early warning signals of local and global stressors; the authors would have to discuss this further and/or provide evidence where this has been done for comparable datasets. I'd suggest implementing a table summarising the pros and cons for each site and conclude whether to consider a particular site for ongoing monitoring to detect early warning signals and why.

We discussed this issue further but we didn’t provide a table as suggested by the reviewer. Indicating which the best sites within the CARICOMP network are is not a trivial task, because other factors not taken into account for this work (presence of gaps in the data, changes in personnel conducting measurements) can also affect the quality of the trends and therefore the choice. We feel that including such a table without considering all the aspects is somewhat irresponsible (we would be suggesting dropping monitoring at certain sites with incomplete information!) and outside the scope of this paper: this was an element of the discussion, after all. However, we agree with the reviewer that the subject would benefit with an extended discussion. The relevant paragraphs are copied below, new text in italics. Additionally, we included the information of Figure 6 as supplementary by expanding tables S3-A and S3-B to include the residuals and the number of years needed per station and called the supplementary material within the text.

> "…Low precision of *in situ* measurements due to external influences [*such as changes in sampling methodology, observers, instrumentation, or gaps in the time series: 27, 53]* could also increase variability and limit the ability to detect trends. Besides the issue of increased variability, the inability to detect trends might be related to the length of the CARICOMP time-series (from three to 22 years). This timeframe can be insufficient to provide enough statistical power to assess long-term changes in temperature due to intrinsic characteristics of the location, particularly in stations where the magnitude of the trend is small, the memory (i.e. temporal autocorrelation) is high or temperature is especially variable [27].
>
> Site-specific information on the inherent characteristics of the time-series can be used to aid in the identification of monitoring sites that are cost-effective in the sense that they are able to detect trends earlier [27], if the detection of early changes is the main objective of the monitoring. Significant trends will be faster to detect in sites characterized by low variability and temporal autocorrelation of the noise, which is a measure of the 'memory' or inertia of the time-series. For example, within in the CARICOMP network, the time period to detect an expected change varies greatly among stations (Fig 6, *Table S3-A*). Within this dataset, Puerto Morelos in Mexico might be a good location to identify trends in temperature early, while the seagrass meadow and mangrove stations in Eastern Venezuela might need the longest sampling (Fig 6, *Table S3-A). This result is not rare: research in atmospheric [27] and oceanographic [54, 55] science has shown that for most expected environmental changes, several decades of high-quality data may be needed to detect significant trends. For example, many years of continuous data were needed to distinguish a climate change trend in pH and sea surface temperature (about 15 years), chlorophyll concentration and primary production (between 30 and 40 years) from the background natural variability [54, 55]. The process of deciding which site can be useful for future detection of trends is very similar to conducting power analysis to estimate the number of samples needed to detect a particular effect. This type of analysis can be done if the data has already been collected (as in the example in Fig 6) or before collecting the data assuming a range of effect sizes, autocorrelation, and noise [27] and taking into account any external forces that might be affecting the accuracy of the data [see previous paragraph: 53].* This information can be used to set realistic expectations on trend detectability at different sites. It could also help select sites for further monitoring of chronic impacts [56]*, where trends can be detected sooner, after taking other considerations into account such as the relevance of the site to answer the focal scientific question, or logistic factors such as accessibility and maintenance of the monitoring site, which are also important."*

This manuscript is well written and is based on a significant dataset – and after a thorough revision by the authors - will be of great interest not only to the scientific community but also to environmental managers in the Caribbean.

Thank you!

General comments:

Water quality, especially for coastal marine habitats, is described by a multitude of environmental variables such as content of dissolved oxygen, concentration of inorganic nutrients, environmental pollutants, biological oxygen demand as an indicator of eutrophication, particulate / dissolved organic matter among others. Turbidity is just but one variable – at most, it can be indirectly used to make conclusions on overall water quality.

We had acknowledged in the methods that turbidity is just a proxy for water quality, now we added a sentence expanding the issue even further (new text in italics).

> “Secchi depth is strongly correlated to the amount of particulate material in the water column and it has been used as a cheap, fast, and simple proxy for visibility and water quality [24]. *We are aware, however, that this is only one of the multiple environmental variables that characterize water quality at a site, and that a full assessment of this component would require also the measurement of other variables (e.g. concentration of nutrients, pollutants, dissolved matter).*

I would advise the authors to be careful when using turbidity as sole indicator to deduce a decline in water quality since an increase in turbidity has also been reported as beneficial in times of intense coral bleaching e.g. Guest et al. 2016.

Refs:
Guest, J. R. et al. Coral community response to bleaching on a highly disturbed reef. Sci. Rep. 6, 20717; doi: 10.1038/srep20717 (2016).

Fair point, but we would like to remind the reviewer that we’re looking at long-term patterns of increase, not at pulse events, which could have limited beneficial effects to **some** coastal ecosystems if co-occurring with other disturbances.

Specific comments:

Abstract:
Data sharing, especially from long-term monitoring, is crucial for environmental management. Instead of stating that CARICOM data is now openly available, I would like the authors to rather put into context what the availability of data means for the future of Caribbean coastal marine habitats.

We edited the final sentence in the abstract, which now reads (new text in italics):

> “All CARICOMP environmental data are now available, *providing an invaluable baseline that can be used to strengthen research, conservation and management of coastal ecosystems in the Caribbean basin*.”

Line 131-133: Rather than referring to the literature and R packages, the authors are advised to provide more information on the reasoning behind choosing these methods e.g. what is a brief and simple explanation of the Satterthwaite's approximation and why is it important for the analysis of trend information? This will enhance readability and understanding of the reader especially if they are no experts on trend analyses. Keep in mind, PloS ONE is an open access journal - your readership will contain a large proportion of managers who will be very interested in your long-term data but I doubt that they will be experts on trend analyses.

As indicated above, we have expanded the methods section to explain the methods a bit more, including the rationale behind using the Satterhwaite’s approximation. We believe with these changes we are providing enough detail to allow “*suitably skilled investigators* to fully replicate your study” as stated in PLOS ONE guide for authors (our italics).

Line 135-137: It would be interesting to know what proportion of the overall data actually complied with the requirements of a minimum of 3 monitoring years and 30 monthly records.

Fair point. This information was included in the results but we have now also included it in the methods. Please see the relevant text below, new text in italics:

> "To ensure meaningful quantification of a linear trend, only stations with data for at least three years and a minimum of 30 monthly records were included in subsequent analyses (*60% of the sites*: Table 1, Fig 1)."

Line 165: Parameters and source of formula need to be described.

We included the information, see below (new text in italics):

> "In this model, the seasonal component *is allowed to include up to two cycles, and* is described by the formula:
>
> $$S_t = \sum_{j=1}^{4} \beta_{1,j} \, sin \frac{2\pi jt}{12} + \beta_{2,j} cos \frac{2\pi jt}{12} \quad (2)$$
>
> *Where t is the number of months, and β are parameters to be estimated."*

Line 167: What is an AR-1 autocorrelation form? Please describe and provide references to the literature.

We complemented the information as shown below, new text in italics

> "And the residuals have an AR-1 autocorrelation form*, the simplest form of autocorrelation*. That is, the residuals at time t are a function of the residuals at time t-1 *(i.e. the temporal "memory" of the time series has a one month lag)*, depending on the station-specific autocorrelation parameter ϕ, along with the noise [ϵt, 27]:"

Line 300: Suggest using different titles in Methods and Results part for 'Explaining Trends'

We replaced the title of this section by "*Correlates of global and local-scale changes*"

Comment on salinity: you describe how salinity was measured and provide salinity data in your dataset added to supplement the publication. Yet, you do not perform any analyses regarding salinity which focus largely on explaining trends in temperature and visibility. You will need to justify why these data were provided but not analysed – or alternatively, integrate salinity into your analyses.

We are sorry for the confusion. We did not analyze salinity because it does not provide any relevant information given our objectives: assessing local and global-scale changes. We did include it in the methods, however, because it was also measured by CARICOMP and we wanted to release the entire dataset.

We have now explained this succinctly. The relevant text is copied below:

> "*Although information from all three variables in included in the appendix, to address the aims of this research only temperature and secchi data were analyzed*".

Comment on data file and trend analysis: You state that seawater temperature has been measured differently throughout time and between the different stations – this is what I understand from 'inherent variability of CARICOMP's in situ measurements [of temperature].' in Line 51 of your abstract. I did not find an explanation of this issue within the manuscript body (have I misunderstood or overlooked something?). Is it possible to track down how temperature was measured for each record and add an additional field in the dataset on 'Method used for measurement? My concerns here are that your trends will be confounded if you use time-series data for which the methods have changed between sites and through time. One of the fundamental assumptions of trend analysis is that time-series data has been taken by the exact same methodology and using a standardised monitoring – if the methods change, you will be comparing different units e.g. apples with oranges. I recommend the authors to explore a way of performing a trend analysis for temperature based on data taken by the exact same method. I assume, visibility/turbidity was measured by Secchi disk since this is the most common, easy and cheapest method – so that one should be fine.

We are sorry this caused confusion. This is not true. Temperature was measured in the same way through time, what is *naturally* variable is temperature per se. We rephrased the sentence to make this clear

> "On the other hand, only 18% of the stations showed increases in water temperature that would be expected from global warming*, partially reflecting the limits in detecting trends due to inherent natural variability of temperature data.*"

Figure 2: Does it make sense to report boxplots with medians, quantiles and outliers for regions where you have extreme changes due to natural seasonality in comparison to other locations where seasonality is not that pronounced? E.g. due to seasonal upwelling at the Colombian site 'Chengue', water temperature has been reported to change between 20 and 31°C (Salzwedel & Müller 1983 or more recently Bayraktarov et al. 2014). In fact, you can see these large seasonal changes also in your Figure 4. I would rather like seeing these boxplot diagrams drilled down to seasons to show the variability in temperature for the different seasons through time. Same may apply for visibility and Figure 3.

Figures 2 and 3 are only there to show the reader the data for all stations, to give them a "feel" for the data that is being released with this paper. Adding multi-panel figures with each of 4 seasons would require 20 figures, about five entire pages (!), which we do not believe is reasonable given that there are no particular objectives associated to these figures. This of course could be done if the editor believes is needed.

Refs:

Salzwedel H & Müller K (1983) A summary of meteorological and hydrological data from the bay of Santa Marta, Colombian Caribbean. Anales del Instituto de Investigaciones Marinas de Punta de Betín, 13, 67–83.

Bayraktarov E, Pizarro V, Wild C (2014) Spatial and temporal variability of water quality in the coral reefs of Tayrona National Natural Park, Colombian Caribbean. Environmental Monitoring and Assessment, 186, 3641–3659.

Figure 5: The CARICOMP dataset is available for the time between 1992 and 2015 but you used change in human population for the time interval between 1990 and 2000 to explain increase/decrease in visibility trends. I am wondering whether this mismatch in time periods that do not overlap entirely with your data will influence how much of the trend in visibility you can explain? Depending on data availability, I would recommend the authors to redo the analyses with data on human population change between 1990 and 2015 (if possible).

Actually this data range better coincides with the length of CARICOMP timeseries. To illustrate that, we added the dates into Table I and specified it in the methods when talking about the human population dataset (paragraph below, new text in italics):

> "Gridded human population density data for the years 1990 and 2000 (the most recent dataset available at that spatial detail) were obtained from the Global Rural-Urban Mapping

> Project, Version 1 [GRUMPv1: 39]. *These years coincide with most of CARICOMP sampling took place between those decades, with time series beginning in average in February 1994 and finishing in average in September 2007 (Table 1).”*

Additionally, as indicated in the methods, the most recent data on human population density at the required spatial resolution is for the year 2000. After that year the only option would be to use modeled data (http://sedac.ciesin.columbia.edu/data/set/gpw-v3-population-density-future-estimates) which is fundamentally different and would prevent a fair comparison with 1990’s data and calculating rates of increase.

General comment on the outcome: in the discussion, you state that Puerto Morelos would be a good site to detect early changes in trends while for Eastern Venezuela, more time would be required for detection of any changes. If you were asked to provide a recommendation for program managers, for which sites would you recommend continuing the monitoring and with what sampling frequency? Can you sum your practical recommendations for managers e.g. in a nice table outlining pros and cons of each site that could help them to make decisions?

This echoes a previous suggestion by this reviewer. With the information we have, is not possible to make black and white recommendations regarding if to keep a monitoring site, and we believe that doing so would be irresponsible and misleading. As stated now in the discussion (see response to comment above) the value of each site also depends on exogenous factors (e.g. data quality, changes in observers, logistics) and a thorough assessment of the value of each site including all those aspects would need to respond in a satisfactory manner to this question. We included that information in the discussion.

I hope you find my comments fair, useful and constructive and some of my suggestions will help to improve your manuscript significantly as well as increase the numbers of your readers.

Thanks for the comments. They were very constructive, although ambitious!

Reviewer #2:

Overall comments:

Overall, this manuscript is very well structured, presented and written. The CARICOMP dataset represents an exceptionally valuable record of changes in the Caribbean at substantial spatial and temporal scales. The authors have used appropriate statistical tests to analyse this data to examine the influence of regional and global scale stressors in the Caribbean basin, using the proxies of turbidity/visibility and temperature to present a concise, technically sound, and well organised study, with conclusions that are supported by the data.

Thank you

The proxies used are good indicators of these different scale stressors, and the authors do recognise and discuss the limitations of the data, however I would suggest not overstating the conclusions on global scale processes based on a single proxy. For the most part the authors have phrased their conclusions well to reflect this understanding, I would suggest possibly rephrasing the statement in the abstract in lines 49-51 to avoid inferring that the study area is not experiencing global-scale chronic stress: “…only 18% of the stations showed increases in water temperature that would be expected from global warming, reflecting limited evidence of global-scale chronic stress…”.

We understand it’s a delicated topic… and we rephrased the sentence in the abstract as suggested. The sentence now reads:

> “only 18% of the stations showed increases in water temperature that would be expected from global warming, partially reflecting the limits in detecting trends due to inherent natural variability of temperature data.”

It is not necessary, but it might be useful to broaden the discussion of the results slightly to expand on what the potential uses of such an exceptional dataset might be in practical terms e.g. in supporting/guiding management.

We included a paragraph on the subject on the discussion, which we copied below:

> “CARICOMP’s environmental dataset provides an invaluable baseline that can be used to strengthen research, conservation, and management of coastal ecosystems in the Caribbean basin. In the first place, the dataset provides context for other local studies, aiding comparisons and understanding of observations at single locations [67]. CARICOMP’s environmental measurements also provide a powerful in situ dataset to help improve satellite observations in coastal areas, where accuracy is currently limited [15]. In addition, in situ CARICOMP datasets can help ground truth environmental reconstructions of coastal ecosystems based on geochemical analyses of natural archives (e.g. massive corals). Particularly, calibrations of temperature and salinity proxies can be achieved using CARICOMP data. Such calibrations and reconstructions are indispensable to extend time scales prior to monitoring and instrumental records [68-69] and to infer the magnitude of human-induced impacts within the context of natural variability. Because CARICOMP sites are located in areas with contrasting setting (not only in terms of oceanography but also human influence) the dataset could be used to assess the impact of these potential controls in key physicochemical variables. For example, the CARICOMP data can be useful in identifying and assessing indicators of the long-term effects of Marine Protected Areas (MPA), by comparing sites outside an inside MPAs [e.g. Costa Rica, Colombia, Venezuela: 46, 49,70]. Furthermore, CARICOMP data can be used to assess the impact of disturbances. For example, the dataset has been used to show a relationship between high sea surface temperatures and coral bleaching [e.g. 71]. Finally, CARICOMP environmental data may support models of marine ecosystem dynamics in the Caribbean region which can be translated into applicable inputs for science-based decision-making of recovery, restoration or conservation of these ecosystems.”

The English is good throughout the paper for the most part, but I have provided minor corrections mostly related to grammar, and suggestions for rephrasing to improve readability. Besides these very minor editorial corrections, I feel that the manuscript is appropriate and ready for publication.

Thanks!

Specific comments:

- The sentence in lines 66-68 is cumbersome, and would benefit from being rephrased, simplified, or split into two sentences.

We split the sentence in two:

> “Such a strategy provides information that informs identification of threatened areas and provides potential explanations for and predictions of ecosystem responses. A long-term

> approach also allows the assessment of progress towards management objectives and planning for mitigation or adaptation accordingly [5]."

- Oxford commas missing after 'and' in numerous sentences, e.g. lines 68, 101, 110, 246, 292, 301, 330.

We reviewed the document and added commas when missing

- Lines 135 – 137: To improve clarity of the text, I would suggest potentially rephrasing the sentence to read: "To ensure meaningful quantification of a linear trend, only stations with data for at least three years and a minimum of 30 monthly records were included in subsequent analyses (Table 1, Fig 1)."

We edited the sentence as suggested. It reads better now.

- Lines 145 – 146: It is very minor, but the legend for Fig 1. Would read better with the inclusion of "Map of CARICOMP stations showing significant increases…"

We edited the sentence as suggested.

- Line 152: "…are common proxies for changes at both scales"; suggest substituting "each scale" to make it clearer that each variable measured applies to its' respective scale and not to both global and local scales.

We edited the sentence as suggested.

- Line 167: I would suggest including the full text for AR-1 when mentioning it here for the first time.

We expanded the text when mentioning the autocorrelation (new text in italics)

> "And the residuals have an AR-1 autocorrelation form*, the simplest form of autocorrelation (aka, the similarity between a time series and a lagged version of itself)*. That is, the residuals at time t are a function of the residuals at time t-1 (i.e. the temporal "memory" of the time series has a one month lag), depending on the station-specific autocorrelation parameter ϕ, along with the noise (ϵt, 27):"

- Line 246: Consider rephrasing the sentence "Data are still being collected at some stations today.", to read "Data collection is ongoing at some stations."

We rephrased the sentence as suggested.

- Lines 259-275: It is not clear from the methods text or figure legends what time period is covered by the data presented in figures 2 and 3. Is this from 1992 until present? If so, it would be worth explicitly stating this in each figure legend.

We included this information in the legend, which reads:

> "all data are presented, including all years (i.e. since 1992) and all stations, with and without long-term (> 3 years) data"

- Line 277: The authors state that 60% of stations had sufficient long term data for inclusion in subsequent analyses. It might be useful to highlight/mark (e.g. with asterisk) these stations in figures 2 and 3 to aid readers' interpretation of the data and analyses.

Good idea. We added this into the figure and this sentence to the caption: “Sites with an asterisk were included in subsequent analyses.”

- Line 281-282: I would suggest qualifying this statement with a reference to the fact that this is based on the two proxies chosen. I would assume that there may well be evidence of global-scale change within the dataset, even if not specifically evident as a warming trend in the temperature data.

We edited the sentence and added the specifics; see the text below (new text in italics)

“Data collected by the CARICOMP network offered evidence of widespread local, but not global-scale changes across the wider Caribbean *using visibility and sea temperature as proxies*.”

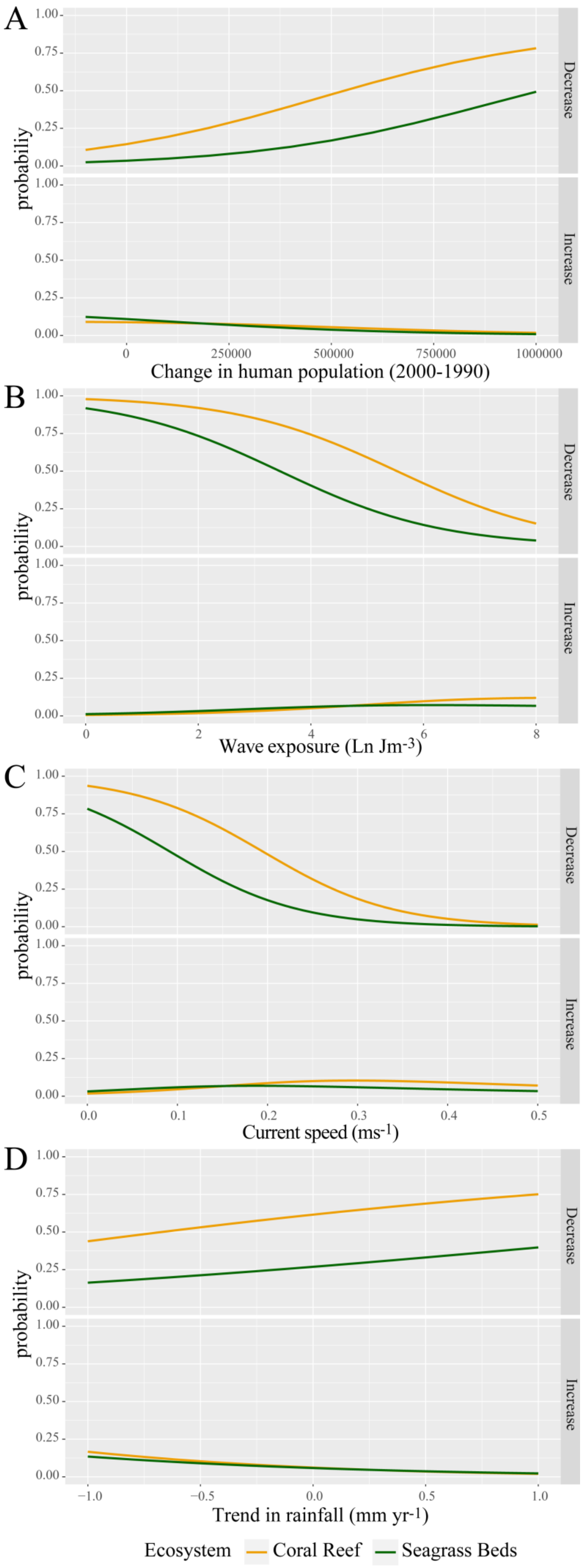
- Line 301: “…was not explained by any of…” – substituted ‘either’ for ‘any’, as there are only two variables. It would also aid readers if the two local factors assessed (wave exposure, current speed) were mentioned in this sentence.

We edited the sentence as suggested. It now reads:

> “The presence of negative, positive, or non-significant trends in temperature was not explained by *either* of the two local factors assessed (*wave exposure and currents,* multinomial regression, p > 0.05 for both variables).”

- Figure 5: It is difficult to distinguish the two lines in each panel denoting ecosystem type (i.e. coral reef vs seagrass beds). It would be beneficial to either use colour or different line types (e.g. dashed, solid) to make the difference more distinct for readers.

In general we like to keep most figures in B&W because people keep printing papers, but the reviewer is right. We edited the figure so the difference between the habitats is more contrasting now, please see the new version below.


A
B
C
D
probability
Decrease
Increase
1.00
0.75
0.50
0.25
0.00
0
250000
500000
750000
1000000
Change in human population (2000-1990)
0
2
4
6
8
Wave exposure (Ln Jm-3)
0.0
0.1
0.2
0.3
0.4
0.5
Current speed (ms-1)
−1.0
−0.5
0.0
0.5
1.0
Trend in rainfall (mm yr-1)
Ecosystem
Coral Reef
Seagrass Beds

Discussion:

- Line 328: “However, already 15 years ago it was suggested…” - change word order to “However, 15 years ago it was already suggested…”

Done!

- Line 334: “along” should rather be “in”, and similarly in line 336 I would use “throughout” or “in” given the non-linear layout of coastlines within the Caribbean basin.

We included both changes

- Line 352: “will be faster to detect in sites” -> “…will be detected faster at sites…”

Done

- Line 354 (and Figure 6): the discussion of this finding regarding the time period required to detect changes at particular stations is interesting and valuable, however these results on autocorrelation (and Fig. 6) should be first presented in the results section, and then only referred to and discussed within in the discussion section.

Because this is not related to any of the objectives, and is truly a matter of discussion (i.e. it argues about the strength of the results) we decided to leave this figure in the discussion. We know is not very traditional to include figures in the final section, but after all, what a more objective way of discussing your results than with a quantitative exercise?

- Line 379-380: “…also provide advice for the identification of…” -> “… can also assist in the identification of…”

Done

Referencing:
- Several references contain “[Internet]” (e.g. 5, 6, 7, 14). I am not sure whether this is a link that has been lost in my pdf version of the manuscript or an automated error that has crept in via a reference manager.

This was an error introduced by the reference manager. We deleted all that text now.

Based on the current reference formatting guidelines for PLoSOne, and recent publications in the journal, it appears that the reference formatting in this manuscript needs some minor updating throughout:
- The month and date of publication are not required for standard referencing of published academic articles. (e.g. line 415, line 417 etc), only for references where the DOI number is provided as an alternative to the traditional volume and page numbers.
- According to the journal’s reference formatting guidelines, it appears that a space is required after the colon following the volume number, which is lacking in most references (e.g. lines 415, 417, 434 etc). However, I recognise that there has been some flexibility around this formatting in recent articles published by the journal.

Thanks for the heads up. We were using Zotero as reference manager, but we now edited by hand all references to agree to the journal’s format.

Reviewer #3:
Comments for Author – PONE-D-03684
Chollett et al “Widespread local chronic stressors in Caribbean coastal habitats”
This manuscript has collated and analysed data available from the Caribeean Coastal Marine Productivity program (CARICOMP). These data are the longest and largest monitoring program in the wider Caribbean. The results reveal changes in water quality conditions, over time, and the authors believe this is due to human land use changes.
Comments provided:
• the summarization of data – the authors claim to have taken monthly averages calculated from the weekly data for each station. Immediately this presents problems as the generalization of the data could in fact contribute to overlooking important data points in the time series (for example, a rainfall event could become overlooked);

We agree that monthly means could mask pulse events. However, we would like to remind the reviewer that we’re looking at long-term patterns and not at pulse disturbances, and therefore including summaries does not represent a problem. Using summaries (particularly to get rid of those small or “low frequency” events) is a common and robust approach when analyzing time series in this context (e.g. Weatherhead 1997, Good et al. 2007) and is the approach followed by work cited in the last IPCC report for the detection of climate change effects (e.g. Palmer et al. 2009; Pierce et al. 2012).

> Good SA, GK Corlett, JJ Remedios, Ej Noyes, DT Llewellyn-Jones. 2007. The global trend in sea surface temperature from 20 years of advanced very high resolution radiometer data. Journal of Climatology. 20: 1255-1264
> Palmer MD, SA Good, K Haines, NA Rayner, PA Scott. 2009. A new perspective on warming of the global oceans. Geophysical Research Letters. 36: L20709
> Pierce DW, PJ Glecker, TP Barnett, BD Santer, RJ Durak. 2012. The fingerprint of human-induced changes in the ocean’s salinity and temperature fields. Geophysical Research Letters. 39: L21704
> Weatherhead EC, Reinsel GC, Tiao GC, Meng X-L, Choi D, Cheang W-K, et al. Factors affecting the detection of trends: Statistical considerations and applications to environmental data. J Geophys Res Atmospheres. 1998;103(D14):17149–61.

• There is no indication if these water quality data represent surface or are depth integrated? This is very important when considering water temperature (which the authors present) given water temperature can be thermally stratified.

We specified this in the text. The relevant paragraph is copied below, new text in italics:

> “Visibility was measured with a Secchi disk in seagrass (measured horizontally 0.5 m below the surface, *as these habitats are often too shallow for a standard vertical measurement*) and reef habitats (typically measured *vertically* over the drop-off)*, and can be assumed to indicate water quality at the surface.*”

• There is no indication if these water quality data were standardized to the same time each day – e.g. morning water temperature would be very different to afternoon temperature.

This was already specified in the text. The relevant paragraph is copied below:

> “Weekly (whenever possible) physical measurements were taken at each station between 10:00 and 12:00 local standard time.”

• Secchi disk measurements provides important insight in to the light attenuation in the water column, which is important for sensitive receptor habitats (such as corals and seagrass). Here secchi depth was measures horizontally at a depth of 0.5m – this requires more detailed explanation why 0.5m and whether horizontal provides a better measure of light attenuation compared to vertical secchi depth?

We specified this in the text. The relevant paragraph is copied below (new text in italics). Although the way visibility is measured in reefs and seagrass beds is different, this does not represent a problem in our analyses given that we are not mixing data from different habitats:

> "Visibility was measured with a Secchi disk in seagrass (measured horizontally 0.5 m below the surface, *as these habitats are often too shallow for a standard vertical measurement*) and reef habitats (typically measured *vertically* over the drop-off)*, and can be assumed to indicate water quality at the surface.*"

- The manuscript requires more detail to justify the assumptions and rules made – for example, line 2018, a buffer of 1 degree diameter around each station – what is the basis for this and how sensitive is this criterion to changes?

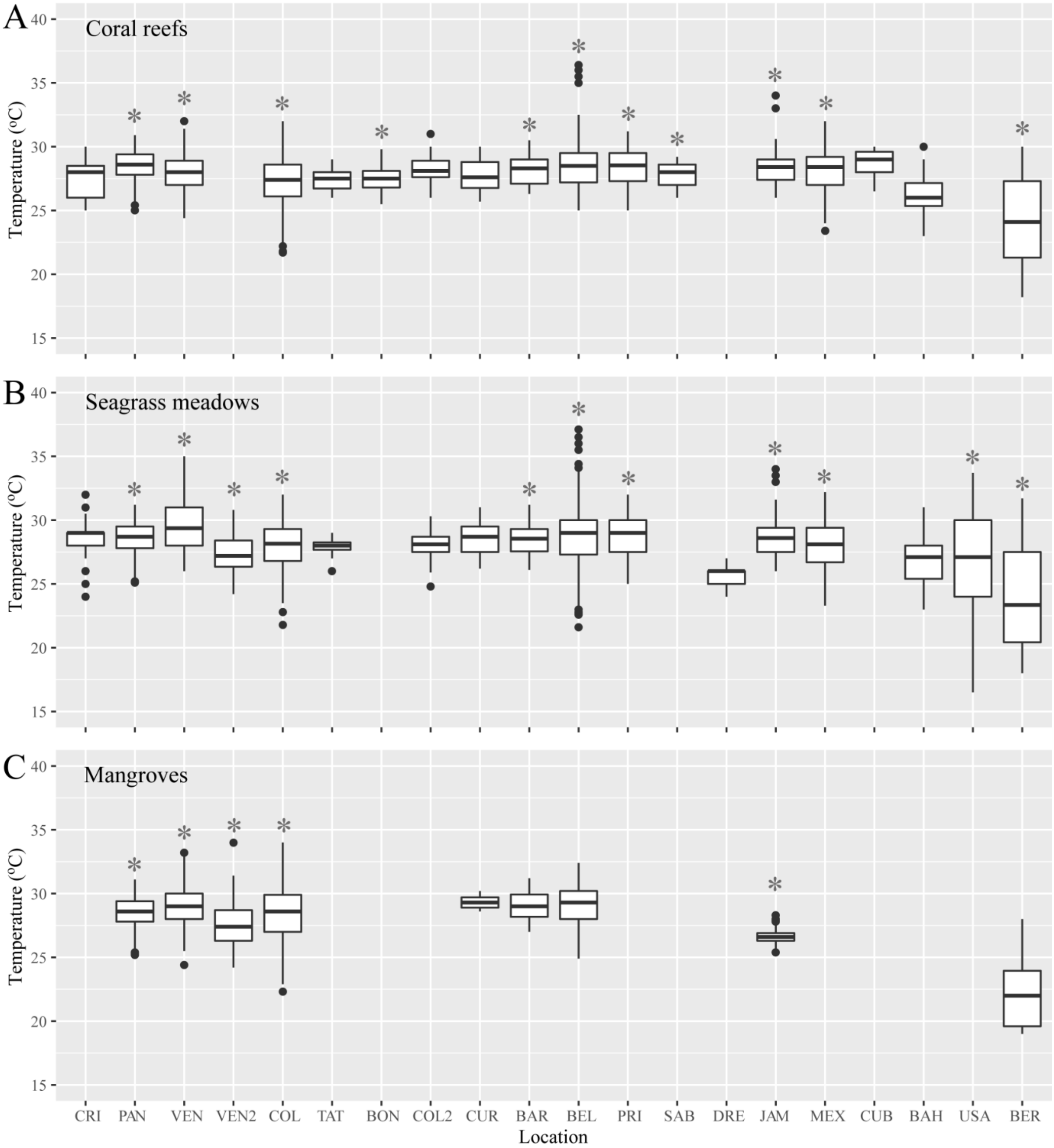
The methods section has improved considerably and is now more self-explanatory also thanks to the comments from other reviewers. Regarding this specific issue, we are following the approach of a piece of research recently published in Nature. We included the information below:

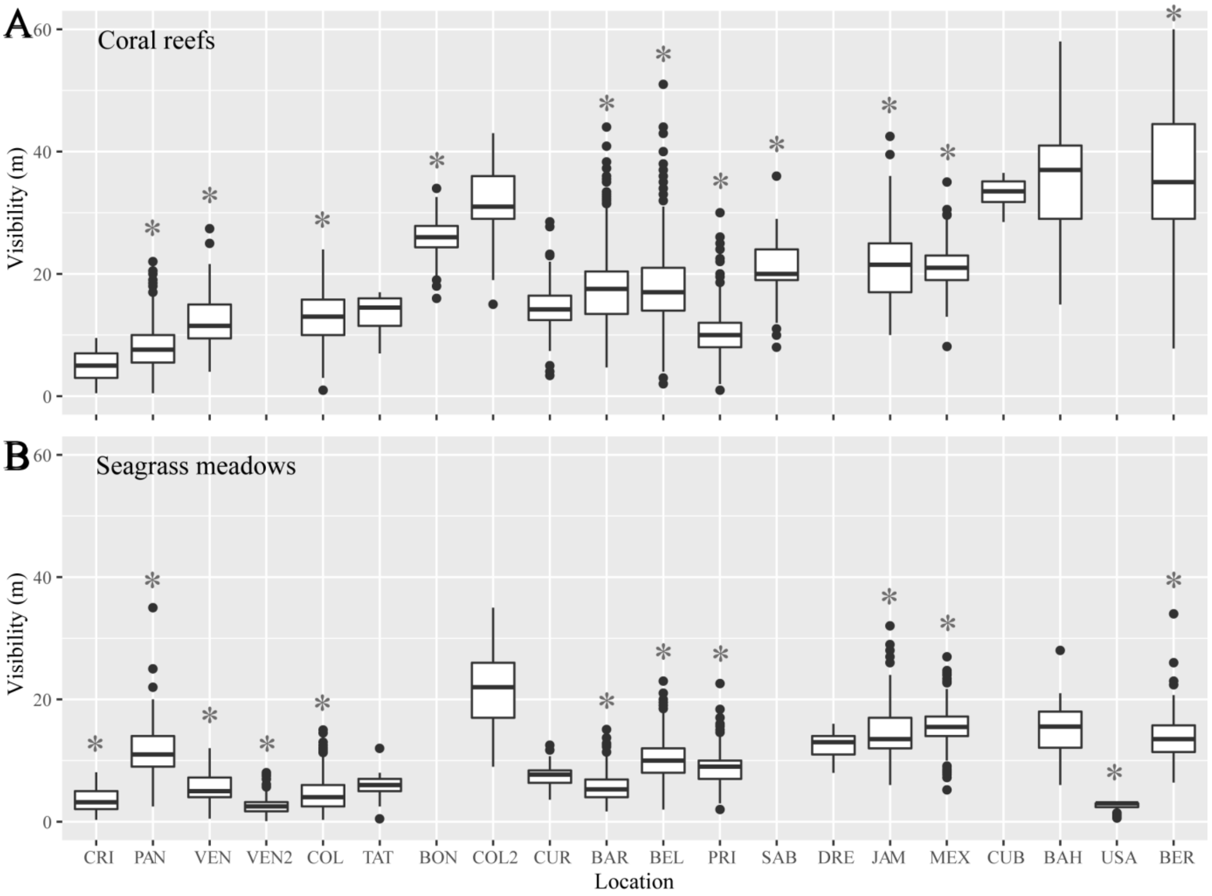
> "A one degree buffer was considered as a reasonable range at which many human impacts might affect coastal ecosystems, as it has been shown before [41]."
>
> 41. Cinner JE, Huchery C, MacNeil MA, Graham NA, McClanahan TR, Maina J, Maire E, Kittinger JN, Hicks CC, Mora C, Allison EH. Bright spots among the world's coral reefs. Nature. 2016 Jul 21;535(7612):416-9.

Furthermore, moderate changes in buffer size produce a similar metric: when extracting population density data around the CARICOMP sites with a buffer of 0.5 and 1.5 degrees, correlation with data extracted using a 1 degree buffer is very high (0.70 and 0.85 respectively) and the variable is still significant ($p>0.05$) in the multinomial model, indicating our results are robust to changes in this variable.

- Line 248 – why present median temperature data when you have used average monthly (based on weekly data records). This inconsistency presents some confusion

We used average monthly data to calculate trends which was a separated analysis. However, to satisfy the reviewer, we redid the figures using averages instead of medians. The figures are qualitatively identical, and copied below.


A
Coral reefs
B
Seagrass meadows
C
Mangroves
Temperature (ºC)
40
35
30
25
20
15
CRI
PAN
VEN
VEN2
COL
TAT
BON
COL2
CUR
BAR
BEL
PRI
SAB
DRE
JAM
MEX
CUB
BAH
USA
BER
Location



- Term “Global” and “Local” is not clear

We made a further effort to define those terms in the introduction. Please see the relevant text below:

> “Here we use the terms global and local to define scales of action of anthropogenic stressors, ranging from disturbances acting on broad spatial scales, such as ocean warming, to those acting at very localized scales, such as dredging [1,2].”

- Line 325 – a change in water quality conditions (over 15yrs of monitoring) is a very central point in these data, and requires more detailed assessment and discussion. Why is this important, how is this important and what can be done to address the problem contributing to poor water quality?

Good point. We included a paragraph on the subject in the discussion, which we copied below:

> “Chronic decreases in coastal water quality can be linked to the increase in marine diseases [62] and the demise of seagrass [63] and coral reef ecosystems [57]. Furthermore, declines in water quality have been linked to economic losses such as decreases in property value and tourism revenues [reviewed in 64]. Results presented here pinpoint areas that might require management interventions. Such interventions may include identifying the cause of decreased water quality, and implementing changes in management practices and long-term commitments towards change. Improving water quality could also have the added benefit of improving resilience of coastal ecosystems to other disturbances, such as climate change [65,66].”

- Line 336 – lack of signal in the CARICOMP time series – how much more data would be necessary to detect a signal, it seems these data are comprehensive enhance the reason for this study, but there still might not be sufficient data? This is not clear.

We expanded the discussion to tackle this issue and make it clearer. The relevant paragraph is below:

> "…For example, within in the CARICOMP network, the time period to detect an expected change varies greatly among stations (Fig 6, *TableS3-A*). Within this dataset, *given the variability and memory of the time-series,* Puerto Morelos in Mexico *would need the shortest sampling to identify changes in temperature early*, *and might be a good location* to identify trends in temperature early. *On the other hand* the seagrass meadow and mangrove stations in Eastern Venezuela might need the longest *time series to detect a significant trend* (Fig 6, *Table S3-A). This result is not rare: research in atmospheric [27] and oceanographic [54, 55] science has shown that for most expected environmental changes, several decades of high-quality data may be needed to detect significant trends. For example, many years of continuous data were needed to distinguish a climate change trend in pH and sea surface temperature (about 15 years), chlorophyll concentration and primary production (between 30 and 40 years) from the background natural variability [54, 55]. The process of deciding which site can be useful for future detection of trends is very similar to conducting power analysis to estimate the number of samples needed to detect a particular effect. This type of analysis can be done if the data has already been collected (as in the example in Fig 6) or before collecting the data assuming a range of effect sizes, autocorrelation, and noise [27] and taking into account any external forces that might be affecting the accuracy of the data [see previous paragraph: 53].* This information can be used to set realistic expectations on trend detectability at different sites. It could also help select sites for further monitoring of chronic impacts [56], *where trends can be detected sooner, after taking other considerations into account such as the relevance of the site to answer the focal scientific question, or logistic factors such as accessibility and maintenance of the monitoring site, which are also important.*

- Figure 4 – I question the use of a straight line fit to these data, there is much scatter in the data and therefore it is not clear if the pattern shown in the figure are actually true.

As the reviewer pointed out the data actually presents some scatter but the linear fit is significant, which in a statistical sense means the pattern "is true". For Figure 4A, the fit is a mixture of seasonal component (the sinusoidal line) and linear trend (the straight line). Because this might not be obvious to the reader, we included the information in the caption (new text in italics):

> "Fig 4. Time series example. Time series for sea temperature (A) and visibility (B) for the reef at Chengue Bay (Colombia), showing significant increases in temperature and significant decreases in visibility. *For temperature, the model fit takes into account both seasonality (sinusoidal line) and a linear trend (straight line)."*

- There are numerous errors in the manuscript that require closer attention. In addition, the manuscript changes between American and English spelling (Line 151 analyses, line 192 characterised).

We're sorry to hear that. We revised the lines mentioned by the reviewer but we could not detect any issues: "analyses" in the context of the text is a noun and is appropriate in both American and British English, and we used "characterized" (American spelling, as in the rest of the document) in line 192. We reviewed the manuscript for inconsistencies in spelling and grammatical issues, some which have been kindly highlighted by reviewer 2. We believe the manuscript has improved with the revision.

Comments from the editor

The authors have offset reference numbers in the text with parentheses, but the PLoS format is to use square brackets so please change throughout manuscript.

We were using zotero and PLoS style, we're bummed the referencing had issues. We have changed them all by hand

Line 56: Should be ‘data are now available’

We corrected the text (sorry!)

Line 62: Should read ‘…broad spatial scales, such as ocean warming, to those acting at very localized scales, such as dredging.’

We edited the text as suggested

Lines 66-68: ‘that allows for’ is awkwardly written, as is the whole sentence. I would rewrite.

We edited the sentence and split it in two (also as a suggestion from one of the reviewers). The sentence now reads:

> “Such a strategy provides information that informs identification of threatened areas and provides potential explanations for and predictions of ecosystem responses. A long-term approach also allows the assessment of progress towards management objectives and planning for mitigation or adaptation accordingly [5].”

Line 71: Need a comma before ‘respectively’
Line 72: Should be ‘In’
Line 75L Should be ‘coral bleaching’
Line 78: Need a comma after ‘information’
Line 87: The colon should be a semicolon

We included all these changes and checked the entire document. Thanks for casting an eye over the text.

Line 95: ‘where most valuable ecosystems are located’ sounds a bit strange. Valuable how? There are certainly other valuable ecosystems not in coastal areas so this statement needs to be qualified.

Economically valuable. We added the information to the text.

Line 97: Should be ‘allow for’

Edited

Line 109: I am not sure ‘in situ environmental variables’ makes sense. Aren’t all environmental variable in situ??”

You’re right. We edited the sentence, it now reads:

> “First, quantifying significant changes in these environmental variables over time.”

Line 111: Should be ‘In this study’

Edited

Line 120: ‘anthropogenic sources of disturbance’ such as? Need to be more specific on how site were selected

We edited the sentence to make it specific to CARICOMP’s original idea of an ‘ideal location’ (new text in italics):

> “Effort was made to select stations that specifically avoided anthropogenic sources of disturbance, *particularly coastal development and pollution* [21].”

Line 121: Should be 10:00 and 12:00
Line 122: Delete ‘psu’ as salinity is a ratio and unitless
Line 151: Need a comma after ‘Caribbean’

We included these changes

Lines 277-278: This is a sentence, not a paragraph and seems very out of place

We moved the sentence as the final bit of the previous paragraph

Line 282: Need a comma after ‘changes’

We did not include this change because we don’t think is appropriate. Here you have the sentence again:

> “Data collected by the CARICOMP network offered evidence of widespread local, but not global-scale changes across the wider Caribbean using visibility and sea temperature as proxies”

Line 294: Check how supporting tables and figures are referenced. The submission guidelines note:
Authors may use almost any description as the item name for a supporting information file as long as it contains an “S” and number. For example, “S1 Appendix” and “S2 Appendix,” “S1 Table” and “S2 Table,” and so forth.

Thanks for the clarification. We edited all the references to supporting information

Line 301-302: Again, this is a sentence, not a paragraph.

We merged this sentence with the paragraph below.

Line 308: Should be ‘were more likely’
Line 310: Same as above
Line 311: ‘had a very small effect’
Line 312: ‘were also’
Line 313: ‘were getting drier’
Line 314: were similar’

We changed all these from present to past.

Line 320: I found the Discussion weak and it essentially restates the results. Think there needs to be some revision to make it clear why the results are important and how they can be used.

We have included additional information in the discussion, related to (1) the need of long-time series to detect trends in environmental data; (2) the relevance of the water quality results; (3) how can this dataset be used in the future. We are confident these changes make this section stronger.

Lines 321-323: This paragraph is almost not a real paragraph (2 sentences) and is very weak. Need a strong first paragraph to make it clear what this study found
Lines 325-328: A bit repetitive from the paragraph above

We linked these two paragraphs and removed some of the redundant information to provide a more concise idea. The paragraph is copied below:

> "The longest and most spatially comprehensive in situ monitoring effort in the wider Caribbean provides evidence of widespread local changes within the basin. This is a relatively unexpected result, given that CARICOMP stations were intended to be established in pristine areas under minimal local impacts that could serve as a baseline against which to measure degradation [21]. However, 15 years ago it was already suggested that some stations were under the influence of human activities [22]. Results presented here support this statement, agree with results of localized studies in some of these locations [e.g. 46-50], and indicate that human impacts on coastal habitats are ongoing and pervasive within the Caribbean basin."

Line 328: Delete 'already'

Done

Line 341: Should be 'are more variable, making trend….'
Line 344: Write as '3'

We included these changes

Line 356: Why is this site in Mexico a good location?
Line 357: Why is this site in Venezuela going to need more time?

We specified it in the text:

> "Within this dataset, *given the variability and memory of the time-series*, Puerto Morelos in Mexico *would need the shortest sampling to identify changes in temperature*, and it might be a good location to identify trends in temperature early. *On the other hand* the seagrass meadow and mangrove stations in Eastern Venezuela might need the longest *time series to detect a significant trend*"

Line 358: Should be 'at different sites'

We edited the text

Lines 365-368: Weak paragraph and out of place.

We deleted the paragraph

Lines 375: Need a comma after 'stations'

We included this edit

Lines 384-385: This statement is strange as it makes it sound as if that was one of the objectives of this paper. If you look at the intro, it clearly is not. Great to talk about future work that can build on this work, but that needs to be clear. So maybe say something like 'One of the larger objectives of the CARICOMP program is to…… This study has contributed to the first step….' Or something like that.

We edited the sentence as suggested, which now reads:

> "The CARICOMP program aimed to relate environmental data to observed changes in mangrove, seagrass meadow and coral reef communities over time [22], *and this study has contributed as a first step towards that goal.*"