FINAL REPORT

National Marine Aquaculture Initiative: Using GIS for Offshore Aquaculture Siting in the U.S. Caribbean and Florida

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Summary

Geographic Information Systems (GIS) would appear to offer an ideal tool for optimizing the location of offshore cage aquaculture installations, which should in theory be sited so as to maximize the co-occurrence of desirable regulatory and biophysical parameters. In this project it was planned to use GIS to integrate and assess very large remote sensing data sets, and, in conjunction with an objective “Cage Aquaculture Suitability Index” (CASI) analogous to the Habitat Suitability Index models already being used in fisheries and Coastal Zone Management, to pinpoint optimal marine sites.

While regulatory data are widely available for the three regions under investigation (Florida, the Commonwealth of Puerto Rico (CPR), and the U.S. Virgin Islands (USVI), we have discovered that the necessary synoptic biophysical oceanographic coverages are either unavailable or unsuitable in this application. For Florida it is possible to draw some qualitative conclusions regarding offshore cage aquaculture location; a zone off North Palm Beach appears to meet all the regulatory and environmental parameters. The available information is even scarcer for the CPR or the USVI, making GIS a less than ideal tool for siting offshore aquaculture operations in the US Caribbean region.

Besides enhancing the body of knowledge about GIS applications in aquaculture, this research refutes the assumption that GIS data about the most important parameters for site selection in offshore aquaculture criteria are readily available. Conversely, it corroborates that site selection for offshore aquaculture is a process of elimination, that there are no ideal sites and compromising is required, and that it is necessary to conduct detailed localized studies once any given pre-selected site is chosen.

Introduction

GIS has been used in aquaculture since the mid-1980s. Meaden and Kapetsky (1991) combined several of the earliest case studies in an FAO technical paper along with complete information on the use of GIS and remote sensing in inland fisheries and aquaculture. These include the use of SPOT imagery to select shrimp farm sites, of remote sensing and limited GIS to find oyster culture sites, and of GIS for catfish farming development by mapping and analyzing the physical characteristics of soils, to assess the potential for salmonid sea cage culture in Camas Bruich Bay, west coast of Scotland, and to find where the best opportunities for fish farming in Ghana. Another early study conducted by Meaden (1987) suggested the criteria necessary for GIS assessment of areas for culture of rainbow trout. In the same year, Kapetsky et al. described the use of GIS for site evaluation for mollusk, shrimp and fish culture in coastal areas of Costa Rica. In 1994 Kapetsky continued his studies using GIS and its applications to aquaculture to determine the warm water fish pond farming potential in Africa. All of these studies involved relatively small areas that could be analyzed with large-scale data sets.

Nath et al. (2000) give a detailed evaluation of the potential applications of GIS for spatial decision support (SDS) in aquaculture, emphasizing the constraints (primarily limited understanding of GIS principles and methodologies, plus inadequate commitment to ensure continuity of GIS use in SDS) that limit its application. However Nath et al. 2000 do not address a more fundamental limitation discovered during this project: the general lack of suitable digital datasets of relevant biophysical parameters.

Although GIS proved to be of limited value in this study, it is still recommended that, prior to the establishment of any offshore aquaculture operation, a detailed site assessment be conducted to evaluate – at the very minimum - the following parameters. Almost all of these are spatial and should be analyzed at the largest scale available:

- Conflicting uses of area
- Shore line contour
- Depth profile
- Exposure to wind
- Fetch
- Currents
- Maximum wave height
- Tides
- Water temperature
- Salinity
- Dissolved oxygen concentration
- Pollution (organic and inorganic)
- Phytoplankton and zooplankton occurrence and distribution
- Potential danger of red tides, plankton blooms, biofouling
- Predators - crabs, fish, birds, seals, etc.
- Flora and fauna studies (indicator organisms)
- Accessibility to the site – roads, transportation, airport, port, etc.
- Infrastructure - facilities, security, communication, electricity, freshwater
- Potential for expansion - availability of adjacent area
- Environmental assessment, monitoring and control – bioremediation and mitigation
- Legal framework – policies, regulations, licenses, permits, concessions, etc.
- Public and government acceptance of project

Interpretive Data Model

Interest in offshore aquaculture has increased substantially over the past decade due in part to the negative environmental impacts of nearshore cage culture of marine fishes in fijords and bays around the world. The objective of this study was to find offshore areas representing the intersection of relevant regulatory and biophysical parameters through overlays of raster, vector, and CAD coverages of those parameters. Two categories of spatial data were envisioned for analysis:

1) those concerning the regulation and management of offshore resources (e.g., Endangered Species, NEPA, CZMA, OCSLA, SLA, MARPOL, Magnuson-Stevens Act, National Pollutant Discharge Elimination System Permit Sites, Ocean Dredged Material Disposal sites, artificial reef sites, offshore resources, Marine Protected Areas, navigational aids, coral reefs, MMS/OCS active lease blocks, EEZ, state and federal jurisdictional

boundaries, Intracoastal Waterway route (FL), and Department of Defense Seaways and Restricted Areas;

2) oceanographic biophysical parameters that might directly or indirectly affect offshore cage aquaculture operations (e.g., bathymetry, currents [directions and speeds, monthly maxima and averages], turbidity, bedrock geology, sediment substrate type, benthic habitats, monthly temperatures [sea surface and bottom], monthly winds [speeds and directions], fetch, maximum wave heights, salinity, dissolved oxygen, seasonal phytoplankton and zooplankton occurrences).

Spatial data concerning the first category are abundant for Florida, and adequate for the CPR and USVI. Oceanographic biophysical coverages that (1) include the continental shelf, and (2) possess high spatial and temporal resolution are remarkably lacking for all three regions.

General Discussion of Regulatory Issues: Applicable U.S. Federal Law

Policy. Codified in the National Aquaculture Act of 1980, the U.S. Congress declared that it was in the "national interest" of the U.S. and should be the "national policy" to "encourage the development of aquaculture in the United States."

Regulations. Generally applicable to <u>all</u> U.S. waters, be they state or federal waters within 12 nautical miles (nm) of coastal baselines, and (in limited cases out to 200 nm), U.S. federal law relating to offshore aquaculture is widely distributed, with at least 11 federal agencies and over 50 federal laws that could apply to an offshore aquaculture activity. This project made the following assumptions regarding federal regulations:

Operations within 12 nm of the coast. The vast majority of applicable federal laws will apply (whether operating within state or federal waters). The number of laws that will apply, however, will directly relate to the specifics of the area involved (i.e., the possibility of endangered species in the area would trigger Endangered Species Act analysis; marine mammals in the area will trigger

Marine Mammal Protection Act requirements; etc.). At a minimum, any aquaculture activity can expect to be covered by several US Coast Guard regulations (relating to the cages and method of seabed attachment), the EPA under the Federal Water Pollution Control Act (involving a pollution discharge permit for escaping effluent), and the ACOE under the Rivers and Harbor Act (regulating the placing of an object in navigable waters that could pose a hazard to navigation). Additionally, though no permit is required, it is likely that the applicable Regional Fishery Management Council will have to comment on any effects on fisheries in federal waters beyond state jurisdiction.

In waters beyond 3 nm (9 nm along the Texas and Florida Gulf coasts), state law will generally not be able to reach these operations (though indirectly, the consistency requirements of the federal Coastal Zone Management Act may require that offshore activities not violate adjacent state plans for coastal management, and state laws relating to health may apply should the aquaculture products be landed there). In terms of analysis, one would incur more federal regulatory requirements when operating within 12 nm, and substantially more overall regulatory requirements when operating within 3 nm where both state and federal laws will apply.

Operations between 12 and 200 nm of the coast. Fewer federal laws will apply and no state laws will apply, because these waters are not exclusively U.S. (technically they are “high seas”, subject to the rights/duties of the Exclusive Economic Zone and certain applicable federal laws).

In terms of analysis, operations beyond 12 nm will incur fewer regulatory requirements; however, without knowing the specifics of the area selected, one cannot say which laws will actually apply. But in these areas, fewer federal laws have jurisdiction and no state law can directly affect this area (though again, indirectly, the consistency requirements of the federal Coastal Zone Management Act may require that offshore activities not violate adjacent state plans for coastal management, and state laws relating to health may apply should the aquaculture products be landed there).

Applicable State and Commonwealth Law. State laws, which often mirror federal law, will apply to all operations within 3 nm of the coast. Note that waters off the Gulf Coast of Florida fall under state jurisdiction to 9 nm. Likewise, some state requirements, if tied to their approved Coastal Zone Management Plan, may also apply beyond state waters (as noted above, under the consistency requirement of the federal Coastal Zone Management Act). As with federal waters, the precise laws that will apply will again be based on the specifics of the selected area. One can assume the following:

Problems associated with "use conflicts" will increase as the proximity to shore increases. Very simply, more people use the nearshore zone than the deeper offshore areas. Recreational as well as commercial fishers will likely object to area closures for aquaculture projects. Additionally, in Florida, Puerto Rico, and the U.S. Virgin Islands, an extensive tourist industry exists. As such, one can expect substantive (and well funded) resistance as offshore cage sites move closer to shore. This will be led by environmental groups and local governments, which depend on tourism.

Though most environmentalists do not buy the "dilution is the solution" argument, aquaculture activities in deeper, swifter water are more easily defended (and less polluting). Further concerns include escapes by farmed species, and gear entanglements with marine mammals and seabirds.

Florida aquaculture policy and regulations.

The state is very supportive of aquaculture operations, having passed its Aquaculture Policy Act in 1984. To date, most marine aquaculture has been in near shore waters involving shellfish growout (clams/oysters) and live-rock production. Consequently, most regulations are currently written with these products in mind (i.e., shellfish leases allow for use of only 6 inches of the corresponding water column). Nevertheless, state law does allow for aquaculture leases of sovereign submerged lands and the associated water columns.

Florida waters extend to 3 nm on the Atlantic Coast and 9 nm on the Gulf of Mexico. Florida does have a Coastal Zone Management Plan, and possible consistency requirement for adjacent operations in federal waters.

The Division of Aquaculture, part of the Florida Department of Agriculture and Consumer Services, is primarily responsible for aquaculture in state waters. Leases and various permits are coordinated through this agency. Growers are required to obtain an Aquaculture Certificate and abide by promulgated "best management practices". Additionally, expect (at a minimum) permit and license requirements (water quality, special activity, aquaculture permits, etc.) from the Florida Department of Environmental Protection and the Florida Fish & Wildlife Conservation Commission.

The U.S. Virgin Islands (USVI) aquaculture policy and regulations.

USVI statutes (USVI Code, Title 12, Chap. 21), relating to establishment of their Coastal Zone Management Plan, call for development policies that "…encourage fishing and carefully monitor mariculture".

The USVI has jurisdiction, subject to <u>all</u> applicable federal laws, for all coastal waters (including bays and inland waters) from the established low water mark out to 3 nm. USVI does have a Coastal Zone Management Plan, with possible consistency requirement for adjacent operations in federal waters.

Not an incorporated territory of the United States, the USVI are governed under the 1954 (revised 1984) Organic Act, whereby the inhabitants are citizens, but do not vote for U.S. president or have a voting representative in congress. The USVI Department of Conservation and Cultural Affairs, and its Division of Coastal Zone Management, could be involved with aquaculture and possible permitting actions. Leases of submerged lands are allowed, though it does not appear they are presently (2003) used for aquaculture purposes. Federal laws (specifically clean water act regulations) apply and are enforced by the USVI authorities under USVI law, as well as by federal agents. There could be significant environmental/ "competing uses" resistance for any offshore aquaculture operations within or essentially adjacent to these islands, as tourism and its related services are the only industry in these islands. The USVI does not appear to have any established regulatory system that specifically addresses offshore/near shore aquaculture.

The Commonwealth of Puerto Rico (CPR) aquaculture policy and regulations

The CPR has declared (in Title 5, Chapter 52 of its 1999 Laws), that "…fishing and aquaculture shall be promoted as important activities for the economic development and nutrition of the Puerto Rican people." As such, systems are in place to assist with expansion of aquaculture into offshore waters (i.e., coordinated, single application procedure).

The CPR has jurisdiction, subject to all applicable federal laws, for all coastal waters (including bays and inland waters) from the established low water mark out to 12 nm.

All CPR laws are subject to applicable U.S. federal laws (i.e., the CPR can enforce stricter laws but cannot relax or limit federal laws). The Department of Agriculture and the Department of Natural and Environmental Resources each oversee different regulatory aspects of the aquaculture industry in the CPR. However, the Fishing and Aquaculture Industry Council (with a separate representative for mariculture) works as an interagency group to ensure that these industries thrive with the least governmental interference. Leases are available for submerged lands and associated water columns.

Conclusions concerning aquaculture policy and regulations

The USVI seem less amenable, in terms of their existing regulatory framework, to offshore cage aquaculture projects than either Florida of the CPR. Florida's regulatory environment is so favorably disposed towards aquaculture that there seems little reason to assume a larger burden for projects in State waters; i.e., the 3/9 nm boundary around the state does not represent a major regulatory divide for offshore aquaculture operations. We have been working towards regulating these activities in Florida. A recent master's thesis from RSMAS-

University of Miami deals extensively with the subject and proposes a whole set of regulations for open ocean aquaculture in Florida (Compton 2004).

This also appears to be the case in the CPR, although there the 12 nm boundary is equivalent between the CPR's jurisdiction and federal Territorial waters. From the standpoint of minimizing potential conflicts with other interested groups, siting of offshore cages in the Contiguous Zone (12 – 24 nm) would be advisable, up to the limits of economic logistical support of the offshore operation.

Spatial Data on the Regulation and Management of Offshore Resources

For the Southeastern US there exists a comprehensive, web-based regional ocean governance GIS. Called the Ocean Planning and Information System (OPIS), it was developed during the late 1990s by the Coastal Services Center of the National Oceanic and Atmospheric Administration (Treml et al. 1999). The spatial datasets are complete, documented and verified coverages available for download from www.csc.noaa.gov/opis. They provided all the regulatory data required for this project.

These spatial datasets, almost always involving boundaries, grids, and buffer zones, usually are stored and analyzed as vectors (known as shapefiles in ESRI terminology). Bathymetric information may exist in this format—which is analogous to an analog bathymetric chart, but it also may exist in a raster data format (see next section).

No comparable single source of regulatory data is available for the CPR or USVI. While the area involved is an order of magnitude smaller than the Florida Peninsula, not as much synoptic data have been collected for the eastern Greater Antilles, and the synoptic digital data sets that were located and evaluated tend to have large spatial and temporal gaps. For example, Figure 1 shows the December mean Sea Surface Temperature (SST) for the CPR and the USVI for the period 1985 – 1995, derived from Pathfinder AVHRR satellite imagery. For this data set, limitations caused by the interaction of reflected

Infrared radiation from the top millimeter of the sea surface with shallow continental shelf water mass caused a masking of the nearshore zone in the depth range of interest to offshore cage siting.

Figure 2 shows a three-day composite mean of the Caribbean Basin on 31 December 2003, as downloaded from the University of South Florida's Institute for Marine Remote Sensing website. The entire Caribbean Basin is mapped to a cylindrical equidistant projection at an image size of 512 x 512 pixels, producing a 3.5 x 6.7 km/pixel spatial resolution. When the CPR and USVI are cropped out of the entire region, the resulting image (Fig. 3) is essentially useless for analytical purposes.

In studies based on the GIS analysis of very high resolution imagery (e.g., Perez et al. 2003, based on custom processed NOAA-14 AVHRR imagery of the Canary Islands with a spatial resolution of 10 x 10m/pixel) results are very satisfactory.

Fortunately, as mentioned, much more suitable digital coverages exist for the Florida Peninsula, but even here only two parameters of interest to offshore cage siting are adequately represented: surface chlorophyll concentration and sea surface temperature. They are discussed in the next section.

Oceanographic Biophysical Parameters 1: chlorophyll

Spatial data of this type generally exists as rasters, because, in contradistinction to regulatory and management coverages, the data represent continuous environmental variables. The best known example of this data type would be bathymetry in the form of digital elevation models (DEMs). But it was assumed that this project would make more use of a relatively new source of digital data: remotely sensed imagery.

Satellite remote sensing has truly revolutionized oceanography over the past several decades. Ninety-five percent of the ice-free world ocean may be scanned from a satellite in a ten-day period. Such synoptic remote sensing data sets enable marine scientists to analyze small-scale oceanographic phenomena on a weekly to yearly basis, including surface currents and water temperatures, waves, phytoplankton and suspended sediment concentrations.

The primary limitations of satellite remote sensors is that (1) they rely primarily on measurements of electromagnetic radiation, and therefore cannot record anything deeper than a few decimeters below the sea surface, and (2) the radiation cannot penetrate any cloud cover that might lie between the ocean surface and the satellite.

Satellite infrared sensors can detect small variations in ocean surface temperature with great accuracy by measuring sea surface heat radiation. Satellite optical sensors calibrated to various wavelengths of visible and near infra-red light can map ocean color by measuring backscattered sunlight. However, these color and temperature variations are relatively small and must be digitally enhanced as part of the standard post-processing algorithms applied to satellite imagery. The enhancement algorithms also generally assign a spectrum of “false colors” to the range of radiation values present in each image so that humans can qualitatively assess the variations. Finally, biophysical parameters such as chlorophyll-a concentration may be indirectly derived from the digital data through the application of complex transfer functions that mathematically relate one to the other.

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) is an ocean color sensor carried by the SeaStar satellite, launched in 1997. It has eight spectral bands and a ground resolution of approximately 1 km/pixel. Complete data sets have been processed for the years 1998-2004 by the Institute for Marine Remote Sensing of the University of South Florida and posted for limited distribution at //imars.marine.usf.edu/sst/index_rm.html. (Unfortunately coverage of the eastern Greater Antilles is not available.) This site also documents the numerous processing steps applied to the raw data, including the OC4 bio-optical algorithm of O’Rilley et al. (2000) to compute chlorophyll concentrations. It is cautioned, however, that under the best conditions an accuracy of only ±35% can be expected in surface chlorophyll concentrations.

SeaWiFS chlorophyll (specifically chlorophyll-a) concentrations are computed as either daily or composite imagery. The latter type is computed as seven-day running means, weekly and monthly images. (Composite images are preferred to average images as they exclude image areas with cloud cover.)

The relatively high-resolution (1200 x 999 pixels at 1km/pixel) monthly composite imagery from 1998-2004 (inclusive) was used in this project. Images cover the “West Florida Shelf,” which includes all the eastern half of the Gulf of Mexico and the Florida Peninsula. All images were cropped to include only Florida and its continental shelf, which was defined as:

N bounding coordinate: 30◦ S bounding coordinate: 24◦
W bounding coordinate: -84◦ E bounding coordinate: -79◦

Figure 4a is an example of a West Florida Shelf monthly composite SeaWiFS image (January 2000). Note that an 8-bit custom false color table uses 255 arbitrary colors to display variations in surface chlorophyll concentrations, according to the colorbar index common to all images. For comparison, an 8-bit grayscale color table applied to the same image is shown in Figure 4b. It is obvious that the human eye can better interpret variations in a false color spectrum than in a grayscale spectrum.

Use of such an 8-bit false color table is standard for visual inspection of satellite imagery, but it is unsuitable for quantitative analyses in which precise intervals of the biophysical parameter—here chlorophyll concentration in mg/m^3—must be established. A substantial amount of time was spent during this project to reclassify all the 8-bit false color raster imagery into a much smaller number of intervals that would correspond, as closely as possible, to the original range of values. It was eventually discovered that the unsupervised classification technique termed Adaptive Resonance (Carpenter and Grossberg 1988) produced very acceptable results with eight classes of chlorophyll concentrations. Figure 5 shows the relationship between the original 8-bit colorbar and the 4-bit colorbar created by unsupervised adaptive resonance classification. All the subsequent figures (13 – 18) of chlorophyll concentration for Florida use this 4-bit colorbar.

Oceanographic Biophysical Parameters 2: Sea Surface Temperatures (SST)
The GOES-SST data (http://coastwatch.noaa.gov/goes_sst-geographic.html) for the Southern US and the Caribbean regions are available as GeoTIFFs, but their spatial resolution is 6x6 km, too coarse to be applicable to this project.

Because this project's objective was to determine the average biophysical conditions around Florida, the CPR and the USVI, the three-day composite images of SST available from the University of South Florida IMARS website also were not used, but a custom set of twelve images was prepared from Pathfinder AVHRR satellite data by personnel in the Division of Meteorology and Physical Oceanography. These images (figures 6 – 8) represent averages of SST around Florida by month during the eleven-year period 1985-1995. (Limitations of the SST imagery for the CPR and the USVI were discussed in the previous section of this report.)

Other oceanographic biophysical parameters
Despite extensive searches for synoptic digital coverage of turbidity, salinity, surface and subsurface currents, winds, and dissolved oxygen, no useable data sets were located for Florida, the CPR, or the USVI. The problem lies in the fact that although vast quantities of raw satellite imagery have been collected and archived over the past decade, relatively little has been processed into a useable form and made available as a finished digital coverage. The coverages that have been released tend to be of such a small scale that they are essentially useless for purposes of determining optimal locations of offshore cage aquaculture installations (Fig. 9 shows an example of such a small-scale image of winter currents around the Florida Peninsula).

Furthermore, *in situ* data measurements of parameters such as currents and salinity, which are taken from vessel or data buoy platforms and therefore inform us about the subsurface marine environment, are of very limited spatial extent and time duration. For example, Figure 10 shows the index map and CTD station logs for 57 stations that are part of the Florida Bay Circulation and Exchange Study of the South Florida Ecosystem Research and Monitoring Program (http://mpo.rsmas.miami.edu/flabay/). The data for one station (FEB00295, water depth 30 meters) are plotted in Figure 11; it shows, at a depth of 12 m, substantial changes in temperature and density, probably indicating two distinct water masses present at this station. This kind of information could be critical for decisions about offshore cage aquaculture siting, but it is generally unavailable, and *cannot* be derived from synoptic satellite imagery, which only records the surface parameters.

The rest of this report focuses on the analysis of the limited synoptic data analyzed for the Florida Peninsula.

Florida

Florida's continental platform is more than twice as large as the emergent peninsula and its shelf margin is very asymmetrical due to the slight westward tilting of the platform and the influence of the Gulf Stream on the southeast coast during the Neogene Epoch (Lane 1994).

The continental shelf off the Gulf coast of Florida has been termed the West Florida Shelf (WFS) by oceanographers. Water circulation on this feature is driven by winds, tides and buoyancy flux (Yang et al. 1999: 1222), and constrained by the Gulf of Mexico Loop Current. Yang et al. (1999) discovered that WFS circulation is characterized by a generally offshore surface water movement, while subsurface and bottom water movement is toward the south or non-existent, producing a so-called "forbidden zone" that comprises the southern half of the WFS, from off Tampa Bay south to the Dry Tortugas (Yang et al. 1999: figs. 2, 12). The implication of this unusual shelf circulation pattern for offshore cage aquaculture siting is that seasonal biological phenomena such as red tides (dinoflagellate blooms or HABs) that form north of Tampa may reach the Forbidden Zone through southerly movement of subsurface and bottom water currents. As almost no data are available on subsurface and bottom current movement on the WFS, it would entail some risk to locate offshore cages in this region.

The initial analysis of suitable areas off the coast of Florida for cage aquaculture siting was predicated on two primary assumptions:

- different regulatory regimes exist in state versus federal waters (see previous discussion)
- the cage designs assumed for use have an optimal installation depth range of ca. 30 – 40 meters.

These two regulatory parameters may be displayed with two simple vector coverages as shown in Figure 12. For historical reasons, the boundary between state and federal waters around Florida differs depending on whether the Atlantic (3 nm) or Gulf (9 nm) coast is under consideration. The 30 – 40 m bathymetric zone's shape and location reflects the different nature of the continental shelf off the Gulf and Atlantic coasts: very wide of the former and almost non-existent off the later until the latitude of West Palm Beach.

When these two regulatory parameters are mapped with monthly decadal-averaged Sea Surface Temperature (SST) images for the period 1985-1995 (introduced above as figures 6 - 8) they show SST values north of Tampa Bay (on the west coast) and Cape Canaveral (on the east coast) reaching minima of 18-20 °C during January-April. Thus certain species would probably not thrive during the winter months. It must be kept in mind, however, that these maps only show surface temperature, which is closely linked to cold fronts pushing south from the continental landmass, and especially off the Atlantic coast water temperatures at depth are more controlled by the Gulf Stream location.

Figures 13 - 15 display the monthly averages of SeaWiFS chlorophyll imagery (adaptive resonance supervised classification) for 2001, while figures 16 - 18 show the same for 2003. These were chosen as representative of the conditions that existed during the period 1998 – 2004, for which such data exist. It is assumed that (1) chlorophyll concentrations at least greater than 10 mg/m^3 (orange and red zones) will also contain algal blooms, and (2) some of these may be harmful (so-called "red tides").

Three fundamental problems in using these images to determine offshore cages locations in order to avoid Harmful Algal Blooms (especially off the Gulf coast), are that (1) the exact relationship between HABs and elevated chlorophyll concentrations has not been determined, (2) these data only reflect surface chlorophyll concentrations and not what might be occurring at depths where cages might be holding the majority of the fish stocks, and (3) chlorophyll concentrations *less* than 7-8 mg/m^3 almost always characterize the 30-40 m bathymetric zone throughout the year, and it is assumed that such relatively low concentrations would have no effect on fish stocks in offshore cages.

In summary neither the SST nor chlorophyll data offer much guidance in where to locate aquaculture cages off the Florida Peninsula. Of far greater weight are the two regulatory parameters of the 30-40m bathymetric zone and the state-federal water boundary.

From a practical standpoint the 30-40 m depth zone lies some 50 km west of the entrance to Tampa bay, and increases to 75-100 km west-southwest of Naples (see fig. 12). Such distances offshore would likely pose unacceptable logistical problems for cage maintenance. Moreover, the southern half of the West Florida Shelf is the area most likely to experience Harmful Algal Blooms that could adversely affect fish stocks in offshore cages, given the existence of the so-called "forbidden zone" (Yang et al. 1999).

In the case of Florida it seems more appropriate to consider a few continental shelf areas in more detail and qualitatively assess their suitability for cage siting, in the framework of the two regulatory parameters discussed previously.

Figure 19 shows the western islands of the Florida Keys, the federal – state boundary, the 30 – 40m bathymetric zone, and the western boundaries of the Florida Keys National Marine Sanctuary (FKNMS). It is in this region, at the juncture of the Atlantic and Gulf of Mexico that the 30 – 40 m bathymetric zone narrows to less than a few hundred meters as it turns around the continental shelf continues east and then northeast along the Atlantic coast of the peninsula.

From the standpoint of biophysical parameters this is an ideal region for offshore cage siting, given that it is the origin of the Gulf Stream. Unfortunately this is also the most sensitive marine environmental region in Florida, containing the last relatively un disturbed shallow coral reef in the US.

Figure 20 is a larger-scale view of this critical region, again showing the 30-40 m depth zone, the state-federal boundary, and the FKNMS boundary. In addition it shows the southern part of the Tortugas Ecological Reserve (TER South) and a bathymetric feature called “Riley’s Hump.”

Effective July 1, 2001 the Tortugas Ecological Reserve (TER) came into existence (NOAA 2000). It is designed to protect one of the last relatively undisturbed coral reef ecosystem in the Florida Keys, and as such implementation of the reserve involves stringent regulations against fishing and SCUBA diving, as well as “Discharge or deposit of any material except cooling water or engine exhaust” within reserve boundaries (Tortugas Ecological Reserve Public Notice, 2001).

The final implementation of the TER includes two areas, Tortugas North and Tortugas South. The latter is a N-S rectangular area of ca. 60 nm^2 designed to protect Riley’s Hump, a unique region of deep reef that is a key spawning aggregation site for almost all species of fish to be found in the lower Florida Keys (Franklin et al. 2003). While there is an area of ca. 20 km^2 lying in state waters between the TER-South and the western edge of the FKNMS where cages could be located (Fig. 20, checked box) it is still some 100 km away from the nearest commercial port (Key West) and would likely be considered as a potential source of contaminants affecting the Sanctuary.

In the immediate vicinity of Key West (Fig. 21) a similar situation obtains: a small area of ca. 10 km^2 lies in state waters and within the 30-40 m depth zone (checked box), but its proximity to the FKNMS boundary almost certainly would raise questions of potential impact of cage aquaculture operations on the Sanctuary ecosystem.

Moving further north, off West Palm Beach, the 30 – 40 m depth zone begins to diverge from the northwest-trending coastline, and crosses the federal – state boundary some 5 km off North Palm Beach (Fig. 22). It is this offshore region between North Palm Beach and Jupiter that a decision could be made to site offshore cages in either state or federal waters, and also fulfill biophysical requirements such as minimal cool winter temperatures and presence of sustained currents.

Conclusions

- GIS analysis of potential offshore cage locations is a viable technique, assuming that spatial oceanographic data are available at the requisite scale.

- In this project, which was based on 1 x 1 km/pixel imagery (at best), and attempted to deal with an area that is about one order of magnitude larger than the Canary Islands, the results were less useful than was initially expected.

- Unless or until such high-resolution satellite imagery is available for the US Caribbean region, GIS analysis for optimal offshore cage locations in this region will be rather limited.

- Based on the limited digital datasets available, two areas in Florida are possible locations for offshore cage aquaculture installations: (1) in the Dry Tortugas, east of the Tortugas Ecological Reserve, and (2) due east of the North Palm Beach – Jupiter coastal zone, in either state or federal waters.

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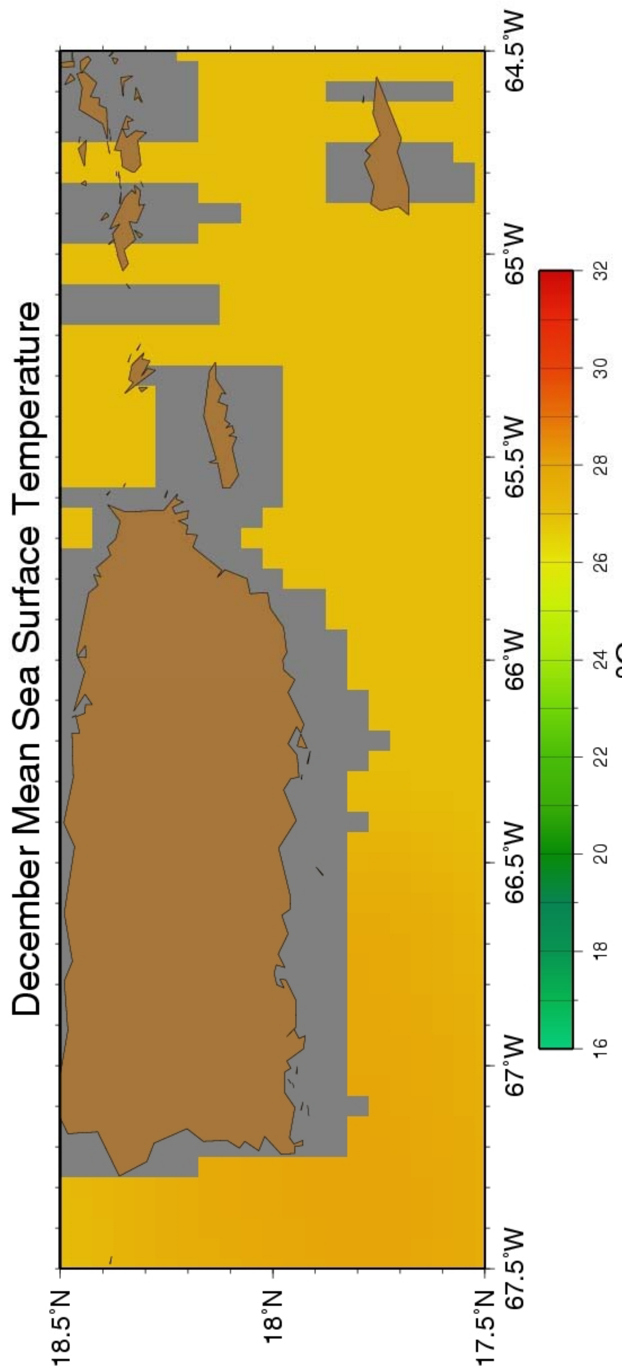

Figure 1. December mean SST for the CPR and the USVI for the period 1985 – 1995, from Pathfinder AVHRR data.

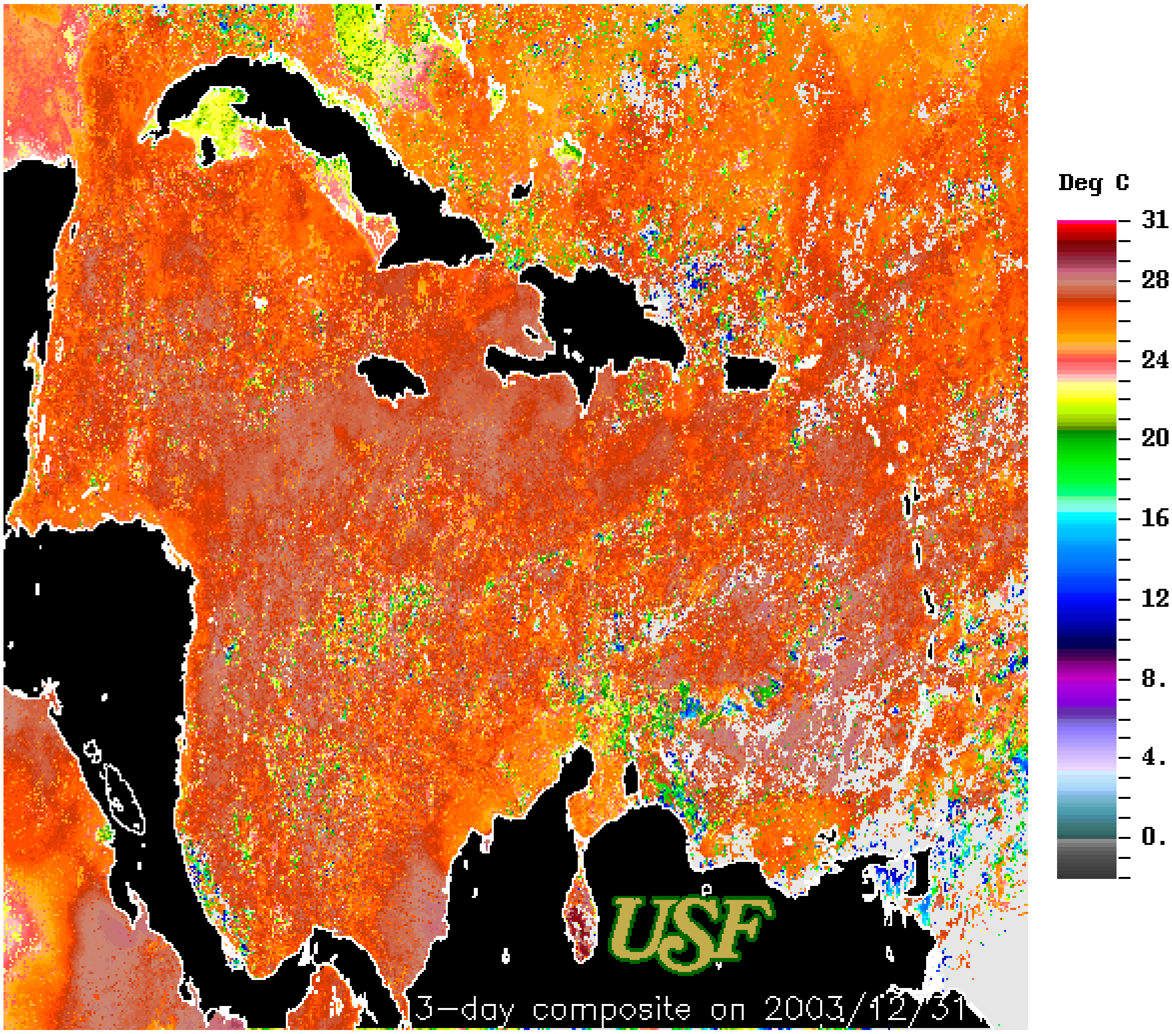

Figure 2. Three-day composite mean of Caribbean Basin Sea Surface Temperature, 31 December 2003. Original pixel size: 512 x 512.

Figure 3. 800% enlargement of the CPR and USVI from previous image. Spatial resolution is very poor.

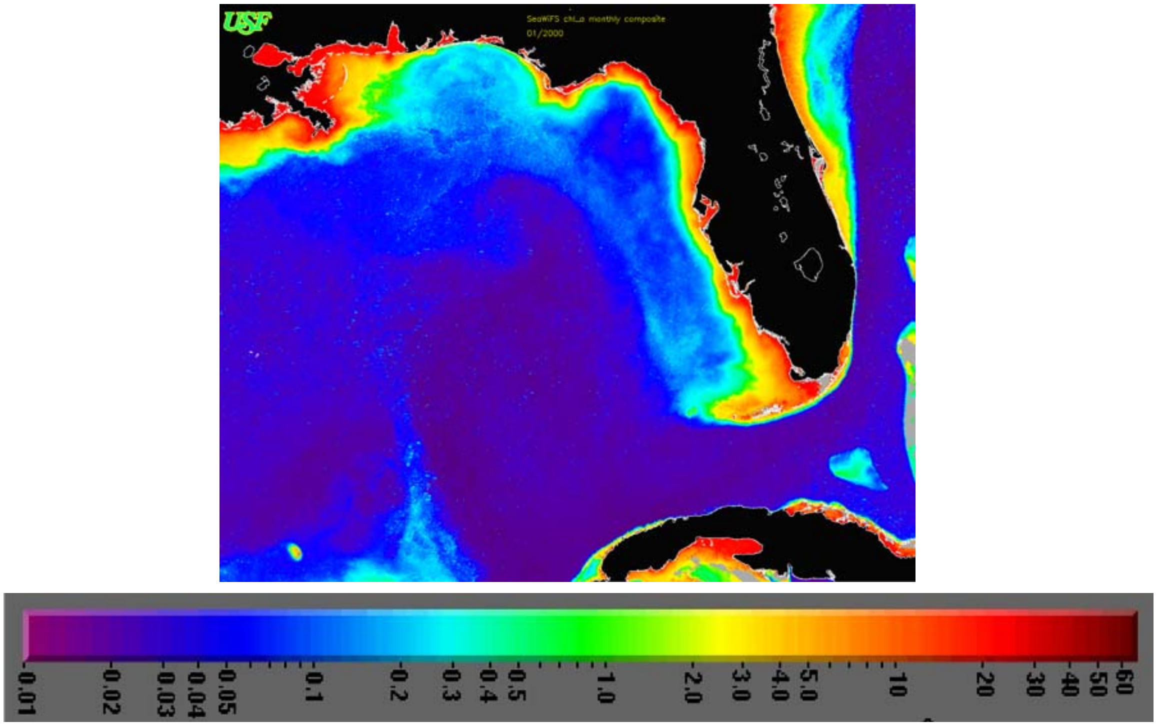

Figure 4a. High-resolution (1200 x 999 pixels) SeaWifs image of West Florida Shelf for January, 2000, with colorbar indicating approximate chlorophyll concentrations (mg/m^3) from 0.01 (purple) to 60 (deep red).

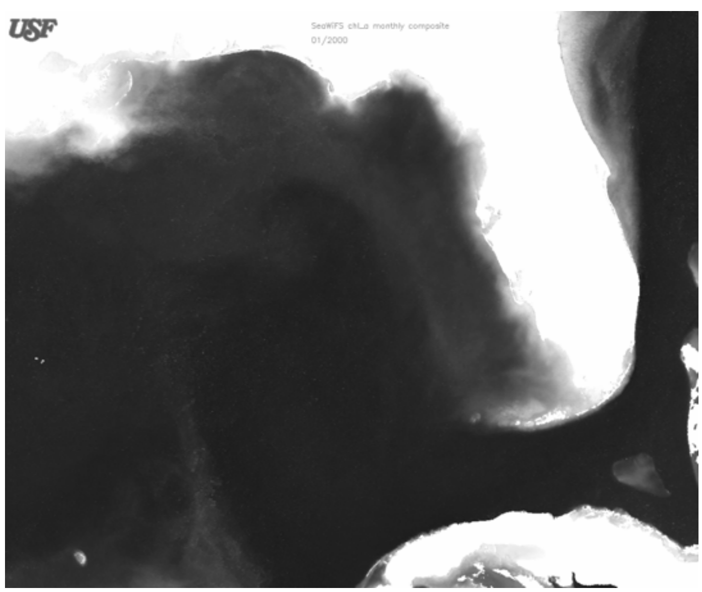

Figure 4b. Same image as above, displayed with an 8-bit grayscale color table.

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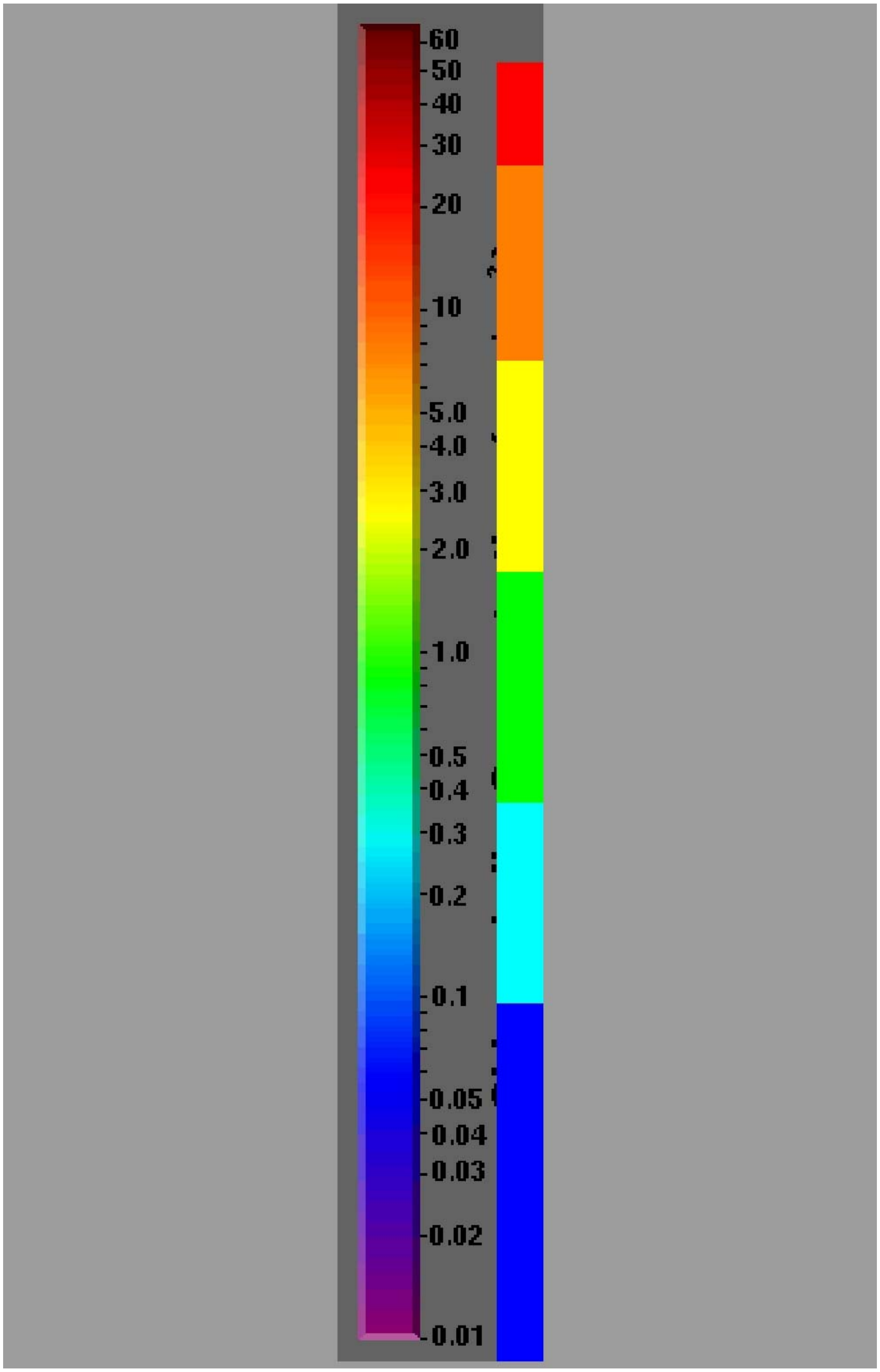


Figure 5. Original SeaWiFS chlorophyll concentration 8-bit colorbar (mg/m^3) compared with 4-bit colorbar derived from adaptive resonance unsupervised classification (right).

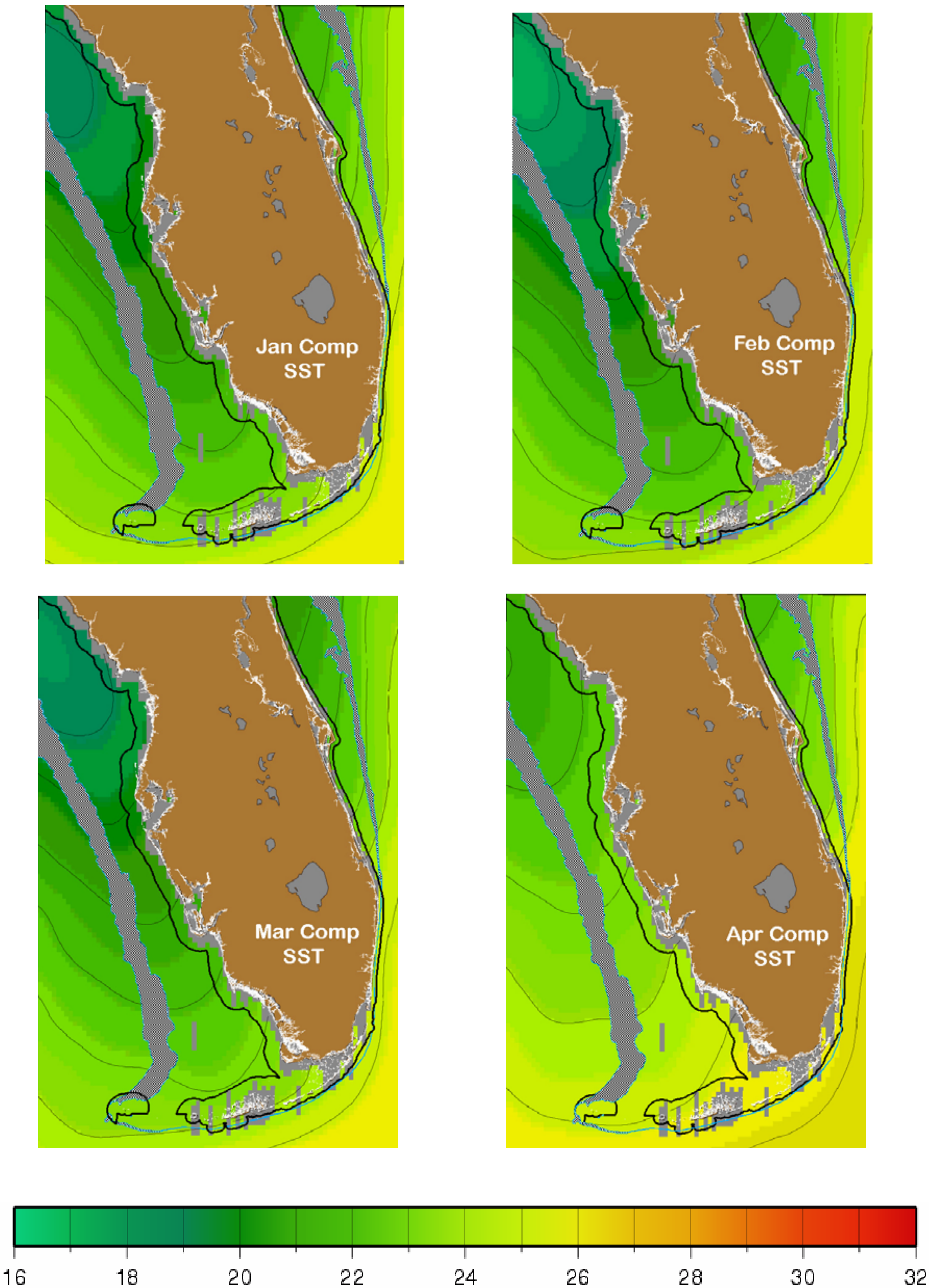


Figure 6. 1985 – 1995 Mean SST, Florida Peninsula, January – April.

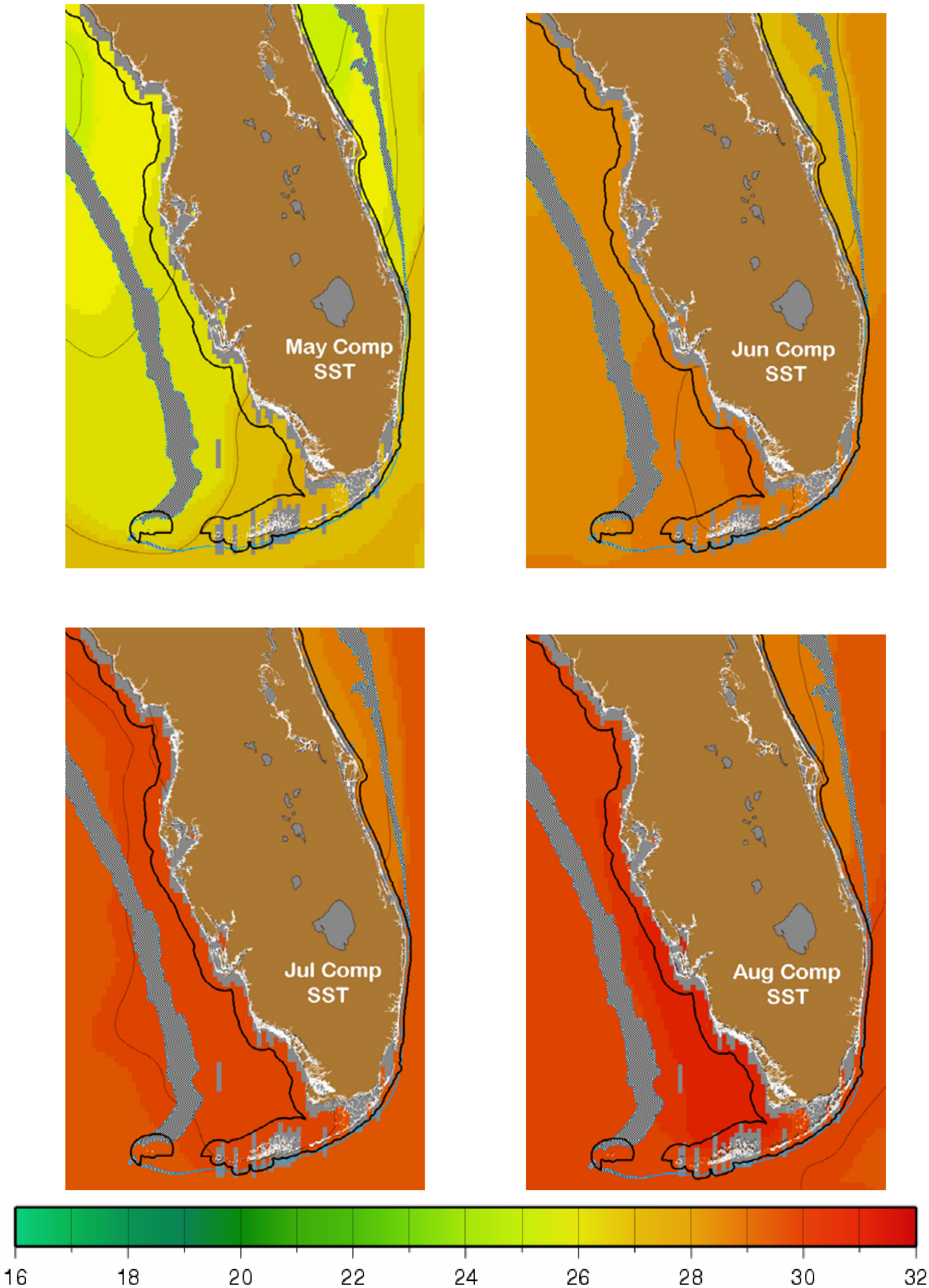


Figure 7. 1985 – 1995 Mean SST, Florida Peninsula, May – August.

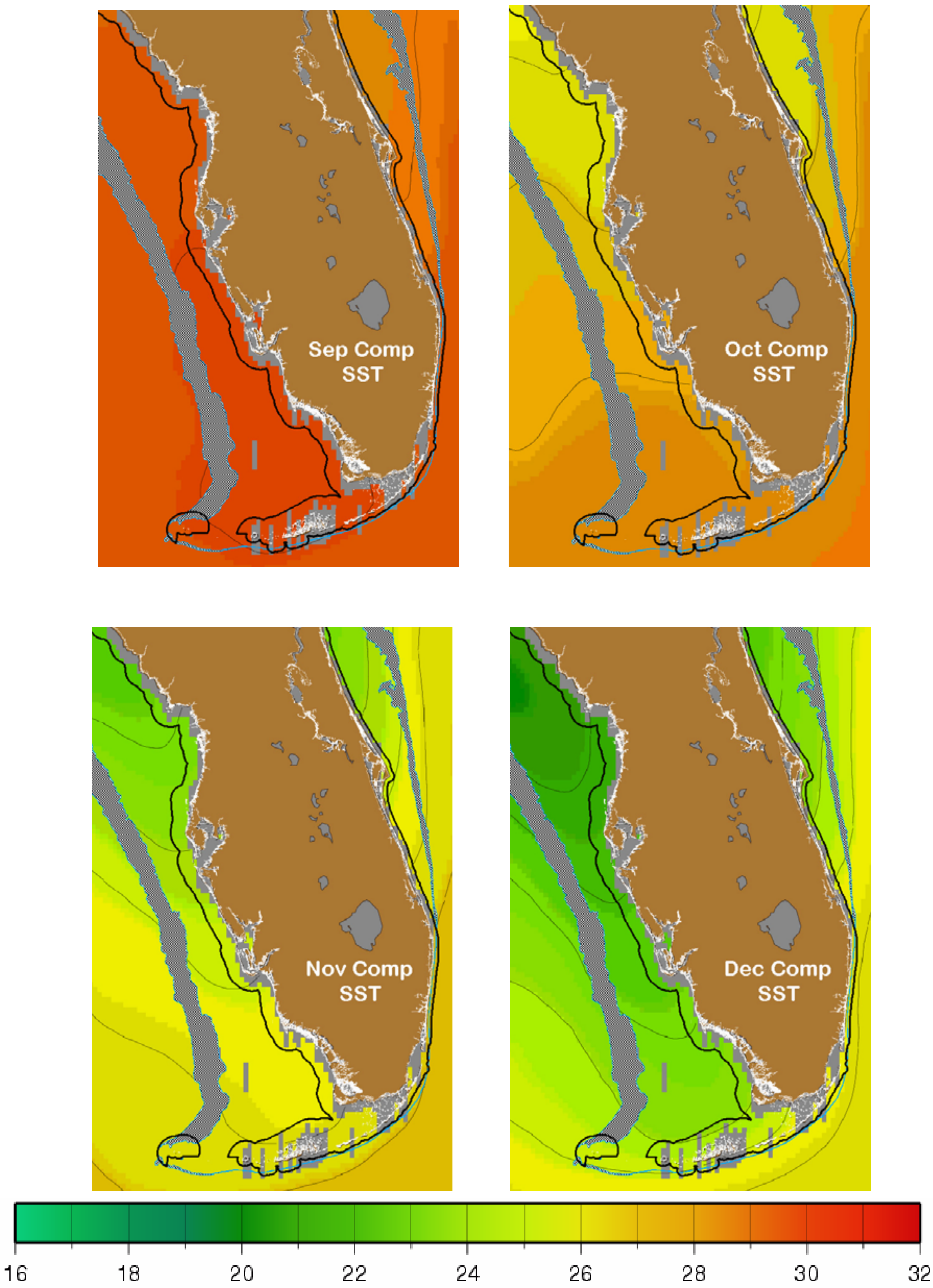


Figure 8. 1985 – 1995 Mean SST, Florida Peninsula, September – December.

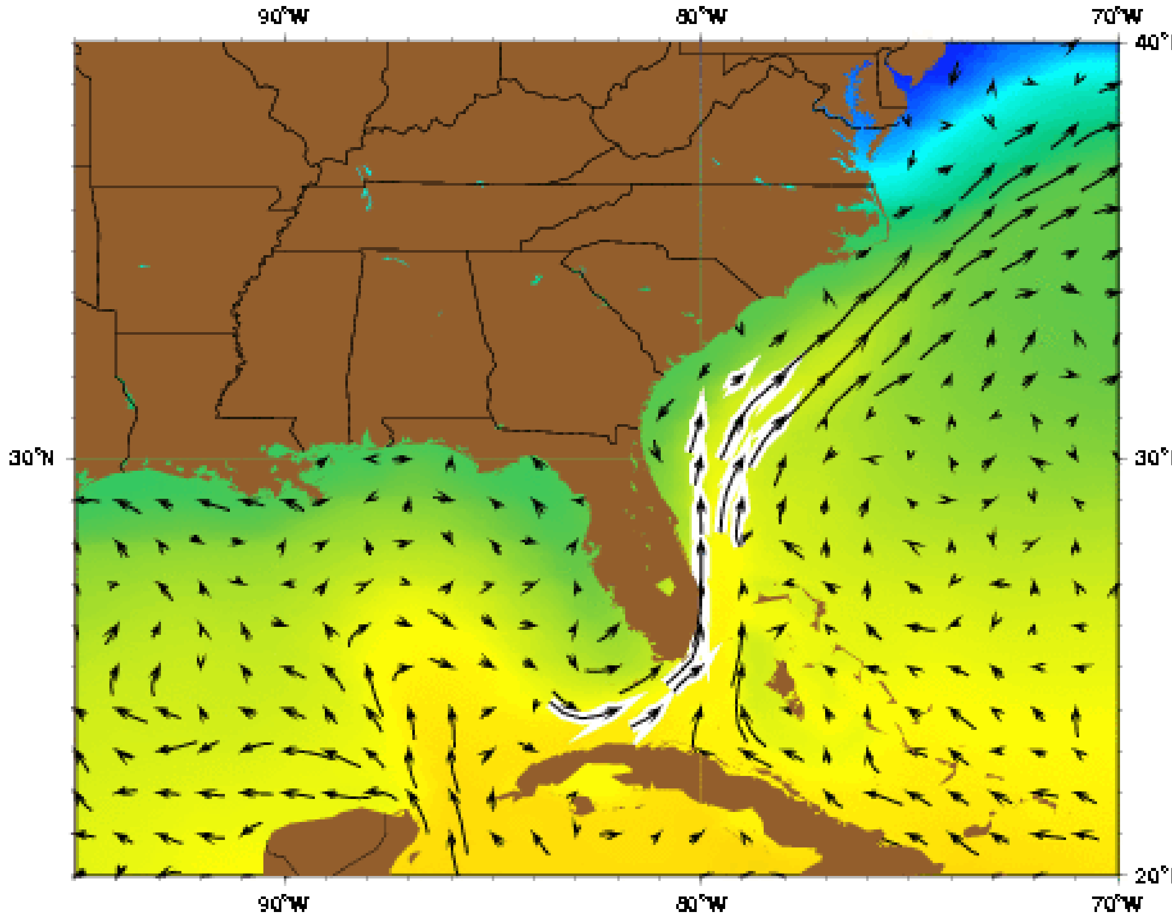
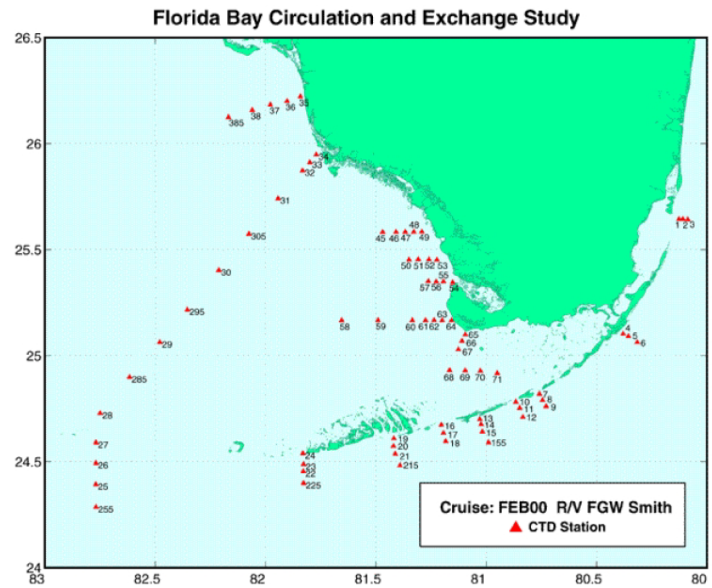


Figure 9. Synoptic image of winter currents around Florida (January – March). Such small-scale imagery is not useful for offshore cage location analysis.



Click on each station to display S,T,σ profiles

- **Stations Log**
- **Data**

FEB0001	FEB0002	FEB0003
FEB0004	FEB0005	FEB0006
FEB0007	FEB0008	FEB0009
FEB0010	FEB0011	FEB0012
FEB0013	FEB0014	FEB0015
FEB00155	FEB0016	FEB0017
FEB0018	FEB0019	FEB0020
FEB0021	FEB00215	FEB0022
FEB00225	FEB0023	FEB0024
FEB0025	FEB00255	FEB0026
FEB0027	FEB0028	FEB00285
FEB0029	FEB00295	FEB0030
FEB00305	FEB0031	FEB0032
FEB0033	FEB0034	FEB0035
FEB0036	FEB0037	FEB0038
FEB00385	FEB0045	FEB0046
FEB0047	FEB0048	FEB0049
FEB0050	FEB0051	FEB0052
FEB0053	FEB0054	FEB0055
FEB0056	FEB0057	FEB0058
FEB0059	FEB0060	FEB0061
FEB0062	FEB0063	FEB0064
FEB0065	FEB0066	FEB0067
FEB0068	FEB0069	FEB0070
FEB0071		

Last Updated on 11/09/2001

Figure 10. Index map and CTD station logs for 57 stations off the SW Florida coast and Keys. The profile of Station FEB00295 is shown in the next figure.

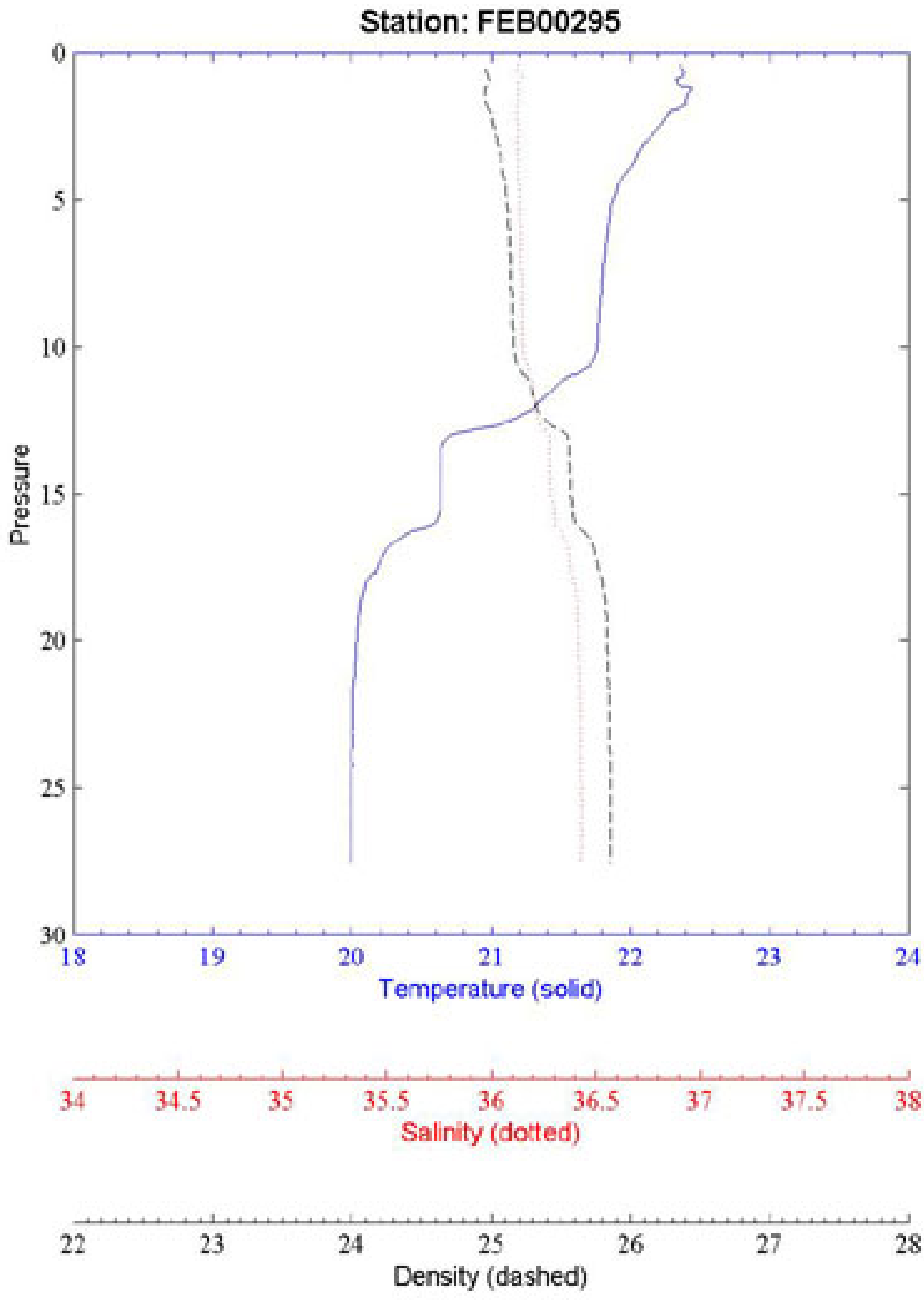


Figure 11. Plot of temperature, salinity and density for Station 00295 as a function of pressure (= depth in meters). Note the thermo- and pycnocline at 12 m.

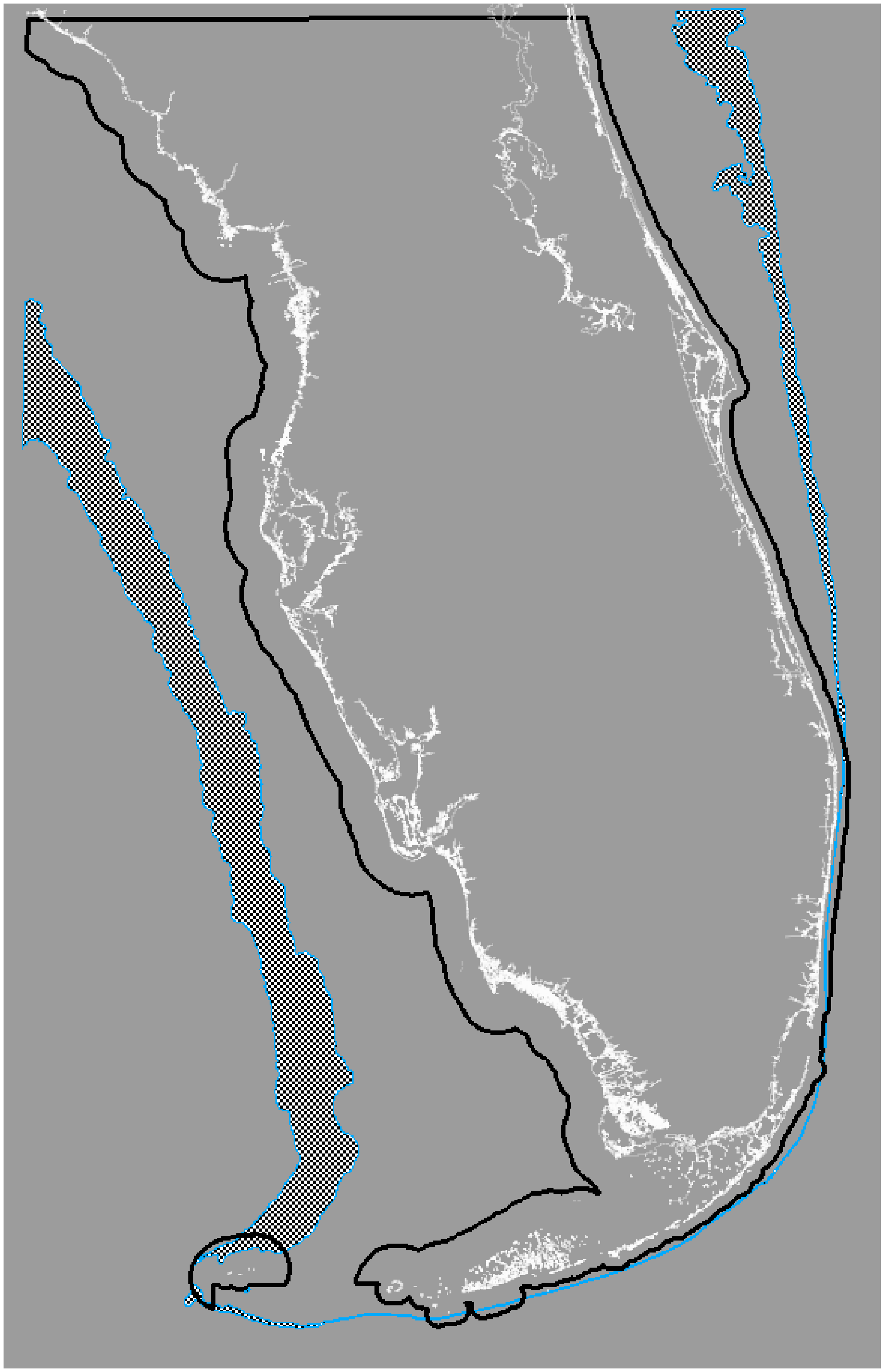


Figure 12. Two fundamental regulatory parameters: the state-federal boundary (black line) and the 30-40 m depth zone (grey stippled area).

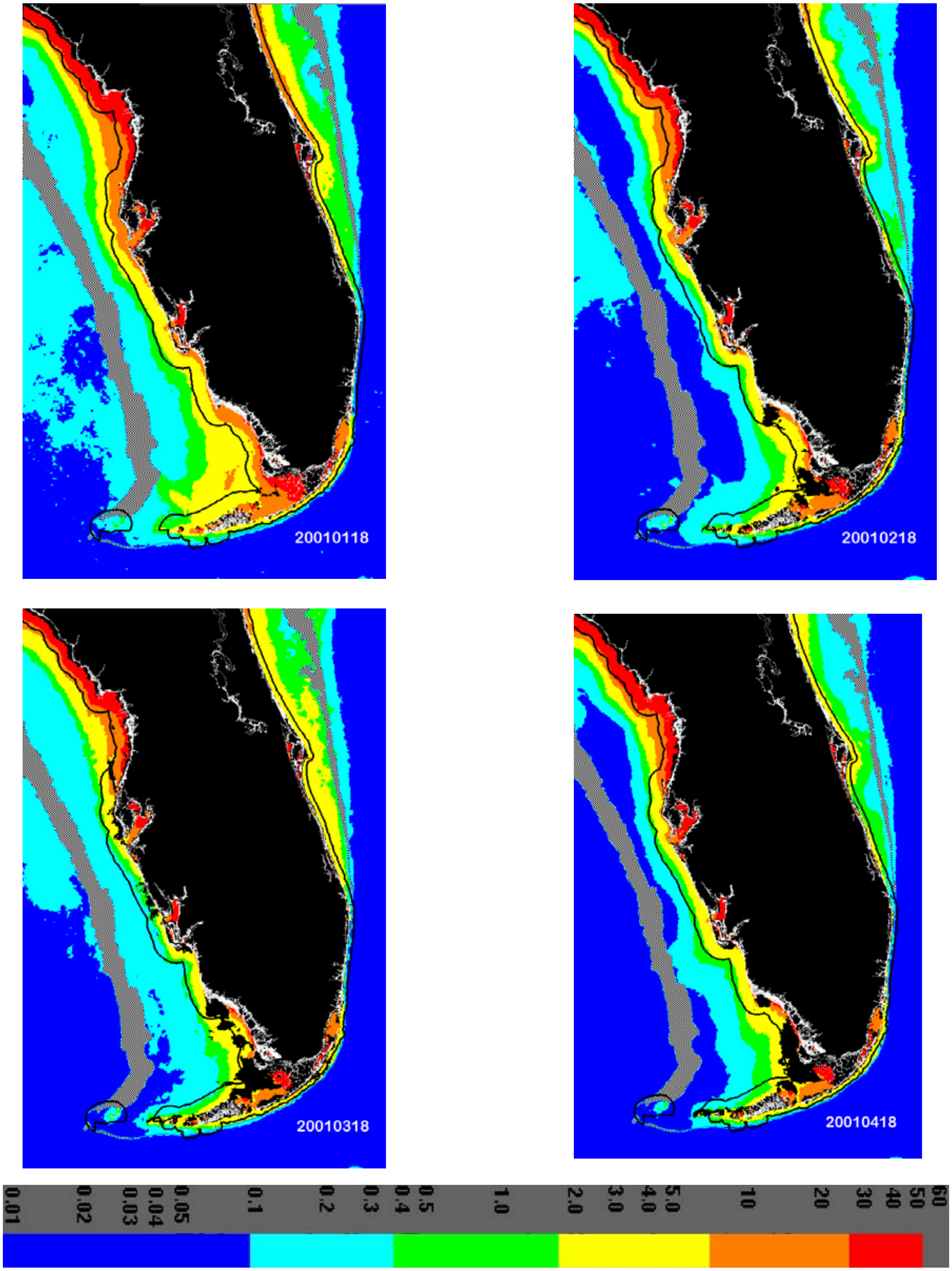


Figure 13. Monthly averages of SeaWiFS Chlorophyll imagery (adaptive resonance supervised classification), January – April 2001. Colorbar values in mg/m^3.

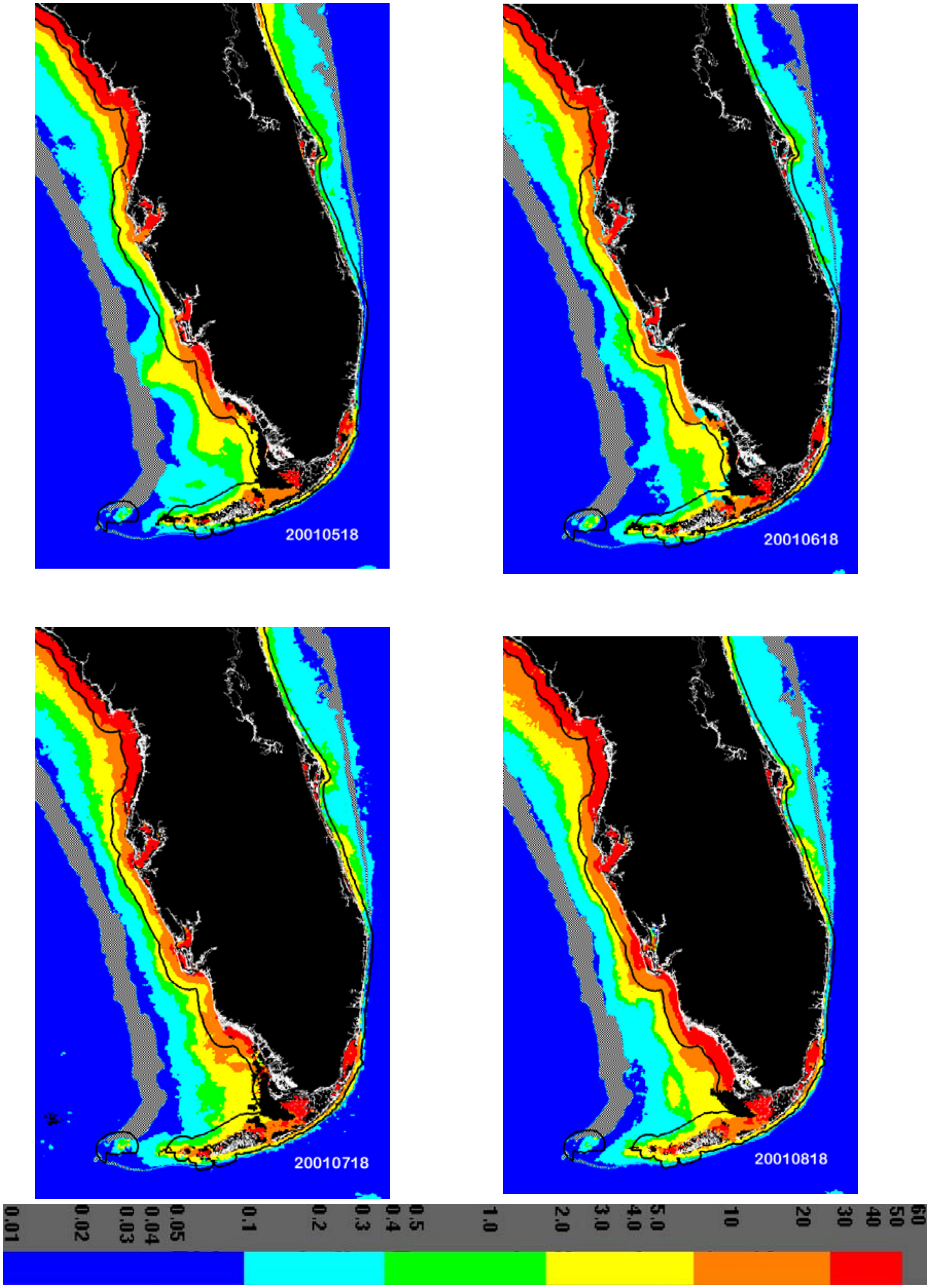


Figure 14. Monthly averages of SeaWiFS Chlorophyll imagery (adaptive resonance supervised classification), May – August. Colorbar values in mg/m^3.

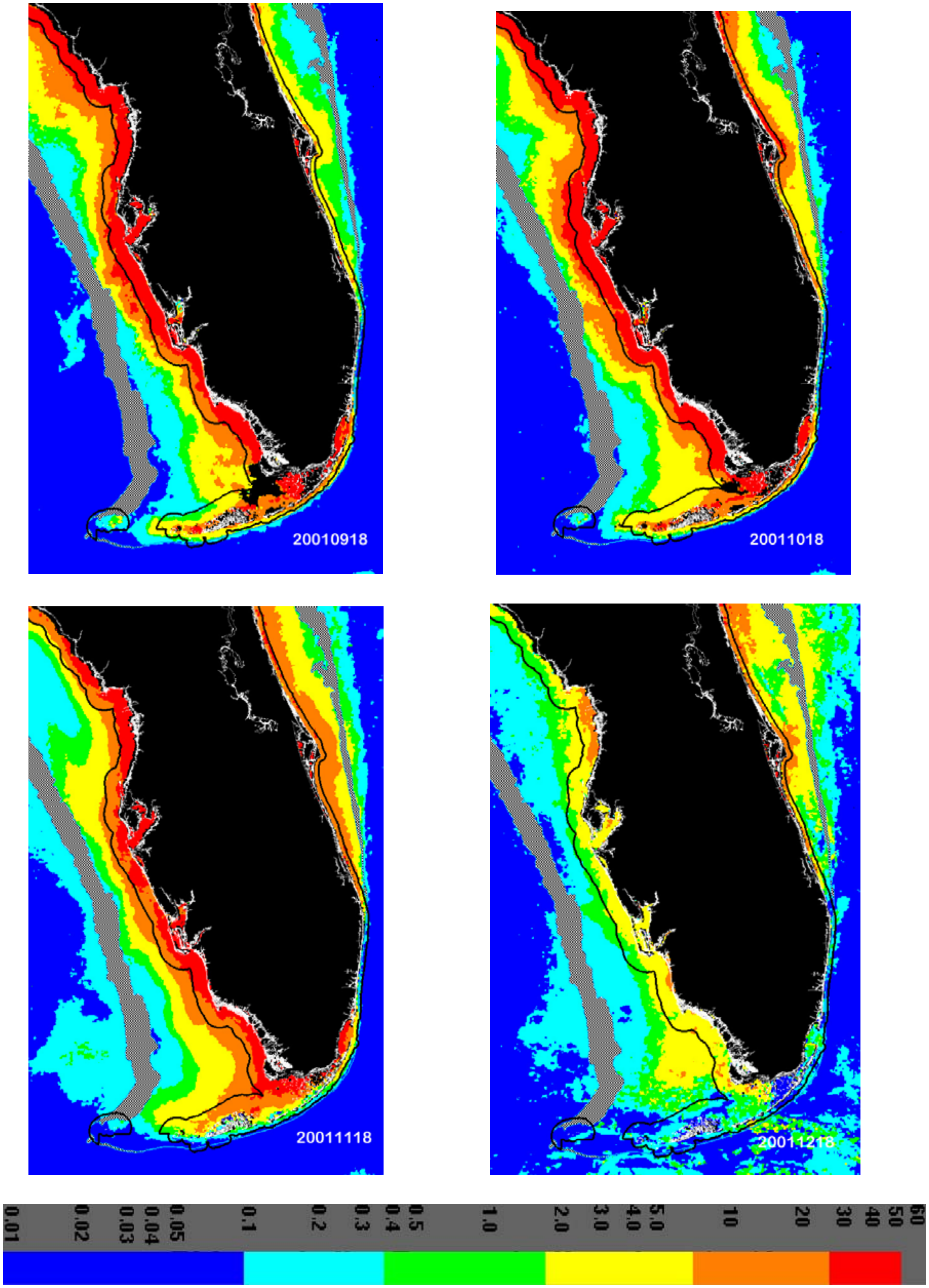


Figure 15. Monthly averages of SeaWiFS Chlorophyll imagery (adaptive resonance supervised classification), September – December 2001. Colorbar values in mg/m^3

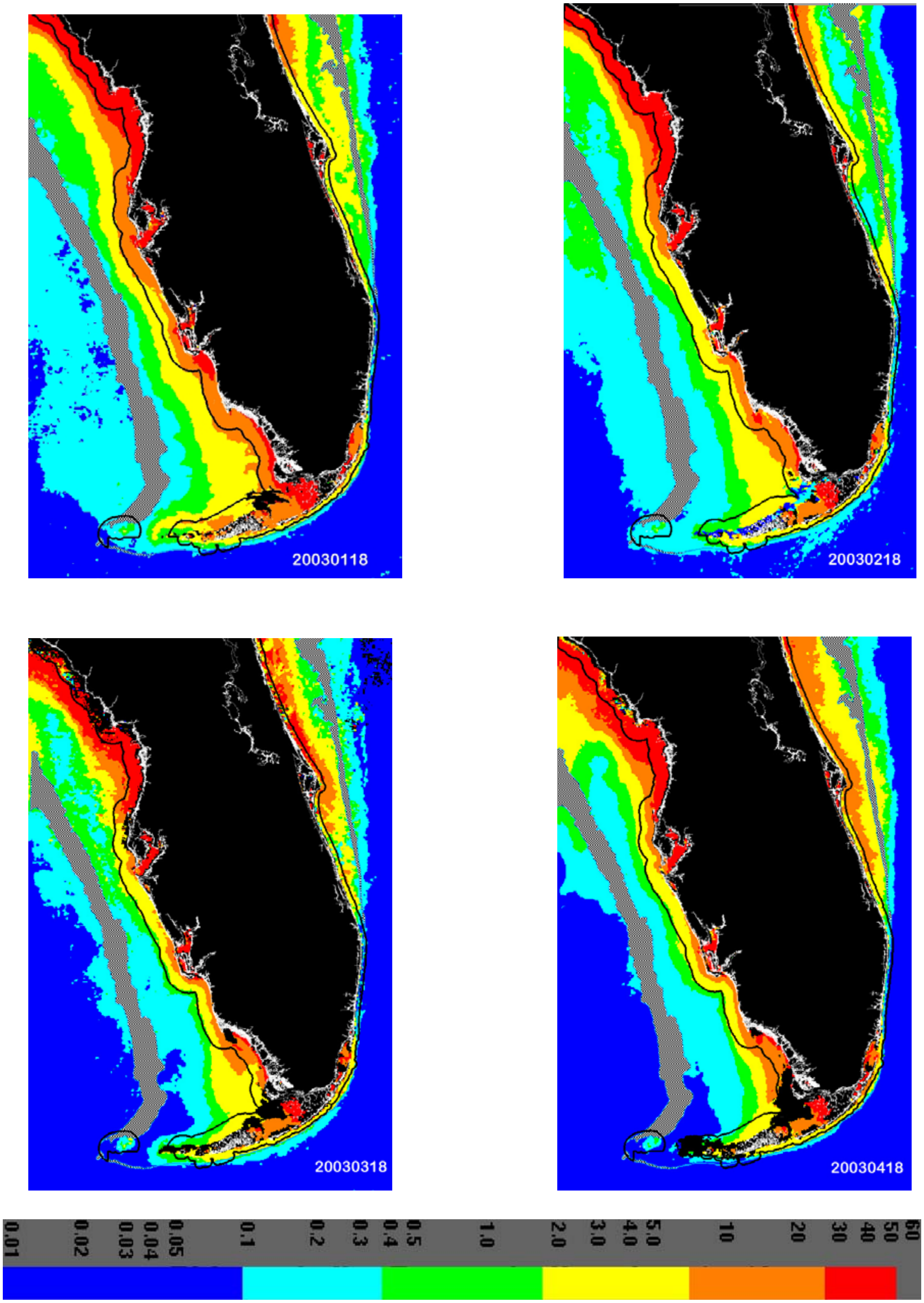


Figure 16. Monthly averages of SeaWiFS Chlorophyll imagery (adaptive resonance supervised classification), January – April 2003. Colorbar values in mg/m^3.

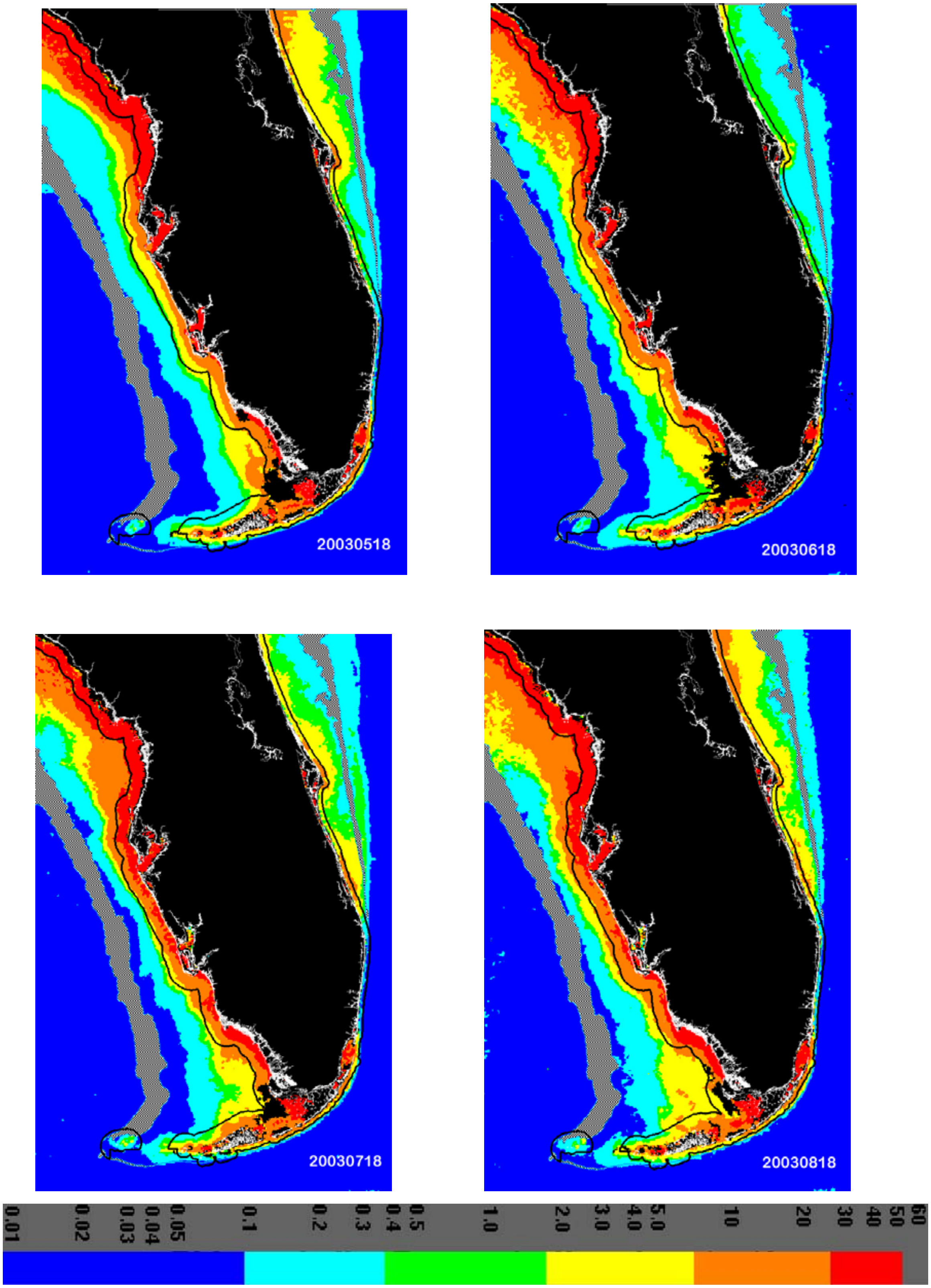


Figure 17. Monthly averages of SeaWiFS Chlorophyll imagery (adaptive resonance supervised classification), May – August 2003. Colorbar values in mg/m^3.

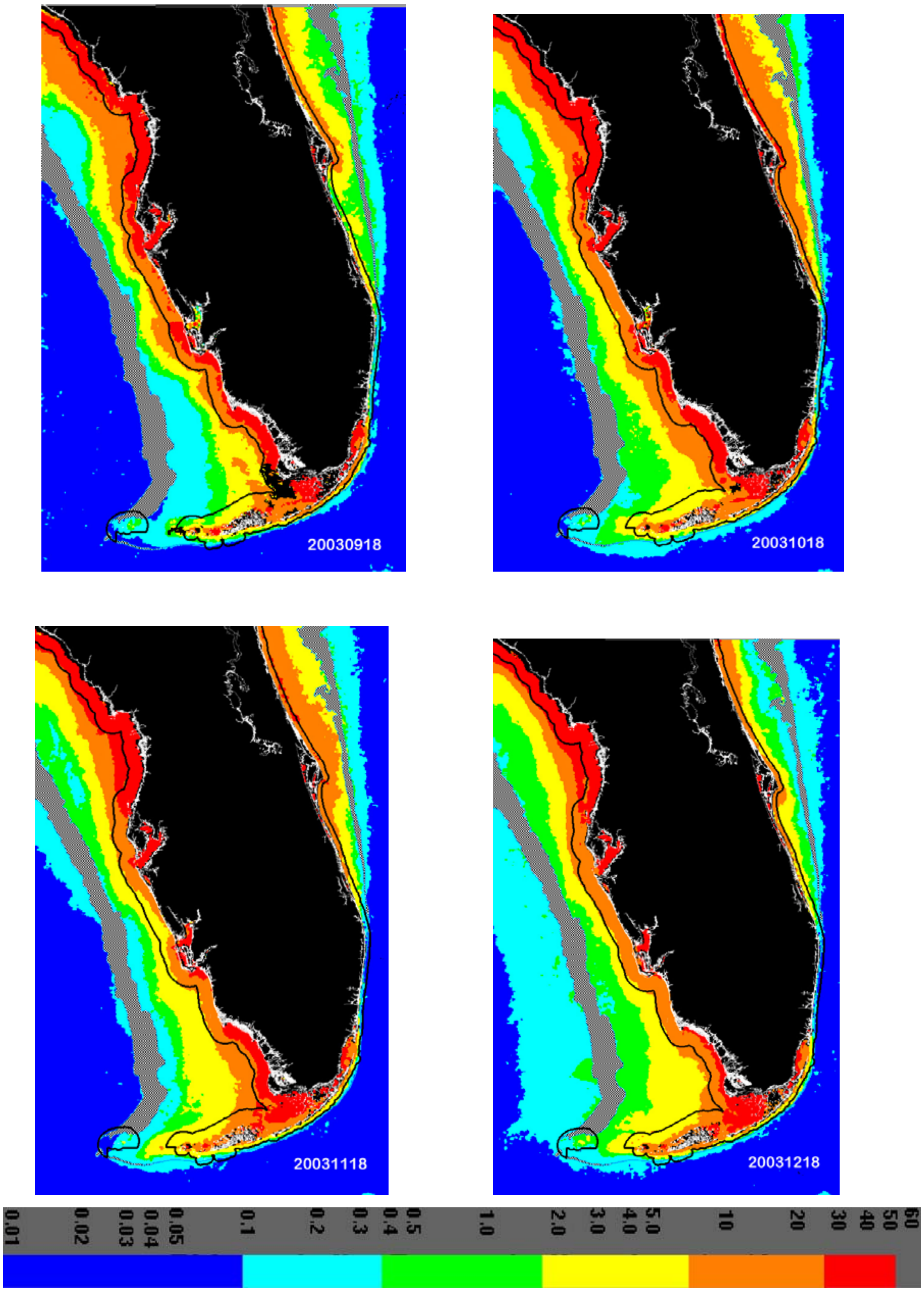


Figure 18. Monthly averages of SeaWiFS Chlorophyll imagery (adaptive resonance supervised classification), September – December 2003. Colorbar values in mg/m^3.

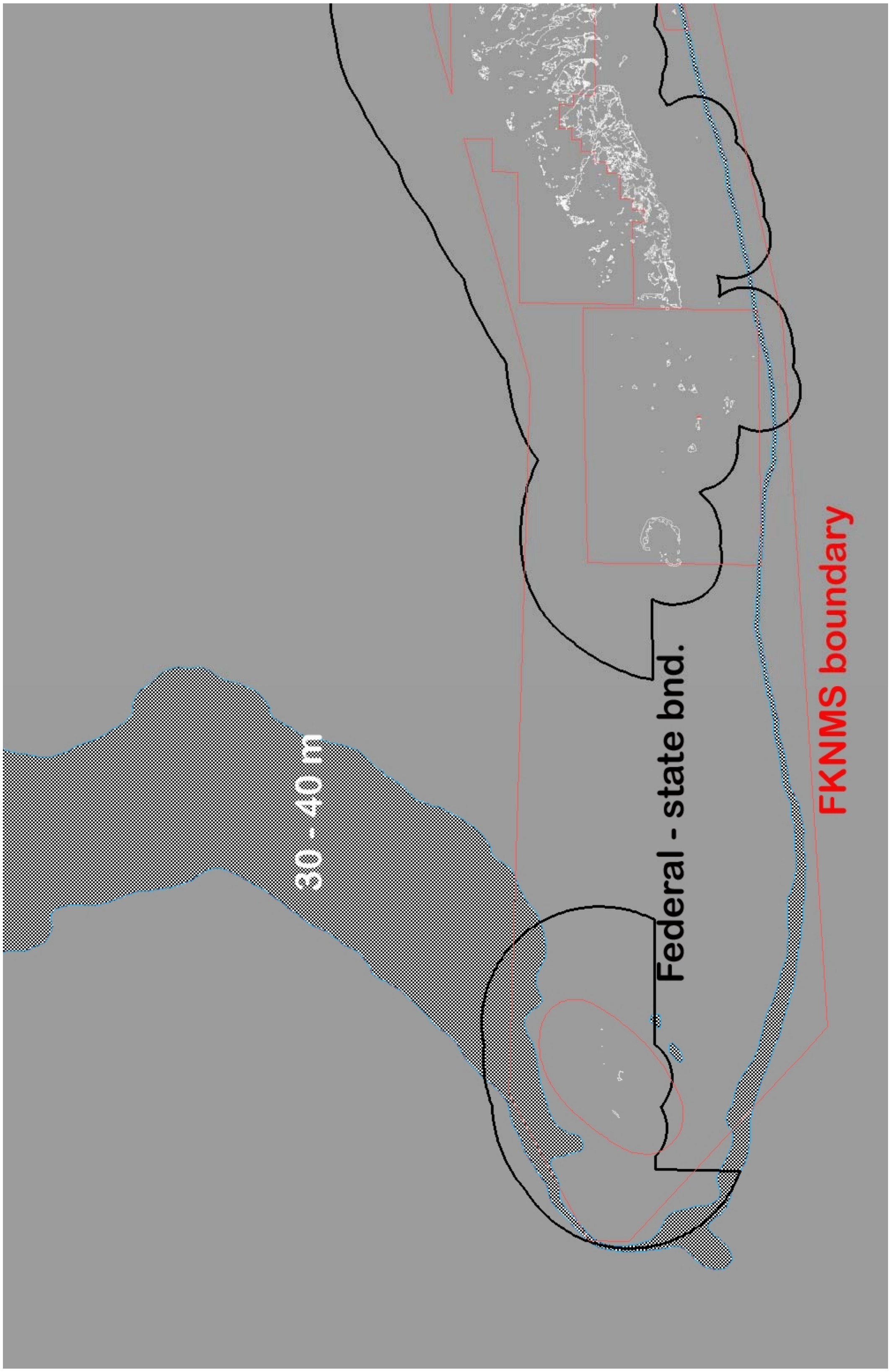


Figure 19. Westernmost Florida Keys, the federal-state territorial waters boundary (black), 30-40 m depth zone (stippled), and FKNMS boundary (red).

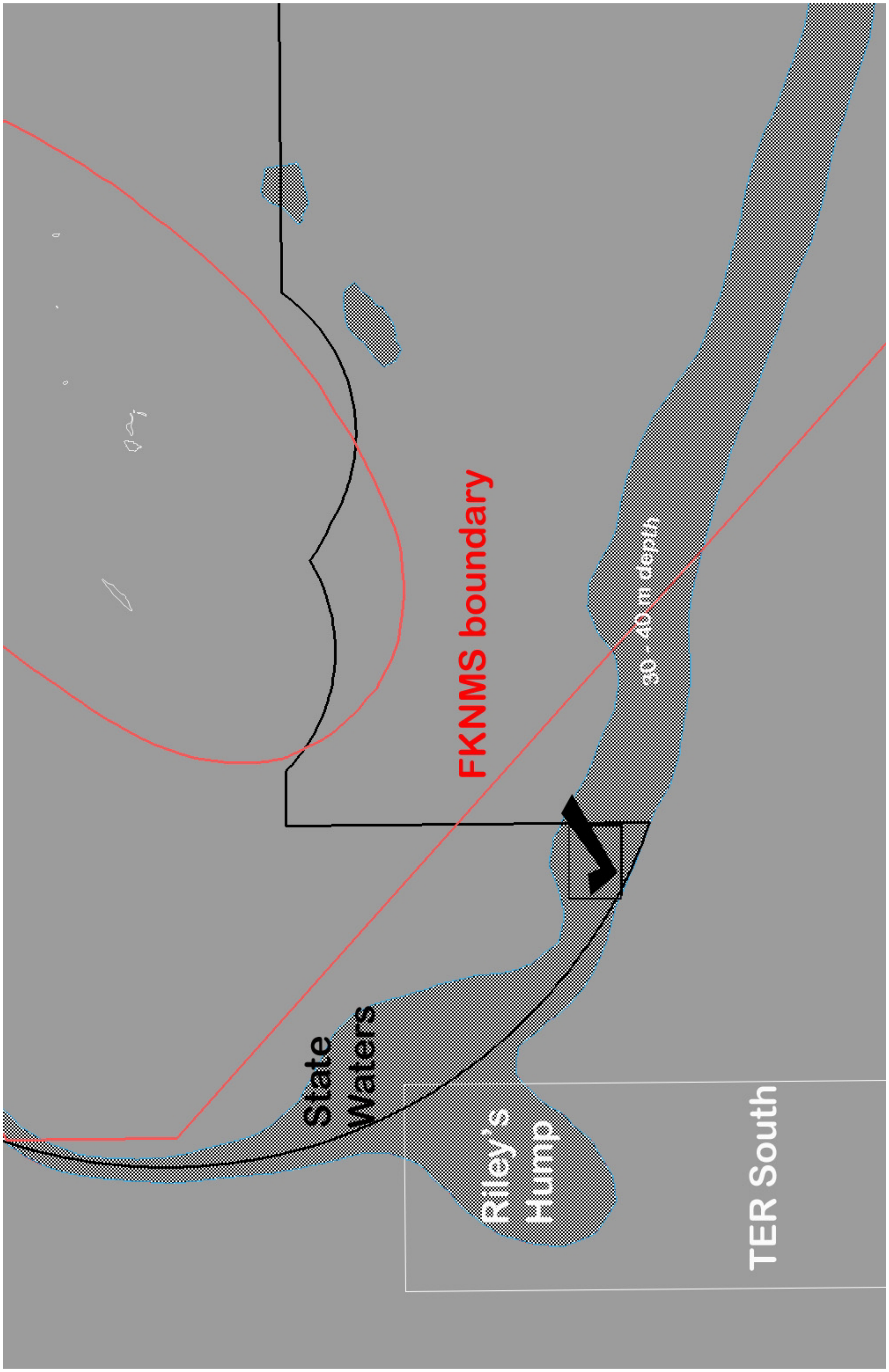


Figure 20. Larger-scale view of Figure 19, including the Tortugas Ecological Reserve South and Riley's Hump. See text for discussion.

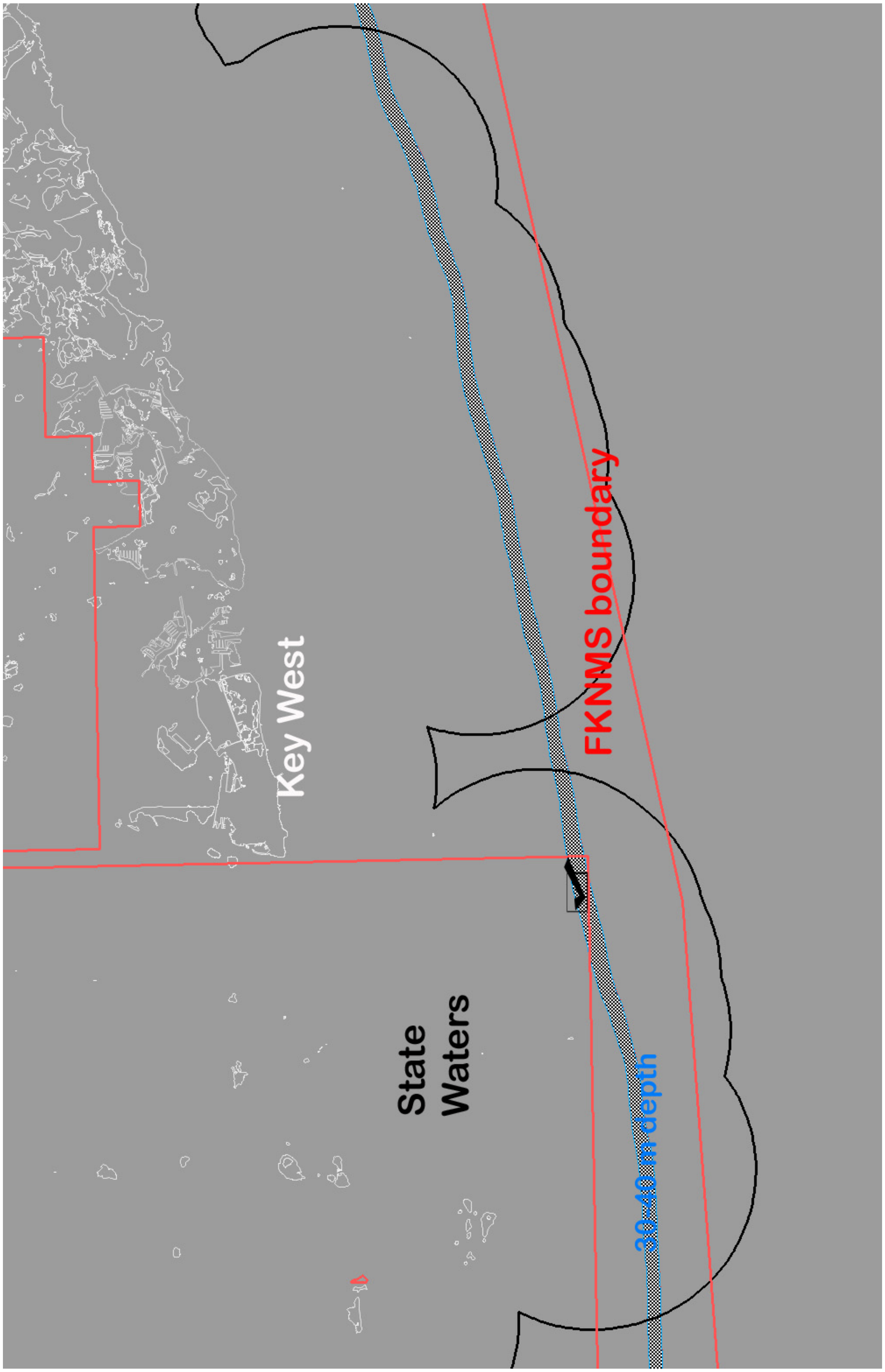


Figure 21. Regulatory boundaries south of Key West. See text for discussion.

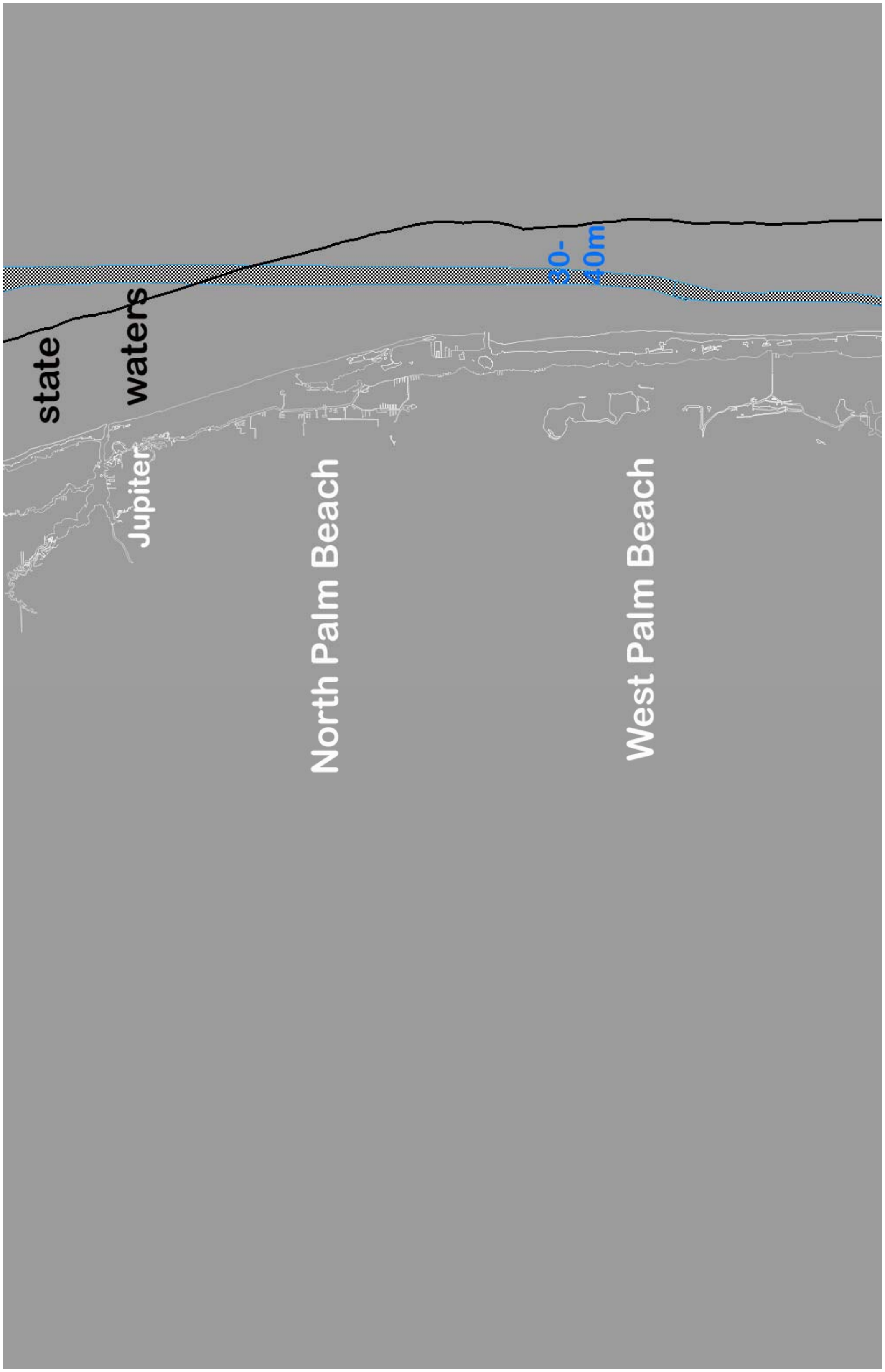


Figure 22. Regulatory boundaries off West Palm Beach to Jupiter.