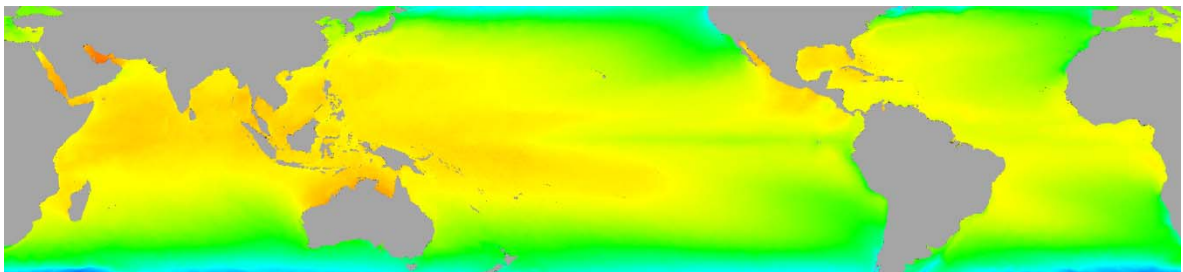


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Climatology Development for NOAA Coral Reef Watch's 5-km Product Suite



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*Cover image shows the 5-km maximum of the monthly means climatology (MMM) developed as described by this report for application in the Coral Reef Watch 5-km satellite product suite for monitoring global thermal stress.

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Climatology Development for NOAA Coral Reef Watch's 5-km Product Suite

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Executive Summary

The U.S. National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW) program has used a 50-km resolution “Heritage” analysis of satellite sea surface temperature (SST) observations to monitor coral reef thermal stress for more than 15 years. The most frequently requested upgrade by coral reef managers and scientists has been for increased spatial resolution. The recent operational production of a satellite-based, global SST analysis at 5-km resolution has provided the basis for high-resolution monitoring of thermal conditions not only in oceanic waters, but also at and near coral reef locations. Evaluating thermal stress on coral reefs requires knowledge of historical baseline temperature (climatology) at the same spatial resolution to identify and assess anomalous temperatures. This report documents the development of a 5-km SST climatology for use with the 5-km SST analysis.

The climatology was developed using a NOAA climate data record for SST: the 4-km Advanced Very High Resolution Radiometer Pathfinder Version 5.2 SST (PFv5.2) dataset for 1985-2012. This period is much longer than that used in CRW’s Heritage 50-km climatology (1985-1990 and 1993) and, because of the warming trend in recent decades, the new climatology was adjusted using local temperature trends to match the Heritage product period. This was undertaken to maintain consistency of the new monitoring products with the Heritage products. In general, not all SST datasets are identical (e.g., due to differences in instrument frequencies, algorithms and water depth used for validation), so the PFv5.2 SST climatology was bias adjusted to better resemble the 5-km SST analysis, providing better consistency between the SST and climatology for producing anomaly-based products. The bias-adjusted monthly climatology was then re-gridded to the 5-km SST grid for application in the thermal stress monitoring product suite.

Recent thermal stress events and associated observations of coral bleaching provide a means to evaluate the performance of the thermal stress monitoring products. Initial comparisons of thermal stress with bleaching reports from the Mariana and Hawaiian archipelagos and the Florida region during 2013 and 2014 indicate that the high-resolution thermal monitoring products are performing well.

Development of the high-resolution temperature climatology documented in this report provides a key component of CRW’s next-generation high-resolution global coral bleaching thermal stress satellite monitoring products. The 5-km products, monitoring at or near the scale of coral reefs, have provided unprecedented spatial and temporal resolution for the management of coral reefs worldwide and have been enthusiastically employed by numerous resource managers and other coral reef ecosystem stakeholders.

1 Introduction

Tropical coral reefs are ecologically and economically important marine ecosystems that are found across the global ocean within the latitude range 35°S to 35°N. Reefs provide numerous social, cultural, and economic services; however, reefs are also vulnerable to a wide range of chronic and acute environmental disturbances that can result in the loss of key ecosystem functions. Monitoring of exposure to such disturbances provides reef managers with information to manage reef ecosystems in the face of extreme events and rapid climate change and thereby enhance the sustainability of reef ecosystems and their dependent industries. Mass coral bleaching events due to anomalously warm ocean water temperature have increased in frequency and severity (Eakin et al. 2010) and become one of the most significant contributors to the deterioration of global coral reef ecosystems (Wilkinson 2008). Thermal stress that persists for several weeks with ambient water temperatures as little as 1 to 2 °C above a coral's tolerance level has been shown to cause bleaching, often on broad geographic scales (Glynn and D’Croz 1990, Berkelmans and Willis 1999).

Since 1997, the Coral Reef Watch (CRW) program at the National Oceanic and Atmospheric Administration (NOAA) has used satellite-derived products to monitor the thermal stress that leads to mass coral bleaching. CRW’s thermal stress products depend upon measured temperature values and a defined temperature threshold above which stress is determined to have occurred. An accurately defined threshold is critical in determining the magnitude of warm anomalies. CRW’s most accurate predictor of potential bleaching impact (the Degree Heating Weeks product) accumulates individual anomalies through time and, as such, any over-estimates of the anomaly would be summed through time, amplifying the error. Through CRW’s operation of satellite-based coral bleaching thermal stress monitoring, the critical importance of accurate and consistent temperature thresholds used in producing anomalies has become evident.

CRW has historically produced global coral bleaching thermal stress monitoring tools at 0.5-degree (approximately and hereafter referred to as 50-km) resolution, using night-only SST values to eliminate the issue of surface warming during the day and to avoid contamination from sun glint (Liu et al. 2012, 2013). These “Heritage” products are based on a twice-weekly near real-time 50-km SST analysis, and a 50-km temperature baseline (climatology) developed in the mid-1990s (Liu et al. 2013). It is of note that the climatology was derived using data from 1985-1990 and 1993 (omitting the data from 1991-92, which were affected by intervening aerosol contamination following the eruption of Mt. Pinatubo). As such, SST anomalies and other parameters in the 50-km products are referenced to conditions of that era. The 50-km product suite includes SST Anomaly (variation in current conditions from what is expected at the particular time of year at each location); Coral Bleaching HotSpots (magnitude by which current temperature exceeds the warmest monthly climatology value for each pixel – a measure of current thermal stress); and Degree Heating Weeks (DHW; accumulation of HotSpots when SST exceeds the bleaching threshold – a measure of accumulated thermal stress). The HotSpots and DHW products were designed specifically to relate to known coral responses to thermal stress, and are referenced to the warmest value of the monthly climatology at each pixel (maximum of the monthly means climatology, MMM).

In 2007, CRW launched the Enhanced 50-km (E-50) product suite, which contained two significant improvements (Heron et al. 2014). The first of these was increased coverage of the 50-km SST data in coastal locations (due to the inclusion of satellite temperature values from

coastal water pixels), whereas the Heritage products only provided values for 50-km pixels that were entirely oceanic. The second improvement was an updated climatology that addressed known errors in the Heritage climatology and provided values for the new coastal pixels. The E-50 climatology was constructed from Pathfinder v5.0 SST values from the period 1985-2006, and the methodology provided a precursor to the later development of a higher-resolution climatology.

Through recent years, the Center for Satellite Applications and Research (STAR) within NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) undertook development of higher-resolution SST products. This resulted in the 0.05-degree (approximately and hereafter referred to as 5-km) near real-time, geo-polar Blended day-night and night-only SST analyses, available since March 2012 and March 2013, respectively. Development of a high-resolution thermal stress product suite from the Blended SST data necessitated a high-resolution temperature climatology. This report describes the development of the temperature climatology currently in use with the CRW 5-km global coral bleaching thermal stress monitoring product suite.

2 Source SST data

Ideally, a climatology would be developed directly from the dataset to which it is being applied so to ensure internal consistency. However, the NESDIS night-only 5-km SST products have only been available since March 2013. As the dataset was not of sufficient length to build a climatology, a separate source dataset was required. The Advanced Very High Resolution Radiometer (AVHRR) Pathfinder version 5.2 SST (PFv5.2) dataset is an official climate data record (CDR) for SST (<http://www.ncdc.noaa.gov/cdr/operationalcdrs.html>) and is the longest satellite-only SST dataset. It is of sufficient length for this application (Heron et al., 2014) and thus was selected to be the basis of the climatology development. PFv5.2 SST values at 1/24° (approximately and hereafter referred to as 4-km) and daily resolution were derived using AVHRR data from the series of NOAA polar-orbiting satellites. At the time of analysis, data for 1982-2012 were available from the NOAA/NESDIS National Oceanographic Data Center (NODC) (<http://pathfinder.nodc.noaa.gov>) and the Group for High Resolution Sea Surface Temperature (GHRSSST). The PFv5.2 dataset is an updated version of the Pathfinder Version 5.0 and 5.1 described in Casey et al. (2010). Data prior to 1985 were excluded due to concerns over values in coastal pixels (cold bias). Because the new CRW 5-km products use only nighttime satellite data to avoid potentially significant effects of diurnal variation in SST and to better represent temperature anomalies at the depths corals are found (Heron et al. 2013), only nighttime PFv5.2 data were used to develop the climatology. Following Kilpatrick et al. (2001), SST values were deemed "high quality" (and therefore used) if their corresponding PFv5.2 quality level was four or greater (on a scale from zero to seven). High quality values were distinguished based on: having physically sensible temperature, passing a cloud test, showing spatial consistency of the satellite data, demonstrating consistency with another broad-scale temperature dataset, and meeting Earth-Sun-satellite configuration criteria (Kilpatrick et al. 2001).

3 Climatology development

The first stage was to develop a monthly climatology at the native spatial resolution of the PFv5.2 dataset and using the full temporal extent of that dataset in a way that ensured consistency with the Heritage climatology so as to maintain existing management interpretation. In the second stage, the climatology values were bias adjusted to ensure consistency with the near real-time Blended 5-km SST data. The third stage was to re-grid the monthly climatology from the PFv5.2 4-km grid to that of the Blended 5-km data.

3.1 PFv5.2 SST climatology

The first stage of development involved producing a monthly climatology at the 4-km resolution of the PFv5.2 dataset, using only high-quality values from the 28-year period, 1985-2012. This involved five distinct steps.

[1] Daily SST data at each pixel were averaged for each month through the 28-year period (1985-2012) to produce 336 (=28×12) monthly mean SST fields (Figure 1a). Pixels that did not contain any daily SST of the required quality levels during a particular month (Figure 1b) were flagged as missing data pixels for that month and year. As less than 13% of the daily PFv5.2 data between 35°N and 35°S latitudes were of quality level 4 or higher, an attempt was made to fill gaps at a daily level. However, analysis showed that gap-filling techniques magnified errors or did not provide additional information to the resultant month mean SST fields, making the added data unreliable and/or redundant. As a result, we concluded that there was no added value and used the available high-quality PFv5.2 data directly to derive monthly means.

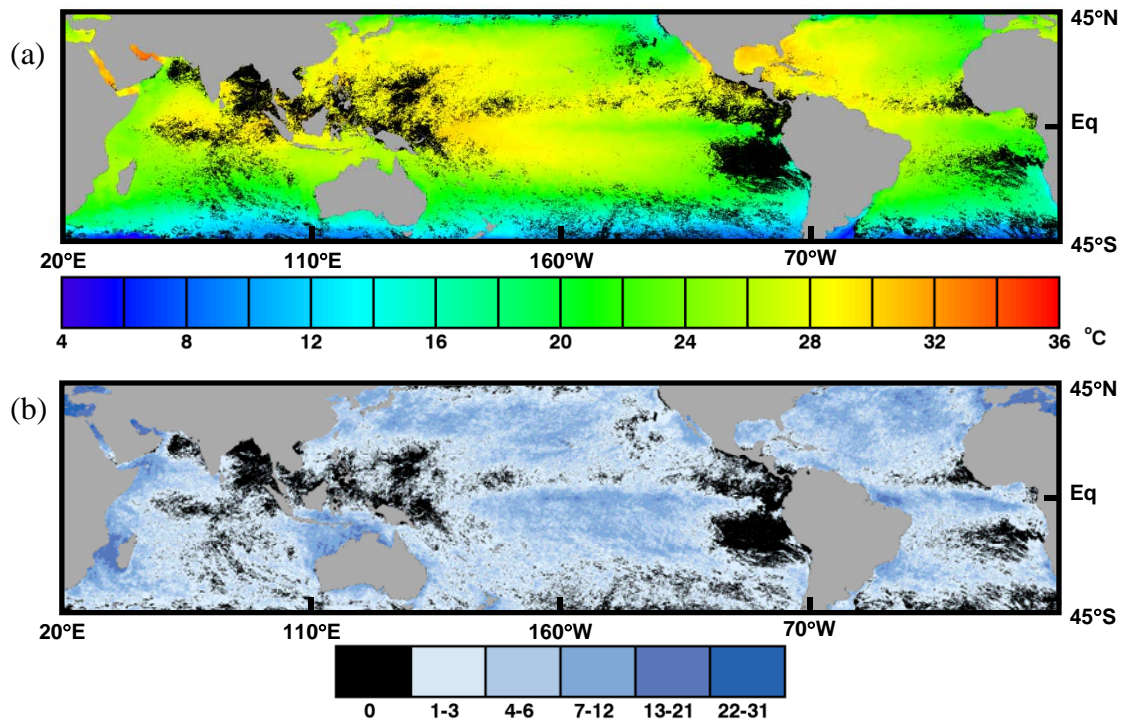


Figure 1. August 2005 (a) monthly mean SST data; and (b) number of contributing days. Missing values (black pixels) in the upper panel correspond with zero counts (black pixels) in the lower panel.

Across the entire dataset of 24,975,883 ocean pixels and 28 years of 12 monthly values (totaling over 8.3 billion pixel-months), over one-third of global pixel-months had no high-quality daily SST values (34.9%, Figure 2). Of the 65.1% of global monthly mean SSTs that were assigned a value, the great majority resulted from 1-6 daily values (55.7 of 65.1%). There were only 74 instances of pixel-months having 100% of daily SST values. In ‘tropical’ waters (35°S to 35°N) the proportion of missing pixel-months was reduced: 10.6% of over 3.5 billion pixel-months had no high-quality daily SST values. Similar to the global domain, the great majority of values in tropical waters resulted from 1-6 daily values (71.8 of 89.4%); however, there were no instances of pixel-months having 100% of daily SST values.

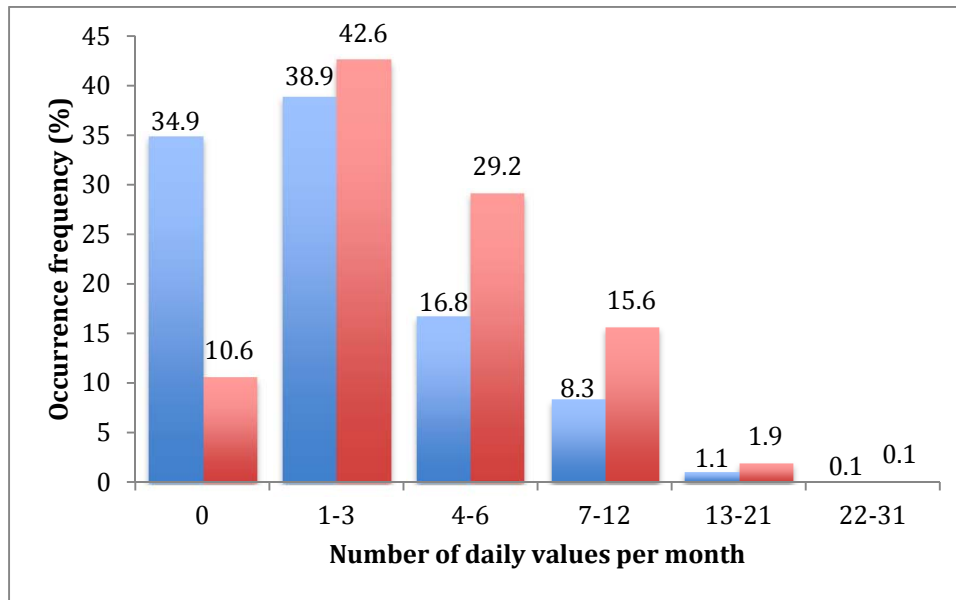


Figure 2. Frequency histogram of the number of values per month for global (blue) and tropical (35°S-35N, red) ocean pixels (including coastal pixels) in Pathfinder v5.2 SST data.

[2] At each pixel and for each month, the (up to) 28 monthly mean SST values were averaged to produce the monthly mean climatology (hereafter, the “raw” climatology; Figure 3), resulting in 12 values (for January, February, etc.) for each pixel. The number of contributing monthly mean SST values was also recorded (number between 0 and 28). Where no monthly mean SST values existed for a pixel (e.g., permanent ice), the monthly mean climatology was left empty. While some polar regions had no monthly mean values because of ice cover, some tropical and temperate pixels contained no PFv5.2 values of quality 4 or higher for particular months because of persistent cloud cover. All available PFv5.2 data across the entire 28-year period were used for this calculation to minimize effects from short-term (several years) variability and to maximize data density for deriving the climatology.

[3] The use of 28 years (1985-2012) of SST data created a climatology with a temporal mid-point in mid-1998. This was more than 10 years later than the temporal mid-point of the 50-km Heritage climatology (early-1988). In an era of rapid warming, this had the potential to substantially modify the historical baseline temperature, the resulting anomaly values, and the derived products. To use the full available data period, but also to maintain consistency with the

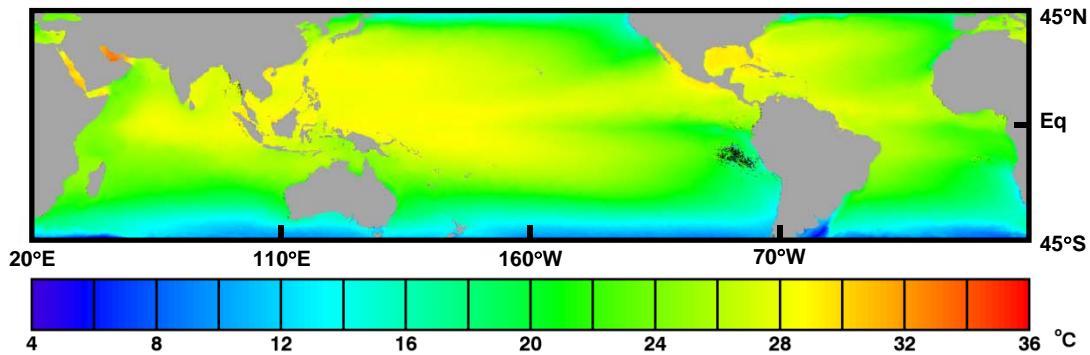


Figure 3. Monthly mean “raw” climatology for August calculated by averaging the August monthly mean SST values across the 28-year period. Black pixels off the west coast of South America indicate that no August monthly mean SST values existed for the entire 28 years.

interpretation of the Heritage 50-km products, climatological average values were re-centered to match the temporal mid-point of the 50-km climatology. Furthermore, there is limited evidence for the capacity for coral ecosystems to adaptively respond to increasing temperature under climate change (see Logan et al. 2013 and references therein). Adjusting the new 28-year climatology values to the time-center of the existing Heritage products presents a conservative position with respect to thermal stress monitoring and resultant impacts.

Re-centering of the climatology to the temporal mid-point of the Heritage climatology followed the methodology described in Heron et al. (2014) in the development of the Enhanced 50-km climatology. This involved calculating the linear trend in the monthly mean SST for each month and at each pixel over the data period and applying the linear trend to adjust the values to represent temperatures at the earlier time. Recognizing that warming trends vary both spatially and seasonally (Chollett et al. 2012), linear trends in monthly mean SST values were separately calculated for each of the 12 calendar months at each pixel (Figure 4). The trend at each pixel was used to adjust the 28-year climatology value for each month to match the temporal mid-point of the original 50-km climatology (Figure 5). This produced the “re-centered” monthly climatology at the time-center of the Heritage products but derived from the full 28-year dataset (Figure 6). The trend at some pixel-months could not be determined as there were less than two monthly mean SST values; the re-centered monthly climatology value was left unassigned in such instances.

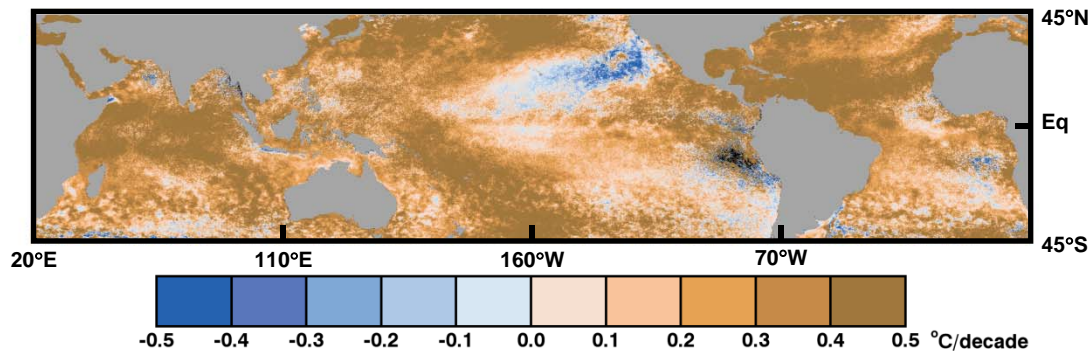


Figure 4. Linear trends for the month of August calculated at each pixel through the 1985-2012 time-series. Black pixels off the west coast of South America indicate that no trend value was determined due to insufficient (less than two) monthly mean SST values. Some calculated trends for August were clearly erroneous, ranging from -100 to 124 °C/decade globally and -68 to 109 °C/decade within [45°S, 45°N].

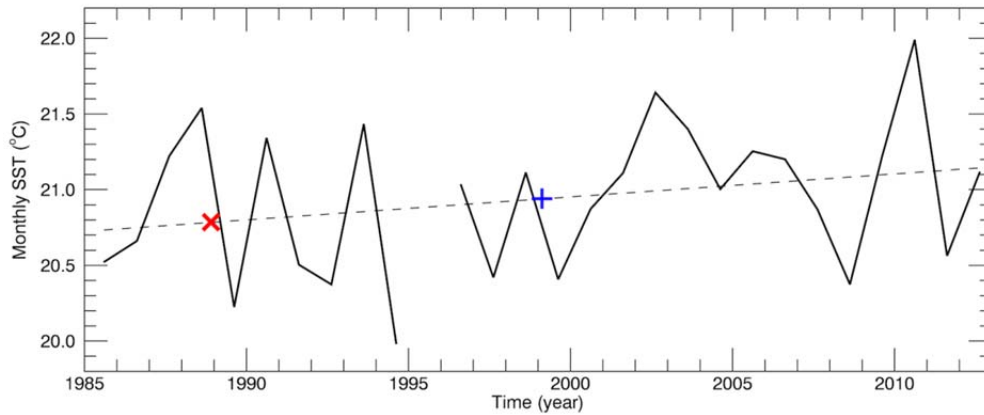


Figure 5. Time series of August monthly-mean temperature from Pathfinder v5.2 (solid line) observed at 151.94°W, 23.48°S, near Heron Island in the Great Barrier Reef, Australia. No high-quality daily SST values existed during August 1995, resulting in the gap in the monthly time series. The linear trend (dashed line) shows warming through the record. The 28-year August climatology temperature (1985-2012, blue +) was re-centered using the linear trend to the time-center of the CRW 50-km climatology (1985-1990 + 1993, red x) to maintain consistent interpretation of derived products.

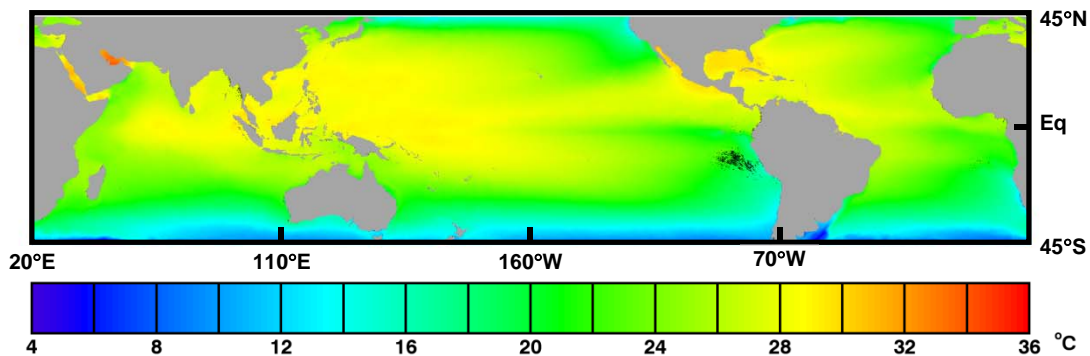


Figure 6. Monthly mean climatology for August re-centered in time to match the temporal mid-point of the original CRW 50-km climatology (i.e., early-1988). Re-centering was undertaken using the linear trend in SST for each pixel and each month separately. Black pixels off the west coast of South America indicate that no re-centered value was determined due to insufficient (less than two) monthly mean SST values.

[4] Pixels with low data density had the potential to result in erroneous trend values, which in turn resulted in erroneous re-centered climatology values. Erroneous values in the re-centered climatology were identified for each pixel as being outside the range of monthly mean SST values for that pixel calculated in step [1]. The identified erroneous values were replaced based on spatial patterns immediately surrounding the pixel in the raw climatology, following the method applied in Heron et al. (2010). Briefly, valid re-centered climatology values in the (up to eight) pixels surrounding the erroneous climatology value were compared with the raw climatology values from the same pixels. The mean difference between these was used to adjust the raw climatology temperature to provide the revised re-centered climatology value. Where necessary (e.g., where multiple adjacent pixels were erroneous), this process was applied iteratively.

[5] For locations with less than two monthly mean SST values, no trend could be determined and therefore no re-centered climatology value was calculated. Due to the spatially smooth nature of

climatological averages, these remaining data gaps were assigned values using kriging (Krige, 1951). Kriging is a spatial interpolation method that uses spatial patterns in existing data to assign values to data gaps based on distance from data points and their spatial covariance. As such, distant data have dramatically less input to an assigned value, compared with nearby data points. Due to requirements in building the covariance matrix, the time required for kriging increased exponentially with the size of the spatial domain (exponent = 0.106) and increased with number of existing values within that domain. For efficiency, kriging was performed using overlapping small-size tiles across the global domain rather than kriging the entire global data dataset as a whole. Overlapping adjacent tiles ensured continuity of values across tile edges. Tile dimensions were 60×60 pixels (i.e., $2.5^\circ \times 2.5^\circ$) with an additional 10 pixels (0.417°) on each side as the overlap (excepting at the northern- and southern-most polar extremes). This resulted in 144 tiles zonally and 72 tiles meridionally. The use of tiles also permitted parallelizing the kriging process (i.e., running different global sectors at the same time).

These first five steps resulted in a spatially replete monthly climatology at the 4-km resolution of the PFv5.2 dataset, derived from the 28 years of available data and adjusted to reflect the time-center of the existing (Heritage) CRW products (Figure 7).

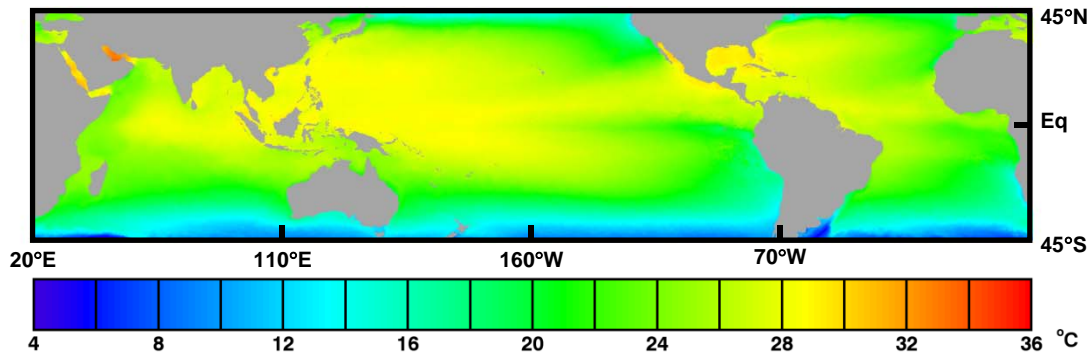


Figure 7. Spatially replete monthly mean climatology for August. Kriging was employed to provide climatology values for pixels where fewer than two monthly SST values existed.

3.2 Bias adjustment

Typically, different SST algorithms produce slightly different values. The second stage of the climatology development involved comparing the PFv5.2 and Blended 5-km SST datasets to quantify differences between them (i.e., the bias). The determined relationship would be used to bias-adjust the climatology values derived from PFv5.2 to ensure consistency with the near real-time Blended SST data.

However, determining the bias-adjustment relationship was confounded as there was no overlap between the night-only 5km SST (released March 2013) and PFv5.2 SST (available through December 2012). An earlier version of the Blended 5-km SST product, including geo-polar retrievals from both day and night, was available from March 2012. Comparisons between the night-only and day-night Blended SST products indicated that they were not statistically different; therefore we used the day-night product to statistically determine bias between PFv5.2 and night-only Blended 5-km SST values.

Though limited in duration, the full overlap period (27 March–31 December 2012) was used to pair spatio-temporally co-located 4-km daily PFv5.2 night-only SST values with their corresponding daily Blended 5-km day-night SST values for ‘tropical’ waters (35°S–35°N, which encompasses all coral reef-containing locations). These data pairs involved individual daily SST values, not climatology values. This resulted in over 361 million pairs. The bias-adjustment relationship was determined by binning the pairs by Blended SST values (0.1 °C bins) and calculating the mean and standard deviation of matching PFv5.2 SST values within each bin (see also Garde et al. 2014). This demonstrated a generally linear relationship between the datasets (Figure 8).

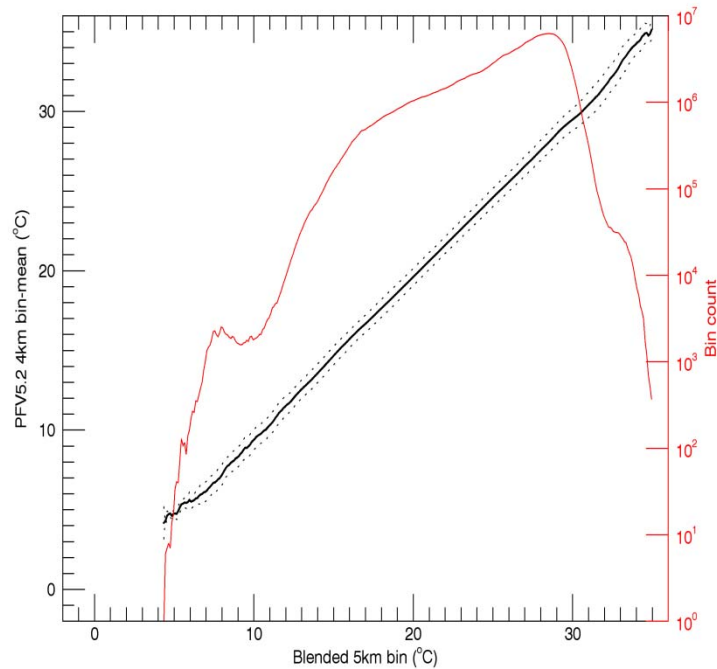


Figure 8. Comparison of the Blended 5-km and PFv5.2 4-km SST data from tropical waters [35°S–35°N]. Blended 5-km values were binned into 0.1 °C increments and paired with the mean of corresponding PFv5.2 4-km values (thick black line). The standard deviation of PFv5.2 values in each bin is shown above and below the mean (dotted lines). The number of pairs in each bin (red line) is referenced to the right-hand axis.

At both low and high limits of the Blended 5-km SST distribution, substantial fluctuations in the bias-adjustment relationship coincided with low density of paired SST values (Figure 8). While coral reef locations have infrequently experienced temperatures at the low end (below Blended SST values of 6.1 °C), global application required that the bias-adjustment relationship below this threshold be determined. Because tropical pixels don’t experience these low temperatures, the binning approach was repeated using pairs from global coastal pixels (i.e., adjacent to land). Only coastal ocean pixels (adjacent to the dataset land mask) were used to maintain the focus of the analysis in near-shore regions. Bin-mean PFv5.2 values from the global coastal analysis were used below Blended SST values of 6.1 °C (Figure 9a).

More pertinent to the application for coral reefs, Blended SST values above 34.6 °C were also infrequent and the relationship (dashed line in Figure 9b) clearly departed from the strong linearity. This may have resulted from a constraint in the Blended SST algorithm, where geostationary SST values are capped at 35.0 °C. To provide a reasonable adjustment relationship

for Blended SST values above 34.6 °C, the linear relationship of the 10 warmest binned values immediately below this threshold (Blended 5-km SST: 33.65–34.55 °C) was calculated ($PFv5.2 = -3.265 + 1.104 * \text{Blended SST}$, $r^2 = 0.992$) and extrapolated for higher temperatures (red line in Figure 9b). For reference, the warmest value in the final PFv5.2 monthly climatology described in Section 3.1 was 35.18 °C, which is in the extrapolation domain and corresponds to a Blended 5-km SST of 34.82 °C.

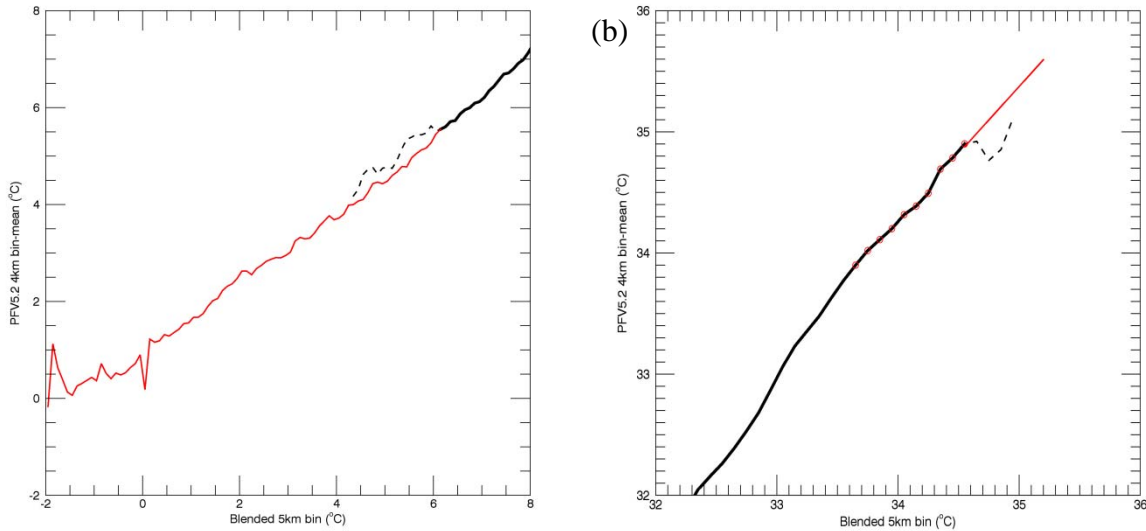


Figure 9. Correction of the bias-adjustment relationship between the Blended 5-km and PFv5.2 4-km SST data in regions with low data density. (a) Below 6.1 °C, the relationship at tropical reef locations (black dashed) is replaced with the relationship from global coastal pixels (red line). (b) Above 34.6 °C, the relationship at tropical reef locations (black dashed) is replaced by extrapolation (red line) of the 10 warmest reliable binned values (red circles). In both panels, the solid black line indicates unaltered values.

An essential criterion of the bias-adjustment relationship is monotonicity; i.e., each Blended SST value must have a mutually unique PFv5.2 SST value. The only temperature values that were not monotonic were at Blended SST values below 6.1 °C and in the range 9.35–9.45 °C; i.e., cooler than normal summertime temperatures at reef locations. Monotonicity of the relationship in these regions was achieved through local linear interpolation. Linear regression of 11 points centered on each non-monotonic value was undertaken. Outliers in the regression were identified as having a residual of more than 1.5 times the standard error of estimate when the overall goodness of fit was below $r^2 = 0.99$. Any points determined as outliers were excluded and the local regression repeated (with fewer points). When no outliers remained, only non-monotonic values were replaced by linear interpolation.

The final bias-adjustment relationship between the PFv5.2 and Blended 5-km SST datasets was strongly linear ($r^2 = 0.998$; Figure 11). Despite the strong linearity, variations still remained – particularly at higher temperatures associated with coral bleaching. Therefore, to retain as much information as possible, the bias adjustment was undertaken using a “lookup table” approach (Table 1), with localized linear interpolation between binned values. The bias adjustment was applied to the spatially replete PFv5.2 monthly climatology (Figure 7) and resulted in the bias-adjusted monthly climatology (Figure 12) to best match values of the 5-km night-only Blended SST.

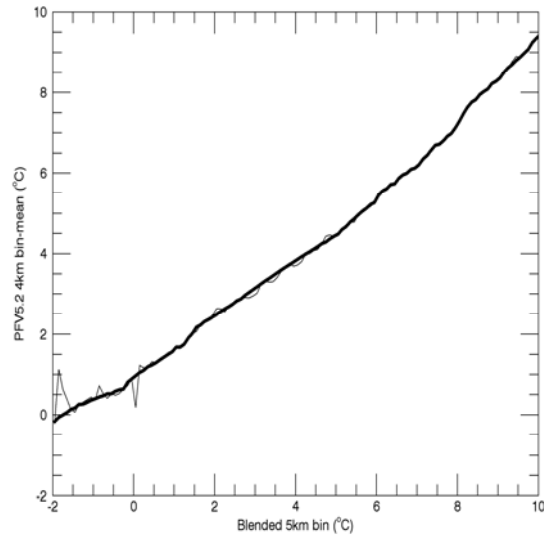


Figure 10. Replacement of non-monotonic values (thin line) was performed by local linear interpolation based on non-outlier values at the low range of temperature.

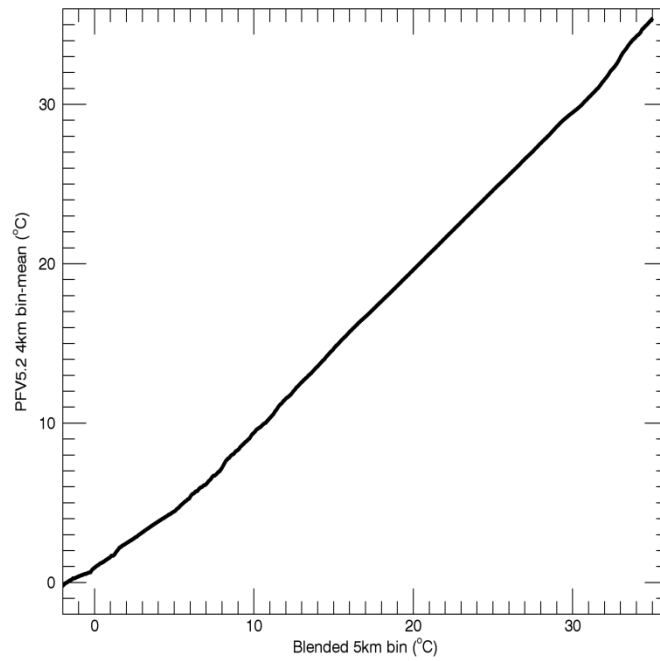


Figure 11. Graphical representation of the final bias-adjustment relationship between the PFv5.2 and Blended 5-km SST datasets.

Table 1. Bias-adjustment lookup table to convert between the PFv5.2 and Blended SST datasets.

Blended	PFv5.2	Blended	PFv5.2	Blended	PFv5.2	Blended	PFv5.2	Blended	PFv5.2
-1.95	-0.17	2.45	2.74	6.85	6.09	11.25	10.60	15.65	15.35
-1.85	-0.07	2.55	2.83	6.95	6.12	11.35	10.77	15.75	15.45
-1.75	-0.01	2.65	2.87	7.05	6.21	11.45	10.89	15.85	15.55
-1.65	0.05	2.75	2.96	7.15	6.35	11.55	11.05	15.95	15.66
-1.55	0.13	2.85	3.03	7.25	6.44	11.65	11.16	16.05	15.77
-1.45	0.17	2.95	3.10	7.35	6.57	11.75	11.25	16.15	15.87
-1.35	0.26	3.05	3.18	7.45	6.69	11.85	11.38	16.25	15.97
-1.25	0.26	3.15	3.25	7.55	6.71	11.95	11.47	16.35	16.07
-1.15	0.31	3.25	3.32	7.65	6.80	12.05	11.58	16.45	16.16
-1.05	0.36	3.35	3.39	7.75	6.91	12.15	11.65	16.55	16.27
-0.95	0.40	3.45	3.46	7.85	6.98	12.25	11.73	16.65	16.36
-0.85	0.44	3.55	3.53	7.95	7.12	12.35	11.84	16.75	16.45
-0.75	0.47	3.65	3.60	8.05	7.29	12.45	11.96	16.85	16.54
-0.65	0.52	3.75	3.66	8.15	7.47	12.55	12.08	16.95	16.63
-0.55	0.52	3.85	3.72	8.25	7.64	12.65	12.20	17.05	16.72
-0.45	0.58	3.95	3.79	8.35	7.76	12.75	12.31	17.15	16.81
-0.35	0.62	4.05	3.86	8.45	7.82	12.85	12.42	17.25	16.91
-0.25	0.64	4.15	3.92	8.55	7.95	12.95	12.52	17.35	17.01
-0.15	0.80	4.25	3.99	8.65	8.02	13.05	12.62	17.45	17.10
-0.05	0.88	4.35	4.05	8.75	8.09	13.15	12.72	17.55	17.20
0.05	0.97	4.45	4.11	8.85	8.22	13.25	12.81	17.65	17.30
0.15	1.05	4.55	4.17	8.95	8.28	13.35	12.91	17.75	17.40
0.25	1.10	4.65	4.25	9.05	8.36	13.45	13.01	17.85	17.50
0.35	1.19	4.75	4.29	9.15	8.50	13.55	13.09	17.95	17.60
0.45	1.23	4.85	4.37	9.25	8.61	13.65	13.20	18.05	17.69
0.55	1.29	4.95	4.43	9.35	8.69	13.75	13.31	18.15	17.79
0.65	1.36	5.05	4.48	9.45	8.79	13.85	13.42	18.25	17.89
0.75	1.43	5.15	4.60	9.55	8.88	13.95	13.52	18.35	17.98
0.85	1.50	5.25	4.67	9.65	8.98	14.05	13.62	18.45	18.08
0.95	1.56	5.35	4.78	9.75	9.07	14.15	13.74	18.55	18.17
1.05	1.67	5.45	4.87	9.85	9.24	14.25	13.84	18.65	18.27
1.15	1.68	5.55	4.96	9.95	9.35	14.35	13.94	18.75	18.37
1.25	1.75	5.65	5.05	10.05	9.44	14.45	14.05	18.85	18.47
1.35	1.90	5.75	5.13	10.15	9.58	14.55	14.17	18.95	18.57
1.45	2.02	5.85	5.22	10.25	9.65	14.65	14.28	19.05	18.67
1.55	2.17	5.95	5.27	10.35	9.72	14.75	14.39	19.15	18.77
1.65	2.23	6.05	5.45	10.45	9.78	14.85	14.50	19.25	18.87
1.75	2.32	6.15	5.55	10.55	9.89	14.95	14.60	19.35	18.97
1.85	2.37	6.25	5.60	10.65	9.98	15.05	14.72	19.45	19.07
1.95	2.43	6.35	5.71	10.75	10.02	15.15	14.83	19.55	19.16
2.05	2.49	6.45	5.73	10.85	10.15	15.25	14.94	19.65	19.26
2.15	2.56	6.55	5.87	10.95	10.27	15.35	15.04	19.75	19.36
2.25	2.62	6.65	5.95	11.05	10.36	15.45	15.16	19.85	19.46
2.35	2.68	6.75	6.00	11.15	10.47	15.55	15.26	19.95	19.56

Table 1. Bias-adjustment lookup table to convert between the PFv5.2 and Blended SST datasets. (cont.)

Blended	PFv5.2	Blended	PFv5.2	Blended	PFv5.2	Blended	PFv5.2
20.05	19.66	23.85	23.45	27.65	27.20	31.45	30.89
20.15	19.76	23.95	23.55	27.75	27.31	31.55	30.98
20.25	19.86	24.05	23.65	27.85	27.41	31.65	31.09
20.35	19.96	24.15	23.75	27.95	27.51	31.75	31.23
20.45	20.06	24.25	23.85	28.05	27.61	31.85	31.36
20.55	20.16	24.35	23.95	28.15	27.71	31.95	31.48
20.65	20.26	24.45	24.05	28.25	27.81	32.05	31.61
20.75	20.36	24.55	24.15	28.35	27.91	32.15	31.74
20.85	20.47	24.65	24.25	28.45	28.01	32.25	31.87
20.95	20.56	24.75	24.35	28.55	28.11	32.35	32.05
21.05	20.66	24.85	24.45	28.65	28.21	32.45	32.16
21.15	20.76	24.95	24.55	28.75	28.32	32.55	32.26
21.25	20.86	25.05	24.65	28.85	28.43	32.65	32.39
21.35	20.96	25.15	24.75	28.95	28.54	32.75	32.53
21.45	21.06	25.25	24.85	29.05	28.65	32.85	32.68
21.55	21.16	25.35	24.95	29.15	28.76	32.95	32.87
21.65	21.26	25.45	25.04	29.25	28.86	33.05	33.06
21.75	21.36	25.55	25.13	29.35	28.95	33.15	33.23
21.85	21.46	25.65	25.22	29.45	29.04	33.25	33.36
21.95	21.56	25.75	25.32	29.55	29.12	33.35	33.48
22.05	21.66	25.85	25.42	29.65	29.21	33.45	33.63
22.15	21.76	25.95	25.52	29.75	29.29	33.55	33.77
22.25	21.86	26.05	25.62	29.85	29.38	33.65	33.90
22.35	21.96	26.15	25.72	29.95	29.45	33.75	34.02
22.45	22.06	26.25	25.82	30.05	29.53	33.85	34.11
22.55	22.16	26.35	25.91	30.15	29.61	33.95	34.20
22.65	22.26	26.45	26.01	30.25	29.69	34.05	34.32
22.75	22.36	26.55	26.11	30.35	29.77	34.15	34.39
22.85	22.45	26.65	26.21	30.45	29.86	34.25	34.49
22.95	22.56	26.75	26.31	30.55	29.95	34.35	34.69
23.05	22.66	26.85	26.42	30.65	30.06	34.45	34.78
23.15	22.76	26.95	26.52	30.75	30.16	34.55	34.90
23.25	22.86	27.05	26.62	30.85	30.27	34.65	34.99
23.35	22.96	27.15	26.71	30.95	30.37	34.75	35.10
23.45	23.05	27.25	26.81	31.05	30.47	34.85	35.21
23.55	23.15	27.35	26.90	31.15	30.57	34.95	35.32
23.65	23.26	27.45	27.00	31.25	30.67		
23.75	23.35	27.55	27.10	31.35	30.78		

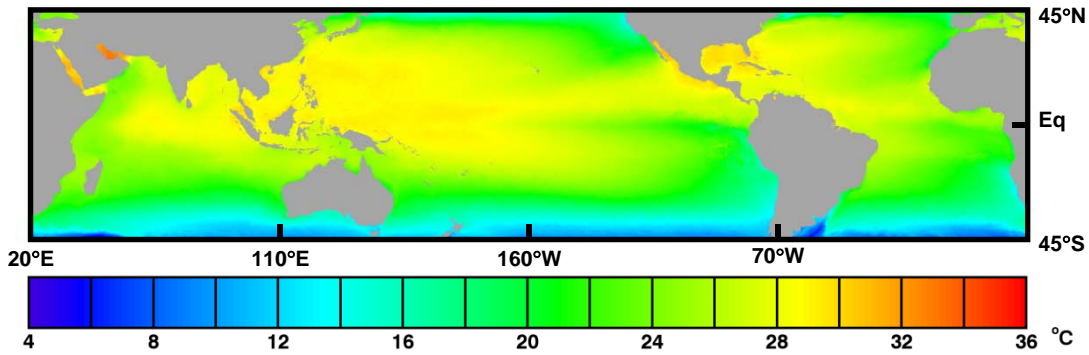


Figure 12. Bias-adjusted monthly mean climatology for August, produced using the PFv5.2 climatology shown in Figure 7 and the bias-adjustment relationship between the PFv5.2 and Blended SST values shown in Table 1.

3.3 Regrid to 5-km

The third stage of the climatology development was to re-grid the bias-adjusted PFv5.2 4-km monthly climatology to the Blended 5-km SST grid. This was undertaken using a pixel weighting based on the area of overlap between the PFv5.2 and Blended pixels. Considering the precise spatial resolutions ($1/24^\circ$ and $1/20^\circ$, respectively), there is a repeating pattern of the overlap every $1/4^\circ$ which contains 6×6 PFv5.2 4-km pixels (Figure 13a) and 5×5 Blended 5-km pixels (Figure 13b). When aligned, each Blended 5-km pixel overlaps four PFv5.2 4-km pixels, with six unique combinations of overlap (A-F in Figure 13c). For example, each of the 5-km pixels in the corners of Figure 13c follows the pattern of pixel “A”. The weighting assigned to each contributing PFv5.2 SST value is based on the area of overlap with the Blended 5-km pixel (Figure 13d), with the Blended SST values calculated as:

$$SST5 = \frac{\sum_{i=1}^4 weight_i * SST4_i}{\sum_{i=1}^4 weight_i}$$

As an example for the 5-km pixel labeled “B”, contributing PFv5.2 SST values [29.0, 28.8, 28.7, 28.7] °C, corresponding to weights [20, 10, 4, 2], will result in a re-gridded Blended SST value of $(29.06*20 + 29.12*10 + 28.98*4 + 29.10*2)/(20 + 10 + 4 + 2) = 29.07$ °C. Comparing the PFv5.2 4-km August climatology (Figure 12) with the re-gridded 5-km climatology (Figure 14) demonstrates their spatial consistency.

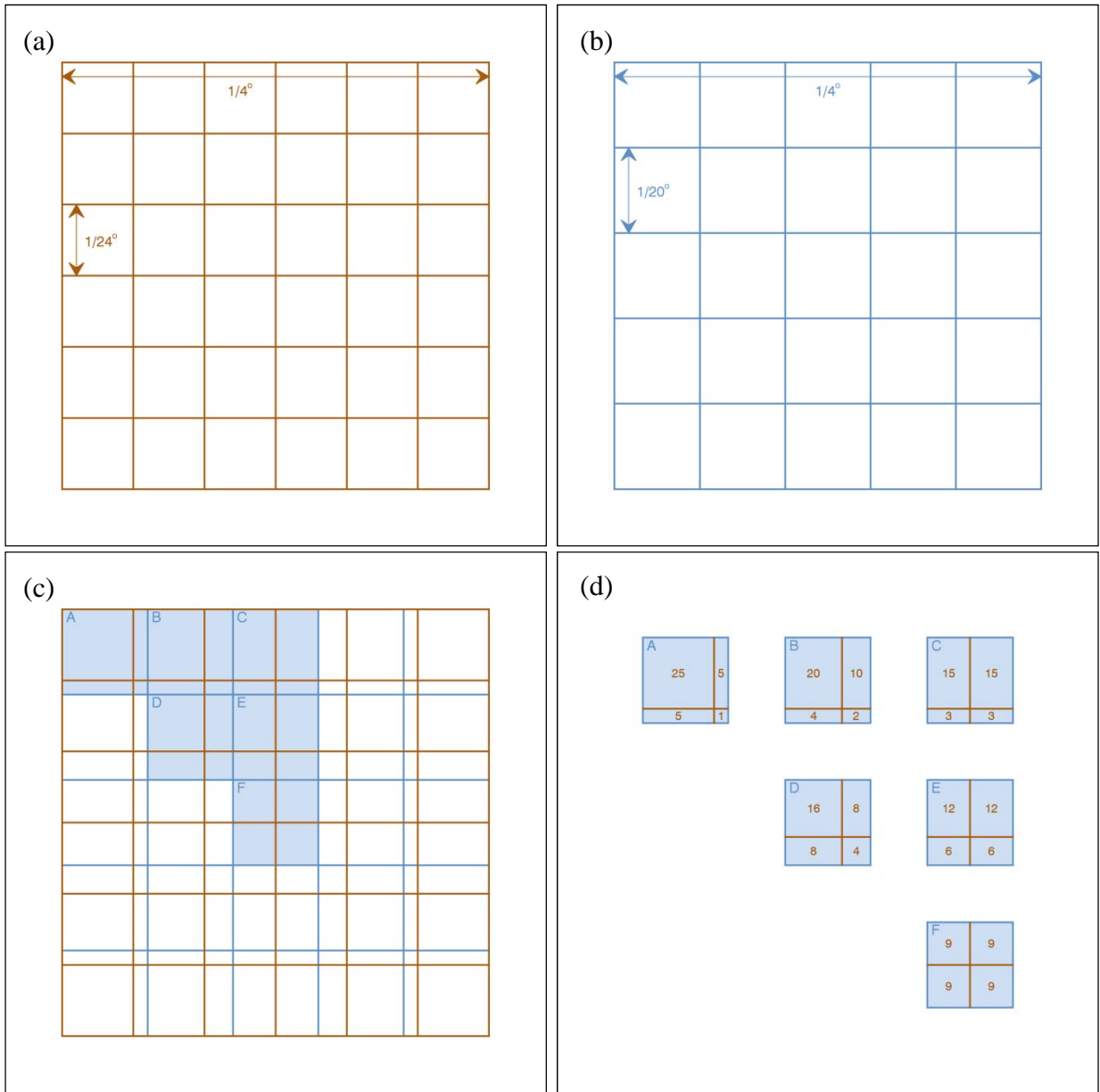


Figure 13. Schematic of the re-gridding process from the PFv5.2 4-km grid to the Blended 5-km grid. The grid repeats every 0.5° (in latitude and longitude) in both the (a) PFv5.2 grid; and (b) the Blended 5-km grid. (c) Overlaying these reveals six unique combinations of overlap between a single Blended 5-km pixel and four PFv5.2 4-km pixels, A-F. (d) Each PFv5.2 SST value is weighted according to the relative area of overlap with the Blended 5-km pixel.

The final step in the climatology development for application to the CRW 5-km product suite was to determine the warmest monthly climatology value at each pixel resulting in the 5-km maximum of the monthly means (MMM) climatology (Figure 15). While each of the monthly and MMM climatologies vary spatially they are, by definition, static in time.

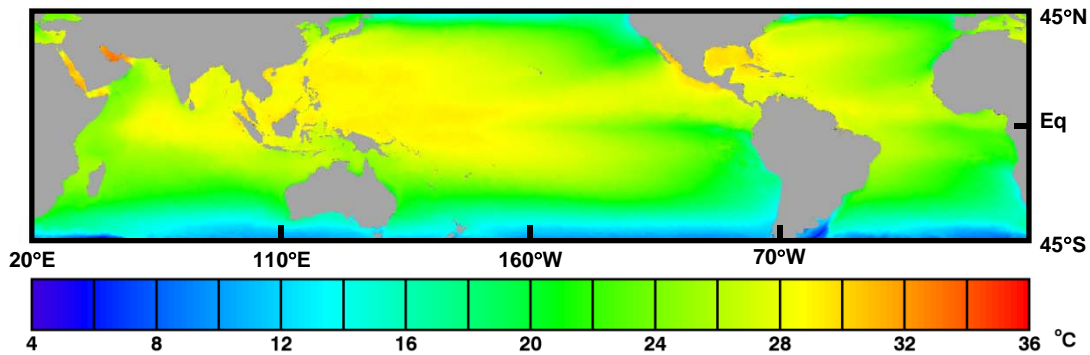


Figure 14. Final monthly mean climatology for August re-gridded to 5-km resolution, used in the production of the CRW 5-km SST Anomaly product.

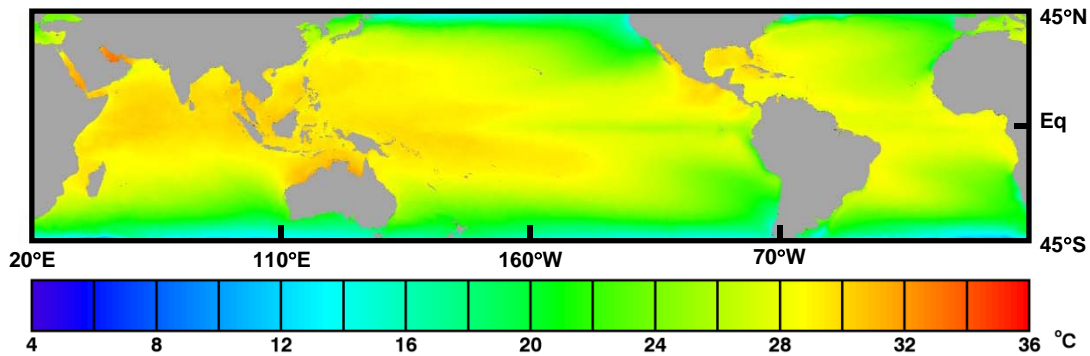


Figure 15. The maximum of the monthly means (MMM) climatology at 5-km resolution for application in the CRW 5-km product suite for coral-specific products (HotSpots and Degree Heating Weeks).

4 Discussion

Direct comparison of the new 5-km MMM climatology with the existing Heritage and Enhanced 50-km MMM climatologies can provide an indication of changes in spatial patterns that may result when the 5-km climatology is applied. For the purpose of comparison between the datasets, the 50-km MMM data were re-sampled to 5-km resolution (precisely 0.5-degree and 0.05-degree, respectively). This was performed by assigning the same 50-km temperature value to each of the contained 100 pixels at 5-km resolution. No smoothing or interpolation was undertaken. However, comparison between the MMM values could also be confounded by a lack of bias adjustment necessary to ensure consistency of the SST datasets.

To estimate the bias-adjustment relationship (and in lieu of a full bias adjustment calculation), SST data from one randomly selected date (28 August 2014) were compared. This revealed strong linearity of the 5-km SST with each of the 50-km datasets, when considering the global domain [90°S-90°N]:

$$\text{Blended 5-km SST} = -0.46 + 1.02 * \text{Heritage 50-km SST} \quad (r^2=0.99, \text{SE}=1.02), \text{ and}$$

$$\text{Blended 5-km SST} = -0.54 + 1.03 * \text{Enhanced 50-km SST} \quad (r^2=0.99, \text{SE}=1.08).$$

These global relationships reveal that the 5-km SST is cooler than the 50-km SST data at low temperatures (as evidenced by the negative intercepts). From the calculated relationships, the 5-km SST is warmer than (i) the Heritage 50-km SST values above 19.3 °C; and (ii) the Enhanced 50-km SST values above 20.2 °C.

Considering only the tropical domain [35°S-35°N], the linear relationships were determined as:

$$\text{Blended 5-km SST} = 0.65 + 0.98 * \text{Heritage 50-km SST} \quad (r^2=0.98, \text{SE}=0.58),$$

$$\text{Blended 5-km SST} = 0.65 + 0.98 * \text{Enhanced 50-km SST} \quad (r^2=0.98, \text{SE}=0.59)$$

For the tropical domain, the 5-km SST is warmer than the 50-km SST data for the range of oceanic temperatures generally experienced by corals (up to 35.5 °C for the Heritage 50-km SST and up to 35.7 °C for the Enhanced 50-km SST). In summary, the comparison of SST values from a single date suggests that 5-km SST values are warmer than 50-km SST values in the range 20-35 °C.

With these SST relationships in mind, a direct comparison of the 5-km and (re-gridded) 50-km MMM climatologies from each of the Heritage and Enhanced product suites was undertaken. The global median difference between the 5-km and Heritage 50-km MMM climatologies was +0.07 °C, indicating that the 5-km MMM is, as expected, generally warmer (Figure 16a). In the [35°S, 35°N] domain, the median difference was +0.15 °C. The consistency of the 5-km SST and MMM values both being warmer than the corresponding 50-km values points to consistency in the difference between these; i.e., the HotSpots value. However, there are several regions for which the new climatology is clearly cooler than the Heritage MMM (e.g., the northwestern and southeastern Pacific Ocean, the equatorial and southern Atlantic Ocean, parts of the southern Indian Ocean). Such locations are important to identify and closely monitor because of the lower threshold for defining thermal stress in these areas. However, there is also the possibility of regional variation in the difference between the SST datasets. A more rigorous analysis is required, beyond the scope of this report.

Comparison of the 5-km MMM with the Enhanced 50-km MMM climatology was very similar, revealing a median difference of +0.06 °C, again indicating that the 5-km MMM is, as expected, generally warmer (Figure 16b). The great majority of locations within [35°S, 35°N] were also warmer in the 5-km MMM, with a median value of +0.15 °C. The reduced spatial variation seen in Figure 16b, compared with Figure 16a, is likely related to the similarity in methodology and datasets used to produce the 5-km and Enhanced 50-km climatologies.

The true performance test of the new 5-km climatology and product suite comes through comparison of accumulated thermal stress (DHW) with the 50-km monitoring products and, especially so with observations of ecosystem impacts from thermal stress (e.g., coral bleaching). As stated above, one of the development priorities was to maintain consistency with the existing interpretation of the monitoring products for application in coral reef management. Initial visual comparisons of the DHW charts of 28 August 2014 from the 5-km, Heritage 50-km and Enhanced 50-km product suites showed general consistency of accumulated thermal stress values (Figure 17).

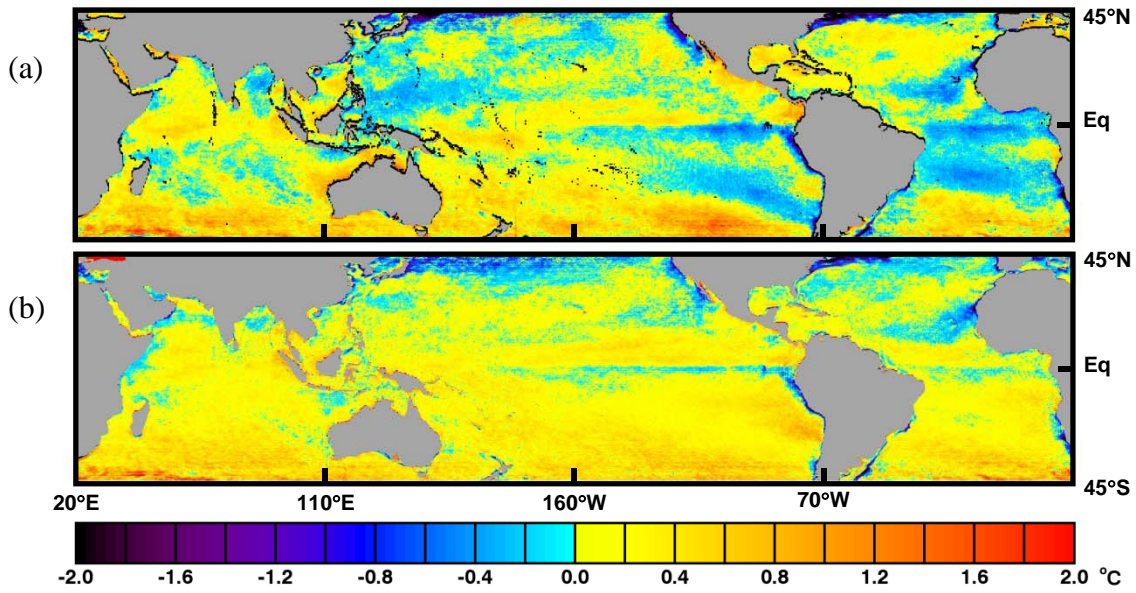


Figure 16. Difference in 5-km MMM climatology as compared with (a) the Heritage 50-km climatology; and (b) the Enhanced 50-km climatology. Positive values indicate the new 5-km climatology is warmer. Black coastal pixels, clearly visible in the upper panel, had no value assigned in the 50-km climatologies.

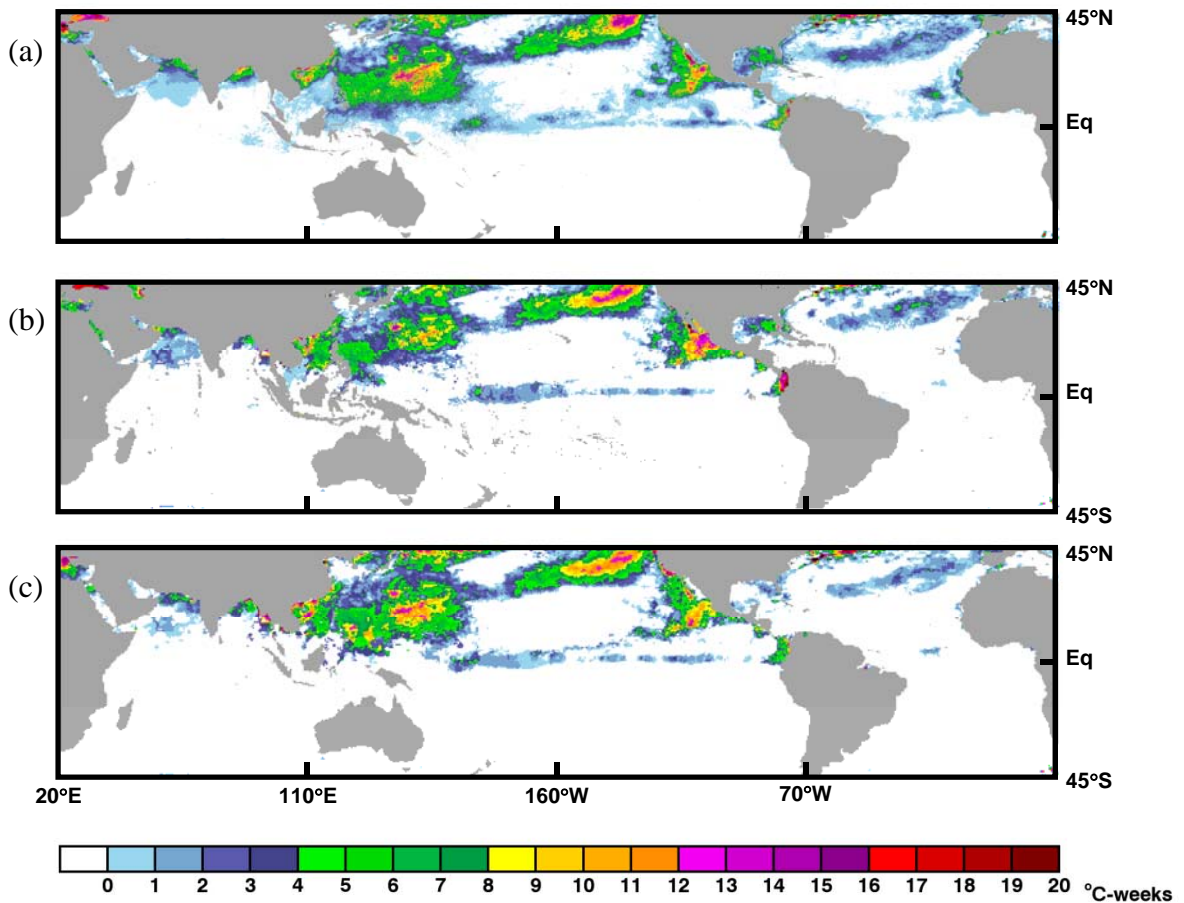


Figure 17. Accumulated thermal stress (Degree Heating Weeks) on 28 August 2014 in CRW's (a) new 5-km product suite; (b) Heritage 50-km product suite; and (c) Enhanced 50-km product suite.

The development of the 5-km MMM climatology and the launch of the 5-km product suite to monitor thermal stress in near real-time have been timely due to recent observations of coral bleaching in the Commonwealth of the Northern Mariana Islands, the Hawaiian archipelago, and the Florida Keys. Initial comparison of the new satellite 5-km product suite with in situ bleaching observations indicates that the 5-km product suite (including the new MMM climatology) is performing well. For example, in the Mariana Islands (Figure 18) local partners reported that bleaching was most severe in the northern islands of the archipelago, consistent with the highest exposure to thermal stress, and less severe in the south (Liu et al. 2014). A complete quantitative analysis of field survey data and the new 5-km thermal stress products is planned. More importantly, though, resource managers in all of these jurisdictions have enthusiastically employed CRW's higher resolution remote sensing products.

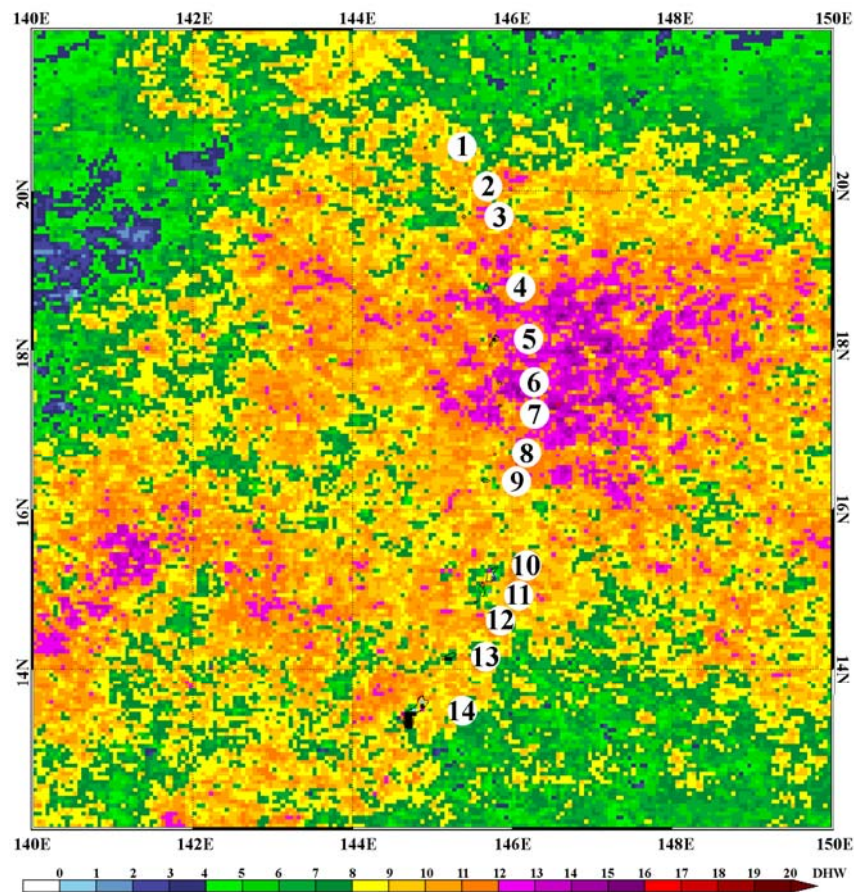


Figure 18. Thermal stress in the Commonwealth of the Northern Mariana Islands (islands numbered 1-13) and Guam (14) on 24 August 2014 showed a consistent spatial pattern with reports of bleaching severity across the archipelago (after Liu et al. 2014).

5 Conclusion

The development of high-resolution temperature climatologies has provided the capacity for global satellite monitoring at or near the scale of coral reefs. The new climatologies are a critical component of the new CRW 5-km global coral bleaching thermal stress monitoring product suite. Recent thermal stress events and associated observations of coral bleaching allowed an initial evaluation of the performance of the products. The new products provide managers

worldwide with unprecedented spatial and temporal resolution for management of coral reef resources.

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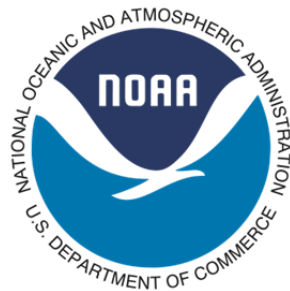
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