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Article

Reef-Scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch

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Abstract: The U.S. National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch (CRW) program has developed a daily global 5-km product suite based on satellite observations to monitor thermal stress on coral reefs. These products fulfill requests from coral reef managers and researchers for higher resolution products by taking advantage of new satellites, sensors and algorithms. Improvements of the 5-km products over CRW's heritage global 50-km products are derived from: (1) the higher resolution and greater data density of NOAA's next-generation operational daily global 5-km geo-polar blended sea surface temperature (SST) analysis; and (2) implementation of a new SST climatology derived from the Pathfinder SST climate data record. The new products increase near-shore coverage and now allow direct monitoring of 95% of coral reefs and significantly reduce data gaps caused by cloud cover. The 5-km product suite includes SST Anomaly, Coral Bleaching HotSpots, Degree Heating Weeks and Bleaching Alert Area, matching existing CRW products. When compared with the 50-km products and *in situ* bleaching observations for 2013–2014, the 5-km products identified known thermal stress events and matched bleaching observations. These near reef-scale products significantly advance the ability of coral reef researchers and managers to monitor coral thermal stress in near-real-time.

Keywords: bleaching; thermal stress; satellite; remote sensing; sea surface temperature (SST); monitoring; climatology; hotspots; degree heating week; bleaching alert area

1. Introduction

Shallow-water tropical coral reef ecosystems are often compared with rainforests because of their high biodiversity and complexity. These bio-geological structures have formed over thousands of years by small, colonial organisms dependent on microscopic algal partners. Over recent decades, coral reefs have faced mounting natural and anthropogenic pressures, resulting in their decline worldwide.

Mass coral bleaching events due to anomalously warm ocean water have increased in frequency and severity [1] and become one of the most significant contributors to the deterioration of global coral reef ecosystems [2]. Coral bleaching occurs when the symbiotic relationship between dinoflagellates (zooxanthellae) and their host coral breaks down under various environmental stresses [3,4]. When stressed, the host expels its zooxanthellae, and the white calcium carbonate skeleton beneath becomes visible through the transparent coral tissue; this phenomenon is known as bleaching. 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 geographical scales [5–7]. Corals can die if thermal stress is severe or long-lasting or if it leads to subsequent disease in the colony [1,8,9]. Extensive bleaching events have dramatic long-term ecological and social impacts, including loss of reef-building corals, changes in benthic habitat, changes in associated fish populations [10] and economic loss [11]. Even under favorable conditions, it can take decades for severely bleached reefs to fully recover [2]. As the climate continues to warm, bleaching is a major threat to the future of coral reefs [12].

The timing of the peak bleaching season varies among ocean basins and hemispheres, but is generally during the warmest months of the year at each locality. The peak season is July–September for the northern Atlantic and Pacific Oceans, January–March for the southern Atlantic and Pacific Oceans, April–June for the northern Indian Ocean and January–April for the southern Indian Ocean [13]. Near the equator, there are often two potential bleaching seasons following the equinoxes. While the potential bleaching season for a particular reef region is generally well defined, the extent and magnitude of thermal stress that can lead to coral bleaching varies from year to year.

Reliable global monitoring and prediction of environmental conditions leading to bleaching is used to guide targeted observations and management responses [14–16]. Satellite remote sensing provides such monitoring with synoptic views of the global oceans in near-real-time and allows monitoring of both easily accessed reefs and remote reef areas. Consequently, remote sensing products have become essential for coral reef ecosystem monitoring. In 1997, the U.S. National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data and Information Service (NESDIS) began operating a near-real-time, web-accessible, satellite sea surface temperature (SST)-based product suite for monitoring global oceanic thermal conditions to pinpoint areas where corals were at risk of mass bleaching and to assess the extent and intensity of thermal stress [17]. The NESDIS Coral Bleaching HotSpots was the first near-real-time global satellite thermal stress monitoring product used to assess the likelihood of coral bleaching [18,19]. It was derived from an earlier concept introduced in [20] and became the foundation for NOAA's Coral Reef Watch (CRW) program, established in 2000 [21]. Building on this initial framework, CRW developed a suite of products that formed the first global near-real-time decision support system (DSS) to inform management of tropical coral reef ecosystems [19]. Widely used by the global coral reef community, CRW's original satellite thermal stress monitoring products have proven highly successful in nowcasting mass coral bleaching episodes globally [1,22–30]. More recently, this has been expanded to use climate models to forecast potential bleaching months in advance [31,32].

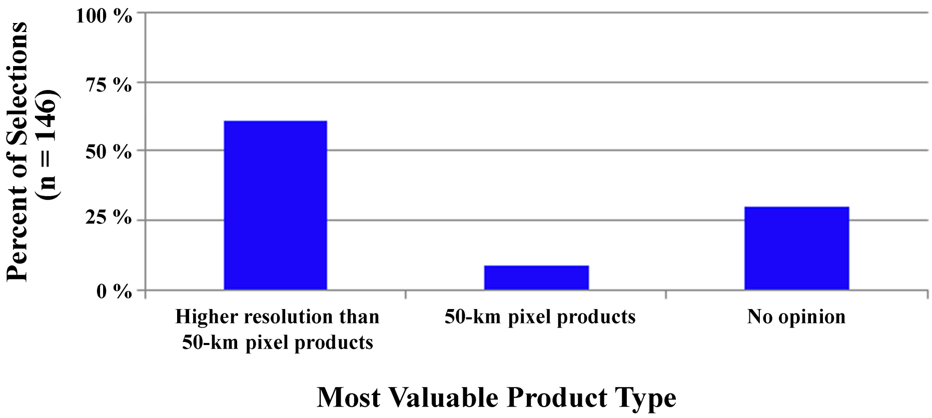
CRW computes the thermal stress that can lead to coral bleaching by comparing near-real-time SST values with a long-term baseline SST (climatology) at each reef location. The algorithm supporting CRW's satellite coral bleaching thermal stress monitoring products was used to derive CRW's first monitoring products: the Coral Bleaching HotSpots and subsequent Degree Heating Weeks (DHW) [19]. It uses an SST climatology that is, for each location, the warmest of the 12 climatological monthly mean temperatures (*i.e.*, the maximum of the monthly mean SST climatology, known as the MMM climatology). HotSpots are positive-only anomalies, derived by subtracting the MMM from SST values. This has proven to be a good measure of current levels of thermal stress ([19] and the references therein). The DHW provides a measure of accumulated thermal stress experienced by corals and is a better predictor of bleaching. It is calculated by summing HotSpots of 1 °C or greater from the preceding 12-week period; the DHW has been directly correlated with bleaching occurrence and severity. The HotSpots/DHW algorithm is now well established, and the two decades of monitoring data are widely used by the research and management communities. The heritage versions of these products are generated at a 50-km (precisely 0.5° in latitude and longitude) spatial resolution at twice-weekly (alternating three- and four-day periods) temporal resolution. They are based on NESDIS' twice-weekly global 50-km night-only SST analysis [33]. The night-only SST measurements are used instead of day-night measurements to avoid potentially significant effects of diel variation in SST and to better represent temperature anomalies at the depths corals are found [34]. The climatology used as a baseline to compare with satellite SST values in the 50-km products was derived using satellite SST data from 1985 to 1990 and 1993 [19].

Although highly successful and still served with 24/7 operational support at the time of writing, the 50-km products have four identified shortcomings for use in coral reef management. Firstly, only pure-water pixels are used to avoid land contamination in the satellite SST. This was achieved using a 50-km land mask that eliminated SSTs as far out as 50 km from the coast. This means that over 60% of the global shallow water coral reefs did not have direct coverage. However, during most mass bleaching events, SST anomalies occur in-phase or nearly in-phase over a broad area that includes both coral reefs and their adjacent open ocean waters [35]. Due to this spatial auto-correlation, CRW's 50-km heritage products have generally worked well in detecting reef conditions by monitoring thermal stress in offshore waters adjacent to coral reef areas. More recently, CRW has produced an experimental "enhanced" 50-km product suite that includes coastal pixels, which provide water-only information closer to land [36], as a temporary solution during the development of the higher resolution SST analysis. Secondly, while representing broad-scale oceanic thermal anomalies, the 50-km products have a much coarser resolution than was desired by managers and can miss local-scale variations in temperature. Reefs in shallow coastal waters can experience greater horizontal temperature gradients and temporal variability than the twice-weekly 50-km products can resolve. In some cases, this has led to underestimation of bleaching thermal stress by the 50-km products. Other localized effects, such as tidal mixing and coastal runoff, can cause the 50-km products to overestimate thermal stress in areas that are naturally cooled. Thirdly, NESDIS' twice-weekly global 50-km SST analysis is produced by the heritage NOAA SST system developed in the 1970s [37] that will soon be retired. This 50-km SST analysis is derived from a very limited subset of SST measurements by a single polar-orbiting environmental satellite and is based on a now obsolete cloud screening algorithm and a primitive gap-filling technique [35,38]. It is produced at much coarser twice-weekly and 50-km resolutions than satellite sensors' ~1–4 km resolutions, to aid in filling gaps due to clouds and other contamination in the data. Finally, to detect thermal stress levels capable of causing coral bleaching, CRW's heritage 50-km products were created using a climatological baseline temperature developed from SST observations of an early satellite data record. This climatology had limited temporal coverage and relatively low quality, which resulted in known errors in some coral reef regions [36], and provided no values for pixels within 50 km of the coast.

Advances in coral reef management have driven the need for higher resolution monitoring at or near reef scales. During discussions with reef managers over the past several years, the most frequent request has been for CRW to develop higher spatial resolution products that provide more detail over individual coral reefs (Figure 1). Addressing the growing demand for high-resolution thermal stress products and taking advantage of new satellites, sensors and algorithms, CRW has developed a daily global 5-km product suite. Developed with support from the U.S. National Aeronautics and Space Administration (NASA) and NOAA, this suite uses NESDIS' next-generation operational daily global 5-km geostationary and polar-orbiting (geo-polar) blended night-only SST analysis and a new climatology.

The 5-km CRW product suite using these new inputs was officially released in May, 2014. It currently includes global SST Anomaly, Coral Bleaching HotSpots, Degree Heating Weeks and Bleaching Alert Area products, matching the core heritage twice-weekly global 50-km satellite products [19]. It is accessible online at http://coralreefwatch.noaa.gov.

Figure 1. Results of user needs survey conducted by the University of Colorado Cooperative Institute for Research in Environmental Sciences in 2010 indicating the overwhelming request for higher-resolution Coral Reef Watch (CRW) products.



In this paper, we describe NOAA/NESDIS' daily 5-km SST analysis and development of the 5-km climatology, introduce CRW's daily global 5-km product suite derived from these new inputs, then show examples of its improvements over the heritage 50-km products and discuss the performance of the 5-km products during the major bleaching events of 2013–2014. Finally, we address plans for continued product validation and development.

2. Methods

2.1. Geo-Polar Blended SST Analysis

CRW's 5-km satellite coral bleaching thermal stress monitoring algorithm requires a gap-free global SST field. The NESDIS near-real-time operational daily global 5-km geo-polar blended night-only SST analysis [39,40] (Figure 2a) was developed at the request of CRW, to replace the NESDIS twice-weekly 50-km night-only SST analysis. The 5-km geo-polar blended night-only SST analysis, released in March, 2013, is derived from SST measurements taken by a combination of geostationary and polar-orbiting environmental satellites operated by NOAA, the Japan Meteorological Agency (JMA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The blended SST is presently generated using data from four geostationary satellites and two polar-orbiting satellites (Table 1). The constellation of geostationary satellites delivers near-global coverage for most of the tropics and mid-latitudes, with the exception of the Indian Ocean between ~60E and ~80E. Each of these geostationary satellites provides repeat SST measurements as often as every 15 minutes. Complementing this, each polar-orbiting satellite provides global coverage, including coverage for the region missed by the geostationary satellites, by making near-polar orbits roughly 14 times within a 24-h period. Due to their lower altitudes, polar-orbiting satellites also provide higher spatial resolution SSTs than geostationary satellites [34]. The combination of the six satellites provides the 5-km geo-polar blended night-only SST analysis with as many as 50 SST observations each night over the same location. These are then combined into a single SST analysis, for each pixel, each night.

Figure 2. NOAA CRW's daily global 5-km products for 3 October 2013: (**a**) sea surface temperature (SST); (**b**) SST Anomaly; (**c**) Coral Bleaching HotSpots; (**d**) Degree Heating Weeks; and (**e**) 7-day maximum composite Bleaching Alert Area, in which Alert Levels 1 and 2 values around Guam and the Commonwealth of the Northern Mariana Islands (CNMI) identified areas where bleaching was underway at that time.

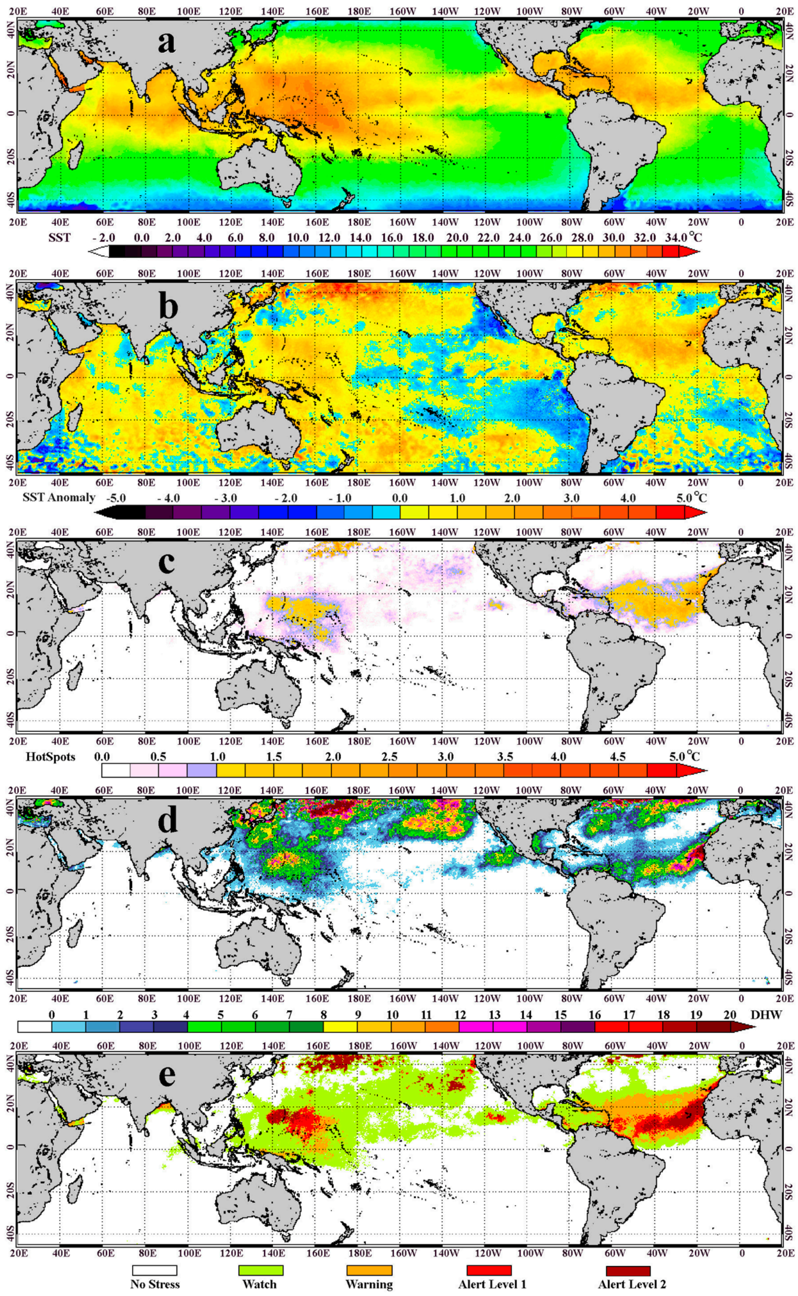


Table 1. Characteristics of geostationary and polar-orbiting satellites currently used in the production of the National Environmental Satellite, Data and Information Service (NESDIS) daily global 5-km geo-polar blended sea surface temperature (SST) analysis. JMA, Japan Meteorological Agency; EUMETSAT, European Organisation for the Exploitation of Meteorological Satellites; GOES-E and -W, Geostationary Operational Environmental Satellite (GOES)-East and -West; MTSAT, Multi-functional Transport Satellite; MSG, Meteosat Second Generation; NPP, National Polar-orbiting Partnership; MetOp-B, Meteorological Operational Satellite-B.

Geostationary			
Satellite	Agency	Altitude	Longitude
GOES-W (GOES-15)	NOAA	~35,800 km	135 W
GOES-E (GOES-13)	NOAA	~35,800 km	75 W
MTSAT-2	JMA	~35,800 km	0
MSG-3	EUMETSAT	~35,800 km	140 E
Polar-Orbiting			
Satellite	Agency	Altitude	
Suomi-NPP	NOAA	~824 km	
MetOp-B	EUMETSAT	~817 km	

The geo-polar blended SST analysis performs a multi-scale optimal interpolation (OI) at three different correlation length scales, and the final result is interpolated based on local data density [40]. This preserves mathematical rigor and fine detail, while filling gaps for any regions with no satellite observations due to cloud cover or other contamination. SST observations from various satellites are treated independently for each data source, gridded at 0.05°, and then bias corrected to the same reference prior to the OI analysis. Only observations for which the sun elevation angle is below zero (*i.e.*, the sun is below the horizon) contribute to the night-only blended SST. An automated validation and quality control system is in place that issues warnings when any unexpected bias or deterioration in the SST analysis is detected. This ensures the long-term accuracy of the SST used by CRW's thermal stress monitoring products.

The geo-SST and polar-SST retrievals used for generating the blended SST analysis are produced separately by NESDIS' operational geo-SST processing system and by the Advanced Clear-Sky Processor for Oceans (ACSPO) system for polar-SST, respectively. They are briefly introduced below.

2.1.1. Geostationary Satellite SST

NESDIS has generated operational SST products from the NOAA Geostationary Operational Environmental Satellite (GOES) Imagers since December, 2000 [41,42]. In recent years, NESDIS has also produced operational SST retrievals from imagers onboard the Japanese Multi-functional Transport Satellites (MTSAT-1R and MTSAT-2) and the European Meteosat Second Generation satellites (MSG-1, 2 and 3), thereby extending coverage to near-global. Recent application of the latest algorithms improves aspects, such as cloud screening and retrieval quality. An advanced cloud masking methodology based on a probabilistic "Bayesian" approach [43] has been implemented since April 2006 [41,42]. In August, 2013, a new deterministic physical retrieval methodology was implemented to generate geo-SST retrievals and improved the accuracy of the retrievals by using local atmospheric information [44], as compared with the previous global regression approach [42]. An automated validation system is also in place for the geo-SST, using an *in situ* matchup database for quality monitoring, maintenance and improvement of the geo-SST in near-real-time.

2.1.2. Polar-Orbiting Satellite SST

Since the early 1980s, SST products have been operationally produced at NESDIS from the Advanced Very High Resolution Radiometers (AVHRR) onboard NOAA's Polar-Orbiting Environmental Satellites (POES) [37]. The ACSPO system is the most recent NESDIS system for generating SST from the AVHRR sensors onboard POES and EUMETSAT's Meteorological Operational (MetOp) satellites, Moderate Resolution Imaging Spectroradiometers (MODIS) onboard NASA's Terra and Aqua satellites and the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard NOAA-NASA's Suomi-National Polar-orbiting Partnership (Suomi-NPP) satellite. SST retrieval algorithms are regression-based, whereas ACSPO also incorporates a community radiative transfer model and employs an internal Clear-Sky Mask module [45]. Version 1.0 of the ACSPO SST processing system, released in May 2008, has since been updated to the current Version 2.3. ACSPO processes observations at both spatial resolutions received from AVHRR instruments: local area coverage (LAC)/full resolution area coverage (FRAC) data at ~1-km satellite nadir resolution; and global area coverage (GAC) data at ~4-km resolution, sub-sampled onboard from the full resolution AVHRR LAC data. The VIIRS and MODIS SST retrievals are processed at ~0.75-km and ~1-km resolutions, respectively. Every satellite sensor observation is processed at its acquired resolution. ACSPO SST quality is continuously monitored in near-real-time using an automated NOAA SST Quality Monitor system (SQUAM) [46], and products are also continuously validated against quality-controlled *in situ* SST data available from the NOAA *in situ* SST Quality Monitor (iQUAM) [47]. Results of *in situ* validation are also reported in SQUAM. In close coordination with the CRW program, capabilities are being built to use the ACSPO system to reprocess all historical polar-orbiter data.

2.2. Climatology Development

CRW's bleaching thermal stress products are based on SST anomaly values and therefore require a climatology (historical baseline temperature) from which thermal stress is determined. While a detailed description of the development of the new 5-km climatology is provided elsewhere [48], a brief summary follows. The 5-km blended night-only SST dataset only began in March, 2013, and is too short to build a climatology. Thus, the climatology was produced using night-only values for the period 1985–2012 from the 4-km AVHRR Pathfinder Version 5.2 SST (PFV5.2), an official NOAA climate data record. For each pixel, daily SST data of high quality (quality $\geq$ 4) [49] were averaged for each month to produce monthly composites. These were then averaged across the 28-year period to produce 12 monthly mean climatologies. The use of newer data resulted in a ten-year shift in the temporal mid-point of the data used in the climatology (mid-1998) when compared with the heritage 50-km climatology (early-1988). In an era of rapid warming, this would have substantially modified the anomalies and therefore the magnitude of the 5-km HotSpot and DHW values relative to the heritage products. As such, the climatological average values were re-centered to the time-center of the corresponding heritage climatology, following the approach of [36].

As different SST datasets have slightly different values, we tested for bias between the PFV5.2 and NESDIS 5-km geo-polar blended datasets. Because there was no temporal overlap between the 5-km geo-polar blended night-only SST and PFV5.2, we determined this bias using a day-night version of the NESDIS 5-km geo-polar blended SST that overlapped with the PFV5.2 data for the period March–December, 2012. The 5-km blended day-night SST analysis was statistically indistinguishable from the 5-km blended night-only SST analysis [48]. Consequently, matchups between daily 4-km PFV5.2 and 5-km blended day-night SST values were constructed, which reveal a strong linear relationship ($SST_{PFV5.2} = 0.0637 + 0.982\ SST_{Blended5km}$, $r^2 = 0.998$) [48]. Using this analysis, the PFV5.2 SST climatology values were adjusted to resemble 5-km blended night-only SST values. Following this, the bias-adjusted monthly climatologies were re-gridded to the 5-km blended SST grid. The warmest 5-km monthly climatology value at each pixel was set as the 5-km MMM climatology.

Note that climatology derived from geo-polar blended SST analysis is preferred for CRW applications. Work is therefore underway at NOAA to reprocess polar- and geo-SSTs and blend them into geo-polar product, for a period sufficient to construct a more consistent SST climatology.

2.3. Bleaching Thermal Stress Monitoring Algorithm and Products

The satellite coral bleaching thermal stress algorithm developed for CRW's heritage 50-km products [19] was applied to NESDIS' daily global 5-km geo-polar blended night-only SST and the new 5-km PFV5.2 SST climatology. Small modifications to the product algorithms were required for the daily production of the 5-km product suite. For example, the (low) data density in the 50-km SST analysis required that it be composited twice each week. This was no longer required with the 5-km SST analysis, which is now produced daily. Other changes are detailed below within the product descriptions.

2.3.1. SST Anomaly

CRW's daily SST Anomaly product (Figure 2b) is the difference between the daily SST and the corresponding daily SST climatology. The daily climatology is determined by linearly interpolating the adjacent monthly mean SST climatologies (which were considered to represent the 15th day of each month). The SST Anomaly product detects anomalous thermal conditions, indicating whether current temperatures are cooler or warmer than the long-term mean temperature at each location for the time of year. Warm anomalies can lead to the development of bleaching thermal stress; this is especially useful when monitoring oceanic conditions prior to a bleaching season. For example, the SST Anomaly product revealed that the record-breaking 2005 Caribbean mass coral bleaching event and North Atlantic Ocean hurricane season were preceded by anomalously high SSTs in the tropical North Atlantic Ocean that started unusually early in March, 2005, and persisted through December, 2005 [1]. In addition, the SST Anomaly product has effectively demonstrated the large inter-annual variability in the tropical Pacific Ocean surface temperatures associated with the El Niño-Southern Oscillation (ENSO) cycle, which has been related to global scale mass coral bleaching events (e.g., the 1997–1998 global-scale bleaching event) [50]. Negative SST anomalies have been very useful in monitoring and observing tropical cyclone "wake" cooling and major shifts in coastal upwelling, which may provide relief to corals under thermal stress [51,52].

2.3.2. Coral Bleaching HotSpots

CRW's 5-km Coral Bleaching HotSpots product (Figure 2c) measures the magnitude of daily thermal stress that can lead to coral bleaching. It is a positive-only anomaly product based on the MMM climatology (described above):

$$HS = \begin{cases} SST_{daily} - MMM, & SST_{daily} > MMM \\ 0, & SST_{daily} \leq MMM. \end{cases} \quad (1)$$

A HotSpot value of 1.0 °C or more is indicative of thermal stress, potentially leading to coral bleaching. To highlight this threshold on a CRW HotSpots map (Figure 2c), HotSpot values above 0 °C, but below 1.0 °C, are shown in shades of purple, and HotSpots of 1.0 °C or greater range from yellow to red as thermal stress increases.

2.3.3. Degree Heating Weeks (DHW)

Whereas the 5-km Coral Bleaching HotSpots product provides a measure of daily thermal stress, CRW's DHW product accumulates prolonged periods of thermal stress and has been shown to be more predictive of mass coral bleaching [5]. CRW's 5-km DHW product (Figure 2d) is a cumulative measure of thermal stress intensity (HotSpots) and duration integrated over the most-recent 12-week period (*i.e.*, the most recent 84 days). It is expressed in the unit °C-weeks. One week of HotSpots at 2 °C and two weeks of HotSpots at 1 °C would each contribute 2 °C-weeks to a DHW accumulation. Based on the finding that temperatures exceeding 1 °C above the usual summertime maximum are sufficient to cause thermal stress to corals [5], the bleaching threshold temperature of MMM + 1 °C is set as a high-pass filter for accumulating thermal stress (*i.e.*, only HotSpots, HS, ≥ 1 °C are accumulated in the DHW):

$$DHW = \frac{1}{7}\sum_{i=1}^{84}\left(HS_i, if\, HS_i \geq 1^{\circ}C\right) \quad (2)$$

Since the DHW is a 12-week accumulation of HotSpots, it is possible for a location to have a non-zero DHW value when the HotSpot value is currently less than 1 °C or even 0 °C. This circumstance indicates that thermal stress had accumulated at that location within the most recent 12 weeks, but local conditions are not currently stressful for corals. Prior exposure to thermal stress may still have adverse impacts on corals, although recovery may be underway. An increase in SST above MMM + 1 °C in the coming days would resume the 12-week accumulations of stress.

As part of the 5-km product development, CRW has implemented a new DHW color palette that differs from the one used with the heritage 50-km products. This palette helps to better visualize the relationship between DHW values and the potential coral bleaching severity (Table 2). The new color groupings distinguish different thermal stress levels (Watch, Warning, and Alert Levels 1 and 2), and the upper end of the color palette was extended to 20 °C-weeks.

2.3.4. Bleaching Alert Area

CRW's 5-km Bleaching Alert Area (BAA) product (Figure 2e) identifies areas where bleaching thermal stress satisfies specific criteria (Table 2) based on CRW's HotSpot and DHW values. The BAA is updated daily, but shows the maximum Alert Level of the preceding seven days, due to the high temporal variability in the daily 5-km SST and, thus, HotSpots. The compositing of BAA values results in greater methodological consistency with CRW's heritage twice-weekly composite 50-km BAA and is more useful in management applications. The BAA provides a single, convenient tool for users to monitor recent thermal conditions. A status level of "No Stress" or "Bleaching Watch" can occur when the DHW value is greater than 0 °C-week (as described in the DHW section above), indicating a period of recent stress.

Table 2. CRW's coral bleaching thermal stress levels based on Coral Bleaching HotSpots and Degree Heating Weeks (DHW) products.

Stress Level	Definition	Ecosystem Impact
No Stress	HotSpot ≤ 0	--
Bleaching Watch	0 < HotSpot < 1	--
Bleaching Warning	1 ≤ HotSpot and 0 < DHW < 4	Possible Bleaching
Bleaching Alert Level 1	1 ≤ HotSpot and 4 ≤ DHW < 8	Bleaching Likely
Bleaching Alert Level 2	1 ≤ HotSpot and 8 ≤ DHW	Mortality Likely

3. Results and Discussion

The daily global 5-km CRW satellite coral bleaching thermal stress monitoring products, and tutorials on the application of this information, are available at: http://coralreefwatch.noaa.gov. These products significantly advance the ability of researchers and resource managers to monitor coral bleaching thermal stress at spatial scales much closer to that of coral reefs and in near-real-time. Below, we discuss the improvements these products impart over CRW's heritage 50-km products and demonstrate how the new products successfully identified three bleaching events of 2013–2014.

3.1. Improvements over CRW's Heritage 50-km Products

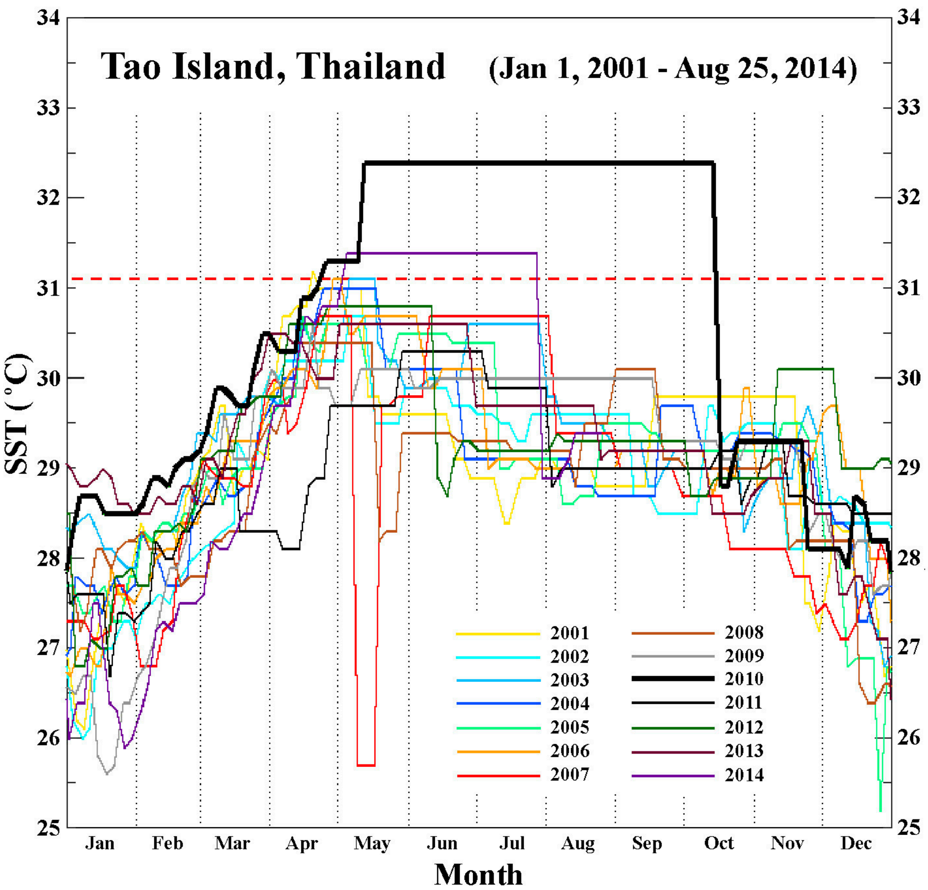
3.1.1. Improvement Gained from the Blended SST

A major improvement in the new products was the increase in the amount of satellite data available to estimate SST for any location around the globe. NESDIS' heritage 50-km SST analysis uses data from a single satellite platform (NOAA POES) at any time and processes only AVHRR 4-km GAC data [38]. These are sub-sampled from AVHRR's native LAC data onboard the satellite due to storage constraints. In the heritage 50-km SST processing system, GAC data away from the swath edges are further sub-sampled as part of the cloud identification process by selecting the warmest pixel and three adjacent pixels to contribute to the 50-km SST analysis (see [33,36] for details). This multi-step sub-sampling approach can discard substantial amounts of valid SST observations. Although providing global coverage, a single polar-orbiting satellite allows, at most, one nighttime observation in a 24-h interval in the tropics. The processing applies a distance-weighted averaging algorithm using SST retrievals up to

150 km from the center of 50-km pixels. When no new observation is detected during the twice-weekly time period at a 50-km pixel, the previous 50-km SST analysis value at the pixel persists. Given the low data density and low observation frequency from a single POES satellite, some cloudy tropical regions frequently have periods where SST analysis values persist for several months.

Gaps in polar-orbiter satellite data for weeks to months have repeatedly affected the 50-km CRW products in Southeast Asia, due to cloud cover during the Monsoon season. The Monsoon season usually starts in May, lasts for months and overlaps the bleaching season (April–June). In 2010, the 50-km SST near Tao Island, Thailand, did not update for over five months after the SST had exceeded MMM + 1 °C (Figure 3). As a result, the SST remained at the same elevated value through this period, causing the DHW at the pixel to erroneously accumulate through this period and reach 27.6 °C-weeks before a new SST retrieval became available. In reality, persistent cloud cover usually results in reduced SST and brings relief to stressed corals [53].

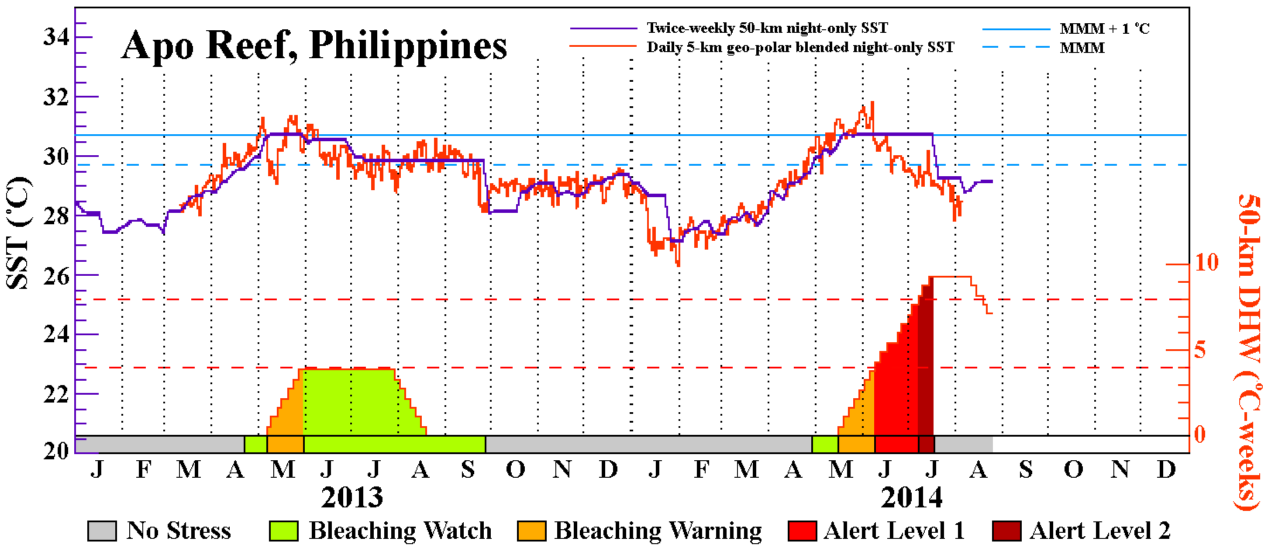
Figure 3. CRW's twice-weekly, 50-km, night-only SST time series of 2001–2014 from a pixel near Tao Island, Thailand. The flat portions of the SST time series indicate the periods with no SST update. Note that the longest period with no SST update spanned from May to October 2010. The MMM (maximum of the monthly mean) + 1 °C (31.1 °C) is shown as a red dashed-line across the figure.



The 5-km blended night-only SST analysis includes up to 50 observations from multiple geostationary and polar-orbiting satellites. The ACSPO system that analyzes polar-orbiting satellite SST retrievals for the blended SST uses no sub-sampling [45]. This increases the availability of quality observations for each pixel and reduces the chance of cloud-caused data gaps in the daily SST analysis.

Because intermittent regions of clear sky generally open up even during heavy cloud cover, the next-generation 5-km blended SST is substantially less prone to extended data gaps. Continuity in daily observations is achieved by multiple satellite inputs each day from geostationary and polar-orbiting satellites. An example from Apo Reef, Philippines (Figure 4), showed that the 5-km blended SST analysis continued to update during three extended periods for which the 50-km SST incorrectly persisted high temperature values in 2013–2014. The long period of persistent SST during May–July 2014, led to an overestimation in the 50-km DHW product (Figure 4).

Figure 4. CRW's twice-weekly, 50-km, night-only SST (purple line) from a 50-km pixel near Apo Reef, Philippines (see arrows in Figure 5c,d), overlaid with the daily, 5-km, night-only SST (red line) from a 5-km pixel located at the center of the 50-km pixel, for January, 2013–August, 2014. The lower portion of the graph shows the twice-weekly, 50-km DHW and bleaching stress levels (colored polygons). The flat portions of the purple 50-km SST time series indicate periods with no SST update. The persistent data gap during May–July 2014, caused the 50-km DHW product to overestimate the accumulated thermal stress.



The ability of the 5-km products to overcome this problem was seen in maps of the 50-km and 5-km products from 10 July 2014, for the South China Sea (Figure 5a,b). Both DHW products showed accumulation over the period of 18 April–10 July 2014. The significant overestimation by the 50-km DHW product in the South China Sea (Figure 5a) was caused by a gap in SST observations due to persistent cloud cover. The 5-km DHW product for the same time period shows only low levels of thermal stress, because of the nearly continuous acquisition of new observations (Figure 5b). Both the 50-km and 5-km SST time series at the pixel near Apo Reef, Philippines (marked by an arrow in Figure 5c,d) during that time period are shown in Figure 4.

Figure 5. Comparison of CRW products in the South China Sea on 10 July 2014: (**a**) twice-weekly 50-km DHW product and (**b**) daily 5-km DHW product; also shown are (**c**) NESDIS' twice-weekly 50-km SST analysis (*i.e.*, SST composite of 7–10 July 2014) used by the 50-km DHW; and (**d**) the age (in days) of the newest SST retrievals used in the 50-km SST analysis for that region. The overestimation of the 50-km DHW shown in (a) is a result of persistent cloud cover partially demonstrated in the SST analysis (c) and explained by the retrieval ages plotted in (d); red arrows in (c) and (d) point to the pixel whose time series data are displayed in Figure 4. (Dark grey pixels in the 50-km images are land pixels).

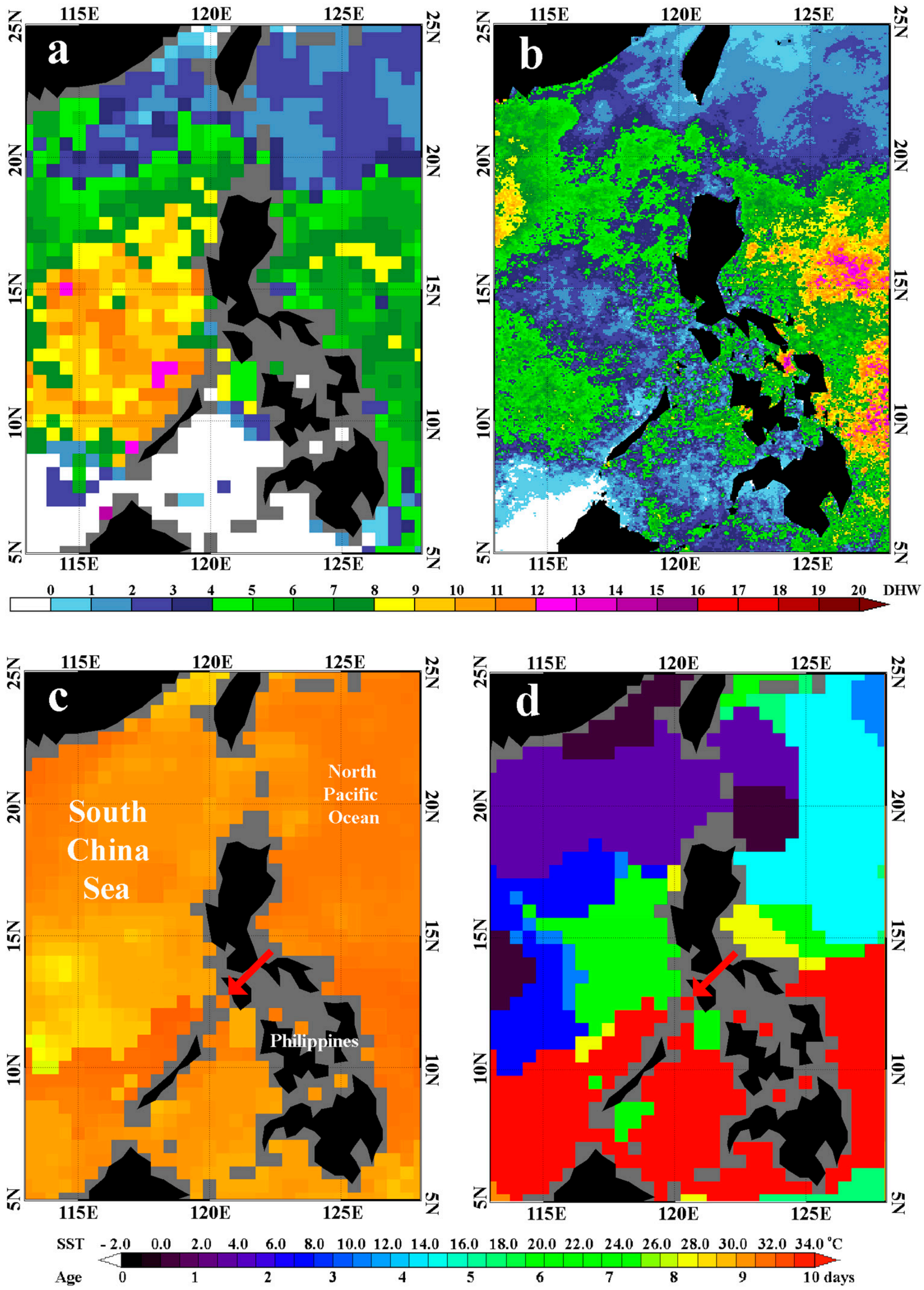


Figure 4 demonstrated that the two SST time series traced each other well, except for the time periods when the 50-km SST analysis did not receive new satellite observations, indicated by a long, flat SST line in the figure. Although the 50-km and 5-km DHW products were derived using their own MMM climatologies, which are different from each other, as described in Section 2.2, Figure 4 demonstrates that the significant accumulation of 50-km DHWs in 2014 corresponded to the time period with a persistently high 50-km SST value caused by the lack of new satellite SST observations during May–July 2014. Meanwhile, the 5-km satellite SST decreased rapidly after peaking in early June. The spatial discontinuity in the high SST pattern in the southern region of the South China Sea (Figure 5c) of 10 July 2014, is the result of using old, high SST values updated more than 10 days and up to about two months earlier, marked by the red pixels shown in Figure 5d.

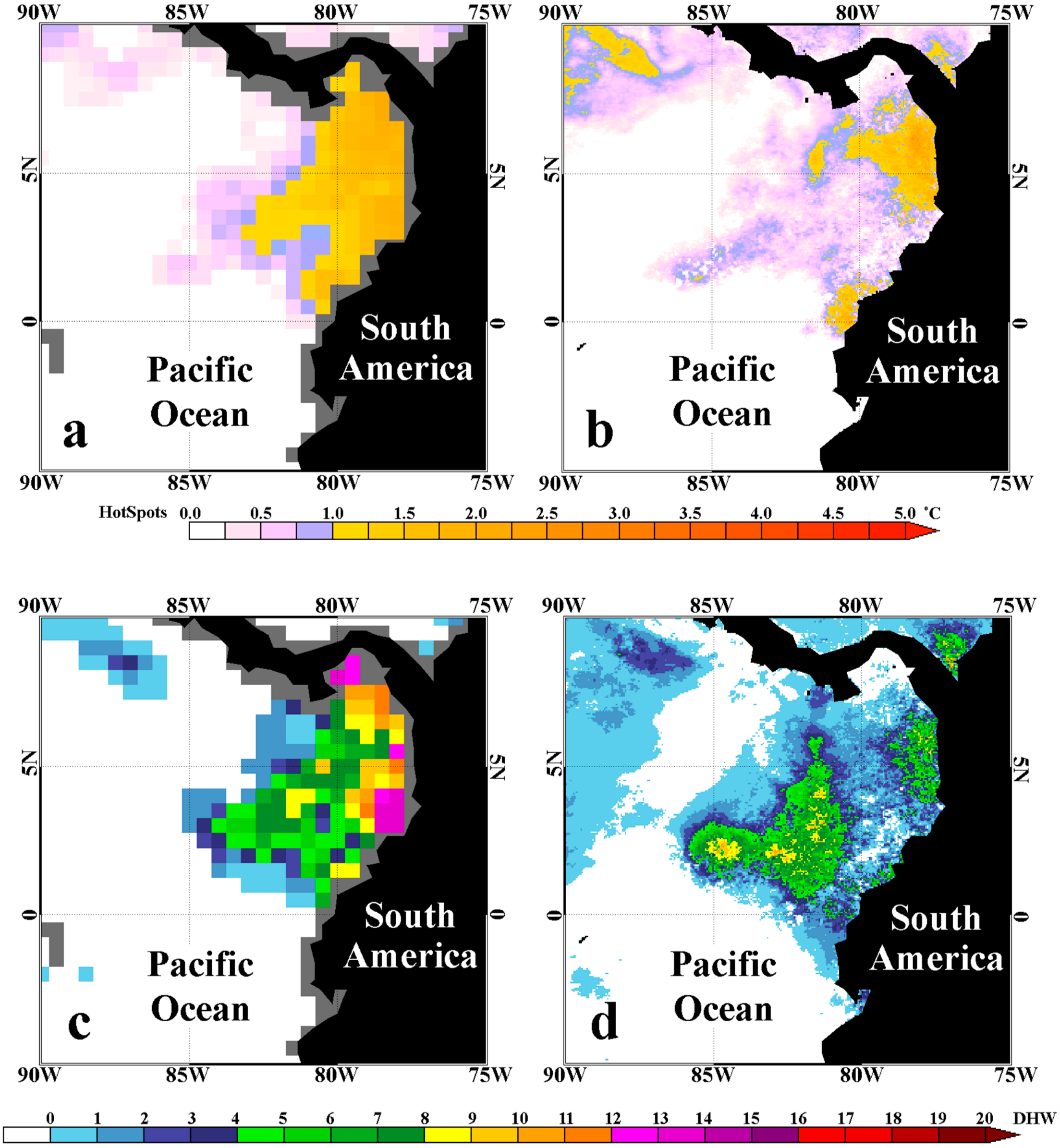
In addition to improved accuracy in areas with frequent cloud cover, CRW's 5-km product suite provides satellite monitoring over or in close vicinity to coral reefs, revealing much finer details of SST spatial distribution (Figure 5b) and day-to-day variability (Figure 4). Where the 50-km products (Figure 5a) provide no thermal stress monitoring in waters between islands in the central Philippines, the 5-km products (Figure 5b) monitor detailed thermal conditions on many central Philippines reefs and among the islands. Globally, while CRW's 50-km products provide satellite observations for only 39% of actual reef-containing pixels [36], the new 5-km products allow direct monitoring over more than 95% of coral reefs identified in the ReefBase reef locations dataset [54].

3.1.2. Improvement Gained from the Pathfinder Climatology

The new 5-km climatology resolves several known errors in certain regions that existed in CRW's heritage 50-km climatology [36]. Due to inherent differences between SST datasets and hence between their derived climatologies, a direct comparison of these climatologies would require bias adjustment to ensure the consistency of the SST datasets [48]. However, because any bias between the 5-km and 50-km data would consistently alter both the SST and the climatology, improvements in the climatology are best demonstrated by comparing the derived anomaly products (*i.e.*, HotSpots and DHW).

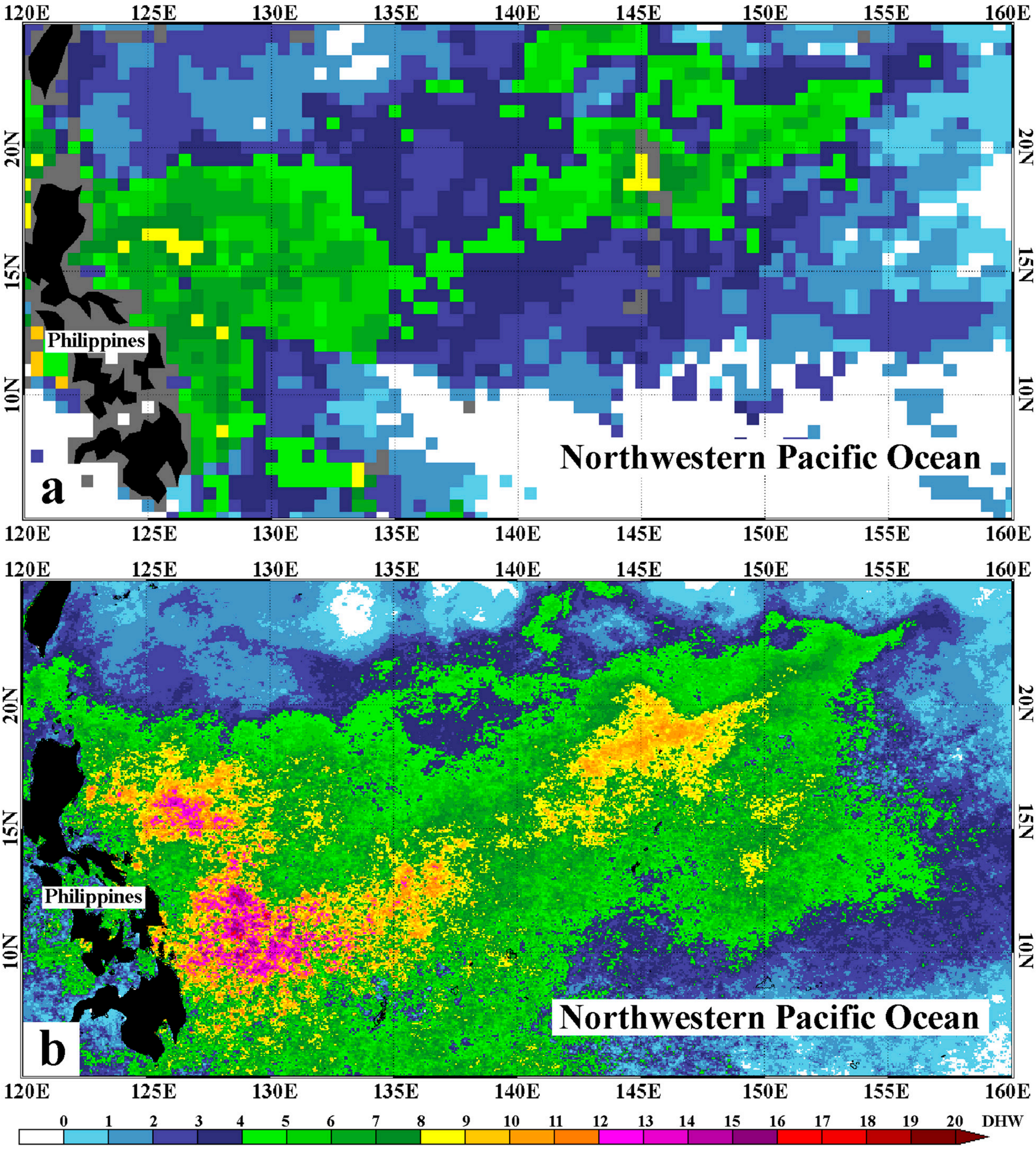
The Gulfs of Panama and Oman are examples of locations that have erroneously low 50-km climatology values. This has resulted in excessive thermal stress accumulation (DHW) that was inconsistent with reports of bleaching from scientists in the regions [36]. The 50-km DHW values exceeded 4 °C-weeks for most of the years and 8 °C-weeks for many years since the beginning of CRW's 50-km monitoring for these two regions, but bleaching was only infrequently observed in these regions [55]. In early 2013, for instance, erroneously low 50-km MMM climatology values in the Gulf of Panama caused unrealistically high HotSpot values in the region (Figure 6a), leading to significant overestimation of DHW values (Figure 6c). In comparison, the 5-km HotSpots and DHW show much lower levels of thermal stress (Figure 6b,d), indicating that CRW's 5-km products provide improved accuracy for these regions. By the end of 2015, reprocessing of past satellite data will make available longer time series of these 5-km products. CRW will then be able to perform qualitative comparisons of the new products against *in situ* bleaching observations.

Figure 6. CRW's twice-weekly 50-km Coral Bleaching HotSpots product (**a**) and daily global 5-km Coral Bleaching HotSpots product (**b**) of 9 May 2013, for the Gulf of Panama; CRW's twice-weekly 50-km DHW product (**c**) and daily global 5-km DHW product (**d**) of 1 July 2013, for the Gulf of Panama. (Dark grey pixels in the 50-km images are land pixels).



Erroneously high 50-km climatology values have also been apparent in several areas of the ocean, including the tropical northwestern Pacific Ocean to the east and southeast of the Philippines [36]. This has affected thermal stress monitoring values for the Commonwealth of the Northern Mariana Islands (CNMI), Guam and Palau, leading to underestimation of bleaching thermal stress for these regions [36]. Comparison of the 50-km and 5-km DHWs for these regions (Figure 7) indicates that the new 5-km climatology corrected the underestimation seen in accumulated thermal stress. Further discussion, including qualitative comparison with bleaching observations from this region, is provided in Section 3.2.

Figure 7. Comparison of NOAA CRW's (**a**) twice-weekly 50-km DHW product and (**b**) daily 5-km DHW product for 21 July 2014, showing accumulated bleaching thermal stress from 29 April to 21 July (Dark grey pixels in the 50-km images are land pixels).



The new 5-km climatology has resulted in significant differences in the distribution and intensity of thermal stress in some areas when compared with the 50-km products. We expect that the 5-km product suite will be more accurate in general; evaluations, including comparisons with *in situ* bleaching observations, are ongoing.

3.2. Application of 5-km Products

The 5-km SST Anomaly and Coral Bleaching HotSpots products are, at present, available since the beginning of the 5-km blended night-only SST record (12 March 2013). The DHW (3 June 2013) and BAA (9 June 2013) products begin three months later, as they rely upon the 12-week temporal compositing of the DHW and seven-day compositing of the BAA. A reprocessing effort to extend the 5-km blended SST analysis back in time is underway in NESDIS, at the request of CRW, which will allow CRW to validate the 5-km products with bleaching observations from earlier years.

Because CRW's new 5-km products were not available until May 2014, researchers used the older 50-km products in 2013, but were quick to apply the new products in 2014. Two major bleaching events occurred in 2013 and three more in 2014, providing preliminary observations against which the new products could be compared. These events occurred in Guam, the CNMI and Bermuda during 2013, and in Guam/CNMI, Florida and Hawai'i during 2014.

Corals experienced bleaching in Guam and the CNMI in 2013 [56] and again in 2014 ([57] and the references hereafter). Spatial distributions of thermal conditions monitored by the 5-km satellite products during the two events in Guam and CNMI (Figures 8 and 9) agreed with field observations of bleaching. The 2014 bleaching in Guam and CNMI lasted from July until September, 2014 (Figure 9). Consistent with the thermal stress values in the 5-km products, bleaching in both the 2013 and 2014 events was more severe and widespread in the northern parts of CNMI than in the southern parts of CNMI and Guam. In particular, early reports from a monitoring cruise to the northern CNMI in July, 2014, conducted by the CNMI Marine Monitoring and Coral Reef Program [58], indicated bleaching along with signs of high coral mortality from the 2013 event, including over 90% mortality of *Pocillopora* and *Acropora* spp. [59]. By mid-August, the survey team saw extensive bleaching and high mortality of *Pocillopora*, *Acropora*, *Astreopora* and *Isopora* corals in Maug (northern CNMI) [59], while bleaching around Guam and Saipan was documented to be serious, but much less severe.

In July–August, 2013, approximately 1%–15% of corals around Bermuda experienced bleaching as observed by *in situ* surveys [60] and Catlin Seaview Survey images [61,62]. The 5-km DHW started to accumulate at the south and north ends of Bermuda on July 10 and July 12, respectively, and reached 4 °C-weeks at the south and north ends by July 30 and August 3, respectively. By 28 August 2013, the 5-km DHW values reached 9 °C-weeks at the north end and 11 °C-weeks at the south end of Bermuda (Figure 10), consistent with field observations of bleaching. Although exposed to high stress levels, Bermuda was at the southern extent of the large patch of the highest thermal stress and was not exposed to the brunt of the warm water.

2014 has turned out to be a significant year for coral bleaching globally. In addition to the bleaching in Guam and CNMI, widespread bleaching occurred in the Florida Keys in August and September, 2014 [63,64]. Bleaching in Hawaiʻi began in the western part of the Northwestern Hawaiian Islands in late August, 2014, and by early October had spread to the main Hawaiian Islands [65,66]. CRW's new 5-km products were immediately adopted by programs in Florida and Hawaiʻi and used in their online newsletters that direct volunteer observers [63–65]. Preliminary results from surveys in September 2014, indicate that the patterns of bleaching severity in the Papahānaumokuākea Marine National Monument followed thermal stress patterns seen in CRW's new 5-km products [66]. In the Florida Keys, the ability of the 5-km products to provide data right over reefs was reported to be a major improvement by field teams [67].

Figure 8. CRW's daily 5-km DHW maps of the tropical northwestern Pacific Ocean (**a**) and CNMI/Guam (**b**) of 20 September 2013; the box in (a) shows the spatial coverage of (b). Location names: 1, Uracas; 2, Maug Islands; 3, Asuncion; 4, Agrihan; 5, Pagan; 6, Alamagan; 7, Guguan; 8, Sarigan; 9, Anathan; 10, Saipan; 11, Tinian; 12, Aguijan; 13, Rota; 14, Guam.

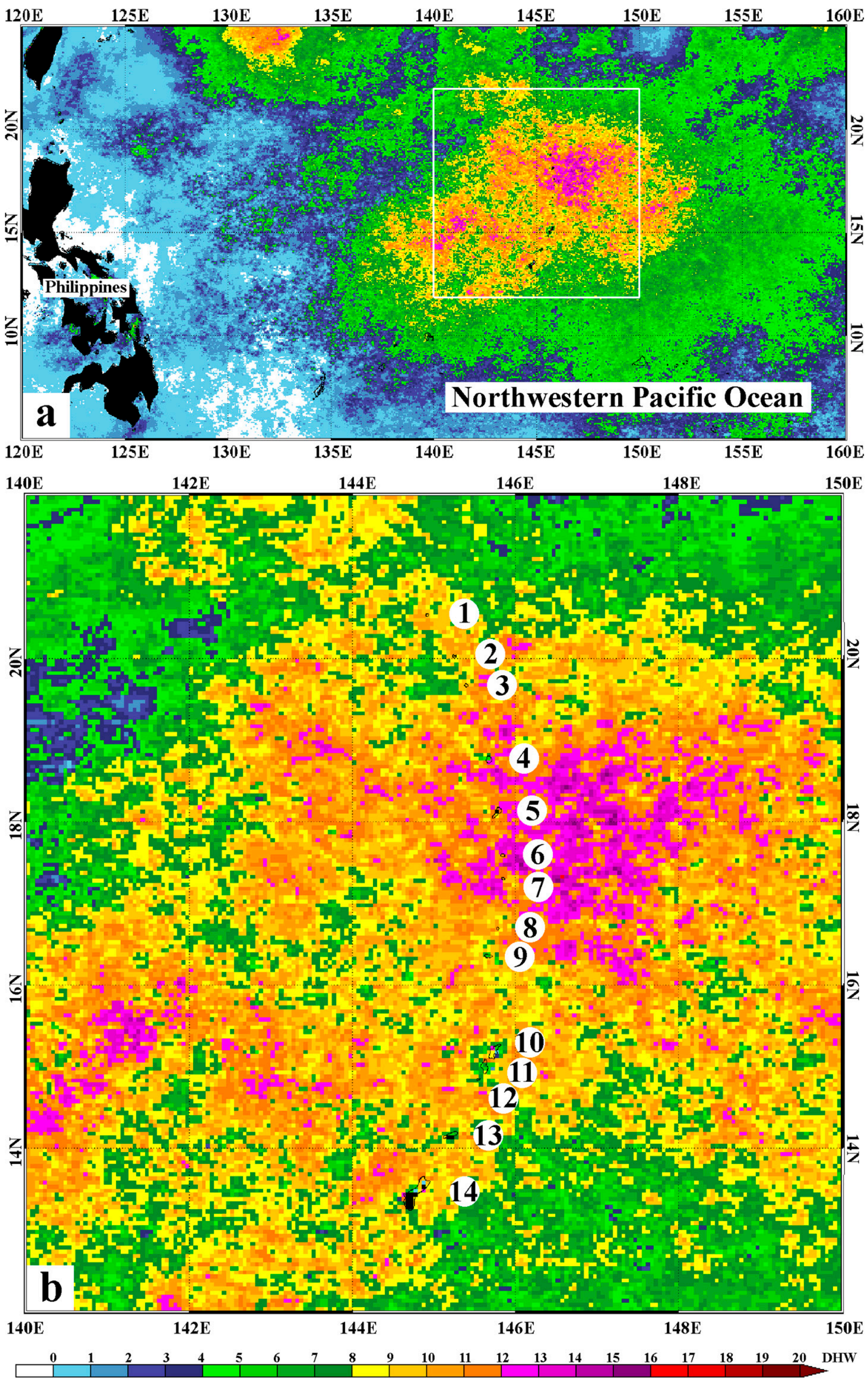


Figure 9. CRW's daily 5-km DHW maps of the tropical northwestern Pacific Ocean (**a**) and CNMI/Guam (**b**) of 24 August 2014; the box in (a) shows the spatial coverage of (b). Location names: 1, Uracas; 2, Maug Islands; 3, Asuncion; 4, Agrihan; 5, Pagan; 6, Alamagan; 7, Guguan; 8, Sarigan; 9, Anathan; 10, Saipan; 11, Tinian; 12, Aguijan; 13, Rota; 14, Guam.

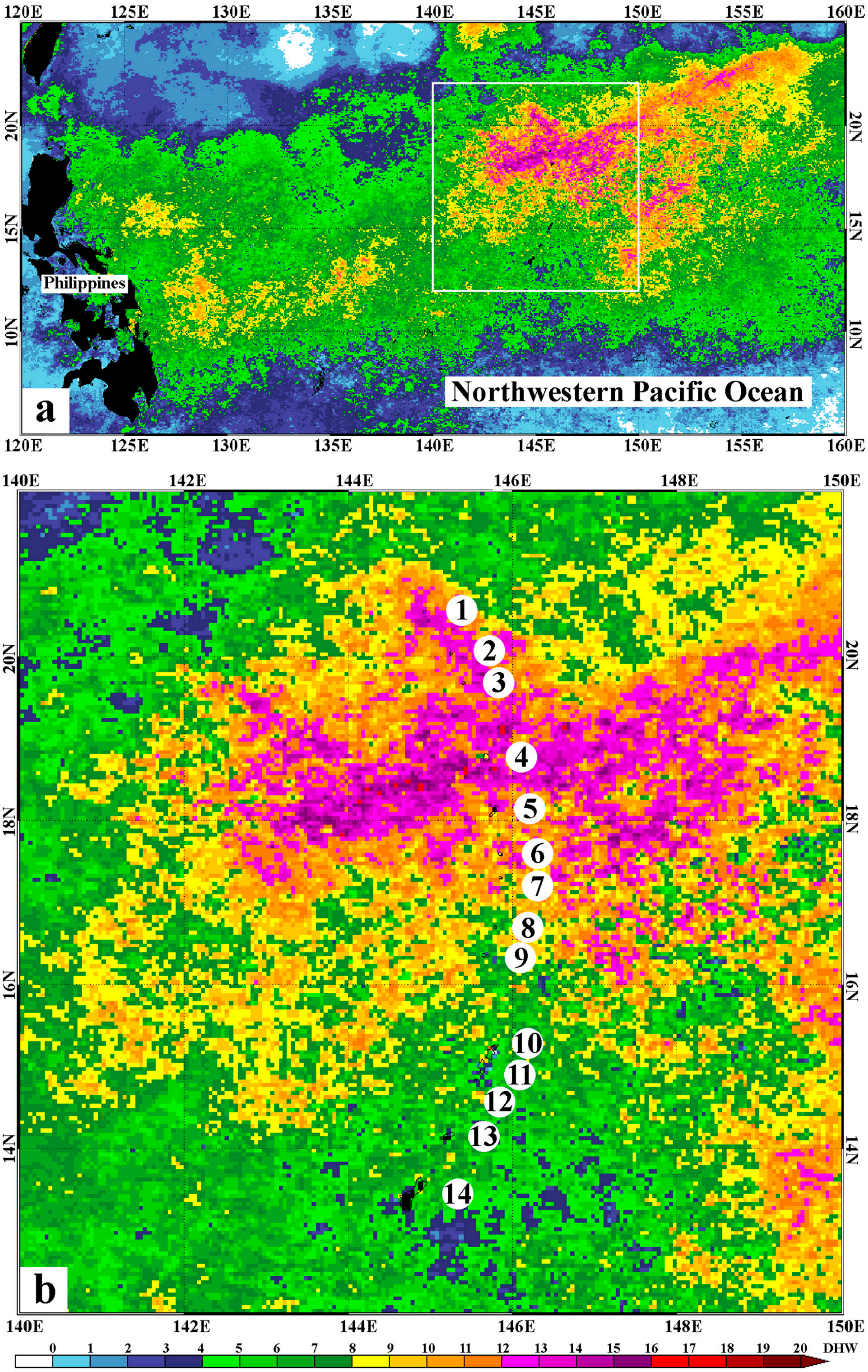
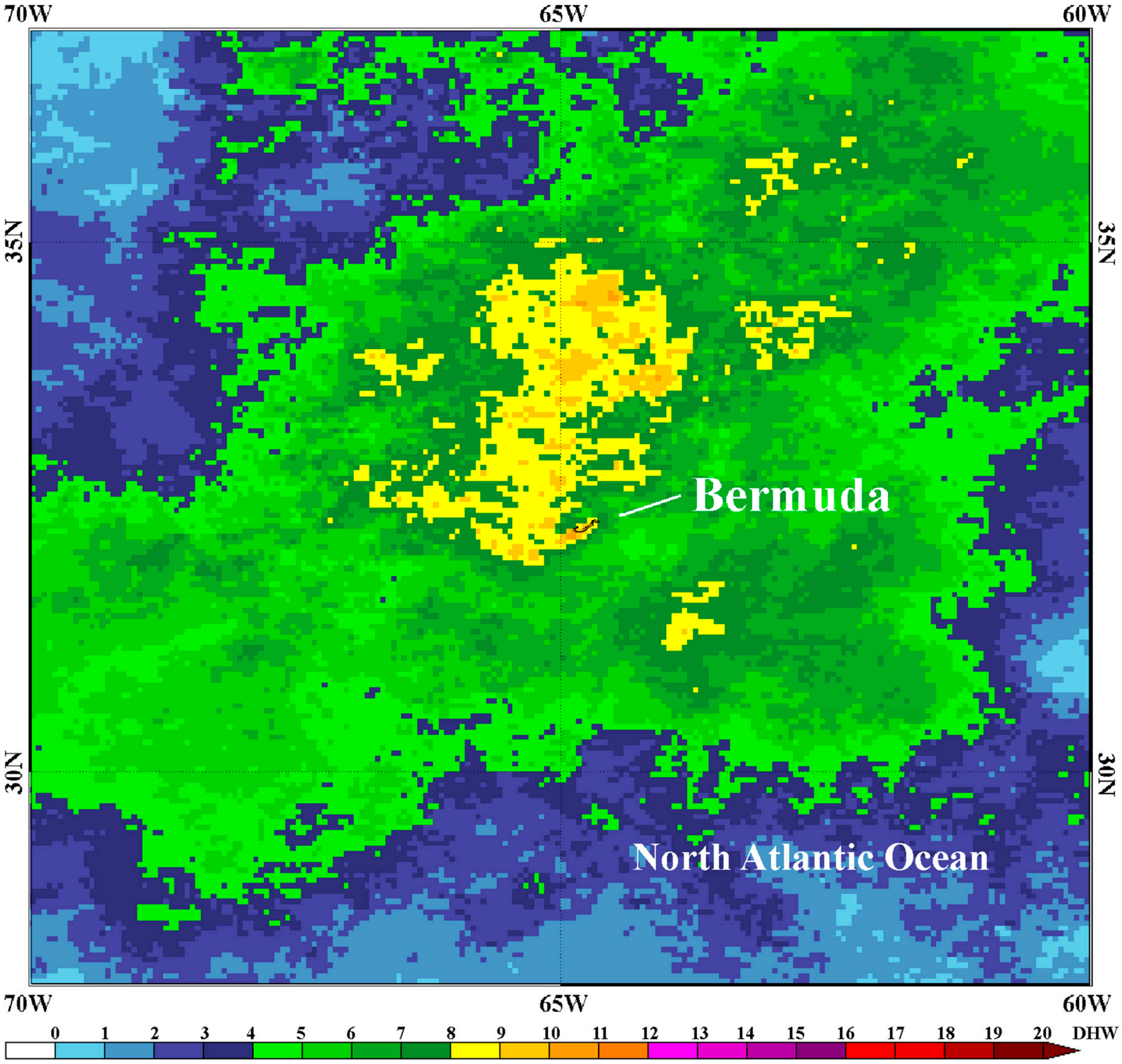


Figure 10. CRW's daily 5-km regional DHW image for Bermuda on 28 August 2013.



As far as we know, no direct management responses have been undertaken during the 2013–2014 events discussed here. This is in contrast to the Southeast Asian bleaching event in 2010, when agencies in Thailand and Malaysia responded to observed severe bleaching [68] and CRW's satellite near-real-time monitoring and Seasonal Coral Bleaching Thermal Stress Outlooks of continued bleaching [31,32] by closing reef sites in the Andaman Sea for the season [69,70]. However, local managers are currently using field surveys and CRW's thermal stress products to identify areas more resilient to thermal stress [57].

We are in communication with field teams who are gathering quantitative field data on the extent of bleaching for these events. CRW plans to work with these collaborators to undertake quantitative analyses both comparing the values and timing of the 5-km DHW with observed bleaching and comparing the performance of the 50-km and 5-km products.

4. Conclusions

With improved near-real-time SST and climatology data, CRW's next-generation near-real-time daily global 5-km satellite coral bleaching thermal stress monitoring product suite substantially advances the services that CRW provides to local resource managers, scientists and the public. The products improve our ability to monitor locations where corals are experiencing thermal stress and to nowcast episodes of bleaching. CRW now uses data from directly over coral reefs globally to inform reef managers and allow them to make targeted observations and take management actions specific to stressed reefs. Feedback from users shows that the CRW 5-km products are already being used routinely in management activities, and the response has been overwhelmingly positive.

Additional improvements planned for NESDIS' 5-km blended SST analysis include: (1) applying a model-based diurnal correction on SST retrievals to reduce the impacts of diurnal warming at the ocean surface; and (2) incorporating SST observations from satellite microwave sensors to further improve observation continuity and product accuracy in areas of persistent cloud cover. The latest algorithms and analyses will continue to be applied to the best and most recent satellite sensors to derive the SST analysis used in CRW's 5-km product suite.

Reprocessing efforts are underway in NESDIS, at the request of CRW, for the geo-SST and polar-SST products and the geo-polar blended SST analysis. The reprocessing capability will eventually provide an internally consistent blended SST analysis time series to extend back to 1994, the start of the second-generation GOES satellite record. This will allow CRW's 5-km products to be produced retrospectively and further validated to potentially refine the interpretation of thermal stress thresholds relating to bleaching impacts. More importantly, this will enable CRW to develop new internally consistent SST climatologies directly from the geo-polar blended night-only SST data, thus eliminating potential errors introduced by using climatology derived from different data sources.

As CRW's 5-km products provide monitoring for environmental conditions at and near coral reefs, further evaluation of the new products on regional and local scales, based on *in situ* water temperature measurements and bleaching observations, is now feasible. This may lead to the refinement of CRW's satellite coral bleaching thermal stress monitoring algorithm or even the development of enhanced or new algorithms to better serve these environments.

Development of 5-km versions of CRW's other operational products, such as the virtual stations that focus on individual reef areas and the automated Satellite Bleaching Alert (SBA) e-mail system (described in [19]), is underway. CRW plans to continue producing the heritage 50-km product suite until the 5-km product suite becomes fully operational. We anticipate that there will be some differences between the two product suites in certain areas, and user discretion is advised.

The 5-km coral bleaching thermal stress products are available online for free to the public via CRW's website: http://coralreefwatch.noaa.gov.

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Applied Sciences Biodiversity and Ecological Forecasting program Grant NNX09AV24G and the NOAA Coral Reef Conservation Program. The CRW team at NOAA/NESDIS that develops and generates these monitoring products comprises scientists from the Center for Satellite Applications and Research (STAR) and the Office of Satellite and Product Operations (OSPO). The contents in this manuscript are solely the opinions of the authors and do not constitute a statement of policy, decision or position on behalf of NOAA or the U.S. Government.

Author Contributions

Gang Liu, Scott F. Heron, C. Mark Eakin, Frank E. Muller-Karger, Liane S. Guild, Jacqueline L. De La Cour, William J. Skirving and Alan E. Strong designed the study. Gang Liu, Scott F. Heron, C. Mark Eakin, Frank E. Muller-Karger, Maria Vega-Rodriguez, Jacqueline L. De La Cour, Erick F. Geiger, William J. Skirving, Timothy F.R. Burgess, Alan E. Strong, Andy Harris, Eileen Maturi, Alexander Ignatov, John Sapper and Jianke Li developed the products. Gang Liu, Scott F. Heron, C. Mark Eakin, Frank E. Muller-Karger, Maria Vega-Rodriguez, Liane S. Guild, Jacqueline L. De La Cour, Erick F. Geiger, William J. Skirving and Alan E. Strong performed the product evaluations. Susan Lynds evaluated user needs and user perceptions of product relevance and project success. Gang Liu, Scott F. Heron and C. Mark Eakin wrote the paper with revisions, comments and suggestions from all other co-authors.

Conflicts of Interest

The authors declare no conflicts of interest. The funding sponsors had no role in the design of the study, in the collection, analyses or interpretation of data, in the writing of the manuscript and in the decision to publish the results.

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