

NOAA Coral Reef Watch

2015 Annual Summaries of Thermal Conditions Related to Coral Bleaching for NCRMP Jurisdictions

Executive Summary

2015 was the warmest year ever recorded on land and in the ocean. On October 2, 2015 NOAA's Coral Reef Watch (CRW) [declared](#) the third confirmed global coral bleaching event (after the 1997-1999 and 2010 global events) was underway, as anomalously warm ocean temperatures were causing widespread coral bleaching in Hawai'i and the Caribbean. This global event began in the North Pacific Ocean in the summer of 2014 and expanded to the South Pacific Ocean, Indian Ocean, and Atlantic Ocean in 2015. The event has been closely associated with an extensive warm "Blob" in the northeastern Pacific Ocean lasting from late 2013 through late 2015, a partially-formed 2014-15 El Niño, and a [record-strength El Niño event](#) that developed in mid-2015 and peaked in late 2015. This bleaching event is still ongoing in 2016 and will likely persist into 2017.

U.S. coral reefs have been hit disproportionately hard. For two years in a row, U.S. coral reefs experienced bleaching on a large spatial scale, including record-breaking events in the Hawaiian Islands, American Samoa, the Commonwealth of the Northern Mariana Islands (CNMI), and Florida. Data analysis based on CRW's daily global 5-km satellite monitoring shows that during the two-year period of 2014-2015, 100% of the U.S. coral reef areas experienced some levels of bleaching thermal stress, with Alert Level 2 thermal stress (typically associated with widespread coral bleaching and mortality) experienced by 41% of the U.S. coral reef areas and Alert Level 1 thermal stress (typically associated with significant bleaching) by 30% of the U.S. coral reef areas. Meanwhile, globally 99% of coral reef areas (including U.S. reef areas) experienced some levels of bleaching thermal stress, with only 9% for Alert Level 2 and 22% for Alert Level 1.

While CRW's heritage, [operational twice-weekly global 50-km satellite coral bleaching thermal stress monitoring products](#) (Liu et al., 2013) continued to alert coral reef communities to the development of thermal stress, in February 2015, CRW released an enhanced version of its next-generation [daily global 5-km satellite coral bleaching thermal stress monitoring products](#) (Liu et al., 2014) that are now featured on the CRW website as core products of CRW's management decision support system. The 5-km global products include Sea Surface Temperature (SST), SST Anomaly, Coral Bleaching HotSpot, Degree Heating Week (DHW), a 7-day maximum Bleaching Alert Area, and a 7-day SST Trend product. The 5-km products provide much higher spatial and temporal resolutions, and more data per pixel, and use a new climate-data-record based climatology, which allow them to monitor thermal conditions globally at or near reef scales.

February 2015 also saw the release of CRW's new [Regional Virtual Stations/Bleaching Thermal Stress Gauges](#), based on this 5-km product suite and CRW's [Coral Bleaching Thermal Stress Outlook](#). CRW's both 5-km Regional Virtual Stations and heritage 50-km Virtual Stations provide detailed coral bleaching thermal stress information for select global and U.S. reef locations based on CRW's near-real-time satellite monitoring products, but the 5-km Regional Virtual Stations are much more comprehensive than the 50-km Virtual Stations they replace. The configurations of the 5-km

and 50-km Virtual Stations are fundamentally different, as a result of the significant differences in the spatial and temporal resolutions. The concept of CRW's Virtual Station has advanced from using data extracted from a single 50-km pixel at or near a reef area to using data from all 5-km pixels at and surrounding all coral reefs for an entire jurisdiction or archipelago. To reflect the difference in spatial configuration between the two types of Virtual Stations, the product name was changed from Virtual Stations to Regional Virtual Stations.

To develop the Regional Virtual Stations, reef-containing 5-km pixels within a coral reef jurisdiction or archipelago were first identified and then augmented with a 20-km buffer around each 5-km reef pixel to identify all the 5-km water pixels of the Regional Virtual Station. Thus, each 5-km Regional Virtual Station provides comprehensive, collective information (including regionally representative statistics based on all water pixels) for a large coral reef region. The thermal stress level of a Regional Virtual Station is determined spatially using the pixels experiencing the highest stress levels each day—the most stressed 10% of the satellite pixels in that defined region. In other words, the stress level of a 5-km Regional Virtual Station is provided as the 90th percentile value of all individual 5-km water pixels in the station. Note that in a Regional Virtual Station at any given moment some water pixels (less than 10% of all the water pixels in the station) may experience higher stress level(s) than the stress level reported for the station. In the current setting, the number of water pixels varies between Regional Virtual Stations due to the difference in geo-political definition and difference in the number and spatial distribution of reef containing water pixels between jurisdictions, ranging from 39 (Easter Island Station) to 12,014 (Papua New Guinea Station) water pixels, with an average of 1,156 pixels per station for a total of 212 stations in the global oceans. One example from among the U.S. jurisdictions, the 5-km Regional Virtual Station for the Commonwealth of the Northern Mariana Islands (CNMI) contains 813 water pixels whereas Guam contains only 275. This results in Regional Virtual Stations providing a more comprehensive tool for coral reef managers than the single-pixel-based 50-km Virtual Stations that CRW has been using for more than 15 years.

In this report the spatial distribution of thermal stress for each U.S. jurisdiction is described synoptically based on both 5-km and 50-km global products, along with the comprehensive and statistical thermal stress information provided by the corresponding 5-km Regional Virtual Station and single-pixel-based information provided by the corresponding 50-km Virtual Station(s). (The bleaching thermal stress outlook component of the 5-km Regional Virtual Stations is not discussed in this report.)

Note that the 5-km and 50-km satellite products, especially the Virtual Station products, may differ in their interpretations of the onset, duration, and severity of thermal stress within a U.S. jurisdiction, as described throughout this report. Discrepancy between the two product suites is expected as different SST analyses and climatologies are used, and higher-resolution products may require adjusted thresholds. With the generally higher quality SST analysis and climate-data-record based climatology used in the 5-km monitoring, along with increased spatial and temporal resolutions, the overall accuracy of the 5-km products is expected to be higher. However, as CRW continues the analysis of its new 5-km products, we recommend that resource managers continue to consult both the 5-km and 50-km product suites, especially both Virtual Station products, to best understand coral reef environmental conditions in near-real-time in their jurisdictions. Therefore, this report provides thermal stress information from both the 5-km and 50-km product suites. For some regions, the difference between the two can be significant. In some cases, further high-quality *in situ* observations will be needed to qualitatively and quantitatively evaluate both products. We look forward to utilizing NCRMP *in situ* SST monitoring and bleaching observations to assist with this evaluation.

ATLANTIC OCEAN

Florida:

The summer of 2014 was reported by the Florida Reef Resilience Program (FRRP) Disturbance Response Monitoring (DRM) as the most severe bleaching season since their surveys began in 2005, especially in the Florida Keys. Following that, and for the second year in a row, the FRRP reported bleaching in 2015. CRW's twice-weekly global 50-km satellite products and its daily global 5-km satellite products detected and monitored the development of coral bleaching thermal stress in the region from late June until early October 2015 and again provided important advance warning to the FRRP and other management and scientific users.

In the Florida Keys region, CRW's 5-km products showed that in 2015 the bleaching thermal stress first appeared on both the Gulf side of the Lower Keys and the Florida Bay side of the Upper Keys; the stresses in these two local areas remained higher than other areas in the region throughout the 2015 bleaching season (Figure 1). Two CRW 5-km Regional Virtual Stations cover Florida's coral reefs: Florida Keys Station (Figure 2) and Southeast Florida Station (Figure 3).

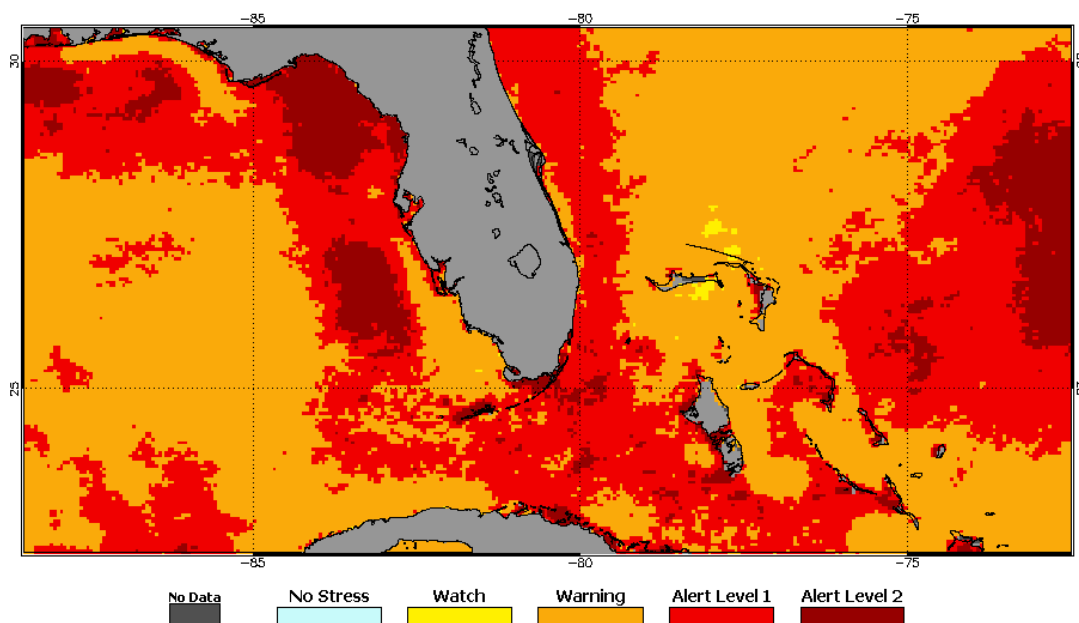


Figure 1. CRW's 2015 annual maximum composite of daily 5-km Bleaching Alert Area for Florida.

Temperatures first reached Bleaching Watch level in the 5-km Regional Virtual Stations for Florida Keys and Southeast Florida on June 20 and 19, 2015, respectively, when for the first time in 2015 at least 10% of their 5-km water pixels exceeded the Maximum Monthly Mean SST climatology for these stations (Figure 4). (The Maximum Monthly Mean SST climatology is one of the spatially variable thresholds that CRW uses in its bleaching thermal stress monitoring products to determine thermal stress levels. When SST exceeds the Maximum Monthly Mean SST climatology, the reefs are placed at least at a Bleaching Watch level.) In Florida, the temperatures quickly reached Bleaching Warning on June 28 for the Florida Keys Station and June 30 for the Southeast Florida Station, but the

threat of mass bleaching continued to remain moderate until mid-August. (A Bleaching Warning is reached when the temperature reaches 1°C over the Maximum Monthly Mean SST climatology and we begin to accumulate thermal stress in the DHW product. DHW is a CRW product that CRW's Bleaching Alert Area product is based on and accounts for the intensity of accumulated thermal stress.) As thermal stress continued to accumulate, Alert Level 1 bleaching conditions ($DHW \geq 4$ °C-weeks, typically associated with significant bleaching) were reached by the Florida Keys Station and Southeast Florida Station on August 10 and 17, respectively. Tropical Storm Erika's arrival on August 30 brought some relief to areas already experiencing thermal stress and mild to moderate bleaching.

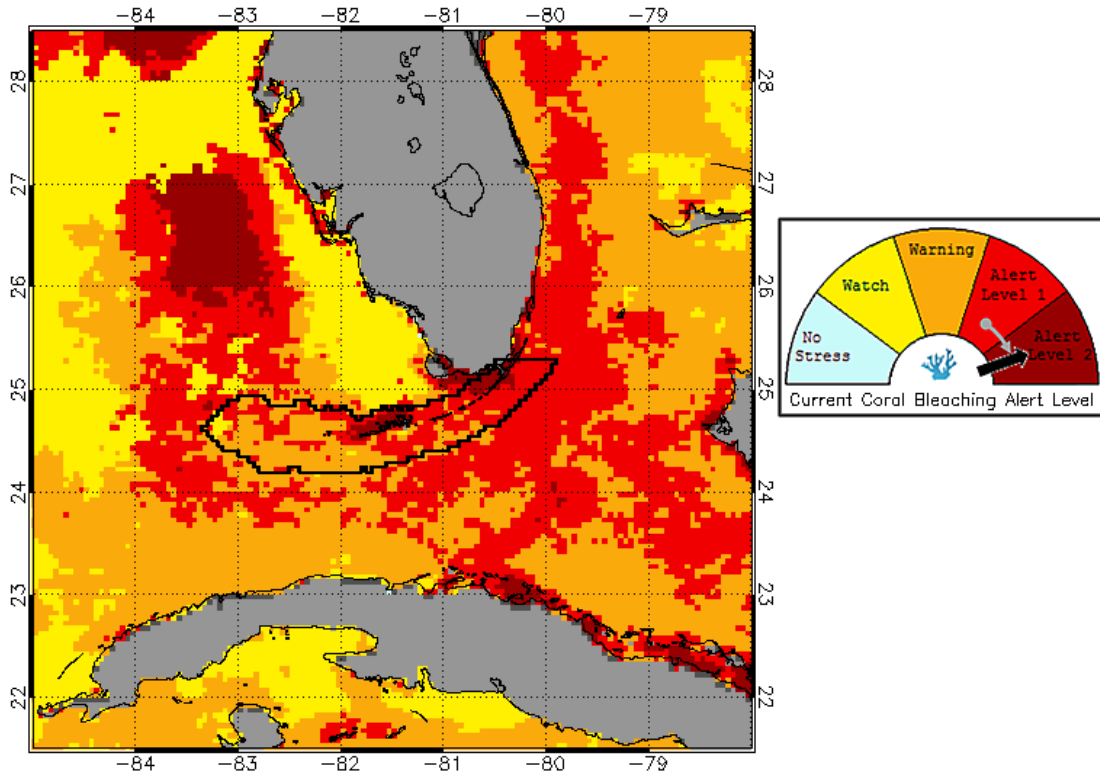


Figure 2. Spatial coverage (black polygon) of CRW's 5-km Florida Keys Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for September 7, 2015 when the station's stress first elevated to Alert Level 2, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level on that day as the 90th percentile value of thermal stress level in the station.

On September 7, the Florida Keys Station reached Alert Level 2 bleaching stress conditions ($DHW \geq 8$ °C-weeks, typically associated with widespread coral bleaching and mortality, Figure 2); this high level bleaching stress persisted for two weeks, reaching $DHW=8.9$ °C-weeks. On September 22 cooler waters returned to the region (Figure 4). The areas affected by Alert Level 2 were mainly on the Gulf side of the Lower Keys and Florida Bay side of the Upper Keys (Figure 1). The Florida Keys Station returned to No Stress on October 10 when temperatures cooled to below the Maximum Monthly Mean SST climatology at more than 90% of the station pixels.

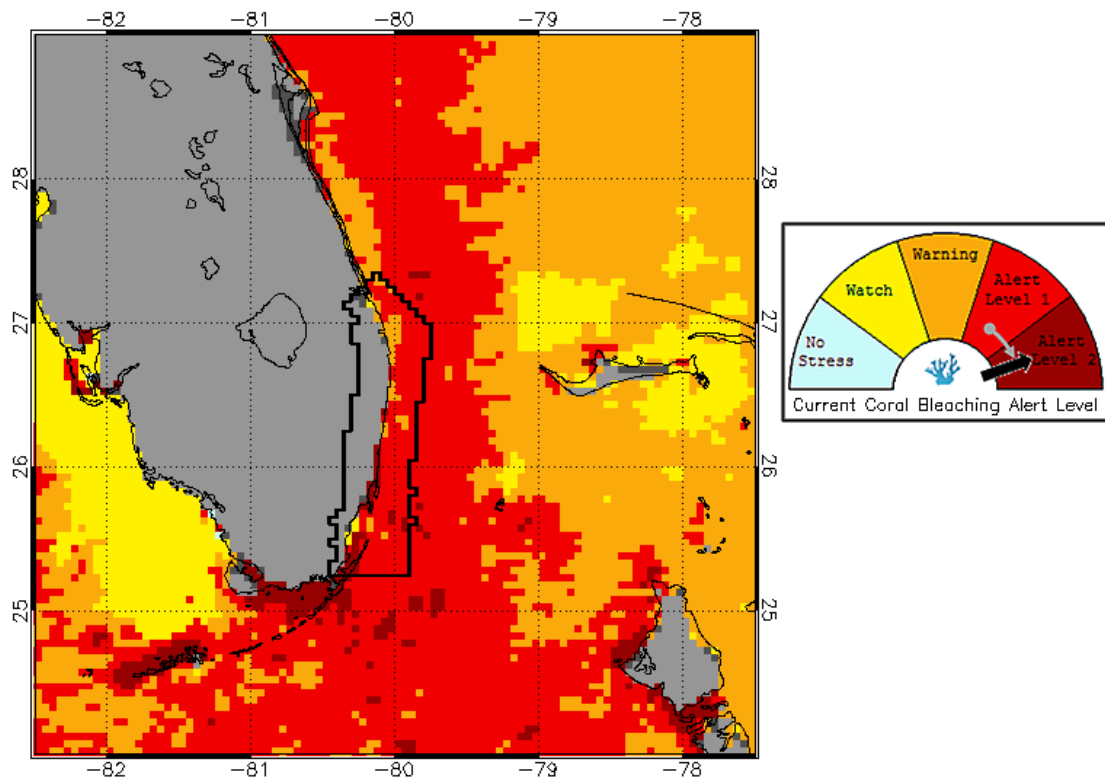


Figure 3. Spatial coverage (black polygon) of CRW's 5-km Southeast Florida Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for September 13, 2015 when the station's stress first elevated to Alert Level 2, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level on that day.

The Southeast Florida Station was generally cooler but also reached Alert Level 2 on September 13, one week later than the Florida Keys Station. Alert Level 2 conditions appeared only around the northern portion of Key Largo at the southwest end of the station – resulting from the highest stress patch that was located in the Florida Bay where the two stations meet (Figure 2 and 3). The stress in the Southeast Florida Station quickly returned to Alert Level 1 three days later, then Bleaching Watch by September 22, and No Stress by the first week in October (Figure 4). The spatial distribution of the maximum thermal stress levels reached in 2015 in the Florida region is provided in Figure 1.

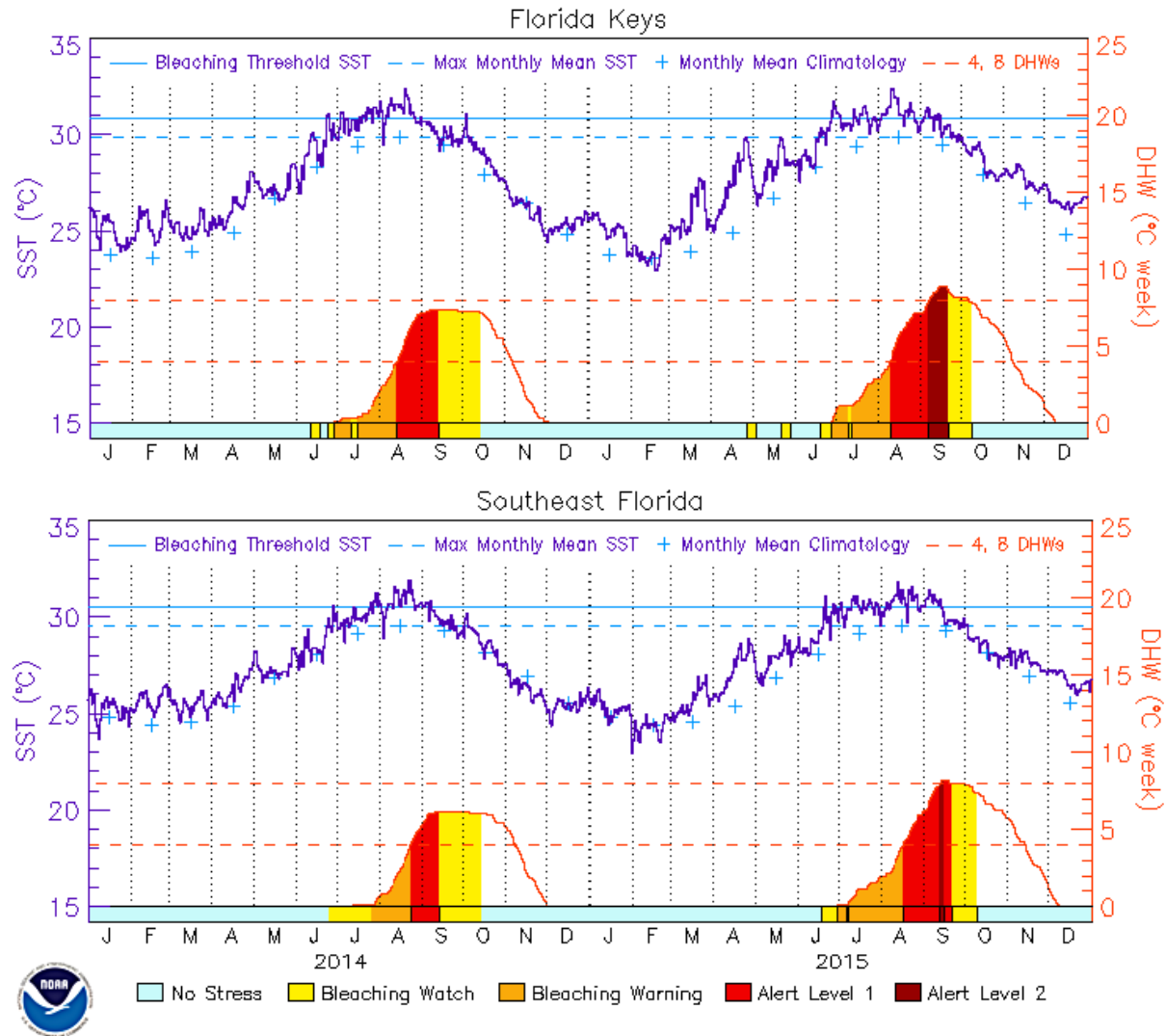


Figure 4. Two-year (2014-15) time series graphs for CRW's 5-km Florida Keys (top panel) and Southeast Florida (bottom panel) Regional Virtual Stations. In each graph, the station's SST values (purple curve) are shown in the center of graph and read using the vertical axis on the left; the station's Degree Heating Week (DHW) values (red curve) are shown in the bottom portion of the graph and read using the vertical axis on the right; the station's Bleaching Alert Levels are colored along the horizontal axis and under the DHW curve and read using the color legend underneath the horizontal axis. Values plotted are the 90th percentile values of the corresponding variables.

There are eight and four individual 50-km single-pixel-based Virtual Stations overlapping the 5-km Florida Keys and Southeast Florida Regional Virtual Stations' coverage areas, respectively (Figure 5). Four additional 50-km Virtual Stations around the Florida Keys that were used in the reports for the past years are far away from the coral reef areas and beyond the coverage of the 5-km Florida Keys Regional Virtual Station (Figure 5) and not discussed in this report. The eight 50-km Virtual Stations corresponding to the 5-km Florida Keys Regional Virtual Station are Upper Keys, Middle Keys, Lower Keys, and Lower Keys-Marquesas along the open ocean side from the Upper Keys to Lower Keys; Rebecca Shoal and Dry Tortugas to the west of the Lower Keys; and Gulf SW Florida Shelf

and Gulf Sloughsway on the Gulf side of the Lower and Middle Keys. The four 50-km Virtual Stations corresponding to the 5-km Southeast Florida Regional Virtual Station are Martin, Palm Beach, Broward, and Biscayne (from north to south). Given the twice-weekly temporal resolution of the 50-km monitoring products, throughout this report, date ranges of corresponding twice-weekly time periods are used in analysis and discussion.

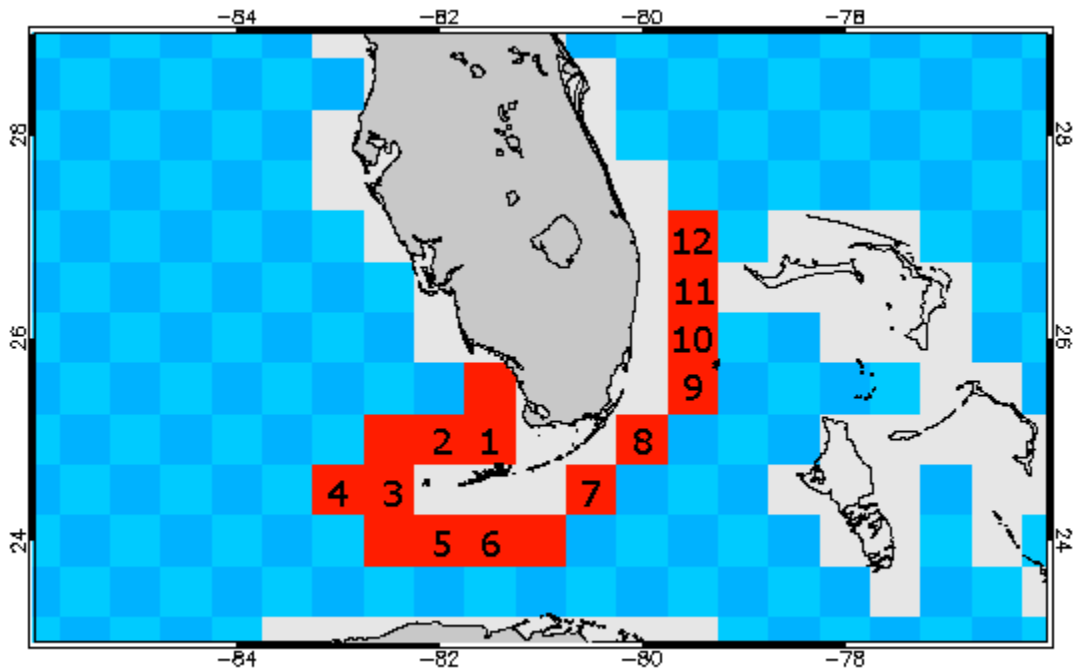


Figure 5. CRW's single-pixel-based 50-km Virtual Stations (red pixel squares) in the Florida region. Numbered Virtual Stations overlap CRW's two 5-km Regional Virtual Stations in the region (Florida Keys Station and Southeast Florida Station) shown in Figure 1 and 2 and are discussed in this report: (1) Gulf Sloughsway, (2) Gulf SW Florida Shelf, (3) Rebecca Shoal, (4) Dry Tortugas, (5) Lower Keys-Marquesas, (6) Lower Keys, (7) Middle Keys, (8) Upper Keys, (9) Biscayne, (10) Broward, (11) Palm Beach, and (12) Martin. Four unnumbered red Virtual Stations are not discussed in this report. Pixels in light gray are land-mask pixels where no data are provided by the 50-km products.

CRW's 50-km satellite products detected the onset of thermal stress in Florida slightly later than the 5-km satellite products. In the Florida Keys region, Bleaching Watch appeared first at the Gulf Sloughsway and Gulf SW Florida Shelf Stations on the Gulf side of the Lower Keys during the twice-weekly time period of June 22-24, 2015 (Figure 6 and Table 1), followed by the Rebecca Shoal and Dry Tortugas Stations to the west of the Lower Keys during June 25-28 and the Upper Keys Station on the open ocean side of the Upper Keys during June 29-July 1, then much later the Middle Keys, Lower Keys, and Lower keys-Marquesas Stations (all on the open ocean side of the Keys) during July 13-15. At all of these stations, the status elevated to Bleaching Warning between June 25 and August 30. However, all but the Upper Keys and Middle Keys Stations reached Bleaching Alert 1 between July 16 and September 23, with the Gulf Sloughsway and Gulf SW Florida Shelf Stations leading the way. These two stations on the Gulf side of the Lower Keys were the only 50-km stations in the Keys that reached Alert Level 2 and their Alert Level 2 warnings were issued on August 2 and

August 16, respectively (Figure 6 and Table 1). The maximum accumulated thermal stresses, measured by CRW's 50-km DHW product, at these stations are provided in Table 2. The highest stress level reached at each station remained steady into mid-September. The spatial pattern of the stress in the 50-km monitoring was consistent with that in the 5-km monitoring, with the Gulf side of the Lower Keys experiencing Alert Level 2. There is no 50-km water pixel available over the Florida Bay and the Bay side of the Upper Keys where the 5-km products also detected Alert Level 2.

Table 1. List of 50-km Virtual Stations in Florida, station geo-locations, onset dates of Bleaching Watch, Bleaching Warning, Alert Level 1, Alert Level 2, and stress dissipation.

#	Station Name	Lat, Lon	Bleaching Watch	Bleaching Warning	Alert Level 1	Alert Level 2	Stress Dissipation	End of Stress
1	Gulf Sloughsway	25.0N, 81.5W	Jun 22-24	Jun 25-28	Jul 16-19	Aug 3-5	Sep 24-27	Oct 5-7
2	Gulf SW Florida Shelf	25.0N, 82.0W	Jun 22-24	Jun 29-Jul 1	Jul 23-26	Aug 17-19	Sep 21-23	Oct 5-7
3	Rebecca Shoal	24.5N, 82.5W	Jun 25-28	Jul 16-19	Aug 27-30	N/A	Sep 21-23	Oct 5-7
4	Dry Tortugas	24.5N, 83.0W	Jun 25-28	Jul 16-19	Aug 27-30	N/A	Sep 17-20	Oct 5-7
5	Lower Keys-Marquesas	24.0N, 82.0W	Jul 13-15	Aug 27-30	Sep 17-20	N/A	Sep 21-23	Oct 1-4
6	Lower Keys	24.0N, 81.5W	Jul 13-15	Aug 27-30	Sep 21-23	N/A	Sep 24-27	Oct 1-4
7	Middle Keys	24.5N, 80.5W	Jul 13-15	Jul 23-26	N/A	N/A	Sep 14-16	Oct 8-11
8	Upper Keys	25.0N, 80.0W	Jun 29-Jul 1	Jul 23-26	N/A	N/A	Sep 21-23	Oct 8-11
9	Biscayne	25.5N, 79.5W	Jun 22-24	Jul 23-26	Sep 7-9	N/A	Sep 14-16	Oct 5-7
10	Broward	26.0N, 79.5W	Jun 22-24	Jul 20-22	Sep 7-9	N/A	Sep 14-16	Oct 5-7
11	Palm Beach	26.5N, 79.5W	Jun 22-24	Jul 20-22	Aug 24-26	N/A	Sep 14-16	Oct 15-18
12	Martin	27.0N, 79.5W	Jun 22-24	Jul 23-26	N/A	N/A	Sep 14-16	Oct 19-21

Table 2. List of 50-km Virtual Stations in Florida and their maximum Degree Heating Week (DHW) values and dates.

#	Station Name	Lat, Lon	Max DHW (°C-weeks)	Dates of Max DHW
1	Gulf Sloughsway	25.0N, 81.5W	19.1	Sep 17-20
2	Gulf SW Florida Shelf	25.0N, 82.0W	15.4	Sep 17-20
3	Rebecca Shoal	24.5N, 82.5W	7.6	Sep 17-20
4	Dry Tortugas	24.5N, 83.0W	6.9	Sep 14-16
5	Lower Keys-Marquesas	24.0N, 82.0W	4.1	Sep 17-20
6	Lower Keys	24.0N, 81.5W	4.0	Sep 21-23
7	Middle Keys	24.5N, 80.5W	2.8	Sep 10-13
8	Upper Keys	25.0N, 80.0W	3.9	Sep 17-20
9	Biscayne	25.5N, 79.5W	5.2	Sep 10-13
10	Broward	26.0N, 79.5W	4.6	Sep 10-13
11	Palm Beach	26.5N, 79.5W	6.1	Sep 10-13
12	Martin	27.0N, 79.5W	3.0	Sep 10-13

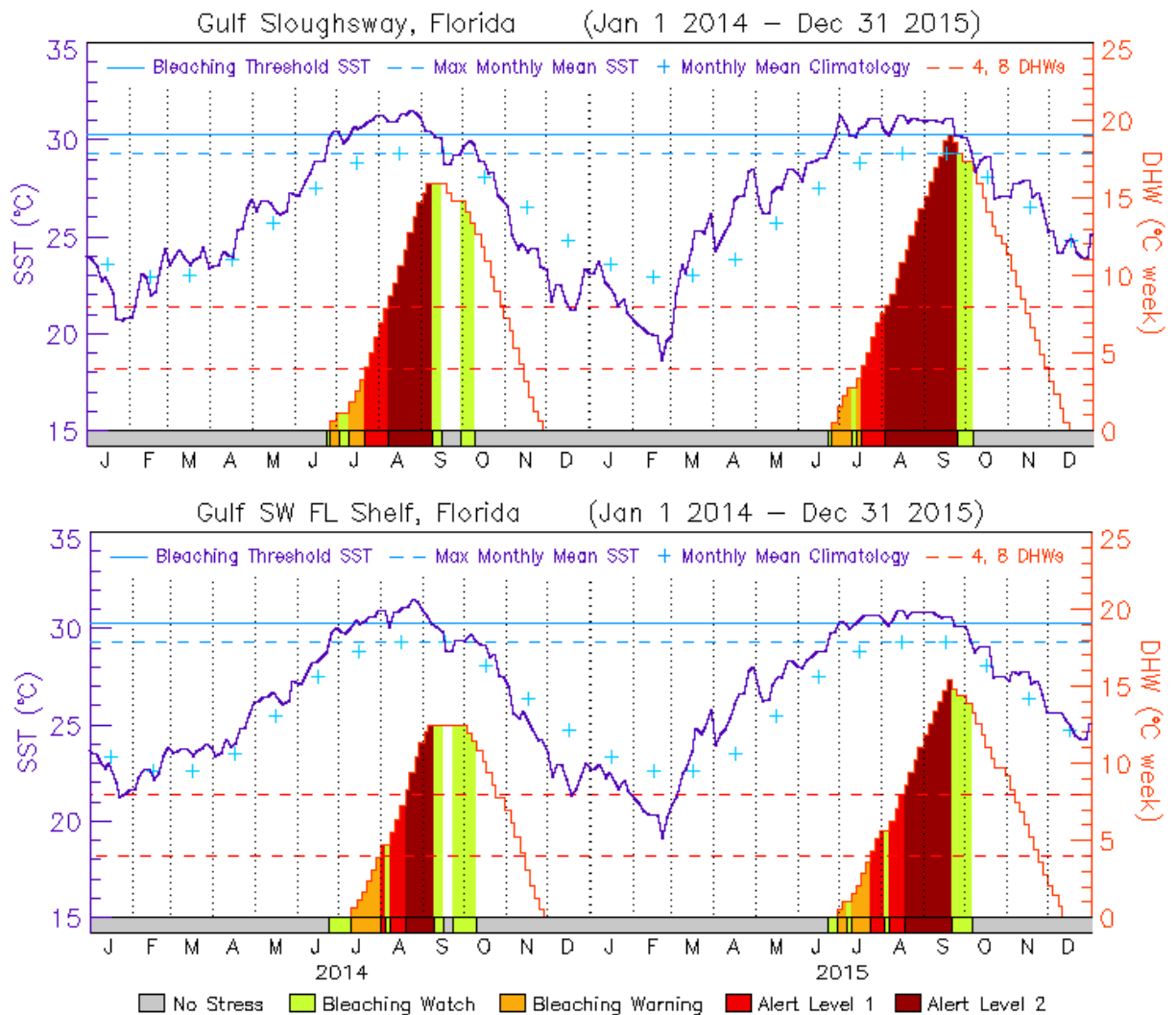


Figure 6. Two-year (2014-15) time series graphs for CRW's 50-km Gulf Sloughsway (top panel) and Gulf SW FL Shelf, FL (bottom panel) Virtual Stations. In each graph, the station's SST values (purple curve) are shown in the center of graph and read using the vertical axis on the left; the station's Degree Heating Week (DHW) values (red curve) are shown in the bottom portion of the graph and read using the vertical axis on the right; the station's Bleaching Alert Levels are colored along the horizontal axis and under the DHW curve and read using the color legend underneath the horizontal axis.

In the Southeast Florida region, Bleaching Watch appeared during June 22-24, 2015 at all four 50-km stations and Bleaching Warning was reached simultaneously during July 20-26 (Table 1). Time series graphs for Biscayne and Broward are provided in Figure 7 as examples. Alert Level 1 was issued for three stations: Palm Beach during August 24-26 and Broward and Biscayne during September 7-9. The highest stresses reached at the stations are provided in Table 2. None of them reached Alert Level 2. The observation made by the 5-km product (Figure 3) revealed that a small portion of the 50-km Biscayne Station might have experienced Alert Level 2 but it was insufficient for the entire 50-km pixel. Bleaching stress dissipated by the end of September 2015. The spatial distribution of the maximum thermal stress levels reached in 2015 in the region is provided in Figure 8.

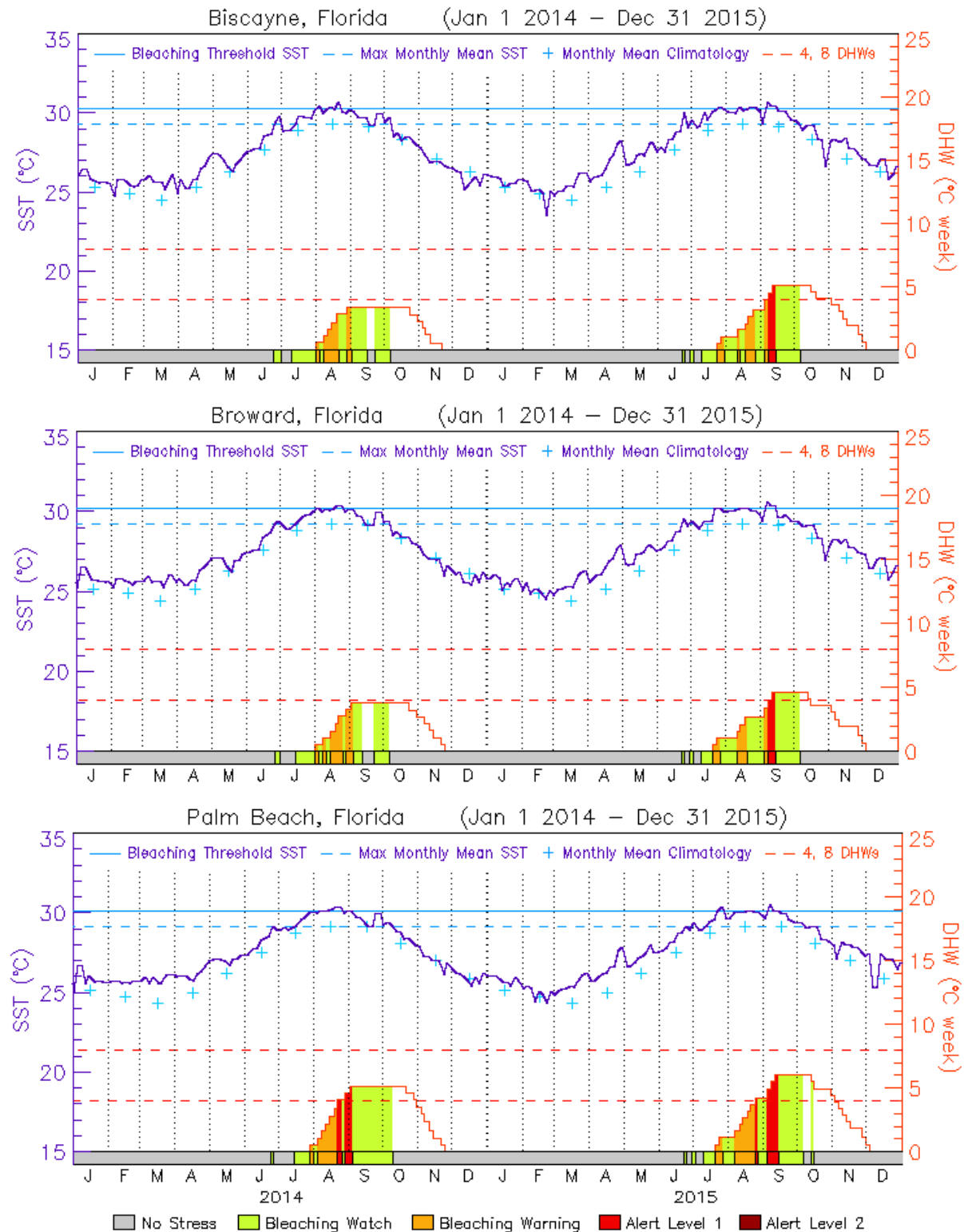


Figure 7. Two-year (2014-15) time series graphs for CRW's 50-km Biscayne (top panel), Broward (middle panel), and Palm Beach (bottom panel) Virtual Stations. See the caption of Figure 6 for how to read the graph.

Overall, the spatial distribution of the 50-km thermal stress levels matched well with the 5-km products in the region covered by both 5-km Regional Virtual Stations. The 5-km products are generally expected to be more accurate and much more capable of identifying localized thermal stress patterns.

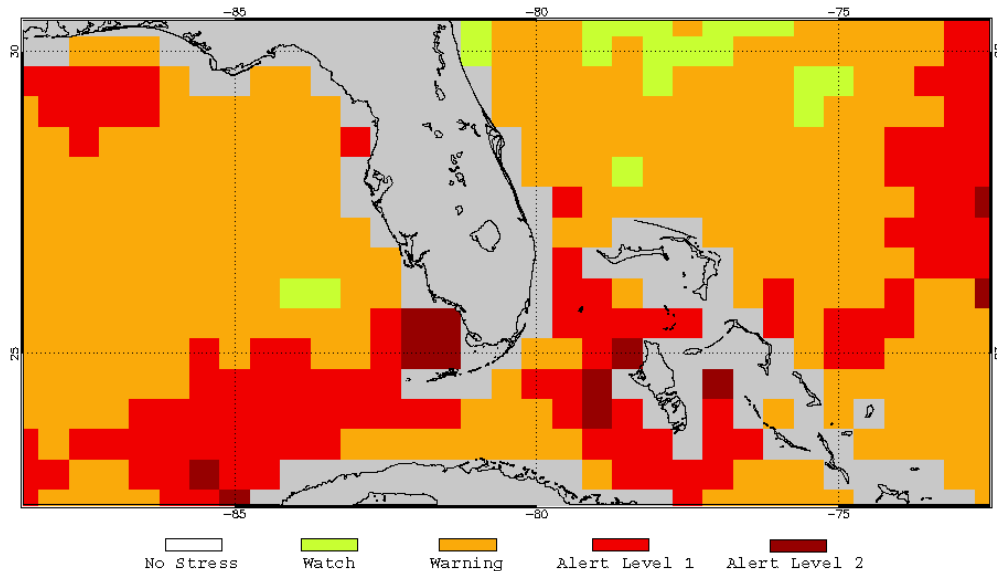


Figure 8. CRW's 2015 annual maximum composite of twice-weekly 50-km Bleaching Alert Area for Florida.

CRW's management and scientific partners in Florida, including the Mote Marine Laboratory / Florida Keys National Marine Sanctuary (FKNMS) BleachWatch program for the Florida Keys and the Florida Department of Environmental Protection's (DEP) Southeast Florida Action Network (SEAFAN) BleachWatch program for the southeastern Florida, utilized the new daily 5-km satellite products, especially the two 5-km Regional Virtual Stations in Florida (Florida Keys and Southeast Florida) to alert local stakeholders to changing thermal stress levels and to coordinate monitoring and reporting of bleaching experienced in the region in 2015.

Reports from field partners in Florida confirmed that bleaching was observed throughout much of the area where bleaching levels of thermal stress were detected by CRW's 5-km and 50-km products, especially patterns seen in the 5-km Regional Virtual Stations. As of mid-August, local partners such as the Florida Keys BleachWatch reported isolated observations of paling and partial bleaching on reefs in the Upper and Lower Keys (such as Molasses Reef). Additionally, coral disease outbreaks (including substantial Black Band Disease on reef corals from Bahia Honda to Looe Key, and White Plague Disease and Black Band Disease in the Upper Keys and Biscayne National Park) were being reported by divers. Per the FRRP DRM, high disease prevalence (>10%) occurred at sites within the Broward-Miami, Biscayne, Upper and Lower Keys sub-regions, with fifty percent of those sites being present in the Broward-Miami sub-region. High recent mortality was documented within the South Palm Beach, Deerfield, Broward-Miami, Biscayne, Upper and Middle Keys, and Dry Tortugas sub-regions, with sixty-five percent of those sites being within the Broward-Miami sub-region. By the end of August/beginning of September, CRW has received numerous reports of paling and partial bleaching from partners surveying local reefs throughout the Florida Keys. As monitored and

predicted by both CRW's 5-km satellite Regional Virtual Stations in Florida, the FRRP DRM reported that the summer of 2015 was a moderate to severe bleaching year for Florida's coral reefs. Severe bleaching occurred in some areas of the Upper, Middle and Lower Keys, and Dry Tortugas sub-regions. High disease prevalence and recent mortality were recorded at sites throughout the Florida Reef Tract. Compared to the summer of 2014, bleaching, disease, and recent mortality were lower, but still significant in certain sub-regions. Compared to 2013, both 2014 and 2015 were significantly higher bleaching years. Per the FRRP DRM, severe bleaching and paling (defined as >50% of all hard corals in the area surveyed displaying signs of bleaching or paling) occurred in the forereef and offshore zones of the Middle and Lower Keys and in all FRRP zones of the Upper Keys and Dry Tortugas sub-regions. Moderate bleaching (21-50%) occurred in at least one zone within the Martin, South Palm Beach, Deerfield, Broward-Miami, Biscayne, Middle and Lower Keys sub-regions. Additionally, mild bleaching (0-20%) occurred in at least one zone in the Broward-Miami, South Palm Beach and Martin sub-regions. In fact, DRM monitoring results indicated that CRW's "high" threats of mass bleaching from mid-August through late September for the Florida Keys and Southeast Florida, between Miami-Dade and Martin County were warranted. Reports of coral disease, especially Black Band Disease, were also received from partners in the Keys into late September. A detailed report by the FRRP DRM is available at http://frp.org/wp-content/uploads/2015/12/2015-Summer-DRM-Quick-Look-Report_vs2.pdf. Personal communication with Florida DEP indicated that well over a million coral colonies were lost to disease in the southeast Florida during 2015. No reports have yet been received from partners related to bleaching on reefs in the eastern Gulf of Mexico.

Puerto Rico:

Puerto Rico is served by one CRW 5-km Regional Virtual Station covering the entire Puerto Rico and its surrounding waters, including the "Spanish Virgin Islands" (Figure 9). The first alert was issued on July 20, 2015 when at least 10% of its water pixels reached a Bleaching Watch level (Figure 10). Temperatures rose slowly until September 5, when a rapid increase in SST pushed the station to Bleaching Warning. The station then remained at Bleaching Warning for most of time, with a couple of short periods when the stress decreased to Bleaching Watch. On October 31, temperatures at the station backed down to Bleaching Watch for the year and then reduced to No Stress by November 24 (Figure 10). Alert Level 1 and 2 were never reached at the station level in 2015. The regional thermal stress distribution map (Figure 11) revealed that the eastern portion of Puerto Rico experienced higher stress than the western portion during the entire bleaching season, influenced by a basin-scale warm water mass at much higher intensity in the Atlantic Ocean to the east. A few 5-km water pixels along the east coast of the main island within the station's boundary did experience Alert Level 1 stress in late October during the peak stress period but didn't warrant an Alert Level 1 for the station which requires at least 10% of the station water pixels experiencing Alert Level 1 simultaneously (Figure 11).

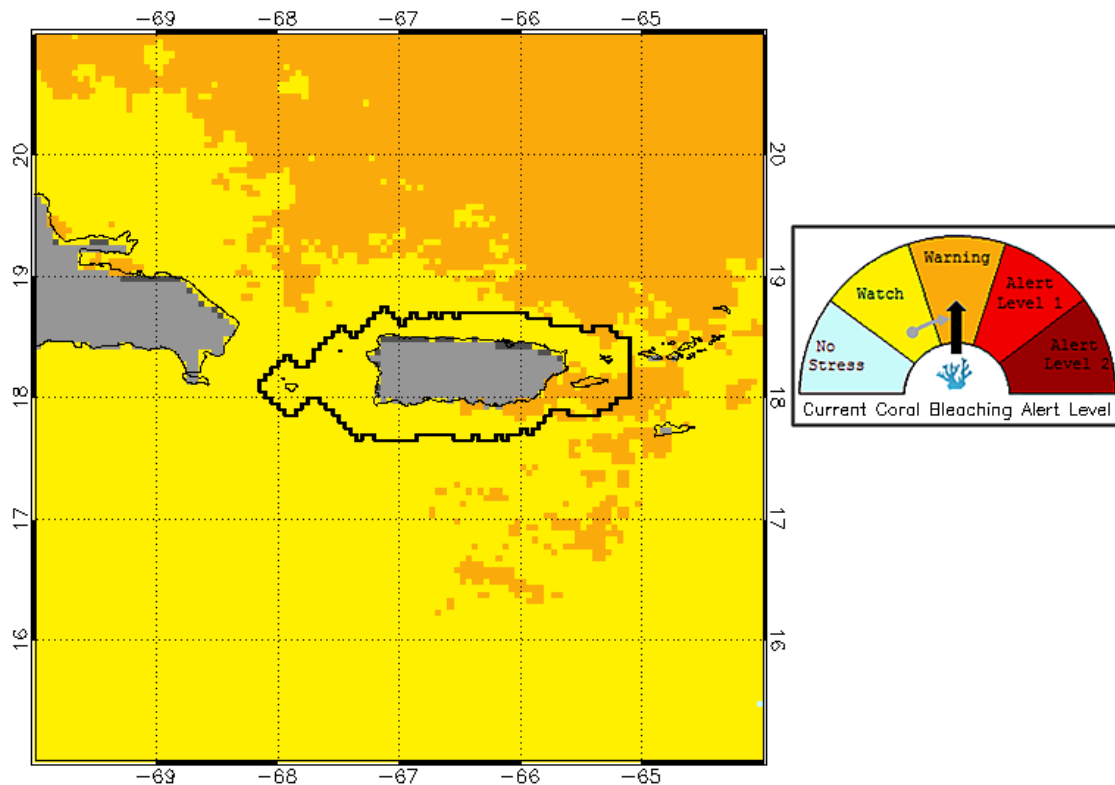


Figure 9. Spatial coverage (black polygon) of CRW's 5-km Puerto Rico Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for September 5, 2015 when the station's stress elevated to Bleaching Warning, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

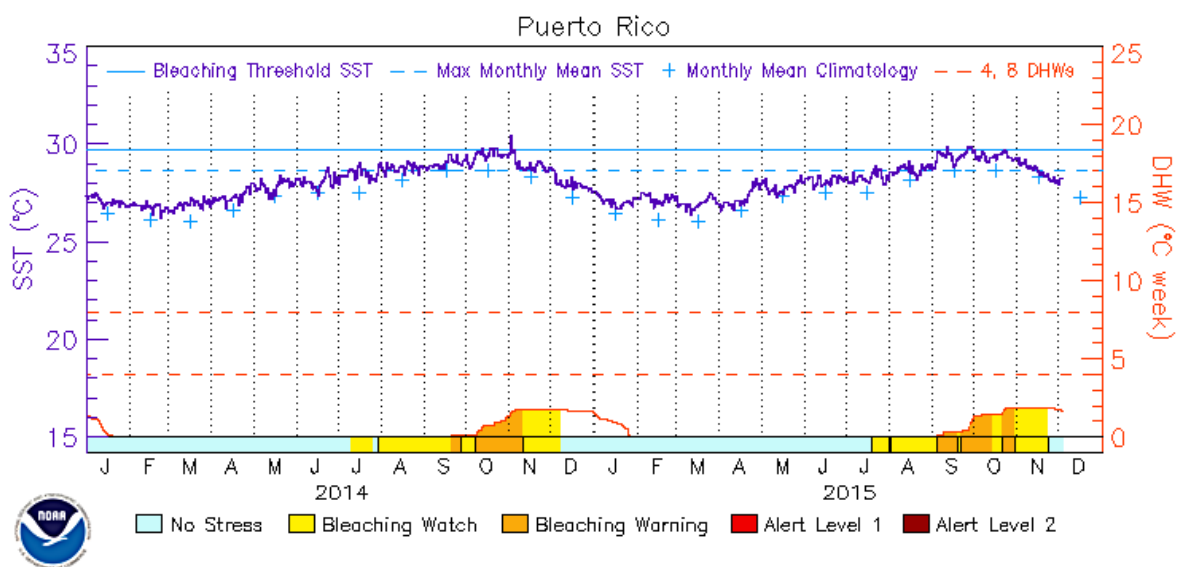


Figure 10. Two-year (2014-15) time series graph for CRW's 5-km Puerto Rico Regional Virtual Station. See the caption of Figure 4 for how to read the graph.

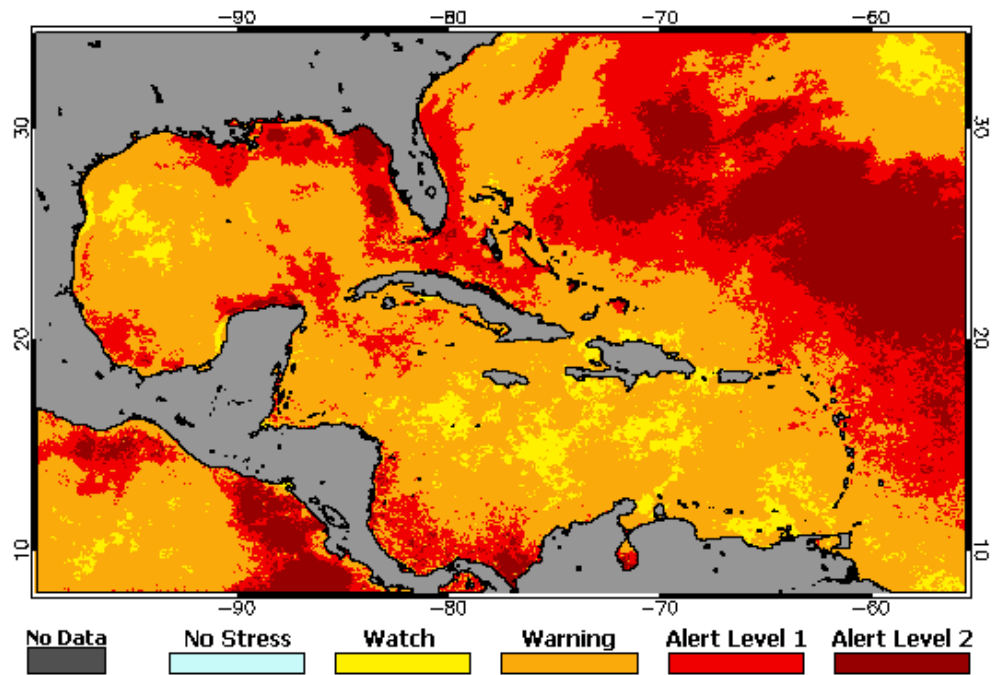


Figure 11. CRW's 2015 annual maximum composite of daily 5-km Bleaching Alert Area for the Greater Caribbean region.

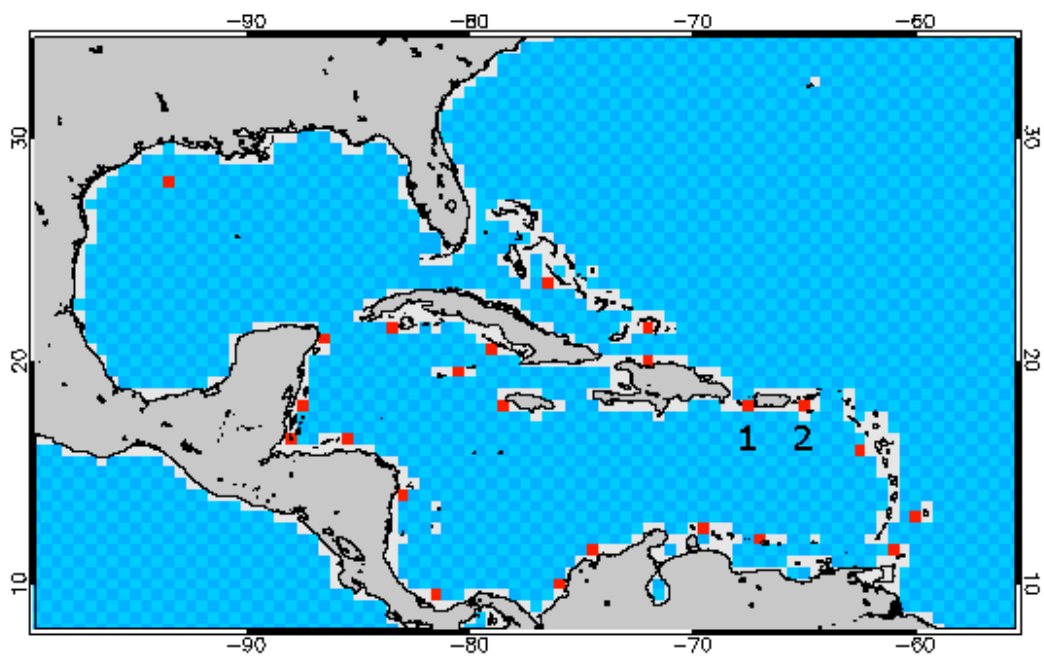


Figure 12. CRW's single-pixel-based 50-km Virtual Stations (red pixel squares) in the Greater Caribbean region. Two numbered Virtual Stations ((1) Puerto Rico and (2) U.S. Virgin Islands) are discussed in this report. Pixels in light gray are land-mask pixels.

CRW's 50-km Virtual Station for Puerto Rico is on a representative 50-km water pixel off the west end of Puerto Rico (Figure 12). Its temperature increased to a Bleaching Watch by the twice-weekly period of August 13-16, 2015 (Figure 13). This lasted until September 24-27 when the temperature reached Bleaching Warning around the east, north, and west side of Puerto Rico, including the station. Fluctuations in SST temporarily reduced the level to Bleaching Watch in mid-October for a week (October 8-14) then the stress continued to build up. Alert Level 1 started to appear in Puerto Rico offshore waters during October 19-21 and around Puerto Rico (including the station) during October 26-28. The stress peaked at DHW=4.8 °C-weeks at the station during October 29-November 1, then started to quickly dissipate and disappeared by the end of November. As observed by the 5-km products, the 50-km products showed that the stress at Puerto Rico was the extension of a large-scale anomalously high temperature water mass centered in the Atlantic Ocean to the east of the island (Figure 14).

Both 50-km and 5-km products showed a similar spatial pattern of stress with the highest stress on the eastern portion of the island connected to a large scale warm water mass further to the east in the Atlantic Ocean and similar timing of the development of thermal stress in Puerto Rico (Figure 11 and 14). The 50-km monitoring showed a much deeper westward intrusion of the large-scale intensive thermal stress in the Atlantic Ocean, largely surrounding the island with Alert Level 1 conditions. As a result, the 50-km Puerto Rico Station briefly presented a higher level of thermal stress at its peak time than the 5-km Puerto Rico Regional Virtual Station.

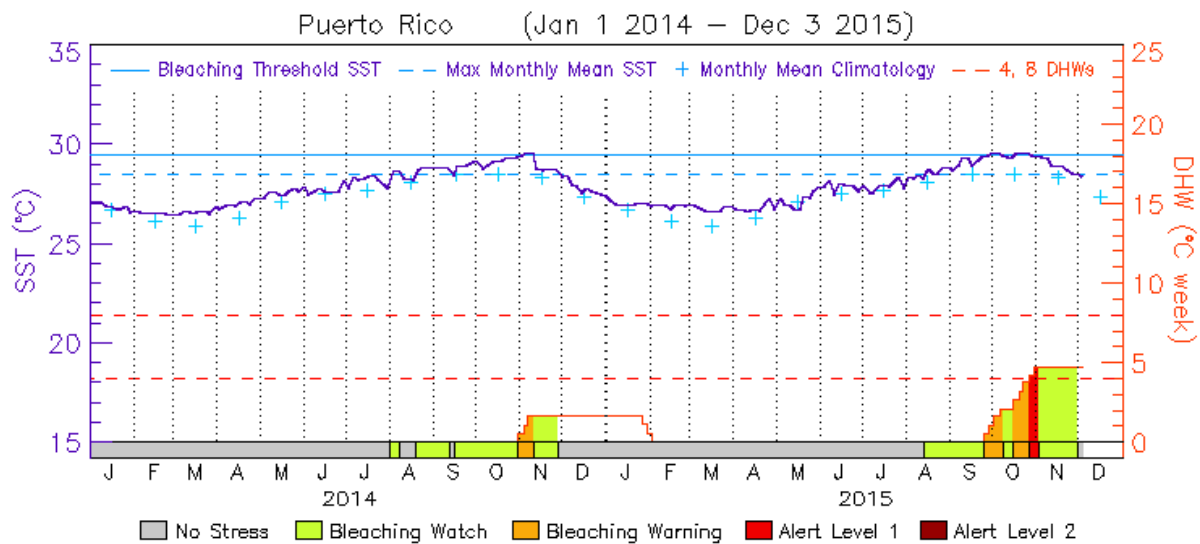


Figure 13. Two-year (2014-15) time series graph for CRW's 50-km Puerto Rico Virtual Station. See the caption of Figure 6 for how to read the graph.

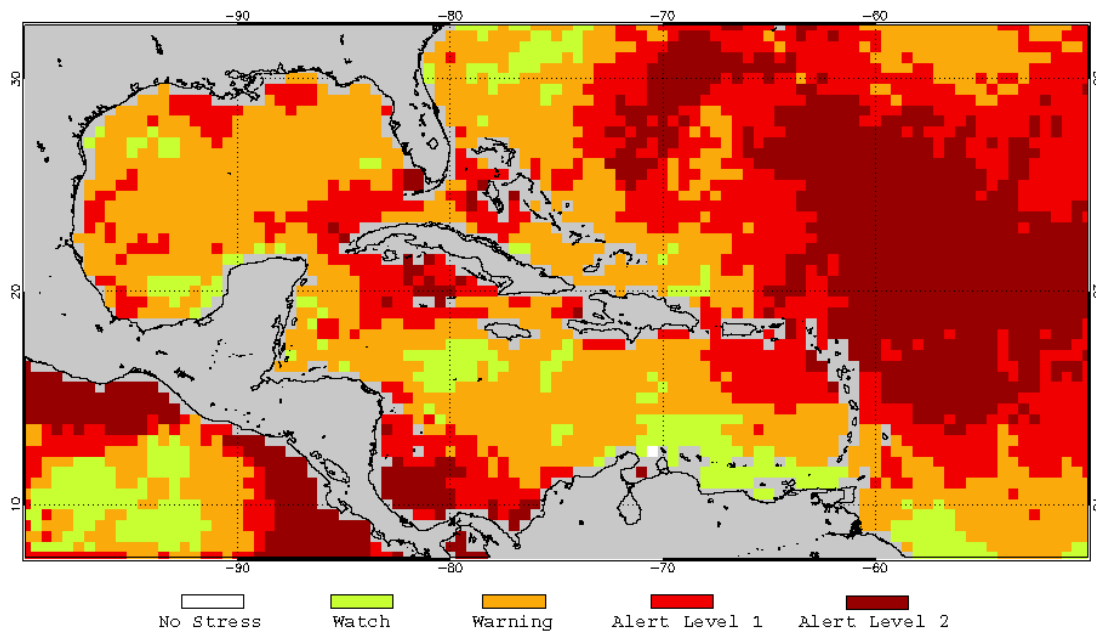


Figure 14. CRW's 2015 annual maximum composite of twice-weekly 50-km Bleaching Alert Area for the Greater Caribbean region.

Note that although CRW's satellite monitoring (at both 5-km and 50-km spatial resolutions) indicated the presence of thermal stress in Puerto Rico in September and October 2015, as of this writing, CRW has yet to receive reports of significant bleaching on Puerto Rican reefs in 2015 from field partners.

U.S. Virgin Islands:

Located between Puerto Rico and the Atlantic Ocean, the U.S. Virgin Islands (USVI) were influenced by the same large scale thermal stress (described in the previous section) centered in the Atlantic Ocean to the east of the islands. CRW's 5-km Virgin Islands Regional Virtual Station (Figure 15) covers both the neighboring USVI and British Virgin Islands (BVI), with the USVI in the south and center and the BVI in the northeast. The 5-km monitoring showed that elevated temperatures advanced southwards into the USVI region from the Greater Antilles, Bahamas, and North Atlantic Ocean. Small isolated patches of Bleaching Watch level temperatures started to appear inside the station boundary and further south in late May 2015. A Bleaching Watch level was triggered at the station when at least 10% of the 5-km water pixels in the station experienced Bleaching Watch for the first time on June 2 (Figure 16), although only isolated thermal stress patches appeared within the station boundary. The St. Croix area of the USVI saw Bleaching Watch level temperatures for the first time of the year much later on July 25. Until around August 5, there were only isolated Bleaching Watch patches dusting the entire region. While the station was still in Bleaching Watch between August 6 and September 4, SST consistently moved up and eventually pushed the station's stress level into Bleaching Warning on September 5. During a brief period of September 16-19 the stress dipped back to Bleaching Watch before Bleaching Warning finally took control of the entire region on September 27. In early October when temperatures in the interior

Greater Caribbean region and especially in the Greater Antilles to the west of the Virgin Islands started to drop out of the Bleaching Warning level, thermal stress increased in the Virgin Islands Station as Alert Level 1 level started to advance and skirt the entire Lesser Antilles from the east, including the Virgin Islands. This advance of the thermal stress set the peak stress level for the year in the region as shown in the 2015 annual maximum composite of Bleaching Alert Area (Figure 11). The Virgin Islands Station reported Alert Level 1 during October 20–30 when at least 10% of its water pixels affected by the stress level (Figure 15). However, Alert Level 1 affected mainly the BVI and in the USVI, barely touched St. John and St. Thomas and did not reach St. Croix (Figure 11). The thermal stress started to dissipate on October 31 and disappeared from the entire region by November 27.

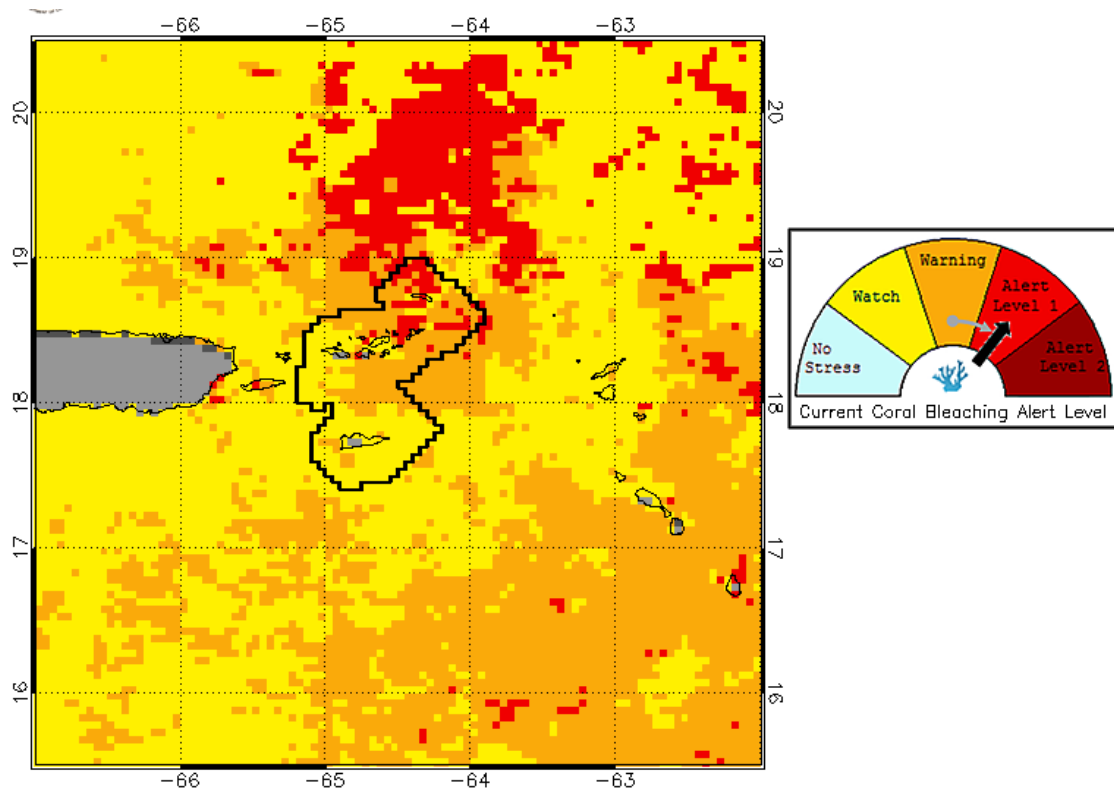


Figure 15. Spatial coverage (black polygon) of CRW's 5-km Virgin Islands Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for October 20, 2015 when the station's stress elevated to Bleaching Alert 1, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

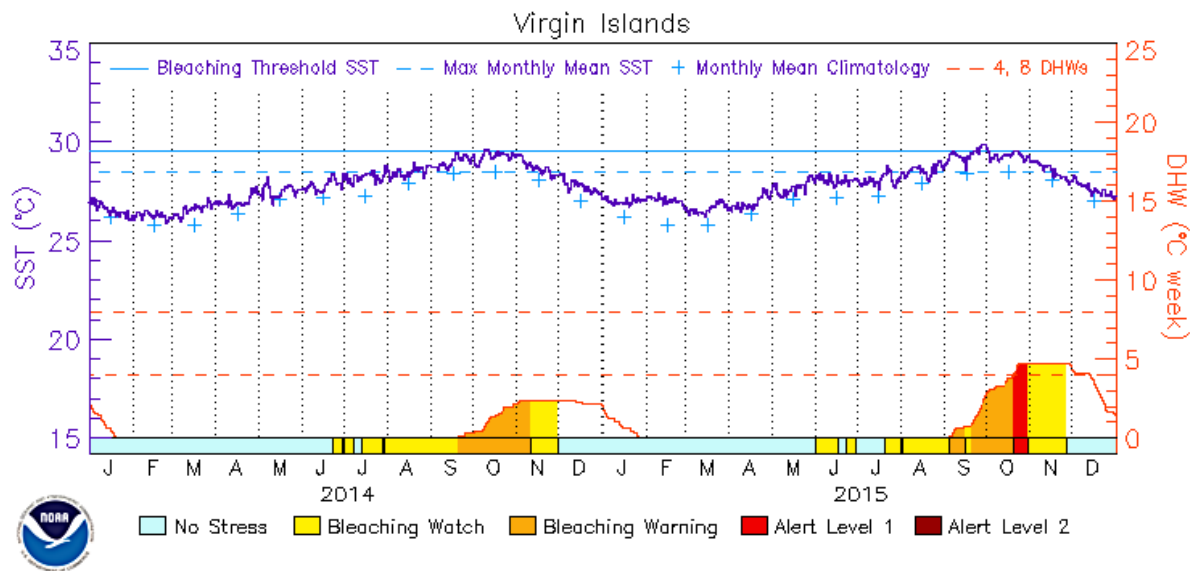


Figure 16. Two-year (2014-15) time series graph for CRW's 5-km Virgin Islands Regional Virtual Station. See the caption of Figure 4 for how to read the graph.

The 50-km Virtual Station for the USVI is at a 50-km pixel situating right over a large open water body between Puerto Rico to the west and the USVI islands of St Croix to the south and St. Thomas and St. John to the north (Figure 12). The station is isolated by land pixels in all four directions. It does not provide monitoring for the BVI, which is northeast of St. John. During August 13-16, 2015, a Bleaching Watch level started to embrace the entire USVI area and its surrounding waters and appeared at the USVI Station during August 17-19 (Figure 17). The entire region was surrounded by Bleaching Warning during September 24-27 and the station hit Bleaching Warning during September 28-30. Within October 1-4, Alert Level 1 intruded the Virgin Islands region from the northeast and affected the BVI first. By October 22-25, Alert Level 1 surrounded the Virgin Islands and further advanced west into Puerto Rico. The USVI Station experienced Alert Level 1 a few days later during October 29-November 1. Within October 26-28, Alert Level 2 appeared first at a 50-km water pixel on the north side of St. Thomas and St. John, followed by a couple of water pixels on the east side of the USVI, as shown in the 2015 annual maximum composite of Bleaching Alert Area (Figure 14). However, Alert Level 2 was not reached at the station, as it is further south and west of the islands. The maximum DHW value of 4.4 °C-weeks was reached by the station during October 29-November 1. Starting on November 4, the stress continuously decreased at the station and disappeared by November 30-December 3.

As in Puerto Rico, the thermal stress in the USVI was influenced by the same large-scale anomalously high temperature water mass centered in the Atlantic Ocean to the east (Figure 14). But with closer proximity to the epicenter of the large scale stress in the Atlantic Ocean, stress in the USVI was more intense than in Puerto Rico.

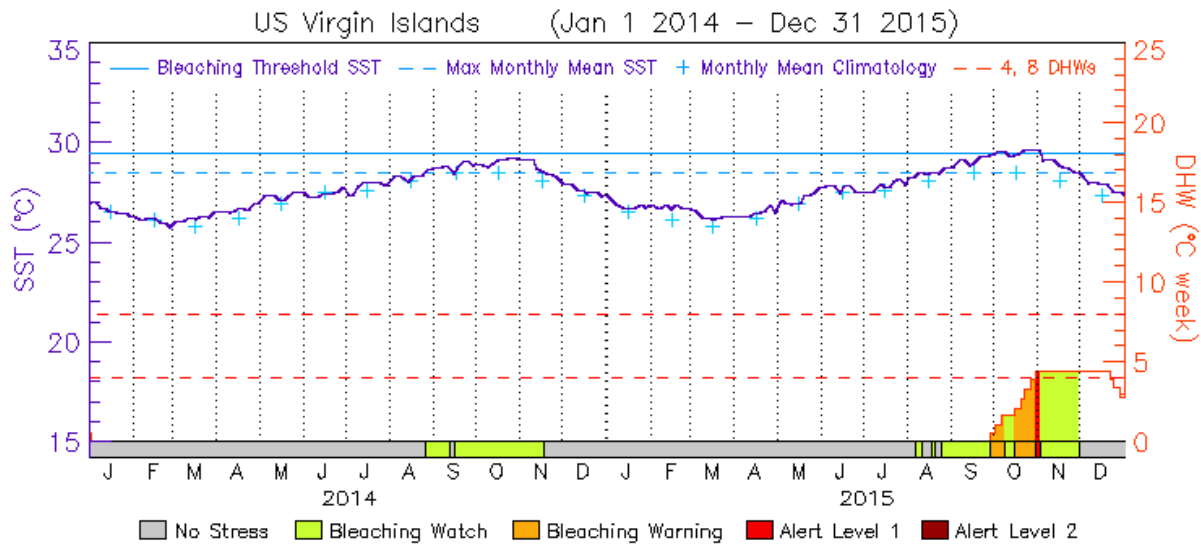


Figure 17. Two-year (2014-15) time series graph for CRW's 50-km U.S. Virgin Islands (USVI) Virtual Station. See the caption of Figure 6 for how to read the graph.

Although CRW's satellite monitoring (at both 5-km and 50-km spatial resolutions) indicated the presence of thermal stress in the USVI in September and October 2015, as of this writing, CRW has yet to receive reports of significant bleaching on local reefs in 2015 from field partners. Note that the 5-km products appeared to match the lack of significant bleaching here better than the 50-km products. As a result, the finer 5-km spatial resolution products were able to pinpoint more accurately the areas impacted by stress.

PACIFIC OCEAN

Hawai'i:

Record thermal stress and bleaching impacted coral reefs across the Hawaiian archipelago (both the Northwestern Hawaiian Islands (NWHI) and the main Hawaiian Islands (MHI)) in 2014. Bleaching thermal stress was higher ($DHW > 12$ °C-weeks) and lasted longer (August-October 2014) than the prior 2002 unprecedented bleaching event in the NWHI. Again in early July 2015, CRW's satellite monitoring detected the arrival of bleaching stress in the Hawaiian Islands (both in the NWHI and MHI). Thermal stress associated with significant bleaching and mortality in corals was detected and monitored by CRW in many locations within the NWHI (the area encompassed by the Papahānaumokuākea Marine National Monument (PMNM)) and in the MHI, where archipelago-wide mass coral bleaching had only been reported previously in 1996, including Kauai and Oahu.

CRW's 5-km monitoring showed that isolated small Bleaching Watch patches popped up spontaneously in Hawai'i in June 2015. In late June, a long patch of Bleaching Watch started to form stretching from the center of the northeastern Pacific Ocean, where an extension from the large-scale warm "Blob" had been seen for quite some time, and through the area between the MHI and NWHI. In the following months, as the SST anomaly further developed in the northeastern

Pacific Ocean in an extension of the warming off the Americas related to the ongoing El Niño, the bleaching thermal stress developed intensively in the MHI while the stress in the NWHI stayed mild to moderate for the rest of the bleaching season. There are two 5-km Regional Virtual Stations in Hawai‘i: Main Hawaiian Islands (MHI) and Northwestern Hawaiian Islands (NWHI) (Figure 18 and 19). Discussions for these two regions, corresponding to the two Regional Virtual Stations, are separated below because of the different characteristics of their thermal stress development.

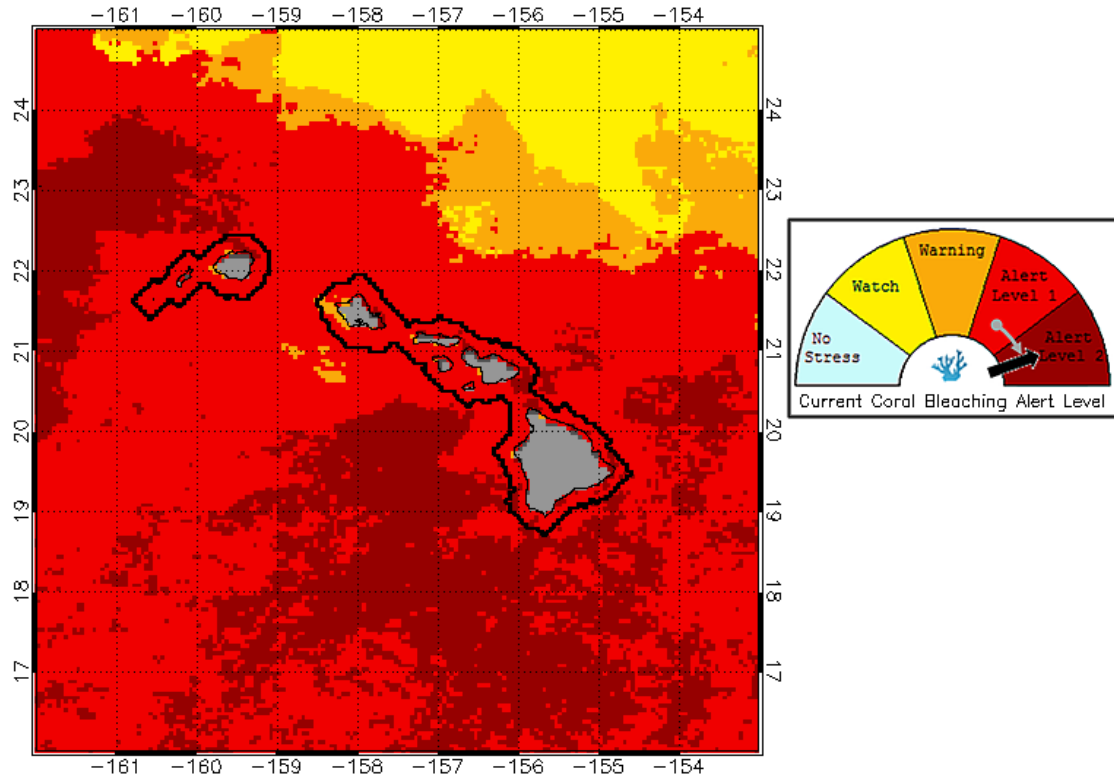


Figure 18. Spatial coverage (all black polygons) of CRW's 5-km Main Hawaiian Islands (MHI) Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for September 19, 2015 when the station's stress elevated to Bleaching Alert 2, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

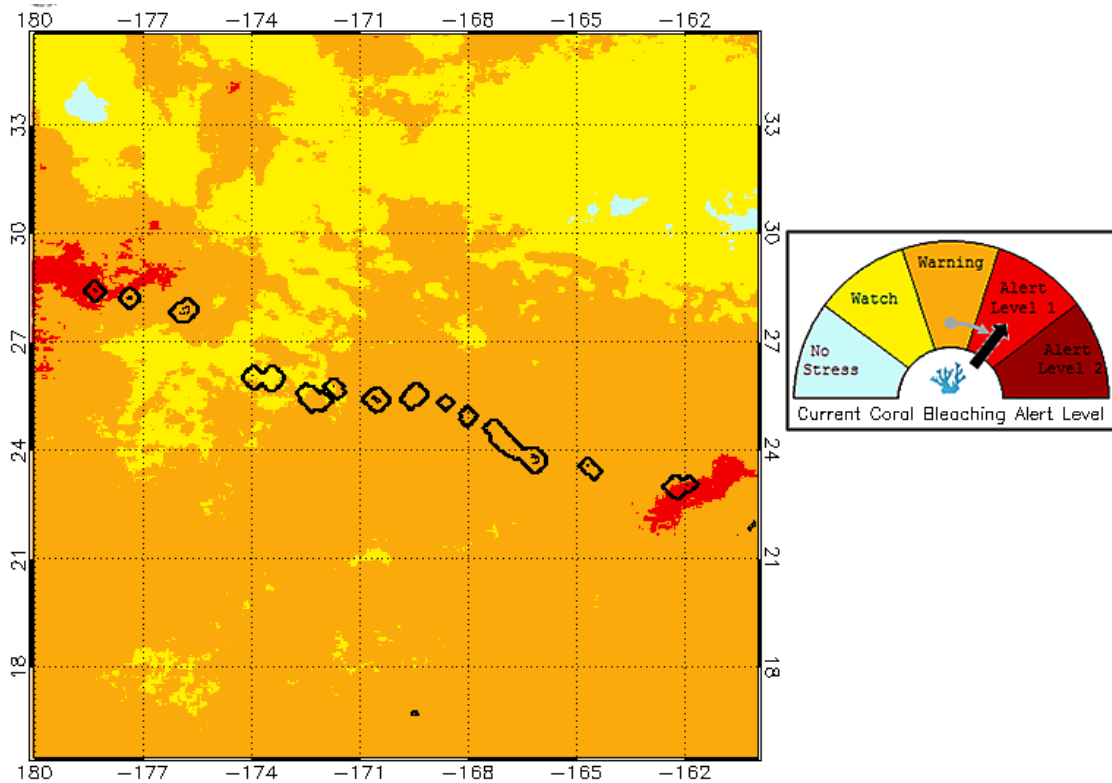


Figure 19. Spatial coverage (all black polygons) of CRW's 5-km North-western Hawaiian Islands (NWHI) Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for August 26, 2015 when the station's stress elevated to Bleaching Alert 1, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

The development of the record-strength El Niño in 2015, on top of an already warm Pacific Ocean, elevated the SST anomaly and bleaching thermal stress along the central and eastern equatorial Pacific Ocean. As time went by, the SST anomaly in the northeastern Pacific Ocean merged with El Niño-related warming, further elevating the thermal stress in the MHI. Starting July 1, 2015, Bleaching Watch firmly settled in the MHI when the temperatures of at least 10% of its water pixels reached the Maximum Monthly Mean SST climatology (Figure 20). Bleaching Warning was issued for the MHI station on August 13 when at least 10% of the water pixels in the MHI Regional Virtual Station experienced the thermal status. September 4 saw the stress at the station elevated to Alert Level 1, typically indicating sufficient thermal stress to cause significant bleaching. The thermal stress continued to escalate quickly throughout September and built up to Alert Level 2 (typically associated with widespread coral bleaching and mortality) at the station on September 19. Eventually CRW's DHW index peaked at 12 °C-weeks on October 26 (compared to a minimum value of 8 °C-weeks to warrant an Alert Level 2 stress). The Alert Level 2 level lasted for more than six weeks from September 19 to November 3. At its peak time, the Alert Level 2 stress extended in the east-west direction from the North American coast through the MHI and the southeast end of the NWHI to the north end of the Marshall Islands, and in the north-south direction from the MHI to the equator (Figure 21). The stress at the station started to drop below Alert Level 2 on November 4 and

disappeared by December 3, 2015. The thermal stress in the MHI in 2015 is much more intensive and lasted much longer than in 2014 (Figure 20).

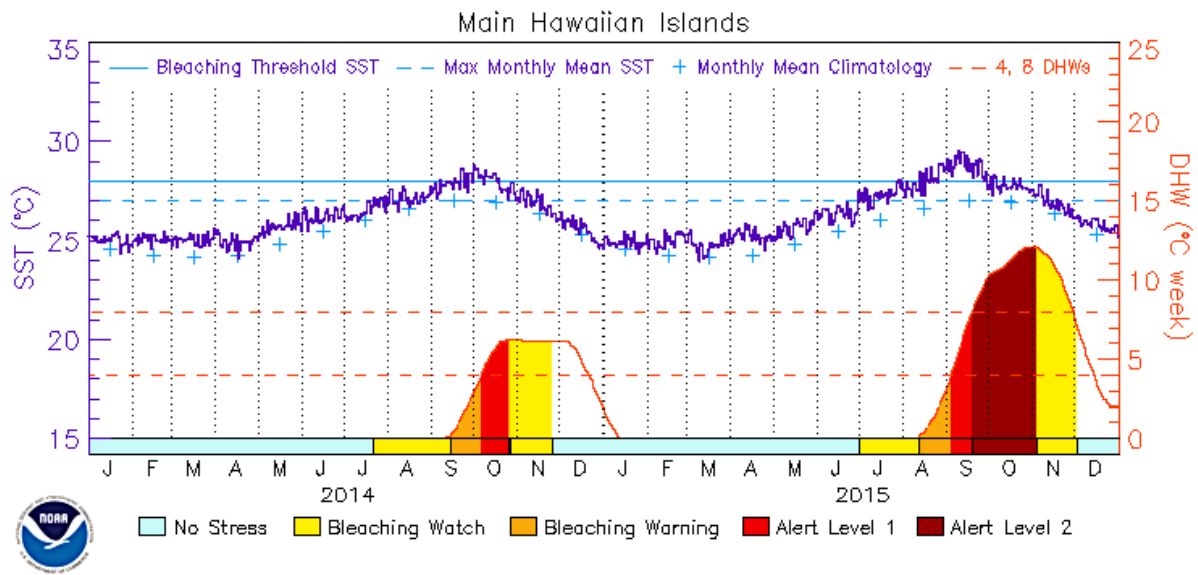


Figure 20. Two-year (2014-15) time series graph for CRW's 5-km Main Hawaiian Islands (MHI) Regional Virtual Station. See the caption of Figure 4 for how to read the graph.

Meanwhile, the thermal stress at the NWHI Station did not reach beyond Alert Level 1, although Alert Level 2 appeared at some isolated pixels within the station's boundary. The stress in the NWHI was higher at the southeastern end of the NWHI – associated to the stress in the MHI – and gradually decreased in magnitude toward the central NWHI. The northwestern end of the NWHI was controlled by a separate high stress patch centered to the west of the NWHI (Figure 21). While the central NWHI reached only Bleaching Warning, both ends of the NWHI reached Alert Level 1 with small patches reaching Alert Level 2 – less than 10% of the NWHI Station's pixels reached Alert Level 2. At the NWHI Station, temperatures rose to a Bleaching Watch level on July 5, 2015, advanced to Bleaching Warning on July 31, and then elevated to Alert Level 1 on August 26 (Figure 22). The stress started to decrease on October 1 and disappeared by November 2. The thermal stress in the NWHI in 2015 is much less intense than in 2014 (Figure 22).

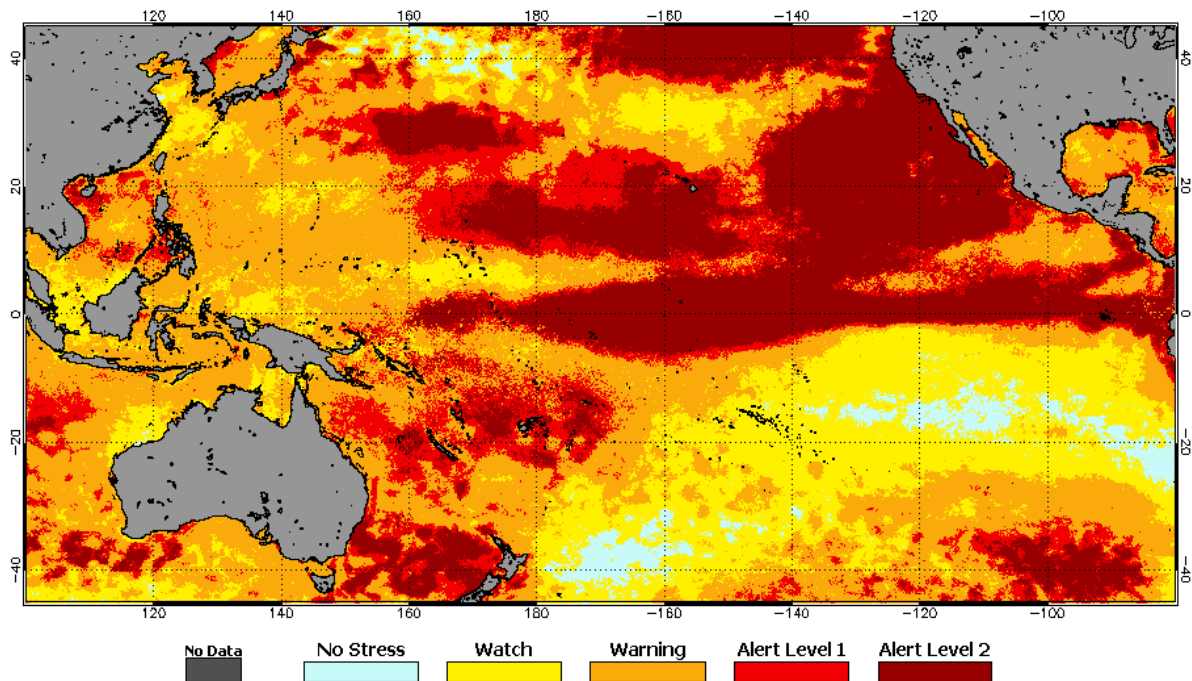


Figure 21. CRW's 2015 annual maximum composite of daily 5-km Bleaching Alert Area for the Pacific Ocean.

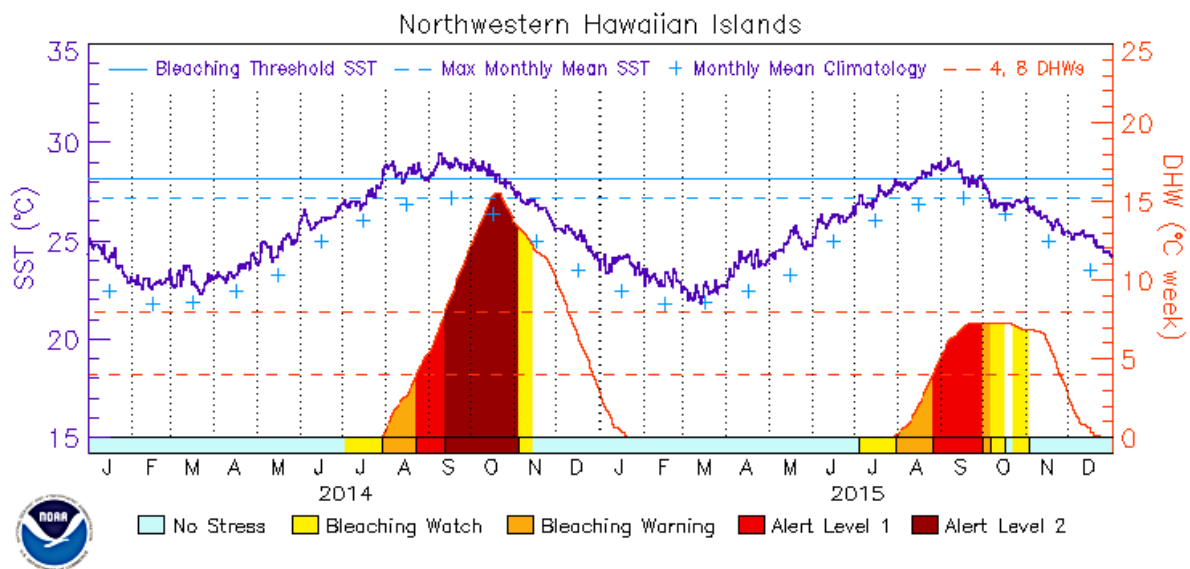


Figure 22. Two-year (2014-15) time series graph for CRW's 5-km Northwestern Hawaiian Islands (NWHI) Regional Virtual Station. See the caption of Figure 4 for how to read the graph.

CRW's 50-km monitoring showed basically the same thermal stress distribution as the 5-km monitoring described earlier. There are seven and eleven single-pixel-based 50-km Virtual Stations for the MHI and NWHI, respectively. The stations in the MHI are (from southeast to northwest) Hilo of Big Island, Kona of Big Island, Kahoolawe, Maui and Molokai, Lanai, Oahu, and Kauai and

Niihau (Figure 23). The stations in the NWHI are (from east to west) Nihoa, Necker Island, French Frigate Shoals, Gardner, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, Midway Atoll North, Midway Atoll West, and Kure Atoll (Figure 24). Table 3 and 4 list the dates when thermal stress reached various stress levels at the Virtual Stations in the MHI and their maximum DHW values reached in 2015, respectively. Table 5 and 6 provide the same information for the Virtual Stations in the NWHI. The 2015 annual maximum Bleaching Alert Area composite of the 50-km products (Figure 25) showed that the spatial distribution and magnitude of the stress monitored by the 50-km products matched well with what the 5-km products presented (Figure 21).

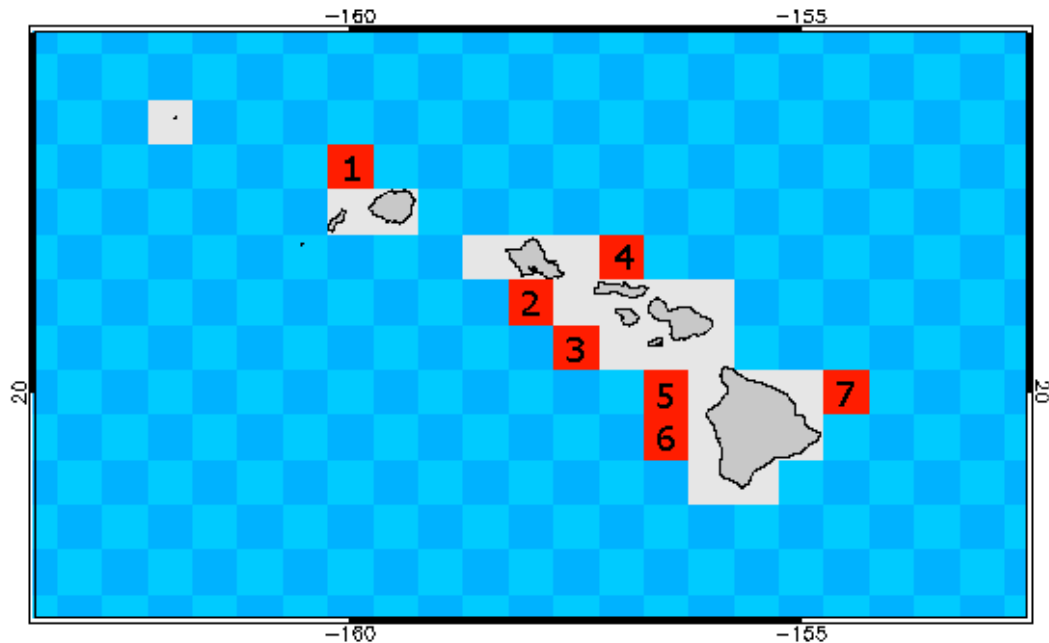


Figure 23. CRW's single-pixel-based 50-km Virtual Stations (red pixel squares) in the Main Hawaiian Islands (MHI): (1) Kauai and Niihau, (2) Oahu, (3) Lanai, (4) Maui and Molokai, (5) Kahoolawe, (6) Kona of Big Island, and (7) Hilo of Big Island. Pixels in light gray are land-mask pixels.

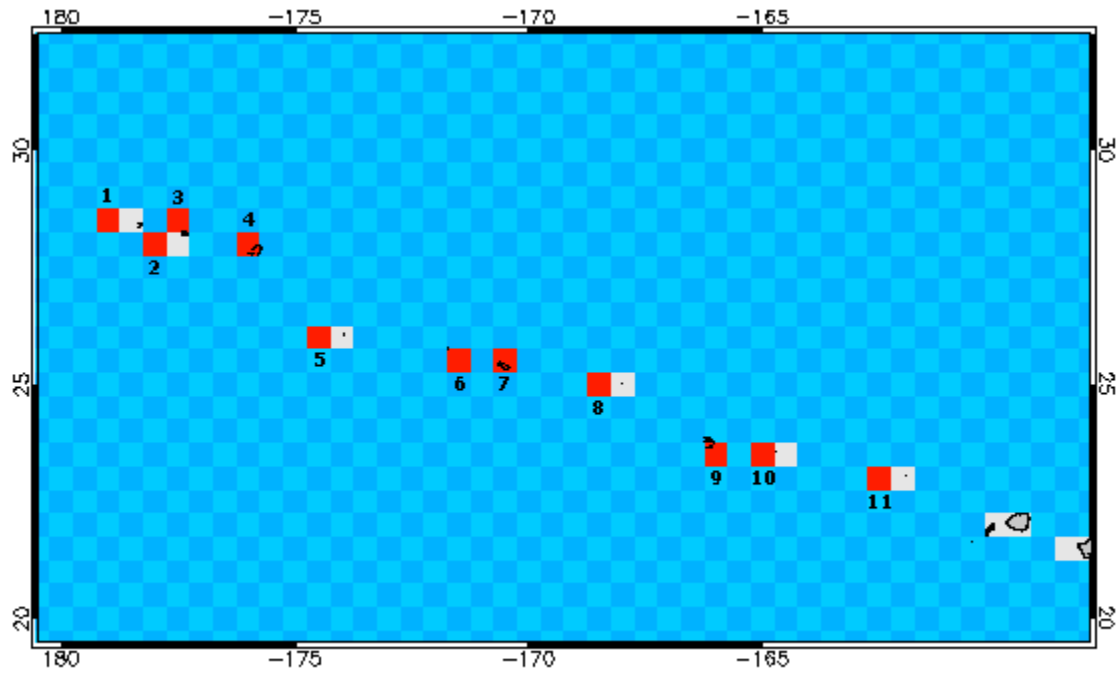


Figure 24. CRW's single-pixel-based 50-km Virtual Stations (red pixel squares) in the Northwestern Hawaiian Islands (NWHI): (1) Kure Atoll, (2) Midway Atoll West, (3) Midway Atoll North, (4) Pearl and Hermes Atoll, (5) Lisianski Island, (6) Laysan Island, (7) Maro Reef, (8) Gardner, (9) French Frigate Shoals, (10) Necker Island, and (11) Nihoa. Pixels in light gray are land-mask pixels.

Table 3. List of 50-km Virtual Stations in the Main Hawaiian Islands (MHI, from northwest to southeast), station geo-locations, onset dates of Bleaching Watch, Bleaching Warning, Alert Level 1, Alert Level 2, and stress dissipation.

#	Station	Lat Lon	Bleaching Watch	Bleaching Warning	Alert Level 1	Alert Level 2	Stress Dissipation	End of Stress
1	Kauai and Niihau	22.5N 160.0W	Jul 2-5	Aug 20-23	Sep 3-6	Sep 17-20	Sep 28-30	Nov 9- 11
2	Oahu	21.0N 158W	Jul 2-5	Aug 17-19	Sep 3-6	Sep 17-20	Oct 15-18	Nov 12-15
3	Maui and Molokai	21.5N 157W	Jul 13-15	Aug 6-9	Aug 31-Sep 2	Sep 17-20	Sep 24-27	Nov 16-18
4	Lanai	20.5N 157.5W	Jul 2-5	Aug 13-16	Aug 31-Sep 2	Sep 14-16	Oct 5-7	Nov 12-15
5	Kahoolawe	20N 156.5W	Jul 9-12	Aug 3-5	Aug 27-30	Sep 10-13	Nov 5-8	Nov 23-25
6	Kona of Big Island	19.5N 156.5W	Jun 29- Jul 1	Jul 30-Aug 2	Aug 20-23	Sep 3-6	Nov 2-4	Nov 23-25
7	Hilo of Big Island	20N 154.5W	Jul 2-5	Aug 17-19	Sep 3-6	Sep 17-20	Nov 5-8	Dec 3-6

Table 4. List of 50-km Virtual Stations in the Main Hawaiian Islands (MHI, from northwest to southeast) and their maximum Degree Heating Week (DHW) values and dates.

#	Station	Lat, Lon	Max DHW (°C-weeks)	Dates of Max DHW
1	Kauai and Niihau	22.5N, 160.0W	9.3	Sep 24-27
2	Oahu	21.0N, 158W	11.7	Oct 12-14
3	Maui and Molokai	21.5N, 157W	8.7	Sep 21-23
4	Lanai	20.5N, 157.5W	12.5	Oct 1-4
5	Kahoolawe	20N, 156.5W	18.3	Nov 2-4
6	Kona of Big Island	19.5N, 156.5W	18.3	Oct 22-25
7	Hilo of Big Island	20N, 154.5W	15.7	Nov 2-4

Table 5. List of 50-km Virtual Stations in the Northwestern Hawaiian Islands (NWHI, from northwest to southeast), station geo-locations, onset dates of Bleaching Watch, Bleaching Warning, Alert Level 1, Alert Level 2, and stress dissipation.

#	Station	Lat Lon	Bleaching Watch	Bleaching Warning	Alert Level 1	Alert Level 2	Stress Dissipation	End of Stress
1	Kure Atoll	28.5N 179W	Jul 16-19	Aug 3-5	Aug 27-30	N/A	Sep 3-6	Oct 5-7
2	Midway Atoll West	28N 178W	Jul 20-22	Aug 6-9	Aug 31-Sep 2	N/A	Sep 3-6	Oct 5-7
3	Midway Atoll North	28.5N 177.5W	Jul 20-22	Aug 6-9	Aug 27-30	N/A	Sep 3-6	Oct 5-7
4	Pearl and Hermes Atoll	28N 176W	Aug 3-5	Aug 17-19	N/A	N/A	Sep 7-9	Oct 5-7
5	Lisianski Island	26.0N 174.5W	Jul 23-26	Sep 10-13	N/A	N/A	Oct 1-4	Oct 8-11
6	Laysan Island	25.5N 171.5W	Jul 30-Aug 2	Aug 27-30	N/A	N/A	Sep 10-13	Oct 5-7
7	Maro Reef	25.5N 170.5W	Jul 30-Aug 2	Aug 24-26	N/A	N/A	Sep 14-16	Oct 5-7
8	Gardner	25N 168.5W	Jul 27-29	Aug 20-23	Sep 7-9	N/A	Sep 14-16	Oct 1-4
9	French Frigate Shoals	23.5N 166W	Jul 16-19	Aug 24-26	Sep 10-13	N/A	Sep 21-23	Oct 1-4
10	Necker Island	23.5N 165W	Jul 16-19	Aug 24-26	Sep 10-13	N/A	Sep 21-23	Oct 29-Nov 1
11	Nihoa	23N 162.5W	Jul 6-8	Jul 30- Aug 2	Sep 3-6	N/A	Sep 17-20	Oct 8-12

Table 6. List of 50-km Virtual Stations in the Northwestern Hawaiian Islands (NWHI, from northwest to southeast) and their 2015 maximum Degree Heating Week (DHW) values and dates.

#	Station	Lat, Lon	Max DHW (°C-weeks)	Dates of Max DHW
1	Kure Atoll	28.5N, 179.0W	5.4	Aug 31-Sep 2
2	Midway Atoll West	28.0N, 178.0W	4.1	Aug 31-Sep 2
3	Midway Atoll North	28.5N, 177.5W	4.6	Aug 31-Sep 2
4	Pearl and Hermes Atoll	28.0N, 176.0W	2.6	Sep 3-6
5	Lisianski Island	26.0N, 174.5W	2.0	Sep 28-30
6	Laysan Island	25.5N, 171.5W	2.5	Sep 7-9
7	Maro Reef	25.5N, 170.5W	3.9	Sep 10-13
8	Gardner	25.0N, 168.5W	5.6	Sep 10-13
9	French Frigate Shoals	23.5N, 166.0W	5.7	Sep 17-20
10	Necker Island	23.5N, 165.0W	5.6	Sep 17-20
11	Nihoa	23.0N, 162.5W	7.0	Sep 14-16

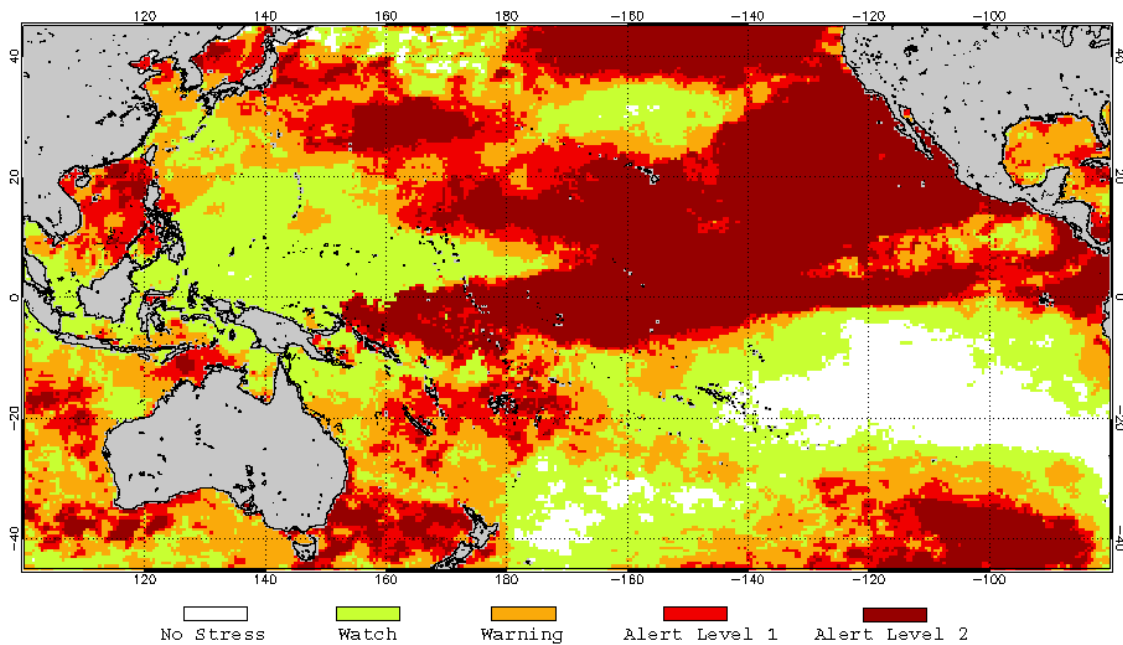


Figure 25. CRW's 2015 annual maximum composite of twice-weekly 50-km Bleaching Alert Area for the Pacific Ocean.

Based on CRW's outlook for a major bleaching season in the MHI and near-real-time satellite monitoring, field surveys were coordinated by numerous partners in the MHI throughout the summer of 2015. A state-wide Bleach Watch "Bleachapalooza" event on October 3, 2015

(<http://dlnr.hawaii.gov/blog/2015/09/25/nr15-148/>) was called for by the “Eyes of the Reef” (EOR) volunteer reporting network which is the critical first tier of Hawai‘i’s Department of Land and Natural Resources Rapid Response Contingency Plan. This intensive training and observing event yielded 85 reports for the MHI. By early October, more than one hundred reports of coral bleaching were collected from the islands of Oahu, Kauai, Maui, Molokini, and Hawai‘i through EOR, indicating the bleaching event was widespread and impacted at least the shallow reefs throughout the MHI.

Oahu alone had bleaching reports from 25 different areas around the island. Pocilloporid corals were hardest hit. Significant bleaching was also seen in montiporids and poritids. A long term observation since early 1980s in the area of Kahe Point – Nānākuli area, in west O‘ahu revealed an unprecedented bleaching in 2015. On September 23 extensive bleaching was observed down to 5 m depth, from Nānākuli to south of Kahe near the Ko Olina harbor channel entrance. *Pocillopora meandrina* was the species showing the most bleaching followed by massive corals *Porites lobata* and *P. evermanni* (*lutea*). Not all corals were affected at the time of the observations, but many were bleached to the point that recovery is not likely, especially for *P. meandrina*. Long term observations in Kane‘ohe Bay and Lanikai in Kailua on the windward side of Oahu reported bleaching for the second year in a row. Most striking was that 2015 was the first time bleaching occurred on the open coast of Oahu, rather than just in enclosed bays. Corals in the Ala Moana Beach Park on the south side of Oahu also bleached with some dramatic bleaching, particularly in pocilloporids and *P. evermanni* (*lutea*).

In early September, a report from the University of Hawai‘i at Manoa described that at Olowalu, Maui, almost all colonies of the genera *Montipora*, *Porites*, and *Pocillopora* were substantially to completely bleached (>75%). Offshore colonies were faring slightly better, with some colonies showing no sign of bleaching. By mid-September, it was observed that around Kauai, 95% of the blue rice corals (*Montipora flabellata*) had died in 2014 and 95% left were bleached; 60% of the brown rice coral species (*Montipora* spp.) had died and 10% were bleached or diseased; 80% of the giant mound, lobe (*Porites lobata*), finger (*Porites compressa*), and pork chop corals (*Pavona duerdeni*) were dead or at least 20% were covered by algae that were slowly killing them; and disease and algae growth rates were expected to increase. The pocilloporid corals appeared to be doing the best in Maui, with little bleaching.

It was also the first time that bleaching was seen in sequential years in Hawai‘i. We are still receiving and compiling bleaching reports from Hawai‘i. Detailed analysis will be conducted subsequently.

American Samoa:

American Samoa is located in the Southern Hemisphere and its bleaching season strides two calendar years. As noted in CRW’s 2014 annual summaries of bleaching thermal stress conditions in the NCRMP jurisdictions, CRW’s 5-km satellite monitoring indicated that American Samoa was already under a Bleaching Watch as of October 2014 entering an active bleaching season that lasted into 2015 (Figure 26). CRW had since communicated with local coral reef management partners throughout American Samoa and the independent Samoa to alert them to a potential bleaching event.

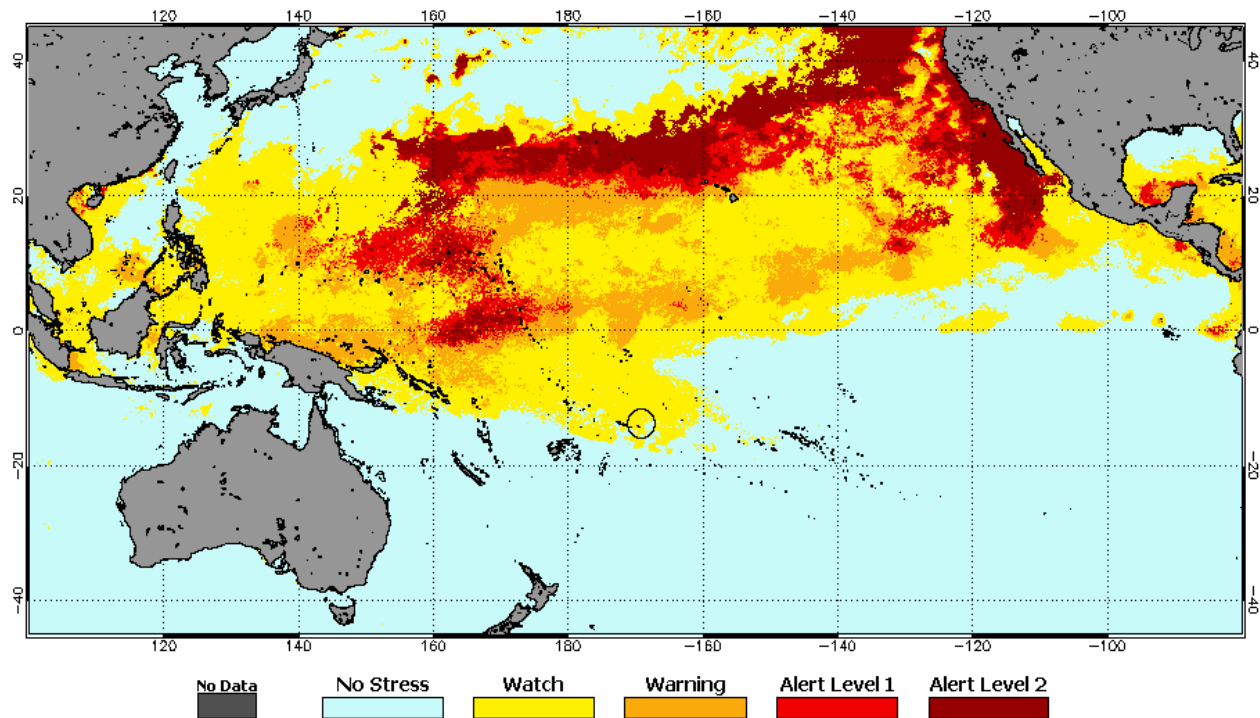


Figure 26. CRW's October 2014 monthly maximum composite of 5-km Bleaching Alert Area for the Pacific (with American Samoa circled in black).

CRW's 5-km Samoas Regional Virtual Station covers both American Samoa and the Independent State of Samoa (Figure 27). The 2014-2015 thermal stress event was first detected in the waters of the Samoas Station in September 2014 as thermal stress propagated into the region southeastwards from the western equatorial Pacific Ocean, as the Southern Hemisphere moved deeply into its spring season (Figure 28). During September-November 2014 (Figure 26), elevated temperatures flirted with the region and the thermal condition of the station alternated between Bleaching Watch and No Stress. On November 28, 2014, the Bleaching Watch level finally took hold at the Samoas Station. Then the slowly rising temperatures elevated the status to Bleaching Warning on January 13, 2015. Alert Level 1 stress typically associated with significant bleaching was first reported by the station on February 21, although isolated patches of Alert Level 1 first appeared within the station's boundary in early February. That high level of bleaching stress continued to elevate throughout a large region, expending from New Caledonia in the west, to Fiji in the south, and to the Samoas in the east. Within this large region, Alert Level 2 appeared as early as late January. On March 16, Alert Level 2 conditions (typically associated with widespread coral bleaching and mortality) were reached by the Samoas Station (Figure 27) with at least 10% of the station's water pixels affected, and then Alert Level 2 persisted for one month. By April 13, cooling finally returned the station to Bleaching Watch, which was followed by a short-lived four-day spike to Alert Level 1 during the week of April 21. The stress then dissipated gradually and disappeared by June 25, 2015 (Figure 28) putting a near nine-month stressful period to an end. At that point, high temperatures retreated back to the equatorial Pacific and advanced to the Northern Hemisphere.

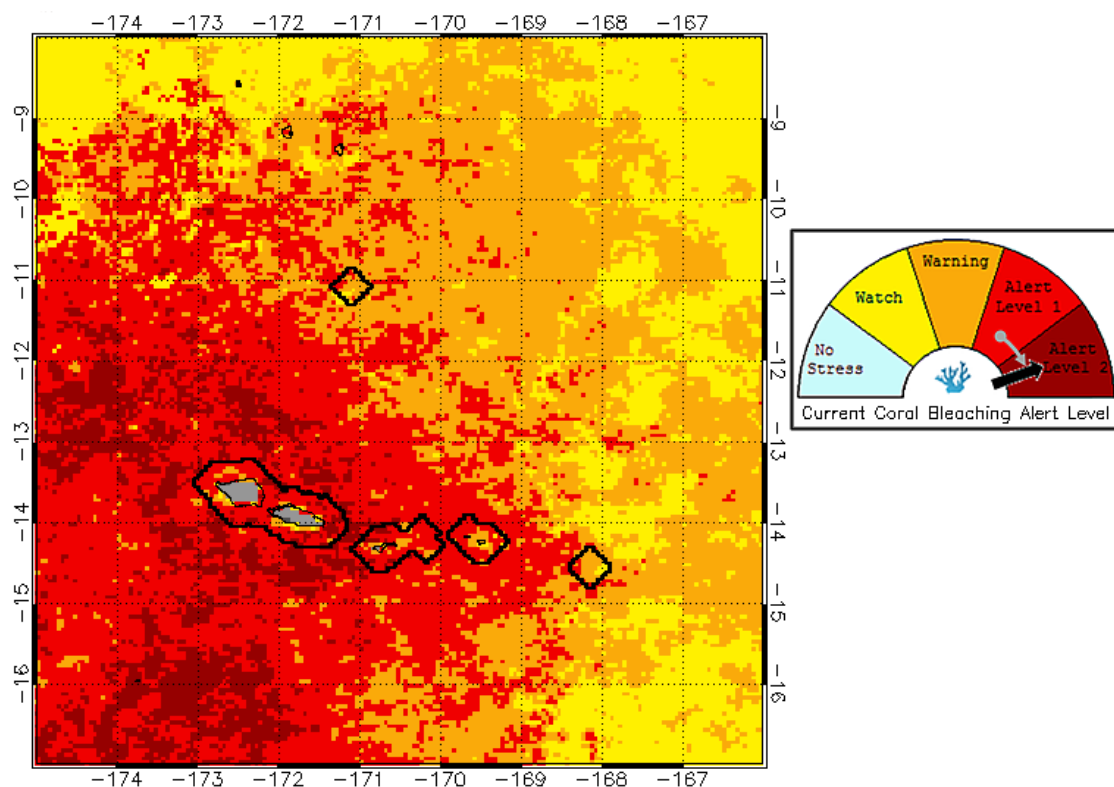


Figure 27. Spatial coverage (all black polygons) of CRW's 5-km Samoa Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for March 16, 2015 when the station's thermal stress elevated to Alert Level 2, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

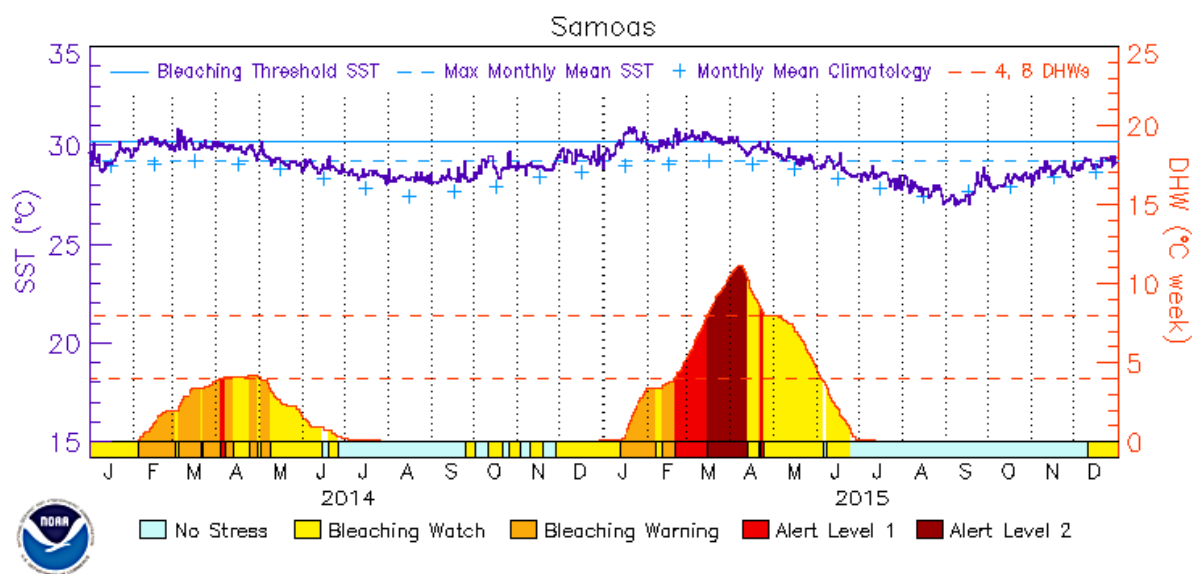


Figure 28. Two-year (2014-15) time series graph for CRW's 5-km Samoa Regional Virtual Station. See the caption of Figure 4 for how to read the graph.

Later in 2015, a record-strength El Niño event peaked during November and December. This brought a new bleaching season to the Southern Hemisphere. The extremely high temperatures parked along the central and eastern equatorial Pacific fueled the development of thermal stress in the central-to-western South Pacific Ocean. In late 2015, the thermal stress propagated south and southwest toward the Samoas.

On December 11, 2015, a new run of yearly thermal stress period kicked off with a Bleaching Watch detected by the 5-km Samoas Regional Virtual Station (Figure 28 and 29). The Samoas are now in an ongoing 2015-2016 bleaching season. CRW's Four-Month Coral Bleaching Thermal Stress Outlook of December 29, 2015 (Figure 30) predicted the Bleaching Watch level would elevate to a Bleaching Warning in early February and an Alert Level 1 (typically associated with significant coral bleaching) in early March 2016, before cooler waters return to the jurisdiction in early April 2016. The 2015-16 Samoas bleaching season will be investigated in the 2016 report.

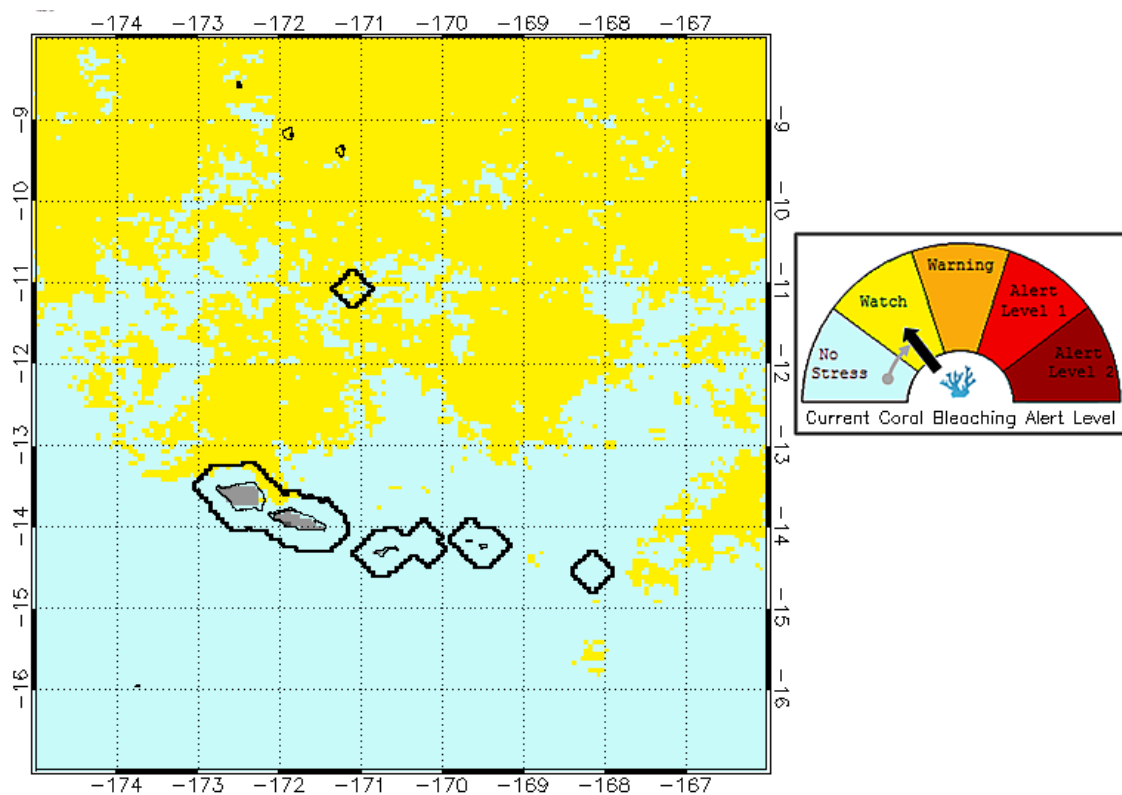


Figure 29. Spatial coverage (all black polygons) of CRW's 5-km Samoas Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for December 11, 2015 when the station's thermal stress elevated to Bleaching Watch. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

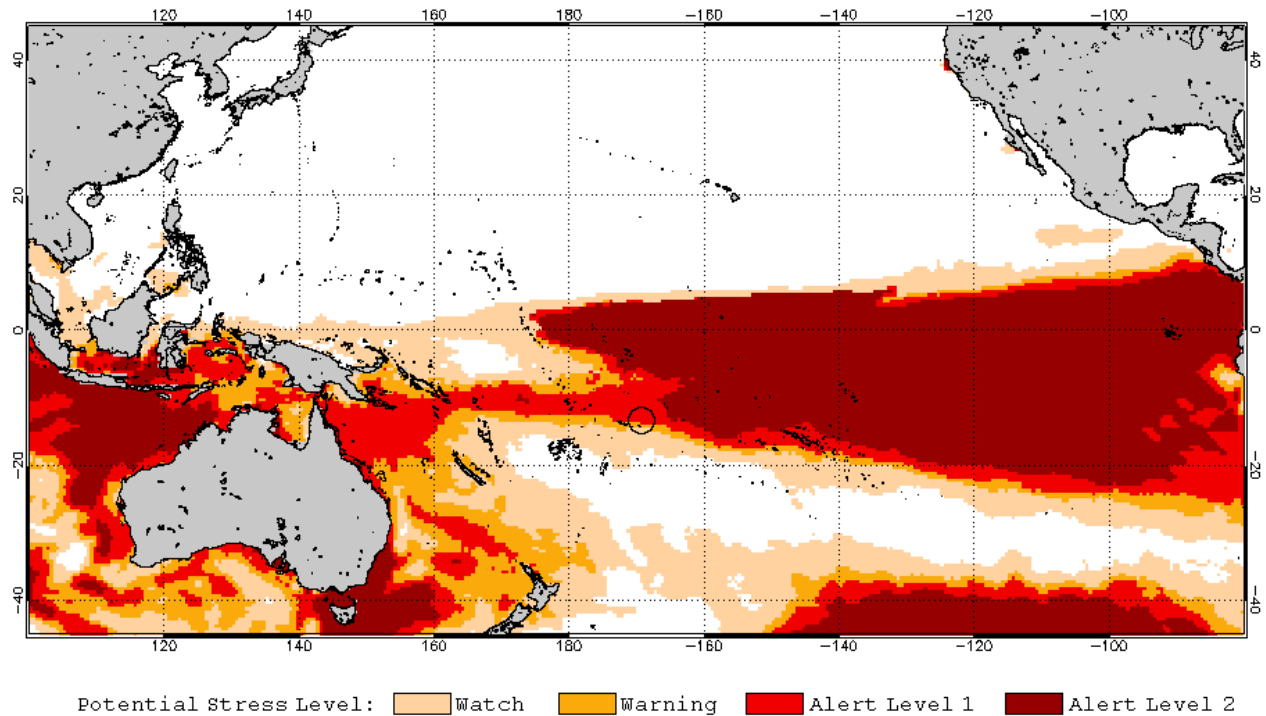


Figure 30. Map of potential coral bleaching thermal stress (60% probability) in the Pacific Ocean for January-April 2016 from NOAA CRW's Four-Month Coral Bleaching Thermal Stress Outlook (version 3) of December 29, 2015, based on NOAA's Climate Forecast System v2 sea surface temperature predictions. American Samoa is circled in black.

There are four CRW 50-km Virtual Stations in American Samoa: Tutuila, Ofu, Rose Atoll, and Swains Island (Figure 31). The pattern of stress development during the 2014-2015 thermal stress event monitored by the 50-km products was similar to what the 5-km products presented: high thermal stress in the western equatorial Pacific Ocean propagated south and southeast toward the Samoas. Although Bleaching Watch level temperatures started to appear in the Samoas region in 50-km monitoring as early as late October and early November 2014, Bleaching Watch did not take control of the islands until early January 2015. Both of these two onset times were about two months later than the 5-km monitoring. Bleaching Warning first appeared at the 50-km American Samoa Virtual Stations during January 15-18, 2015, about the same time as the 5-km monitoring. The Bleaching Warning level reached the Swains Island, Tutuila, Ofu, and Rose Atoll Stations by March 2-4, January 15-18, January 15-18, and January 19-21, respectively. See the time series in Figure 32 for the Swains Island and Tutuila Stations as examples. Bleaching Alert Level 1 appeared in some areas near the Samoas in mid-February, but it never materialized in American Samoa based on the 50-km monitoring. Although the 50-km monitoring showed a large scale thermal stress coverage with the presence of Alert Level 2 in the region extending from New Caledonia in the west to the Samoas in the east as the 5-km monitoring did, the high intensity stress (Alert Level 1 and 2) didn't fully reach the Samoas (Figure 25). The maximum DHW values of only 3.5, 3.0, 1.1, and 1.6 °C-weeks were reached by the Swains Island, Tutuila, Ofu, and Rose Atoll Stations, during March 23-25, March 30-April 1, January 19-21, and March 23-25, respectively. Stress disappeared

at the Swains Island Station in mid-June and at Ofu, Rose Atoll, and Tutuila Stations in mid-May, matching the ending time of the 2014-2015 bleaching season indicated by the 5-km monitoring.

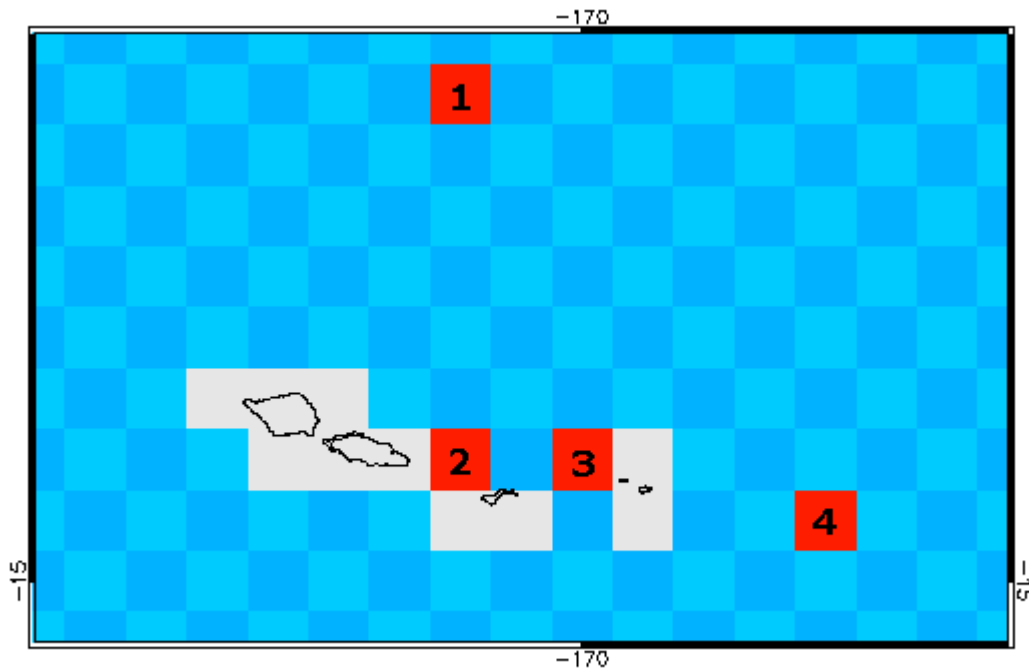


Figure 31. CRW's single-pixel-based 50-km Virtual Stations (red pixel squares) in the American Samoa region: (1) Swains Island, (2) Tutuila, (3) Ofu, and (4) Rose Atoll. Pixels in light gray are land-mask pixels.

The 50-km monitoring showed that the 2015-2016 thermal stress event started during October 19-21, 2015 at the Swains Island Station, which is the closest of the four stations to the equator, but it was not until December 17-20, 2015 that Bleaching Watch level became steady at the Swains Island Station (Figure 32). By the end of 2015, no stress had appeared at the three other 50-km stations, such as the Tutuila Station (Figure 32).

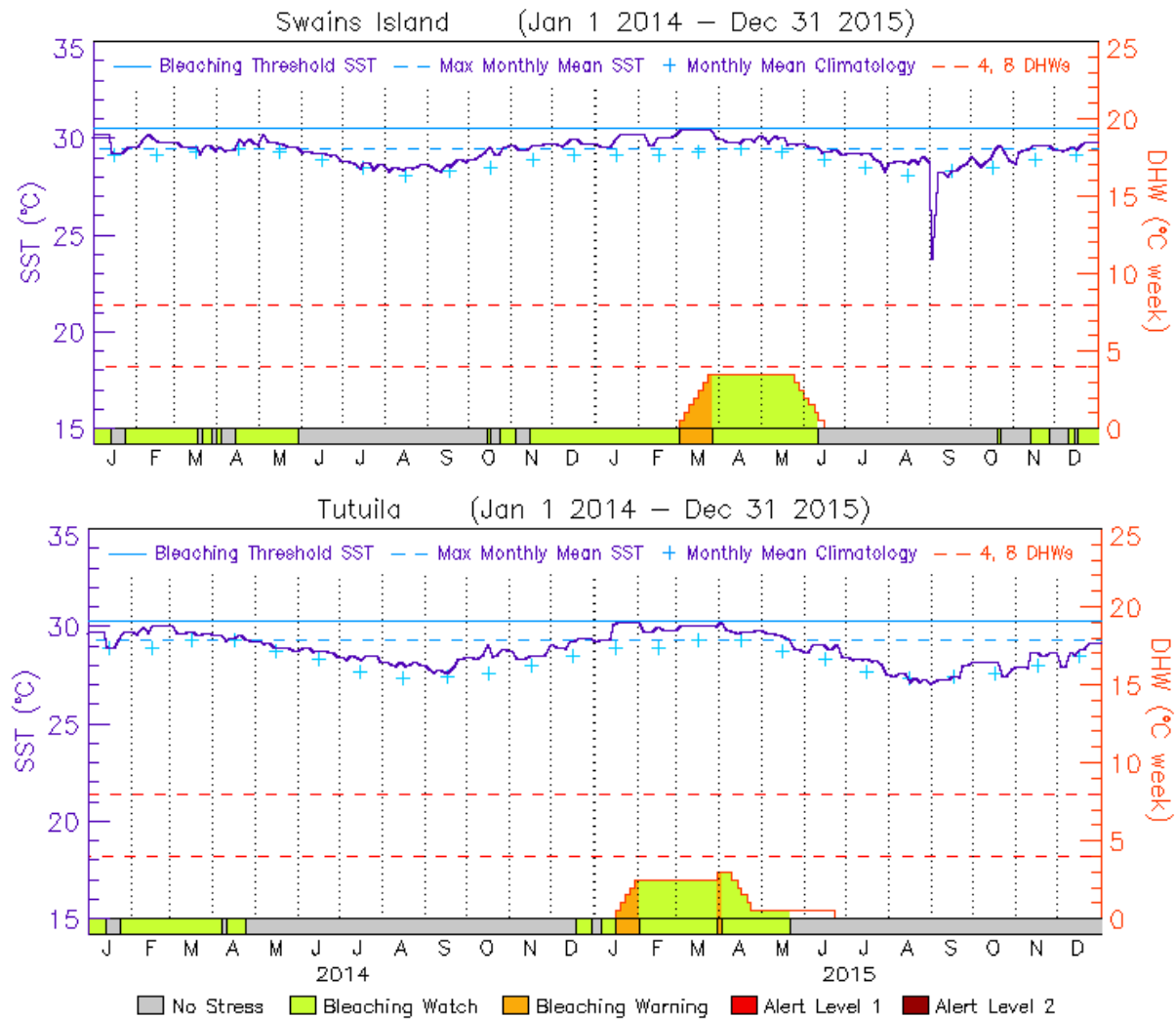


Figure 32. Two-year (2014-15) time series graphs for CRW's 50-km Swains Island (top panel) and Tutuila (bottom panel) Virtual Stations. See the caption of Figure 6 for how to read the graph.

Reports of bleaching on coral reefs in American Samoa in 2015, especially around the island of Tutuila, aligned much more closely with CRW's new 5-km satellite coral bleaching monitoring than its heritage 50-km satellite monitoring. Beginning late January 2015, field partners were already reporting bleaching of corals (including normally resilient *Porites* colonies) in the Coconut Point backreef, nearshore area of Tutuila. Bleaching was also documented in Fagatele Bay on Tutuila, where multiple *Porites* colonies at 2-3m depth in the backreef areas and multiple *Isopora crateriformis* colonies on the reef flat exhibited moderate to high bleaching. Other local partners witnessed bleaching of corals down to 40 m depth. By mid-February, bleaching was reported to be the worst seen in the last 10 years throughout the region and resulted in major coral mortality at many sites (Figure 33). Around Swains Island, widespread partial to moderate bleaching was occurring at all depths (0-30 m). At Airport Reef on Tutuila, all *Acropora cervicornis* colonies were fully bleached, with about 10% completely dead. In Fagatele Bay, as well as on the reef flats at Alofau and Auasi, Tutuila, mass bleaching was reported, especially in fire coral and *Acropora* spp. In other locations around Tutuila, severe bleaching of *Isopora crateriformis*, *A. cervicornis*,

Millepora spp., and other corals was documented. Reports of severe coral bleaching in Fagatele Bay and other areas of Tutuila continued into late March/early April, whereas divers on reefs in Ofu-Olosega, Tau (Manu'a), and Rose Atoll documented only partial bleaching of some colonies. Of note, by the end of March 2015, CRW also was receiving reports of substantial coral bleaching in the Independent State of Samoa, where many coral colonies were documented to be void of tissue and overgrown with algae. Local partners continued to document mass bleaching in American Samoa through the end of May and into June 2015, especially on reefs surrounding Tutuila, such as Airport Reef, where 100% of the *A. cervicornis* colonies bleached and about 90% died (Figure 34). However recovery also was witnessed at some shallow reefs around Tutuila, including at Alofau, in the Onososopo shallow pool, and at the Gataivai shallow reef flat. American Samoa's mass bleaching event of summer 2015 was reported to have subsided finally as of early July 2015.



Figure 33. Photos of before (December 2014) and during (February 2015) bleaching at Flower Pot Island along the shore just to the southwest of Pago Pago Bay, Tutuila, American Samoa. Photo by XL Catlin Seaview Survey.



Figure 34. Photos of before (December 2014), during (February 2015), and after (August 2015) bleaching and mortality at Airport Reef, Tutuila, American Samoa. Photo by XL Catlin Seaview Survey.

Guam and the Commonwealth of the Northern Mariana Islands (CNMI):

Both 2013 and 2014 brought back-to-back record thermal stress and coral bleaching events in the Commonwealth of the Northern Mariana Islands (CNMI) and Guam. Consistent with CRW's 5-km satellite monitoring of the bleaching thermal stress, in 2013 and 2014 local field partners reported significant and extensive bleaching and mortality of reef corals throughout both regions, especially in the northern CNMI islands of Uracas, Maug, Asuncion, Pagan, Anatahan, Sarigan, and Guguan. The release of CRW's new 5-km products in time for the 2014 bleaching in the CNMI, along with field observations by local partners, provided an ideal initial test of the new products (Heron et al., 2015). While CRW's satellite monitoring did detect thermal stress in both Guam and the CNMI in 2015, it was not at a level high enough to cause significant bleaching – giving both regions a much needed reprieve from climate-related heat stress and providing an opportunity for potential recovery and growth of corals and other reef organisms damaged during the previous two years' major bleaching events.

Two 5-km Regional Virtual Stations are constructed for the two separated U.S. jurisdictions in the Mariana Islands: Guam (275 pixels at the southern end of the island chain) and CNMI (813 pixels along the rest of the islands in the chain) (Figure 33 and 34). The development of elevated temperature reaching a Bleaching Watch level was detected on May 3 and May 25, 2015 at the Guam and CNMI Stations, respectively (Figure 35), as a band of slightly elevated temperatures was spreading northwards across much of the northwestern Pacific Ocean. At the Guam Station, temperature elevated to Bleaching Warning on June 28 (Figure 36) but quickly returned to Bleaching Watch on July 5. Bleaching Watch conditions remained in effect at both station until July 28 when Bleaching Warning was issued for both stations. Figure 35 shows the thermal stress distribution and station stress level gauge on July 28 for the CNMI Station. Temperatures fluctuated

between Bleaching Watch and Bleaching Warning in both regions throughout August. On September 7, the Guam Station returned to Bleaching Watch conditions, which remained firmly in place until November 21 when the station returned to a level of No Stress (Figure 37). In the CNMI, temperatures continued to fluctuate between Bleaching Warning and Bleaching Watch throughout September (Figure 35). As of October 2, however, the temperature at the CNMI Station reduced to a Bleaching Watch level and remained at that level until November 13 when cooler waters in the region brought the bleaching season to an end. The year 2015 saw intensive bleaching thermal stress in the central and eastern North Pacific Ocean but only mild stress in most of the western North Pacific Ocean, including Guam and the CNMI (Figure 21).

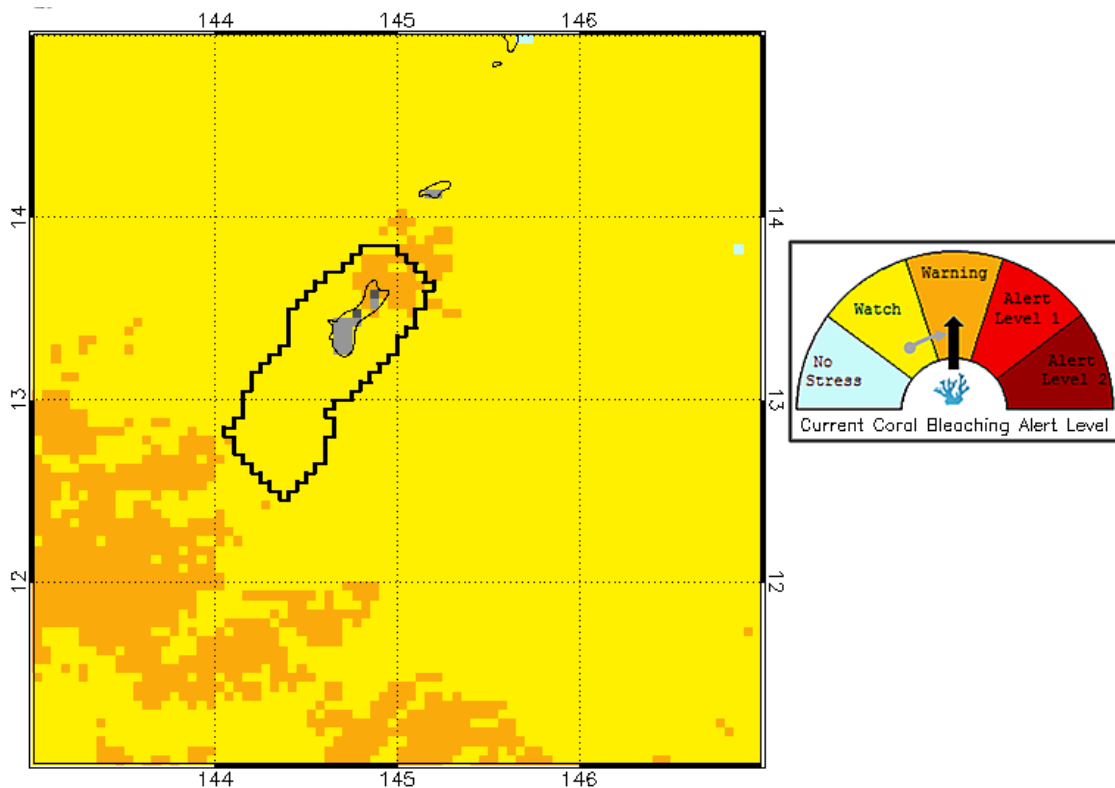


Figure 35. Spatial coverage (black polygon) of CRW's 5-km Guam Regional Virtual Station on a map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for June 28, 2015 when the station's thermal stress advanced to Bleaching Warning level, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

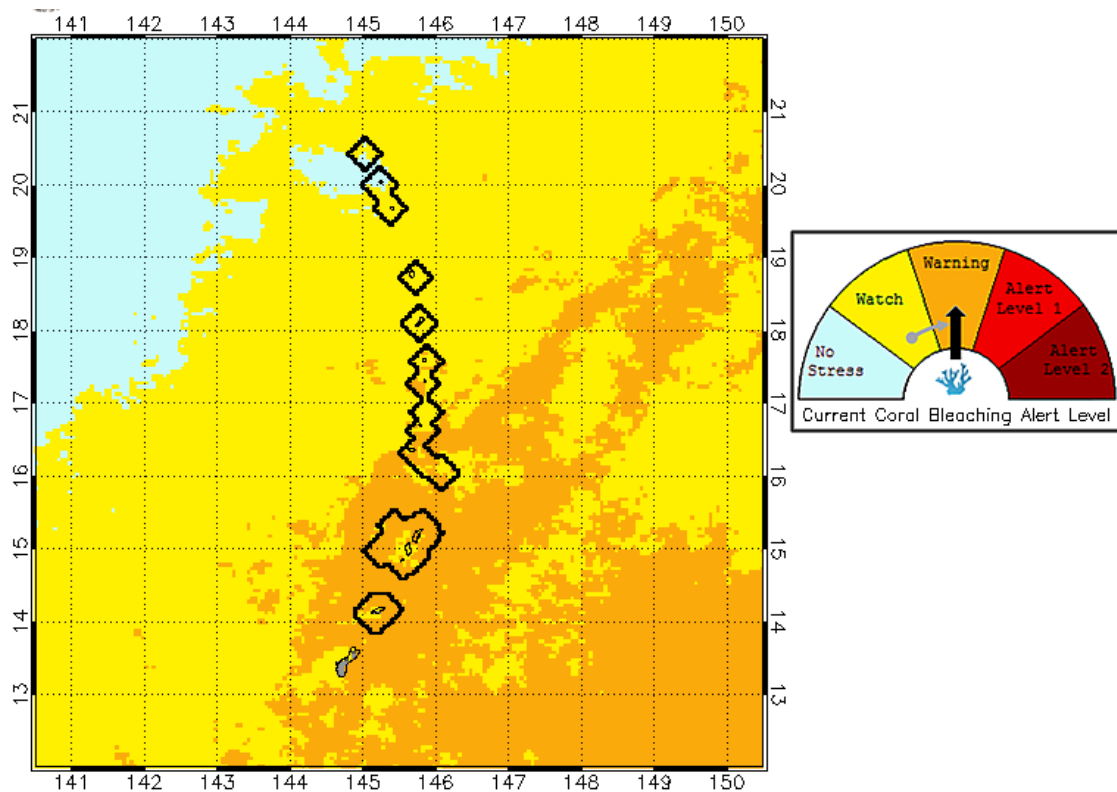


Figure 36. Spatial coverage (all black polygons) of CRW's 5-km Commonwealth of the Northern Mariana Islands (CNMI) Regional Virtual Station on the map of CRW's near-real-time 5-km 7-day maximum Bleaching Alert Area product for July 28, 2015 when the station's thermal stress advanced to Bleaching Warning level, the highest level reached by the station in 2015. The Bleaching Thermal Stress Gauge (dial on the right) shows the station's thermal stress level of the day.

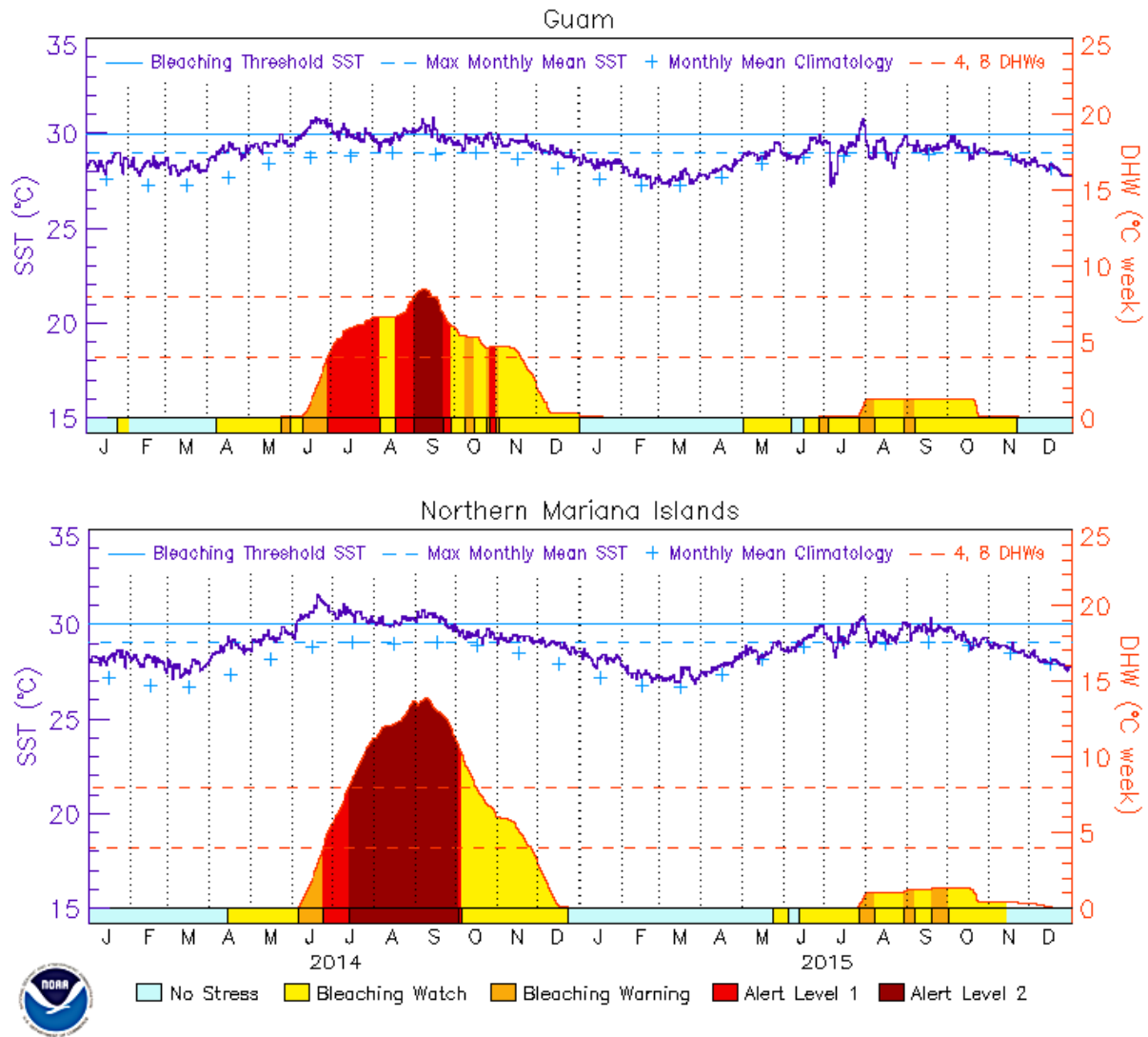


Figure 37. Two-year (2014-15) time series graphs for CRW's 5-km Guam (top panel) and Northern Mariana Islands (bottom panel) Regional Virtual Stations. See the caption of Figure 4 for how to read the graph.

The Mariana Islands are served by ten CRW 50-km Virtual Stations: Santa Rosa Reef, Guam, Guam East, Rota Island, Saipan and Tinian, Sarigan and Anatahan, Guguan and Alamagan, Pagan Island, Agrihan and Asuncion, Maug Island, and Urracas (from south to north) (Figure 38). The time series graphs for the Urracas, Agrihan and Asuncion, and Maug Island Stations, which are at the northern end of the CNMI, are provided in Figure 39 as examples; time series graphs for the Rota Island and Guam East Stations, which are at the southern end of the ten stations, are provided in Figure 40. Satellite monitoring detected the onset of bleaching stress in the CNMI and Guam quite a bit later in 2015 (end of June and mid-July, respectively) than the 5-km satellite products. However, the intensity of the high temperatures and thermal stress measured remotely in the CNMI and Guam between June and November 2015 were comparable between the 50-km and 5-km products, indicating that the thermal stress did not reach a level high enough to cause significant bleaching in either jurisdiction. During June 22-24, 2015, Bleaching Watch conditions started at the

Agrihan and Asuncion, Maug Island, and Urracas Stations (Figure 39); Bleaching Watch reached at Pagan Island, CNMI during June 25-28 as well. At these four 50-km stations in the CNMI, temperatures fluctuated between Bleaching Watch and No Stress from June until early October, when the stress completely subsided; the temperatures at these stations never progressed above the level of Bleaching Watch. On July 23, CRW issued a Bleaching Watch for the 50-km Virtual Stations for Rota Island, Saipan and Tinian, and Sarigan and Anatahan of the CNMI, as well as for Guam East and Santa Rosa Reef of Guam. The Virtual Station at Guguan and Alamagan of the CNMI followed suit during July 23-26. The Guam East Station climbed to a Bleaching Warning during July 27-29, as did the Rota Island Station during July 30-August 2 (comparable to the thermal conditions measured by the 5-km satellite products) (Figure 40). However, all of the 50-km Virtual Stations in Guam and the CNMI, excluding Pagan Island that remained at a Bleaching Watch level, quickly returned to a level of No Stress during August 6-9. Thereafter, between mid-August and early- to mid-October 2015, all of the ten 50-km Virtual Stations continued to oscillate between Bleaching Watch and No Stress, before they returned to a level of No Stress at the end of the summer season. DHW was not accumulated at any of these stations in 2015. Based on the 50-km products, as we saw in the 5-km products, 2015 saw intensive bleaching thermal stress in the central and eastern North Pacific Ocean but only mild stress in most of the western North Pacific Ocean, including Guam and the CNMI (Figure 25) – only reaching Bleaching Watch in the 50-km Annual Maximum Bleaching Alert Area (Figure 25) but Bleaching Warning in the 5-km Annual Maximum Bleaching Alert Area (Figure 21).

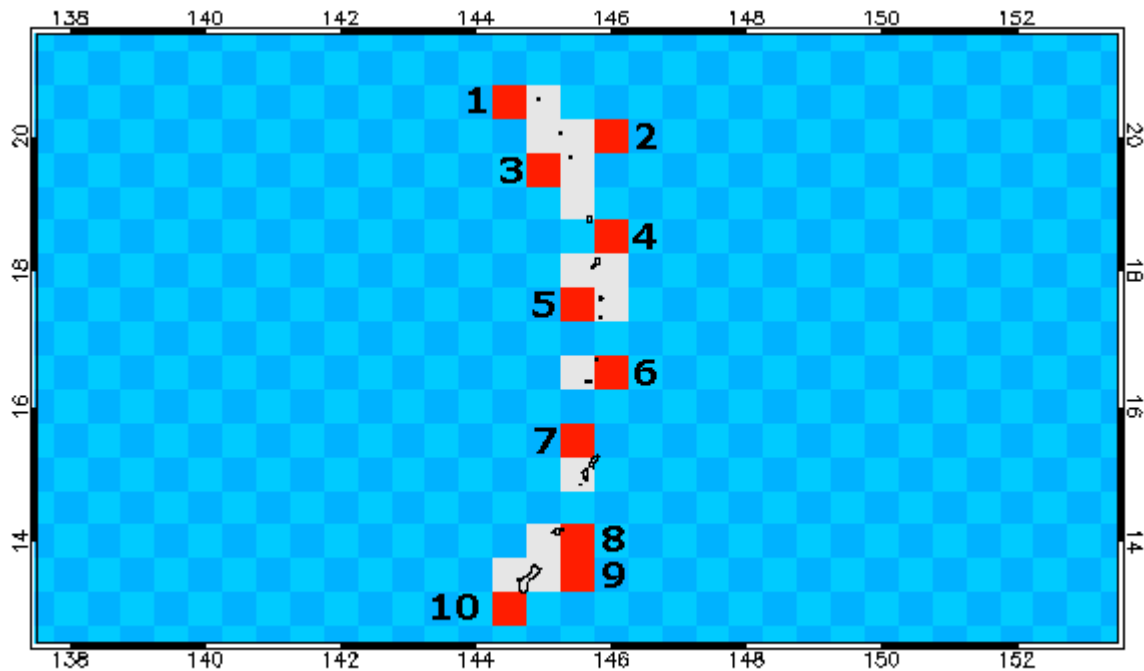


Figure 38. CRW's single-pixel-based 50-km Virtual Stations (red pixel squares) in the Commonwealth of the Northern Mariana Islands (CNMI) and Guam: (1) Urracas, (2) Maug Island, (3) Agrihan and Asuncion, (4) Pagan Island, (5) Guguan and Alamagan, (6) Sarigan and Anatahan, (7) Saipan and Tinian, (8) Rota Island, (9) Guam East, and (10) Santa Rosa Reef, Guam. Pixels in light gray are land-mask pixels.

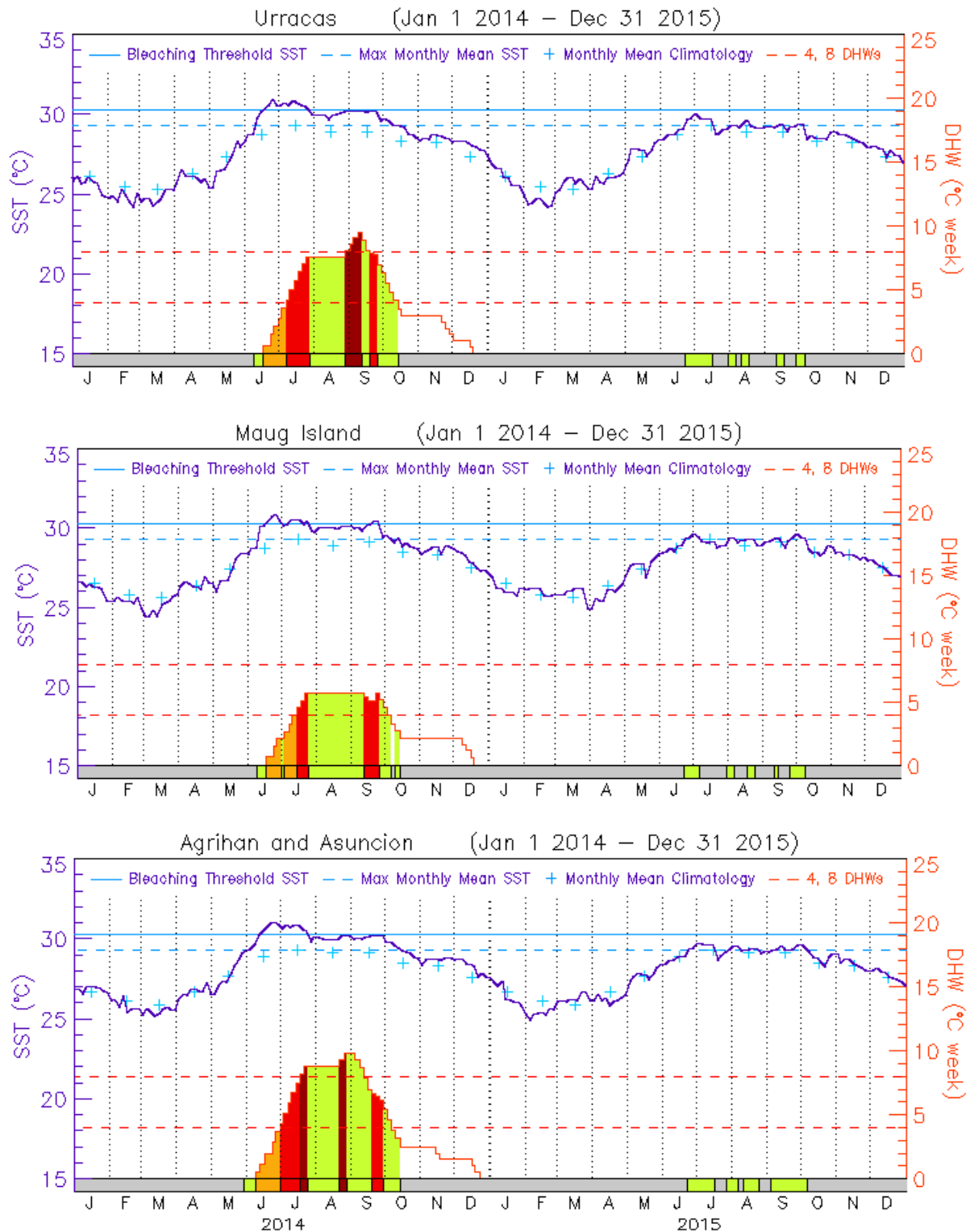


Figure 39. Two-year (2014-15) time series graphs for CRW's 50-km Urracas (top panel), Maug Island (middle panel), and Agrihan and Asuncion (bottom panel) Virtual Stations. See the caption of Figure 6 for how to read the graph.

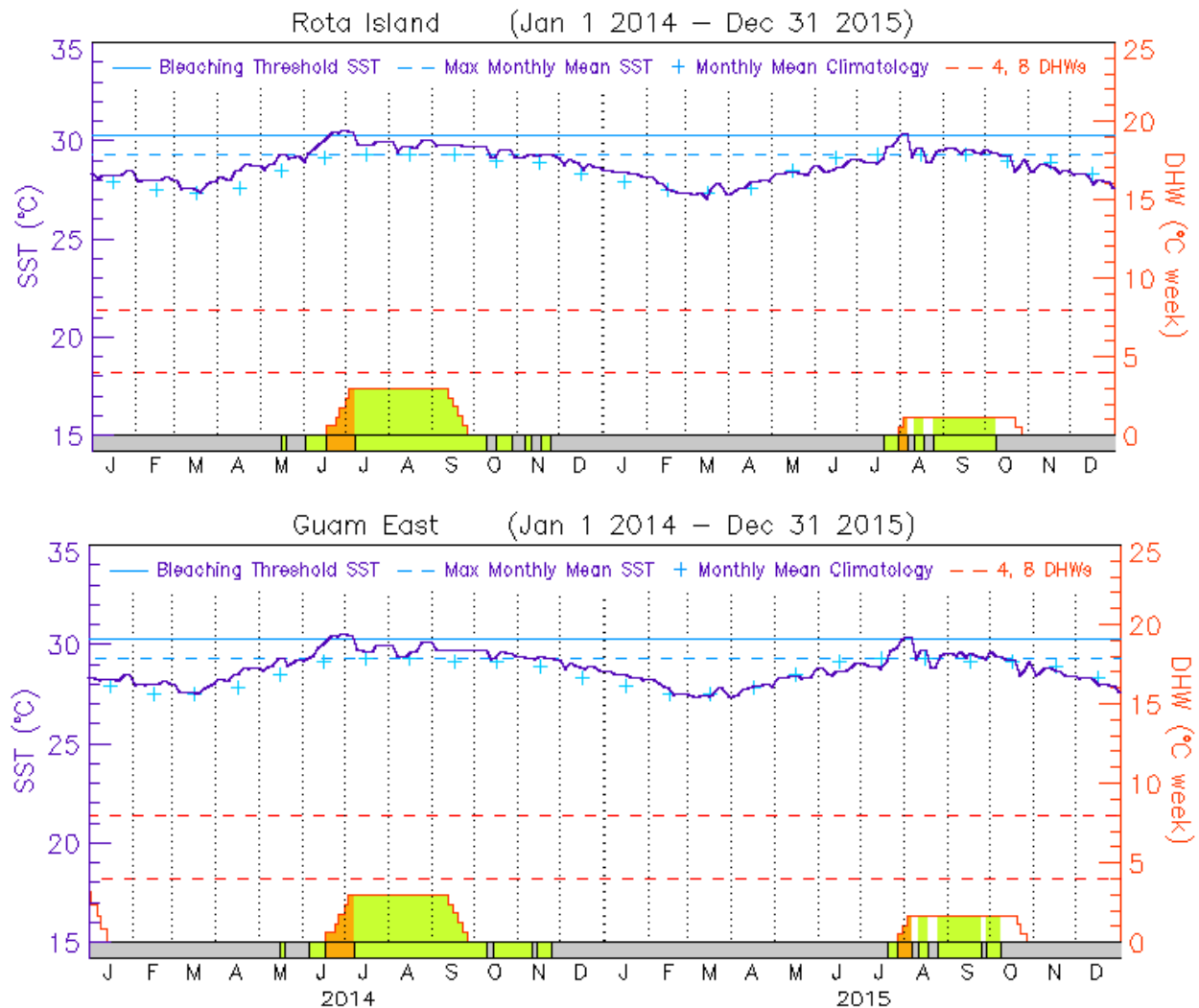


Figure 40. Two-year (2014-15) time series graphs for CRW's 50-km Rota Island (top panel) and Guam East (bottom panel) Virtual Stations. See the caption of Figure 6 for how to read the graph.

As of this writing, NOAA CRW has yet to receive any reports of significant bleaching on reefs throughout Guam and the CNMI in 2015 from field partners.

References:

Heron, S.F.; Johnston, L.; Liu, G.; Geiger, E.F.; Maynard, J.A.; De La Cour, J.L.; Johnson, S.; Okano, R.; Benavente, D.; Burgess, T.F.R.; Iguel, J.; Perez, D.; Skirving, W.J.; Strong, A.E.; Tirak, K.; Eakin, C.M. Validation of Reef-scale Thermal Stress Satellite Products for Coral Bleaching Monitoring. *Remote Sensing* 2016, 8(1), 59, doi: 10.3390/rs8010059.

Liu, G, Heron SF, Eakin CM, Muller-Karger FE, Vega-Rodriguez M, Guild LS, De La Cour JL, Geiger EF, Skirving WJ, Burgess TFR, Strong AE, Harris A, Maturi E, Ignatov A, Sapper J, Li J,

Lynds S (2014). Reef-scale Thermal Stress Monitoring of Coral Ecosystems: New 5-km Global Products from NOAA Coral Reef Watch. **Remote Sensing** 6(11): 11579-11606, doi:10.3390/rs6111579.

Liu, G., J.L. Rauenzahn, S.F. Heron, C.M. Eakin, W.J. Skirving, T.R.L. Christensen, A.E. Strong, J. Li (2013). NOAA Coral Reef Watch 50 km Satellite Sea Surface Temperature-Based Decision Support System for Coral Bleaching Management. **NOAA Technical Report NESDIS 143**. NOAA/NESDIS. College Park, MD. 33pp.

Program Partners:

