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Disclaimer

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Coastal Turbidity on the Southeast Florida Shelf—Monitoring Turbid Water Sources and Fates by Satellite

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Acronyms

AI	Artificial intelligence
AOML	Atlantic Oceanographic and Meteorological Laboratory
CI	Color index
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CNMI	Commonwealth of the Northern Mariana Islands
CRCP	Coral Reef Conservation Program
EPA	Environmental Protection Agency
FACE	Florida Area Coastal Environment
FDEP	Florida Department of Environmental Protection
LBSP	Land-based sources of pollution
MODIS	Moderate-resolution imaging spectroradiometer
NASA	National Aeronautics and Space Administration
NGDC	National Geographic Data Center
NOAA	National Oceanic and Atmospheric Administration
NTU	nephelometric turbidity units
OOL	Optical Oceanography Laboratory
POMF1	Port of Miami
PVGF1	Port Everglades
ROI	Region of interest
SECREMP_PB2	Southeast Florida Coral Reef Evaluation and Monitoring Project
S/RI	Stimulus/Response Index
STSRI	spatio-temporal Stimulas/Response Index
USF	University of South Florida
USGS	US Geological Survey
VAS	Virtual antenna system
VIIRS	Visible-infrared imaging radiometer suite
WW3	WaveWatch III

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Abstract

NOAA's Coral Reef Conservation Program funded a study from 2013 to 2015 to determine the feasibility of monitoring turbidity plumes in reef waters for three U.S. jurisdictions, one of which was the Southeast Florida Shelf and northern Florida reef tract. This report presents the results of that study. It shows that with care, satellite ocean color can be used to remotely monitor sources and instances of coastal ocean turbidity.

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1. Introduction

Turbidity can have a significant impact on coral reef ecosystems through light limitation, sedimentation, and eutrophication (e.g., Bessell-Browne *et al.,* 2017). The Florida Department of Environmental Protection (FDEP) made it a priority in their 2004 local action strategy to determine the tracks and fates of turbidity in the waters of the northern Florida reef tract (FDEP, 2004). The National Oceanic and Atmospheric Administration's Coral Reef Conservation Program (NOAA-CRCP) funded a collaborative project in 2013-2015 (Project No. 881) to help meet this priority.

Potential sources of turbidity described in the literature include natural sediment resuspension due to wind and waves (e.g., Storlazzi and Jaffe, 2008), tidal runoff, coastal inlets, oceanic wastewater outfalls (Staley *et al.,* 2017), and other human activities such as dredging (e.g., Wang and Beck, 2017). Because of the complexity of both the potential sources of turbidity and coastal circulation and mixing patterns, in situ monitoring of turbidity and associated sedimentation is challenging (e.g., Whinney *et al.,* 2017). Using satellite remote sensing to monitor coastal turbidity has a variety of potential advantages (e.g., Hu *et al.,* 2014).

NOAA CRCP Project No. 881 was funded to provide managers with historical maps of turbidity, as well as alerts and maps for near real-time tracking of turbidity plumes, in coastal waters of three CRCP priority jurisdictions: American Samoa (including Faga'alu), the Commonwealth of the Northern Mariana Islands (CNMI), and South Florida (including reefs offshore of projects for port/tunnel expansion and beach refurbishment in three counties). Academic partners (e.g., the University of South Florida, USF) in collaboration with researchers at NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML) began back-processing and analyzing remote-sensing data in 2013 to produce maps of relative turbidity, an indicator of the change in available light, for the three target regions. These relative turbidity or Color Index (CI) maps were gathered via the Moderate-resolution imaging spectroradiometer (MODIS) ocean color instruments on two polar-orbiting satellites at 250 meter spatial resolution. Maps have been produced for analysis from July 2002 to May 2017, and new maps have been made available to management partners in all three jurisdictions in near real-time via a public web site (http://optics.marine.usf.edu).

In-water data from three past projects completed by researchers at AOML have been processed and quality controlled in collaboration with project participants from AOML's Florida Area Coastal Environment (FACE) program. Targeted field observations of turbidity have been completed in South Florida near one major port project. The goal of these observations has been to refine remote sensing ocean color products to provide an approximation of absolute turbidity (nephelometric turbidity units, NTU). In situ data have been processed and furnished to academic partners for the South Florida region to begin calibration of absolute turbidity products from the available remote sensing data.

Key Points

- For each of the three jurisdictions, i.e., American Samoa, CNMI/Saipan, and South Florida, academic partners at USF's Optical Oceanography Laboratory (OOL) configured satellite CI maps. The Southeast Florida Shelf satellite map spans from 25.5-27.5°N latitude, 80.3-79.0°W longitude (there is a similar map region for the Florida Keys, which is not analyzed as part of this project).
- Within each CI map area, smaller regions of interest (ROIs) were selected and analyzed through time. Within the southeast Florida map area, three ROIs were selected, each 17 x 6 km: the Port of Miami, POMF1, centered at 25.74897, -80.13317; Port Everglades, PVGF1, centered at 26.09300, -80.09200; and the Palm Beach renourishment projects region and Southeast Florida Coral Reef Evaluation and Monitoring Project, SECREMP_PB2, centered at 26.67875, -80.01832.
- Satellite ocean color depends on clear skies during a satellite overpass: the shallow waters of the three southeast Florida ROIs were remarkably consistent in clear-day overpasses during all four seasons. For the POMF1 ROI, USF's CI maps out to the second reef line showed fewer than 2.5 days between clear pixels. For

PVGF1, the average number of days between clear pixels was <2.5 days out to the second reef line, <3 days out to the third reef, and <6 days out to the 60-m isobath. For SECREMP_PB2, the average number of days between clear pixels was similar to the other two ROIs. Offshore of the 60-m isobath, the October-December season was, on average, the least clear, but inshore of it the numbers above still applied in all three ROIs for all seasons.

- As a primary driver of coastal turbidity, shelf wave action was modeled using 3-hourly significant wave heights backcast by NOAA's WaveWatch III (WW3) operational products. To apply these products to shallow reef shelves, a simple attenuation model was applied based on coastal bathymetry so that significant wave height reached 0.0 m at the beach. Wave attenuation for South Florida was performed using a 30 m horizontal resolution bathymetry per the NOAA-National Geophysical Data Center/US Geological Survey (NGDC/USGS, see **Figure 1**). Winds from in situ monitoring stations and reanalysis fields (European Centre for Medium-Range Weather Forecasts ERA-Interim) were also considered but were not found to be significant to the analysis.
- The WW3 significant wave height offshore of South Florida was greatest (>0.7 m) during October-April, but near the second reef line at 20-m depth, estimated attenuated wave heights then were only 0.4 m, on average. In April-September at 20 m, attenuated waves were 0.3 m.
- Events of enhanced relative turbidity likely corresponding to human activity were identified as days when any pixel-normalized CI pixel was above its 93rd percentile and when significant wave height was below the median. Extreme events were identified as being when the satellite CI was above its 99th percentile and significant wave height was below its 32nd percentile. Events for analysis and tracking were filtered to exclude those when less than 20 percent of the non-land pixels in a ROI were clear or when days between clear pixels were greater than 1 week.
- Between February 2005 and February 2017 for the PVGF1 ROI, 633 days (overpasses) of enhanced turbidity were identified in at least one pixel, 230 of which did not correspond with high waves. Of these, 75 days were identified as extreme events. Day pixels during these 12 years that showed enhanced relative turbidity were somewhat greater (45-75 days per pixel) to the north of Port Everglades Channel than to the south (20-60); events to the north of the channel also showed a greater tendency to cluster within and across the first reef line, while events to the south of the channel were, on average, 1 km farther offshore.
- Between February 2005 and February 2017 for the POMF1 ROI, we noted 1304 days (overpasses) of enhanced turbidity in at least one pixel, approximately 400 without high waves. Day pixels with enhanced relative turbidity were more common to the north and immediately offshore of the Port of Miami Channel (10-55 days) than to the south (<20 days within 15 km of the channel). Like the PVGF1 ROI, event pixels to the north of POMF1 were nearer to the shore than those to the south. Unlike PVGF1, there was a clustering of extreme event pixels about 18 km to the south of POMF1, 4-6 km offshore, with more than 100 days of enhanced turbidity.
- For the PVGF1 ROI, both events and extreme events occurred with roughly the same frequency during each of the 12 months of the year. The most widespread events of the past 5 years near PVGF1 occurred in April and September-October 2012; July and October 2013; January, August, and November 2015; May 2016; and December 2016-January 2017.
- For the POMF1 ROI, both events and extreme events were somewhat more common in November-March than the rest of the year. The most widespread events of the past 5 years near POMF1 occurred in May and October-November 2012; March, June, and December 2013; May 2014; January, August, and December 2015; June-September 2016; and especially December 2016-March 2017.

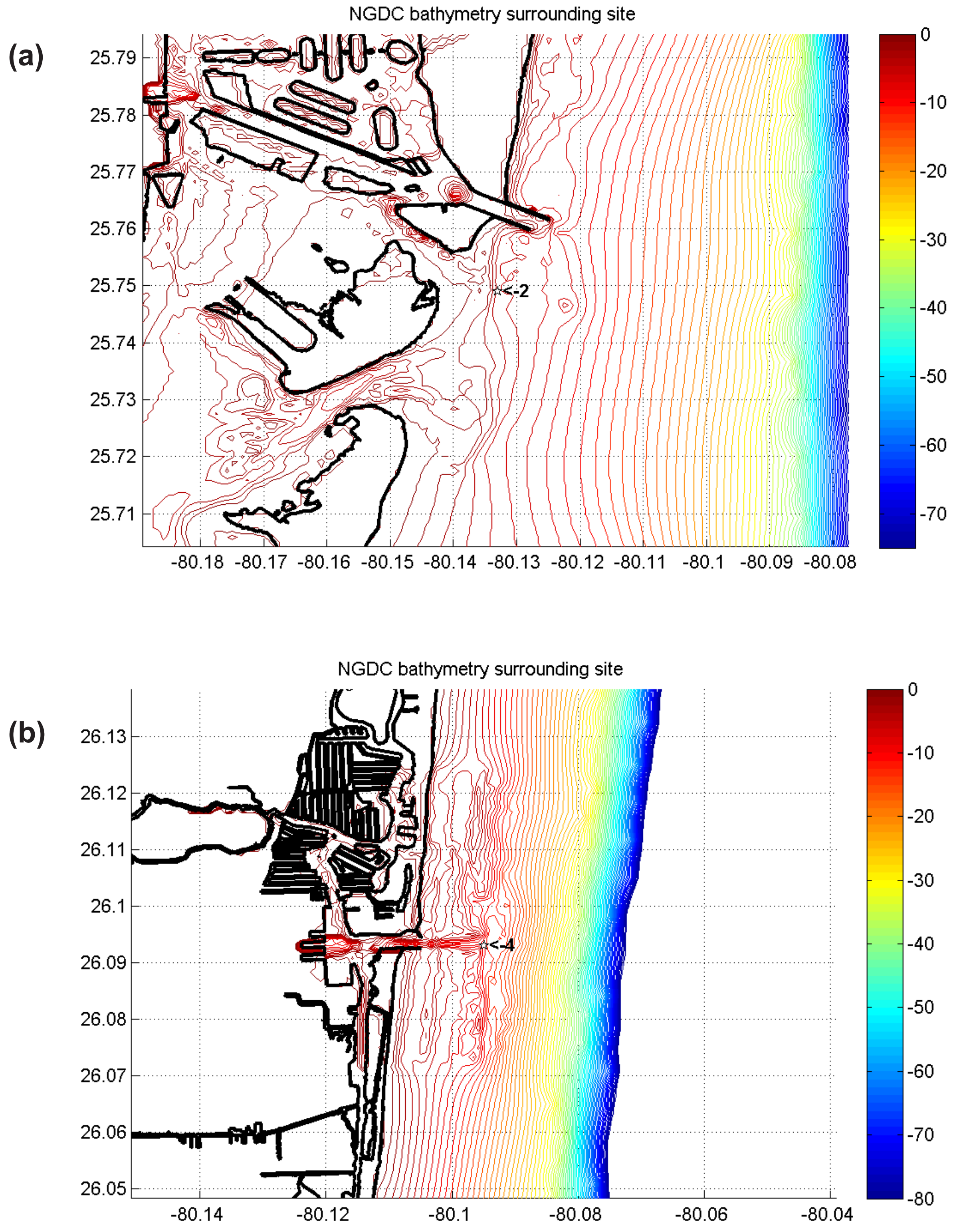


Figure 1. Bathymetry detail (contour every 1 m) for (a) virtual station 2 near the Port of Miami and (b) virtual station 4 near Port Everglades (see map in Figure 3 for Port Everglades, as this bathymetry does not show the port channel).

2. Background

As early as 2001, suspended sediments and turbidity were identified by project scientific team members as important variables for reef monitoring, having a potentially significant impact on coral reef health (Berkelmans *et al.*, 2002). Sediment suspension was identified as playing a positive role by shading light, which helps protect against both temperature- and light-related stress, including reduced coral growth, bleaching, and mortality. However, criteria were also sought for determining when suspended sediments were sufficiently high enough to play a deleterious role in coral health. The need to apply such criteria to priority regions, and to find ways of providing near real-time data at an accuracy and spatial-temporal resolution sufficient to inform those criteria, were identified as priorities if coral reef managers were to have their fingers on the pulse of reef ecosystems.

The implementation of turbidity monitoring at synoptic scales, however, faced significant difficulties due to limited resources. This led to discussions with remote-sensing collaborators in academia and to envisioning methodologies to estimate both relative and absolute turbidity from moderate-resolution ocean color remote-sensing products. The development beginning in 2010 of the virtual antenna system (VAS) for MODIS ocean color data at USF-OOL provided the remote-sensing infrastructure to implement these methodologies for priority-managed coral reefs within all US waters without limiting the area of interest to the physical satellite antenna location.

Academic partners at USF, in collaboration with AOML researchers, began back-processing remote-sensing data in 2013 to produce maps of relative turbidity, an indicator of the change in available light, for the three target regions. In-water data from three past AOML projects have been processed and quality controlled in collaboration with project participants from AOML's FACE program; in situ data have been processed and furnished to academic partners for the South Florida region to begin calibration of absolute turbidity products from the available remote sensing data.

In situ measurements of turbidity have been performed around the Port of Miami, and further fieldwork will be undertaken as opportunities to piggyback off of other operations present themselves. Management and science partners have selected sites for in situ data gathering based on ongoing or planned marine industry and conservation projects, as well as ongoing studies. Currently outstanding permits have been evaluated, and requirements for new permits and *de minimis* findings for proposed fieldwork have also been determined.

Managers for the three CRCP priority jurisdictions of American Samoa, CNMI, and South Florida all identify the management of sediment on coral reefs and adjacent coastal waters as a priority objective of NOAA's CRCP (ASLAS, 2010; CNMI CRMP, 2010; SEFCRI LAS, 2004). These managers have expressed a need for both historical and timely information on coastal turbidity within their jurisdictions.

The goals of project No. 881 were to provide information to assess changes in reef ecosystem health due to turbidity across jurisdictions but at the sub-watershed scale and to communicate these results effectively to managers, as well as build their capacity to apply project results to help meet jurisdiction needs for land-based sources of pollution (LBSP) monitoring. Recent research advances have made it possible to fill a knowledge gap and provide timely information to address turbidity management concerns identified for LBSP. The final project objectives were to provide managers in each of the three jurisdictions with water turbidity maps over time (beginning in 2002) at sub-watershed scales within their coastal waters and with detailed, near real-time alerts, including links to Google Earth maps, to provide a geographic context when turbidity plumes occur.

3. Methods

Academic partners have adapted an existing algorithm to produce a proxy for relative in-water turbidity that works within shallow (≤5 m), relatively clear waters: CI, an index originally designed for open ocean feature detection that uses ocean color data from the MODIS instruments aboard the polar-orbiting satellites Aqua and Terra.

The algorithm was applied to 12 years of daily satellite overpasses in the three areas of particular interest for US coral reef conservation—American Samoa, CNMI, and the Southeast Florida Shelf, respectively. We found linear relationships between relative turbidity and wave action. Periods of high winds also showed some relationship to relative turbidity. After controlling for periods of higher waves, wind variability was not found to show a strong relationship with relative turbidity. Yet, despite controlling for both natural drivers of wind and waves, events of enhanced relative turbidity were still noted throughout the record. It is suggested that a subset of these events will likely correspond with coastal construction and beach renourishment projects inshore: for this purpose, a future direction for this analysis would be to compare dates and geography from such projects (e.g., **Figure 2**) with the dates and geography of enhanced satellite relative turbidity from the regions of interest analyzed below

The project has coordinated with resource management partners (e.g., FDEP, CNMI's Division of Environmental Quality, American Samoa's Department of Marine and Wildlife Resources) and academic partners (e.g., USF, the University of Miami's Cooperative Institute for Marine and Atmospheric Studies, CIMAS), to provide retrospective analysis to determine mean conditions in the past as baseline data. This has allowed current conditions to be represented as anomalies relative to those baselines. The project leverages significant existing resources and expertise within AOML and USF-OOL. A suite of customized satellite maps are now available via Google Earth at 250 m spatial resolution. Tools have been implemented for near real-time assessment and for alerting managers about relative turbidity levels in their jurisdictions. We will work closely with jurisdictional managers to help them understand these tools and take full advantage of them.

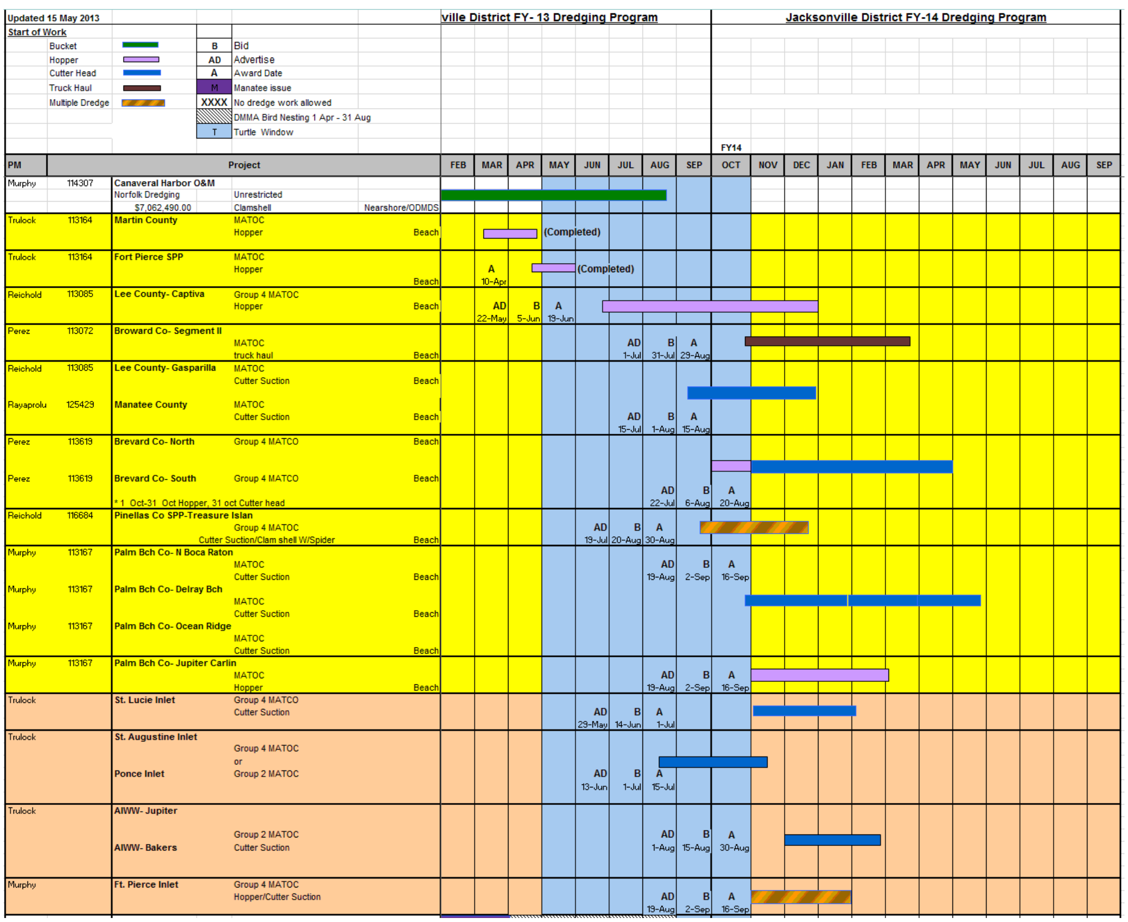


Figure 2. Permitted projects schedule of dredging and similar operations for southeastern coastal Florida, 2013-2014.

The project capitalized on the VAS implemented at the USF-OOL with past support from the National Aeronautics and Space Administration (NASA) and other agencies. The VAS obtains and processes historical and real-time satellite data from NASA and makes higher level customized products available online. Existing sensors and data-gathering equipment were assembled and deployed in South Florida to gather observations necessary to calibrate and refine the satellite products to absolute values of total suspended solids: this will provide managers in this jurisdiction with new information on suspended particle concentration.

3.1 Satellite Ocean Color

Below is a summary of some of the basic facts about satellite turbidity monitoring as performed in this study:

- This satellite relative turbidity product uses four color bands in MODIS; algorithms are now under development for the new Visible-Infrared Imaging Radiometer Suite (VIIRS) satellite instruments as well.
- MODIS instruments have been operating on two polar-orbiting satellites (Aqua and Terra) that have provided four overpasses per day since 2002. Two of the overpasses are in daylight; the VIIRS instruments may add a third day-time overpass.
- Ocean color bands from MODIS provide 250 x 250 m pixels; the VIIRS resolution is less, at 350-750 m.
- Satellite ocean color can view the seafloor in shallow water, the extent of which depends on water column turbidity.
- Uncalibrated color products in shallow waters can show variations over time at a given pixel, for a given season, but with spatial coverage over hundreds of kilometers.
- In-water calibration data can be used by remote sensing scientists to tune algorithms to local conditions.
- Site-calibrated products approximate absolute turbidity (NTU) time series over smaller areas of ~1 km; products are most reliable when calibrated with observations under a variety of conditions (**Figure 3**).

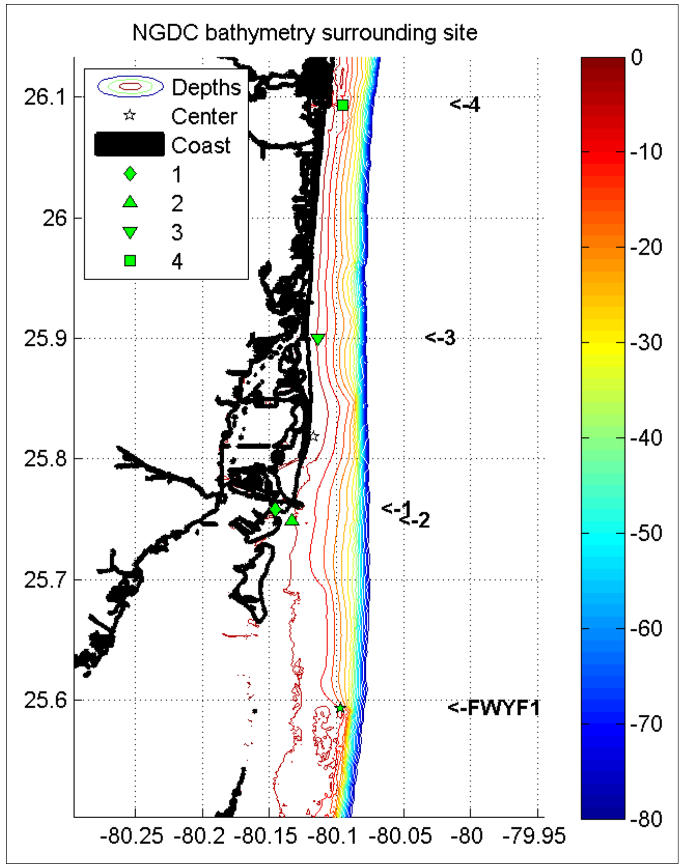


Figure 3. Four monitored pixel groups (virtual stations) for southeast Florida, shown with bathymetry contours (depths every 5-80 m): 1–inshore Port of Miami; 2–Port of Miami; 3–Haulover; 4–Port Everglades. NOAA's Coastal-Marine Automated Network (C-MAN) monitoring lighthouse Fowey Rocks, FWYF1, is also shown.

Both kinds of products—uncalibrated relative turbidity or CI and calibrated absolute turbidity or NTU—can be made available to managers and the public via the Internet. CI maps are available as images, data files, and Google Earth overlays (**Figure 4**). Absolute turbidity data are available as time series at virtual stations: individual pixel groups tracked over time, where the absolute turbidity algorithm is calibrated by in-water measurements to translate satellite relative turbidity into NTU.

3.1.1 Relative Turbidity

Relative turbidity products for this project were based on the CI algorithm developed by C. Hu and colleagues for MODIS (Chen *et al.,* 2007; Barnes *et al.,* 2015; Barnes and Hu, 2016). MODIS CI is derived from reflectance at 555 nm, referenced against a linear baseline between

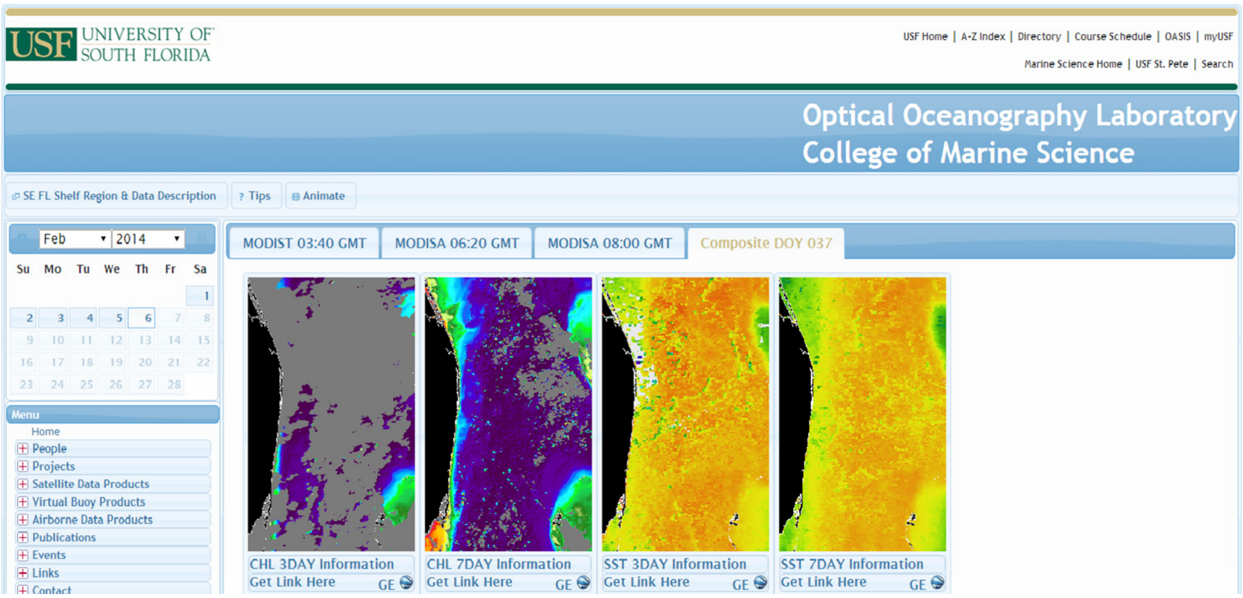


Figure 4. USF-OOL Internet interface to 250-m resolution satellite products for the southeast Florida region.

469 and 645 nm, after correction for gaseous absorption, molecular scattering, and sun glint effects (Hu, 2011). The MODIS standard product MOD35 is used to discern clouds from the water surface (Frey *et al.*, 2008).

These CI products, even when not yet calibrated specifically to show an absolute turbidity, provide information on change in turbidity over time. They are available in near real-time maps on the Internet over wide coverage areas. From these synoptic CI maps, seasonal averages can be developed and historical reports produced showing seasonality, as well as variance, relative to that seasonality (see section 4.1.4). Combining near real-time and historical maps, regions of pixels can be highlighted which are outliers relative to their historical climatology and variance (see section 4.4).

Such temporary regions of enhanced relative turbidity are of interest to resource managers for further monitoring, additional protection, source attribution, and, potentially, for enforcement of protective regulations. Although relative turbidity cannot be compared between areas of a satellite image, it does allow a pixel to be compared with itself over time. We analyzed historical distributions of relative turbidity at each pixel in the ROIs and produced maps showing the anomaly of each pixel's CI intensity relative to its own historical distribution. These maps are presented throughout section 4.

3.1.2 Absolute Turbidity

Absolute turbidity values in this study are called NTU because although, in fact, they are distinct from the US Environmental Protection Agency's (EPA) definition of nephelometric turbidity units, they are intended to mimic them. NTU time series can be estimated from satellite ocean color and infrared data using methods developed by Hu and others (Chen *et al.*, 2007; Hu *et al.*, 2014). Such estimates provide managers with the ability to compare pixels with one another, rather than only comparing changes within a pixel over time, as is the case with relative turbidity. However, a record of in-water turbidity measurements is required at each such pixel to calibrate methods used to make such estimates, particularly in clear, shallow subtropical coastal waters (Barnes *et al.*, 2013; Zhao *et al.*, 2013).

The method we used for estimating absolute turbidity from ocean color in the present project worked well in shallow waters near land. This feature is of particular interest to managers in jurisdictions with coral reefs. One intensive ground-truth study in Tampa Bay (Chen *et* *al.,* 2007) showed useful results over a 2-year period for waters as shallow as 2-3 m (**Figure 5**). In-water turbidity measurements were taken twice in 2015 (see section 4.3) near the Port of Miami to allow the absolute turbidity algorithm to be calibrated for that group of pixels. USF-OOL researchers used these data to produce NTU time series for 2002-2017 for the POMF1 virtual station.

3.2 Map Areas and Regions of Interest

Satellite ocean color data are potentially available globally, multiple times per day. At 250 m horizontal resolution, this represented an overwhelming amount of data. Ocean wave models and other environmental data also present similar challenges. Spatial focus is required to perform a useful analysis and to produce interesting maps. For each of the three jurisdictions, USF-OOL researchers configured satellite CI maps of a sub-area of the region. The southeast Florida satellite map spans from 25.5-27.5°N latitude, 80.3-79.0°W longitude (**Figure 6**). USF-OOL researchers also produced a similar map region for the Florida Keys, which was not analyzed as part of this project.

Within each CI map area, smaller ROIs were furthermore selected and analyzed through time. These ROIs were designed to focus research attention on areas where human activity was most likely to impact coral reefs. Within the southeast Florida map area, three ROIs were selected, each 34 x 12 km in extent: POMF1, centered at 25.74897, -80.13317; PVGF1, centered at 26.09300, -80.09200; and SECREMP_PB2, centered at 26.67875, -80.01832 (**Figure 6**).

3.3 Ocean Surface Waves

As a primary driver of coastal turbidity, we modeled shelf wave action using 3-hourly significant wave height backcasts with NOAA's WW3 operational products. To apply these products to shallow reef shelves, we applied a simple attenuation model based on coastal bathymetry so that significant wave height reached 0.0 m at the beach

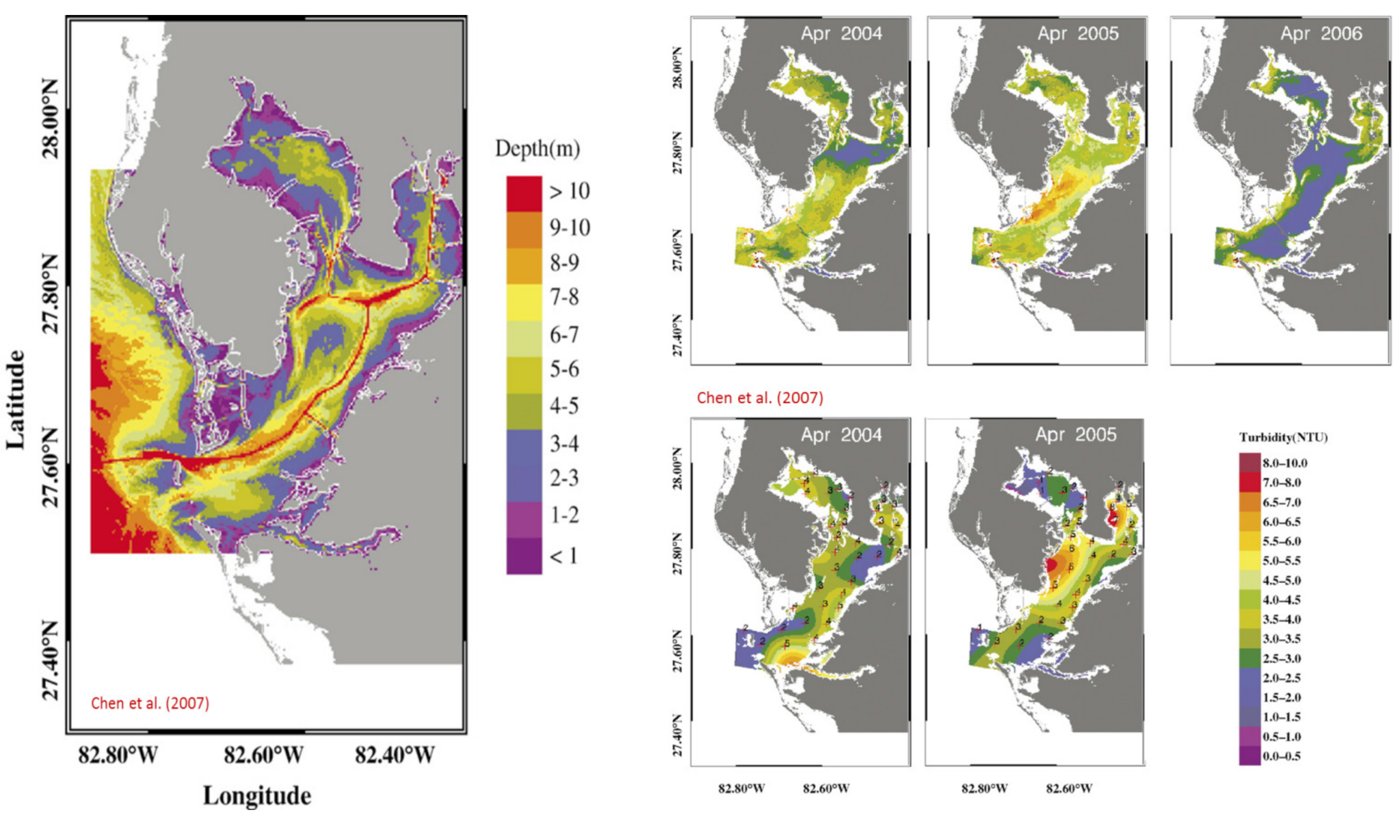


Figure 5. Results of a combined remote sensing and intensive field sampling study in Tampa Bay, Florida (Chen *et al.,* 2007).

(Hardy *et al.*, 1990). Wave attenuation for South Florida was performed using 30 m horizontal resolution from NOAA-NGDC/USGS bathymetry (see **Figures 1** and **3**). Results of the wave attenuation approach are summarized for the PVGF1 ROI in **Figure 7**.

3.4 In Situ Turbidity Measurements

In-water turbidity measurements were previously collected from the southeast Florida map area as part of the NOAA-FACE project. These have included both shipboard turbidity measurements in waters as shallow as 5 m in 2008-2013 (Carsey *et al.*, 2010; Carsey *et al.*, 2015) and in situ turbidity and sediment measurements using kayaks and small boats in waters from 1-5 m depth in 2013-2015 (Stamates *et al.*, 2013).

A turbidity sensor was also deployed in the waters near the Port of Miami as part of this project. An existing WETLabs C-STAR sensor, which had never been deployed, was paired with a power source and datalogger and housed in a deployment cage (**Figure 8**). This work was completed by project contributors Dr. Natchanon Amornthammarong of the University of Miami/CIMAS and Michael Shoemaker of NOAA-AOML.

Deployments were limited by battery power to at most 2 weeks at a time. However, despite short deployment times, the amount of environmental fouling of the sensor package was unexpectedly high. This was likely due to both the level of turbidity encountered and to the action of waves at the site, which was approximately 3 m deep. After each deployment, extensive cleaning, battery replacement, and some repairs were required (**Figure 9**).

3.5 Ecoforecast Alerts

Examining daily maps for even one ROI in one map area would be overwhelming for researchers and managers. Artificial intelligence (AI) provides a way of reducing high-volume data streams to their most useful information. AI ecological forecasts or ecoforecasts allow for an automated daily assessment of near real-time environmental data for potential threats to marine ecosystem health (Hendee *et*

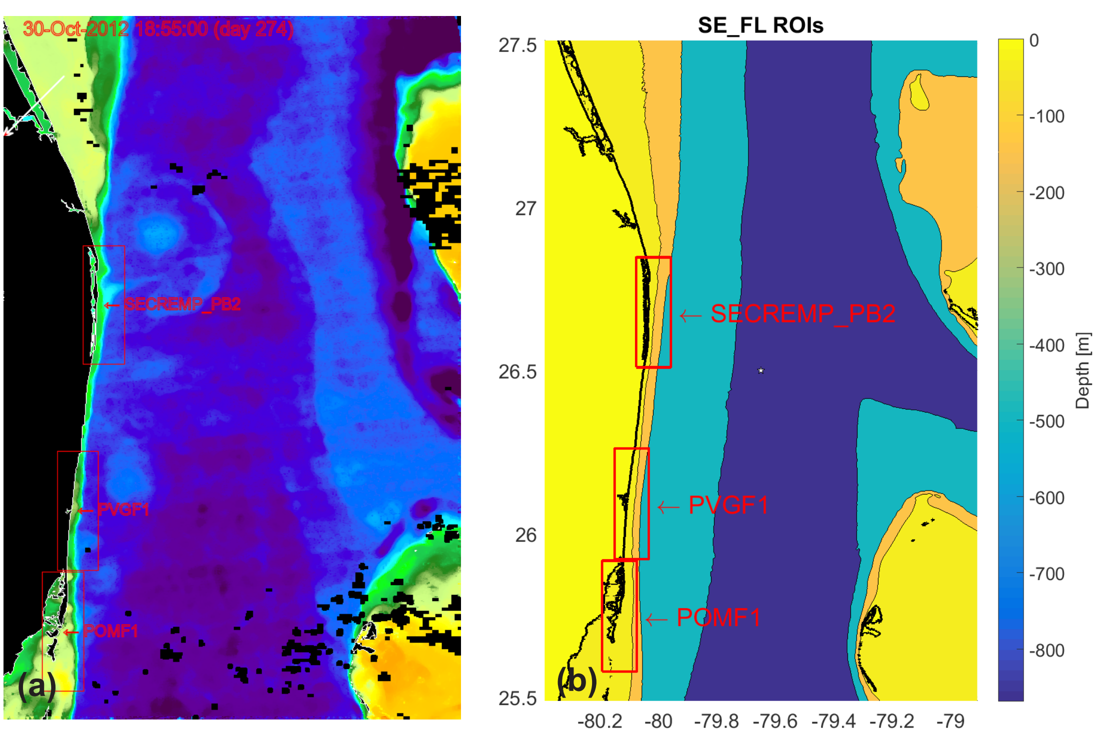


Figure 6. Southeast Florida map area for USF-OOL ocean color, with smaller ROIs marked in red. A portion of Florida's mainland appears along the left edge. (a) An actual CI map of southeast Florida from a clear day in October 2012, and (b) a map of bathymetry across the Straits of Florida from NOAA's National Geophysical Data Center showing depth contours at 30, 150, and 500 m.

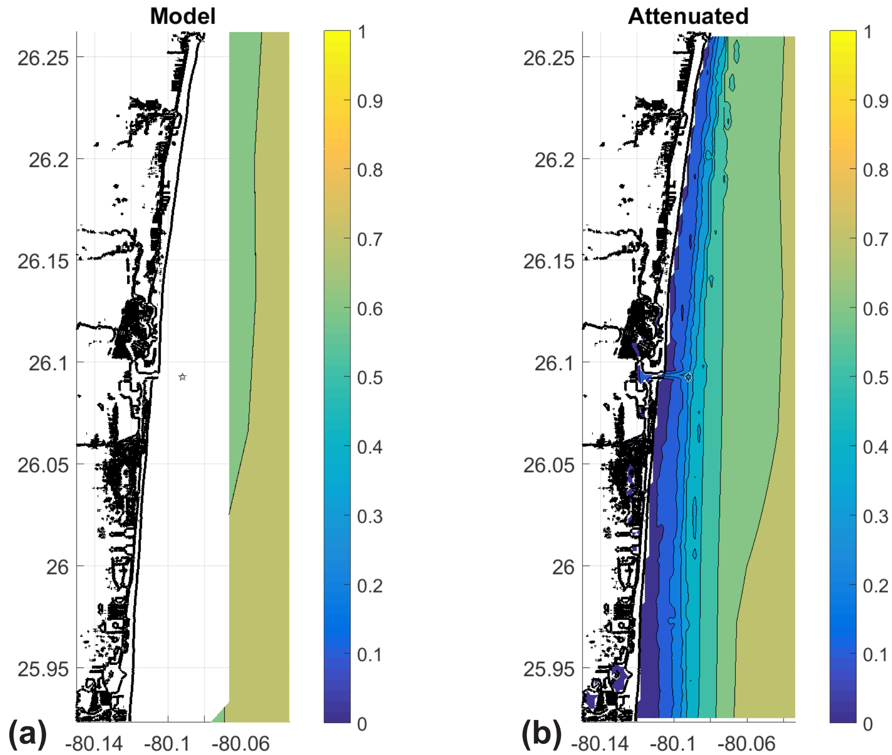


Figure 7. NOAA WaveWatch III modeled significant wave height in meters for the PVGFI ROI: (a) original operational model output; and (b) results of a simple depth-based wave attenuation technique.

Figure 8. (a) WETLabs C-STAR sensor housed in a deployment cage; (b) WETLabs C-STAR sensor ready for deployment.

Figure 9. WETLabs C-STAR sensor undergoes extensive cleaning after deployment due to environmental fouling.

al., 2009). They can integrate in situ, satellite, and model observations and evaluate these data using an AI technique known as an expert system—a set of "fuzzy logic" if-then rules that implement logical pattern-matching on the data stream (Gramer *et al.,* 2009). Ecoforecasts are thus able to monitor multiple criteria for ecosystem health simultaneously using a disparate range of observational data (**Figure 10**).

Expert system if-then rules are developed from:

- Known or hypothesized physical-ecological correlates
- Insight and experience of local experts
- Feedback from in-water observations over time

One challenge in monitoring turbidity impacts with remote sensing data is the uncertainty of attributing causes. A high relative-turbidity signal may appear to trace back to a land source but may still be the result of sediment resuspension due to wave breaking or a phytoplankton bloom due to unrelated causes such as upwelling. The use of the NTU absolute turbidity algorithm in a suite of other products that includes CI, ocean waves, chlorophyll-*a*, and sea surface temperature can reduce the uncertainty of attribution.

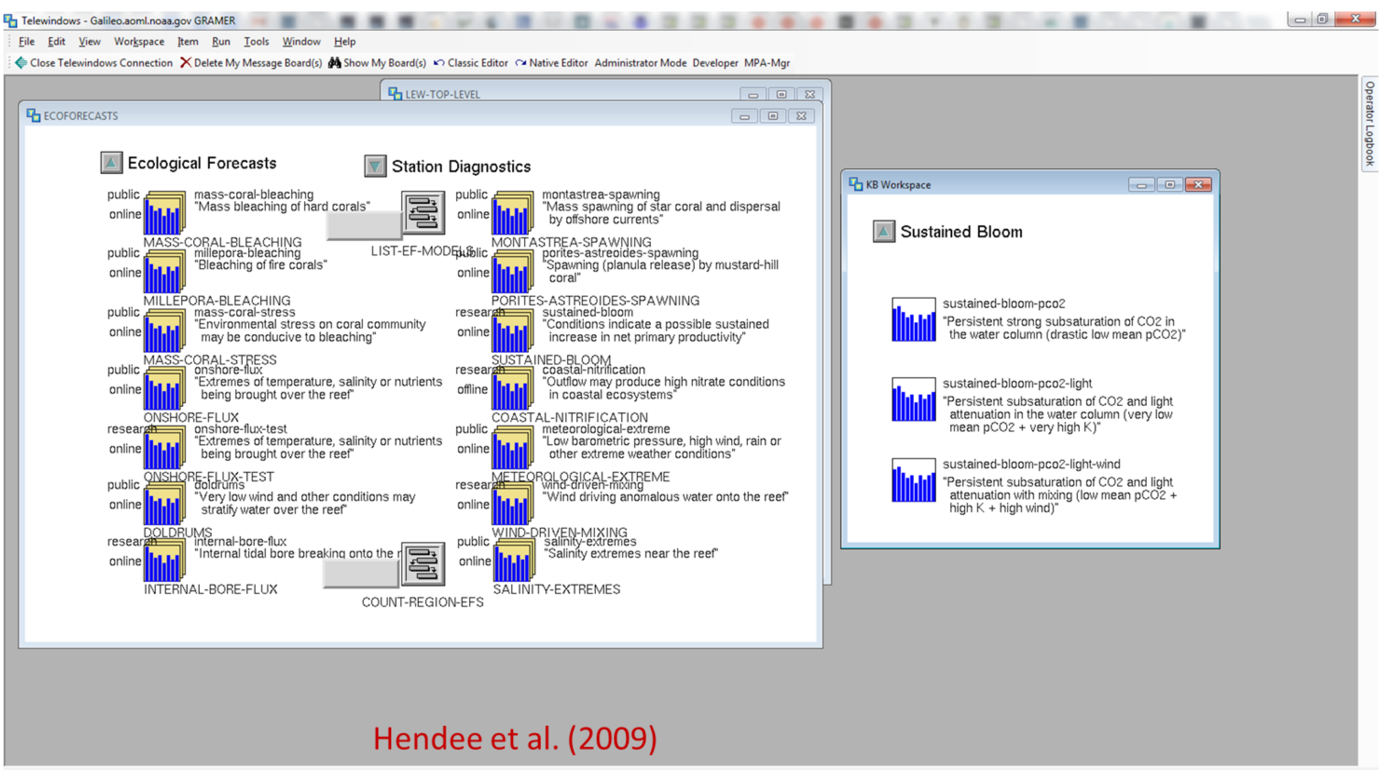


Figure 10. AI expert system development tool G2, a visual programming environment used by NOAA's Coral Health and Monitoring Program, to implement ecoforecasts for coral reefs and other marine ecosystems monitored for environmental data, including relative and absolute turbidity.

Ecoforecasts for events of enhanced relative turbidity likely corresponding to human activity were identified as days when any pixel-normalized CI pixel was above its 93rd percentile and when significant wave height was below its median. Extreme events were identified as days when the satellite CI was above its 99th percentile and significant wave height was below its 32nd percentile. Events for analysis and tracking were filtered to exclude those when less than 20 percent of the pixels in an ROI were clear or when days between clear pixels were greater than 1 week.

The expert system rules were applied to each synoptic (daily) satellite and wave field. To quantify both the severity and likelihood of an ecosystem response, we estimated a Stimulus/Response Index (S/RI), which assigned a value of 8 to a pixel if it met the above criteria for an event, and a value of 16 if it met the criteria for an extreme event. A mean Spatio-Temporal Stimulus/Response Index (STSRI) was then estimated from the sum of S/RIs for all valid CI pixels in a synoptic image.

4. Results

This section summarizes the results of the 3-year NOAA-CRCP project. First, we present summary statistics for the ocean color products spanning the 15-year period of analysis. Both regional maps and time series from individual virtual stations (monitored pixel groups) are summarized. Second, environmental data are analyzed that were expected to be correlated for the observed patterns of ocean color, in particular, ocean waves. Finally, the results of ecological forecasting for turbidity events are summarized for each ROI.

4.1 Ocean Color

4.1.1 Clear Pixel Days

Satellite ocean color depends on clear skies during a satellite overpass: the shallow waters of the three southeast Florida ROIs were remarkably consistent in clear-day overpasses during all four seasons. For the POMF1 ROI, USF's CI maps out to the second reef line showed fewer than 2.5 days between clear pixels. For the PVGF1 ROI, the average number of days between clear pixels was <2.5 days out to the second reef line, <3 days out to the third reef, and <6 days out to the 60-m isobath. For SECREMP_PB2, the average number of days between clear pixels was similar to the other two ROIs (**Figure 11**).

Offshore of the 60-m isobath, the October-December season was, on average, the most cloudy, but inshore of it the numbers above still applied to all three ROIs for all seasons. **Figure 12** presents a set of maps that summarizes the slight seasonality in the average number of days between good CI pixels for two of the three ROIs—PVGF1 and POMF1.

4.1.2 Virtual Station Time Series

Even once normalized, time series for individual pixels or pixel groups of 1 x 1 km size were difficult to interpret by themselves. One issue was that the intermittent presence of clouds or other bad-pixel flags made the time series irregular from pixel to pixel. Another issue was that weather in South Florida and similar subtropical and tropical regions often occurs at small, convective scales on the order of 10 km or less. Thus, on days when one pixel group was clear, nearby pixel groups may have been cloudy, making it difficult to relate time series at different pixel groups to one another even when they were quite close by (**Figure 13**).

4.1.3 Ocean Color Maps

MODIS satellite ocean color bands can be processed to produce images with a variety of information, as summarized by the maps in **Figure 14**. True color (left panel) was achieved using a blend of intensities from all visible-light color bands. In-water chlorophyll-*a* concentration (middle panel) was estimated from a few bands using an algorithm developed by Carder and refined by Hu and others (e.g., Le *et al.*, 2013). Finally, the CI used to estimate relative turbidity (right panel) was estimated from a different set of visible light channels measured by the MODIS instruments.

A great advantage of satellite ocean color is that changes in the scene between successive overpasses can be used to track the fates of material measured by an ocean color

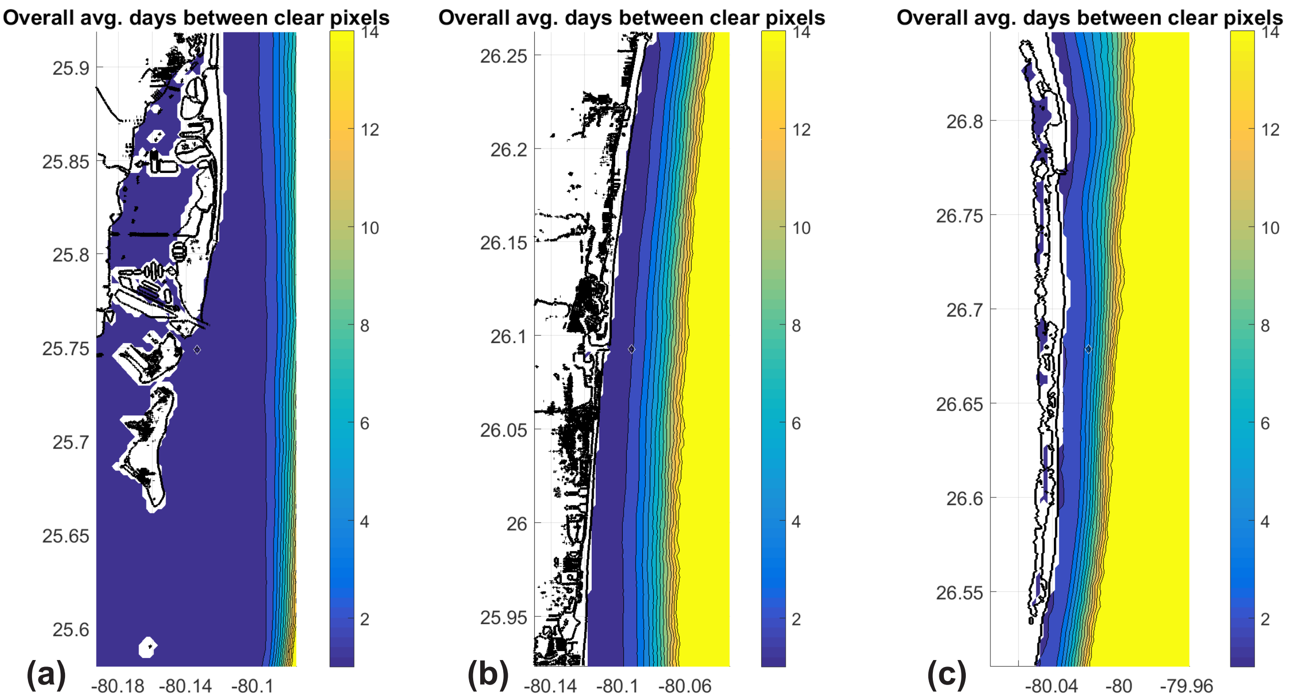


Figure 11. Maps showing the average number of days between good CI pixels, indicating clear day-time overpasses of the MODIS satellites, and color bands within acceptable ranges for the CI algorithm for each pixel in the three ROIs of southeast Florida: (a) POMF1; (b) PVGF1; and (c) SECREMP_PB2.

algorithm. The sequence of CI images in **Figure 15** shows a potentially useful example of this: a source of relative turbidity near the bottom of the map area (near the Port of Miami Channel) continues to produce turbid water which is advected into an offshore eddy that is translating northward through the Straits of Florida. An additional nearshore source of turbidity is also visible mid-scene to the north of the Port Everglades Channel.

4.1.4 Color Index Seasonality

Seasonality was apparent in monthly distributions of normalized values (see section 3. Methods above) of the MODIS CI at distinct 1 x 1 km pixel groups within southeast Florida (**Figure 16**). Peaks in both the median and variability occurred in November in the central pixel group of the northernmost Florida ROI, SECREMP_PB2 (**Figure 16c**). A November peak in the median was apparent in the central pixels of the other two ROIs as well, although both showed peaks in variability during other months, i.e., March at POMF1 (**Figure 16a**) and October at PVGF1 (**Figure 16b**). As will be seen below, some of the high median and increased variability values at these sites were directly attributable to enhanced wave action (and potentially to enhanced winds as well).

4.2 Environmental Correlations

The primary natural environmental correlate found for periods of high relative turbidity in the coastal waters of southeast Florida was ocean surface waves, propagating through the Straits of Florida, shoaling onto the shallow shelf, and ultimately breaking near shore. Modeled (WW3) significant wave heights offshore of South Florida were greatest (>0.7 m) during October-April (**Figure 17a,d**) but, near the second reef line at 20-m depth, estimated attenuated wave heights (see section 3. Methods) were only 0.4 m on average. In April-September at 20 m, attenuated waves were 0.3 m (**Figure 17b,c**).

The close relationship between these attenuated significant wave heights and the uncalibrated NTU is represented by data from one of the virtual stations, PVGF1, in **Figure 18**.

A statistical analysis (regression fit) of in situ wind from the meteorological monitoring station FWYF1 at Fowey

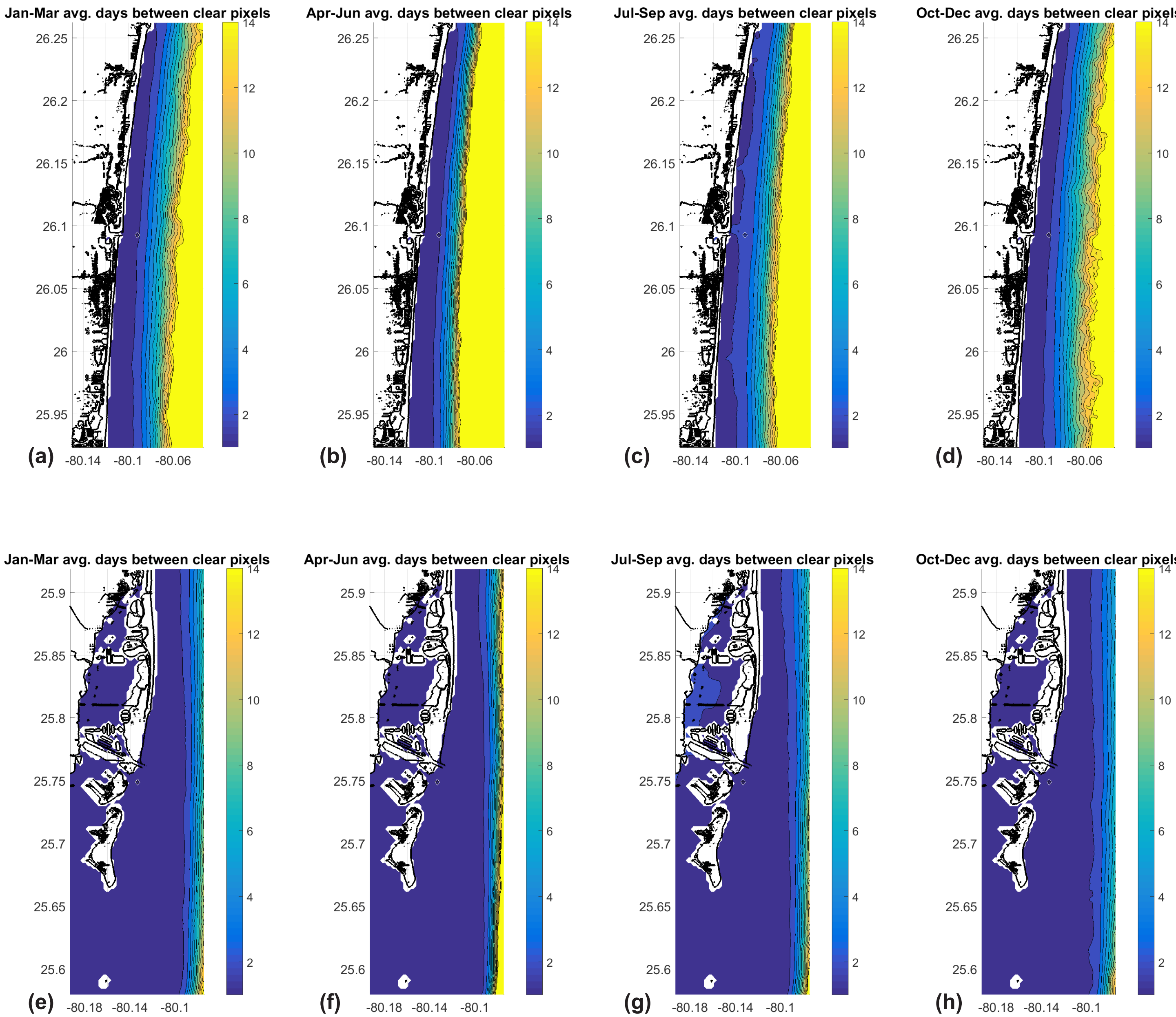


Figure 12. Maps showing the average number of days by season between good CI pixels for the PVGF1 ROI (a-d) and POMF1 ROI (e-h) for the period July 2002 to June 2017. (a,e) January-March; (b,f) April-June; (c,g) July-September; (d,h) October-December.

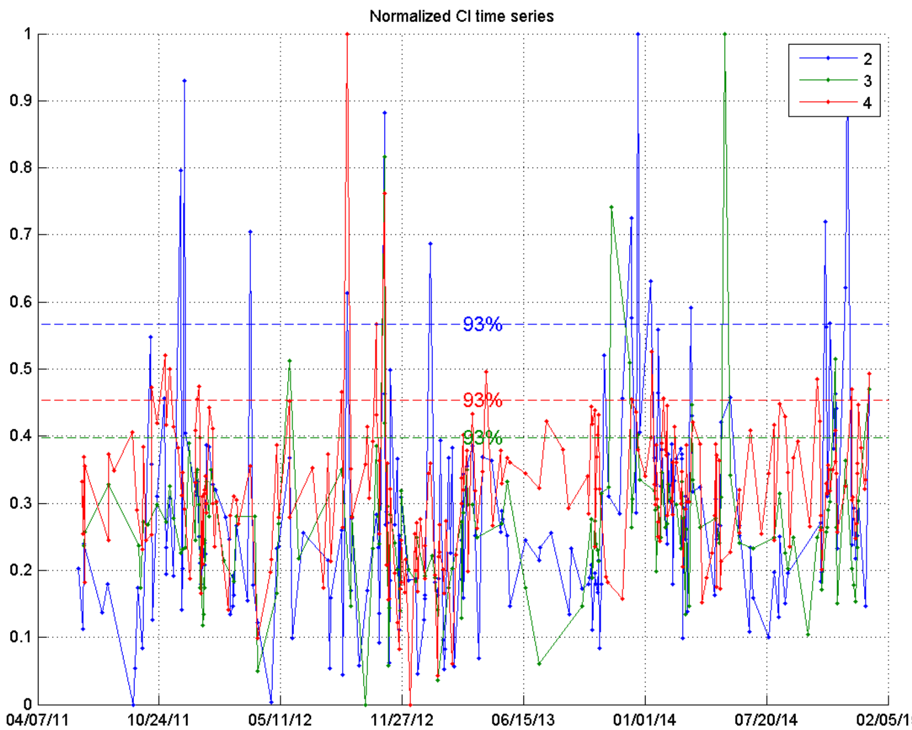


Figure 13. Normalized time series of relative turbidity, CI, for 2011-2015 at virtual stations 2-4 (see map in Figure 3 with 93rd percentile value marked for each).

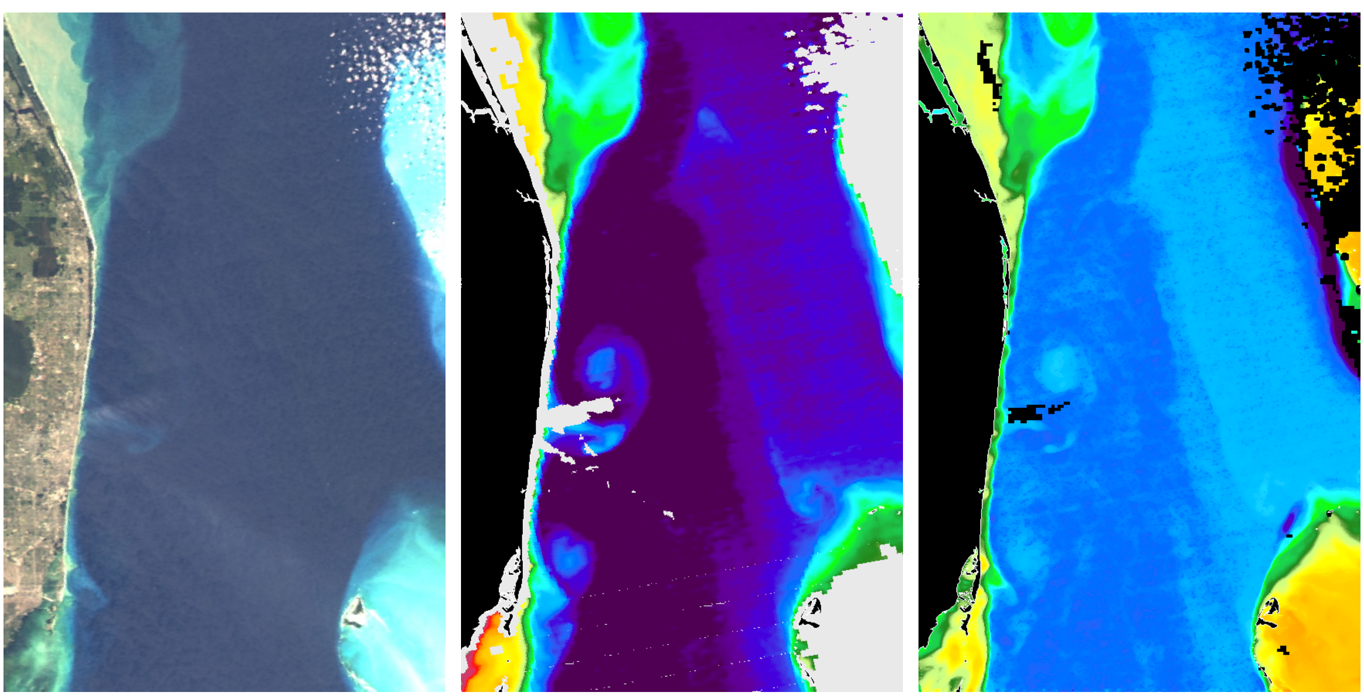


Figure 14. Maps showing the processing sequence from 250 m of true color (left), chorophyll-*a* (middle), and relative turbidity or CI (right).

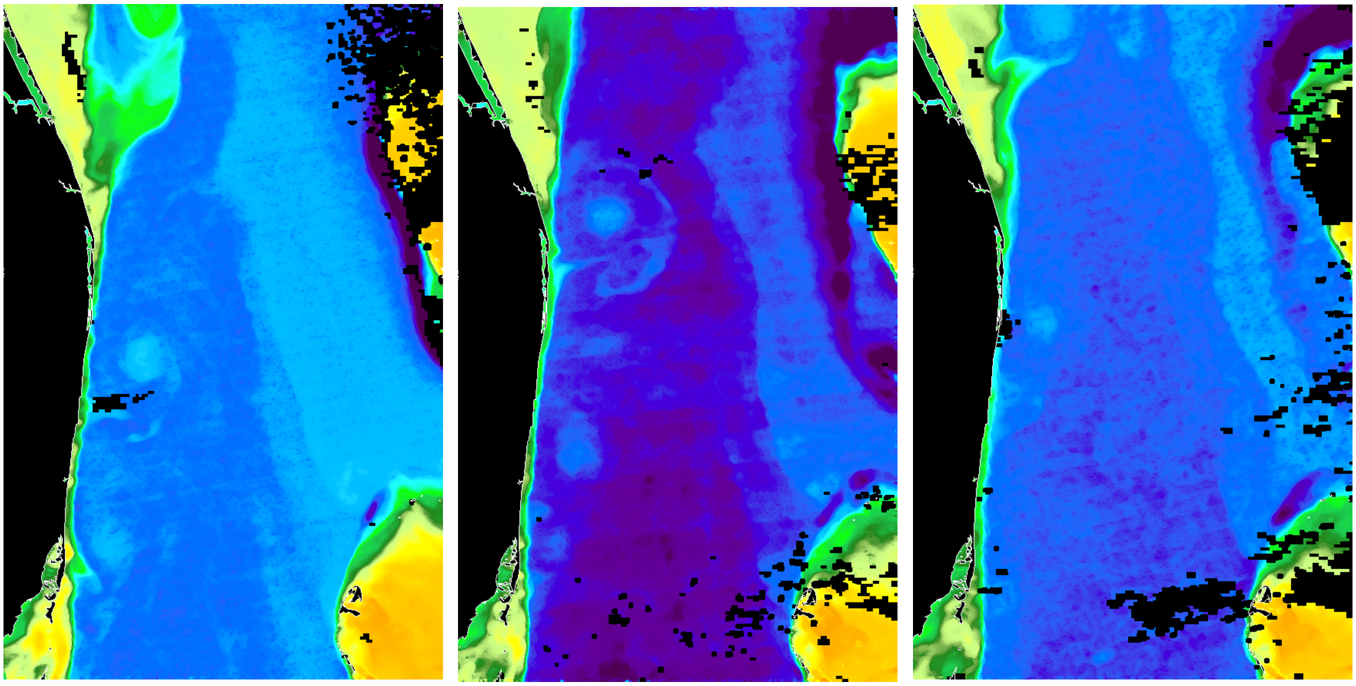


Figure 15. Time sequence showing turbidity plume dynamics offshore of Port Everglades on October 29-31, 2012.

Rocks, attenuated model wave heights, and the CI and uncalibrated NTU calculated pixel intensities for one nearby pixel group are shown in **Figure 19** for one of the analysis sites, site 2, which corresponds to the center of the Port of Miami ROI. These results are representative of the other sites analyzed in all three Florida ROIs. The regression showed a high correlation between CI and both wind and attenuated significant wave height (**Figures 19a** and **19b**). Wind was not found to be predictive as an independent variable: controlling for wave height, regression with wind was not significant.

Notably, an uncalibrated NTU time series was also calculated for the analysis at sites 1-4 by academic partners at USF-OOL. The time series shown did not directly correspond to nephelometric turbidity units as defined by the EPA, as it had not yet been calibrated with in-water turbidity measurements at the time of this report. However, this uncalibrated NTU value nonetheless showed statistical independence from both wind and wave height (**Figures 19c** and **19d**). This suggests that (calibrated) NTU time series for individual monitored pixel groups such as those for POMF1, PVGF1, and SECREMP_PB2 may prove useful as a basis for ecological forecasts independent of natural environmental correlates.

4.3 In situ Measurements

For the present study, in-water measurements from the NOAA-FACE project provided valuable validation data for the relative turbidity products (**Figures 20** and **21**). These, together with new measurements, will be used to calibrate the absolute turbidity satellite products as part of a future project.

4.4 Ecoforecasts

4.4.1 Port of Miami

Between February 2005 and May 2017 for the POMF1 ROI, 1308 days (overpasses) of enhanced turbidity were noted in at least one pixel, 508 of them without high waves. Of these 508, 19 met the criteria for an extreme event. Day pixels with enhanced relative turbidity were more common to the north of and immediately offshore of the Port of Miami Channel (10-55 days) than to the south (<20 days within 15 km of the channel). As for PVGF1, event pixels to the north of POMF1 were nearer shore than those to the south. Unlike Port Everglades, there was a clustering of extreme event pixels about 18 km to the south of POMF1 and 4-6 km offshore, with more than 100 days of enhanced turbidity (**Figure 22**).

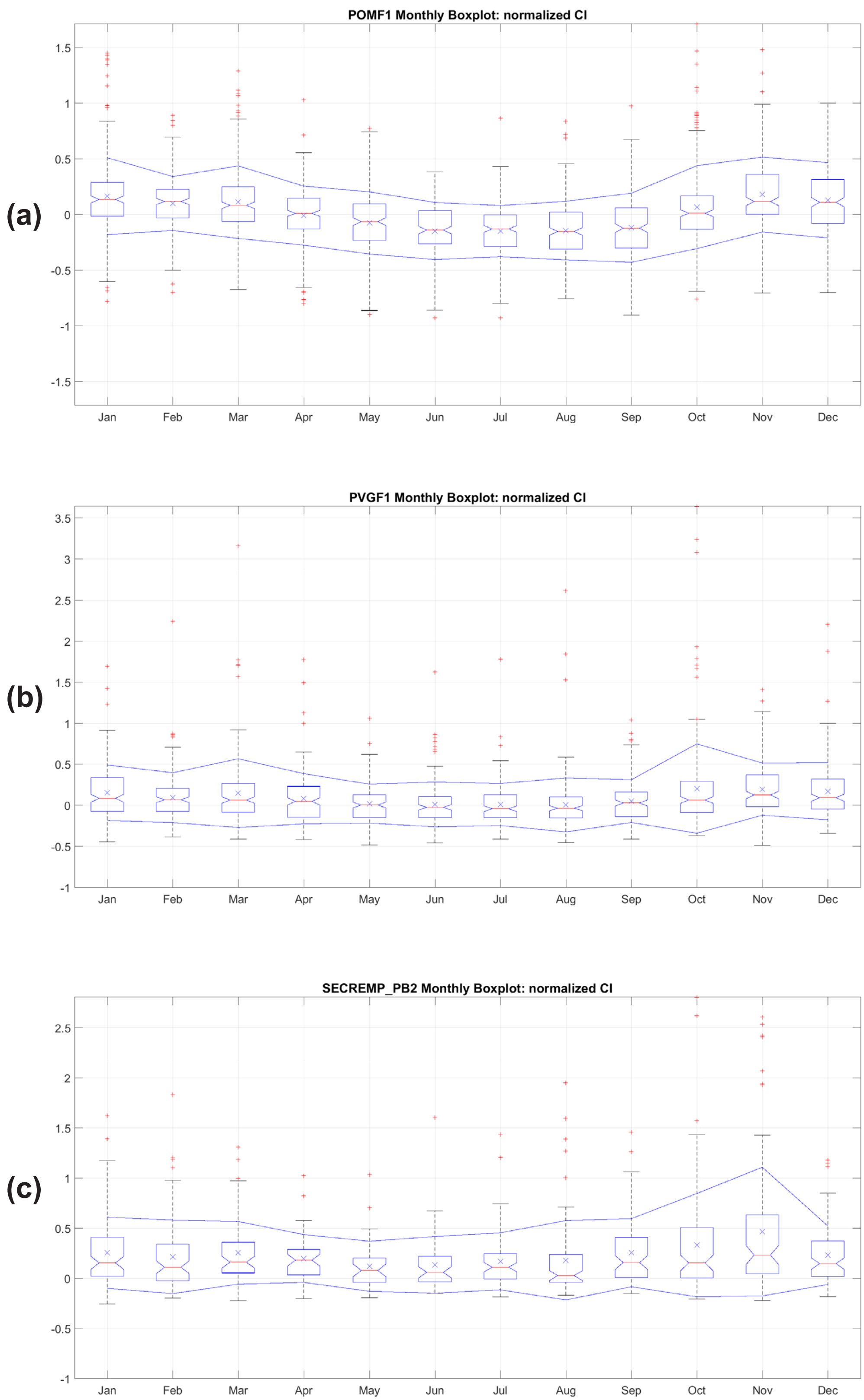


Figure 16. Seasonality of normalized relative turbidity (norm CI) for one 1 x 1 km manually selected pixel group offshore of (a) the Port of Miami, (b) Port Everglades, and (c) the region around SECREMP_PB2 offshore of Palm Beach County (see maps in Figure 6 for locations of individual 1 x 1 km pixel groups marked by red arrows).

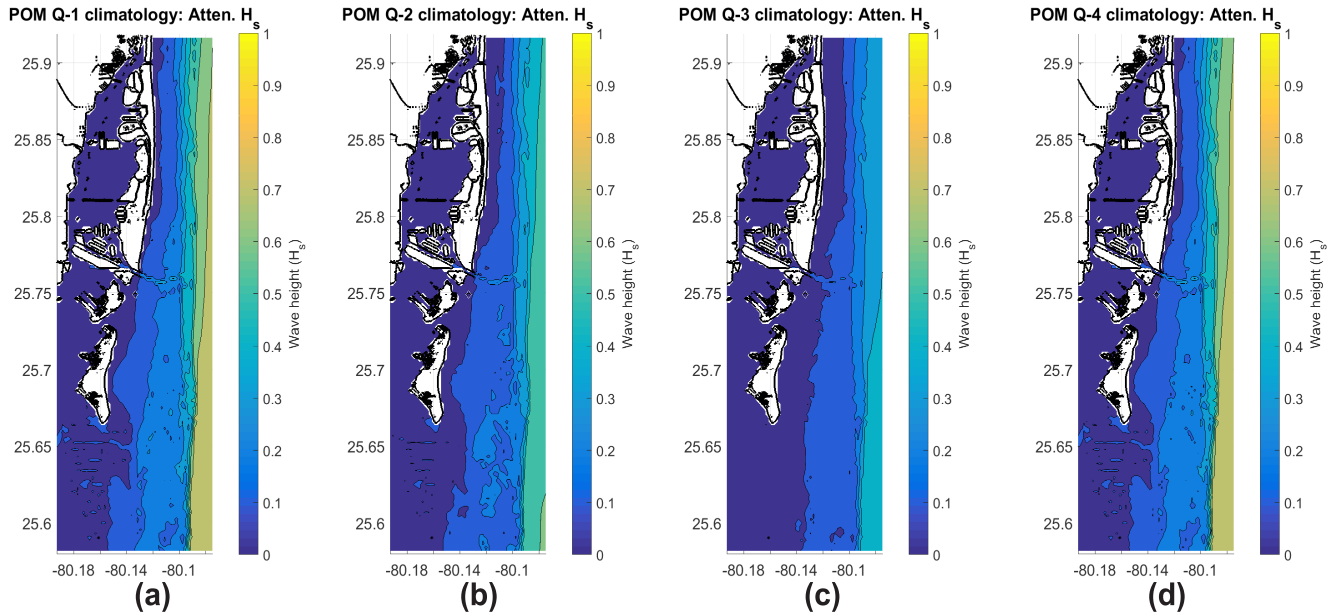


Figure 17. Seasonal climatology of significant wave heights for the POMF1 ROI during the years 2005-2017 and for the months (a) January-March, (b) April-June, (c) July-September, and (d) October -December.

For the POMF1 ROI, both events and extreme events were distributed evenly throughout the year. This is shown in the STSRI monthly values of **Figure 23**.

The most widespread events of the past 5 years near POMF1 occurred in January, April-June, July, August-September, November, and December 2012; March, May, June, 27 September to 2 November, and 2-4 December 2013; February, May, and June 2014; January, August, and December 2015; June-September 2016, and especially December 2016-March 2017 (see **Figure 24**).

Note that “widespread” denotes events with the greatest percentage of clear pixels, which are not necessarily those with the highest STSRI. Raw (non-normalized) ROI satellite CI images of some of these events follow (**Figure 25**). In the upper left corner of each is an arrow showing the direction and attenuated wave height (scale 2.5 cm per m of wave height) of modeled waves at the center of that ROI on the day of the satellite overpass.

Table 1 presents a list of the dates with the highest STSRI during the past 5 years for the POMF1 ROI when skies in the region were clear enough to discern likely spatial relationships between plumes and inshore waters. Dates denoted in bold were particularly persistent or widespread; those in parentheses were dates that, despite all the filters applied, were potentially confounded by persistent cloud cover. Normalized CI data fields for some these dates are shown in **Figure 26**.

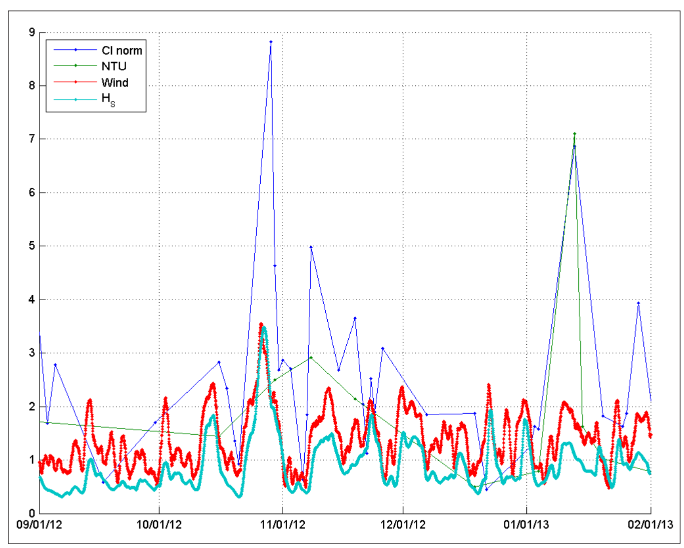


Figure 18. Comparison of time series from satellite relative humidity (CI), an uncalibrated processing algorithm for absolute turbidity (NTU), and low-pass filtered in situ wind speed and attenuated model significant wave heights from site PVGF1.

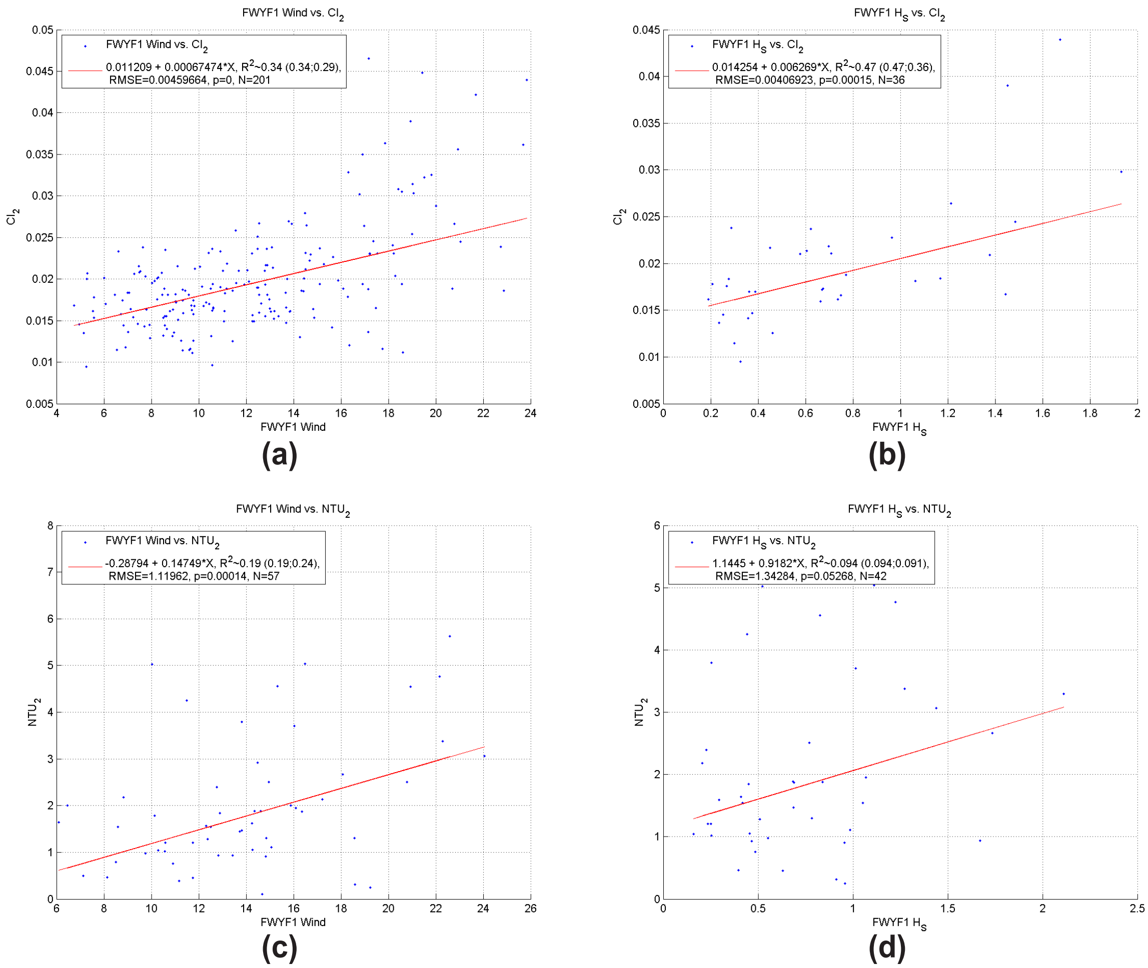


Figure 19. Scatter plots comparing (a,b) relative (CI) and (c,d) uncalibrated absolute turbidity (NTU) for site 2 (see map in Figure 3) to daily averages of (a,c) in situ wind speed (U, knots) and (b,d) significant wave height (H, m) from NOAA's WaveWatch III operational model attenuated with National Geophysical Data Center bathymetry.

4.4.2 Port Everglades

Between February 2005 and May 2017 for the PVGF1 ROI, 729 days (overpasses) of enhanced turbidity were identified in at least 91 pixels, 258 of which did not correspond with high waves. Of these, 19 days were identified as extreme events. Day pixels during these 12 years showed that enhanced relative turbidity were somewhat greater (45-75 days per pixel) to the north of Port Everglades Channel than to the south (20-60); events to the north of the channel also showed a greater tendency to cluster within and across the first reef line, while events to the south of the channel were, on average, 1 km farther offshore (**Figure 27**).

For PVGF1, events occurred with roughly the same frequency during each of the 12 months of the year (see **Figure 28**), while extreme events were concentrated in a few months of the year with extrema represented by red + signs in **Figure 28** and by peak S/RI in the time series (**Figure 29**).

The most widespread events of the past 5 years near PVGF1 occurred in January, April, and September-October 2012; July and October 2013; January, August, and November 2015; and May 2016 and December 2016-January 2017 (**Figure 29**). **Figure 30** presents a sample image at high resolution from one of the widespread event days, January 5, 2012.

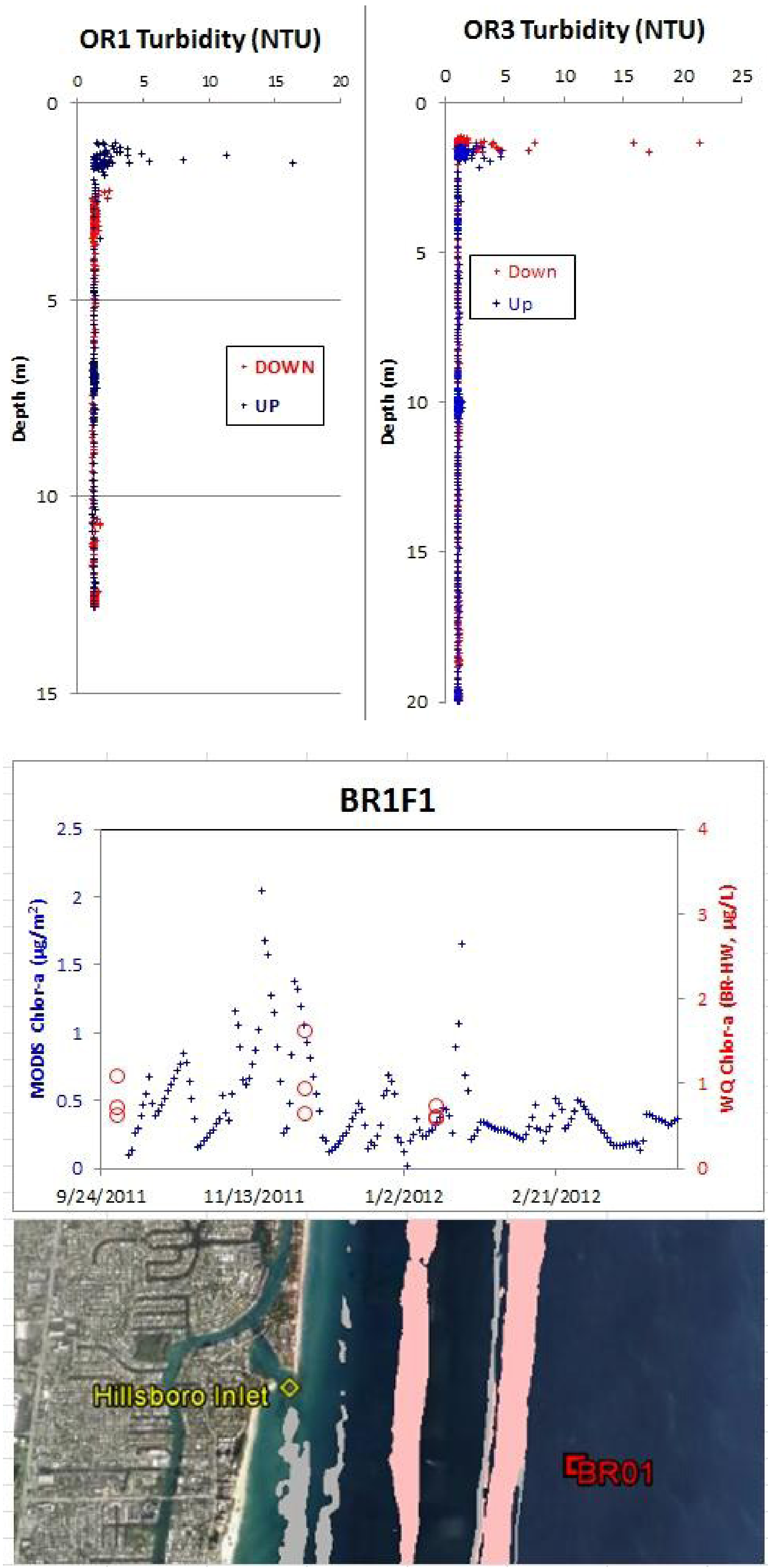


Figure 20. In-water turbidity measurements from a FACE cruise, with remote sensing algorithm comparisons.

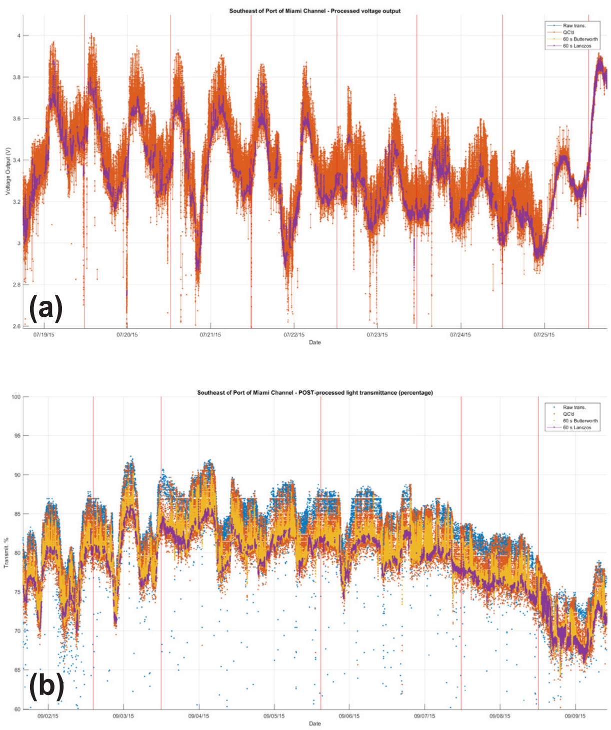


Figure 21. In-water turbidity measurements taken as part of this project at site POMF1 on (a) 18-26 July 2015 and (b) 1-9 September 2015. Dates and times of clear-sky MODIS satellite overpasses are maked with red lines.

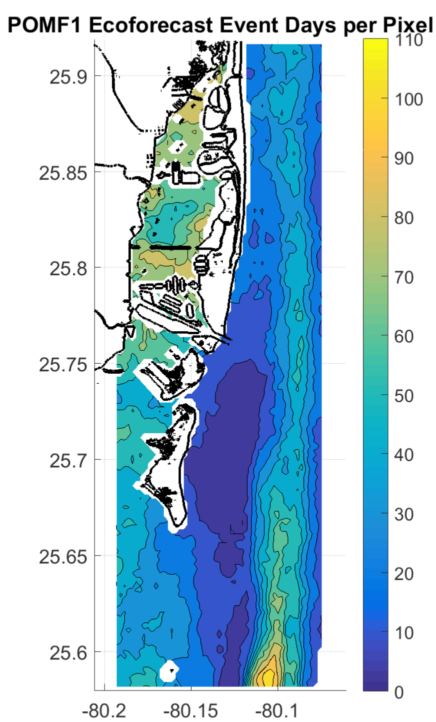


Figure 22. Number of days within each pixel when the CI and wave criteria were met for the POMF1 ROI, 2002-2017.

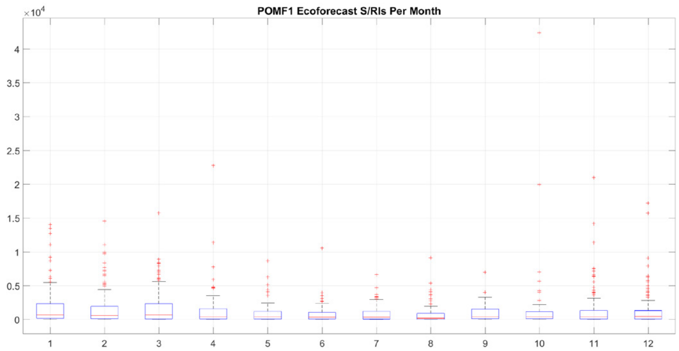


Figure 23. Actual percentage of possible Spatio-Temporal Stimulus/Response Indices within the POMF1 ROI by month, 2002-2017.

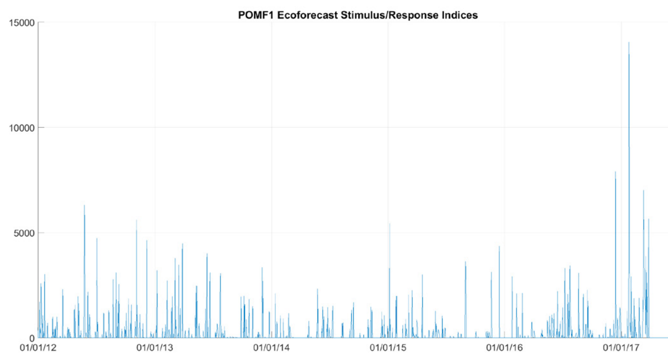
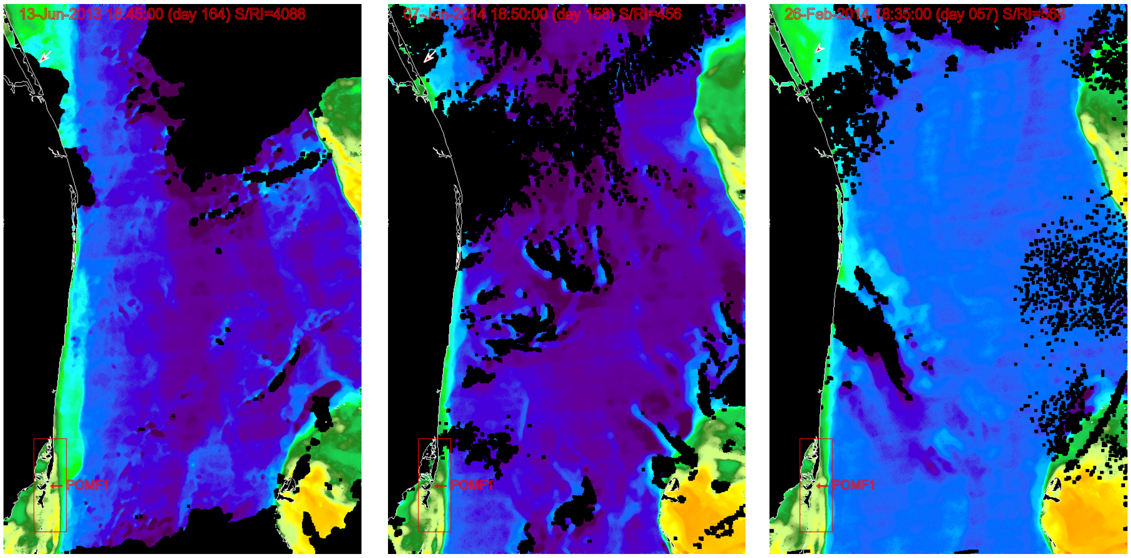


Figure 24. Time series of total S/RIs within the POMF1 ROI (all pixels) between January 2012 and May 2017.

Table 1. Highest STSRI among dates with good spatial coverage in the Port of Miami ROI.

Year	Dates
2012	Jan 21, Feb 15, Feb 22, Feb 24, Jul 03, Sep 05, Sep 12, Oct 31, Nov 04, Nov 08, Nov 15, Nov 24, Dec 06
2013	Feb 03, Feb 08, Mar 05, Mar 07, Mar 16, Mar 28, Apr 17, May 08, May 19, Jun 13, (Jul 29), Dec 06, Dec 09-10, Dec 20-21
2014	Feb 06, **Feb 26**, Aug 26, Oct 25, Nov 11, Nov 30
2015	**Jan 05, Jan 07**, Mar 10, Mar 14, Mar 19, (May 08), **May 20**, (Jun 07), Jun 28, **Aug 31**, (Nov 08), (Dec 21)
2016	May 20, (Jul 28), **Jul 30**, **Aug 22**, Nov 26, Dec 13
2017	(Jan 08), Feb 26, Mar 10, (Mar 29), Mar 31, **May 05**, May 12



(a) (b) (c)

Figure 25. Satellite CI images of the southeast Florida region, highlighting three relatively clear, high STSRI days in the POMF1 ROI (red): (a) June 13, 2013; (b) January 27, 2014; and (c) February 26, 2014. Pixels likely to be cloud-covered are shown in black.

Table 2 shows the dates with the highest STSRIs in the PVGF1 ROI when skies in the region were clear enough to discern likely spatial relationships between plumes and inshore waters. Again, dates denoted in bold were the most widespread and/or persistent: Normalized CI data fields for some these dates are shown in **Figure 31**.

4.4.3 Palm Beach

A final ROI for southeast Florida was selected offshore of Palm Beach County to monitor the potential turbidity associated with beach renourishment projects and coastal construction ashore in that region. Between February 2005 and May 2017 for the SECREMP_PB2 ROI, 653 days (overpasses) of enhanced turbidity were identified in at least one pixel, 257 of which did not correspond with high waves. Of these 257 days, 13 were identified as extreme events. The geographic distribution of day pixels during these 12 years that showed enhanced relative turbidity was somewhat greater in the southern half of the Palm Beach ROI (**Figure 32**). Unlike in the other two ROIs, Palm Beach showed a greater number of events in the months of Nov-Jan (**Figure 33**), and relatively greater event S/RIs throughout the years 2012 and 2013, and during the winter of 2016-2017 (**Figure 34**). Normalized CI data fields for a selection of high S/RI dates are shown in **Figure 35**.

5. Conclusions

High relative turbidity events across the three ROIs in southeast Florida waters for the years 2012-2017 are summarized in this report. It should be emphasized that the absence of events during a particular period does not necessarily imply that waters were not turbid in that region; a series of cloudy days could equally well explain that. The opposite, however, is not true: where turbidity was shown in these dates and figures, it was occurring in these waters and did not appear to coincide with any significant wind or wave breaking that might explain it.

Table 2. Highest STSRI among dates with good spatial coverage in the Port Everglades ROI.

Year	Dates
2012	Jan 18, Apr 01, **May 05**, May 25, (Aug 09), Aug 31, (Oct 04), Oct 05, **Dec 20**
2013	Jan 07, (Feb 24), (Jun 18), **Jun 22**, Oct 06
2014	**Jan 12**
2015	Jan 05, **Mar 06**, **Apr 16**, Apr 18, **May 20**, **Jun 21,** (Aug 31)
2016	Mar 26, May 23, (Jun 01), **Jul 26**, **Dec 14**
2017	May 12, **May 28**

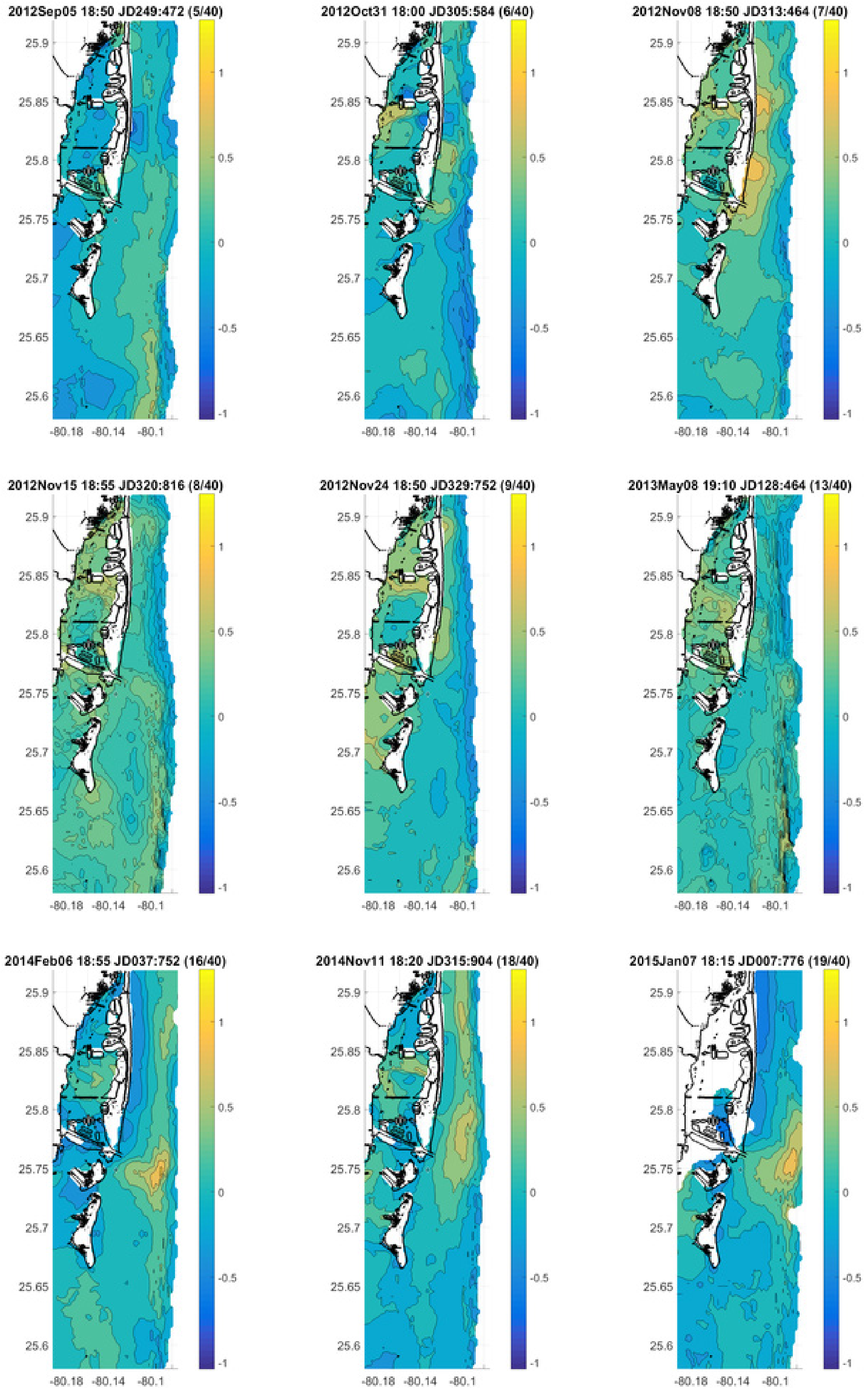


Figure 26. Panels showing normalized CI fields for individual satellite overpasses with very high STSRI values (high normalized CI and low-to-moderate waves) in the POMF1 ROI. This is a subset of the dates in Table 1.

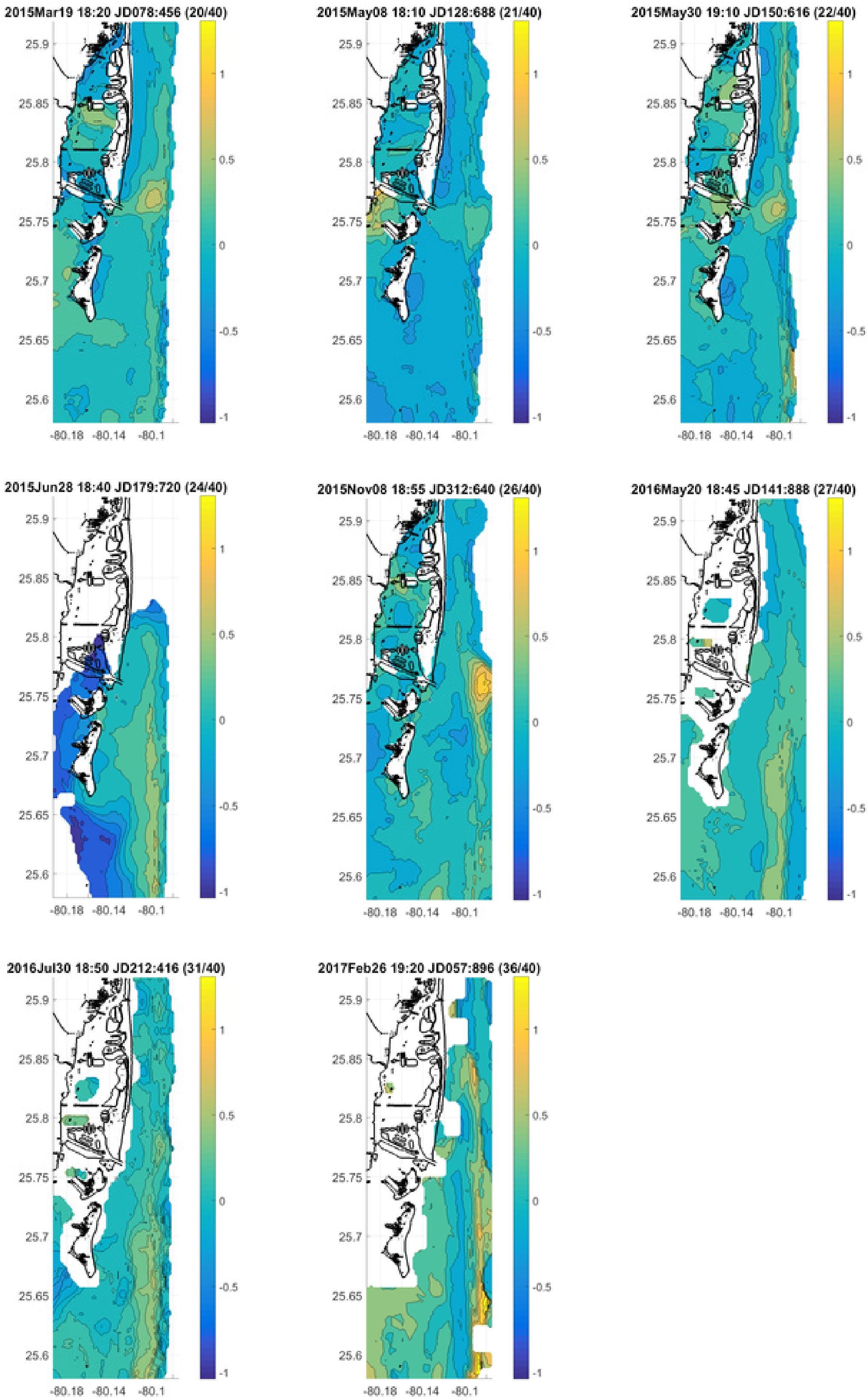


Figure 26 (continued).

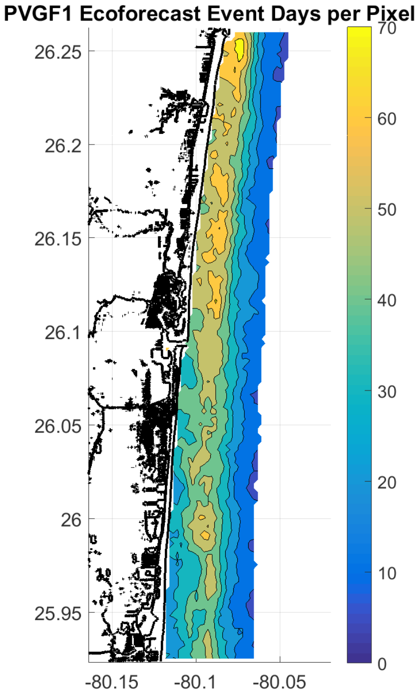


Figure 27. Number of days within each pixel when the CI and wave criteria were met for the PVGF1 ROI by month, 2002-2017.

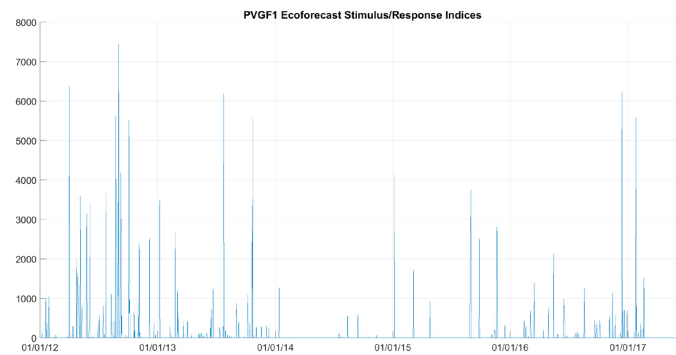


Figure 29. Time series of total S/RIs within the PVGF1 ROI, 2012-2017.

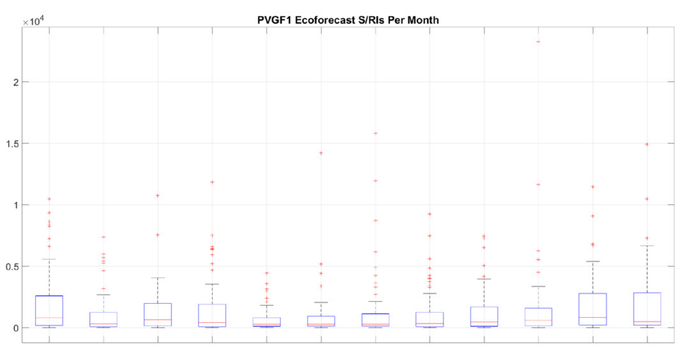


Figure 28. Actual percentage of possible Spatio-Temporal Stimulus/Response Indices within the PVGF1 ROI by month, 2002-2017.

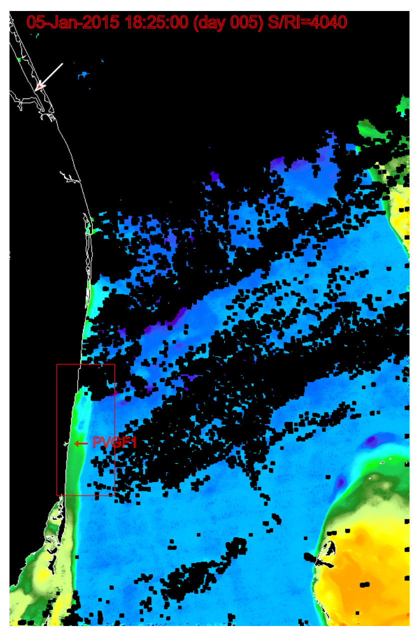


Figure 30. Satellite CI image of the southeast Florida region showing a high STSRI day in the PVGF1 ROI.

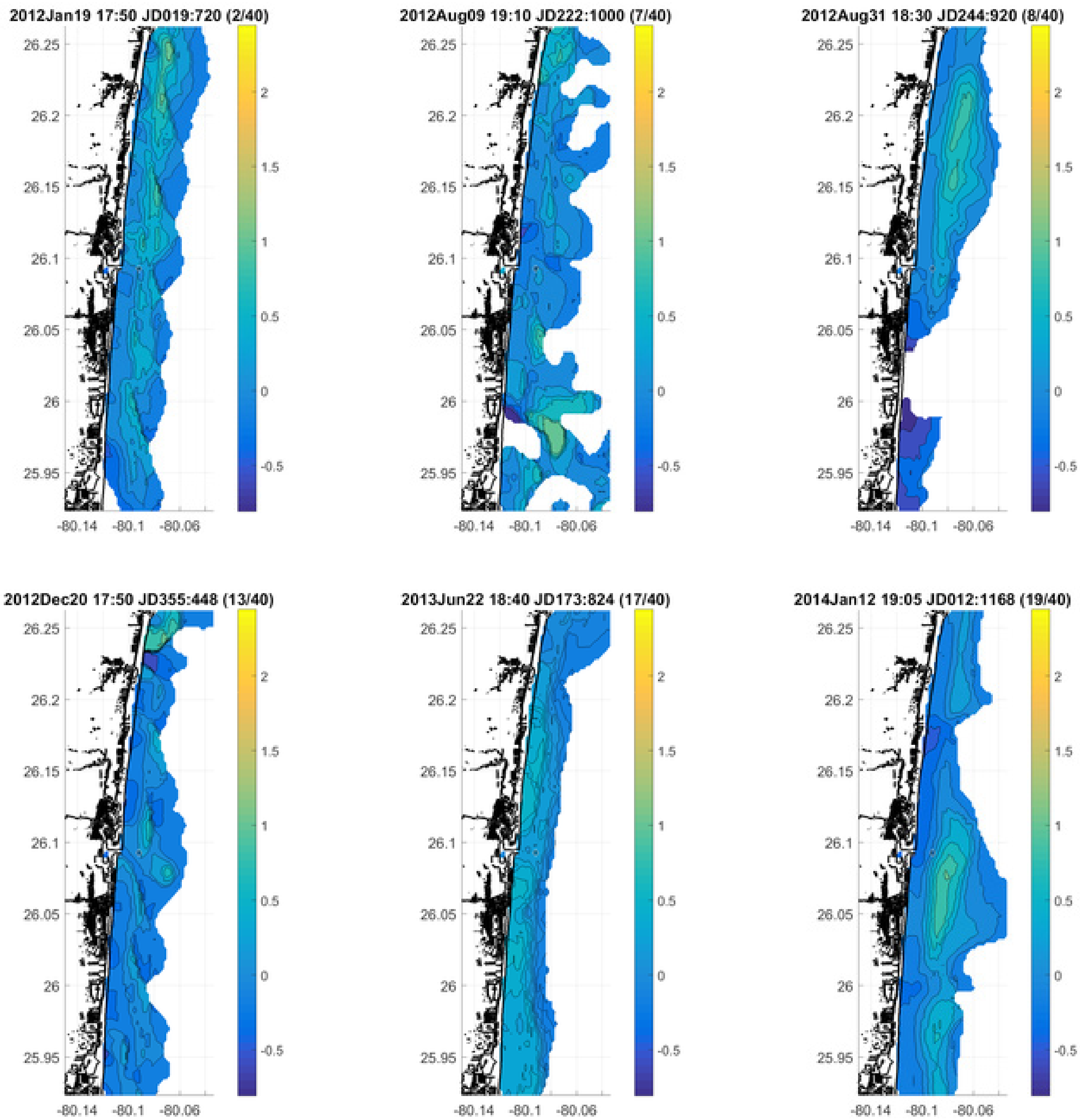


Figure 31. Panels showing normalized CI fields for individual satellite overpasses with very high STSRI values (high normalized CI and low-to-moderate waves) in the PVGF1 ROI. This is a subset of the dates in Table 2.

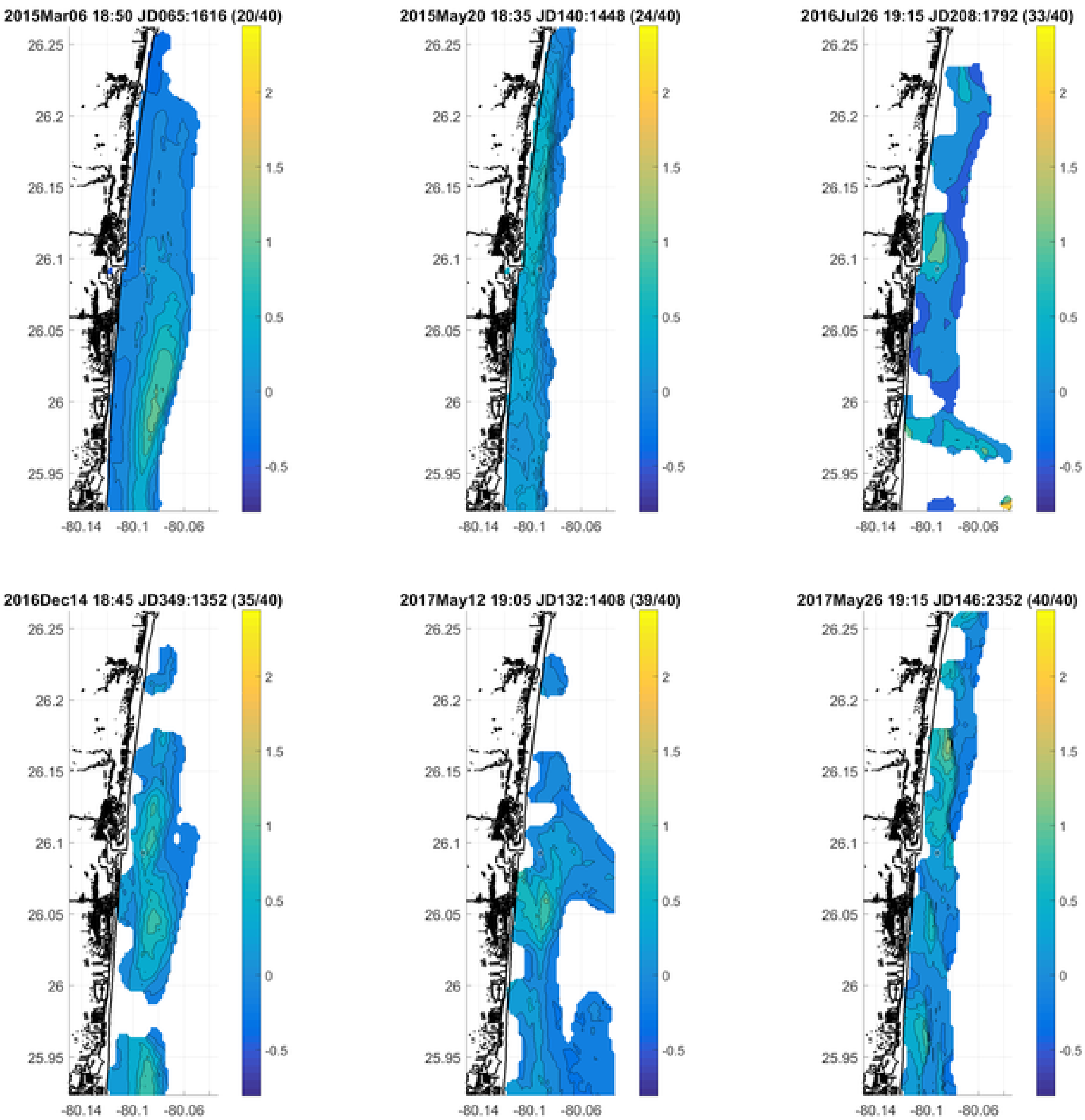


Figure 31 (continued).

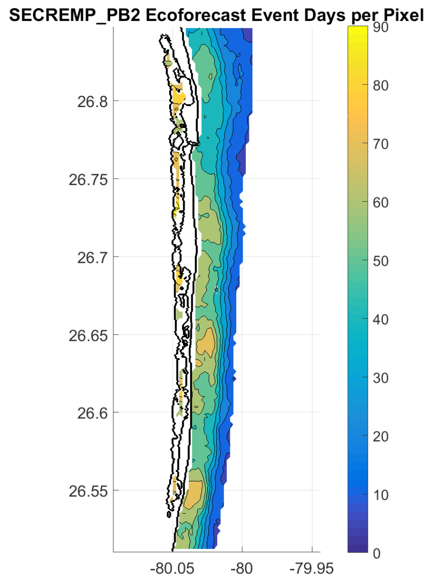


Figure 32. Number of days within each pixel when the CI and wave criteria were met for the SECREMP_PB2 ROI, 2002-2017.

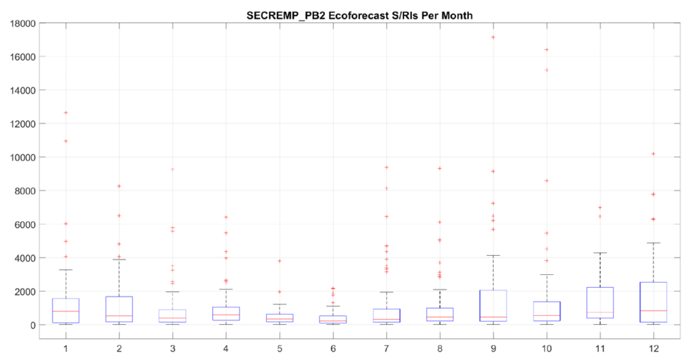


Figure 33. Actual percentage of possible Spatio-Temporal Stimulus/Response Indices within the SECREMP_PB2 ROI by month, 2002-2017.

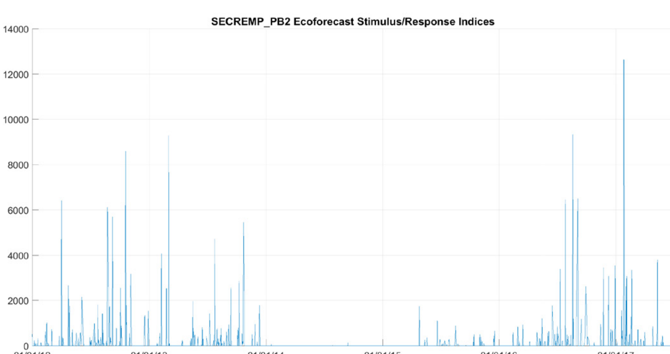


Figure 34. Time series of total S/RIs in the SECREMP_PB2 ROI, 2012-2017.

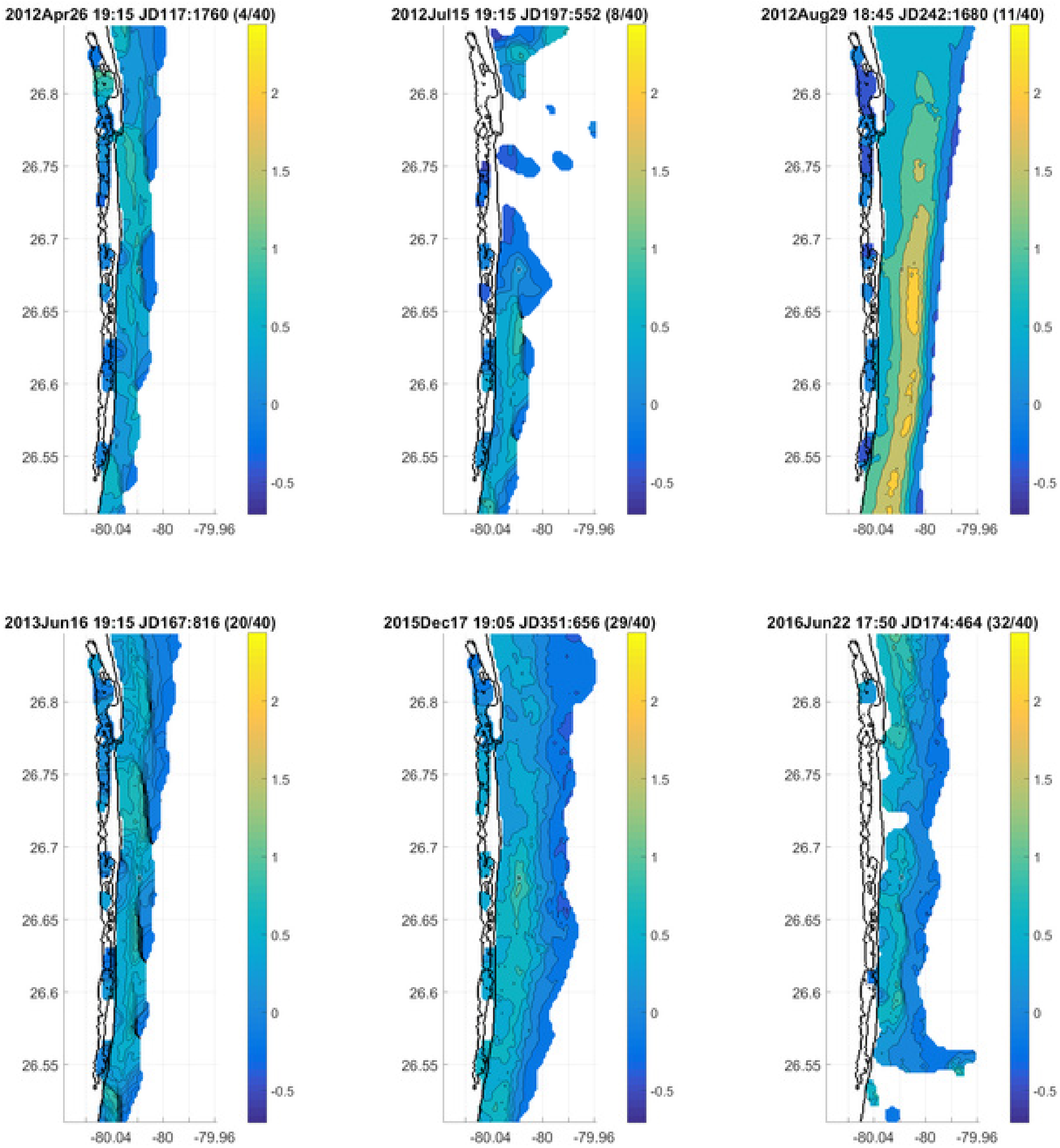


Figure 35. Panels showing normalized CI fields for individual satellite overpasses with very high STSRI values (high normalized CI and low-to-moderate waves) in the SECREMP_PB2, the Palm Beach ROI.

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