NEAR REAL-TIME VALIDATION OF SATELLITE SEA SURFACE TEMPERATURE PRODUCTS AT RAINBOW GARDENS REEF, LEE STOCKING ISLAND, BAHAMAS*

James Hendee
Atlantic Oceanographic and Meteorological Laboratory
National Oceanic and Atmospheric Administration
4301 Rickenbacker Causeway
Miami, FL 33149-1026 USA
Email: Jim.Hendee@noaa.gov

Gang Liu, Alan Strong, John Sapper
Office of Research Applications
National Oceanic and Atmospheric Administration
5200 Auth Road
Camp Springs, MD 20746 USA
Email: Gang.Liu@noaa.gov, Alan.E.Strong@noaa.gov
John.Sapper@noaa.gov

Desiree Sasko, Craig Dahlgren
Perry Institute for Marine Science
Caribbean Marine Research Center
12300 Alt A-1-A, Suite 102
Palm Beach Gardens, FL 33410 USA
Email: disarray24@yahoo.com, CDahlgren@cmrc.org

ABSTRACT

The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch program is installing *in situ* monitoring stations at strategic coral reef areas for purposes of establishing long-term data sets, providing near real-time information products, and surface-truthing NOAA satellite sea surface temperature (SST) products used for coral bleaching predictions ("HotSpots"). The suite of stations, which transmit data hourly, together with custom artificial intelligence software that analyzes the data, is called the Coral Reef Early Warning System (CREWS) network. At each CREWS station local maintenance and calibration of the sea temperature sensor ensures high quality data. Local collaborators also provide feedback on the presence and progress of coral bleaching and thus validate coral bleaching predictions made by HotSpot and CREWS information products. Near Rainbow Gardens Reef, where the first CREWS station was installed, additional *in situ* data loggers were deployed to compare with CREWS and satellite SST data for both the relatively shallow Great Bahama Bank and much deeper Exuma Sound. During summer, 2001, CREWS successfully transmitted daily email satellite SST and *in situ* temperature comparisons, which showed good agreement. Logger data were used to validate and interpret the satellite SST and CREWS station readings.

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1.0 INTRODUCTION

The National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Watch (CRW) program is a collaborative effort between two line organizations within NOAA: Oceanic and Atmospheric Research (OAR), and the National Environmental Satellite, Data and Information Service (NESDIS). The Atlantic Oceanographic and Meteorological Laboratory (AOML) of OAR is conducting research on the influence of meteorological and oceanographic factors upon coral bleaching, and other biogeochemical processes occurring on coral reefs. Instrument arrays to measure the various environmental influences are being deployed at key coral reef areas to gain long-term temporally intensive data coverage. NESDIS, on the other hand, seeks to monitor sea surface temperature (SST) anomalies at coral reef areas throughout the world in a spatially intensive manner, and relate these to incidences of coral bleaching. OAR has developed expert system software plus the instrument array (together called a Coral Reef Early Warning System, or CREWS, station) to screen data in near real-time to test for appropriate data ranges for each of the instruments, and to issue "alerts" as to conditions thought to be conducive to coral bleaching (Hendee 1999; Hendee et al., 2001; Hendee and Berkelmans, *in press*), and other modeled events (Hendee 2000).

NESDIS near real-time global 50-km twice-weekly nighttime satellite Advanced-Very-High-Resolution-Radiometer (AVHRR)-derived sea surface temperature (SST) products have been used to derive bleaching "HotSpot" anomaly charts and bleaching Degree Heating Weeks (DHW) charts as indices of coral bleaching related thermal stress (Strong et al., 1997; Strong et al., 1998; Toscano et al., 1999, 2001; Liu et al., 2001). A satellite-derived maximum monthly mean SST climatology is used as a threshold to make bleaching HotSpot anomalies. The HotSpot technique is proving to be highly successful in providing early warnings of coral bleaching on large spatial scales to the coral reef community (Goreau et al., 2000; Wellington et al., 2001a, b).

The Perry Institute's Caribbean Marine Research Center (CMRC), supported in part through OAR funds, furnishes field support in the way of maintaining the instrument arrays for CREWS stations, conducting field experiments as necessary, and by providing coral bleaching observations for CRW in the Caribbean.

Thus, AOML and CMRC of OAR, plus NESDIS, serve in a complementary fashion to monitor and determine the major causes of coral bleaching. However, the purpose of the present report is to describe how the CREWS stations may serve as a near real-time surface-truth for satellite AVHRR-derived SST measurements. The expert system software was developed to compare *in situ* measured sea temperatures (at 1 m) collected at the CREWS station with those of satellite derived SSTs, and report in near real-time of major temperature descrepancies between the two measurements. This theoretically would allow the satellite researchers greater feedback in near real-time to help improve their calculations, if necessary.

2.0 METHODS

Rainbow Gardens Reef, near Lee Stocking Island, Bahamas (Fig 1), has been studied as a representative pristine coral reef for decades (e.g., see Lang, et al., 1988). To build upon and add to these studies, a spot (23°47.76'N, 76°08.56'W) close to this site was chosen for the construction of the first CREWS station. The basic instrumental configuration for the station measures wind speed, wind gusts, wind direction, air temperature, barometric pressure, sea temperature, salinity, photosynthetically active radiation (PAR) and ultraviolet-B (each measurement above and below the water at 1m). The instruments are actually housed on a former ocean-atmosphere buoy, dubbed the *R/V Kristina*, after the Director of AOML, Dr. Kristina Katsaros, who conducted many field experiments with the buoy previously. Field technicians with CMRC maintain the sensors on *Kristina* and periodically conduct calibration checks of the *in situ* temperature sensors with those that have been calibrated from known standards kept with the sea temperature sensor's manufacturer.

The data collected from the *in situ* sensors are averaged over the period of an hour then sent from the station to a GOES satellite, where they are then retransmitted to a land-based NOAA station at Wallops Island, Virginia. Custom Unix cron jobs at AOML collect the last 72 hours worth of data from Wallops Island once in the morning, then every hour from approximately 6:30 am through 6:30 pm (local time). Once acquired, the raw data are posted to the CRW Web site (http://www.coral.noaa.gov/crw), then processed by the CREWS software. The software is engineered to report via email to the knowledge engineer and CMRC field technicians when any measured parameter goes beyond a specified acceptable range of values for each of the four seasons of the year. If an instrument drift is indicated, that instrument is swapped for a new one or re-calibrated. If the value reported is real, an appropriate researcher is contacted to investigate the anomalous event.

The software actually has two components: the first stage prepackages the data to make them suitable for use by the second stage, which is the application specific knowledge base for the problem domain in question (e.g., coral bleaching). In the present experiment, a separate application (called Satellite/In Situ Comparison Algorithm for Temperature, or SISCAT) also compared 24-hour mean *in situ* sea temperature data produced in the first stage, with data acquired from NESDIS satellite sea surface temperature (SST) products.

The satellite SSTs are extracted from NOAA/NESDIS's global 50-km twice-weekly nighttime AVHRR-SST analysis data set at two pixel locations (centered 23^{o}30'N, 76^{o}30'W, noted as SW pixel and 24^{o}N, 76^{o}W, as NE pixel) closest to *Kristina* at Lee Stocking Island. The SW pixel is over the shallow Great Bahama Bank to the west and the NE pixel is over considerably deeper Exuma Sound (characterized by relatively invariant salinity, slowly rising and falling sea temperatures) to the east. By contrast, the shallow Great Bahama Bank is seasonally much warmer or cooler than the Sound, from which it is continually influenced with each cycle of the tide. *Kristina* is about in the middle of the two pixel centers (Fig 2).

Satellite AVHRR-derived SST observations during this time period were from AVHRR on board of NOAA-16. NOAA-16 are polar-orbiting satellites having nighttime passes over Lee Stocking Island region usually between midnight and 03:00 am local time. The 50-km twice-weekly nighttime composite SST fields have been routinely produced by NESDIS on a near real-time basis (composite SST analysis of Saturday through Monday processed on every Tuesday and SST of Tuesday through Friday on every Saturday). The 50-km global composites are produced using an algorithm which computes an analysis temperature using a weighted average of all retrievals within a specified search distance of a grid intersection. The weighting is based on the inverse of the distance squared from the grid intersection. The search distance in each direction (+x, -x, +y, -y) can be variable based on the analysis gradient in each direction.

After the sea temperature products have been finalized they are formatted to be compatible for SISCAT use. For each pixel, the location of the station; the GMT Gregorian date; the Julian year, day and hour; the temperature calculation; the number of observations used to gain that temperature; and the hours since the last usable temperature calculation are recorded in a separate file and uploaded to the workstation. If the sea temperature values for either of the satellite SST pixels differs from the 24-hour mean *in situ* measured sea temperature at *Kristina* by more than 0.1^{o} C, a report is produced (Fig 3).

Finally, in addition to these two methods for measuring sea temperatures, *in situ* sea temperature data loggers were deployed at Rainbow Gardens Reef proper. These data were used as a further comparison against the SISCAT output to help characterize the influence of the two water bodies on the seasonal temperature profile of Rainbow Gardens Reef. The Rainbow Gardens logger (Fig 1, 23°47.80'N, 76°08.79'W), one of the loggers in the area, is positioned at Rainbow Gardens Reef which is located in shallow water adjacent to an active deep tidal channel between Great Bahama Bank and Exuma Sound. *Kristina* is about two km to the south of the Rainbow Gardens logger. The logger is fixed on the bottom (with sensor 0.3 m above the bottom) in 3.5-4 m of water. Bottom water depth at the site varies up to about one meter with the tide.

3.0 RESULTS

As the reader might expect, the automated reports from SISCAT were produced every day when the difference between *in situ* measurements and satellite SST was configured for merely 0.1^{o}C. A reconfiguration to 0.5^{o}C tolerance in difference rarely produced a report except for when there were extensive days between good satellite observations (i.e., during periods of many cloudy days). However, the approach when used during sunny days would be useful for alerting to either a malfunction of the *in situ* sensors, or the satellite algorithm.

There was a very high correlation (0.975) between daily Rainbow Gardens logger temperatures and daily *Kristina* temperatures. However, *Kristina* temperatures were consistently about 1^{o}C cooler than the logger temperatures (Fig 4). The mean difference of daily 24-hour Rainbow Gardens Reef logger temperature from *Kristina* temperature, over an approximate one-month period (29 May through 9 July 2001), was 1.03^{o}C (STD: 0.16^{o}C) with consistently warmer Rainbow Gardens Reef logger temperatures. The daily maximum and minimum temperatures had a similar relationship between the two *in situ* temperatures. This was presumed to be due to the increased flow and mixing at the site of *Kristina*, with the cooler water from Exuma Sound compared with the shallower more protected site of Rainbow Gardens Reef nearly one mile to the north. However, a longer time series is needed to understand the difference.

Fig 4 shows a continuous trace of sea temperatures from the *in situ* logger vs. Kristina vs. the satellite AVHRR SSTs.

4.0 DISCUSSION

To our knowledge, this is the first reported time-series of a near real-time comparison (i.e., surface-truthing) of calibrated *in situ* near-sea surface temperature with satellite SSTs. An additional algorithm was developed to extract *in situ* SSTs during discreet three, six and nine hour periods at night (the same time of the satellite measurements), rather than mean SSTs over 24 hours. However, those reports were rarely produced because SISCAT was configured to look for satellite SSTs acquired the same night the *in situ* temperatures were recorded. This portion of the program needs further refinement.

Overall, NESDIS satellite 50 km twice-weekly nighttime SSTat the SW pixel was better than the NE pixel and mean SST of the two pixels for monitoring both daily *in situ* 24-hour and nighttime 12-hour mean logger temperature at Rainbow Gardens Reef. Satellite (SW pixel) differences from *in situ* for a one-year period (1 October 2000 through 30 September 2001), in terms of daily comparisons, were -0.14 ± 0.64^oC and $0.01\ ^o$C $\pm 0.72^o$C, respectively and for the summer season -0.25^oC $\pm 0.61^o$C and -0.04^oC $\pm$ 0.63^oC. During the summer season, the mean differences of SST at the SW pixel from the logger for the weekly mean daily temperature were -0.27°C ± 0.29°C and -0.05°C ± 0.30°C for the daily *in situ* 24-hour and nighttime 12-hour mean temperature comparison scenarios, respectively.

The accuracy of using weekly mean satellite50-km twice-weekly nighttime SST (at the SW pixel), to monitor summer season weekly means of daily *in situ* nighttime and 12-hour mean temperatures at a depth of about 3 meters at Rainbow Gardens Reef, was about -0.05 ± 0.30°C. Although the complexity of the physical oceanographic characteristics in the region make the satellite monitoring of the reef environment in the region a challenge, our results are promising.

Our results also suggests that although the mean SST of the two pixels had larger annual and summer mean differences from the *in situ* observations, its STD and correlation were greatly improved. Longer time series are required for a better understanding. Other environmental parameters, such as tidal current and wind direction, need to be investigated further and relevant parameters need to be obtained at near real-time, as well, for a more complete validation picture.

Satellite SST measures the skin temperature and is regressed to the surface bulk (1m) temperature; hence, the reasonably good match may suggest that in the region the vertical differences in daily mean temperatures (daily 24-hour and daily nighttime 12-hour) were not significant during the study periods. This might be caused by efficient vertical mixing induced by the strong tidal current in the channel, or caused by wind mixing in shallow water. Further investigation in the vertical distribution of water temperature is needed.

The large difference between the Rainbow Gardens logger temperature and *Kristina* requires more investigation on the physical and dynamic environment at the two sites, as well as a longer time series to work with.

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Figure 1. Study Site: Lee Stocking Island and Rainbow Gardens Reef.

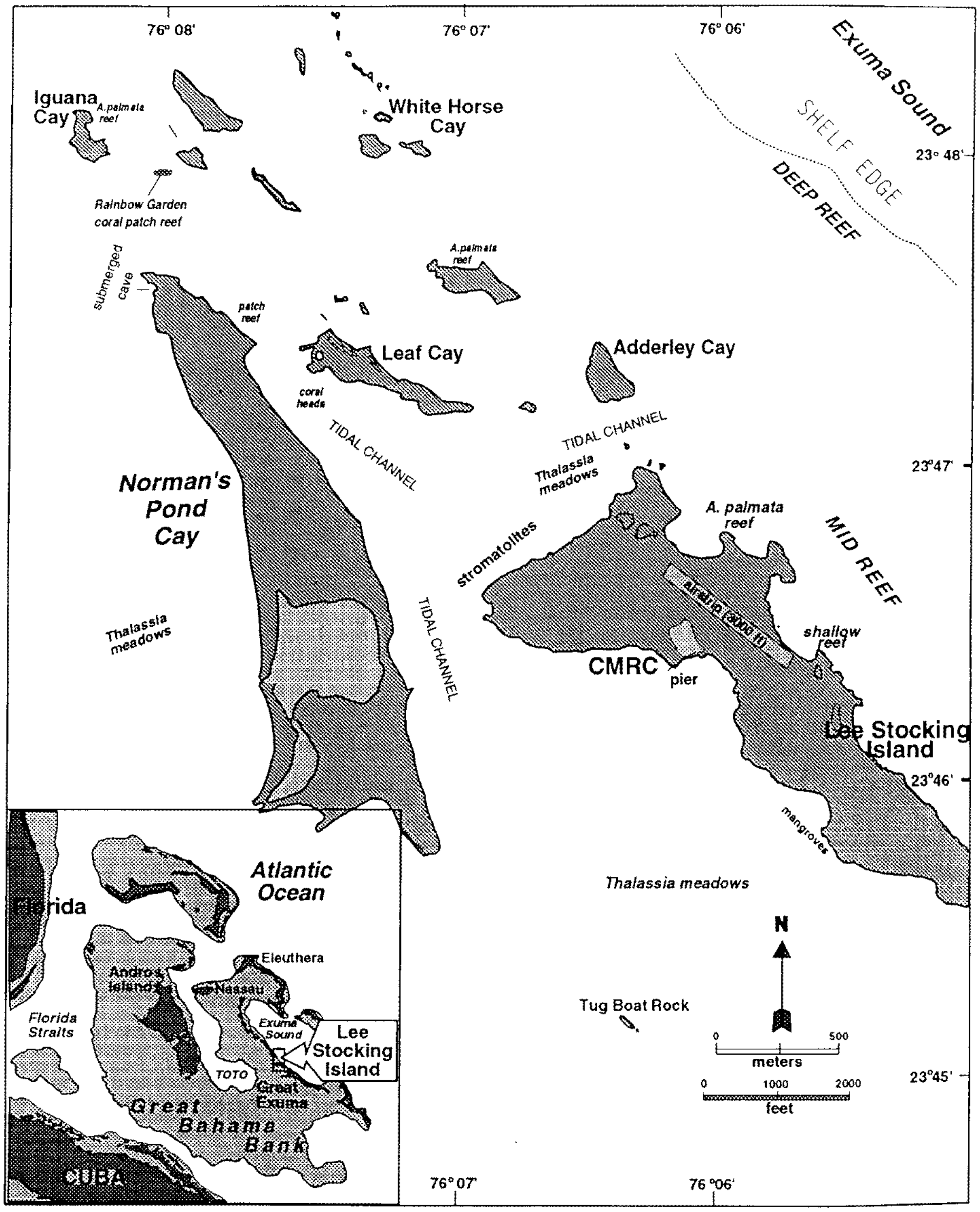

Figure 2. Location of Satellite Pixels and *R/V Kristina*.

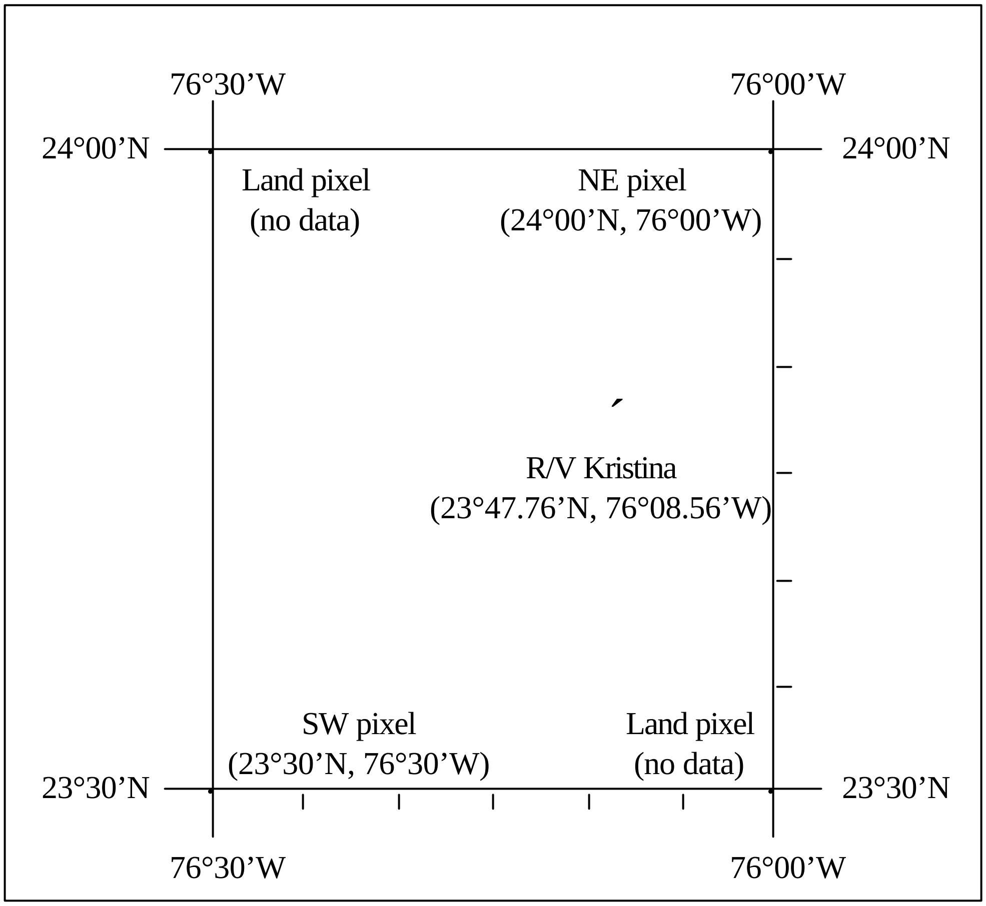

Figure 3. Example Automated SISCAT Email Report.

~~~~ Lee Stocking Island SST/In Situ Report for 09/01/2001 ~~~~

Rule sst-2 (daily mean temp)
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Report for 09/01/2001
In situ temp: 28.6
SST south of station: 29.8 (47 hour reading)
SST north of station: 29.4 (47 hour reading)

Figure 4. Trace of Water Temperaures for Rainbow Gardens Logger, *R/V Kristina*, and Satellite 50-km SST Pixels