Intercomparison of satellite derived SST with logger data in the Caribbean – Implications for coral reef monitoring

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Abstract

Since the early 1980s measurements of Sea Surface Temperature (SST) derived from satellite-borne instruments have provided a wide range of global gridded products documenting changes in SST. However, there are many sources of uncertainty in these records and significant differences exist among them. One use of these products is identification of coral bleaching events, and the predictions of the impact of future warming on coral reefs. This relies on an understanding of how temperatures near reefs as recorded by SST products differ from the in-situ SST experienced by the corals. This difference is a combination of real spatio-temporal variations, differences in product resolution and errors in the products. This paper investigates the relationship between the local temperature measured in-situ by loggers at coral sites in the western tropical Atlantic and two high resolution satellite SST products. Using differences among ESA SST CCI v2.1 (ESA2), NOAA CoralTemp (CT) SST products and in-situ logger data from coral reefs, an assessment of the satellite products with focus on coral reef monitoring is carried out. Discrepancies between the two products can be large, especially in coastal areas and for the hottest and coldest months when there is a particular risk of bleaching. By comparison to the stable ESA2 product, CT was found to overestimate the rise in SST by as much as 0.20 °C per decade. In almost all cases SSTs from ESA2 were more consistent with temperatures measured near the corals than those from CT.

Keywords: satellite SST, ESA CCI, CoralTemp, CRW, in-situ validation, coral reef monitoring, coral bleaching, Caribbean

1 Introduction

Observations of Sea Surface Temperature (SST) from space have been made for over 40 years and contribute to our understanding of Earth's climate and how it is changing. However, attempts to exploit this wealth of data are often hampered by a lack of homogeneity and continuity in the data and by insufficient understanding of the associated uncertainties [1]. Errors related to satellite-derived observations include cloud or other contamination (from water vapor, trace gases, aerosol), inadequacies of the retrieval process, errors in spacecraft navigation, uncertain sensor calibration, sensor noise, and incomplete identification of corrupted retrievals [2, 3] These observations, via various analytical methods are compiled to produce gridded products [4-6]. The Global Climate Observing System has set out requirements for these products to meet the needs of climate science, designating key variables that are important for climate change detection referred to as essential climate variables [ECVs; 7]. The European Space Agency's Climate Change Initiative for SST (ESA CCI SST) has reprocessed over 40 years of multi-sensor satellite records to generate a consistent, traceable, record of SST for climate modelling and research [8].

Satellites use either infrared or microwave sensors to measure radiation from the first micrometers to a few millimeters of the sea surface [4], the skin SST [9]. In-situ measurements are often used for calibration of satellite retrievals and it should be considered that they do not measure temperatures at the same temporal or spatial scales, nor at the same depth [10]. The difference in temperature between the very thin skin layer of the ocean and the near surface water below as measured by in-situ platforms like buoys or loggers can be substantial [11].

Extensive work has been carried out for the latest satellite products to account for atmospheric interference and convert the measurements from skin SST to sub-skin and eventually bulk SST, defined as the temperature a few centimeters below the surface [5]. Nevertheless, on the scale of a coral reef for example, local environmental conditions can still result in significant discrepancies between in-situ and satellite derived SSTs [12-14].

Several studies have focused on evaluating satellite-derived SST data using in-situ data as a reference and described differing offsets between day and night that vary with season and wind conditions. Examples of validation studies and their results are summarized in Table S1. A number of salient points emerge from these studies. Firstly, satellite products, such as the ESA CCI SST [5], where satellite skin-SST observations have been transformed to bulk SST, offer a much better representation of the temperature below the sea surface [15, 16]. Secondly, comparing observations stratified by season has shown that the coldest season usually demonstrates smaller mean differences and standard deviations than summer. Possible explanations for this are stratification in the upper layers, and the formation of spatially and temporally variable hot patches during summer [12, 17]. Thirdly, the uncertainty of any particular grid-box of a gridded SST product depends on the number and distribution of available observations in the area relative to the local temporal and spatial scales of variability. The discrepancy between the gridded SST products and in-situ measurements therefore typically increases with grid size and the variability within a grid-box [12, 18]. Here, logger temperature measurements are used to investigate their mean differences between two satellite SST products at nine shallow (3-6m) tropical coral reef sites. The two satellite products compared here have different characteristics, with the most important ones summarized in Table 1. CoralTemp [CT; 6] , utilized by the U.S. National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) is the most widely used product to monitor coral reefs globally, and is compared to ESA's SST CCI analysis v2.1 [ESA2; 5] which showed high accuracy and stability when compared with independent in-situ near-surface temperature data from Argo floats [19] and drifting buoys [1]. We focus on the difference between satellite SST and the ambient water temperature experienced by coastal coral reefs several meters below the surface, in a dynamic, shallow water environment. The most direct way to record the temperature in such locations is by temperature data loggers placed as close to the studied reef as possible.

Table 1. Key characteristics of the satellite products ESA2 and CT.

Product	ESA2	CT
Resolution	daily - 0.05°	daily - 0.05°
Input data	Polar-orbiting Radiometers	Combination of in situ, polar-orbiting and geo-stationary data
Reference Depth	bulk SST ~20 cm	skin SST
Time of day (local)	10.30 (am and pm)	only night-time
Adjustments for orbital drift	Yes	No
Use of dual view sensors	Yes	No

Coral reefs are among the most important ecosystems on our planet, supporting vast levels of biodiversity [20, 21] being home to an estimated 25% of all marine species [22]. They also provide ecosystem services and resources such as coastal protection, fisheries, and tourism [23, 24] yet are one of the most vulnerable marine ecosystems [25]. In recent years, prolonged, warm water events, known as marine heatwaves, have occurred around the world with severely disruptive consequences for marine ecosystems [26] and coral reefs world-wide are degrading rapidly [27-29]. The predicted monetary loss from the degradation of the global coral reefs under current climate change scenarios is billions of US$ per year [25, 30]. The negative consequences of the predicted rise in SST [31, 32] will be significant for all marine life and stony corals will suffer substantial declines in coral calcification [33] and increasing instances of coral bleaching paired with declines in survival within the next two decades [34].

Coral bleaching occurs when the coral-algal symbiosis is disturbed due to stress, causing corals to expel their endosymbiotic algae (zooxanthellae) and, if prolonged, may result in partial or complete coral mortality [35]. Despite other natural and anthropogenic stressors, a prolonged rise in SST has been found to be the main predictor of coral bleaching occurrence and severity [36]. Coral reefs have thrived in past warmer climates [37, 38] so recent coral bleaching has been linked to the increased frequency and intensity of SST anomalies compared to the climatological conditions suitable for modern corals [39]. Coral bleaching typically occurs when the coral experiences temperatures of 1 °C or more outside its thermal tolerance range for a substantial period, usually days to weeks. Although not as well-studied as much as the anomalously warm case, anomalously cold temperature may also cause coral bleaching [40-44]. The range of a coral's thermal tolerance can shift with time, since some corals and their endosymbiotic algae have shown evolutionary adaptation, or local acclimatization to the thermal environment [45-47], but exactly how this is achieved, and what is potential is to mitigate future coral-reef loss, remains unclear [48-50].

NOAA's CRW program has developed satellite-based tools to monitor the thermal stress that causes coral bleaching events around the world [6, 51]. However, the difference between satellite SST and the temperature at a coral reef can be substantial. For instance, a short-lived, 2 °C warming during the June of 2015 was recorded by the 1° resolution satellite product used by NOAA's Coral Reef Watch in the South China Sea. Although this regional, open-water SST anomaly was not enough to raise a 'Bleaching Alert', unusually weak winds caused weak water circulation locally, leading to water temperatures exceeding 6 °C (measured by nearby temperature loggers) above normal summertime levels and an unprecedented mass bleaching event on Dongsha Atoll, killing 40% of the resident coral community [52]. The CRW Coral Bleaching HotSpots is an anomaly product based on the climatological mean SST of the hottest month [53]. A HotSpot is defined as an area where daily SST exceeds the temperature of the warmest month of the year (Maximum Monthly Mean, MMM) for the region, by 1 °C or more. Daily SSTs and climatology are both estimated from satellite-derived observations. The reference climatology currently in use is the period 1985-2012 [6]. Prolonged periods of thermal stress (a week or more of consecutive daily HotSpots) are a strong predictor of mass coral bleaching [54]. The metric "Degree Heating Week" (DHW) is the accumulated number of daily HotSpots through a rolling 12-week period [55]. The CRW Coral Bleaching suite version 3.1 is described in [6].

A general feature of satellite SST products is they tend to miss extreme temperature anomalies locally (i.e. potential HotSpots) and satellite-derived SST anomalies have been observed to be smaller than the actual temperature anomalies experienced in-situ by corals

[56, 57]. Since surface ocean temperatures are projected to increase by at least 2 °C by the year 2100, coral bleaching events are expected to increase in frequency and intensity [58, 59]. Our ability to monitor and mitigate these events, therefore, depends on the accuracy and stability of the satellite-derived products in use. The aim of this study is to inform coral reef monitoring efforts by assessing the globally used satellite SST product, CT. Their ability to detect temperatures that could cause coral bleaching is assessed by investigating the representativeness of the climatologies, anomalies, and linear trends of CT and ESA2 with respect to the ambient water temperature around the shallow coral reefs of Belize and the Florida Keys. We show that substantial temperature differences exist between the two products and between both products and the in-situ loggers, particularly with respect to the extreme temperatures key for predicting coral bleaching events. A previous comparison of CT with night-only logger observations from Puerto Rico found that during the warm season CT was around 1 °C cooler [57]. Another study compared the bleaching metrics from ESA2 and CT with observed coral bleaching records from five reefs in North-Western to South-Western Australia and also found significant differences between them [39]. A different intercomparison of satellite SST products with buoys found that the satellite products did not accurately capture high summer SST in the shallow bays along US Virginia coast [60]. Here, we focus on the Caribbean Sea due to the availability of long, high-resolution logger data, the lack of such studies previously carried out here, and the high diversity of oceanographic conditions in a relatively small region (Fig 1).

2 Materials and Methods

2.1 Study area

Monthly variations in the oceanography of the Caribbean Sea are linked to the annual evolution of the Atlantic Warm Pool (AWP) which appears at the western part of the Caribbean at the beginning of the year [61]. By March the AWP propagates to the Gulf of Mexico and gradually spreads eastward so that by the start of the Caribbean's early rainfall season in May, warm waters reach the north-eastern border of the Caribbean Sea. By the peak of the hurricane season around October very warm SSTs cover the entire Caribbean and warm waters in excess of 28 °C typically extend from the Gulf through to the west coast of Africa [62, 63]. Studies focusing on coral bleaching in the Caribbean have found that the main bleaching period occurs from August to October [64].

The southern part of the Belize barrier reef, located in the southwestern part of the Caribbean, is isolated from the cool waters of the Gulf of Mexico (arising from the upwelling Loop Current) and Northern Atlantic and is mainly influenced by the warm southern waters of the AWP throughout the year [63]. Water temperatures in the Florida Keys on the other hand show greater variability (Fig 1). Florida has a complex peninsular shape, with over 2,100 km of shoreline influenced by regional and global ocean circulation patterns. The geomorphology of the shelf that encircles Florida influences coastal connectivity to deep basins in the Caribbean and the Atlantic Ocean, causing the formation of local cold-water pools [65].

2.2 In-situ measurements

2.2.1 Belize

In June 2002, loggers were installed at an inshore and an offshore location in the Gulf of Honduras, the southernmost part of the Belize Barrier Reef System (Fig 1). The distance between the two locations was approximately 22 km. A full description of the installation process is available in [13]. HOBO Water Temperature Pro Data Loggers (accuracy ± 0.2 °C and resolution 0.2 °C; http://www.onsetcomp.com) were installed at East Snake Caye within the inner lagoon reef (hereafter inshore), and at White Reef on the outer barrier reef (hereafter offshore). They recorded temperatures from June 2002 to December 2007 (Table 2). The observations were then averaged in daily and monthly resolution. Missing measurements were due to lost or stolen temperature loggers. A field assessment of logger accuracy using one week of higher accuracy temperature measurements as a reference showed that HOBO Water loggers had an average mean difference of -0.006 °C, an average root mean square error of 0.028 °C, and an average correlation (R) of 0.998 ± 0.001 [13].

Fig 1. Study area. Top: Positions of the nine loggers in Belize (a) and Florida Keys (b) indicated by their initials (full names in Table 2). (c) ESA2 minus CT means, (d) ratio of ESA2 SD over CT SD, (e) SD of the difference ESA2 minus CT for the common period (1985-2022) at the Caribbean area, and (f) ESA2 uncertainty of the mean field over the same period.

2.2.2 Florida

The USGS Coral Reef Ecosystems Studies project, following a similar principle to the Belize loggers, collected subsurface temperature data at seven offshore coral reefs in Florida Keys from 2009 to 2022 (Kuffner, 2016). The coral reefs are located inside a bank-reef system that runs semi-continuously along the length of the Florida Keys at 24.5-25.5°N latitude. From northeast to southwest spanning 340 km of the reef tract the sites are: Fowey Rocks, Molasses Reef, Crocker Reef, Sombrero Reef, Pulaski Shoal, Pulaski West, and Garden Key (Fig 1). In Garden Key the data span less than a year, thus were not used here. Temperatures were recorded every fifteen minutes with Onset HOBO Water Temp Pro V2 data loggers (a later model than the ones used in Belize), in duplicate at each site. Unfortunately, no field assessment of the logger accuracy was performed, but the sensor specification is the same as the previous model used in Belize (0.2 °C) and we therefore assume similar accuracy. The coordinates and temporal span of observations for every site are given in Table 2. A more detailed description of these Florida data is available at https://coastal.er.usgs.gov/data-release/doi-F71C1TZK/.

Table 2. In-situ data. Temporal span and locations for all nine sites used in this study.

Site	Fowey	Molasses	Crocker	Sombrero	Pulaski	Pulaski West	Garden Key	Belize inshore	Belize offshore
Start	Aug-09	Apr-09	Jun-13	Jul-09	Jun-09	Dec-16	May-22	Jun-02	Jul-02
Finish	Oct-21	Apr-13	Aug-22	Aug-22	Oct-22	Oct-22	Oct-22	Nov-07	Dec-07
Latitude	25.590°N	25.010°N	24.909°N	24.627°N	24.694°N	24.703°N	24.621°N	16.193°N	16.083°N
Longitude	80.096° W	80.375°W	80.527° W	81.109°W	82.773° W	82.799° W	82.867° W	88.627° W	88.333° W

2.2.3 Satellite SST products

ESA SST CCI analysis v2.1

A set of SST products based exclusively on remotely sensed SST observations have been processed within the ESA's CCI, we use the v2.1 global blended multi-sensor and gap-filled product provided on a daily 0.05° grid (known as the level-4 analysis, L4, [ESA2; 66]). The ESA2 SST fields are estimated at a depth of 20 cm and cover the period 1981-near present. It uses an optimal interpolation approach utilizing the Operational Sea Surface Temperature and Ice Analysis system [67]. Measurements have been adjusted from skin to sub-skin SST following [68] and subsequently converted to 20 cm depth (bulk SST) and either 10:30 or 22:30 local time (when temperatures are most likely to be the closest to the day's average) using the Kantha Clayson diffusion model [69]. ESA2 also comes with estimates of the total uncertainty for each SST value. A comparison between the analyses and drifting buoy measurements showed a robust standard deviation of differences of 0.25 C° and the multi-annual observational stability relative to the reference data was within 0.003 °C yr^{-1} [70]. The version v2.1 used here combines data from the Along Track Scanning Radiometer (ATSR) products (1992 to 2012), Advanced Very High-Resolution Radiometer (AVHRR) and L4 Analysis products (1981 to present), and the Sea and Land Surface Temperature Radiometer (SLSTR) products (2017 to present).

NOAA CoralTemp v3.1

CRW has developed coral-specific satellite-based tools to monitor thermal stress causing bleaching events in coral reefs around the world [53]. CRW used the daily global 5 km SST analysis and reprocessed Pathfinder Version 5.2 AVHRR SST dataset from the National Environmental Satellite, Data, and Information Service to develop a high-resolution coral bleaching monitoring product released in June 2012. NOAA Coral Reef Watch Version 1.0 Daily Global 5-km Satellite Virtual Station Time Series Data (known as CoralTemp) is a gridded SST dataset combining satellite polar-orbiting and geostationary data, spanning the period 1985-2016 [51]. From October 2016 to the present CoralTemp (CT) data come from a near-real time combination of geostationary and polar-orbiting blended satellite SST [6]. The geostationary data used in CT have a calibration bias of up to ~0.7 C° due to the large temperature difference the instrument experiences (~40 C°) between day and night. [71, 72]. Due to changes in the SST products used by CRW for coral reef monitoring since 1997 and the need to combine older data with new, CT utilizes different datasets and has gone through multiple stages of adjustments in an attempt to appropriately combine the various SST datasets [6].

2.2.4 Statistical Analysis

For the first part of the analysis, a comparison between ESA2 and CT for the wider Caribbean area (35°N-10°N, 100°W-60°W) was performed. The overlapping period of the two products is 1985-2022. A set of basic diagnostics to evaluate the similarities and disagreements between the selected SST datasets was used. Some of these metrics, such as the mean difference, standard deviation (SD), and root-mean-square error (RMSE), measure the difference between the two sets of observations. Other metrics, such as the monthly climatology, quantify the long-term mean spatial distribution of the SST for each dataset and can be used to qualitatively evaluate the capability of satellite SST in representing the climatological temperature reference that the corals are acclimatized to. The monthly climatology is the average SST of each of the 12 months of the year for the years between 1985 and 2022. The daily anomalies from that climatology are used to derive metrics for coral reef monitoring, such as HotSpots and DHWs, described previously.

In the next step, the mean differences between the satellite SST observations and in-situ measurements locally and on different temporal scales were determined and used in a comparative analysis. Assuming the accuracy of the HOBO Water Temperature Pro Data Loggers evaluated by [13] is applicable to the later models deployed in Florida, the estimated logger uncertainty (±0.028 °C) is much smaller than the typical mean differences between the in-situ and gridded SSTs found in previous validation studies (S1 Table). Hence, the logger data are chosen as the best approximation for the 'true' temperature on site. Since the loggers are positioned close to the coral, the difference between the gridded SST product and the logger is therefore an estimate of the combination of errors and lack of representativeness of the gridded SST to the water temperature experienced by the coral. For this part of the analysis the in-situ data were converted into daily and monthly averages and the differences (gridded SST minus in-situ) were calculated for each location. Standard deviations around the mean values provide a metric of the total uncertainty due to random variations, and systematic effects that are either not identified or not quantified, called standard uncertainty [73]. The mean difference and the RMSE measure the distance between the satellite product and the reference, which in this case are the logger data. Annual and seasonal cycles were explored in order to assess the timing of the mean differences with respect to the logger observations. Monthly climatologies were then calculated for the period used by CRW as reference (1985-2012) and daily anomalies from that period along with annual trends of SST at the logger sites. The three sites in Florida that had the longest spans (Fowey, Sombrero, Pulaski) were also used in a similar manner and monthly climatologies and daily anomalies were compared to the satellite products for the period 2009-2021. Since the accuracy of the HotSpot metric is sensitive to both long-term stability and short-term (daily) variations, we compare these metrics from the two high-resolution SST products with logger observations in order to assess the ability of the SST products to detect temperatures that are anomalously high for the area.

Finally, the linear SST trends in the daily anomalies between the two products were compared. The Generalized Least Squares (GLS) method was used to calculate long-term trends for the period 1985-2022, accounting for the autocorrelation of the residuals from the linear model. Following the implementation of [74], a preliminary analysis was carried out in order to infer the autocorrelation structure of the timeseries which led to the selection of the 1st order autoregression model, AR(1). The 'gls' function in the 'nlme' package in R [75] fits regression models with a variety of correlated-error and non-constant variance structures. The regression coefficients and Autoregressive moving average parameters were estimated simultaneously using the Maximum Likelihood principle via the gls function. All analyses used R [76].

3 Results

3.1 Comparison of the satellite products

Both products generally show on average hotter and less variable SST for the Belize locations than the sites in Florida, which agrees with the logger observations (S1 Figure). For the study area, ESA2 shows wider ranges than CT for both the mean SST 10.5 °C (20.0-30.5 °C) vs. 8.5 °C (21.0-29.5 °C), and SD which ranges from 0.7 to 6.6 °C for ESA2 and 0.7-6.0 °C for CT (Fig 1).

Fig 1 shows the mean differences between the two products in the Caribbean for the common period (1985-2022). Mean temporal differences (ESA2 minus CT) range from -1.1 to 1.2 °C, with ESA2 being hotter on average at all nine logger sites, and towards the North-East part of the Caribbean while CT is hotter around most of the coastline, and the South-East part of the Caribbean (Fig 1c). The ratios of the SDs of SST (ESA2 over CT) during the common period range from 0.8 to 1.8 with ESA2 SST being predominantly more variable, especially along the coastline (Fig 1d). The SD of mean differences ranges from 0.3 to 1.9 °C with the highest values seen where the Gulf Stream exits the Caribbean area (Fig 1e). The uncertainty of the mean field of ESA2 for the same period stays below 0.1 °C for most of the study area while away from the coast the uncertainty remains below 0.05 °C (Fig 1f). The average uncertainty of the Caribbean region was calculated assuming temporal correlation of seven days and spatial correlation of three degrees and was downloaded from the re-gridding service provided by [3].

Fig 2 shows the time-series of the spatial mean difference (ESA2 minus CT) of the study area for the common period, 1985-2022. The shaded area is the range of twice the ESA2 spatial mean uncertainty (hereafter ESA2unc) for the same area, assuming correlated errors. The ESA2unc is used to illustrate that differences outside this range are most likely due to CT errors. The mean difference decreases as we move forward in time with an abrupt change in magnitude during the late 90's. However, before that, there are many days where the difference is above 0.5 °C or falls out of the ESA2unc, mostly with ESA2 mean SST being higher than CT (Fig 2). This is important because this earlier part is used by CRW as the reference climatology (1985-2012) from which the bleaching metrics are derived.

Fig 2. Top: Timeseries of mean Caribbean ESA2 minus CT plus 2*ESA2 uncertainty range. Bottom: Time and magnitude of the mean difference when it exceeds the confidence interval.

ESA minus CT daily anomalies from the monthly climatologies (ref. 1985-2012) are often beyond ±2 °C and can almost reach ±3 °C. While there are many instances that the differences stay above ±1 °C for consecutive days which would lead to inaccurate bleaching metrics (Fig 3). The mean of the differences is below ±0.1 °C for all sites except for Belize inshore where CT is hotter on average, with a mean difference of -0.13 °C. SDs are over 0.4 °C for all sites with the highest (0.58 °C) at Fowey. In Florida, ESA2 anomalies are on average slightly larger in the beginning and after about 2000s CT anomalies become gradually larger than ESA2. A pattern that is more pronounced at the Belize sites (Fig 3).

Fig 3. Differences of daily anomalies from the monthly climatologies (1985-2012) ESA2 minus CT at the six sites as subplot titles. The rest of the sites showed similar or smaller differences between ESA2 and CT.

Fig 4 shows maps of the wider Caribbean area SST averages for the periods 1985-2004 and 2005-2022 from the two SST products. CT shows a larger difference between the averages of the two periods than ESA2 and the difference is almost uniform for the study area (Fig 4). SST for both products has increased in the period 2005-2022 as expected albeit CT shows an increase 0.42 ± 0.13 °C larger than ESA2 which has an average raise of 0.34 ± 0.09 °C (Fig 4).

Fig 4. The Common period (1985-2022) was separated into two sub-periods (1985-2004 and 2005-2022) and the difference between the mean SSTs of the two periods for (a) ESA2 and (b) CT was plotted.

The daily SST anomalies and long-term trends (ref. 1985-2012) of ESA2 and CT for the period 1985-2022 were calculated. In three out of the four sites shown in Fig 5 the trends are significantly different, with the maximum difference seen at the Belize sites. The warming trend of 0.29 °C per decade (95% CI: 0.25-0.32 °C) at Belize Inshore was the maximum trend of all the sites seen for CT (Table 3). Belize Inshore was also the site where the largest difference between ESA2 and CT trends was observed, which was 0.20 °C per decade. Similarly, the trend of CT and the difference with the trend of ESA2 at the offshore site were only slightly smaller than the inshore (Fig 5). In all of the sites the trend of CT was larger than the trend of ESA2 (Table 3; S2 Figure). Although here we focus on the Caribbean region, it is worth mentioning that the ESA2 global mean SST has high temporal stability after 1994, with a divergence of 0.01 °C per decade between the CCI data and buoy observations [77]. The differences between the trends of the two products at the sites examined here were considerably higher than 0.01 °C per decade with a range of differences from 0.03 to 0.20 °C per decade, and well outside their joint confidence intervals, particularly for the Belize sites (Table 3). Hence, the trends of CT are probably overestimating the increase in SST at least for the locations examined here.

Fig 5. Daily anomalies from the monthly climatology used by CRW (1985-2012) at four sites (as in subplot titles) with the linear trend lines of ESA2 (blue) and CT (green) superimposed. The rest of the sites showed similar or smaller differences between ESA2 and CT trends.

Table 3 Annual trends and 95% C.I. as observed by ESA2 and CT for the period 1985-2022 at the four sites shown in Fig 5.

Product	Site	Annual trend	95% C.I. of slope
ESA2	Fowey	0.014 °C/yr	(0.007, 0.020)
	Sombrero	0.020 °C/yr	(0.013, 0.026)
	Belize In.	0.009 °C/yr	(0.005, 0.012)
	Belize Off.	0.013 °C/yr	(0.010, 0.017)
	Caribbean	0.021 °C/yr	(0.016, 0.027)
CT	Fowey	0.026 °C/yr	(0.021, 0.031)
	Sombrero	0.023 °C/yr	(0.017, 0.030)
	Belize In.	0.029 °C/yr	(0.025, 0.032)
	Belize Off.	0.028 °C/yr	(0.024, 0.031)
	Caribbean	0.022 °C/yr	(0.018, 0.027)

In general, discrepancies between the two products can be locally large (SD of differences; Fig 1e) and though ESA2 uncertainty increases going closer to the coast (where the loggers were placed) it does not get as high as the magnitude of the discrepancies (Fig 1f). Moreover, the climatological monthly means for the coldest and hottest months which are essential for predicting or monitoring coral bleaching events, are considerably different between the two products. As for the spatial average timeseries they also show large differences, outside the ESA2unc for long periods. In addition, the differences between the daily anomalies and annual trends of the two products indicate a potential mismatch in any bleaching metrics calculated from the two SST products.

3.2 Intercomparison of SST products with logger water temperature data

Table 4 Statistics of satellite minus logger data at the nine sites.

		Mean		**Median**		**SD**		**RMSE**	
		ESA2	CT	ESA2	CT	ESA2	CT	ESA2	CT
Daily Means	Fowey	0.00	0.15	0.01	0.10	0.61	0.46	0.61	0.48
	Molasses	0.12	0.17	0.10	0.10	0.48	0.51	0.50	0.54
	Crocker	0.00	-0.05	-0.01	-0.07	0.48	0.42	0.48	0.42
	Sombrero	0.03	-0.09	-0.01	-0.11	0.49	0.55	0.49	0.56
	Pulaski	0.06	0.05	0.05	0.02	0.31	0.32	0.32	0.33
	Pulaski W.	-0.02	-0.07	-0.03	-0.10	0.32	0.33	0.32	0.34
	Belize In.	-0.16	-0.40	-0.18	-0.40	0.46	0.38	0.49	0.55
	Belize Off.	-0.09	-0.31	-0.11	-0.30	0.38	0.33	0.39	0.45

Daily differences between the SST products and loggers across all nine sites were on average -0.01 ± 0.44 °C for ESA2 and -0.09 ± 0.41 °C for CT, while the average of the RMSEs 0.44 °C and 0.46 °C respectively (Table 4). Fig 6 shows that the means are closer to zero for ESA2 at all sites. Overall, the metrics show better agreement of ESA2 with respect to the logger measurements (Table 4 and Fig 6).

Fig 6. Boxplots of daily mean temperature differences (satellite minus logger) for the period of available logger data at the nine sites shown in the x axis. The number of days is shown at the top axis for each site.

CT underestimates on average the hottest monthly temperatures (August, September) relative to logger data in all the sites examined here and overestimates the coldest (January, February) in most sites (Fig 7). In contrast, ESA2 mean differences are closer to zero for all months (Fig 7). In Belize, CT SST is lower than the logger temperature for all monthly climatology averages, while ESA2 shows lower averages in July and August, but is almost the same in September when the SST is slightly higher on average in both sites (Fig 7). All the sites have monthly differences that exceed 0.5 °C but in Fowey and Sombrero the differences for some months are above 1 °C (Fig 8). Specifically, the months when the average difference exceeds 1 °C for ESA2 are: 01-2019. 06-2019, 11-2019 in Fowey, and 12-2010 in Sombrero. For CT: 02-2010, 03-2010, 01-2011 in Fowey, and 03-2010, 12-2010 in Sombrero.

Fig 7. Annual cycle of daily differences (SST product - in-situ), aggregated monthly for the period of available logger data at each site (as subplot title) of ESA2 (blue) and CT (red).

Fig 8. Time series of monthly differences (satellite minus logger) at four sites in Florida with the longest records and for the periods of available logger observations. The red, horizontal, dashed lines indicate differences over 1 °C, considered as threshold for coral bleaching.

The three sites with enough observations to calculate a 13-year monthly climatology (2009-2021) were chosen (as the rest of the sites had considerably less observations) and the climatologies from the logger and satellite observations for the same period were calculated. At Fowey, ESA2 had slightly lower January mean SST (coldest month) and higher August SST (hottest month) than the respective months of the logger climatology while CT showed the opposite results (higher SST in January and lower in August) with respect to the logger climatology (Fig 9a). For the remaining two sites, the satellite and logger climatologies were closer to each other than Fowey but still different for January and August in particular. ESA2 climatology was always closer to the logger climatology than CT (Fig 9b, c). The differences between the satellite and the logger climatologies for January and August (e.g. satellite August minus logger August climatology) are shown in Table 5. CT in all but one cases, underestimates both minimum and maximum monthly climatologies with respect to the logger observations.

Fig 9. (a,c,e) Monthly climatologies for the period of available logger observations (2009-2021) from the two satellite and the logger data at the three sites with the most observations as subplot titles. **(b,d,f) Differences of daily anomalies (satellite minus logger) for ESA2 and CT during the same period** at the same sites.

Table 5. Differences of satellite minus logger climatologies for January (min) and August (max) at the three sites. Mean, SD and metrics for coral bleaching of the daily anomaly differences between the two products and the loggers. Potential HotSpots and DHWs are not exactly the metrics used by CRW as the differences are not derived from the maximum climatological month but from the respective month of the climatology for the period (2009-2021).

Product	Metric	Fowey	Sombrero	Pulaski
ESA2	August (max)	0.21	-0.07	-0.04
	January (min)	-0.21	0.09	0.11
	Mean	0.21	0.28	0.29
	SD	0.57	0.50	0.32
	Potential HS	417	359	109
	Potential DHWs	3	3	0
CT	August (max)	-0.11	-0.14	-0.11
	January (min)	0.38	-0.17	0.20
	Mean	0.35	0.32	0.30
	SD	0.44	0.53	0.32
	Potential HS	324	395	137
	Potential DHWs	3	10	0

Daily anomaly differences for both products exceeded the 1 °C threshold multiple times at all three sites, reaching almost 5 °C in Sombrero (Fig 9b, d, f). The mean and SD of the differences along with the number of days that exceeded 1 °C (potential HotSpots, HS), and the periods of over seven consecutive days with differences over 1 °C (potential DHWs), are shown in Table 5. The term 'potential' is used to show that they are not exactly the metrics used by CRW but rather the daily anomaly differences that exceed 1 °C from the respective climatological month of each dataset. Since the climatology period is not the same, due to lack of longer logger observations it was not possible to calculate the exact metrics used by CRW. However, this is still useful in the sense that the differences have the potential of resulting in wrong bleaching metrics, regardless of the timing of the occasions.

4 Discussion

4.1 Estimating local SST using gridded SST products

It has been widely documented that coastal and reef ecosystems are dynamic environments where rapid changes in temperature can occur on a range of spatial and temporal scales [14, 78]. In addition to the accuracy of the global gridded SST dataset, there are also intrinsic difficulties or discrepancies when trying to estimate the water temperature around a coral reef with this kind of product. The most important discrepancies include the spatial and temporal resolution of the measurements of the gridded dataset. Moreover, the fact that satellite raw observations come from a very thin layer on top of the surface and coral reefs live a few meters below adds a discrepancy between the two temperatures. Therefore, logger observations placed besides the coral reefs were used here to test the ability of the satellite products to sense the water temperature at a few meters depth where the corals reside. Temperature loggers record the temperature at a specific point in the water, which is also the temperature the coral experiences. However, a gridded SST value describes an average temperature of the available observations inside the grid-box (5 km for the two products used here) surrounding the point where the loggers are (Fig 1 top panels). This means that areas with different characteristics and therefore different temperatures are included in this average. Water circulation in shallow, coastal and reef environments is more restricted and consequently solar heating can be significant [79]. Thus, during days of high solar radiation, heat accumulates more efficiently in the shallow waters of the reef resulting in enhanced temporal and spatial gradients in water temperature [52]. On the other hand, outer barrier reef regions are exposed to currents and waves from the cooler open ocean regions potentially causing the outer reef to experience colder temperatures than the nearshore inner reef regions. This pattern is observed at the Belize region where one inshore and one offshore site were compared. Mean differences for Belize inshore were on average larger and more variable than Belize offshore, especially during the summer season (Table 4 and Fig 7). Tidal effects, continental runoff and local currents can play an important role in shaping the thermal regime of a site, contributing to the site-specific and season-specific character of mean differences. Here, particularly for the Florida region, the SST is greatly affected by continental runoff and local current effects [80]. Strong differences related to seasonal cycles in water circulation and characteristics, such as vertical mixing of the water column in winter and stratification in summer are site-specific and can also be abrupt and/or substantial in magnitude.

4.2 Reference time and depth of the analysis

When ESA2 was compared to CT with respect to mean and variance of regional and local SST, monthly maximum and minimum climatologies, and daily anomalies, large differences between the two were identified, parts of which not explained by ESA2's uncertainty (Figs 1-5). Although the two products compared here have the same spatial resolution there are still intrinsic differences between the two. The ESA2 analysis is a more homogenous SST product than CT and has been transformed to represent bulk SST, at a time when diurnal stratification is at its minimum rather than CT which consists of only night-time, skin SST observations (Table 1). Moreover, the ESA2 dataset has many advantages over CT, such as the use of dual view sensors, better quality control, more than a decade of methodological development of Bayesian methods of cloud screening of imagery and many more characteristics described in [5]. These characteristics are probably the reasons ESA2 shows better agreement to in-situ observations in this study (Figs 6 and 7, Table 4).

The same in-situ data from Belize were used in a previous study [13] but were compared to a skin SST satellite product which was not processed to avoid values affected by extreme diurnal stratification. Also, the previous study used satellite measurements from a specific time of the day in contrast to the modelled, close to daily-averaged values of the ESA2 product. The results were larger mean differences, different between day and night, and wider error margins, with RMSEs close to 1 °C for day and over 1.5 °C for night differences [13]. The fact that in this study the compared observations were averages rather than instantaneous, and the characteristics of the ESA2 observations described in the previous paragraph, contribute to the smaller variance of the satellite minus in-situ differences observed here.

4.3 Implications for coral reef monitoring

An important implication of the patterns discussed here relates to the detection of coral bleaching events using satellite-derived temperature data. Under conditions of low wind speeds and tidal activity, current speeds around a coral reef can drop dramatically leading to anomalously high temperatures on the site [39, 52, 57, 60]. As shown here, these conditions of extreme warming for short periods that can lead to bleaching events, even if they prevail for a week or more, are not typically recorded by either gridded SST products (Figs 8 and 9). Moreover, local upwelling and cold-water circulation restricted in very narrow currents (Fig 1) can cause a gridded SST product to miss or smooth out anomalously cold temperatures experienced by corals (Figs 7-9), which can also lead to coral bleaching [41-44].

CRW's coral bleaching HotSpot product is an anomaly product, with satellite-derived anomalies from a satellite-derived monthly climatology. Hence, it is important that the satellite-derived daily anomalies from the satellite derived Maximum Monthly Mean (MMM) accurately represent the daily differences from the MMM experienced in-situ by the corals. Nevertheless, for this to happen the satellite-derived SST product needs to be stable over time so that the differences between daily SST values and the reference climatology represent the actual differences in local SST. Differences between ESA2 and CT MMMs for the common period, at the sites studied here were also substantial, reaching over 0.5 °C in Belize (S3 Figure).

Also, it is important that the climatology used to derive the HotSpots is representative of the coral's current range of thermal tolerance. Here, even though only the later part of the satellite observations (2009-2011) was used, the difference of the maximum or minimum climatologies between CT and loggers reached to 0.38 °C (Table 5) and daily differences exceeded the 1 °C threshold on several occasions for both products (Fig 9).

A pronounced difference between CT and ESA2 which would have a great impact in the determination of satellite-derived HotSpots is the difference in long-term trends, especially for Belize (Fig 5). The two products show substantially different warming trends, with differences as large as 0.029 °C per year (Table 3). A few studies have calculated the historical trends in Caribbean SSTs albeit with lower resolution products [81-83]. Studies that have used high-resolution products have found warming trends but for shorter or earlier periods. The study whose period reaches the most recent year, used the Pathfinder v5.0 SST data derived from the NOAA AVHRR at 4 km resolution and found high spatial heterogeneity in SST trends within the Caribbean Sea [84]. They calculated an annual warming rate of 0.027 °C for a slightly different area than the one studied here, over the period 1985-2009. The Caribbean trends for the common period of the two products (1985-2022) used here, were 0.021 °C/yr for ESA2 and 0.022 °C/yr for CT (Table 3). Both are comparable to previous studies that found trends of 0.012-0.060 °C/yr but for earlier periods and at different areas within the Western Atlantic region [83-85]. As seen in Table 3, the ESA2 uncertainty (Fig 1f) is low enough to offer the confidence that the local trends are different between ESA2 and CT.

5 Conclusions

In this study, it has been shown that the CT product which originates from a blend of various satellite sensors and SST analyses, each with different characteristics [86] is probably not homogenous enough to offer the stability needed for coral reef monitoring. ESA2 on the other hand seems to offer better stability and accuracy in the Caribbean, a finding that agrees with a recent study focusing on Australian reefs [39]. Especially for the earlier part of the record, the mean Caribbean SST difference between CT and ESA2 falls out of the range ESA2unc (Fig 2) at many instances. This earlier part is used as a reference for the bleaching metrics of CRW, meaning that the magnitude of these metrics would be considerably affected if this period is not consistent with the later part of the CT product. We also demonstrated that CT exhibits a much larger increase in SST for the period 2005-2022 than the more stable ESA2 (Fig 4). On the other hand, the ESA2 data were found to be closer to the in-situ logger observations from nine sites in the Caribbean than CT. CT also underestimated the temperatures for the maximum monthly climatologies and overestimated the minimum monthly climatologies with respect to the logger observations which consequently leads to inconsistent anomalies and bleaching metrics (Table 5 and Fig 9). Long periods of several weeks when in-situ temperatures were persistently more than 1 °C higher or lower than satellite-derived SSTs were identified (Fig 8 and Table 5). The results agree with recent studies at coral reefs in the South China Sea and Australia which found that the DHW thresholds of CRW underestimated coral bleaching events using in-situ coral bleaching survey data paleo data and models [39, 87]. Overall, although ESA2 still misses a lot of potential

HotSpots, it performed better than CT in this part of the analysis as well (Table 5).

Given the shortcomings of the gridded products discussed here, we recommend that in-situ loggers should be used to measure water temperatures locally, around a coral reef whenever possible. When in-situ data are not available, a careful examination of the study area with respect to SST characteristics (SST variability, seasonal changes, etc.) with the ESA2 product is recommended. The use of a new metric for detecting areas with anomalously cold SSTs in accord with the already existing HotSpots product used by CRW is also recommended, since coral bleaching is also observed when temperatures are anomalously cold [41-44]. Periods when the satellite products missed the coldest temperatures recorded by the loggers were also found here (Figs 7-9). Studies on the adaptive response of coral reefs to thermal stress have linked bleaching to SST variability of the region and frequency of past thermal disturbance [46, 47, 88, 89]. In some areas, bleaching events have been mitigated by induced thermal tolerance of reef-building corals, although this protective mechanism is likely to be lost under near-future climate change scenarios [48, 90]. There is no single bleaching threshold for all locations, times, or species [45, 49, 89, 91, 92] and bleaching metrics do not always identify bleaching events [39, 87]. Results from in-situ bleaching reports could be utilized in a comparison between SST products in the context of which product would do a better job in recording actual bleaching events locally [93]. Evaluation studies such as performed here could eventually help with the more accurate detection of bleaching events by satellite sensors. By using high-resolution SST products to identify local anomalously hot or cold-water regions and in-situ observations to quantify the difference between local SST and grid-box SST in such areas coral bleaching metrics could be updated and improved. From the two products compared here, ESA2 showed the most accurate representation of in-situ temperatures. It was verified here as well as in other studies that ESA2 is more stable than CT globally and regionally. Hence it should be utilized in the future to improve coral reef monitoring in general. As of July 2024, the latest ESA SST CCI version 3 was available to March 2024 [3], this delay means presently that this product cannot be used for near real time monitoring.

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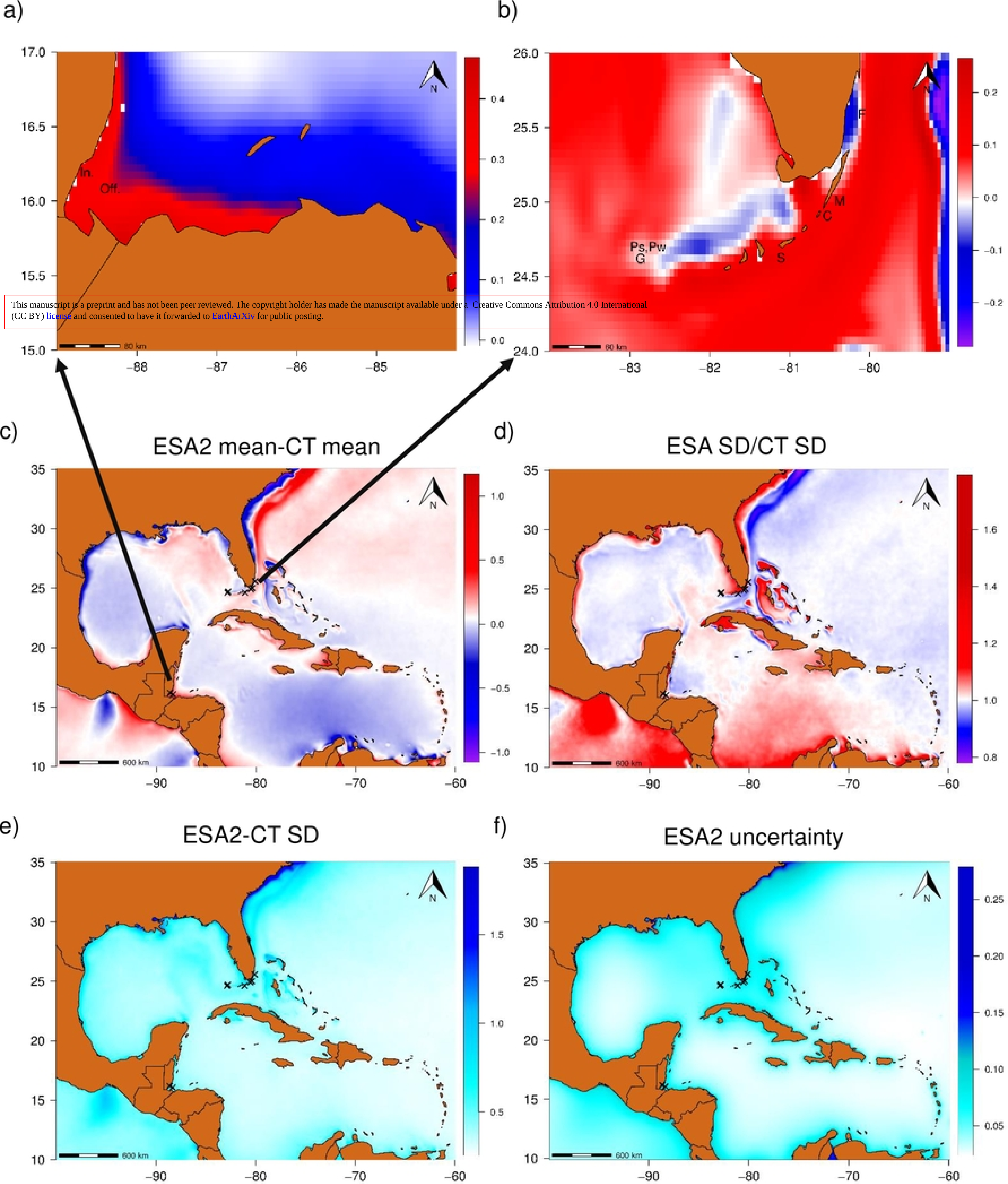
Supporting information

S1 Figure. Boxplots of diurnal temperature variability as recorded by in-situ loggers at each of the 9 sites. Mean diurnal variability for each site calculated as the average of the standard deviations around the daily means of all available sub-daily logger observations. Each box represents the 25% to 75% quartile ranges, the line in the box is the median value, and the whiskers represent the minimum and maximum values.

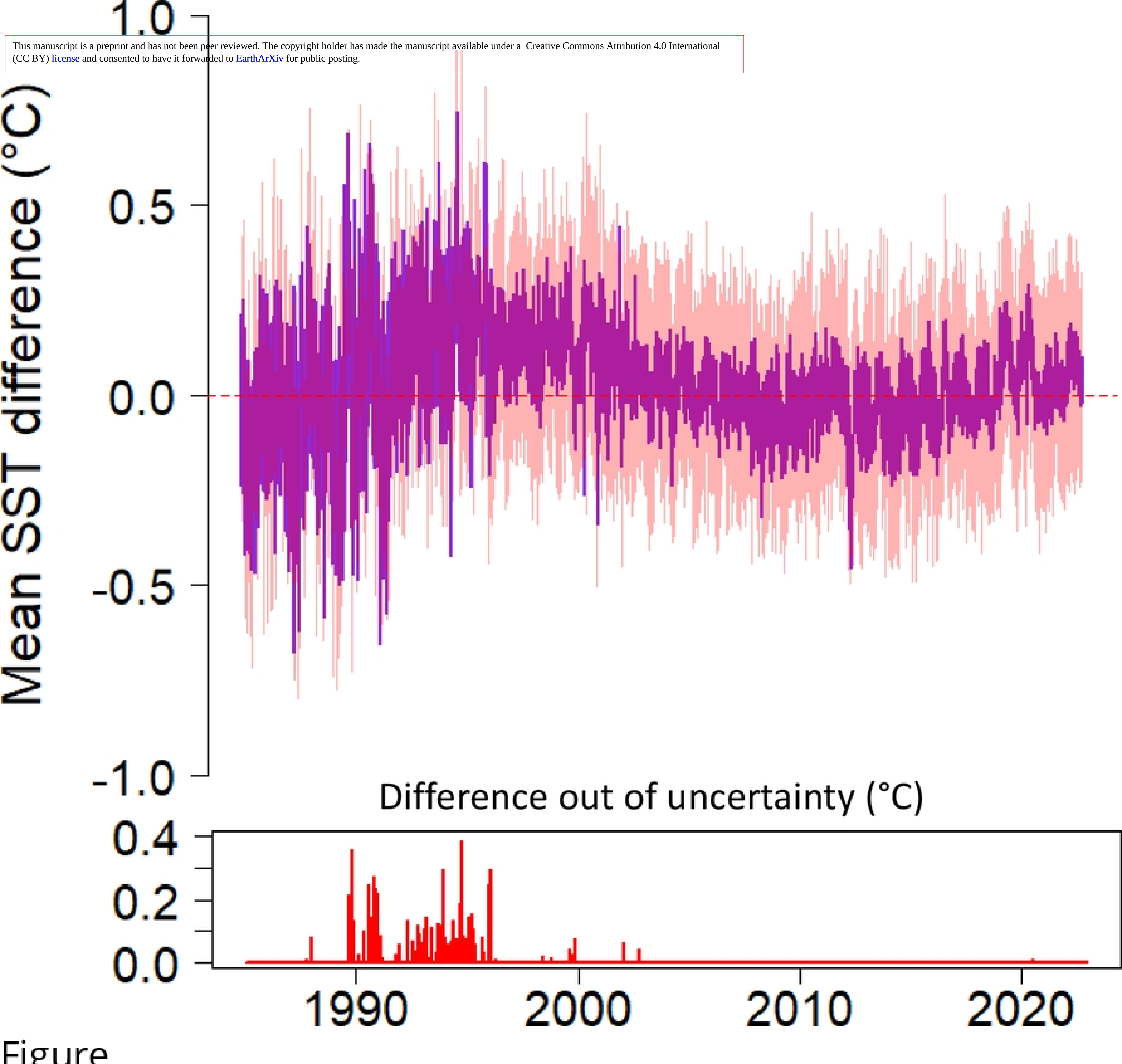
S2 Figure. Daily anomalies from the monthly climatology used by CRW (1985-2012) at all sites.

S3 Figure. Differences of minimum or coldest (blue), and maximum or hottest (red) monthly climatology (ESA2 minus CT) at the nine sites. Monthly climatology is the average SST of each of the 12 months of the year for the years between 1985 and 2022.

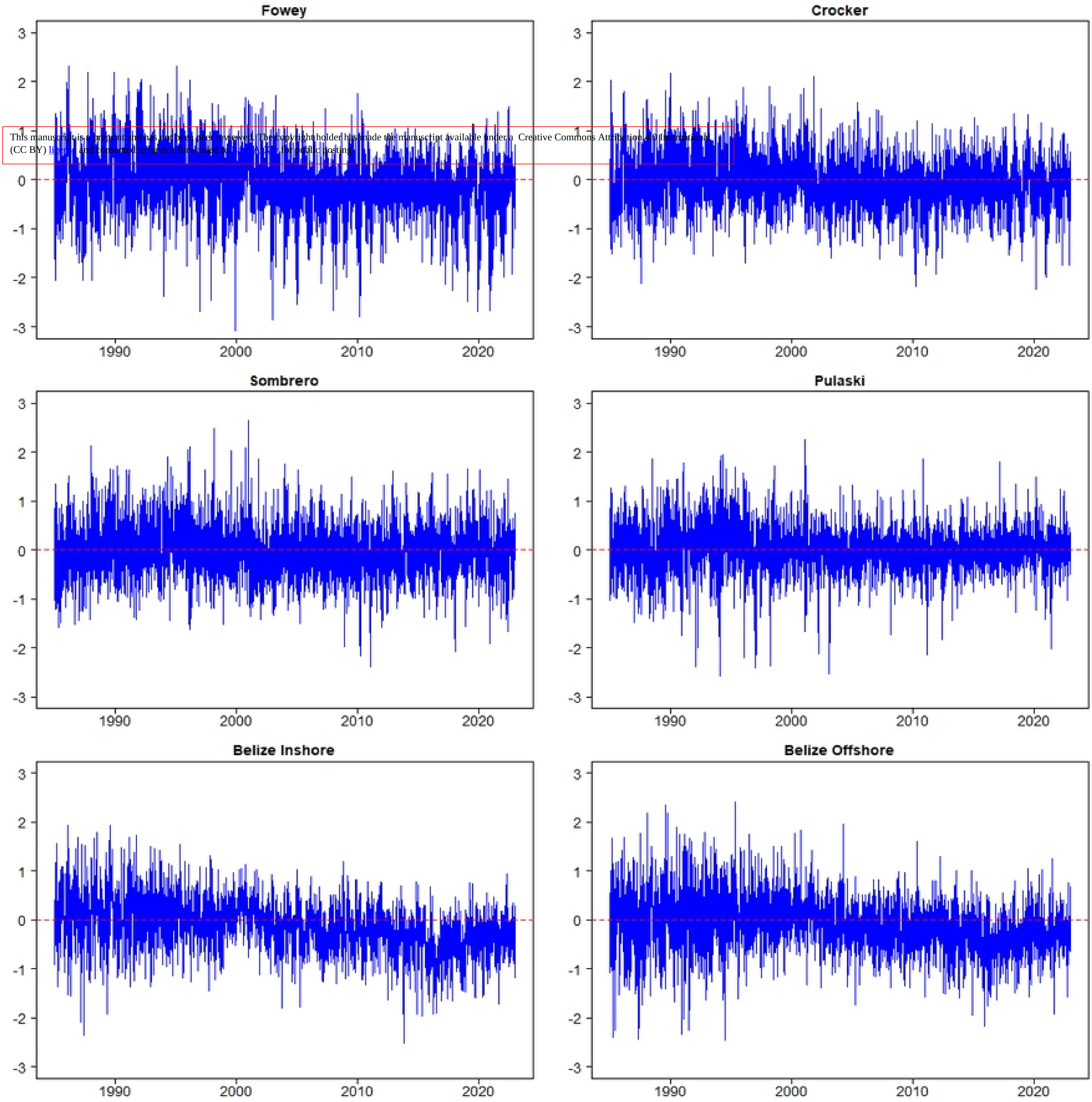
S1 Table. Summary of satellite validation studies. Spatial resolution was converted to km for easier comparison between the papers, using the relation: 1 degree = 60 arc mins = 111 km, which is a good approximation close to the equator. The papers were selected to be representative of a variety of modern sensors and products of the best available quality.


a)
b)
In.
Off.
Ps, Pw
G
S
C
M
F
N
80 km
c)
ESA2 mean-CT mean
d)
ESA SD/CT SD
e)
ESA2-CT SD
f)
ESA2 uncertainty
600 km
17.0
16.5
16.0
15.5
15.0
-88
-87
-86
-85
26.0
25.5
25.0
24.5
24.0
-83
-82
-81
-80
35
30
25
20
15
10
-90
-80
-70
-60

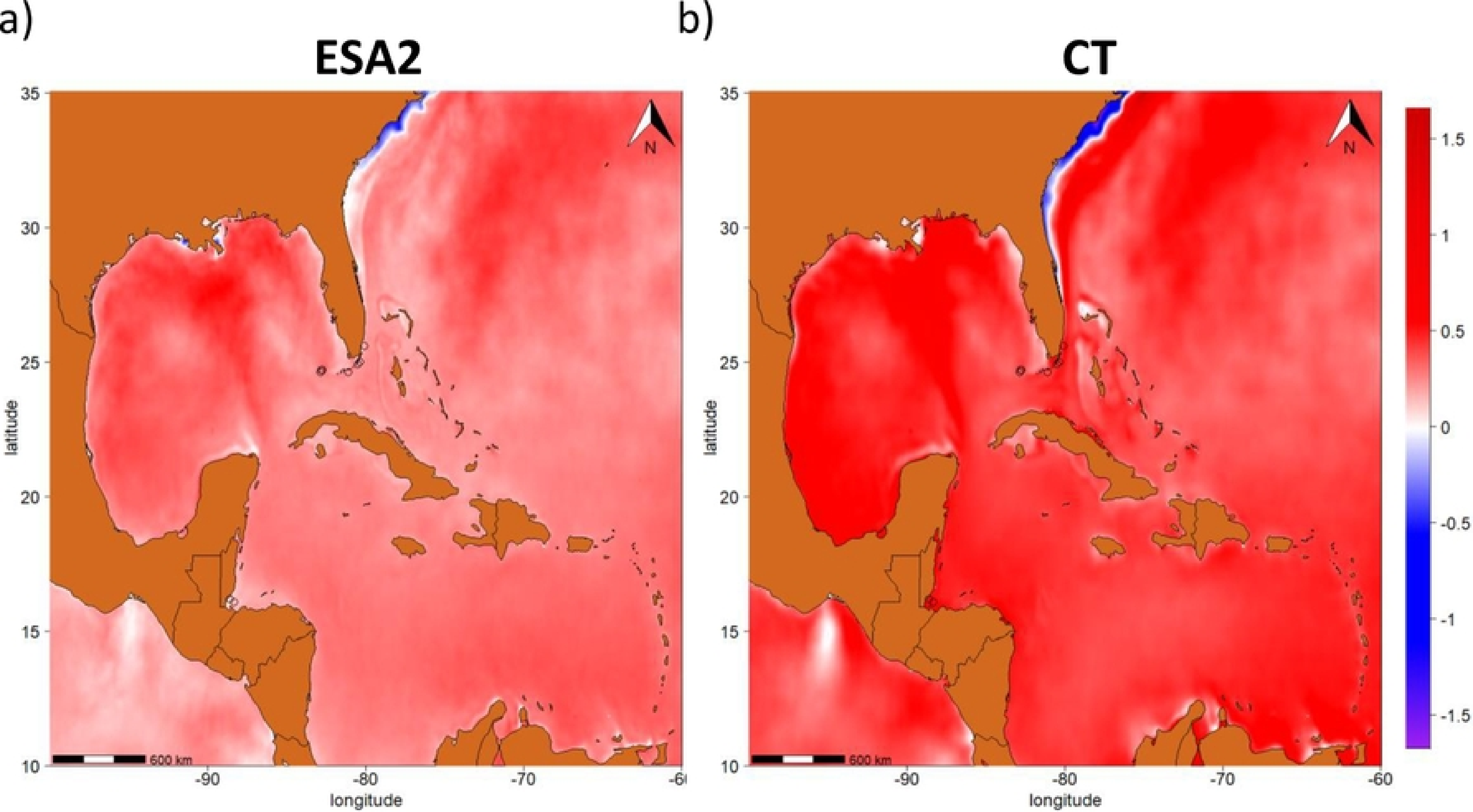
Figure


1.0
0.5
0.0
-0.5
-1.0
Mean SST difference (°C)
Difference out of uncertainty (°C)
0.4
0.2
0.0
1990
2000
2010
2020

Figure

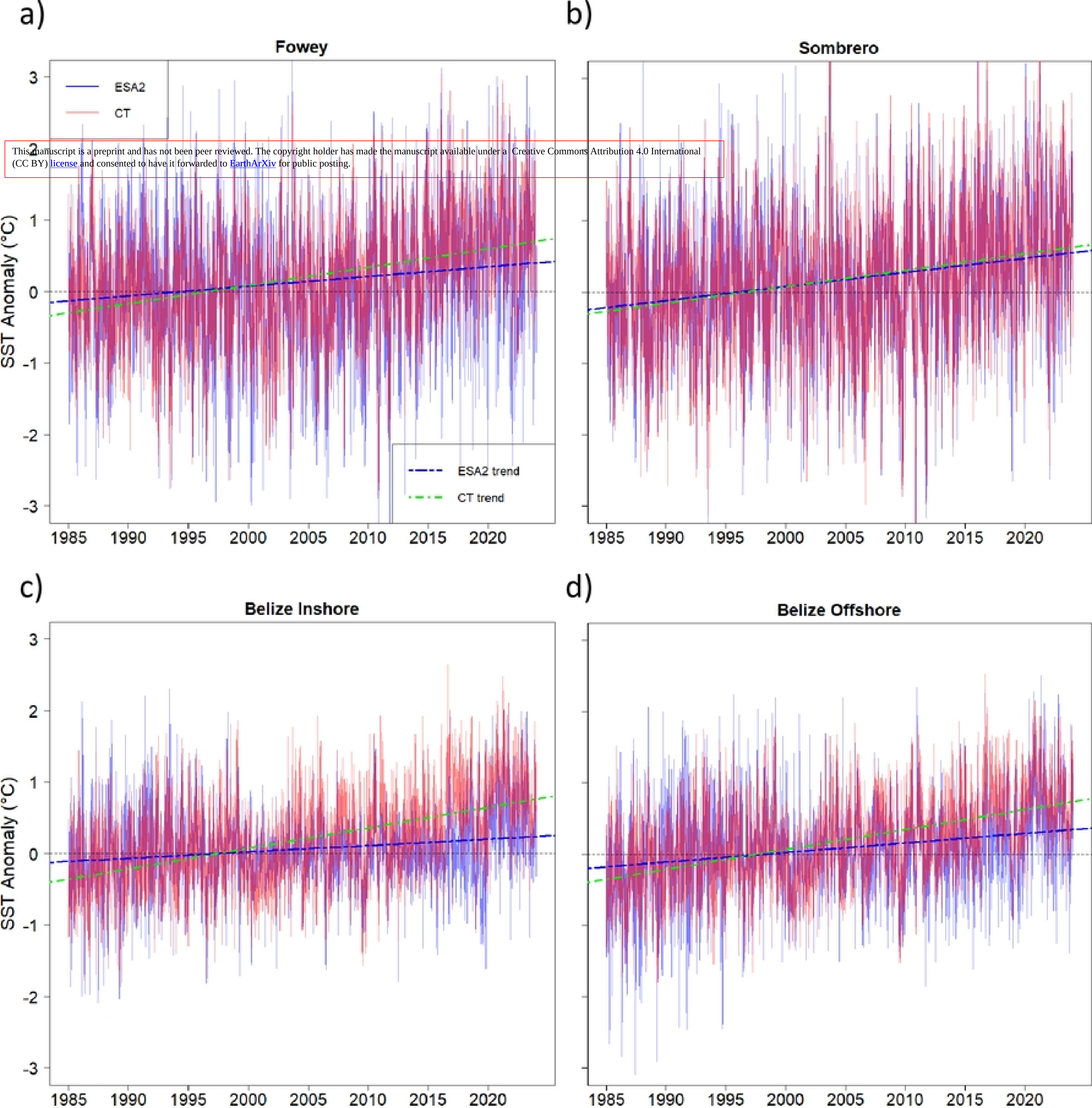

Fowey
Crocker
Sombrero
Pulaski
Belize Inshore
Belize Offshore
3
2
1
0
-1
-2
-3
1990
2000
2010
2020

Figure

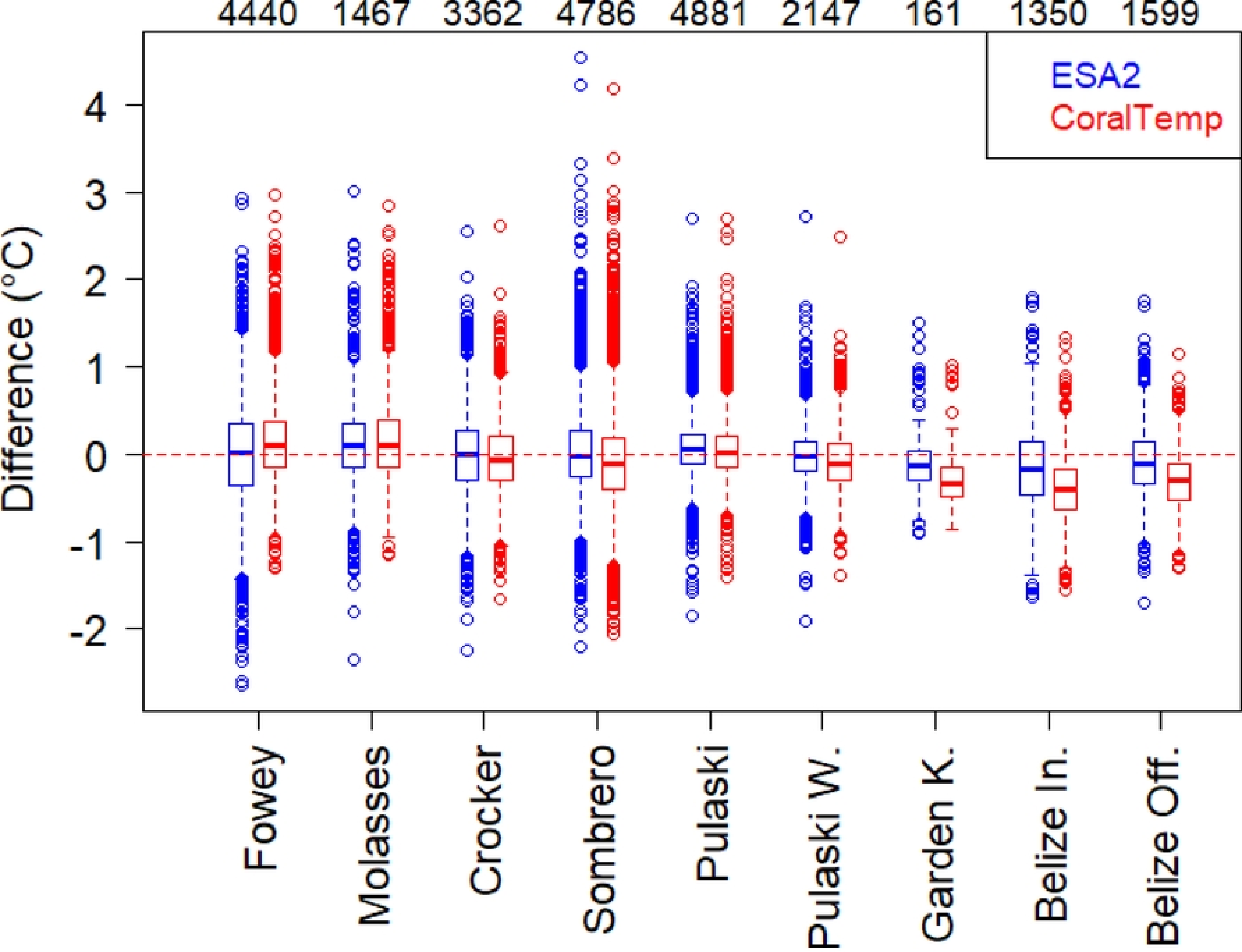


a)
b)
ESA2
CT
35
30
25
20
15
10
-90
-80
-70
-60
latitude
longitude
N
600 km
1.5
1
0.5
0
-0.5
-1
-1.5

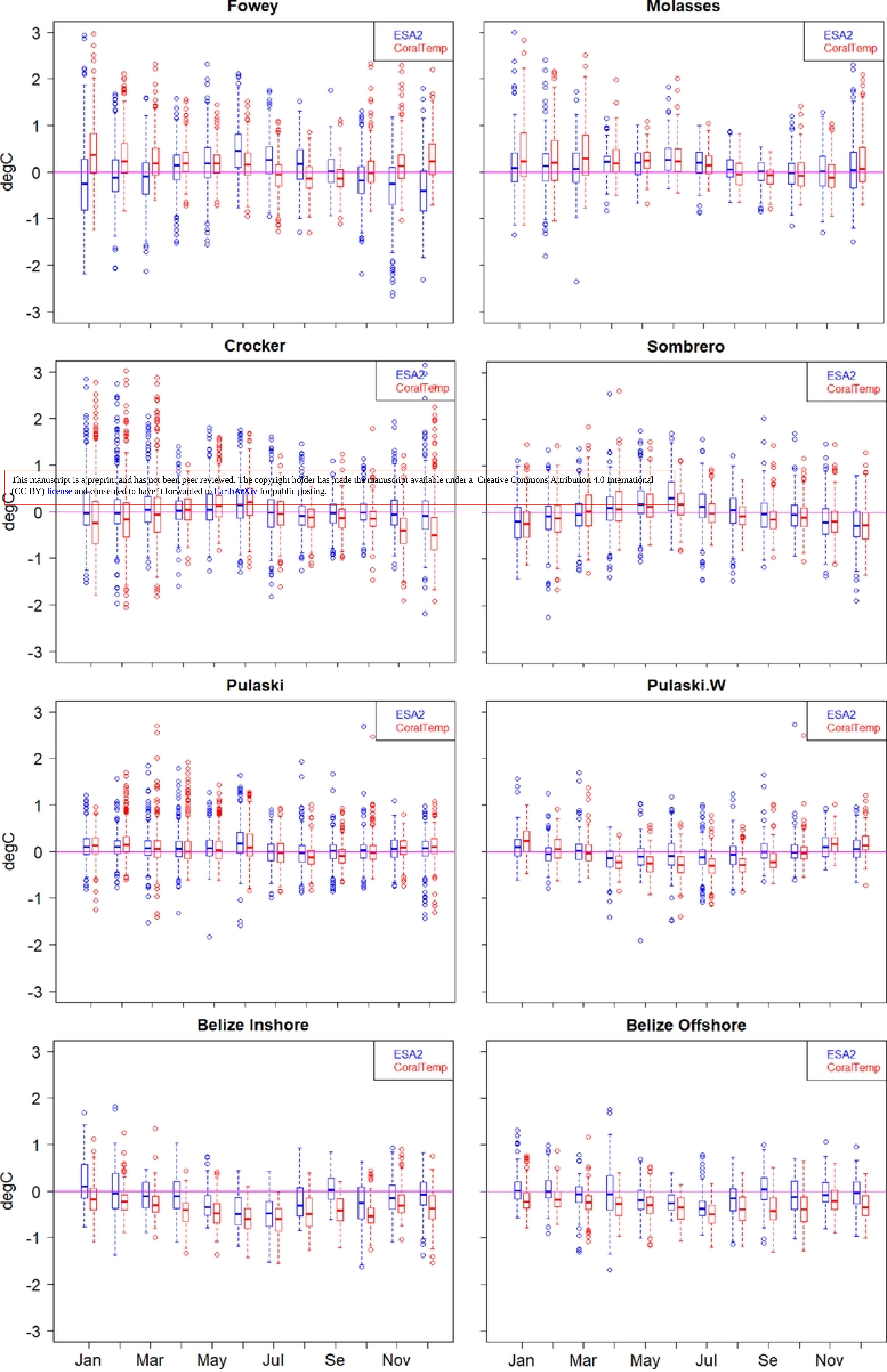
Figure


a)
Fowey
b)
Sombrero
c)
Belize Inshore
d)
Belize Offshore
ESA2
CT
ESA2 trend
CT trend
SST Anomaly (°C)
3
2
1
0
-1
-2
-3
1985
1990
1995
2000
2005
2010
2015
2020

Figure

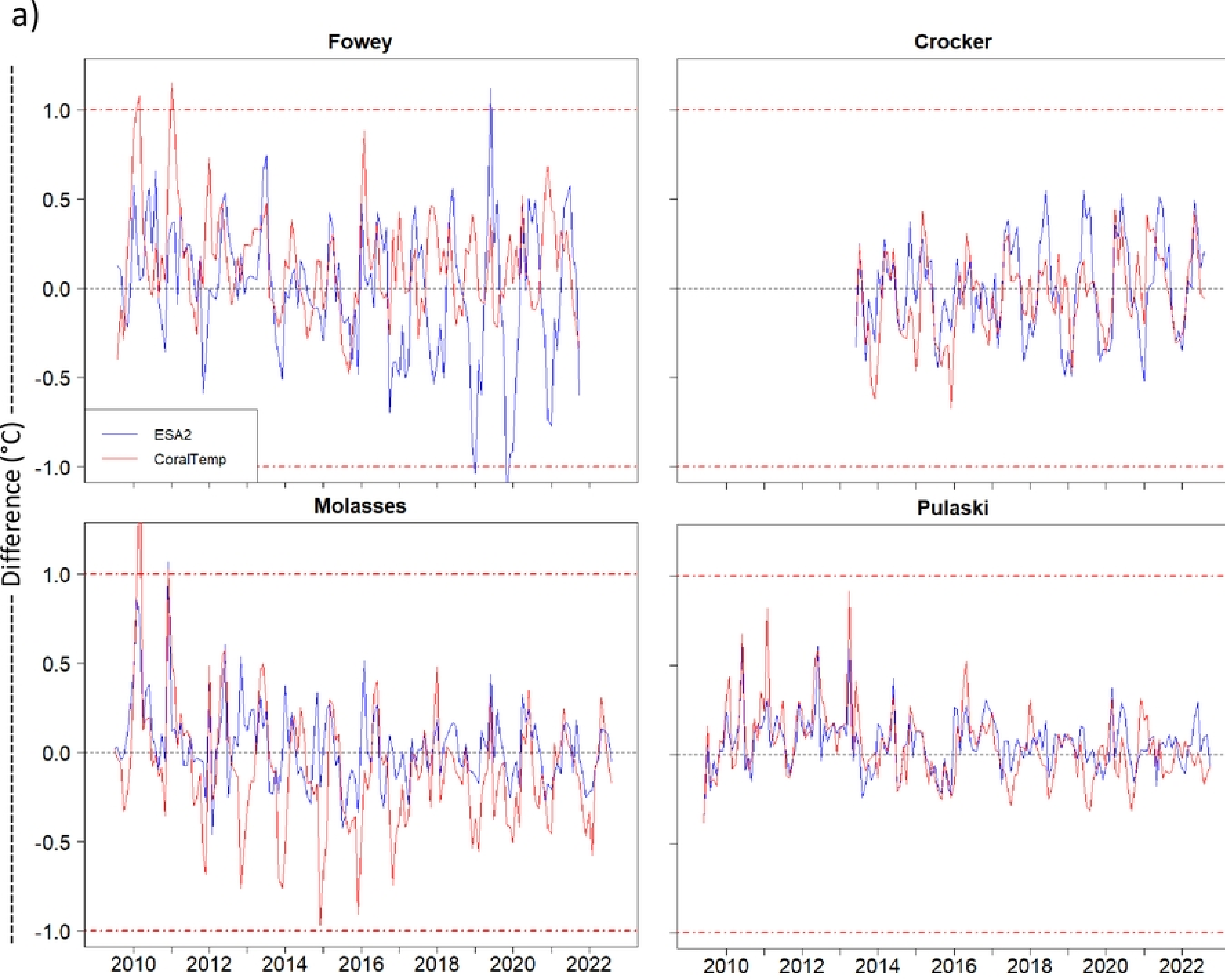

4440
1467
3362
4786
4881
2147
161
1350
1599
ESA2
CoralTemp
Difference (°C)
4
3
2
1
0
-1
-2
Fowey
Molasses
Crocker
Sombrero
Pulaski
Pulaski W.
Garden K.
Belize In.
Belize Off.

Figure



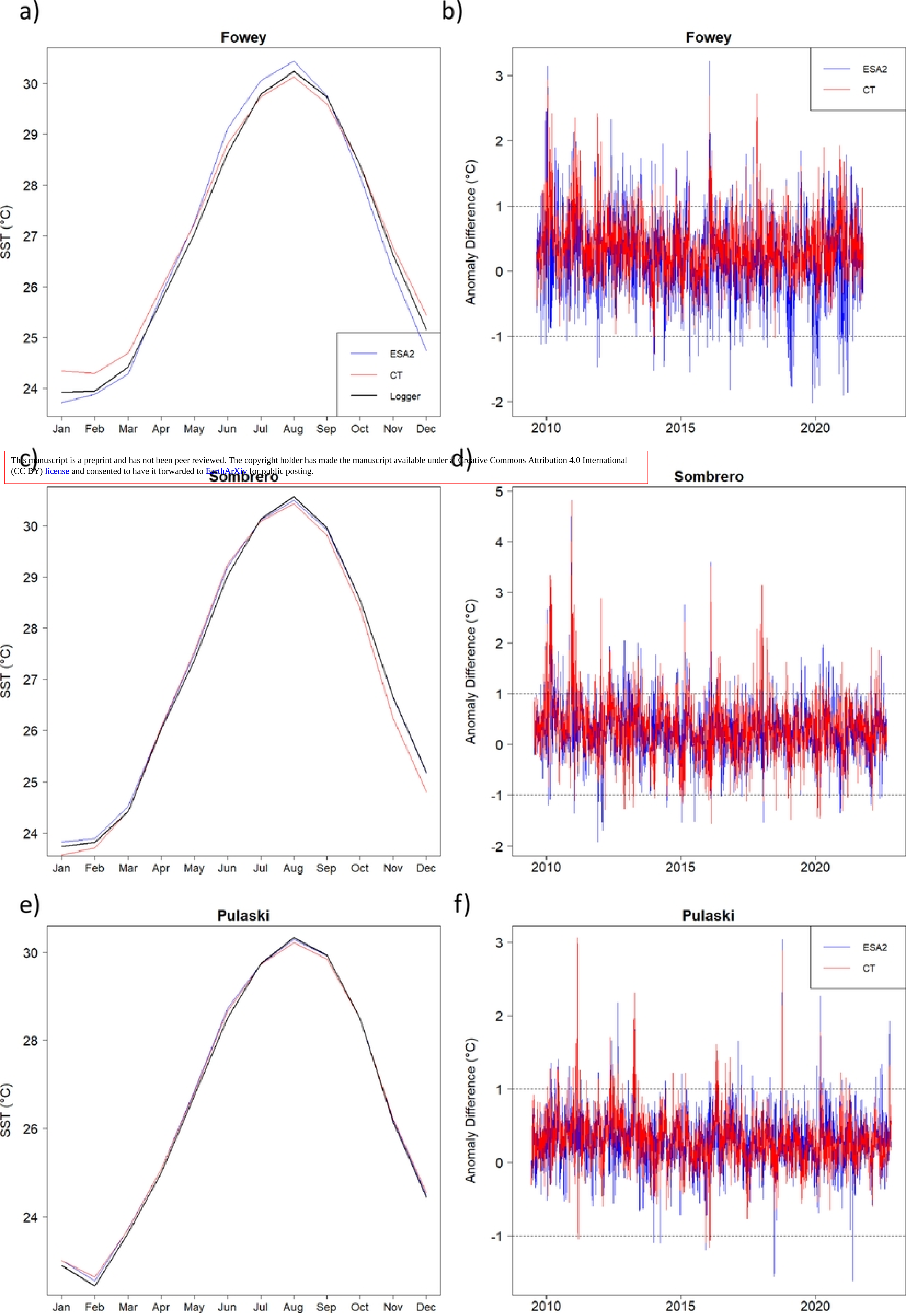
Fowey
Molasses
Crocker
Sombrero
Pulaski
Pulaski.W
Belize Inshore
Belize Offshore
ESA2
CoralTemp
degC
3
2
1
0
-1
-2
-3
Jan
Mar
May
Jul
Se
Nov

Figure



a)
Fowey
Crocker
Molasses
Pulaski
Difference (°C)
1.0
0.5
0.0
-0.5
-1.0
ESA2
CoralTemp
2010
2012
2014
2016
2018
2020
2022

Figure


a)
Fowey
SST (°C)
30
29
28
27
26
25
24
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
ESA2
CT
Logger
b)
Fowey
Anomaly Difference (°C)
3
2
1
0
-1
-2
2010 2015 2020
ESA2
CT
c)
Sombrero
SST (°C)
30
29
28
27
26
25
24
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
d)
Sombrero
Anomaly Difference (°C)
5
4
3
2
1
0
-1
-2
2010 2015 2020
e)
Pulaski
SST (°C)
30
28
26
24
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
f)
Pulaski
Anomaly Difference (°C)
3
2
1
0
-1
2010 2015 2020
ESA2
CT

Figure