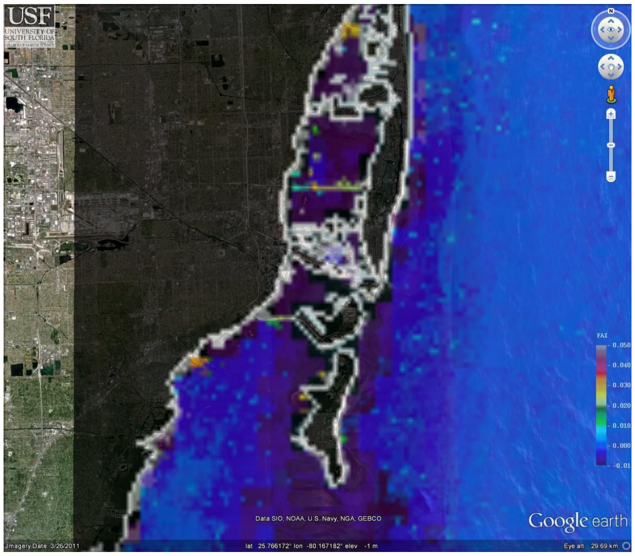

NOAA TECHNICAL MEMORANDUM

COASTAL TURBIDITY ON THE SOUTHEAST FLORIDA SHELF

Monitoring turbid water sources and fates by satellite

Abstract

The NOAA 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 SE Florida shelf and northern Florida reef tract (FRT). 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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2017

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Collaborators

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Introduction

Turbidity can have a significant impact on coral reef ecosystems, through light limitation, sedimentation, and eutrophication (e.g., Bessell-Browne et al. 2017). Florida Dept. of Environmental Protection (FDEP) made as a priority in their 2004 Local Action Strategy (LAS; FDEP 2004), to determine the tracks and fates of turbidity in the waters of the northern Florida reef tract (FRT). National Oceanic and Atmospheric Administration's Coral Reef Conservation Program (NOAA - CRCP) funded a collaborative project in 2013-2015 (Project #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 and coastal inlets and oceanic wastewater outfalls (Staley et al. 2017), and other human activities such as dredging (e.g., Wang and Beck 2017). Because of the complexity both of potential sources and of 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. 2012).

NOAA CRCP Project #881 was funded to provide managers with historical maps of turbidity, and alerts and maps for near real-time tracking of turbidity plumes, in coastal waters of three CRCP priority jurisdictions: American Samoa (including Faga'alu), CNMI, and south Florida (including reefs offshore of projects for port/tunnel expansion and beach refurbishment in three Counties). Academic partners (USF) in collaboration with AOML began back-processing and analyzing remote-sensing data in 2013 to produce maps of "relative turbidity", an indicator of change in available light, for the three target regions. These relative turbidity or "Color Index" (CI) maps are gathered via MODIS ocean color instruments on two polar-orbiting satellites at 250 m spatial resolution. Maps have been produced for analysis from July 2002 to the present, and new maps are made available to management partners in all three jurisdictions in near real-time via public Web site.

In-water data from three past AOML projects have been processed and quality controlled in collaboration with project participants from NOAA-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 is to refine remote sensing ocean color products to provide an approximation of absolute turbidity ("NTU"). In situ data have been processed and are being furnished to academic partners for one region (Florida) to begin calibration of absolute turbidity products from the available remote sensing data.

Key points

- For each of the three jurisdictions (south Florida, American Samoa, and CNMI/Saipan), academic partners (USF-OOL) set up satellite CI maps. The Southeast Florida Shelf "SE_FL" satellite map spans from 25.5 to 27.5 N latitude, 80.3 to 79.0 W longitude. (There is a similar map region for the Florida Keys, which is not analyzed as a part of this project.)
- Within each CI map area, smaller Regions of Interest (ROIs) were selected and analyzed through time. Within the "SE_FL" map area, three ROIs were selected, each 17-by-6 km: Port of Miami ROI "POMF1" centered on 25.74897,-80.13317; Port Everglades ROI "PVGF1" centered on 26.09300,-80.09200; and the ROI for Palm Beach renourishment projects and SECREMP monitoring, "SECREMP_PB2" centered on 26.67875,-80.01832.
- Satellite ocean color depends on clear skies during a satellite overpass: the shallow waters of the three SE_FL 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, average days between clear pixels were <2.5 d out to the second reef line, <3 d out to the third reef, and <6 d out to the 60 m isobath. For SECREMP_PB2, average days between clear pixels were 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 three-hourly significant wave heights backcast by the NOAA WaveWatch III (WW3) operational products. In order to apply these products to shallow reef shelves, a simple attenuation model was applied based on coastal bathymetry, so that significant wave height reaches 0.0 m at the beach. Wave attenuation for south Florida was done using 30 m horizontal resolution NOAA-NGDC/USGS bathymetry. Winds from in situ monitoring stations and reanalysis fields (ECMWF ERA-Interim) were also considered, but were not found to be significant to the analysis.
- 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 median. "Extreme events" were identified when 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% of the non-land pixels in an ROI were clear, or when days between clear pixels were greater than one week.
- Between Feb 2005 and Feb 2017, for Port Everglades 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 greater a tendency to cluster within and across the first reef line, while events to the south of the Channel were on average 1 km further offshore.
- Between Feb 2005 and Feb 2017, for Port of Miami 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 Port of Miami Channel (10-55 days) than to the south (<20 days within 15 km of the Channel). Like PVGF1 above, 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, 4-6 km offshore, with more than 100 days of enhanced turbidity.

- For PVGF1, both events and extreme events occurred with roughly the same frequency during each of the twelve months of the year. The most widespread events of the past five years near PVGF1 occurred in April and September-October 2012; July and October 2013; January, August, and November 2015; and May 2016 and December 2016-January 2017.
- For Port of Miami ROI POMF1, 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 five 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.

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 are 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 for MODIS ocean color data at USF-OOL has now 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 (USF) in collaboration with AOML began back-processing remote-sensing data in 2013 to produce maps of "relative turbidity", an indicator of 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 Florida Area Coastal Environment (FACE) program; in situ data has been processed and furnished to academic partners for one region (Florida) to begin calibration of absolute turbidity products from the available remote sensing data. In situ measurements of turbidity have been done around 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, and already ongoing studies; currently outstanding permits have been evaluated, and requirements for new permits and *de minimis* findings for proposed fieldwork determined.

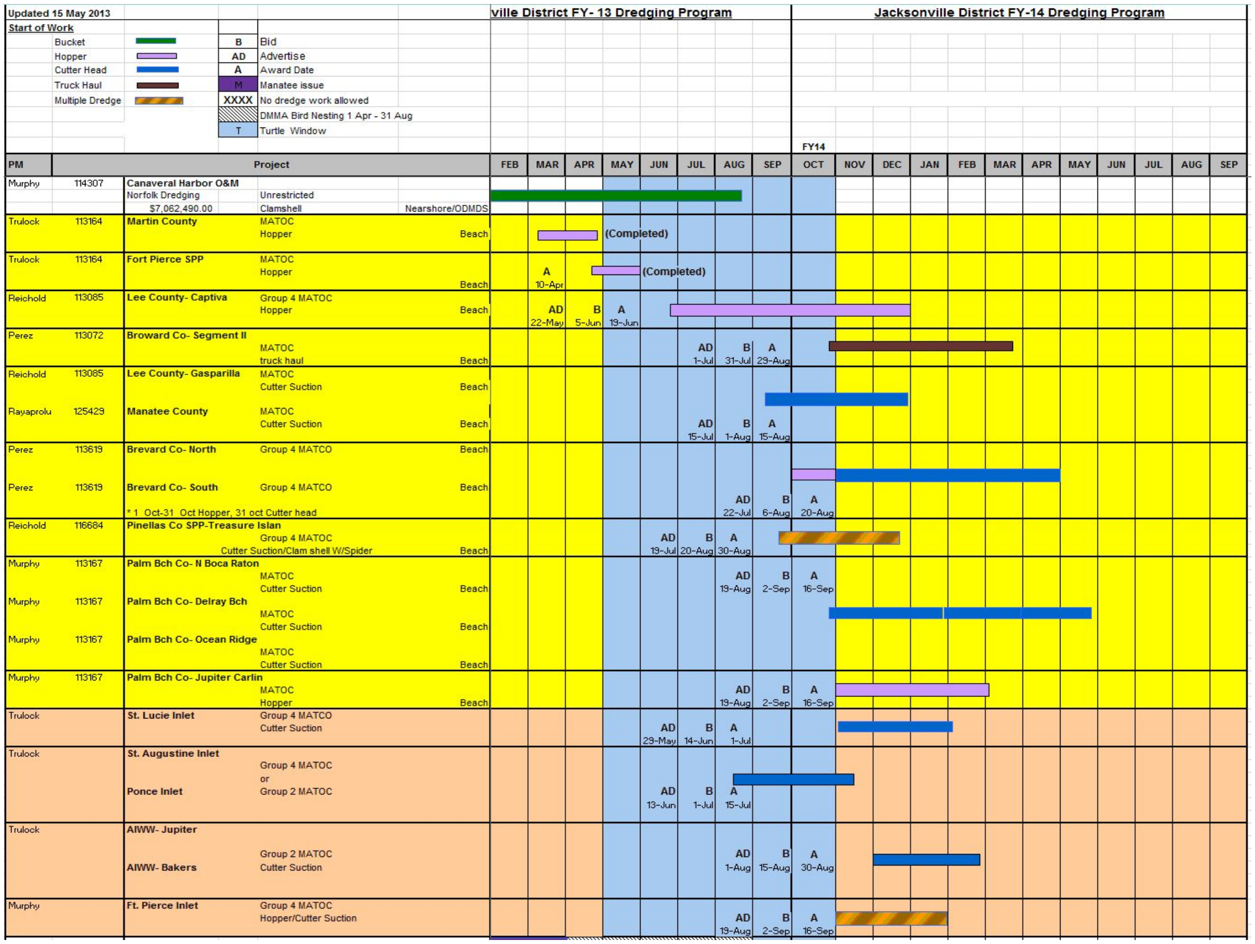
Managers from the three CRCP priority jurisdictions of American Samoa, Florida, and CNMI all identify management of sediment on coral reefs and adjacent coastal waters as a priority objective to NOAA CRCP (ASLAS, CNMILAS/ CAPS, Florida Management Priorities). These managers expressed a need for both historical and timely information on coastal turbidity within their jurisdictions. The goals of project #881 have been to provide information to assess changes in reef ecosystem health due to turbidity, across jurisdictions but at sub-watershed scale, and to communicate those results effectively to managers and build their capacity to apply the project results to help meet jurisdiction needs for LBSP monitoring. Recent research advances make it possible to fill a knowledge gap and provide timely information to address turbidity management concerns identified for LBSP. The final project objectives are to provide managers in each of three jurisdictions with water turbidity maps over time (2002 to present) at sub-watershed scales within their coastal waters, and with detailed, near real-time alerts, including links to Google Earth maps to provide geographic context, when turbidity plumes occur.

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 - Color Index or “CI”, an index originally designed for open ocean feature detection, using ocean color data from the MODIS instruments aboard polar-orbiting satellites Aqua and Terra. The algorithm was applied to twelve years of daily satellite overpasses in three areas of particular interest for U.S. coral reef conservation – southeast Florida shelf, and islands of the Northern Marianas and American Samoa, 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.

The project has coordinated with resource management partners (FDEP, CNMIDEQ, ASDMWR/CMP) and academic partners (USF, CIMAS), to provide retrospective analysis to determine mean conditions in the past as baseline data. This allows 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 alerting of 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.

The project takes advantage of the Virtual Antenna System (VAS) implemented at the USF-OOL with past support from 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.



Updated 15 May 2013

ville District FY- 13 Dredging Program

Jacksonville District FY-14 Dredging Program

Start of Work

Bucket	🟩	B	Bid
Hopper	▬	AD	Advertise
Cutter Head	🟦	A	Award Date
Truck Haul	▬	M	Manatee issue
Multiple Dredge	▨	XXXX	No dredge work allowed
		▨	DMMA Bird Nesting 1 Apr - 31 Aug
		T	Turtle Window

PM		Project			FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT FY14	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Murphy	114307	**Canaveral Harbor O&M** Norfolk Dredging $7,062,490.00	Unrestricted Clamshell	Nearshore/ODMDS																				
Trulock	113164	**Martin County**	MATOC Hopper	Beach				(Completed)																
Trulock	113164	**Fort Pierce SPP**	MATOC Hopper	Beach		A 10-Apr			(Completed)															
Reichold	113085	**Lee County- Captiva**	Group 4 MATOC Hopper	Beach		AD 22-May	B 5-Jun	A 19-Jun																
Perez	113072	**Broward Co- Segment II**	MATOC truck haul	Beach						AD 1-Jul	B 31-Jul	A 29-Aug												
Reichold	113085	**Lee County- Gasparilla**	MATOC Cutter Suction	Beach																				
Rayaprolu	125429	**Manatee County**	MATOC Cutter Suction	Beach						AD 15-Jul	B 1-Aug	A 15-Aug												
Perez	113619	**Brevard Co- North**	Group 4 MATCO	Beach																				
Perez	113619	**Brevard Co- South** * 1 Oct-31 Oct Hopper, 31 oct Cutter head	Group 4 MATCO	Beach							AD 22-Jul	B 6-Aug	A 20-Aug											
Reichold	116684	**Pinellas Co SPP-Treasure Islan**	Group 4 MATOC Cutter Suction/Clam shell W/Spider	Beach					AD 19-Jul	B 20-Aug	A 30-Aug													
Murphy	113167	**Palm Bch Co- N Boca Raton**	MATOC Cutter Suction	Beach							AD 19-Aug	B 2-Sep	A 16-Sep											
Murphy	113167	**Palm Bch Co- Delray Bch**	MATOC Cutter Suction	Beach																				
Murphy	113167	**Palm Bch Co- Ocean Ridge**	MATOC Cutter Suction	Beach																				
Murphy	113167	**Palm Bch Co- Jupiter Carlin**	MATOC Hopper	Beach							AD 19-Aug	B 2-Sep	A 16-Sep											
Trulock		**St. Lucie Inlet**	Group 4 MATCO Cutter Suction						AD 29-May	B 14-Jun	A 1-Jul													
Trulock		**St. Augustine Inlet** **Ponce Inlet**	Group 4 MATOC or Group 2 MATOC						AD 13-Jun	B 1-Jul	A 15-Jul													
Trulock		**AIWW- Jupiter** **AIWW- Bakers**	Group 2 MATOC Cutter Suction								AD 1-Aug	B 15-Aug	A 30-Aug											
Murphy		**Ft. Pierce Inlet**	Group 4 MATOC Hopper/Cutter Suction								AD 19-Aug	B 2-Sep	A 16-Sep											

Figure 1: Permitted projects schedule – dredging and similar operations – for south coastal Florida, 2013-2014.

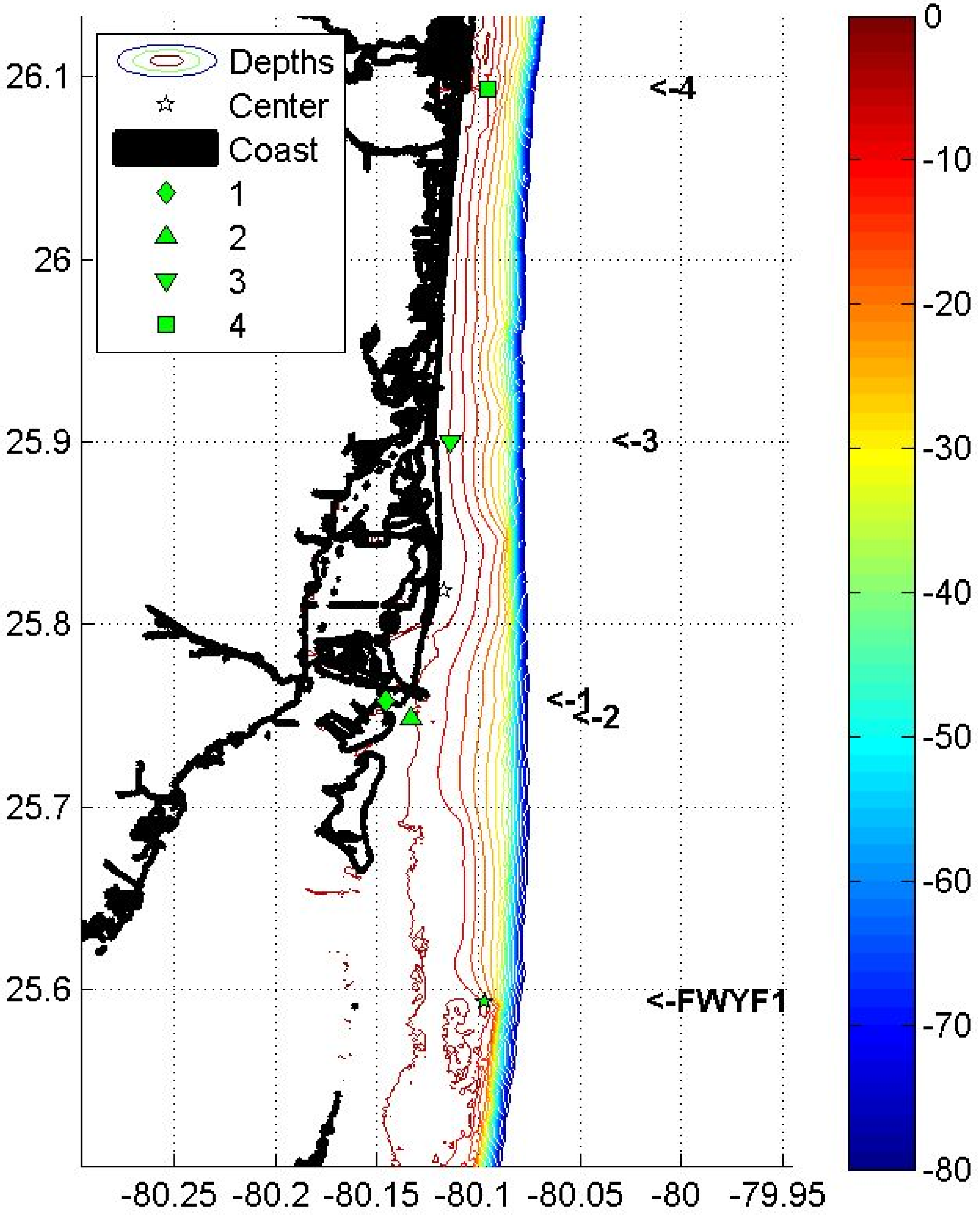


Figure 2: Four monitored pixel groups ("virtual stations") for southeast Florida, shown with bathymetry contours (depths every 5 m to 80 m): 1: inshore Port of Miami, 2: Port of Miami, 3: Haulover, 4: Port Everglades. NOAA C-MAN monitoring lighthouse Fowey Rocks ("FWYF1") is also shown.

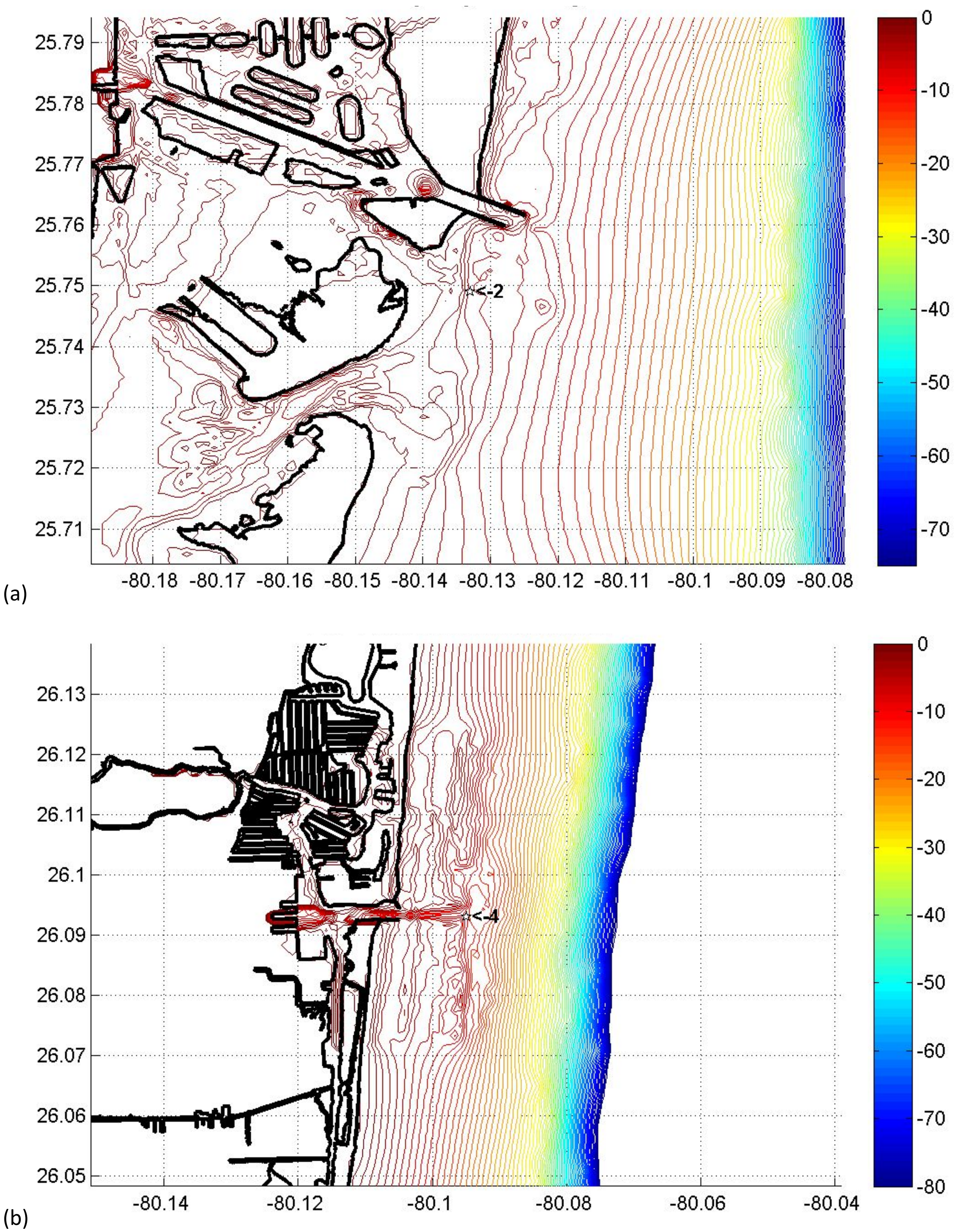


Figure 3: Bathymetry detail (contour every 1 m) for virtual (a) station #2 near Port of Miami and (b) station #4 near Port Everglades (see map above, for Port Everglades, this bathymetry does not show the port channel). In the text below, these stations are referred to by the designator of their Region of Interest, i.e., "POMF1" and "PVGF1", respectively.

Satellite Ocean Color

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

- This satellite relative turbidity product uses four color bands in MODIS (MOderate-Resolution Imaging Spectroradiometers); algorithms are now under development for the new VIIRS (Visible-Infrared Imaging Radiometer Suite) satellite instruments as well.
- MODIS instruments are on two polar orbiting satellites (Aqua and Terra), giving four overpasses per day, 2002 to present. Two of these are in daylight; VIIRS may add a third daytime overpass.
- Ocean color bands from MODIS provide 250x250 m pixels; VIIRS resolution is less, at 350-750 m.
- Satellite ocean color can see the seafloor in shallow water – the extent to which depends on water column turbidity.
- Uncalibrated color products in shallow waters can show variation 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 ~1 km; products are most reliable when calibrated with observations under a variety of conditions.

Both kinds of products – uncalibrated "relative turbidity" or color index (CI), and calibrated "absolute turbidity" (NTU) – can be made available to managers and the public via the Web. CI maps are available as images, data files, and Google Earth overlays (see below). "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".

Relative Turbidity

Relative turbidity products for this project are based on the Color Index ("CI") algorithm developed by C. Hu for MODIS (Hu 2015). MODIS CI is derived from reflectance at 555 nm, referenced against a linear baseline between 469 and 645 nm, after correction for gaseous absorption, molecular scattering, and sun glint effects (Hu 2011). The MODIS standard product MOD35 (Frey et al. 2008) is used to discriminate clouds from the water surface.

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 Web, 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

Seasonality in Results below). Combining near real-time and historical maps, regions of pixels can be highlighted which are outliers relative to their historical climatology and variance (see Ecoforecasts in Results).

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 analyze historical distributions of relative turbidity at each pixel in regions of interest (see ROIs below), and can then produce maps showing the anomaly of each pixel’s CI intensity relative to its own historical distribution. These maps are presented throughout the Results section below.

Absolute Turbidity

Absolute turbidity values in this study are called “NTU”, because although in fact they are distinct from the US EPA definition of “nephelometric turbidity units”, they are intended to mimic it. “NTU” time series an 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 to one another, rather than only comparing changes within a pixel over time, as is the case with relative turbidity (above). However, a record of in-water turbidity measurements is required at each such pixel, in order to calibrate methods used to make such estimates, particularly in clear, shallow subtropical coastal waters (Barnes et al. 2013; Zhao et al. 2013).

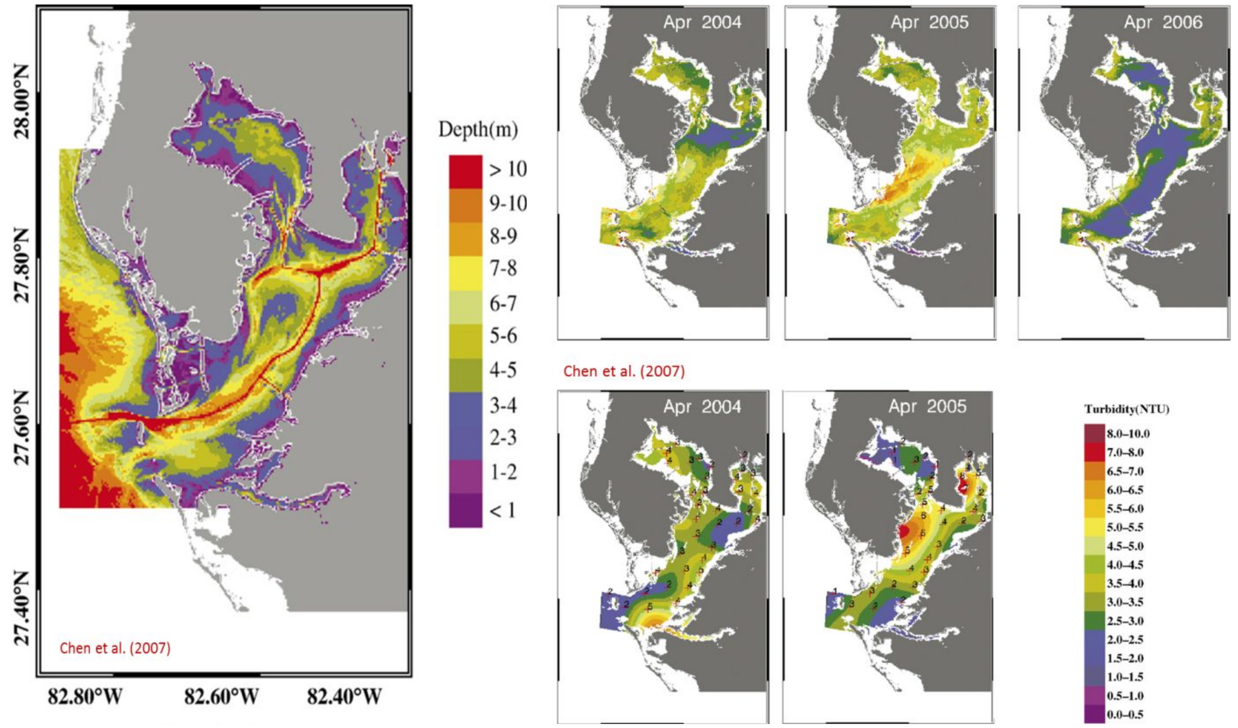


Figure 4: Results of combined remote-sensing and intensive field study in Tampa Bay, Florida (Chen et al. 2007).

The method employed for estimating absolute turbidity from ocean color in the present project works well in very shallow waters, near land. This feature is particular interest to managers in jurisdictions with coral reefs. One intensive ground-truth study in Tampa Bay (Chen et al. 2007; figures reproduced above below) shows useful results over a two-year period for waters as shallow as 2-3 m. In-water turbidity measurements were taken twice in 2015 (see In situ Measurements in Results below) near Port of Miami, in order to allow the absolute turbidity algorithm to be calibrated for that group of pixels. USF OOL will use these data to produce “NTU” time series for 2002-present for Port of Miami virtual station.

Map Areas and Regions of Interest (ROIs)

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

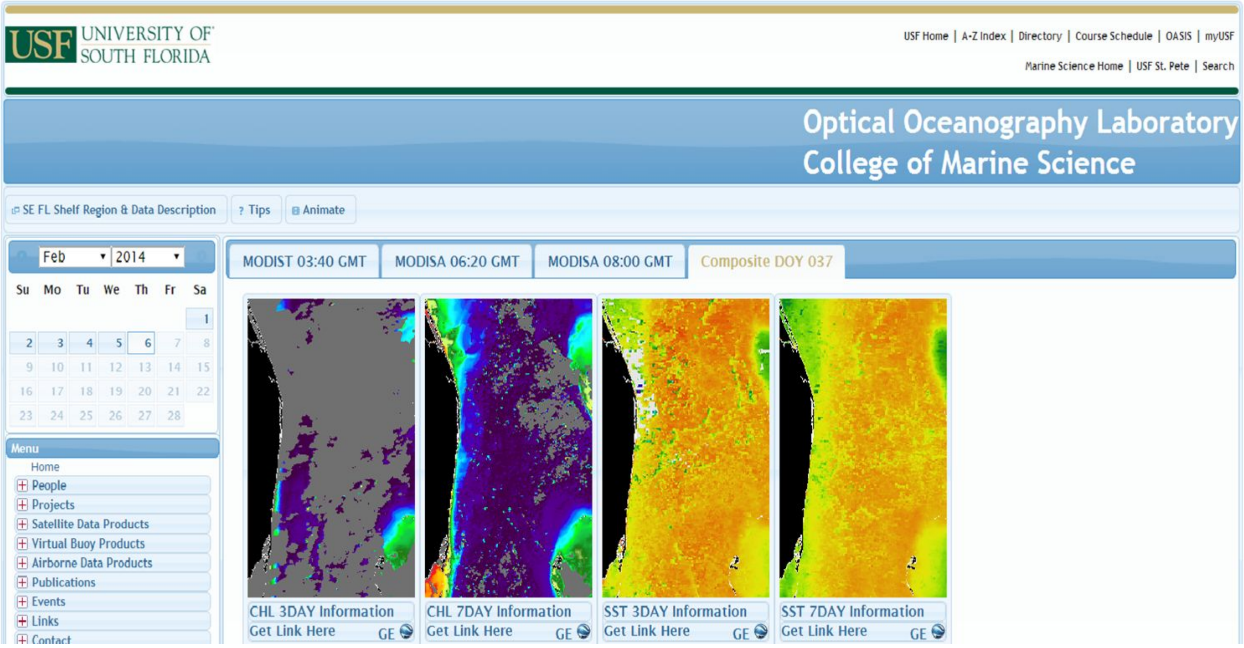
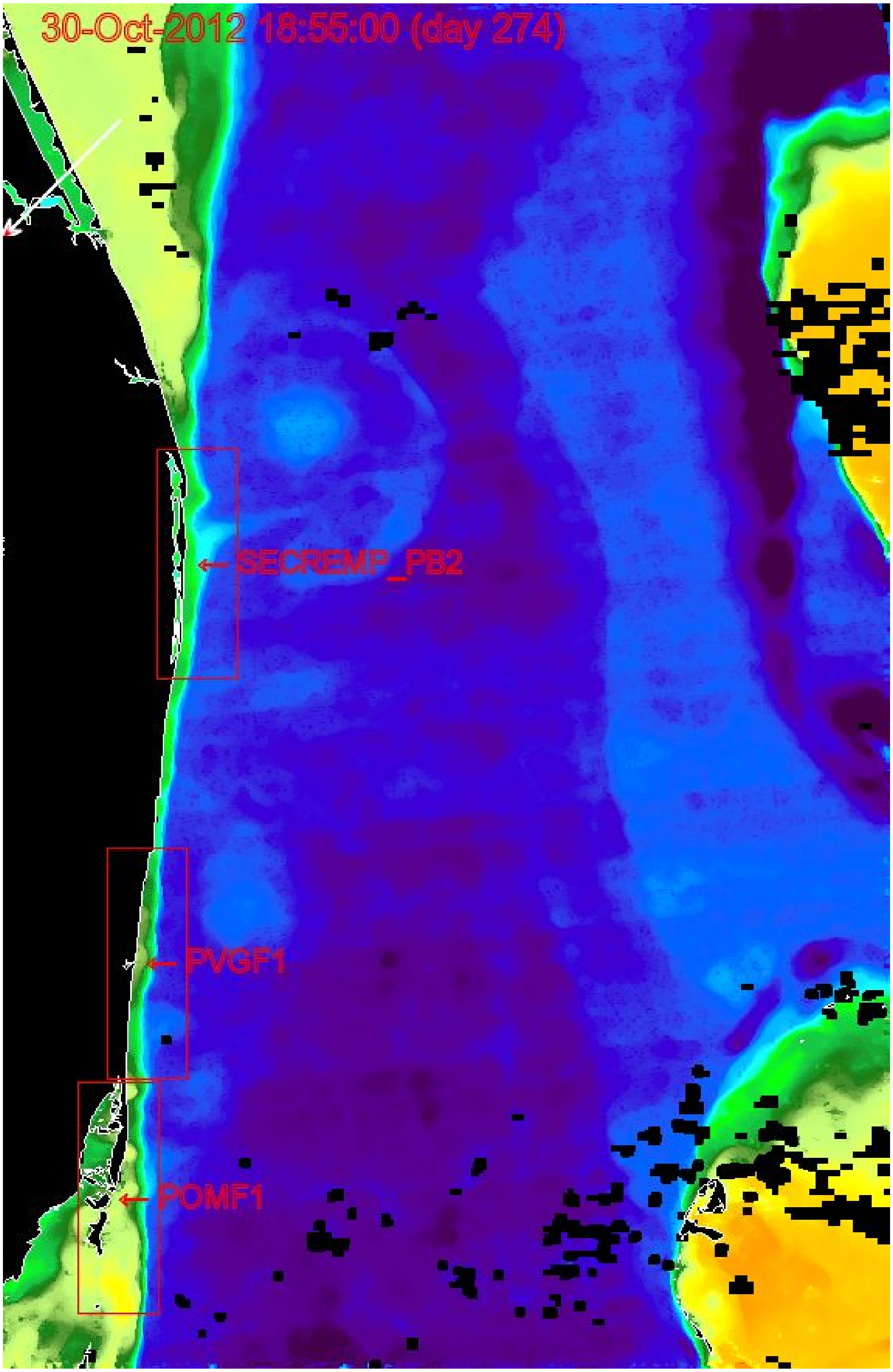


Figure 5: USF-OOL Web interface to 250 m resolution satellite products for the southeast Florida "SE_FL" region.

Within each CI map area, smaller Regions of Interest (ROIs) were furthermore selected and analyzed through time. These ROIs were designed to focus research attention on areas where human activity is most likely to impact coral reefs. Within the "SE_FL" map area, three ROIs were selected, each 34-by-12 km in extent: Port of Miami ROI "POMF1" centered on 25.74897,-80.13317; Port Everglades ROI "PVGF1" centered on 26.09300,-80.09200; and the ROI for Palm Beach renourishment projects and SECREMP monitoring, "SECREMP_PB2" centered on 26.67875,-80.01832 (see annotated image and bathymetry map in the two panels of the Figure below).



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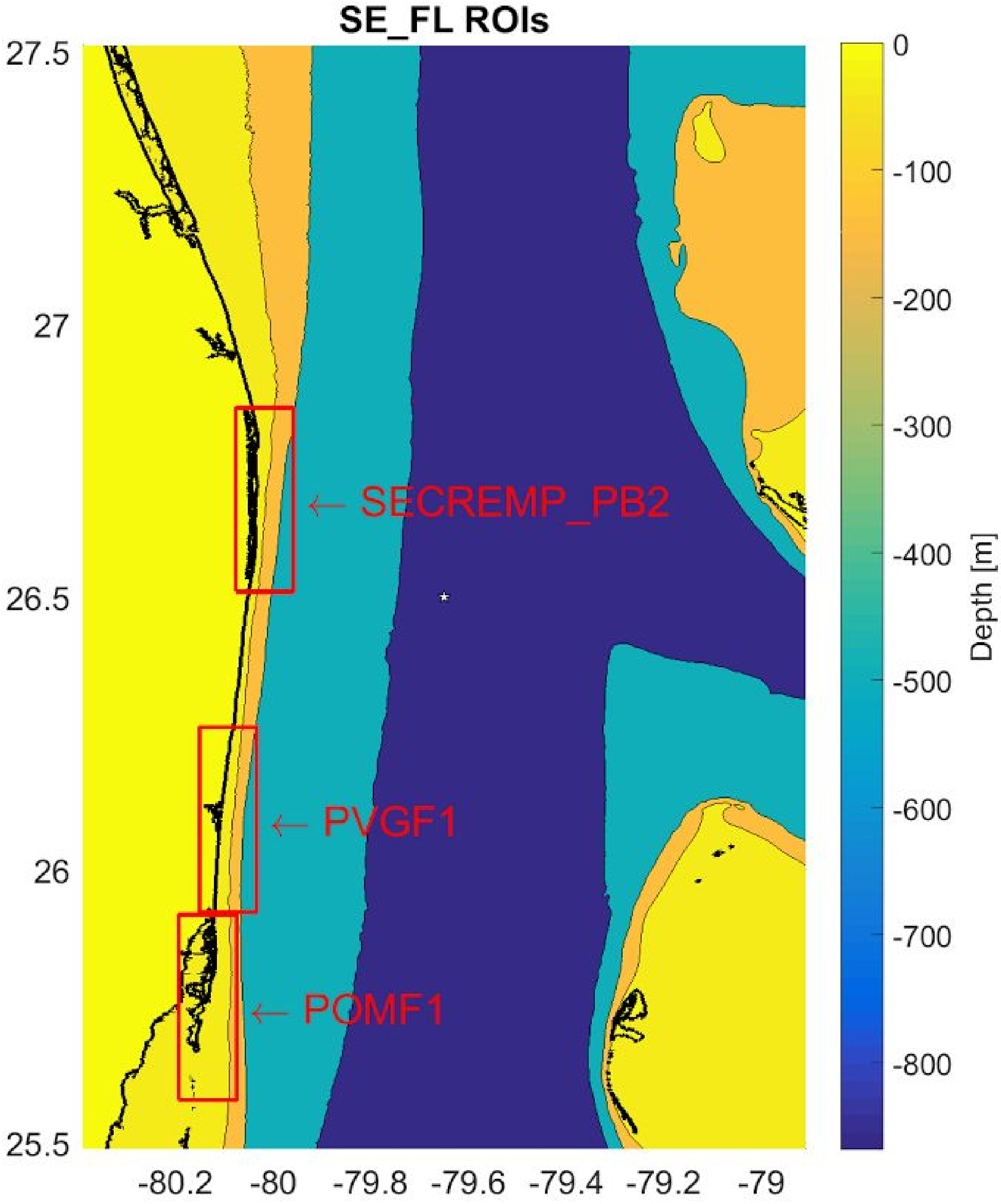


b

Figure 6: South East Florida (SE_FL) map area for USF-OOL ocean color, with smaller Regions of Interest (ROIs) marked in red. A portion of Florida's mainland is along the left edge. (a) An actual CI map of SE_FL from a clear day in October, 2012. (b) A map of bathymetry across the Straits of Florida from NOAA-NGDC, showing depth contours at 30, 150, and 500 m.

Ocean Surface Waves

As a primary driver of coastal turbidity, we modeled shelf wave action using three-hourly significant wave heights backcast by the NOAA WaveWatch III (WW3) operational products. In order to apply these products to shallow reef shelves, we applied a simple attenuation model based on coastal bathymetry, so that significant wave height reaches 0.0 m at the beach (Hardy et al. 1990). Wave attenuation for south Florida was done using 30 m horizontal resolution NOAA-NGDC/USGS bathymetry. Results of the wave attenuation approach are summarized for one ROI (Port Everglades PVGF1) in the figure below.

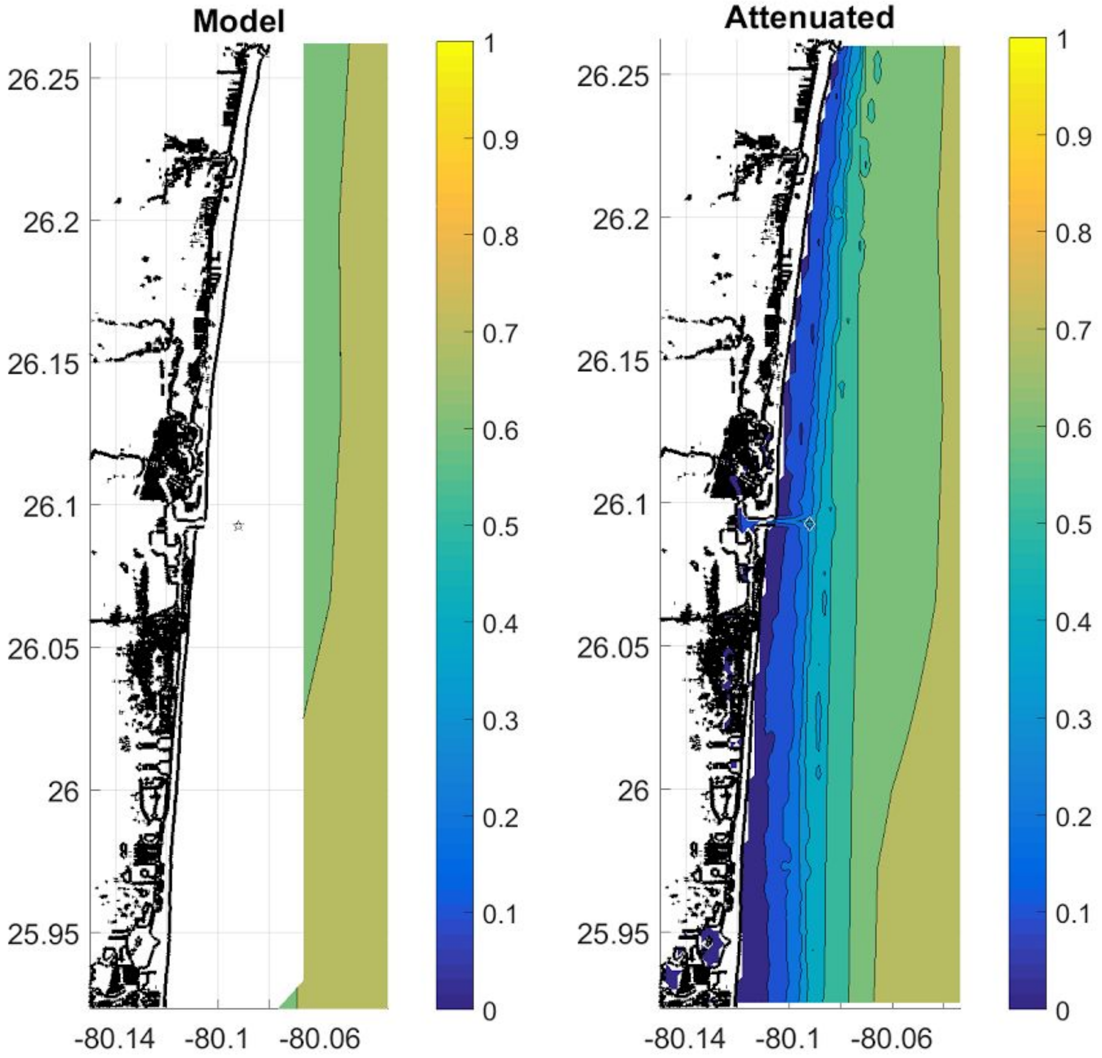


Figure 7: NOAA WaveWatch III modeled significant wave height in meters. (a) Original operational model output. (b) Result of simple depth-based wave attenuation technique.

In situ Turbidity Measurements

In-water turbidity measurements were previously collected in 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. 2013) and in situ turbidity and sediment measurements using kayaks and small boats in waters from 1-5 m depth in 2013-2015 (Stamates 2015).

A turbidity sensor was also deployed in the waters near Port of Miami as a 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 (see unnumbered figure below). This work was completed by project contributors Dr. N. “Mana” Amornthammarong of NOAA/CIMAS and M. Shoemaker of NOAA.

In order to verify pressure containment and sensor function, the instrument was tested extensively at AOML and on the dock of the nearby Rosenstiel School of University of Miami (unnumbered figure below).

Deployments were limited by battery power to at most two 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 both to the levels of turbidity encountered, and to the action of waves at the site, which was approximately 3 m deep. After each deployment, both extensive cleaning, battery replacement, and some repairs were required (unnumbered figure below).

Ecoforecast Alerts

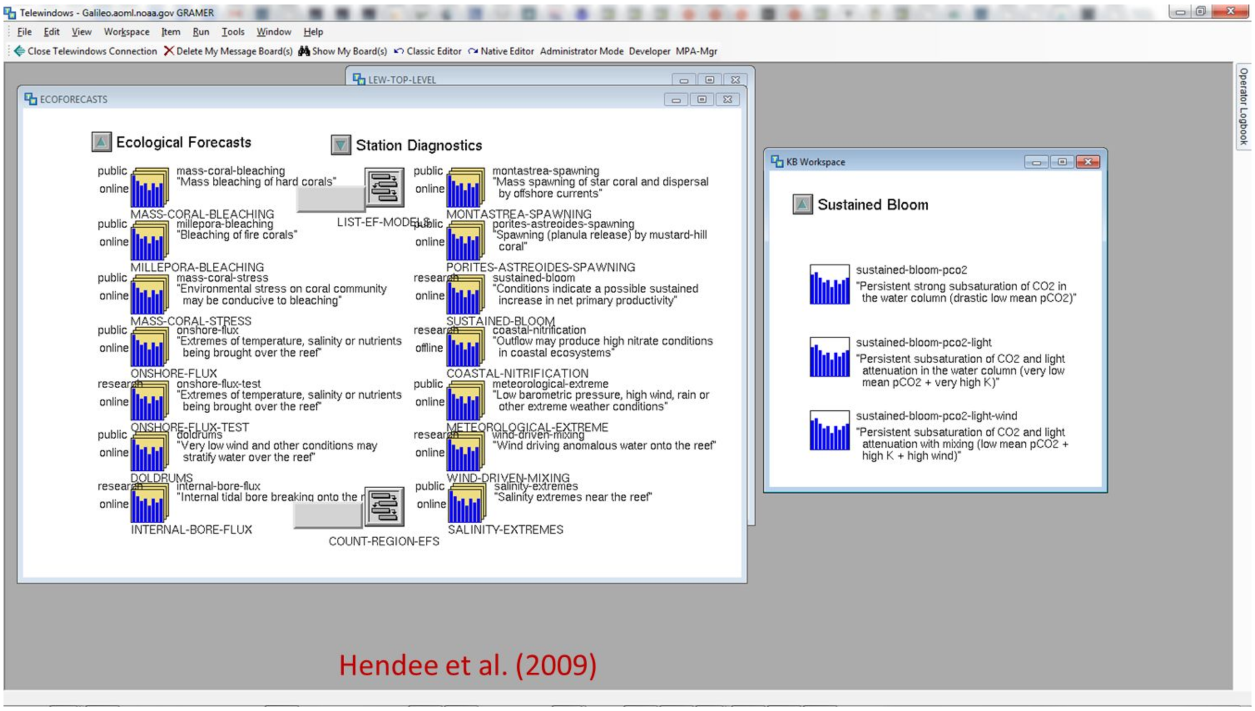
Examining daily maps even for one ROI in one map area would be overwhelming for researchers and managers. Artificial intelligence (AI) provides ways of reducing high-volume data streams to their most useful information. AI ecological forecasts or “ecoforecasts” allow automated daily assessment of near real-time environmental data for potential threats to marine ecosystem health (Hendee et al. 2009). They can integrate in situ, satellite, and model observations, and evaluate those data using an AI technique known as an expert systems – 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.

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



public online MASS-CORAL-BLEACHING mass-coral-bleaching "Mass bleaching of hard corals"

public online MILLEPORA-BLEACHING millepora-bleaching "Bleaching of fire corals"

public online MASS-CORAL-STRESS mass-coral-stress "Environmental stress on coral community may be conducive to bleaching"

public online ONSHORE-FLUX onshore-flux "Extremes of temperature, salinity or nutrients being brought over the reef"

research online ONSHORE-FLUX-TEST onshore-flux-test "Extremes of temperature, salinity or nutrients being brought over the reef"

public online DOLDRUMS doldrums "Very low wind and other conditions may stratify water over the reef"

research online INTERNAL-BORE-FLUX internal-bore-flux "Internal tidal bore breaking onto the r

public online MONTASTREA-SPAWNING montastrea-spawning "Mass spawning of star coral and dispersal by offshore currents"

public online PORITES-ASTREOIDES-SPAWNING porites-astreoides-spawning "Spawning (planula release) by mustard-hill coral"

research online SUSTAINED-BLOOM sustained-bloom "Conditions indicate a possible sustained increase in net primary productivity"

research offline COASTAL-NITRIFICATION coastal-nitrification "Outflow may produce high nitrate conditions in coastal ecosystems"

public online METEOROLOGICAL-EXTREME meteorological-extreme "Low barometric pressure, high wind, rain or other extreme weather conditions"

research online WIND-DRIVEN-MIXING wind-driven-mixing "Wind driving anomalous water onto the reef"

public online SALINITY-EXTREMES salinity-extremes "Salinity extremes near the reef"

sustained-bloom-pco2 "Persistent strong subsaturation of CO2 in the water column (drastic low mean pCO2)"

sustained-bloom-pco2-light "Persistent subsaturation of CO2 and light attenuation in the water column (very low mean pCO2 + very high K)"

sustained-bloom-pco2-light-wind "Persistent subsaturation of CO2 and light attenuation with mixing (low mean pCO2 + high K + high wind)"

Hendee et al. (2009)

Figure 8: AI Expert Systems development tool G2, a visual programming environment used by the NOAA Coral Health and Monitoring Program to implement ecoforecasts for coral reefs and other marine ecosystems monitored for environmental data, including relative and absolute turbidity.

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 a 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 include CI, ocean waves, chlorophyll *a*, and SST, can reduce uncertainty of attribution.

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 median. "Extreme events" were identified when 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% of the pixels in an ROI were clear, or when days between clear pixels were greater than one 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 assigns a value of 8 to a pixel if it meets the above criteria for an "event", and a value of 16 if it meets 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.

Results

This section summarizes results of the three-year NOAA CRCP project. First, we present summary statistics for the ocean color products spanning the fifteen-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 correlates for the observed patterns of ocean color, in particular, ocean waves. Finally, the result of ecological forecasting for turbidity “events” is summarized for each Region of Interest.

Ocean Color

Clear Pixel Days

Satellite ocean color depends on clear skies during a satellite overpass: the shallow waters of the three SE_FL 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, average days between clear pixels were <2.5 d out to the second reef line, <3 d out to the third reef, and <6 d out to the 60 m isobath. For SECREMP_PB2, average days between clear pixels were similar to the other two ROIs.

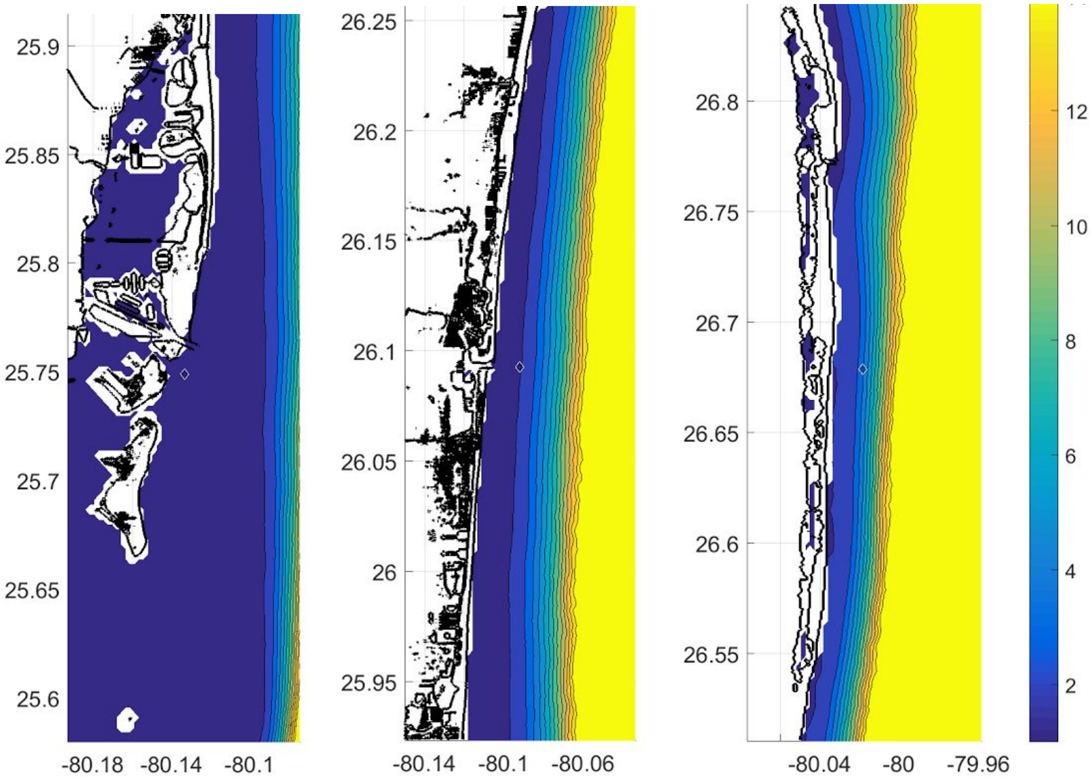


Figure 9: Maps showing average number of days between good CI pixels - indicating clear daytime overpasses of the MODIS satellites, and color bands within acceptable ranges for the CI algorithm - for each pixel in the three ROIs of southeast Florida: (a) Port of Miami POMF1, (b) Port Everglades PVGF1, and (c) SECREMP_PB2 off Palm Beach.

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 in all three ROIs for all seasons.Below is a set of maps summarizing the slight seasonality in the average number of days between good CI pixels for two of the three ROIs, Port Everglades ROI PVGF1 and Port of Miami ROI POMF1.

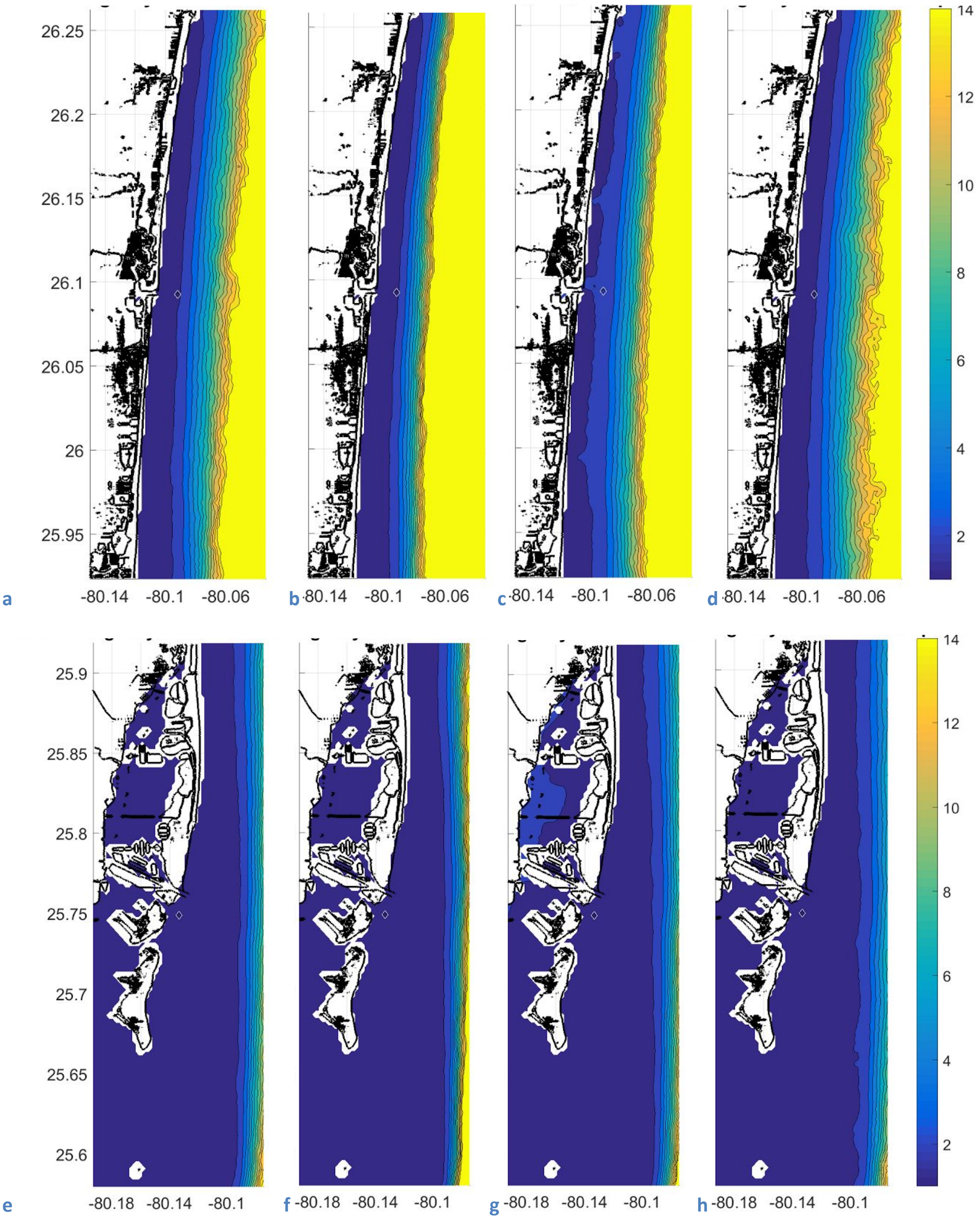


Figure 10: Maps showing average number of days by season between good CI pixels in Port Everglades ROI PVGF1 (a-d) and Port of Miami ROI POMF1 (e-h), for the period July 2002 to June 2017. (a,e) January-March, (b,f) April-June, (c,g) July-September, and (d,h) October-December.

Virtual Station Time Series

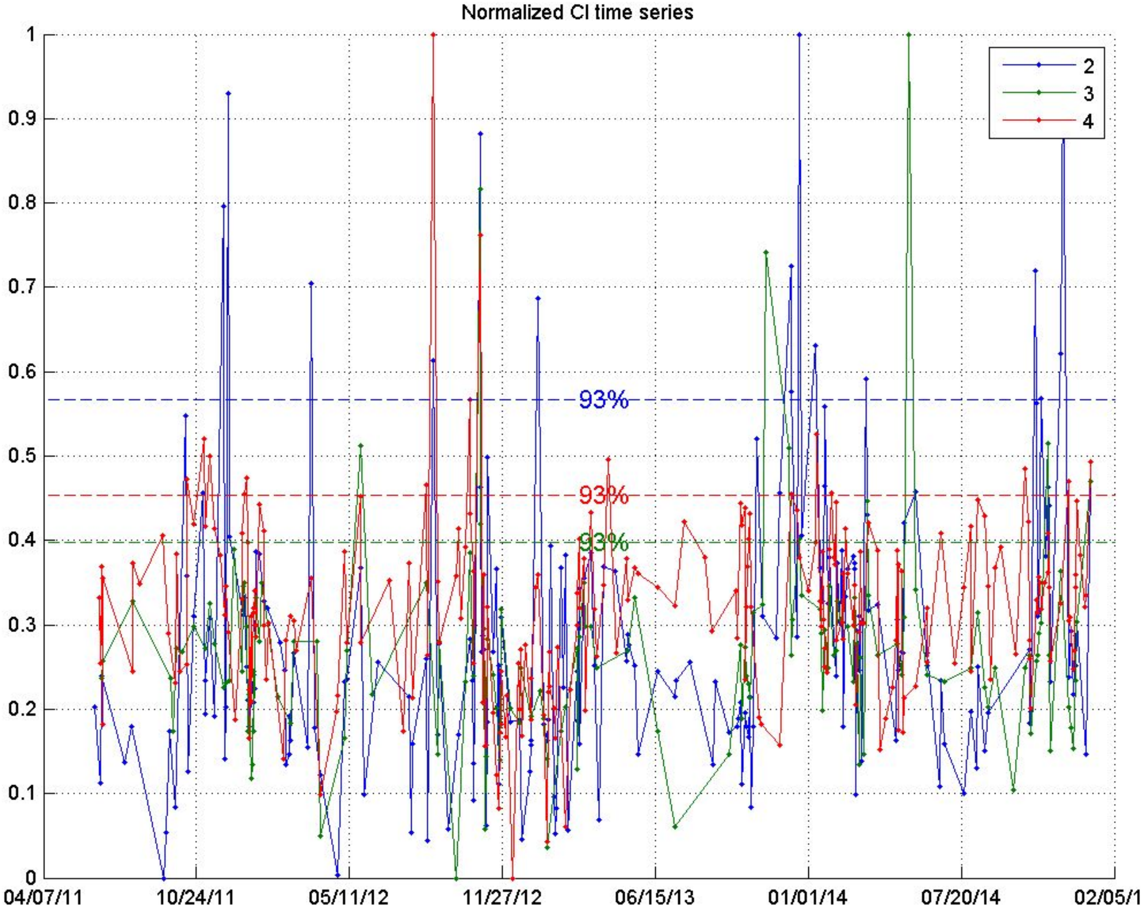


Figure 11: Normalized time series of relative turbidity ("CI") for 2011-2015 at virtual stations 2-4 (see maps above), with 93rd percentile value marked for each.

Even once normalized, time series for individual pixels or pixel groups of 1x1 km size were difficult to interpret by themselves. One issue was that the intermittent presence of clouds or other bad-pixel flags can make the time series very irregular from pixel to pixel. Another issue is that weather in south Florida and similar subtropical and tropical regions often occurs at small, convective scales of order 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.

Ocean Color Maps

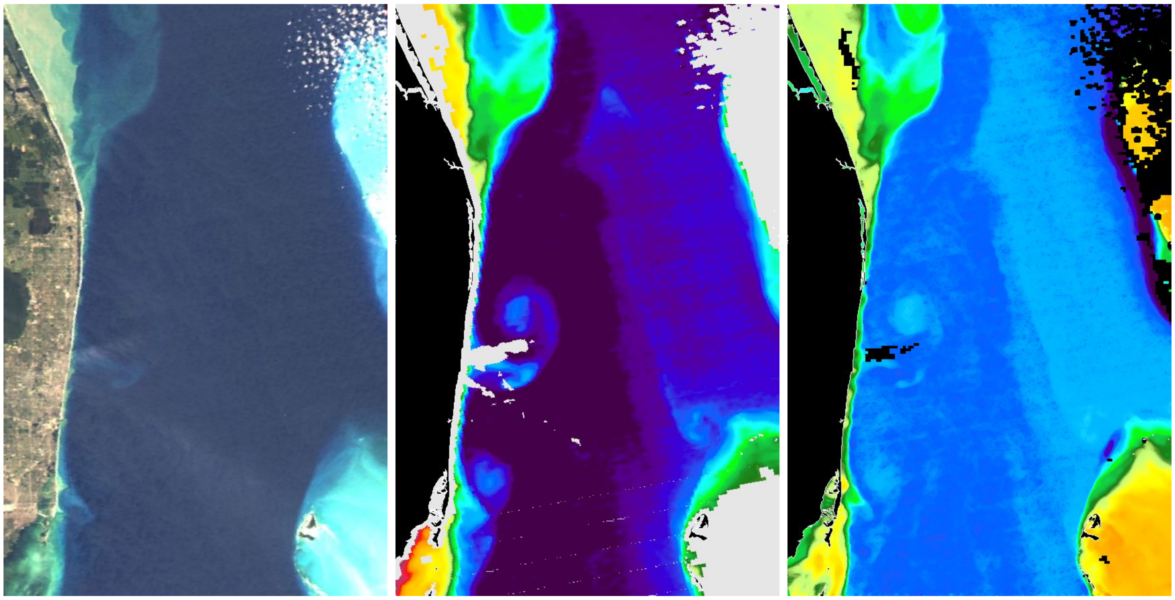


Figure 12: Processing sequence from 250 m true color (left), to chlorophyll a (middle) to relative turbidity or CI (right).

MODIS satellite ocean color bands can be processed to produce images with a variety of information, as summarized by the maps in the figure above. True color (left panel) is achieved using a blend of intensities from all visible-light color bands. In-water chlorophyll a concentration (middle panel) is 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 "Color Index" (CI) used to estimate relative turbidity (right panel) is estimated from a different set of the 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 fates of material measured by an ocean color algorithm. The sequence of CI images in the figure below shows a potentially useful example of this: a source of relative turbidity near the bottom of the map area (near 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 Port Everglades channel).

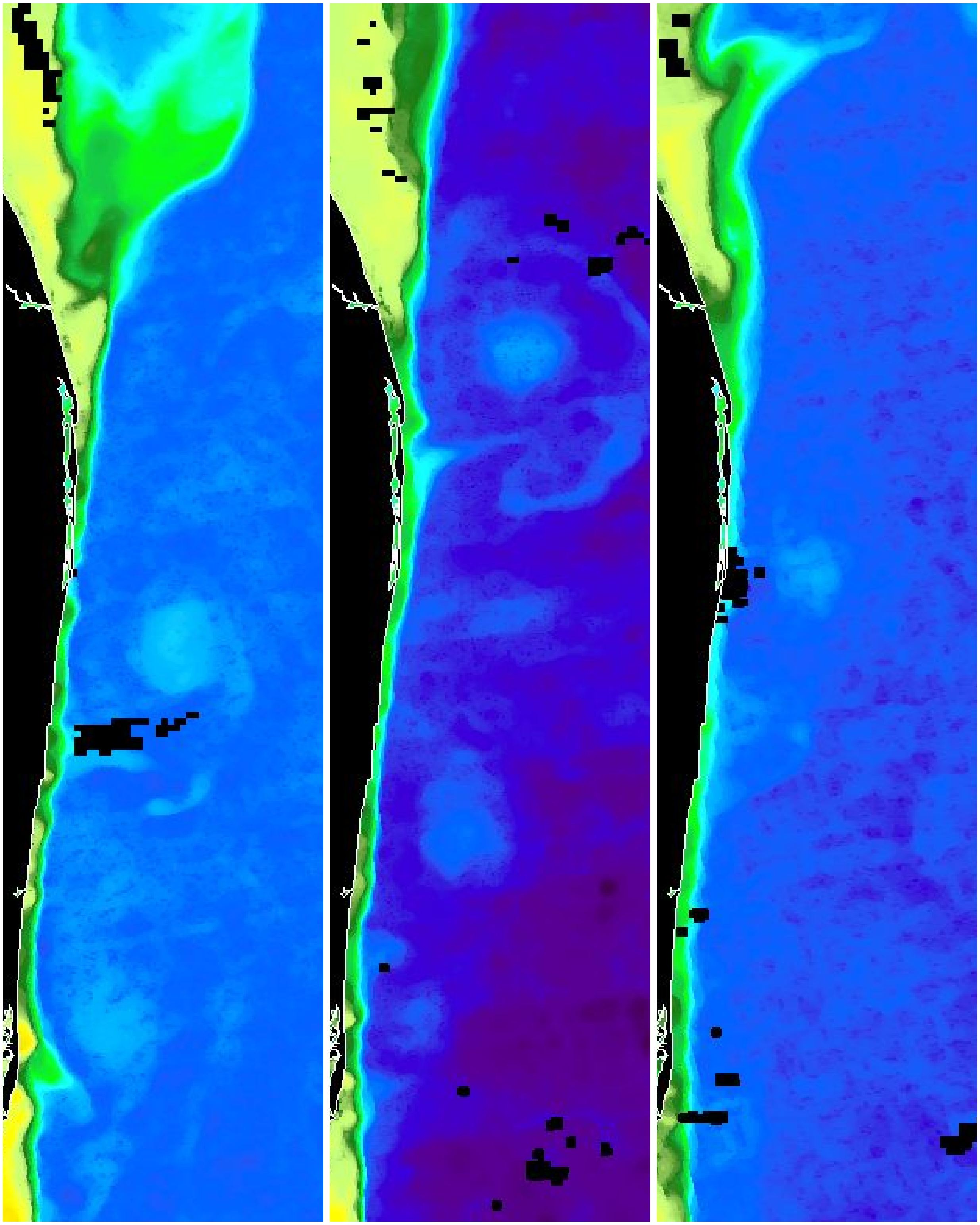
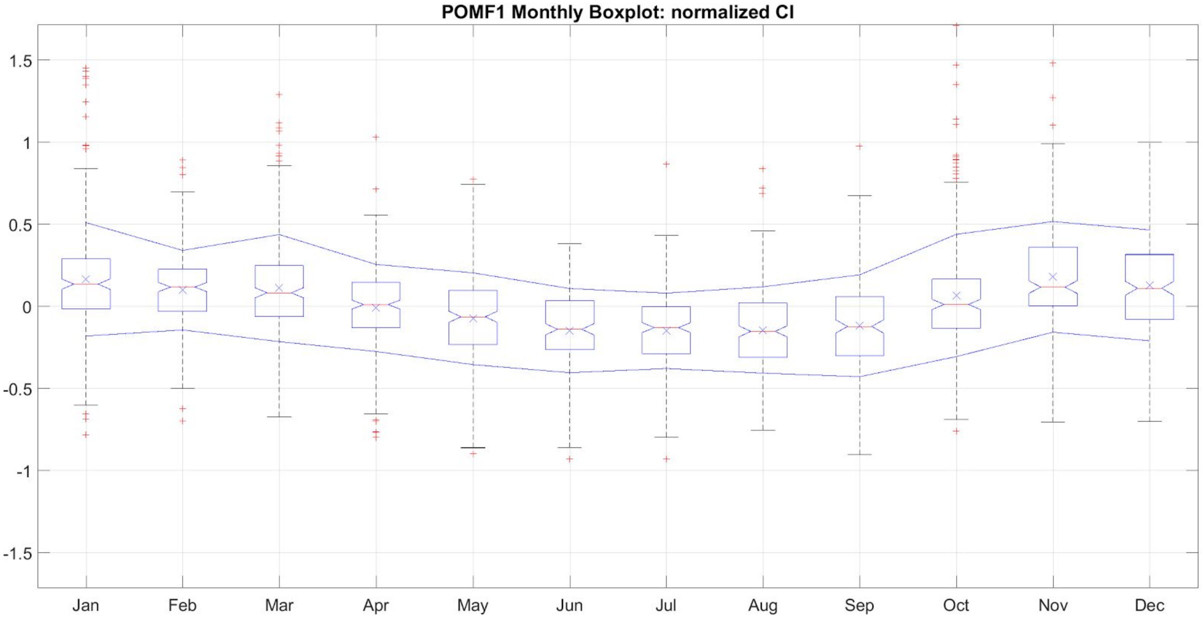
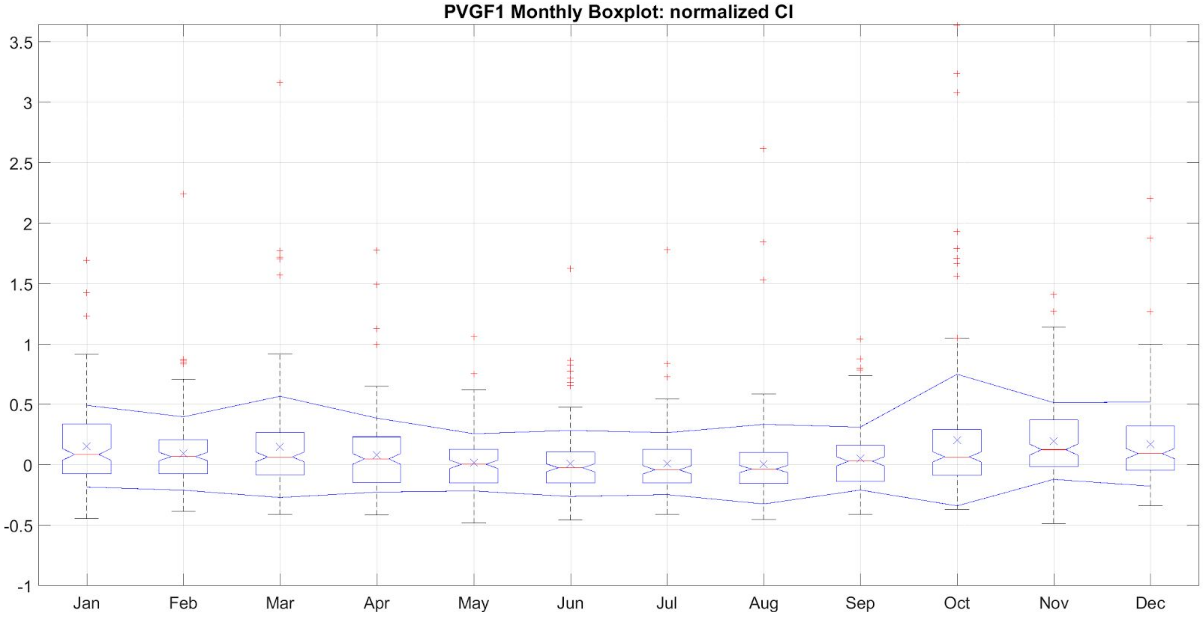


Figure 13: Time sequence showing turbidity plume dynamics offshore of Port Everglades, October 29th, 30th, and 31st, 2012.

Color Index Seasonality



a



b

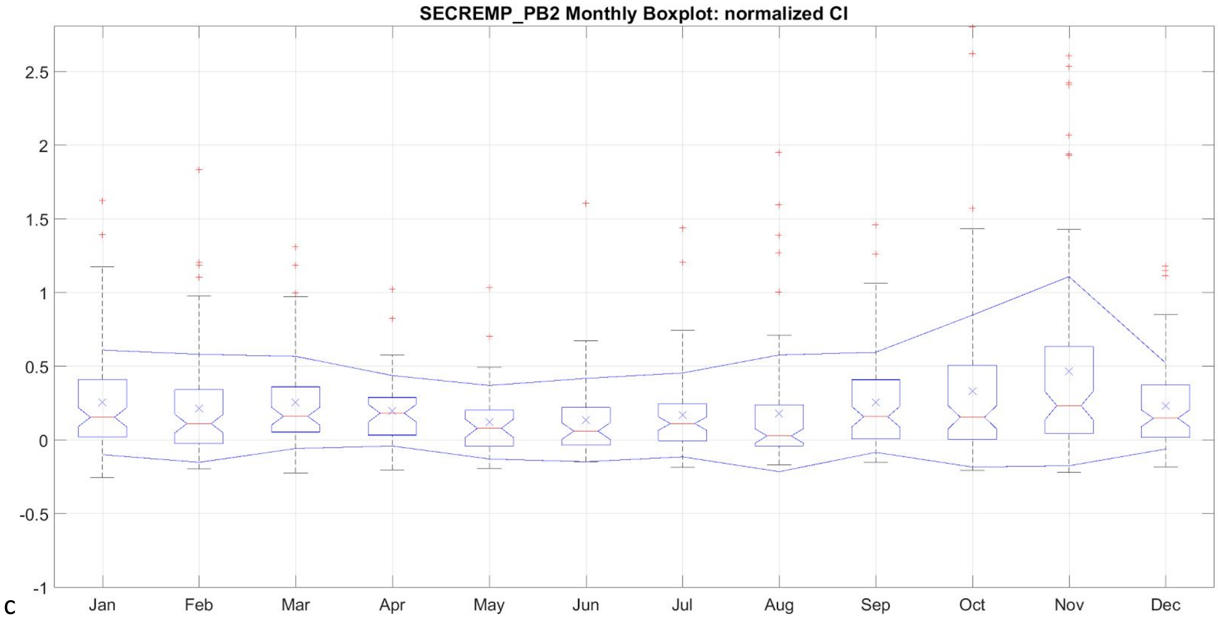
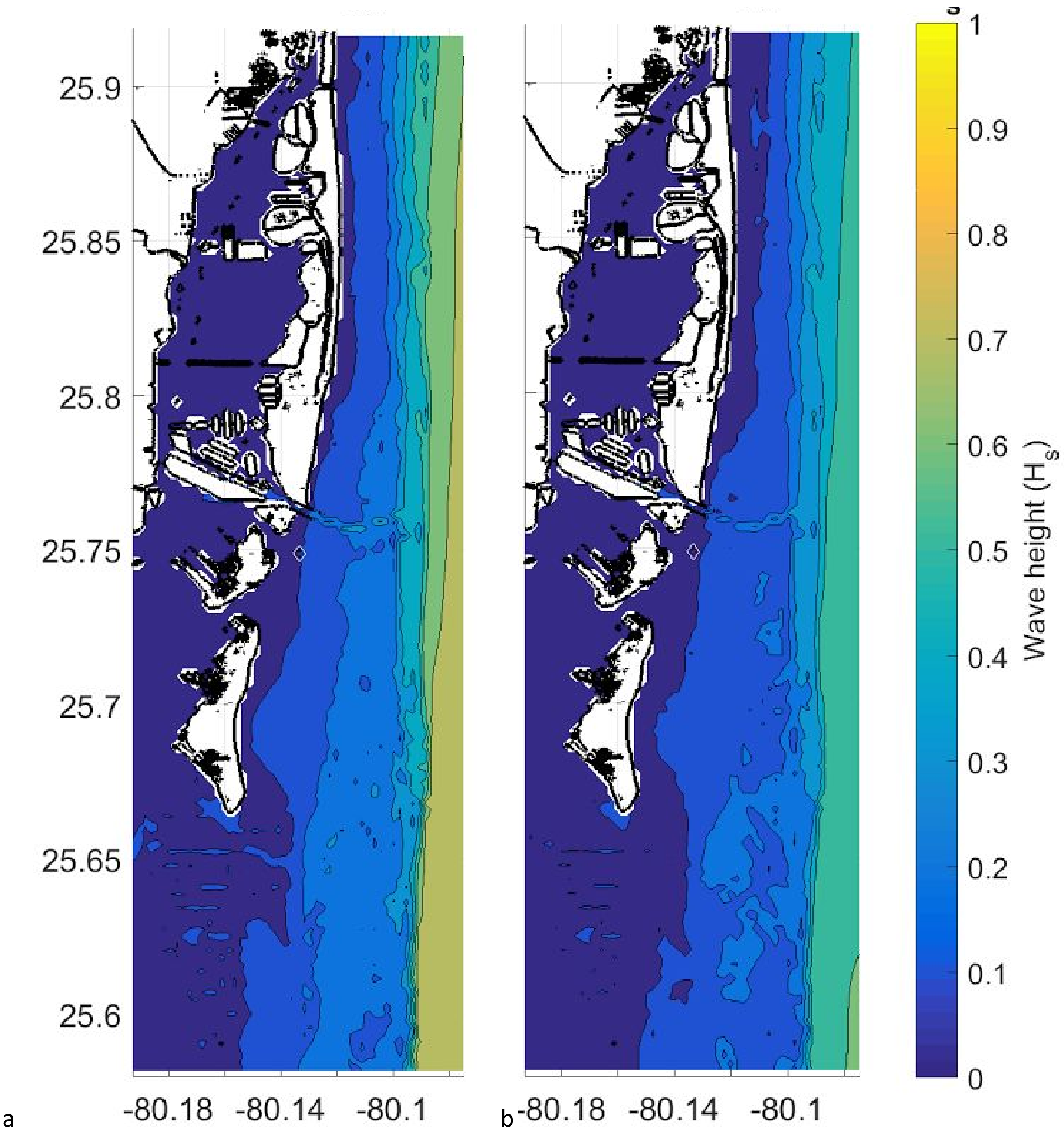


Figure 14: Seasonality of normalized relative turbidity (norm(CI) for one 1x1 km manually selected pixel group offshore of each of (a) Port of Miami, (b) Port Everglades, and (c) Region around "SECREMP_PB2" offshore of Palm Beach County. (See maps in ROI figures above for locations of individual 1x1 km pixel groups.

Environmental Correlations

The primary natural environmental correlate found for periods of high relative turbidity in 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 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 (see Methods above) then were only 0.4 m on average. In April-September at 20 m, attenuated waves were 0.3 m.


25.9
25.85
25.8
25.75
25.7
25.65
25.6
-80.18
-80.14
-80.1
a
b
-80.18
-80.14
-80.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Wave height (H_s)

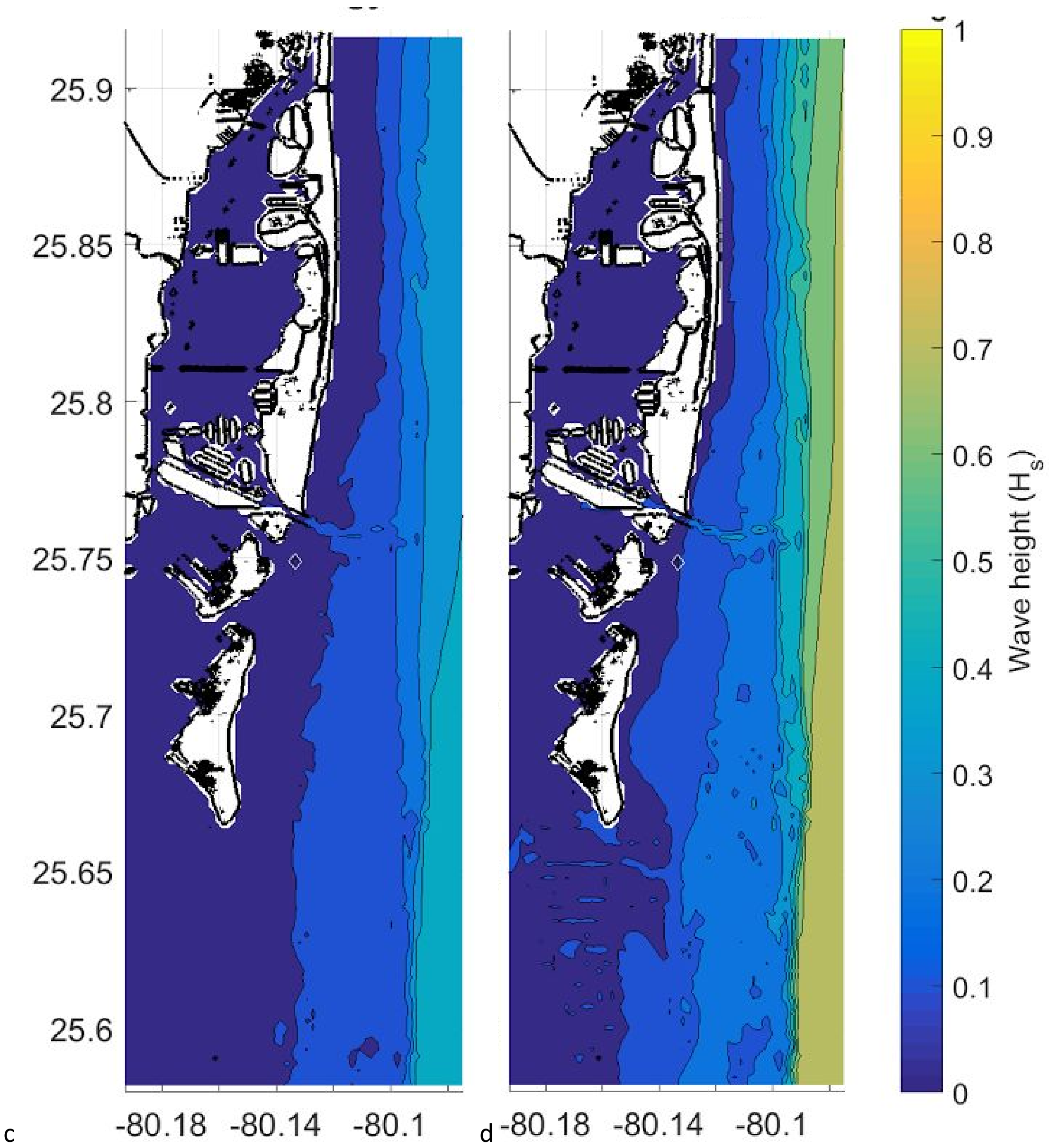


Figure 15: Seasonal climatology of significant wave heights for one of the three regions of interest, Port of Miami ROI POMF1, for the years 2005-2017, for the months (a) January-March, (b) April-June, (c) July-September, and (d) October-December.

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 the figure below.

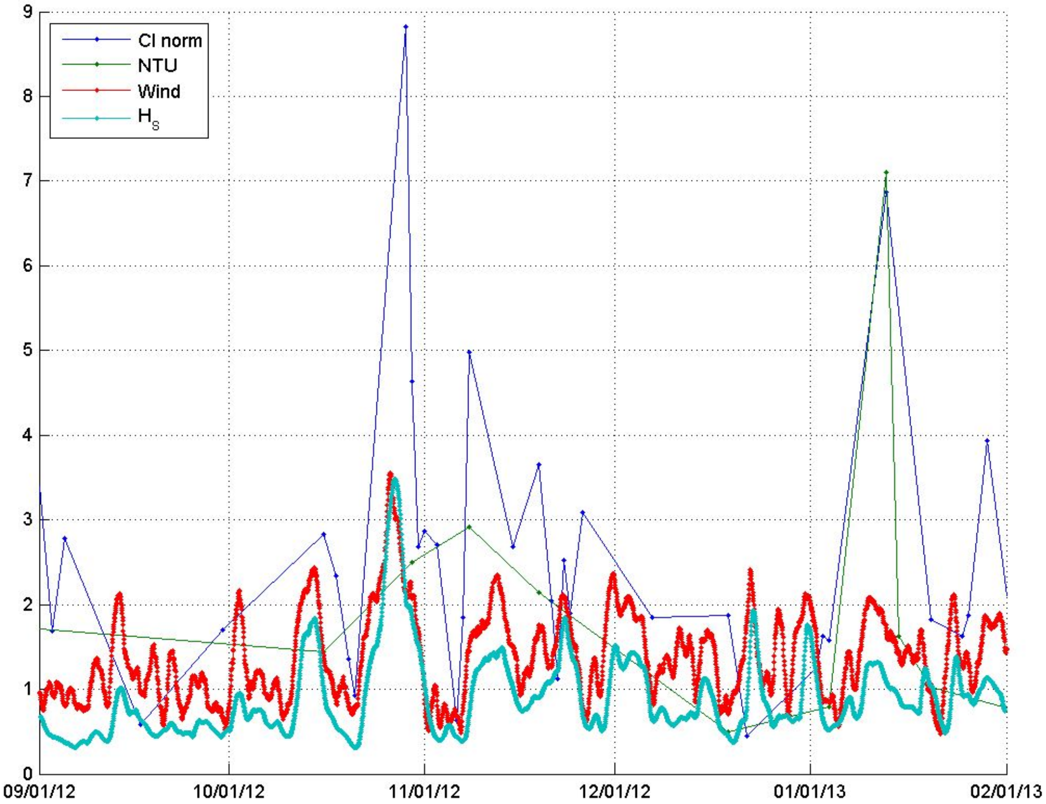
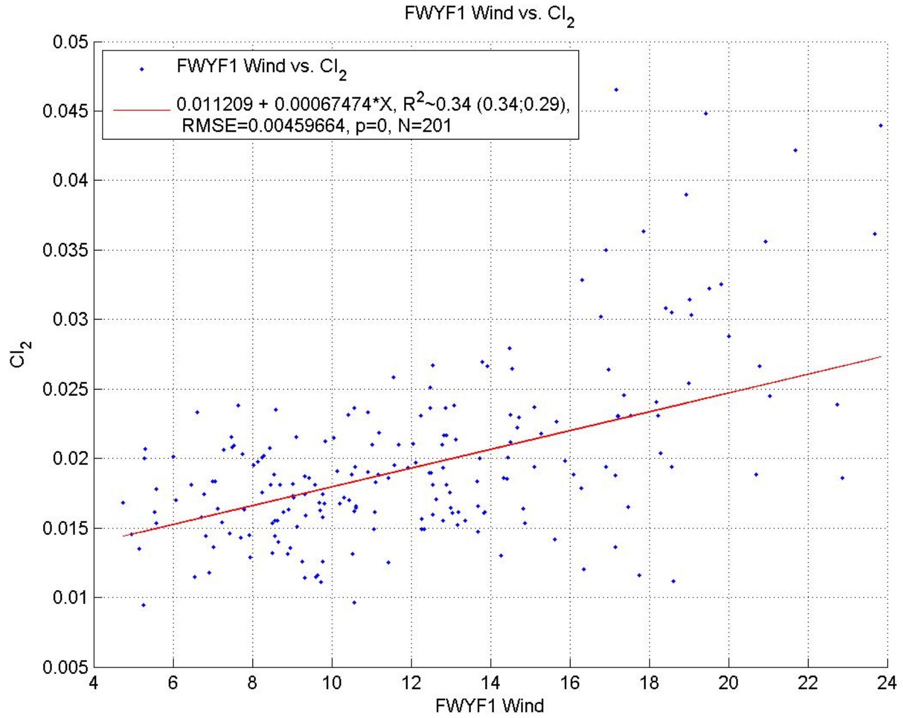


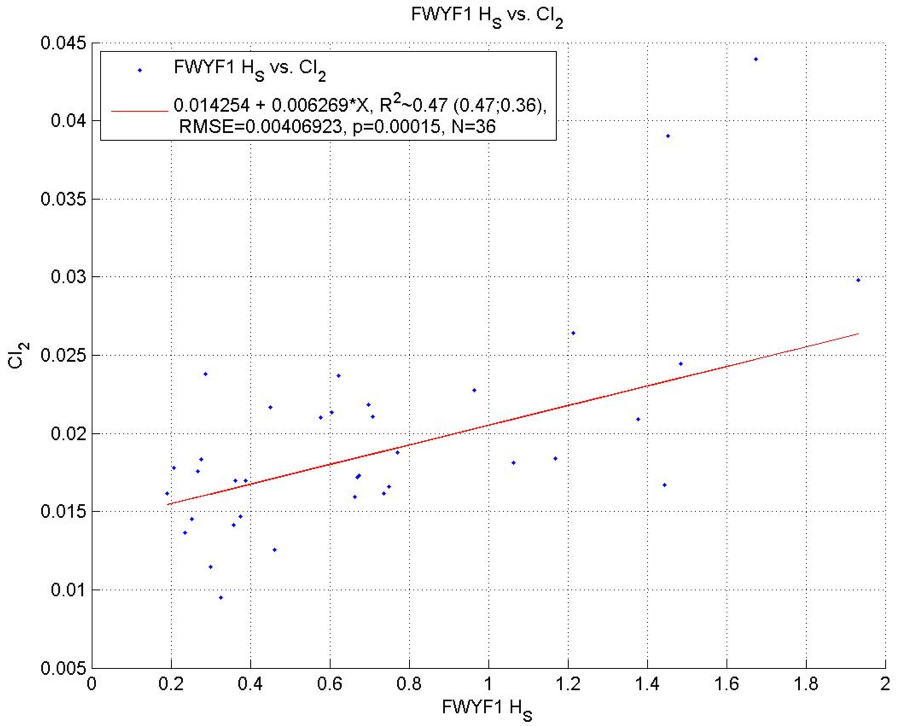
Figure 16: Comparison of time series from satellite relative turbidity (CI), an uncalibrated processing algorithm for absolute turbidity ("NTU"), and low-pass filtered *in situ* wind speed and attenuated model significant wave height from site PVGF1.

A statistical analysis (regression fit) of in situ wind from the meteorological monitoring station FWYF1 at Fowey Rocks, attenuated model wave heights, and the CI and uncalibrated "NTU" calculated pixel intensities for one nearby pixel group are shown in the figures below for one of the analysis sites, site #2 which corresponds to the center of the Port of Miami Region of Interest "PVGF1". These results are representative of the other sites analyzed in all three Florida ROIs. Regression showed a high correlation between CI and both wind and attenuated significant wave height (figure below, panels a and b). Wind was not found to be predictive as an independent variable: controlling for wave height, regression with wind was not significant (figure not shown).

Notably, an uncalibrated "NTU" time series was also calculated for the analysis sites 1-4 by academic partners at USF-OOL. The time series shown does not directly correspond to nephelometric turbidity units as defined by US-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 shows statistical independence from both wind and wave height (panels c and d of the figure below). 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.


FWYF1 Wind vs. Cl_2
FWYF1 Wind vs. Cl_2
0.011209 + 0.00067474*X, R^2~0.34 (0.34;0.29),
RMSE=0.00459664, p=0, N=201
Cl_2
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
4
6
8
10
12
14
16
18
20
22
24
FWYF1 Wind

a


FWYF1 H_S vs. Cl_2
FWYF1 H_S vs. Cl_2
0.014254 + 0.006269*X, R^2~0.47 (0.47;0.36),
RMSE=0.00406923, p=0.00015, N=36
Cl_2
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
FWYF1 H_S

b

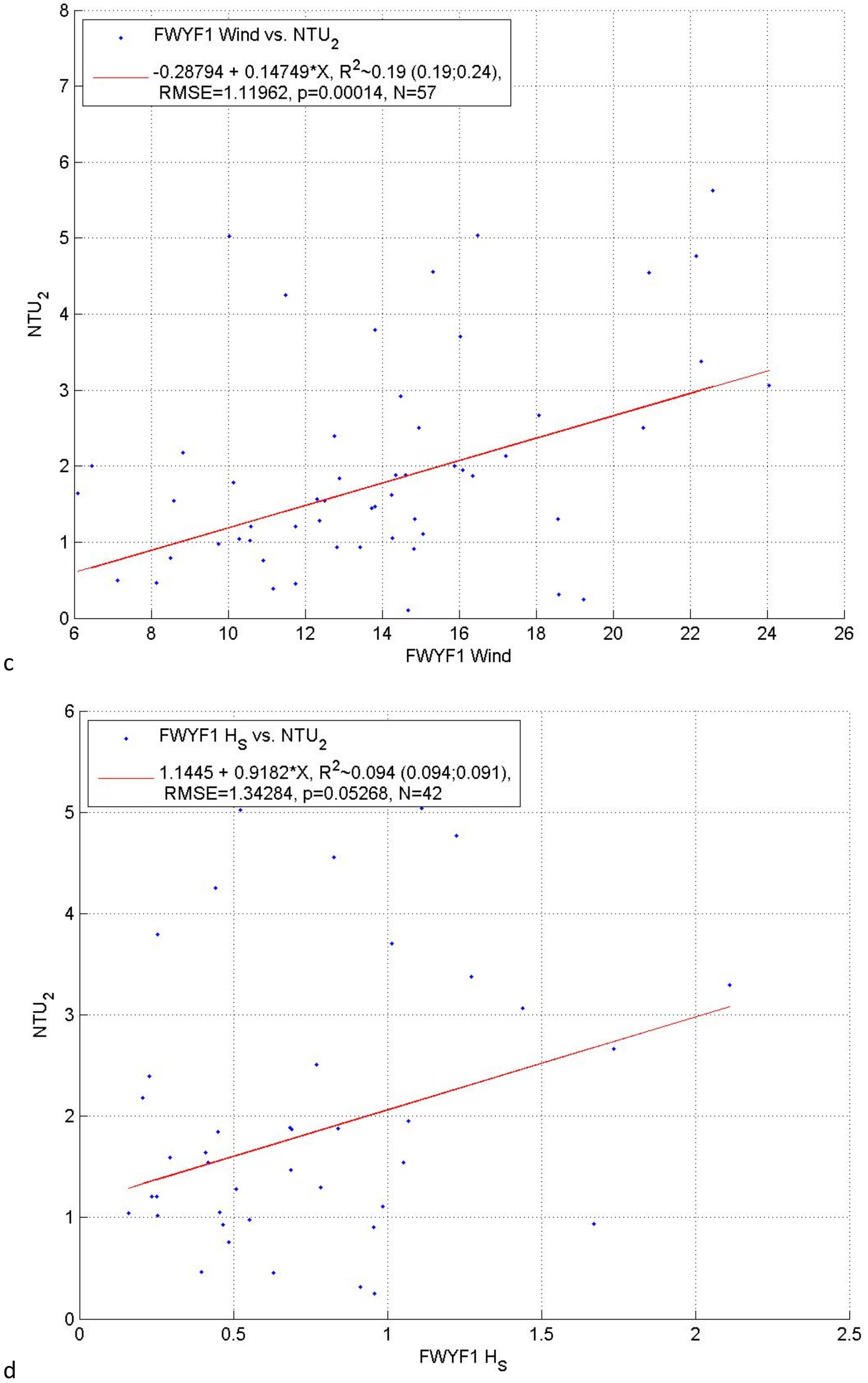
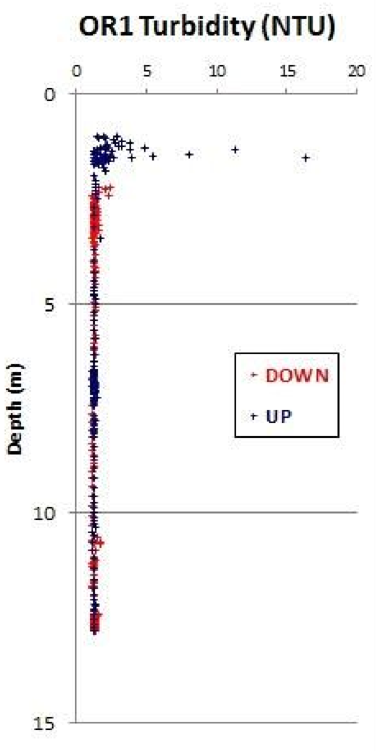
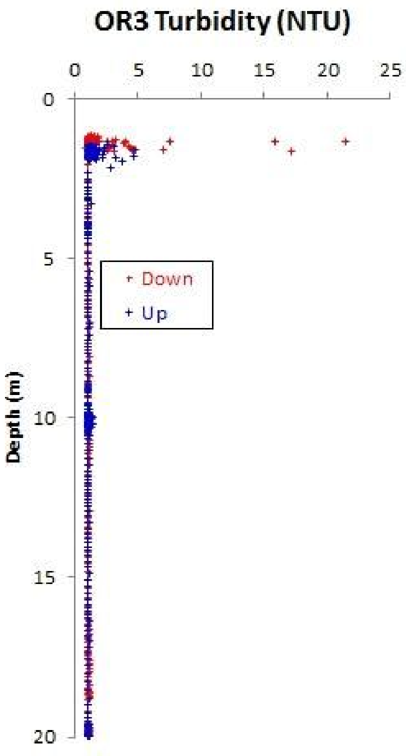


Figure 17: Scatter plots comparing (a,b) relative ("CI") and (c.d) uncalibrated absolute turbidity ("NTU") for site "2" (see maps above) to daily averages of (a,c) in situ wind speed ("U", kts.), and (b,d) significant wave height ("H_S", m) from NOAA WaveWatch III operational model attenuated with NGDC bathymetry.

In situ Measurements

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





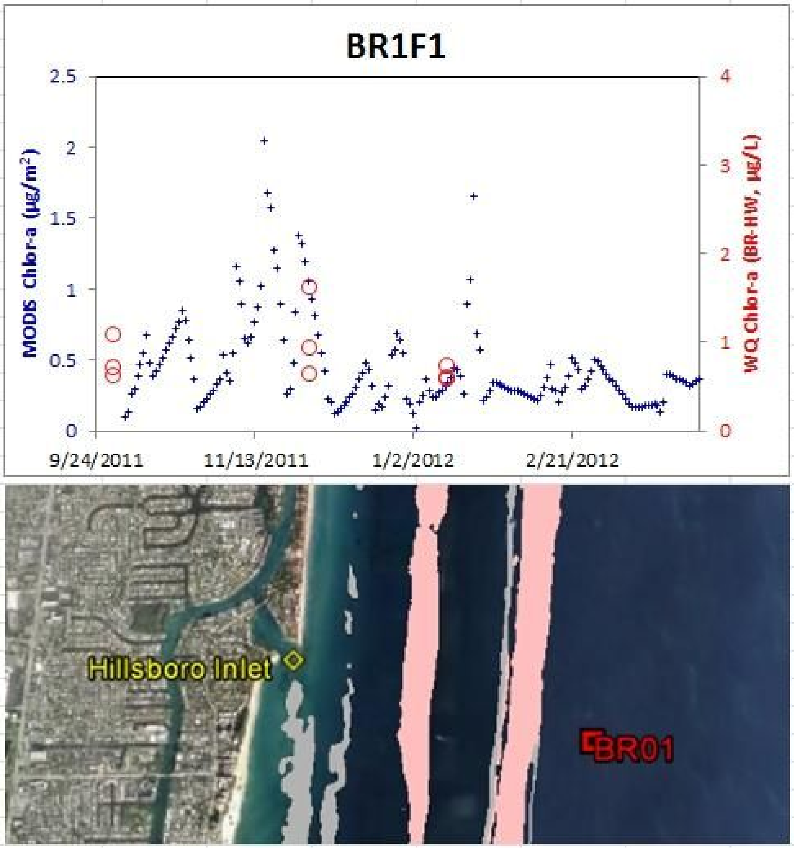


Figure 18: In water turbidity measurements during FACE cruises, with remote sensing algorithm comparisons.

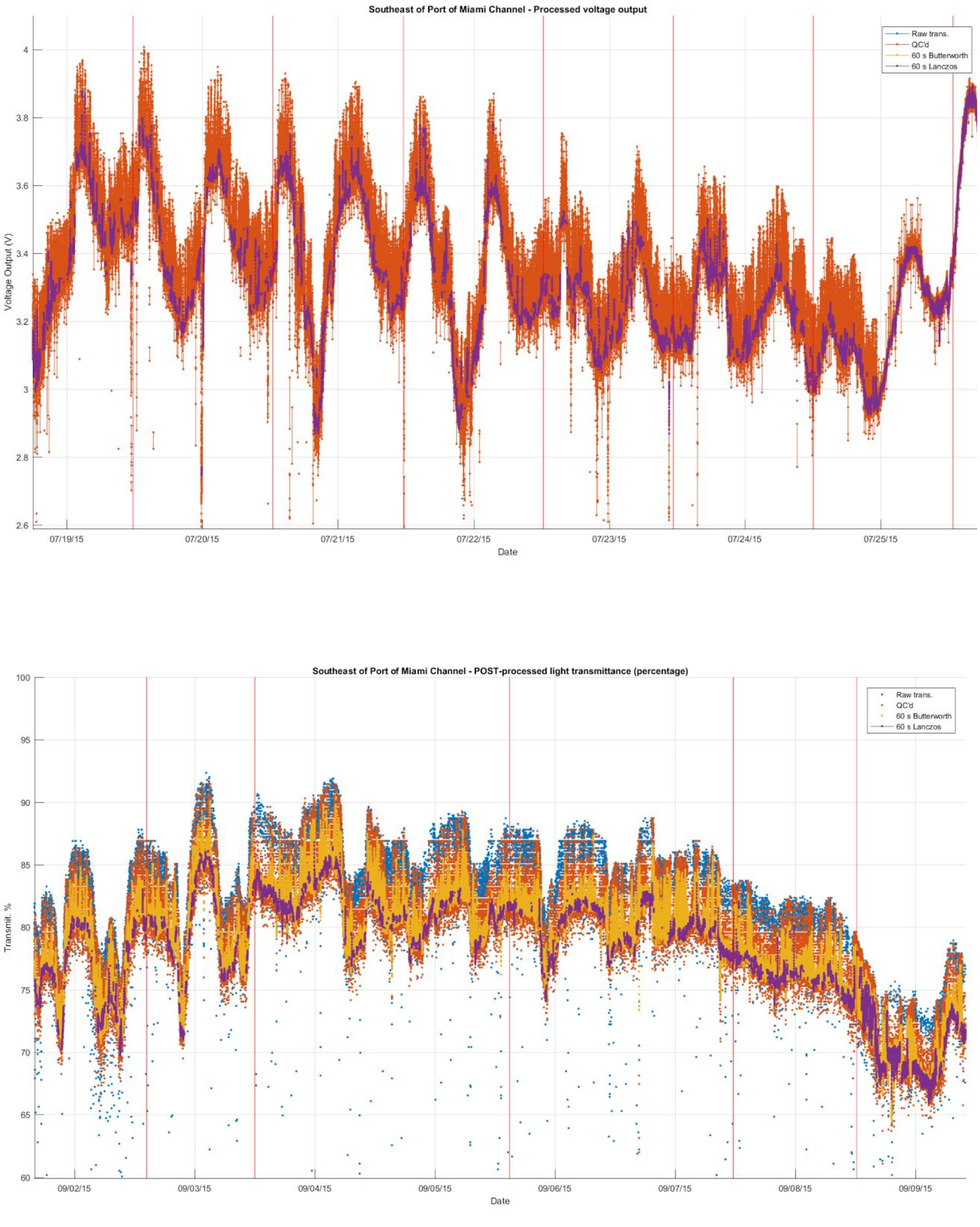
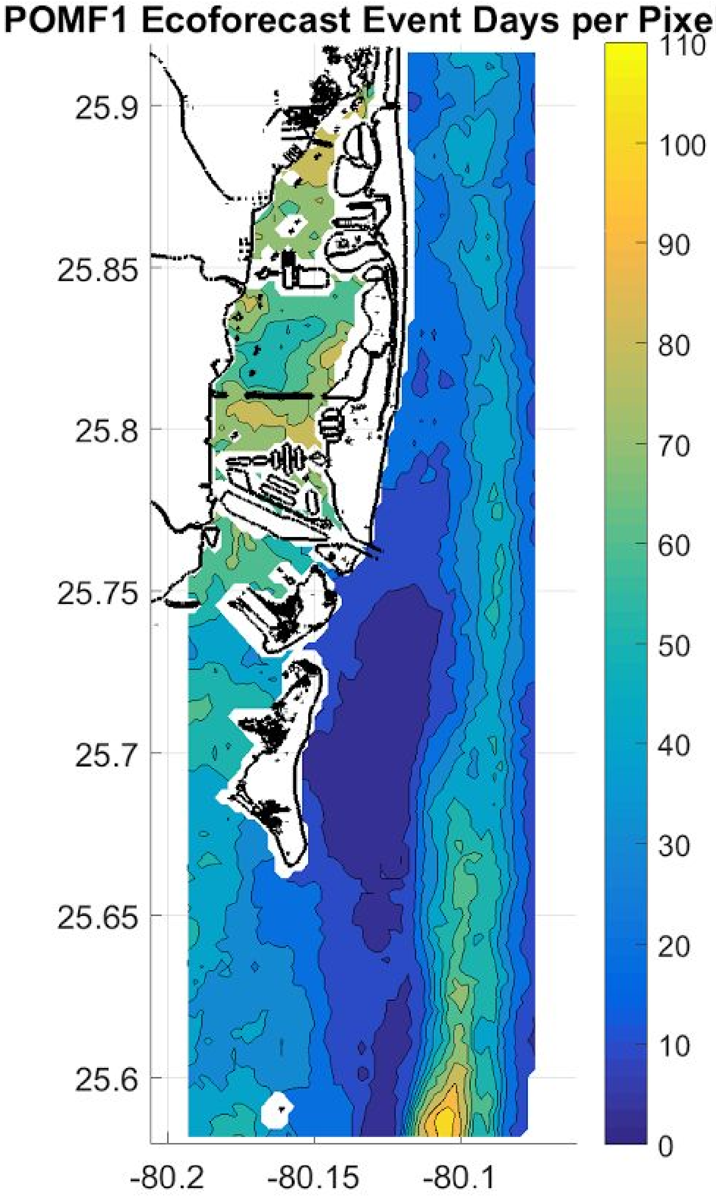


Figure 19: In water turbidity measurements taken as part of this project at site "POMF1" (a) 18-26 July 2015, and (b) 01-09 September 2015. Dates and times of clear-sky MODIS satellite overpasses are marked with red lines.

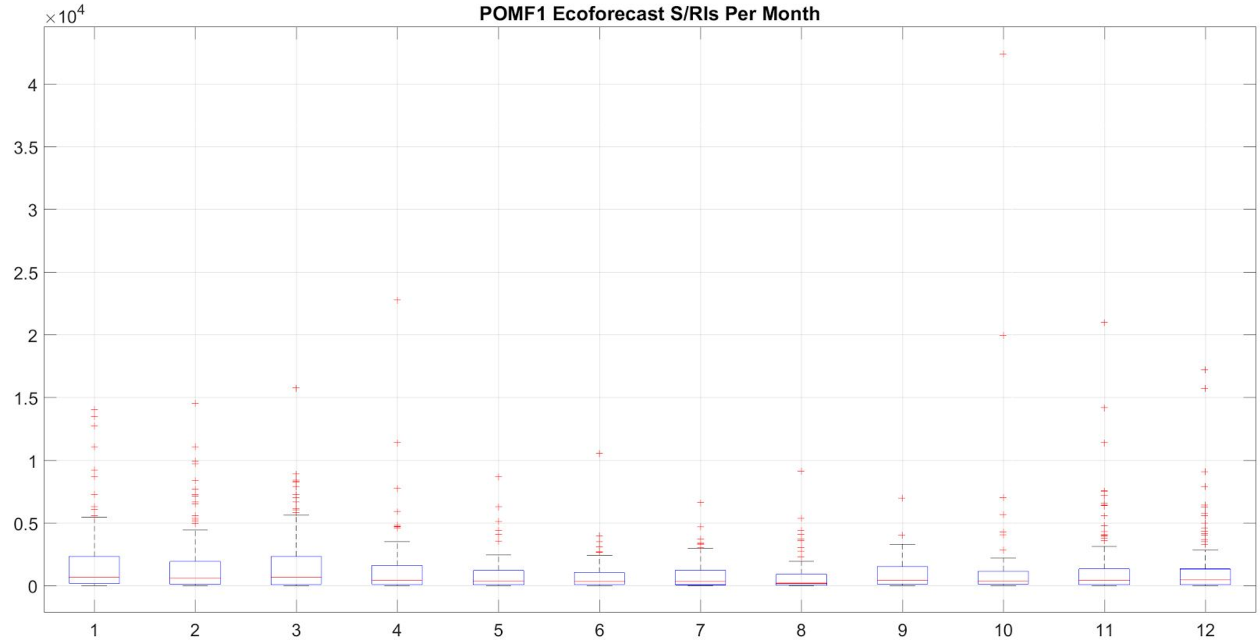
Ecoforecasts

Port of Miami

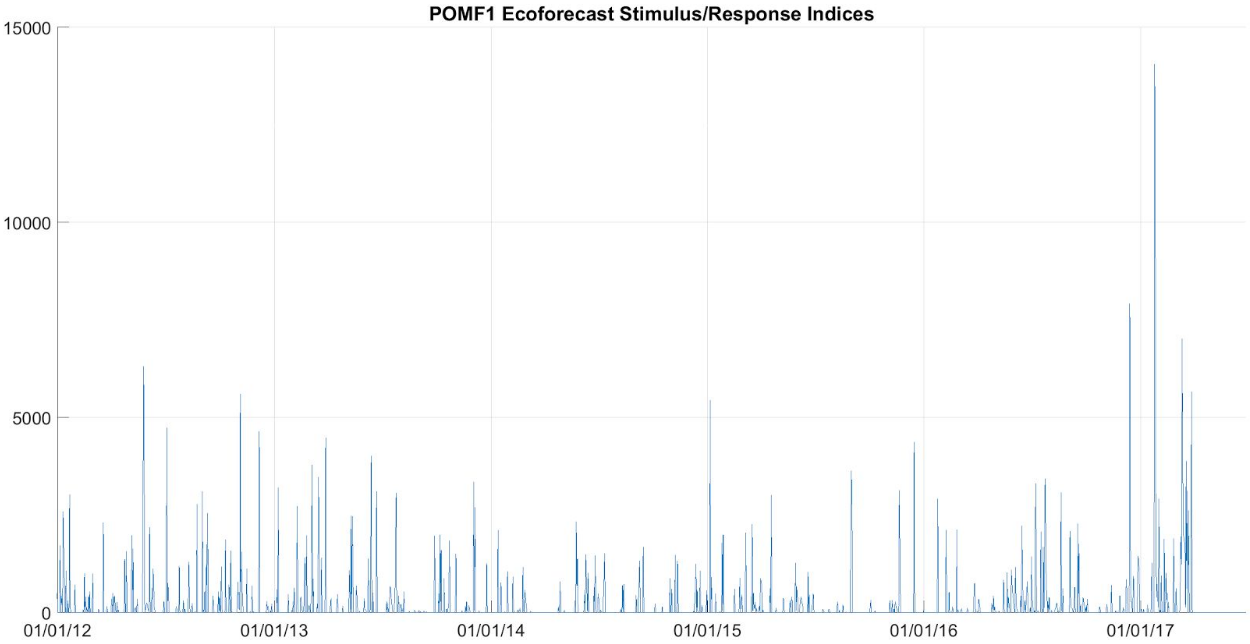
Between Feb 2005 and Feb 2017, for Port of Miami POMF1 ROI, 1304 days (overpasses) of enhanced turbidity were noted in at least one pixel, approximately 400 without high waves. Day-pixels with enhanced relative turbidity were more common to the north of and immediately offshore of Port of Miami Channel (10-55 days) than to the south; (<20 days within 15 km of the Channel). As for PVGF1 (above), 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 4-6 km offshore, with more than 100 days of enhanced turbidity.



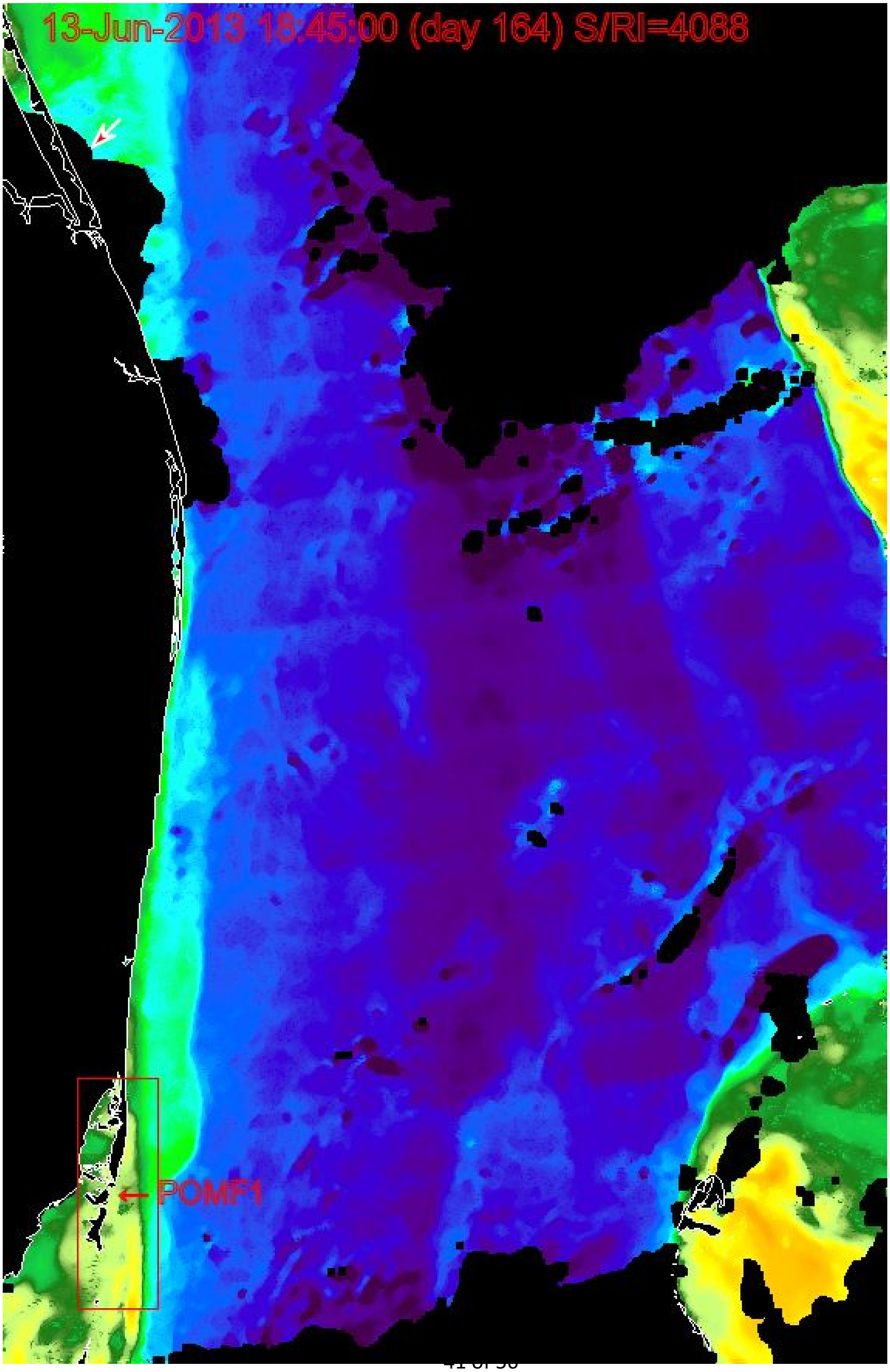
For the POMF1 ROI, both events and extreme events were distributed evenly throughout the year. This is shown in the STSRI monthly values of the boxplot figure below.

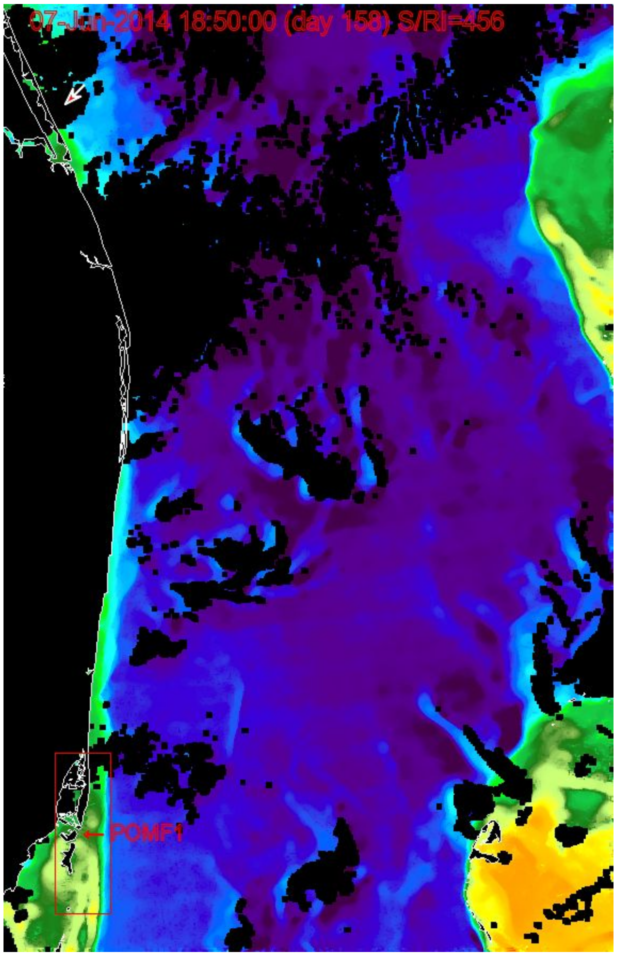


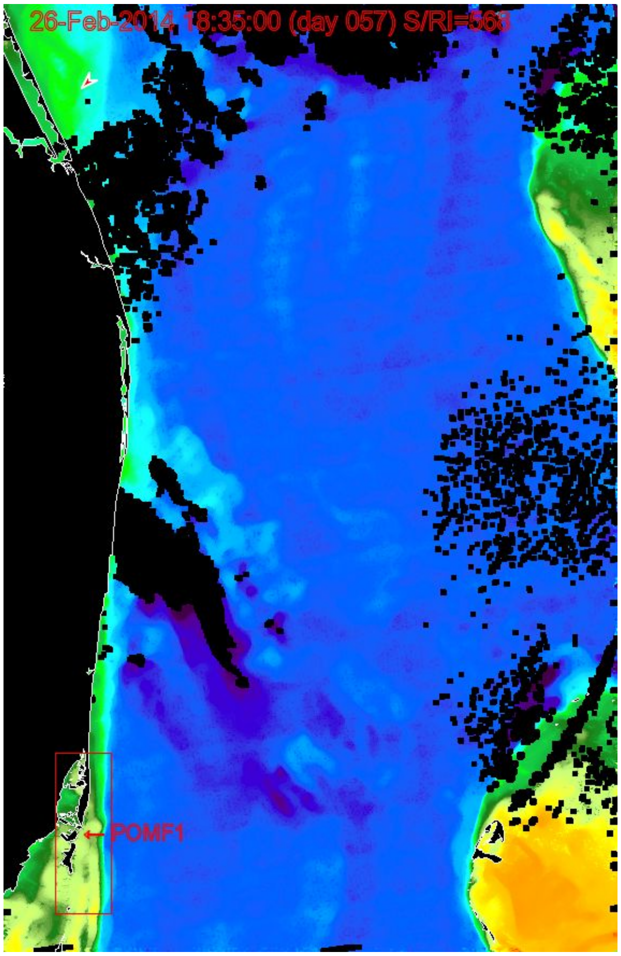
The most widespread events of the past five years near POMF1 occurred in January, April-June, July, August-September, November, and December 2012 ; March, May, June, 27 Sep to 02 Nov, and 02 to 04 Dec 2013; February, May, and June 2014; January, August, and December 2015; June-September 2016; and especially December 2016-March 2017 (see Figure below).



ROI satellite CI images of some of these events follow. In the upper left corner of each is an arrow showing the direction and significant wave height (scale of 2.5 cm per m of wave height) of attenuated modeled waves at the center point of that ROI on the day of the satellite overpass.


13-Jun-2013 18:45:00 (day 164) S/RI=4088
POMF1





These were the dates of the highest STSRI during the past five years in this ROI when skies in the region were clear enough to discern likely spatial relationships between plumes and inshore waters. Those in bold were particularly persistent or widespread; those marked with "?" were dates that, despite all the filters applied, were potentially confounded by persistent cloud cover.:

2012 Feb 15, Feb 22, Feb 24, Sep 05, Oct 31, Nov 08, Nov 15, Nov 24

2013 Feb 03, Mar 07, Apr 17, May 08, May 19, Jul 29?

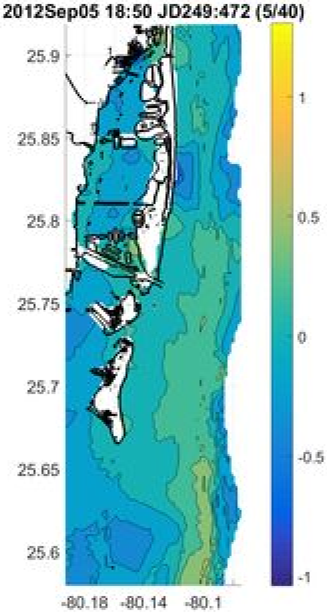
2014 Feb 06, **Feb 26**, Nov 11,

2015 Jan 07!, Mar 19, May 08?, **May 20**, Jun 07?, Jun 28, Nov 08?

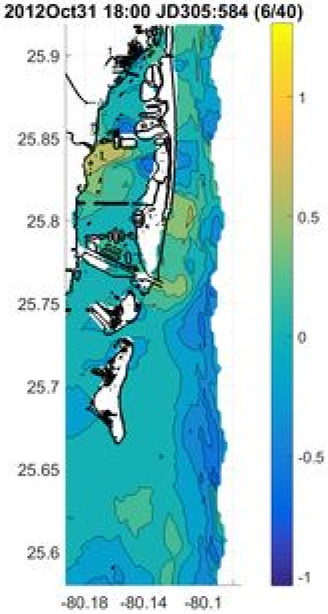
2016 May 20, Jul 28?, **Jul 30**, **Aug 22**, Nov 26

2017 Feb 26, Mar 10, Mar 31, May 12

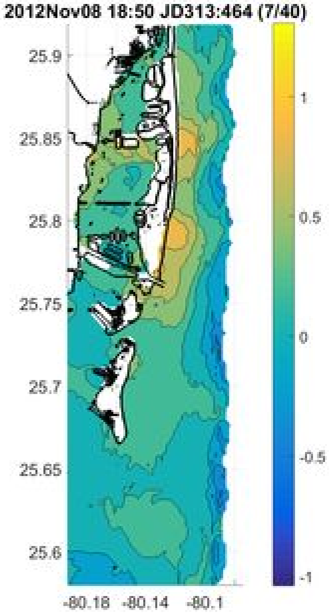
Normalized CI data fields for some these dates are shown below.



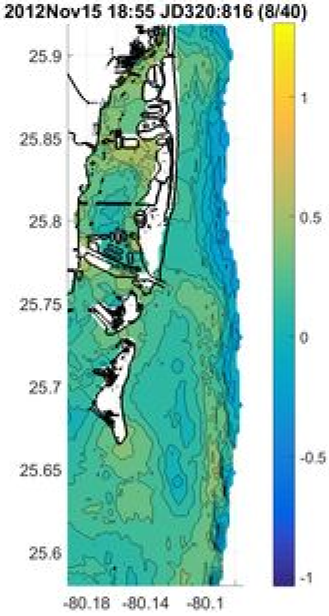
2012Sep05 18:50 JD249:472 (5/40)



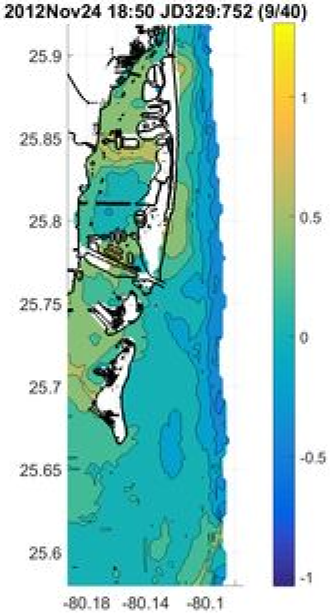
2012Oct31 18:00 JD305:584 (6/40)



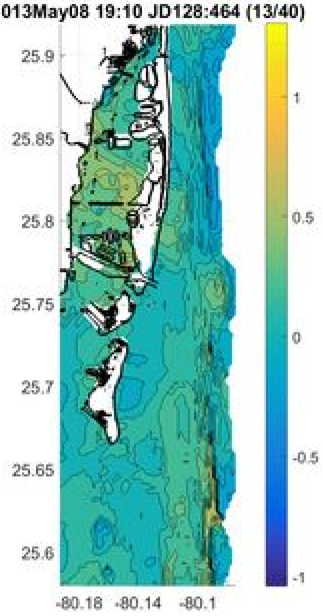
2012Nov08 18:50 JD313:464 (7/40)



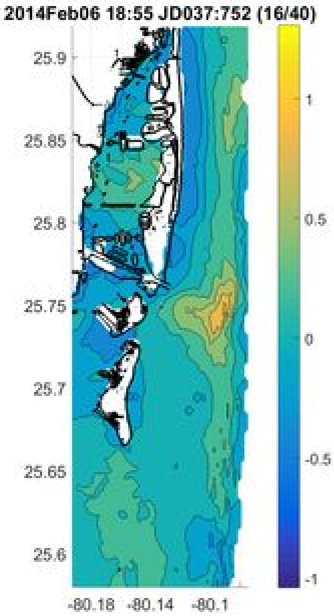
2012Nov15 18:55 JD320:816 (8/40)



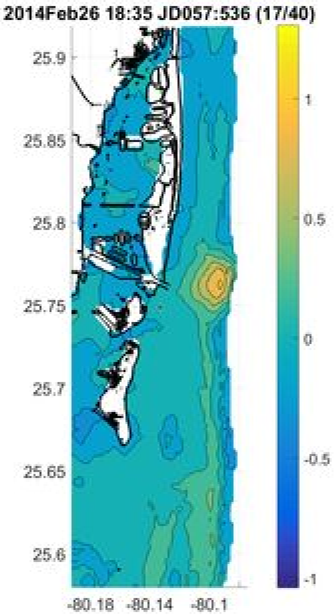
2012Nov24 18:50 JD329:752 (9/40)



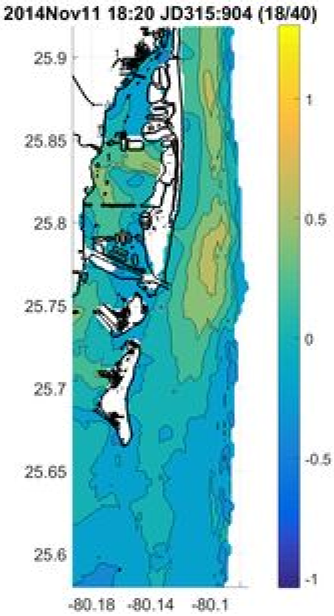
2013May08 19:10 JD128:464 (13/40)



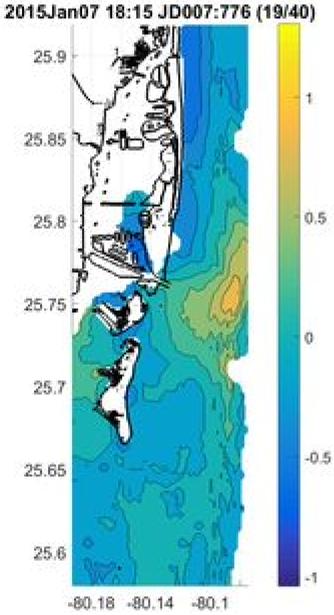
2014Feb06 18:55 JD037:752 (16/40)



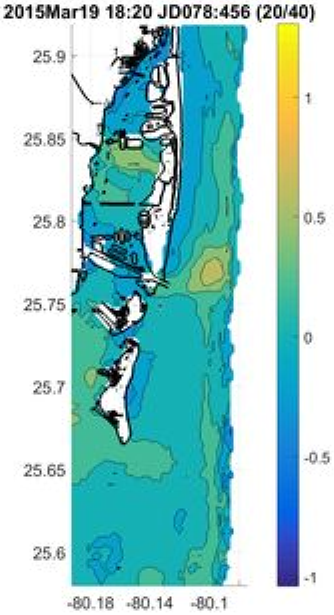
2014Feb26 18:35 JD057:536 (17/40)



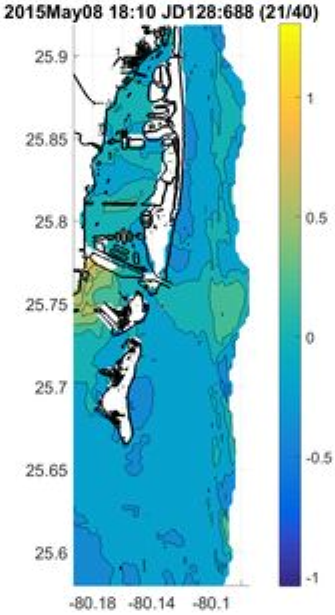
2014Nov11 18:20 JD315:904 (18/40)



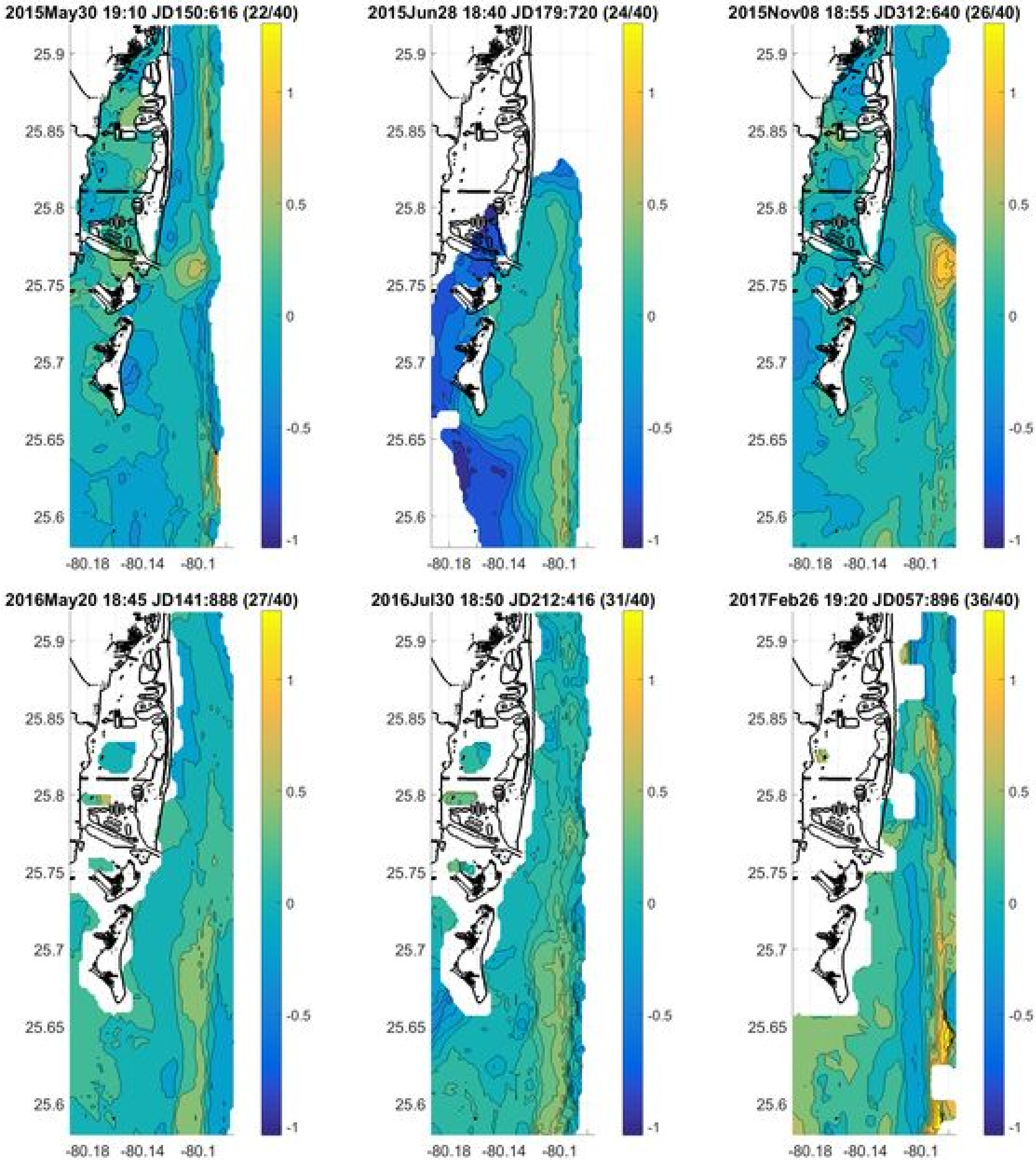
2015Jan07 18:15 JD007:776 (19/40)



2015Mar19 18:20 JD078:456 (20/40)

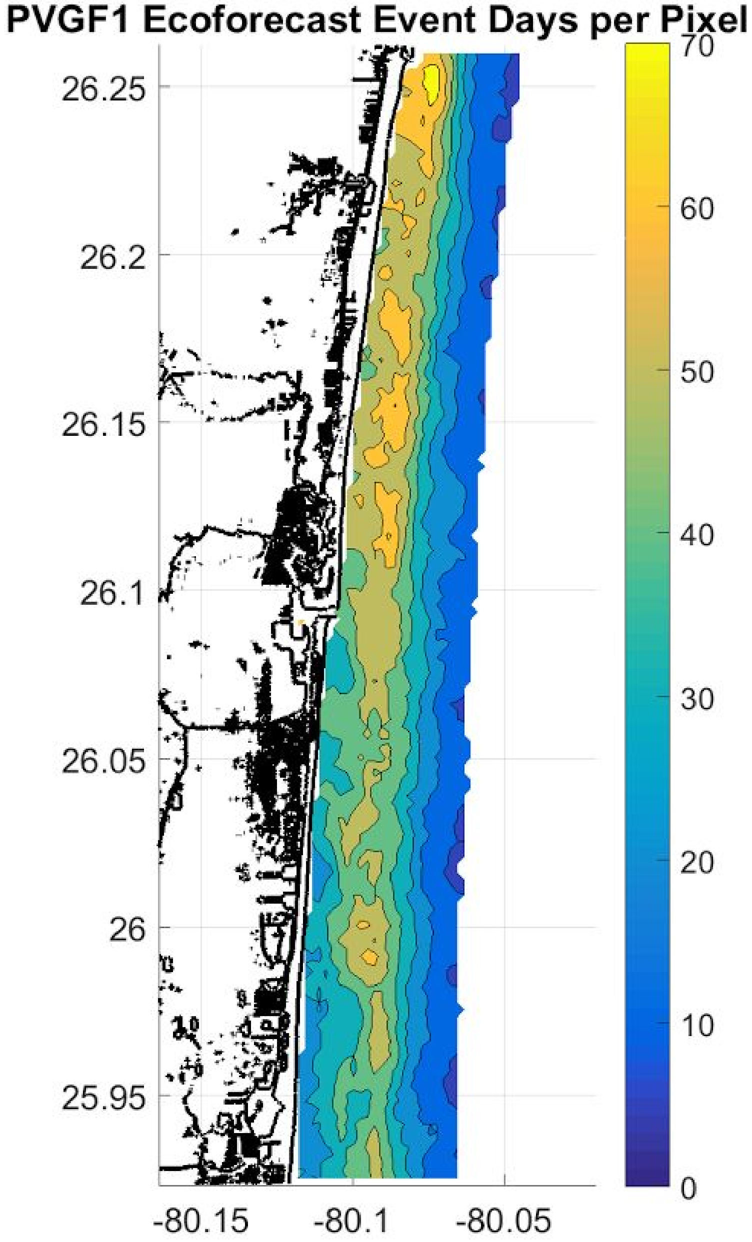


2015May08 18:10 JD128:688 (21/40)

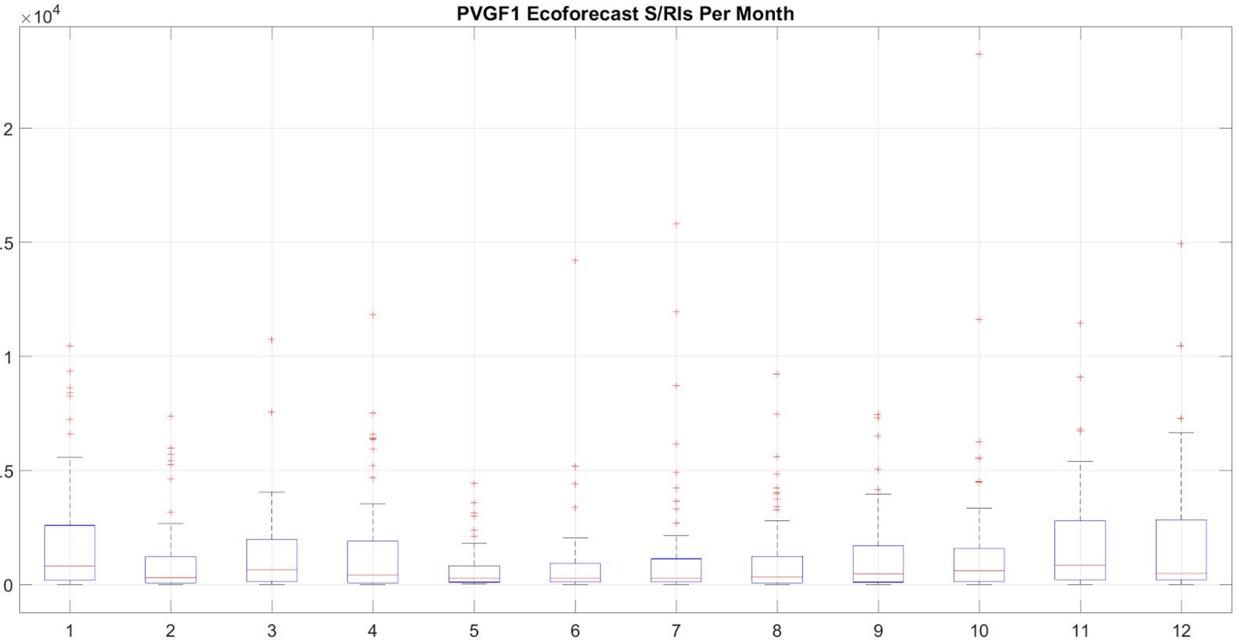


Port Everglades

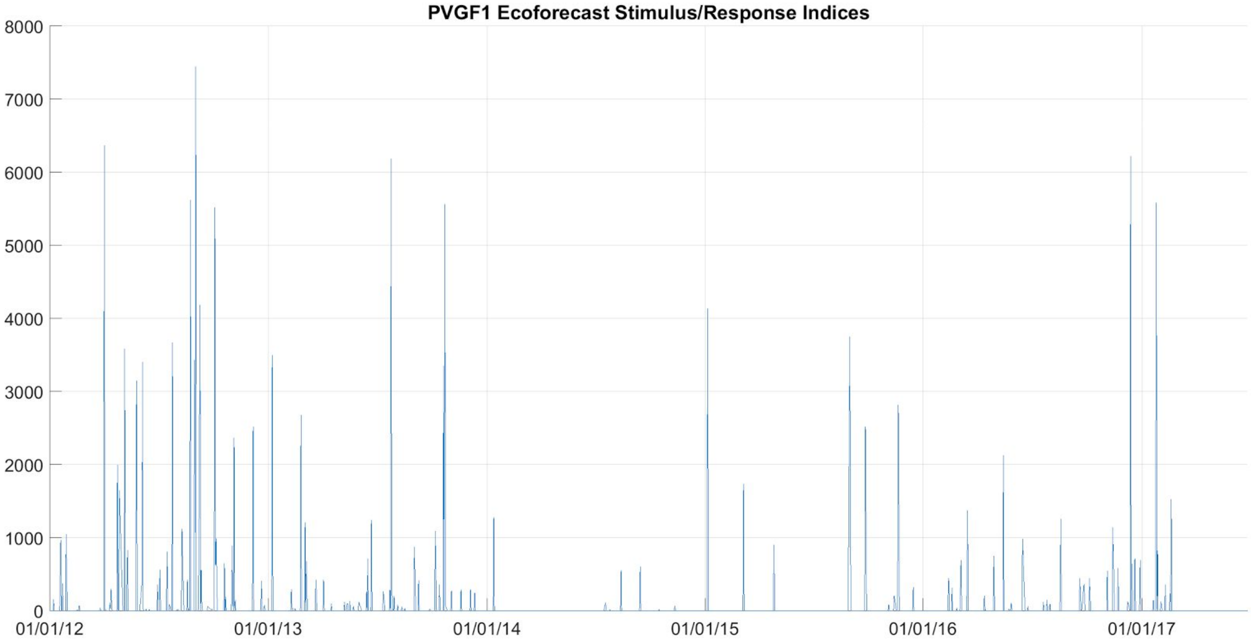
Between Feb 2005 and Feb 2017, for Port Everglades PVGF1 ROI, 633 days (overpasses) of enhanced turbidity were identified in at least one pixel, 230 of which did not correspond with high waves. Of these, 75 days were identified as "extreme events". Day-pixels during these 12 years that showed enhanced 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 greater a tendency to cluster within and across the first reef line, while events to the south of the Channel were on average 1 km further offshore.



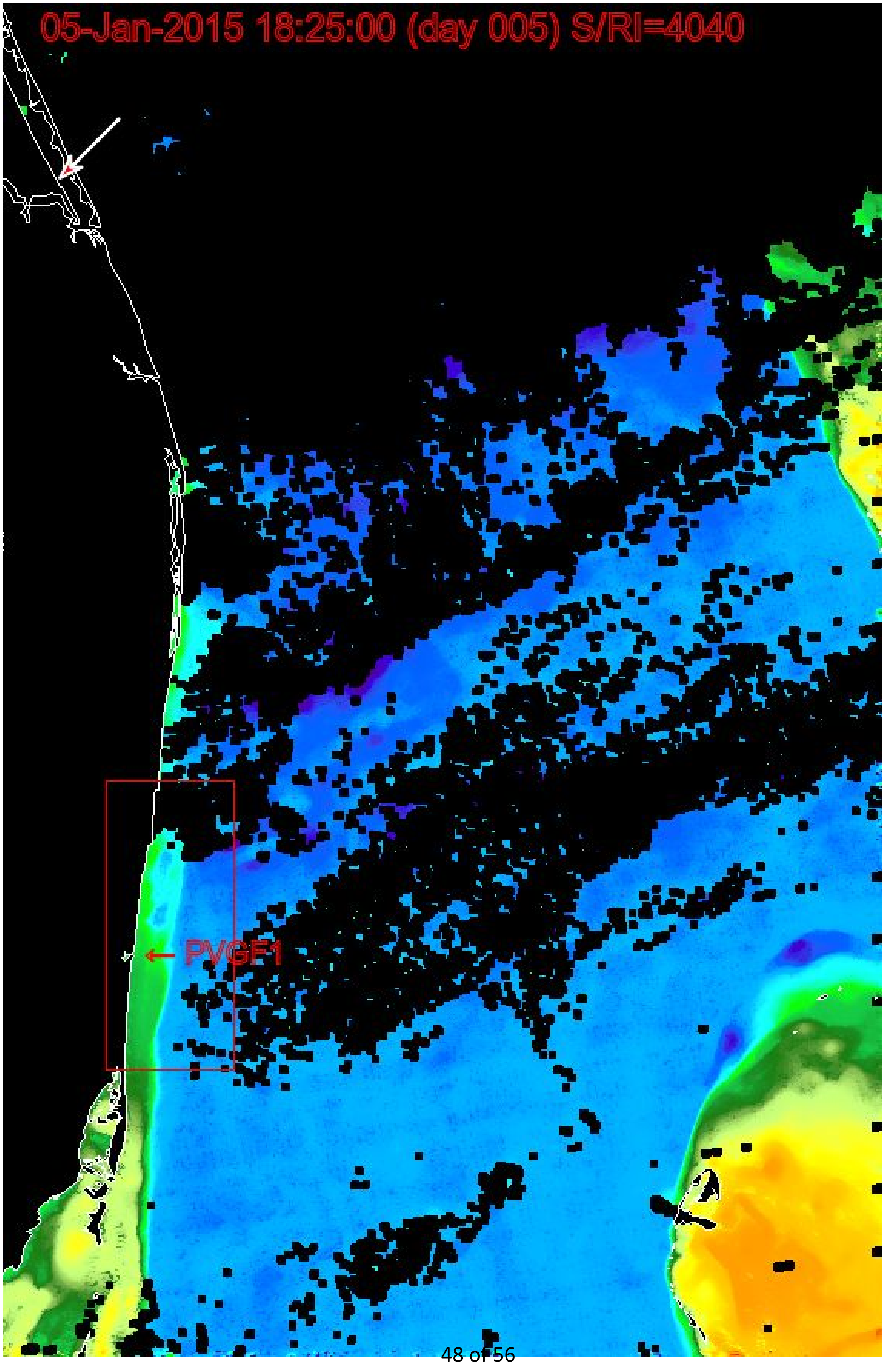
For PVGF1, events occurred with roughly the same frequency during each of the twelve months of the year (see Figure below), while extreme events were concentrated in a few months of the year (extrema represented by red "+" in the boxplot figure below, and peak S/RI in the time series figure following that).



The most widespread events of the past five 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 (see figure below).



Below is a sample image at high resolution from one of the widespread event days, January 5th, 2012.


05-Jan-2015 18:25:00 (day 005) S/RI=4040
← PVGF1

These were the dates of the highest STSRIs in this ROI when skies in the region were clear enough to discern likely spatial relationships between plumes and inshore waters. Again those in bold were most widespread and/or persistent:

2012 Jan 18-19, **Aug 09**, Aug 31, Oct 04, Oct 05, Dec 20

2013 **Feb 24**, Jun 18, **Jun 22**, Oct 06

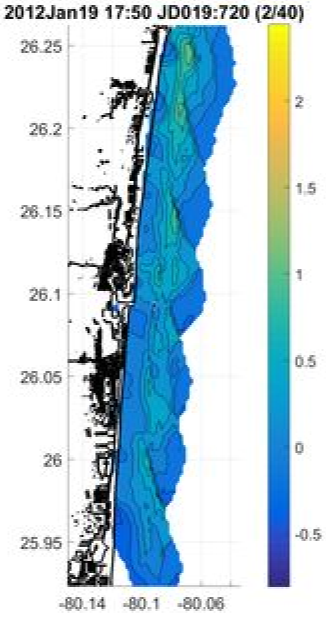
2014 **Jan 12**,

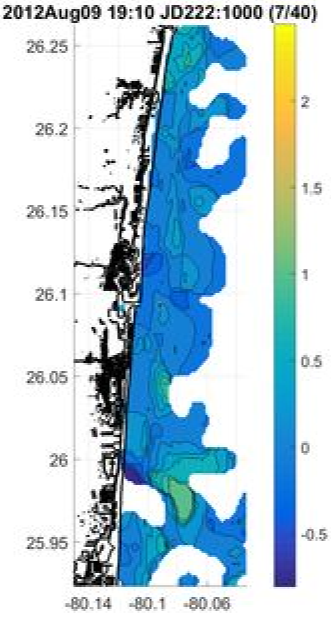
2015 **Mar 06**, **Apr 16**, Apr 18, **May 20**, **Jun 21**

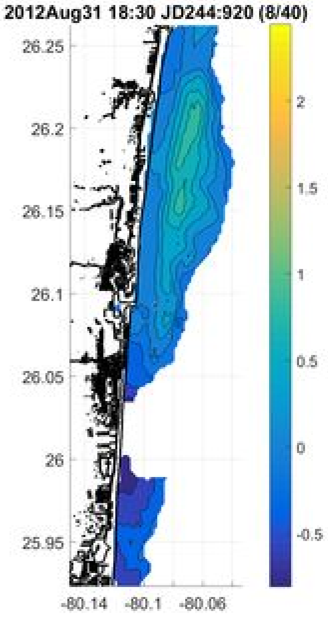
2016 Mar 26, May 23, Jun 01, **Jul 26**, **Dec 14**

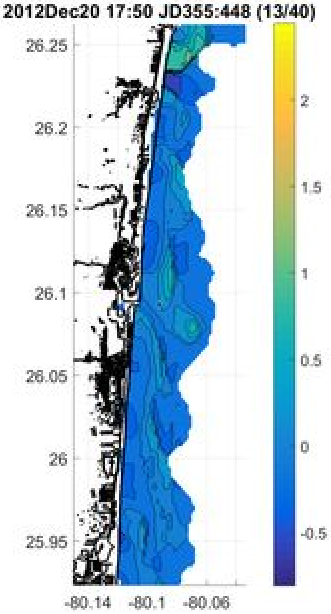
2017 May 12, **May 28**

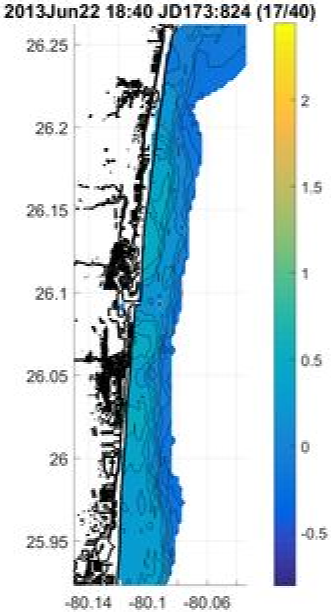
Normalized CI data fields for some these dates are shown below.

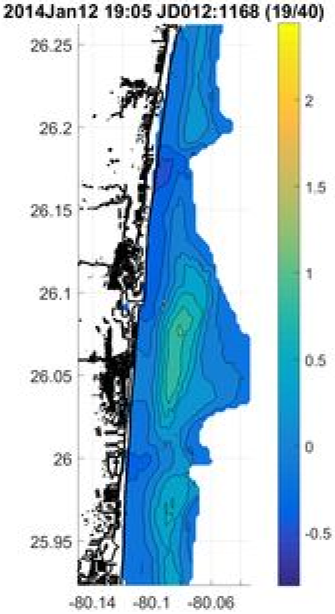

2012Jan19 17:50 JD019:720 (2/40)

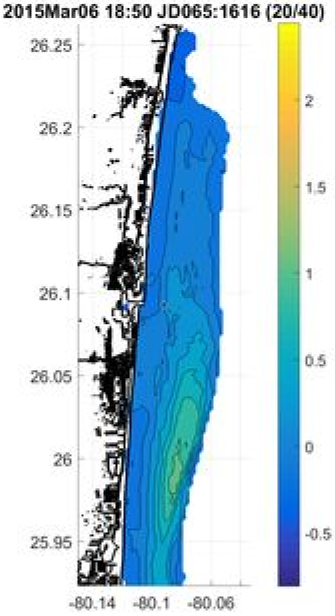

2012Aug09 19:10 JD222:1000 (7/40)

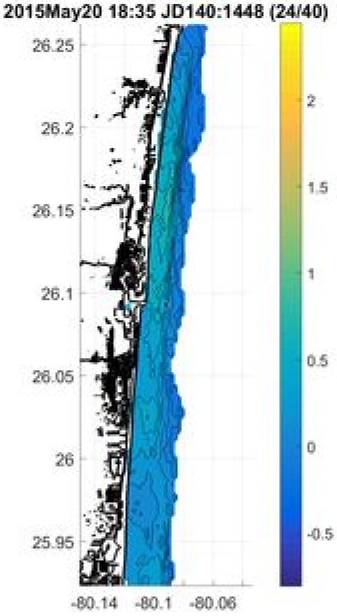

2012Aug31 18:30 JD244:920 (8/40)

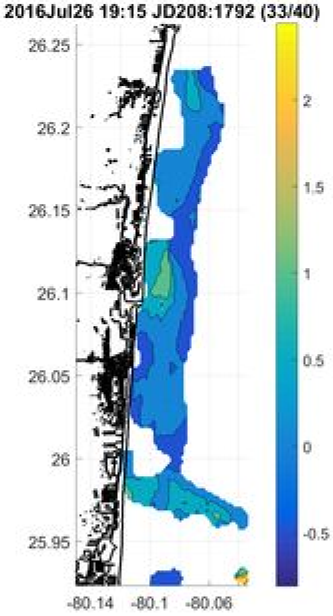

2012Dec20 17:50 JD355:448 (13/40)

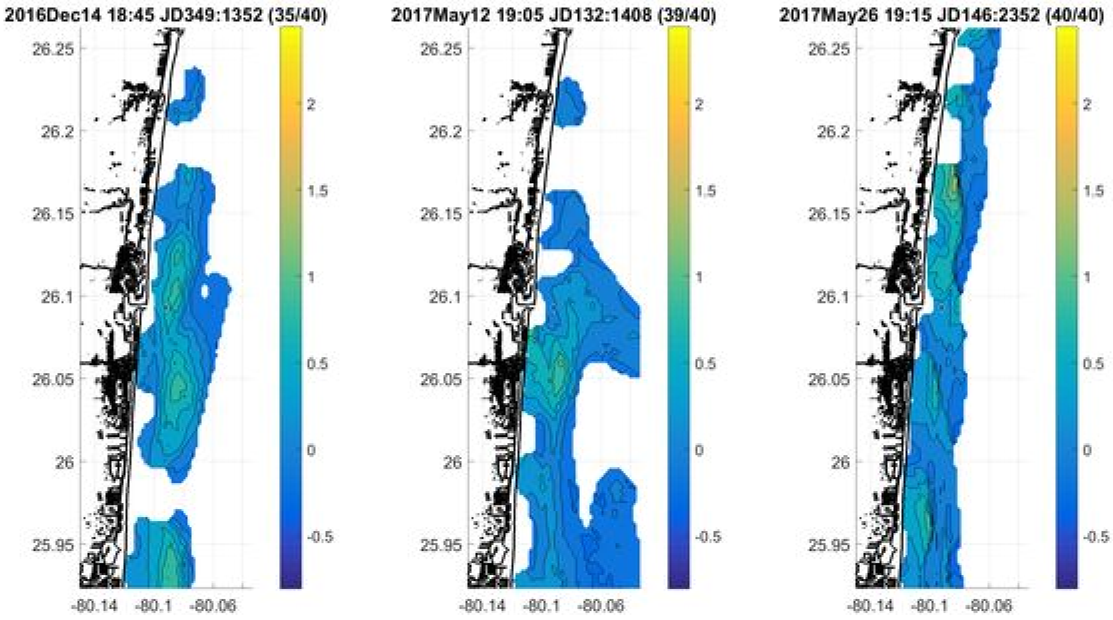

2013Jun22 18:40 JD173:824 (17/40)


2014Jan12 19:05 JD012:1168 (19/40)


2015Mar06 18:50 JD065:1616 (20/40)

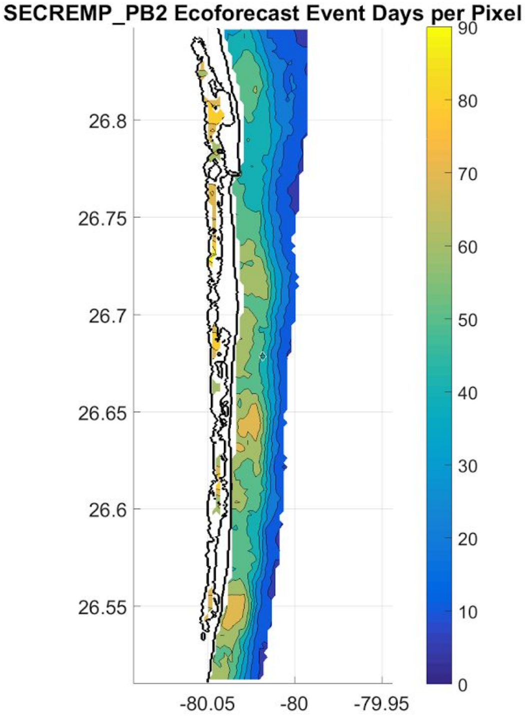

2015May20 18:35 JD140:1448 (24/40)

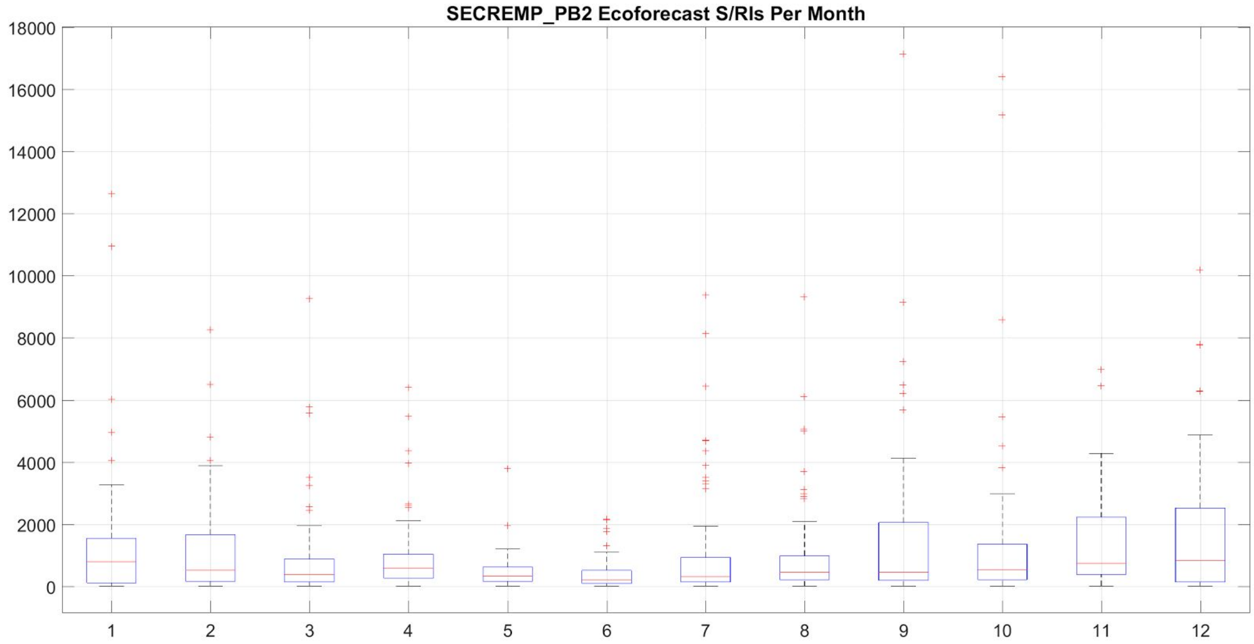

2016Jul26 19:15 JD208:1792 (33/40)

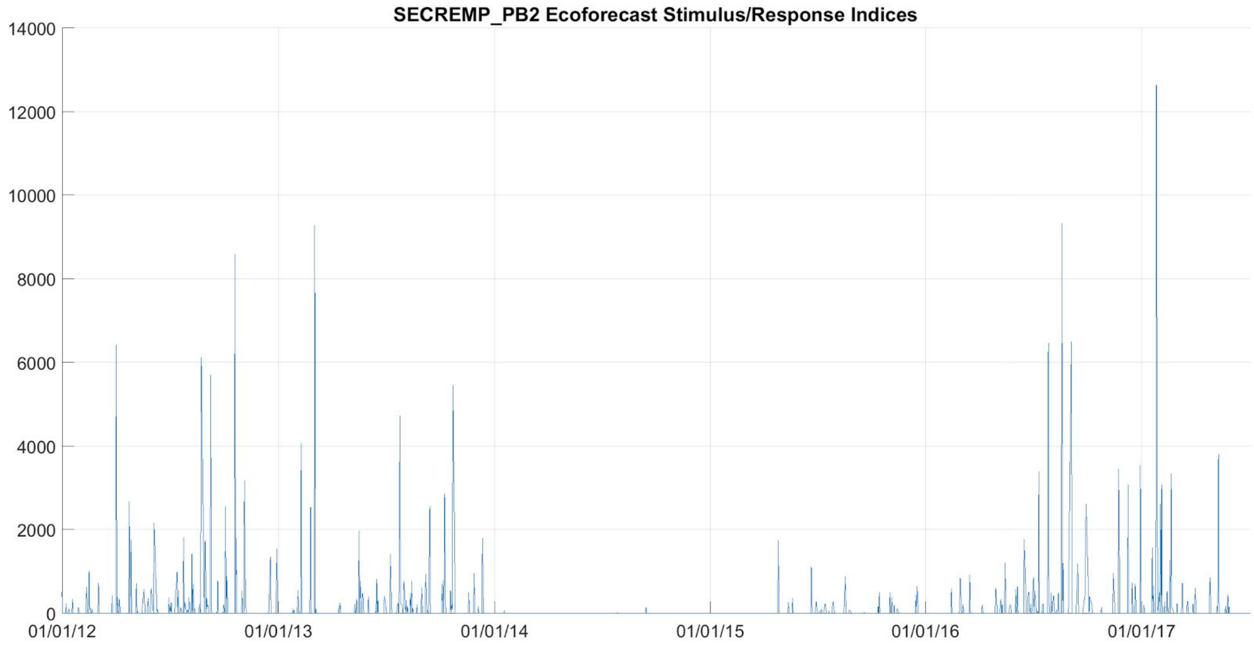


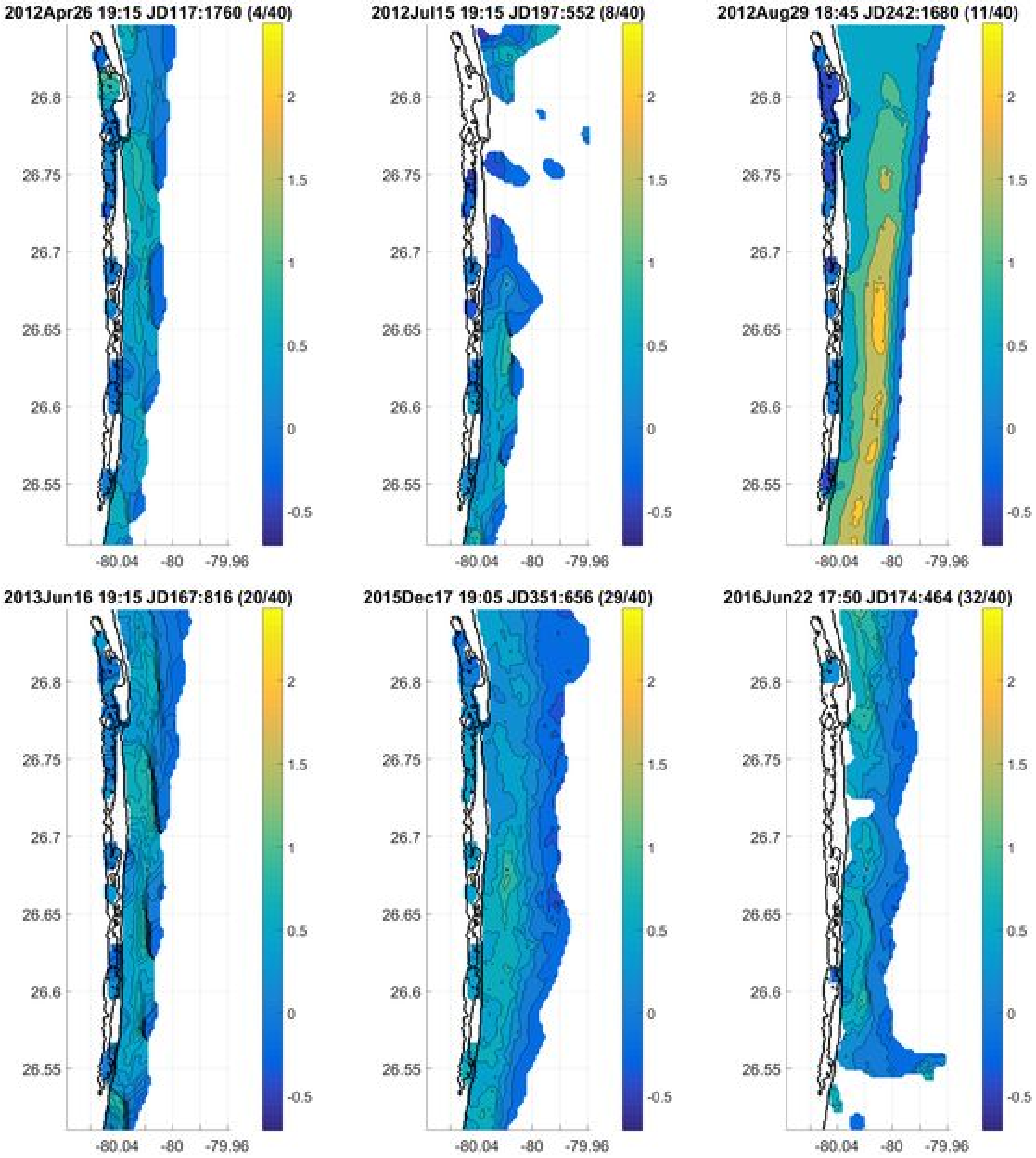
Palm Beach

A final ROI for southeast Florida was selected offshore of Palm Beach county, in order to monitor the potential turbidity associated with beach renourishment projects and coastal construction ashore in that region.




SECREMP_PB2 Ecoforecast S/RIs Per Month
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
2
3
4
5
6
7
8
9
10
11
12


SECREMP_PB2 Ecoforecast Stimulus/Response Indices
14000
12000
10000
8000
6000
4000
2000
0
01/01/12
01/01/13
01/01/14
01/01/15
01/01/16
01/01/17



Conclusions

High relative turbidity events across the three Regions of Interest in southeast Florida waters from the years 2012-2017 are summarized above. 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 is 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.

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