2020 ANNUAL REPORT

OF THE WATER QUALITY MONITORING PROJECT FOR THE WATER QUALITY PROTECTION PROGRAM OF THE FLORIDA KEYS NATIONAL MARINE SANCTUARY

Henry O. Briceño, Ph.D. & Joseph N. Boyer, Ph.D.

July 2021

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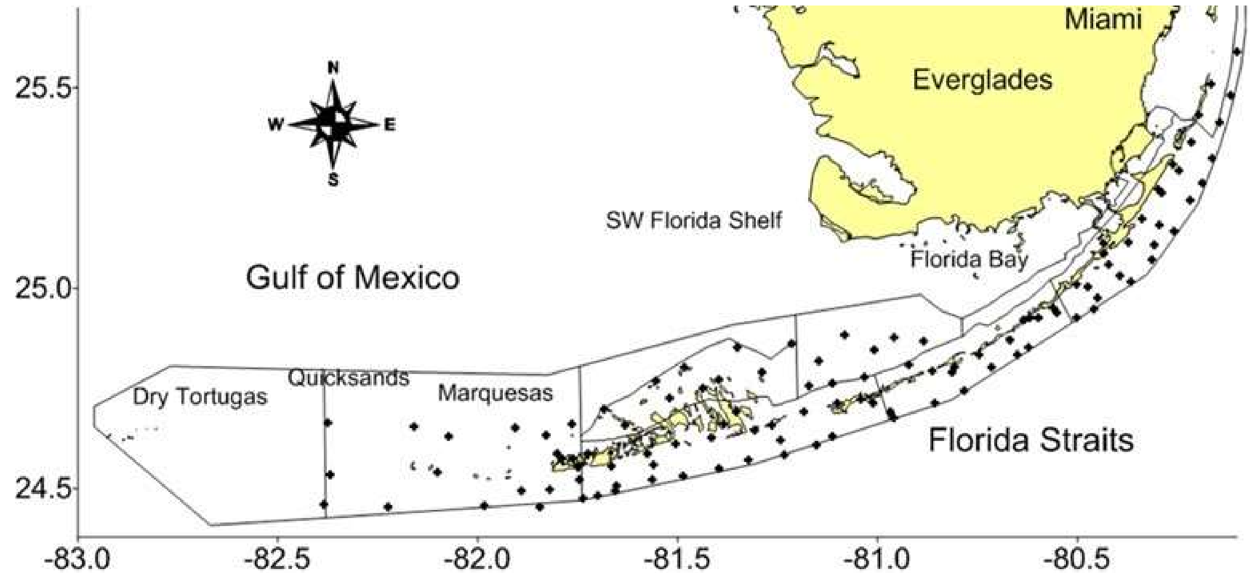

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Funded by the Environmental Protection Agency (#X7-00049716-0)

EXECUTIVE SUMMARY

This report serves as a summary of our efforts to date in the execution of the Water Quality Monitoring Project for the FKNMS as part of the Water Quality Protection Program. The period of record for this report is Apr. 1995 – Dec. 2020 and includes data from 102 quarterly sampling events within the FKNMS (26 years).

Field parameters measured at each station (surface and bottom at most sites) include salinity (practical salinity scale), temperature (°C), dissolved oxygen (DO, mg l^{-1}), turbidity (NTU), relative fluorescence, and light attenuation (K_d, m^{-1}). Water quality variables include the dissolved nutrients nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), and soluble reactive phosphorus (SRP). Total unfiltered concentrations include those of nitrogen (TN), organic carbon (TOC), phosphorus (TP), silicate (SiO_2) and chlorophyll *a* (CHLA, µg l^{-1}). All variables are reported in ppm (mg l^{-1}) unless otherwise noted.

The EPA developed Strategic Targets for the Water Quality Monitoring Project (SP-47) which state that beginning in 2008 through 2020, they shall annually maintain the overall water quality of the near shore and coastal waters of the FKNMS according to 2005 baseline. For reef sites, chlorophyll *a* should be less than or equal to 0.35 µg l^{-1} and the vertical attenuation coefficient for downward irradiance (K_d, i.e., light attenuation) should be less than or equal to 0.20 m^{-1}. For all monitoring sites in FKNMS, dissolved inorganic nitrogen should be less than or equal to 0.75 µM (0.010 ppm) and total phosphorus should be less than or equal to 0.25 µM (0.008 ppm). *Table i* shows the number of sites and percentage of total sites exceeding these Strategic Targets for 2019. In addition, *Figure i* shows percent of sites meeting the targets for DIN, TP, CHLA, and K_d.

The 2011 reduction of sampling sites in Tortugas/western FKNMS (TORT, less human-impacted sites) and addition of close in, shore sites (SHORE, heavily human-impacted sites) introduces a bias to the dataset which might require a revision of SP-47 to correct this deviation. To avoid such complications, we have not included the TORT or SHORE stations in calculation of compliances after 2010.

***Table i*: EPA WQPP Water Quality Targets derived from 1995-2005 Baseline**

For reef stations, chlorophyll less than or equal to 0.35 micrograms liter^{-1} (ug l^{-1}) and vertical attenuation coefficient for downward irradiance (K_d, i.e., light attenuation) less than or equal to 0.20 per meter. For all stations in the FKNMS, dissolved inorganic nitrogen less than or equal to 0.75 micromolar and total phosphorus less than or equal to 0.25 micromolar. Water quality within these limits is considered essential to promote coral growth and overall health. The number of samples and percentage exceeding these targets is tracked and reported annually. Values in green are those years with % compliance greater than 1995-2005 baseline. Values in yellow are those years with % compliance less than 1995-2005 baseline.

EPA WQPP Water Quality Targets				
	REEF Stations		All Stations (excluding SHORE sites)	
Year	CHLA ≤ 0.35 µg l^{-1}	K_d ≤ 0.20 m^{-1}	DIN ≤ 0.75 µM (0.010 mg l^{-1})	TP ≤ 0.25 µM (0.008 mg l^{-1})
1995-05	1778 of 2367 (75.1%)	1042 of 1597 (65.2%)	7826 of 10254 (76.3%)	7810 of 10267 (76.1%)
2006	196 of 225 (87.1%)	199 of 225 (88.4%)	432 of 990 (43.6%)	316 of 995 (31.8%)
2007	198 of 226 (87.6%)	202 of 222 (91.0%)	549 of 993 (55.3%)	635 of 972 (65.3%)
2008	177 of 228 (77.6%)	181 of 218 (83.0%)	836 of 1,000 (83.6%)	697 of 1,004 (69.4%)
2009	208 of 228 (91.2%)	189 of 219 (86.3%)	858 of 1,003 (85.5%)	869 of 1,004 (86.6%)
2010	170 of 227 (74.9%)	176 of 206 (85.4%)	843 of 1,000 (84.3%)	738 of 1,003 (73.6%)
2011	146 of 215 (67.9%)	156 of 213 (73.2%)	813 of 1,012 (80.3 %)	911 of 1,013 (89.9 %)
2012	142 of 168 (84.5%)	135 of 168 (80.4%)	489 of 683 (71.6 %)	634 of 684 (92.7 %)
2013	148 of 172 (86.0%)	150 of 172 (87.2%)	496 of 688 (72.1 %)	603 of 688 (87.6 %)
2014	141 of 172 (82.0%)	133 of 172 (77.3%)	426 of 690 (61.7%)	540 of 690 (78.3%)
2015	122 of 172 (70.9%)	135 of 172 (78.5%)	487 of 688 (70.8%)	613 of 688 (89.1%)
2016	131 of 172 (76.2%)	129 of 170 (75.9%)	427 of 687 (62.2%)	549 of 688 (79.8%)
2017	106 of 172 (61.6%)	120 of 170 (70.6%)	440 of 575 (76.5 %)	581 of 683 (85.1 %)
2018	92 of 170 (54.1%)	108 of 152 (71.7%)	558 of 689 (81.0 %)	573 of 689 (82.3 %)
2019	112 of 171 (65.5%)	133 of 168 (79.2%)	669 of 684 (97.8 %)	587 of 686 (85.6 %)
2020	129 of 172 (75.0%)	141 of 169 (83.4%)	617 of 688 (89.7%)	466 of 688 (67.7%)

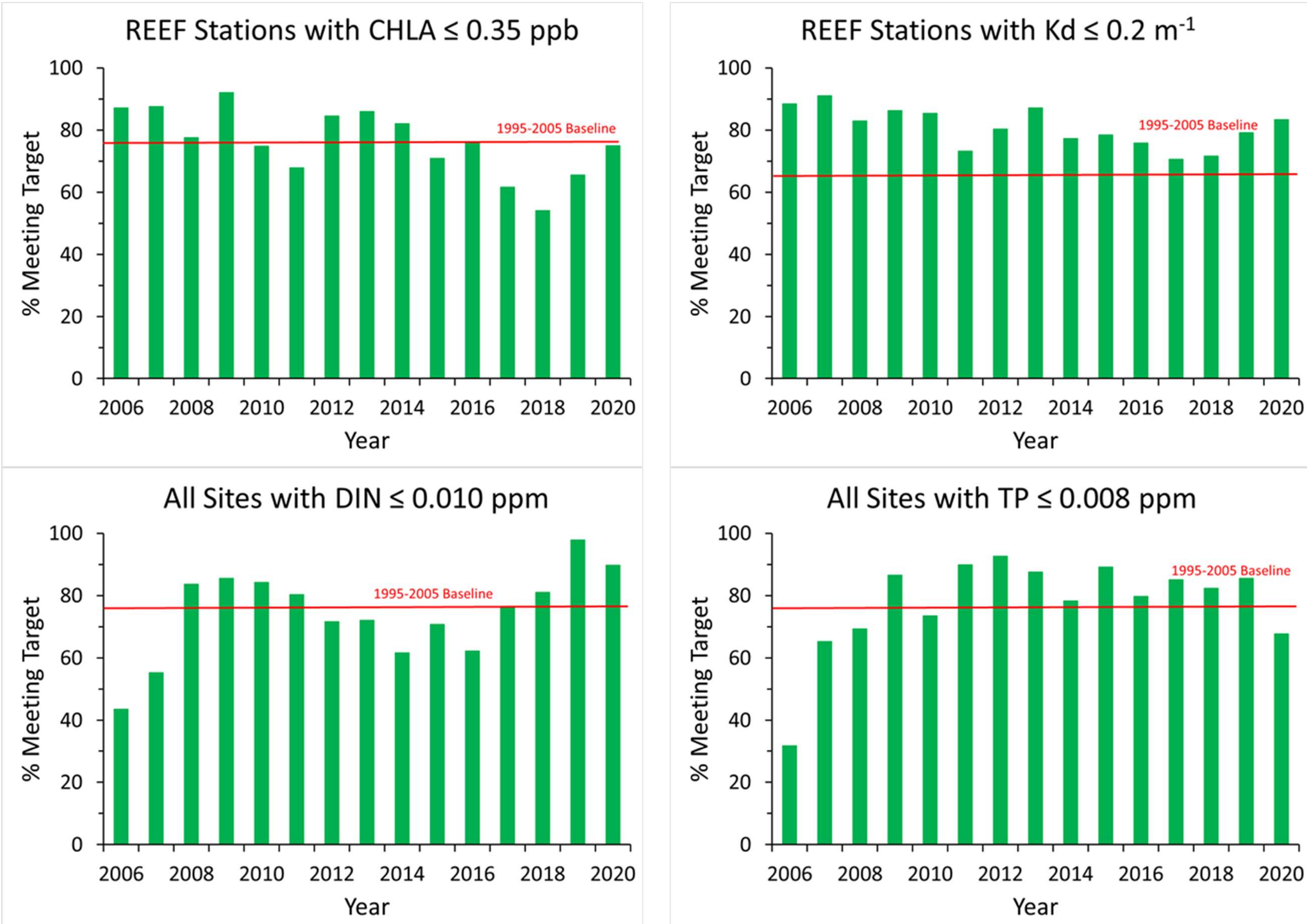

Figure i. *EPA targets expressed as percent of sites meeting baseline criteria by year.*

Trend Analysis – 26 years

Few statistically significant trends were observed for temperature or salinity however, there were patterns in total change for the 26 period of record across the FKNMS (*Fig. ii & iii*). The areas in red – Sluiceway, Backcountry, Upper Keys – show small increase in salinity over time. The offshore Lower Keys exhibited lower salinities. Small overall decreases in temperature were confined to Sluiceway and Lower Keys (<-1.0°C) while increases occurred in Upper Keys and Marquesas.

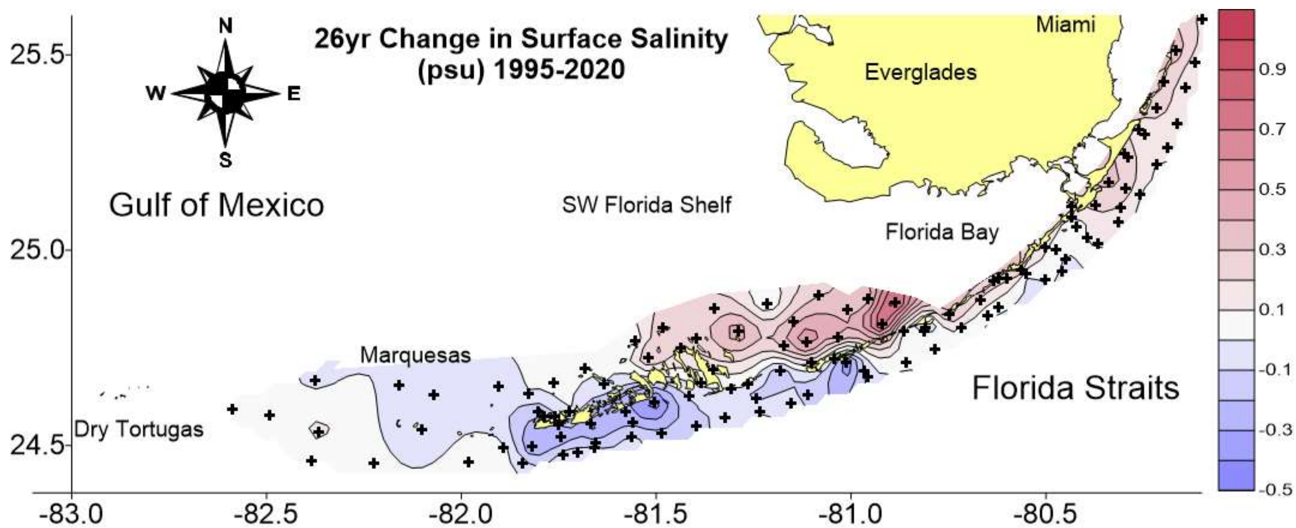

Figure ii. *Total change in salinity of surface waters for 26-year period.*

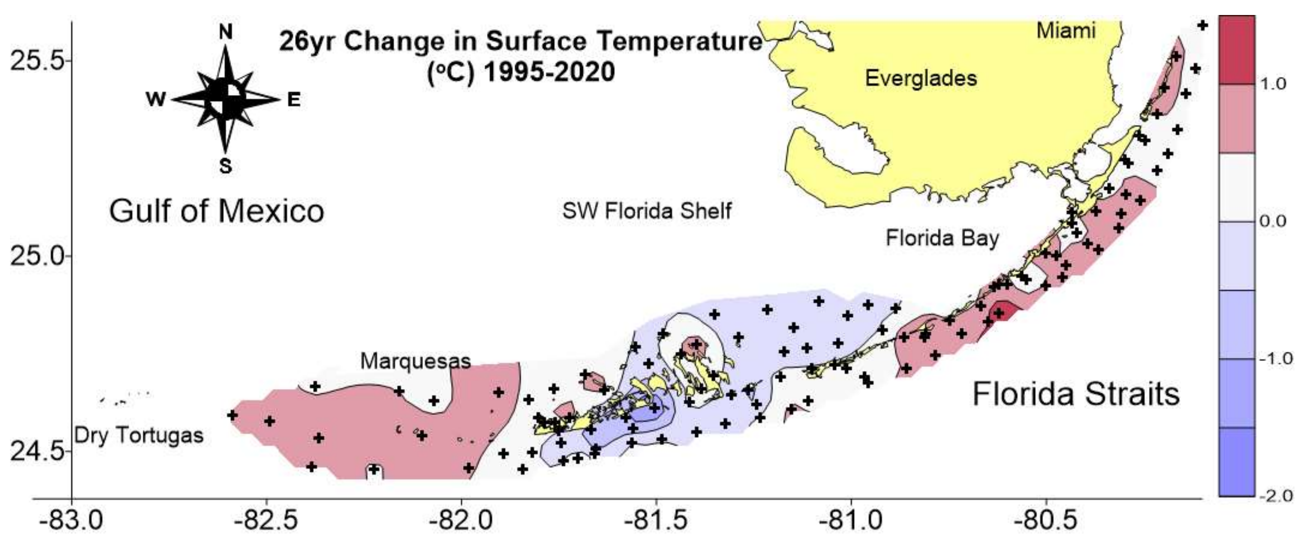

Figure ii. *Total change in temperature of surface waters for 26-year period.*

Greatest increases in DO_{sat} occurred offshore the Keys, Middle Keys passes (*Fig. iv*). Increased DO_{sat} is generally beneficial for animal life. Bottom DO_{sat} trends were similar (not shown).

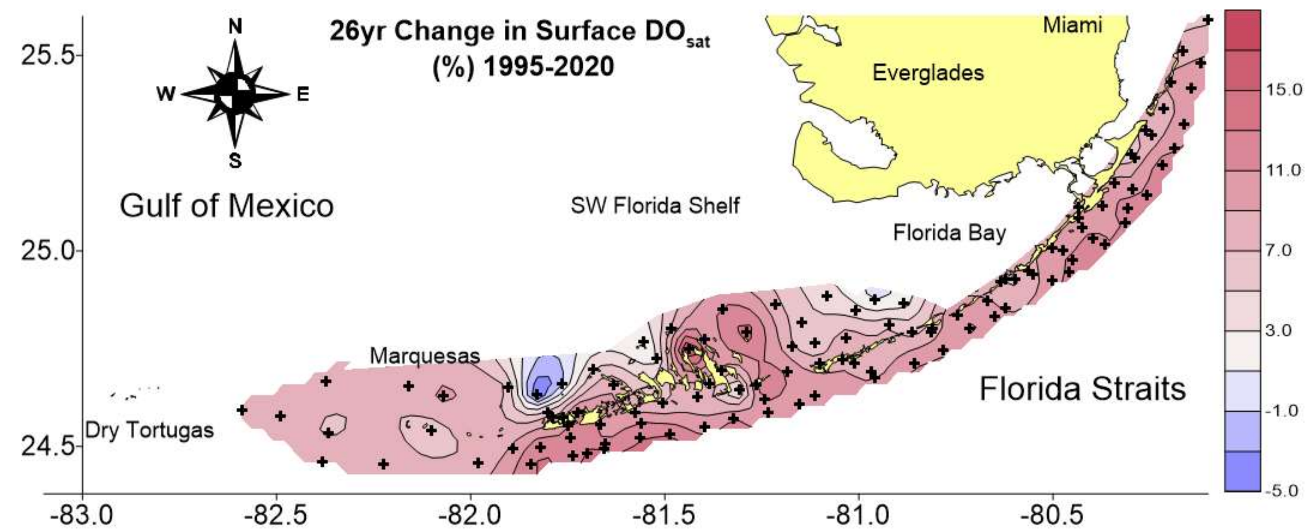

Figure iv. *Total change in DO saturation of surface waters for 26-year period.*

Water column turbidity (cloudiness) declined throughout the FKNMS during the 26-year period (a beneficial trend). The largest declines in turbidity occurred in the Sluiceway, Backcountry, and Marquesas (*Fig v*). Some small changes in turbidity also occurred in bottom waters (not shown).

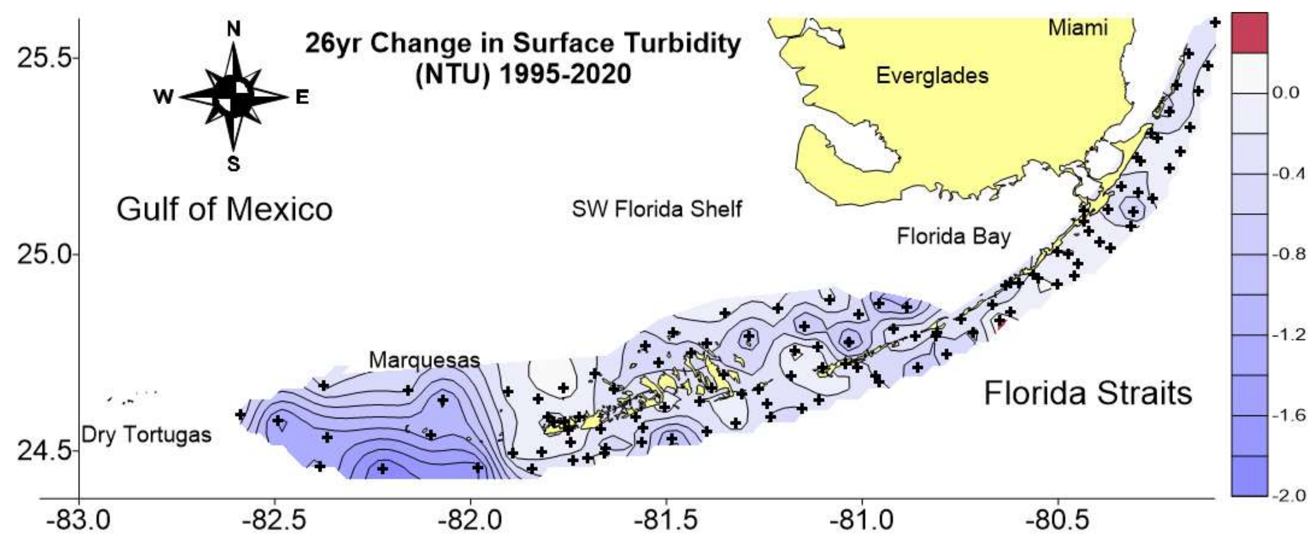

Figure v. *Total change in turbidity in surface waters for 26-year period.*

Decreased turbidity influenced light extinction (K_d) through the water column (*Fig. vi*) but not to a great extent. This inversely affected the percent of surface light (I_o) reaching the bottom. More light on the bottom is beneficial to corals, seagrass, and algae. Bottom light increased at most reef/offshore sites throughout the Keys and Marquesas but decreased in Backcountry, inshore sites along Keys, and Upper Keys in general (*Fig. vii*).

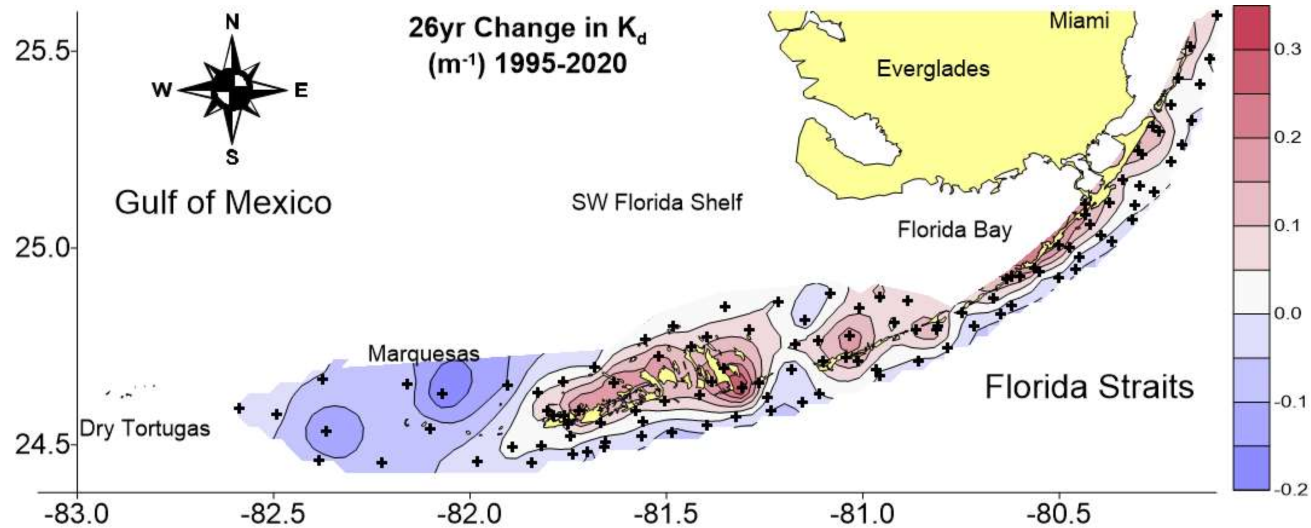

Figure vi. *Total change in K_d in surface waters for 26-year period.*

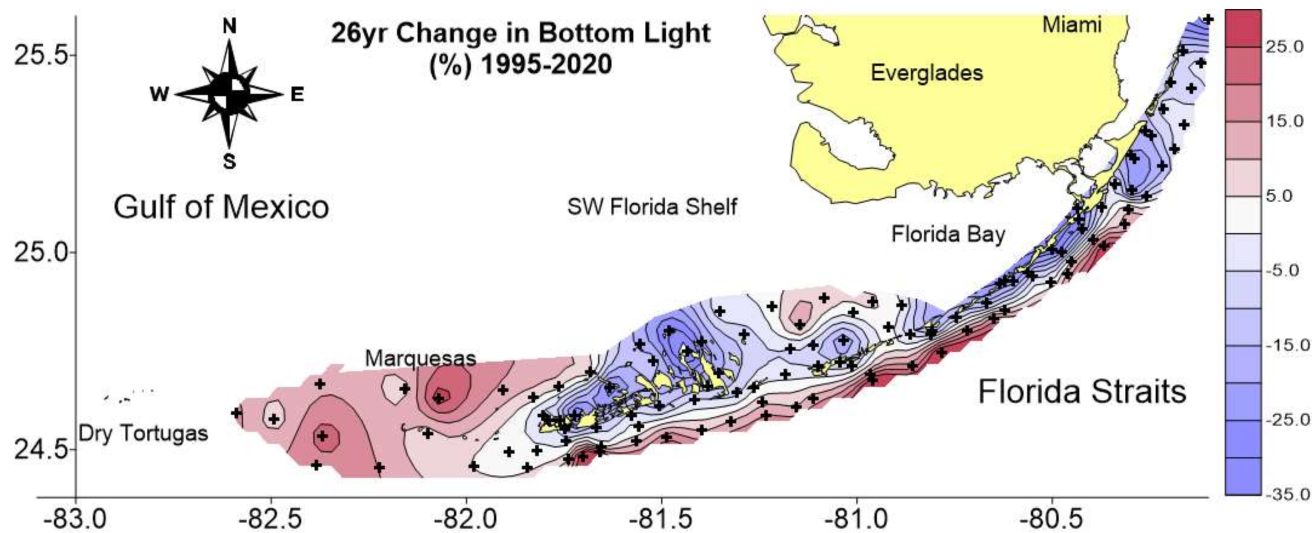

Figure vii. *Total change of incident bottom light for 26-year period.*

Significant Keys-wide trends in NH_4^+, NO_3^-, and SRP were detected but were very minor (not shown). Small declining trends in TP were observed in surface waters of the Marquesas but increases in TP occurred in all other areas of the FKNMS (Fig viii). These trends need to be watched as we expected TP to decline inshore in response to recent central sewer installation.

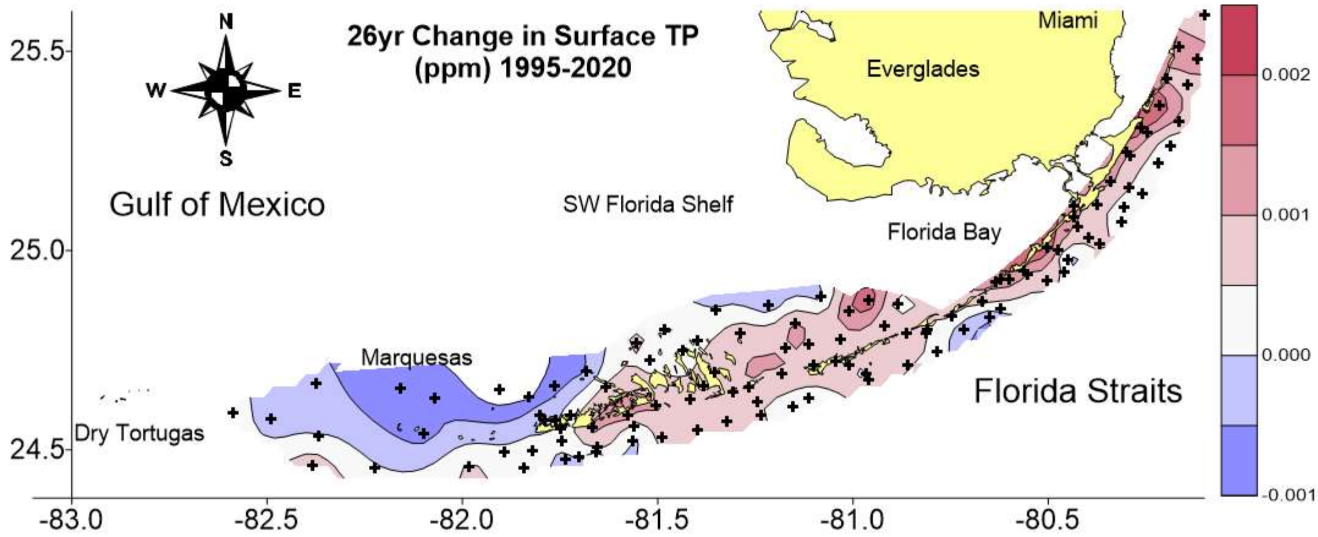

Figure viii. *Total change of TP for 26-year period.*

Chlorophyll *a* (CHLA) mirrored the spatial patterns in TP trends exhibited, declining in the Marquesas while increasing most everywhere else in the FKNMS (*Fig. ix*). Significant increases for the 26-year record ranged from 0.083 0.279 ppb or 28-68% increase.

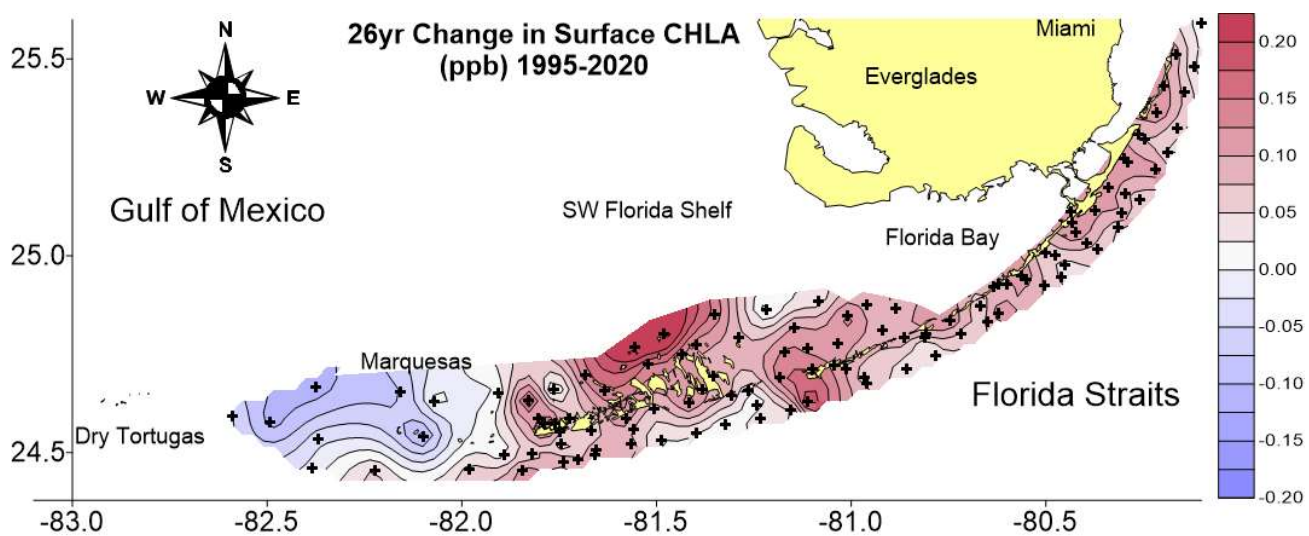

Figure ix. *Total change in CHLA in surface waters for 26-year period.*

The largest sustained trends have been the decline in surface total organic carbon (TOC) and nitrogen (TON, (*Fig. x & xi*). This is part of a regional trend in TOC observed in earlier monitoring on the SW Shelf, Florida Bay, and the Everglades mangrove estuaries. This decline could be considered favorable given that TOC & TON are important components of water color and negatively affect light penetration, but could also be an indication of decreased terrestrial primary production and export. It might also be characteristic of a Gulf-wide trend.

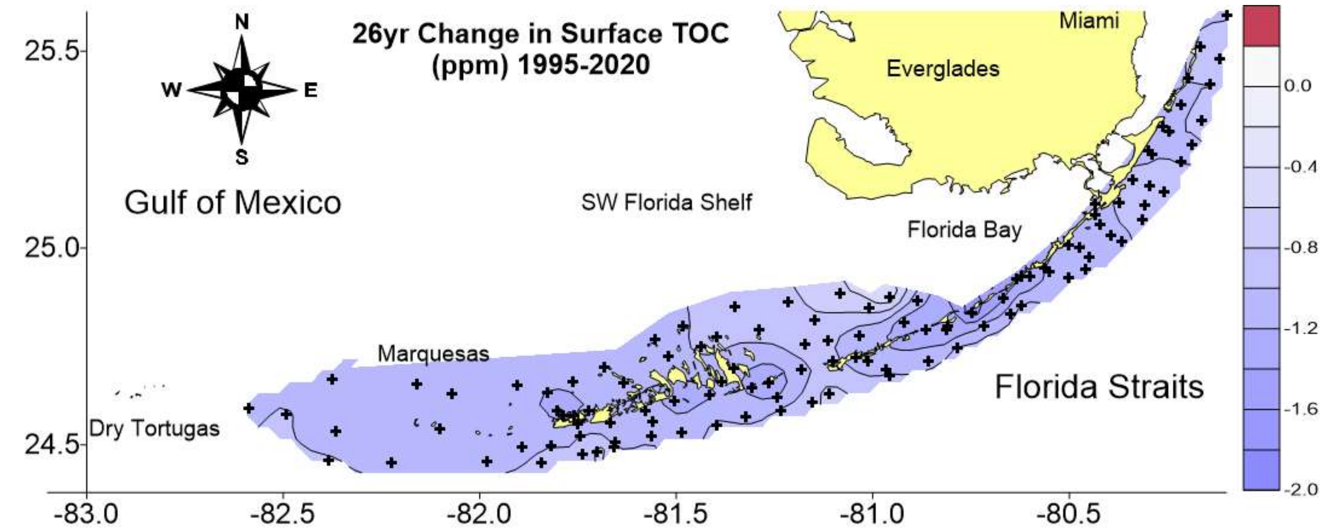

Figure x. *Total change in TOC in surface waters for 26-year period.*

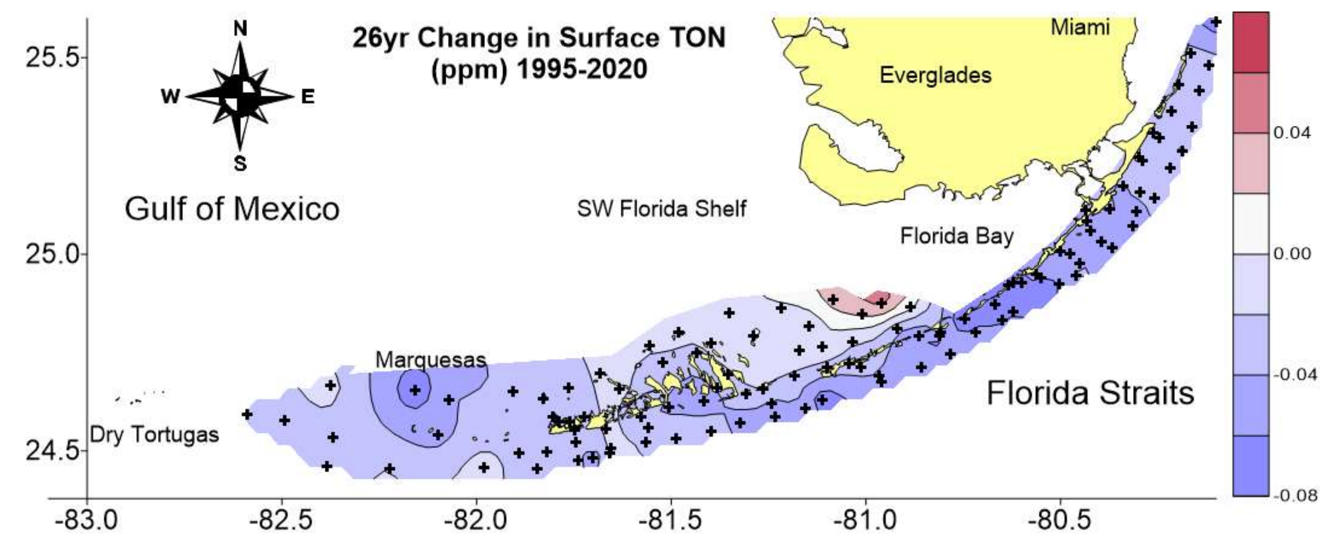

Figure xi. *Total change in TON in surface waters for 26-year period.*

The ratio between dissolved inorganic nitrogen and total phosphorus (DIN:TP) as a indicator for assessing phytoplankton nutrient limitation has also declined overall (*Fig. xii*). This implies that primary production may be becoming more N limited in the FKNMS.

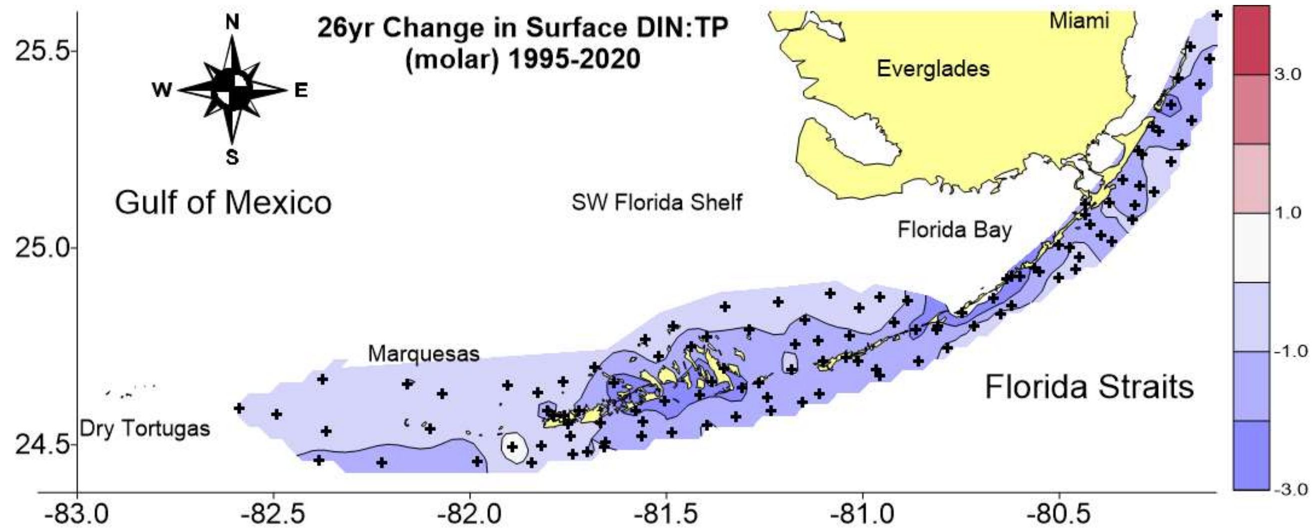

Figure xii. *Total change in DIN:TP ratio in surface waters for 26-year period.*

The large scale of this monitoring program has allowed us to assemble a much more holistic view of broad physical/chemical/biological interactions occurring over the South Florida hydroscape. This confirms that monitoring should be viewed as a tool for answering management questions and developing new scientific hypotheses.

We continue to maintain a website http://serc.fiu.edu/wqmnetwork/ where data and reports from this project accessible to the public.

Table of Contents

1. Project Background

The Florida Keys are an archipelago of sub-tropical islands of Pleistocene origin which extend in a NE to SW direction from Miami to Key West and out to the Dry Tortugas (Fig. 1). In 1990, President Bush signed into law the Florida Keys National Sanctuary and Protection Act (HR5909) which designated a boundary encompassing >2,800 square nautical miles of islands, coastal waters, and coral reef tract as the Florida Keys National Marine Sanctuary (FKNMS). The Comprehensive Management Plan (NOAA 1995) required the FKNMS to have a Water Quality Protection Plan (WQPP) thereafter developed by EPA and the State of Florida (EPA 1995). The original agreement for the water quality monitoring component of the WQPP was subsequently awarded to the Southeast Environmental Research Program at Florida International University and the field sampling program began in March 1995.

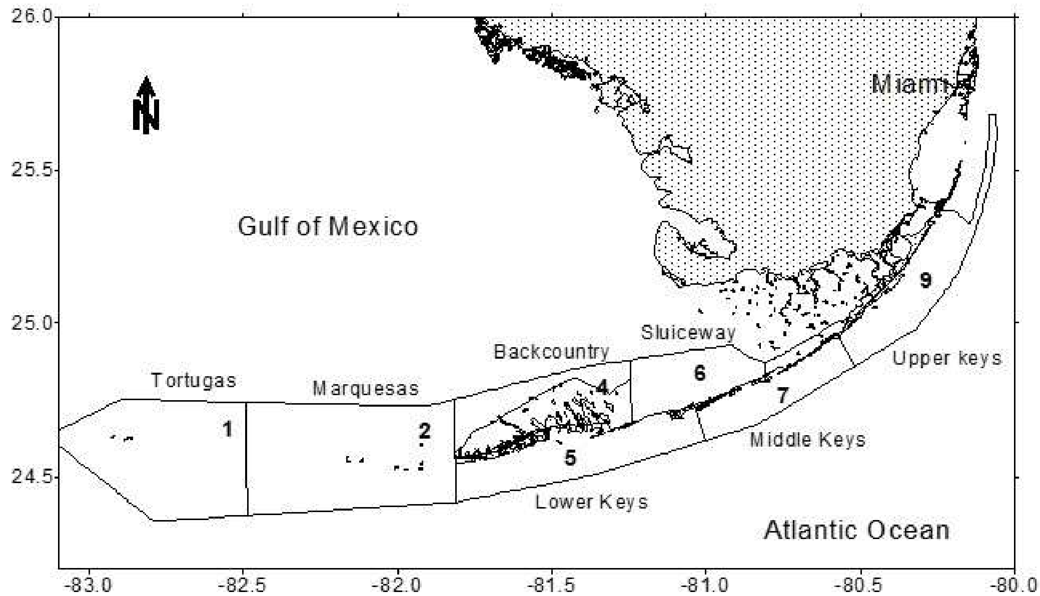

***Figure 1**: Map of original FKNMS boundary including collapsed segment numbers and common names. Modified after Klein and Orlando (1994)*

The waters of the FKNMS are characterized by complex water circulation patterns over both spatial and temporal scales with much of this variability due to seasonal influence in regional circulation regimes. The FKNMS is directly influenced by the Florida Current, the Gulf of Mexico Loop Current, inshore currents of the SW Florida Shelf (SW Shelf), discharge from the Everglades through the Shark River Slough, and by tidal exchange with both Florida Bay and Biscayne Bay (Lee et al. 1994, Lee et al. 2002).

Advection from these external sources may significantly affect the physical, chemical, and biological composition of waters within the FKNMS, as may internal nutrient loading and freshwater runoff from the Keys themselves (Boyer and Jones 2002). Water quality of the

FKNMS may be directly affected by both external nutrient transport and internal nutrient loading sources (Gibson et al. 2008). Therefore, the geographical extent of the FKNMS as a political/regulatory boundary should not be thought of in any way as an enclosed ecosystem.

A spatial framework for FKNMS water quality management was proposed on the basis of geographical variation of regional circulation patterns (Klein and Orlando, 1994). The final implementation plan (EPA 1995) partitioned the FKNMS into 9 sub-areas which was collapsed to 7 for routine sampling (Fig. 1). Station locations were developed using a stratified random design along onshore/offshore transects in sub-areas 5, 7, and 9 or within EMAP grid cells in sub-areas 1, 2, 4, and 6.

Sub-area 1 (Tortugas) includes the Dry Tortugas National Park (DTNP) and surrounding waters and is most influenced by the Loop Current and Dry Tortugas Gyre. Originally, there were no sampling sites located within the DTNP as it was outside the jurisdiction of NOAA. Upon request from the National Park Service, we initiated sampling at 5 sites within the DNTP boundary. Sampling in the Dry Tortugas was discontinued in 2011 due to budget constraints.

Sub-area 2 (Marquesas) includes the Marquesas Keys and a shallow sandy area between the Marquesas and Tortugas called the Quicksands. Sub-area 4 (Backcountry) contains the shallow, hard-bottomed waters on the gulf side of the Lower Keys. Sub-areas 2 and 4 are both influenced by water moving south along the SW Shelf. Sub-area 6 can be considered as part of western Florida Bay. This area is referred to as the Sluiceway as it strongly influenced by transport from Florida Bay, SW Shelf, and Shark River Slough (Smith, 1994). Sub-areas 5 (Lower Keys), 7 (Middle Keys), and 9 (Upper Keys) include the inshore, Hawk Channel, and reef tract of the Atlantic side of the Florida Keys. The Lower Keys are most influenced by cyclonic gyres spun off the Florida Current, the Middle Keys by exchange with Florida Bay, while the Upper Keys are influenced by the Florida Current frontal eddies and to a certain extent by exchange with Biscayne Bay. All three oceanside segments are also influenced by wind and tidally driven lateral Hawk Channel transport (Pitts, 1997).

We have found that water quality monitoring programs composed of many sampling stations situated across a diverse hydroscape are often challenging to interpret due to the "can't see the forest for the trees" problem (Boyer et al. 2000). At each site, the many measured variables are independently analyzed, individually graphed, and separately summarized in tables. This approach makes it difficult to see the larger, regional picture or to determine any associations among sites. In order to gain a better understanding of the spatial patterns of water quality of the FKNMS, we attempted to reduce the complicated data matrix into fewer elements which would provide robust estimates of condition and connection. To this end we developed an objective classification analysis procedure which grouped stations according to water quality similarity (Briceño et al. 2013, Fig. 2).

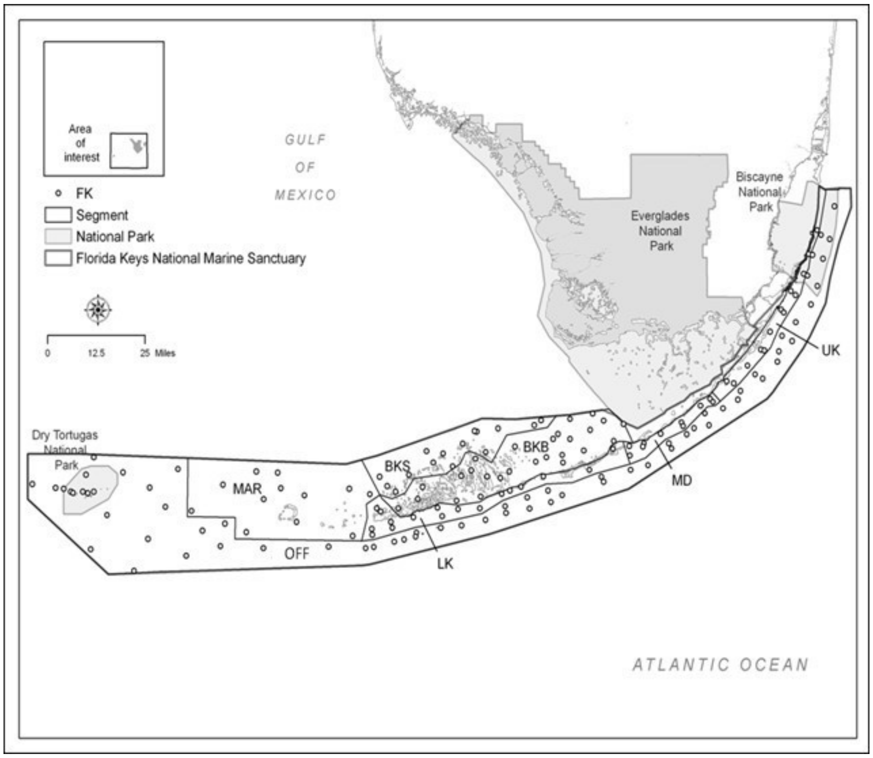

Figure 2: *Map of FKNMS showing segments derived from biogeochemical data: OFF=Offshore; MAR=Marquesas; BKS=Back Shelf; BKB= Back Bay; LK= Lower Keys; MK= Middle Keys; UK= Upper Keys*

Although the original quarterly sampling of 155 stations was cut back to 112 in 2011 (Fig. 3), it still provides a unique opportunity to explore the spatial component of water quality variability in the FKNMS, but decreases the ability of linking the Sanctuary's water quality to external sources of variability.

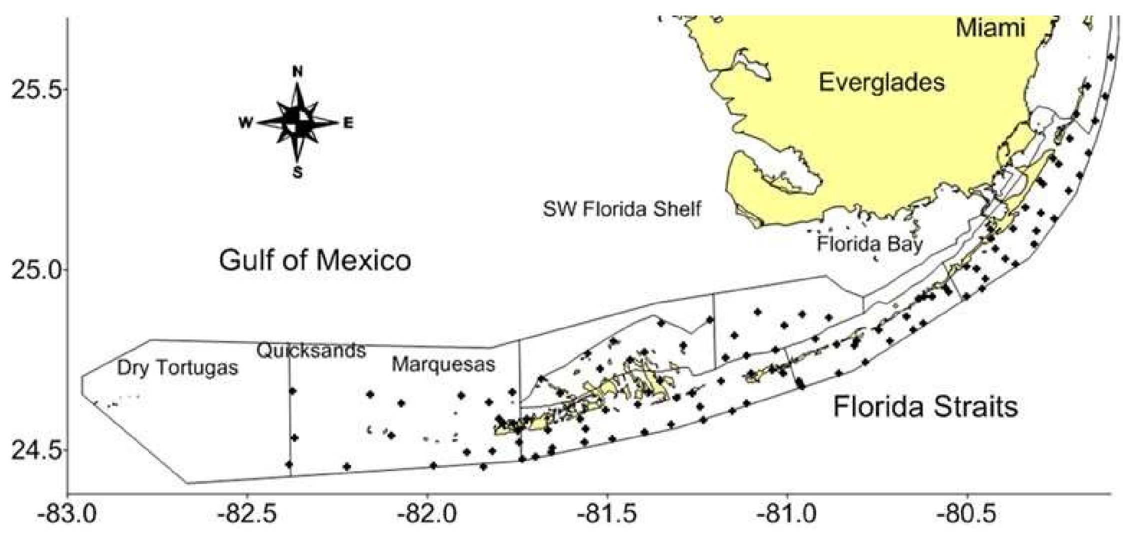

Figure 3*. The SERC Water Quality Monitoring Network showing the distribution of fixed sampling stations within the FKNMS for 2020 sampling.*

2. Methods

2.1. Field Sampling

The period of record of this study was March 1995 to December 2020, which included 102 quarterly sampling events. The 2011 reduction of sampling sites in Tortugas/western FKNMS (TORT, less human-impacted sites) and addition of close in, shore sites (SHORE, heavily human-impacted sites) introduced a bias to the dataset which might require a revision of SP-47 to correct this deviation. To avoid such complications, we have not included the TORT or SHORE stations in calculation of compliances after 2010.

For this year, field measurements and grab samples were collected from 112 fixed stations within the FKNMS boundary (Fig. 3). Depth profiles of temperature (°C), salinity (practical salinity scale), dissolved oxygen (DO, mg l^{-1}), photosynthetically active radiation (PAR, µE m^{-2} s^{-1}), turbidity (NTU), and depth (m), were measured by CTD casts (Seabird SBE 19). The CTD was equipped with internal RAM and operated in stand-alone mode at a sampling rate of 0.5 sec. The vertical attenuation coefficient for downward irradiance (K_d, m^{-1}) was calculated at 0.5 m intervals from PAR and depth using the standard exponential equation (Kirk 1994) and averaged over the station depth. This was necessary due to periodic occurrence of optically distinct layers within the water column. During these events, K_d was reported for the upper layer. To determine the extent of stratification we calculated the difference between surface and bottom density as $\Delta\sigma_t$ (kg m^{-3}) where positive values denoted greater density of bottom water relative to the surface. Values of $\Delta\sigma_t$ between 0.0 and 1.0 are considered weakly stratified, while values >1 are deemed strongly stratified. Negative $\Delta\sigma_t$ conditions occur rarely and denote a unstable water column condition where the surface is denser than the bottom.

In the Backcountry area (Sub-area 4, Fig. 1), where it is too shallow to use a CTD, surface salinity and temperature were measured using a combination salinity-conductivity-temperature-DO probe (YSI 650 MDS display-datalogger with YSI 6600V2 sonde). DO was automatically corrected for salinity and temperature. PAR was measured every 0.5 m using a Li-Cor LI-1400 DataLogger equipped with a 4π spherical sensor (LI-193SB). PAR data with depth was used to calculate K_d from in-air surface irradiance.

Ambient water samples were collected from approximately 0.25 m below the surface and at approximately 1 m from the bottom with a Niskin bottle (General Oceanics) except in the Backcountry and Sluiceway where surface water was collected directly into sample bottles. Duplicate, unfiltered water samples were dispensed into 3x sample rinsed 120 ml HDPE bottles for analysis of total constituents. Dissolved nutrients were defined using Whatman GF/F filters with a nominal pore size of 0.8 µm. Duplicate water samples for dissolved nutrients were dispensed into 3x sample rinsed 150 ml syringes which were then filtered by hand through 25 mm glass fiber filters (Whatman GF/F) into 3x sample rinsed 60 ml HDPE bottles. The resulting wet filters, used for chlorophyll *a* (CHLA) analysis, were placed in 1.8 ml plastic centrifuge tubes to which 1.5 ml of 90% acetone/water was added (Strickland and Parsons 1972). An additional

120 ml sample was collected directly from the Niskin bottle for analysis of total nitrogen, total phosphorus, total organic carbon, and turbidity.

All samples were kept on ice in the dark during transport to the laboratory. During overnight stays in the Lower Keys sampling, filtrates and filters (not total samples) were frozen until further analysis.

2.2. *Laboratory Analysis*

Samples were analyzed for ammonium (NH_4^+), nitrate + nitrite (NO_x), nitrite (NO_2^-), total nitrogen (TN), soluble reactive phosphorus (SRP), total phosphorus (TP), total organic carbon (TOC), total silicate (SiO_2), chlorophyll *a* (CHLA, µg l^{-1}), and turbidity (in NTU) using standard laboratory methods. In accordance with EPA policy, the FKNMS water quality monitoring program adhered to existing rules and regulations governing QA and QC procedures as described in EPA guidance documents. The FIU-SERC Nutrient Laboratory maintained NELAP certification during the duration of this project

NH_4^+ was analyzed by the indophenol method (Koroleff 1983), NO_2^- was analyzed using the diazo method, and NO_x was measured as nitrite after cadmium reduction (Grassoff 1983a,b). The ascorbic acid/molybdate method was used to determine SRP (Murphy and Riley 1962). High temperature combustion and high temperature digestion were used to measure TN (Frankovich and Jones 1998; Walsh 1989) and TP (Solórzano and Sharp 1980), respectively. TOC was determined using the high temperature combustion method of Sugimura and Suzuki (1988). Silicate was measured using the heteropoly blue method (APHA 1995). Samples were analyzed for CHLA content by spectrofluorometry of acetone extracts (Yentsch and Menzel 1963). Protocols are presented in EPA (1993) and elsewhere as noted. All elemental ratios discussed were calculated on a molar basis. DO saturation in the water column (DO_{sat} as %) was calculated using the equations of Garcia and Gordon (1992). Some parameters were not measured directly but calculated by difference. Nitrate (NO_3^-) was calculated as NO_x - NO_2^-; total dissolved inorganic nitrogen (DIN) as NO_x + NH_4^+, and total organic nitrogen (TON) as TN - DIN. All variables are reported in ppm (mg l^{-1}) unless otherwise noted.

2.3. *Spatial Analysis - Contour Maps*

Contour maps (SURFER, Golden Software) of specific water quality variables were used to illuminate the contribution of external factors to the water quality of the FKNMS and to visualize gradients in water quality over the region. Kriging was the geostatistical algorithm of choice because it minimizes the error variance while maintaining point pattern continuity (Isaaks & Srivastava, 1989). Kriging is a global approach which uses standard geostatistics to determine the "distance" of influence around each point and the "clustering" of similar samples sites (autocorrelation). Therefore, unlike the inverse distance procedure, kriging will not produce valleys in the contour between neighboring points of similar value.

Because quarterly field surveys often occurred over more than a one month period, we define the quarterly surveys as: Winter (Jan.-Mar.), Spring (Apr.-Jun.), Summer (Jul.-Sep.), and Fall (Oct.-Dec.).

2.4. *Time Series Analysis*

Least squares, linear regression as a method for measuring change over time is useful for variables that change at relatively continuous rates. The simplicity of this method makes it appealing to those who are tracking water quality, but time series dominated by non-linear drivers may be skewed by trend reversals and endmember conditions. For these reasons, we used the nonparametric Sen slope estimation to determine temporal trends (unit yr^{-1}) for each water quality variable over the 26-year period of record. The Mann-Kendall Test was used to detect monotonic trends without the requirement that the measurements be normally distributed or that the trend be linear. Trend maps were drawn using all stations regardless of whether trends were significant. To show impact of trend over time, trend maps report the additive, total change over the 26-year period of record.

While the Mann-Kendall Test tells us whether the overall trend is increasing or decreasing, it does not provide any information about short-term changers or reversing trends. To address this limitation, time series data were stratified by zone (see above) and fitted using a locally-weighted approach (LOESS, MatLab). The LOESS algorithm is a non-parametric, locally weighted least squares method which combines multiple regression models in a k-nearest-neighbor analysis (Cleveland 1979). The Epanechnikov (1969) parabolic kernel with 10% data bandwidth was used as the time series smoother, except for SHORE sites where 20% was used because of shorter period of record.

3. Results

3.1. *Overall Water Quality of the FKNMS in 2020*

The more recently implemented stations located very close to shore were not used for this assessment. In their short period of record they have displayed a common tendency to be nutrient-enriched and exhibit lower salinity as compared to the rest of the sites. Hence, we have grouped these ten stations as an additional zone (SHORE) for comparison and exploration of terrestrial impacts on water quality.

Summary statistics for all water quality variables (excluding SHORE) from calendar year 2020 sampling events are shown as number of samples (*n*), minimum, maximum, and median (Table 1). Overall, the region remains warm and euhaline with a median temperature of 27.8 °C and salinity of 36.0; DO_{sat} was relatively high at 96.4%. On this coarse scale, the FKNMS exhibited very good water quality with median NO_3^-, NH_4^+, TP, and SiO_2 concentrations of 0.0010, 0.0004, 0.0070, and 0.0070 mg l^{-1}, respectively. DIN comprised a small fraction (3.0%) of the TN pool (0.131 mg l^{-1}) with TON being the bulk (median 0.127 mg l^{-1}). SRP concentrations were very low (median 0.0001 mg l^{-1}) and comprised only 1.4% of the TP pool (0.0070 mg l^{-1}). CHLA concentrations were also low overall (median 0.30 µg l^{-1}), but ranged from 0.03 to 5.67 µg l^{-1}. Median TOC was 1.24 mg l^{-1}; a value higher than open ocean levels but consistent with coastal areas.

For 2020, median turbidity was elevated (0.39 NTU) resulting in median K_d of 0.219 m^{-1}. Overall, 36.7% of incident light (I_o) reached the bottom. Molar ratios of N to P suggested a general P limitation of the water column (median TN:TP = 41.0) but this must be tempered by the fact that much of the TN may not be bioavailable. A potentially more usable DIN:TP ratio was 0.7, indicating strong potential N limitation across the region.

Table 1. *Summary statistics for water quality variables measured in the FKNMS for calendar year 2020 summarized by sampling depth as number of samples (n), minimum value (Min.), maximum value (Max.), and median value.*

Variable	Depth	n	Min.	Max.	Median
NO_3^-	Surface	440	0.0000	0.0342	0.0014
(mg l^{-1})	Bottom	271	0.0001	0.0192	0.0015
NO_2^-	Surface	446	0.0000	0.0019	0.0004
(mg l^{-1})	Bottom	282	0.0000	0.0013	0.0003
NH_4^+	Surface	448	0.0003	0.1097	0.0057
(mg l^{-1})	Bottom	282	0.0003	0.0395	0.0051
TN	Surface	448	0.0357	0.5073	0.1077
(mg l^{-1})	Bottom	282	0.0340	0.4616	0.0808
DIN	Surface	448	0.0014	0.1103	0.0079
(mg l^{-1})	Bottom	282	0.0018	0.0434	0.0072
TON	Surface	448	0.0014	0.4947	0.0984
(mg l^{-1})	Bottom	282	0.0231	0.4596	0.0696
TP	Surface	448	0.0030	0.0181	0.0051
(mg l^{-1})	Bottom	282	0.0027	0.0097	0.0043
SRP	Surface	448	0.0001	0.0040	0.0007
(mg l^{-1})	Bottom	282	0.0001	0.0034	0.0007
CHLA (µg l^{-1})	Surface	444	0.039	5.126	0.237
TOC	Surface	448	0.932	6.877	1.429
(mg l^{-1})	Bottom	282	0.962	4.146	1.236
SiO_2	Surface	448	0.000	0.842	0.009
(mg l^{-1})	Bottom	282	0.000	0.768	0.003
Turbidity	Surface	424	0.000	31.000	0.065
(NTU)	Bottom	270	0.000	7.880	0.000
Salinity	Surface	447	26.28	37.80	36.07
	Bottom	445	27.21	37.81	36.06

Temp. (°C)	Surface	448	20.08	31.94	25.88
	Bottom	446	19.97	31.88	25.69
DO ($mg\ l^{-1}$)	Surface	448	4.23	8.87	6.54
	Bottom	446	4.27	8.99	6.55
K_d (m^{-1})		415	0.001	4.314	0.204
TN:TP	Surface	448	12.7	228.8	42.6
DIN:TP	Surface	448	0.47	37.7	0.7
Si:DIN	Surface	448	0.0	74.4	0.6
DO_{Sat} (%)	Surface	448	64.6	131.9	97.4
	Bottom	448	0.0	134.4	97.4
I_o (%)	Bottom	448	0.2	100.0	38.1
$\Delta\sigma_t$ ($kg\ m^{-3}$)		448	-24.702	1.030	0.010

3.2. General Hydrological Drivers

Water quality is a subjective but powerful measure of ecosystem well-being. Aside from the physical-chemical composition of the water there is also a human perceptual element which varies according to our intents for use (Kruczyinski and McManus 2002). Distinguishing internal from external sources of nutrients in the FKNMS is a difficult task. The finer discrimination of internal sources into natural and anthropogenic inputs is even more difficult. Most of the important anthropogenic inputs are regulated and most likely controlled by management activities, however, earlier studies have shown that nutrients from shallow sewage injection wells may be leaking into nearshore surface waters (Corbett et al. 1999; Shinn 1999a, 1999b; Paul et al. 1995, 1997; Reich et al. 2001; Briceño et al. 2015). Stormwater inputs may be important for the halo zone (within 1,000 m of shore), but the effects are muted at best beyond this distance.

Advective transport of nutrients through the FKNMS was not measured by the existing fixed sampling plan. However, nutrient distribution patterns may be compared to the regional circulation regimes to visualize the contribution of external sources and advective transport to internal water quality of the FKNMS (Boyer and Jones 2002). Circulation in coastal South Florida is dominated by regional currents such as the Loop Current, Florida Current, and Tortugas Gyre and by local transport via Hawk Channel and along-shore SW Shelf movements (Klein and Orlando 1994). Regional currents may influence water quality over large areas by the advection of external surface water masses into and through the FKNMS (Lee et al. 1994, Lee et al. 2002) and by the intrusion of deep offshore ocean waters onto the reef tract as internal bores (Leichter et al. 1996). Local currents become more important in the mixing and transport of freshwater and nutrients from terrestrial sources (Smith 1994; Pitts 1997, Gibson et al. 2008).

Spatial patterns of salinity in coastal South Florida show these major sources of freshwater to have more than just local impacts. In Biscayne Bay, freshwater released through the canal system operated by the South Florida Water Management District may sometimes be seen to affect northern Key Largo by causing episodic depressions in salinity at alongshore sites. Freshwater entering NE Florida Bay via overland flow from Taylor Slough and C-111 basin mix in a SW direction. The extent of influence of freshwater from Florida Bay on alongshore salinity in the Keys is less than that of Biscayne Bay but it is more episodic. Transport of low salinity water from Florida Bay does not affect the Middle Keys sites enough to depress the median salinity in this region but is manifested as increased variability. The opposite also holds true; hypersaline waters from Florida Bay may be transported through the Sluiceway to inshore sites in the Middle Keys.

On the southwest coast, the large influence of the Shark River Slough, which drains the bulk of the Everglades and exits through the Whitewater Bay - Ten Thousand Islands mangrove complex, clearly impacts the SW Shelf waters. The mixing of SW Shelf waters with the Gulf of Mexico produces a salinity gradient in a SW direction which extends out to Key West. This freshwater source may sometimes affect the Backcountry because of its shallow nature but often follows a trajectory of entering western Florida Bay and exiting out through the channels in the Middle Keys (Smith 1994). This net transport of lower salinity water from mainland to reef in open channels through the Keys is observed as an increase in the range and variability of salinity rather than as a large depression in salinity.

In addition to surface currents there is evidence that internal tidal bores regularly impact the Upper Keys reef tract (Leichter et al. 1996; Leichter and Miller 1999). Internal bores are episodes of higher density, deep water intrusion onto the shallower shelf or reef tract. They also entrain high nutrient waters from deeper ocean layers which spread over the reefs (Leichter and Miller 1999). Depending on their energy, internal tidal bores can promote stratification of the water column or cause complete vertical mixing as a breaking internal wave of sub-thermocline water.

3.3. 2020 Seasonal Trends

Surface salinity distributions in 2020 showed lower than seawater conditions in the Sluiceway during summer/fall, probably from SW Shelf transport from the GOM (Fig. 4). This pattern was not consistent with usual observed salinity but the differences were small compared to some other years.

Surface Temperature distributions (°C,Fig. 5) were relatively unremarkable except for low values in Backcountry and Marquesas during late fall sampling. These temperatures coincide with lower salinities from GOM transport.

The circulation drivers mentioned above also influence other water quality variables, such as DO saturation (DO_{sat} in %, Fig. 6). Higher levels of DO_{sat} are generally beneficial for animal life. Lowest DO_{sat} tend to develop inside the Backcountry during warmest months and is most probably due to higher salinities, and longer water residence time. This year, DO_{sat} was relatively high across the region throughout the year.

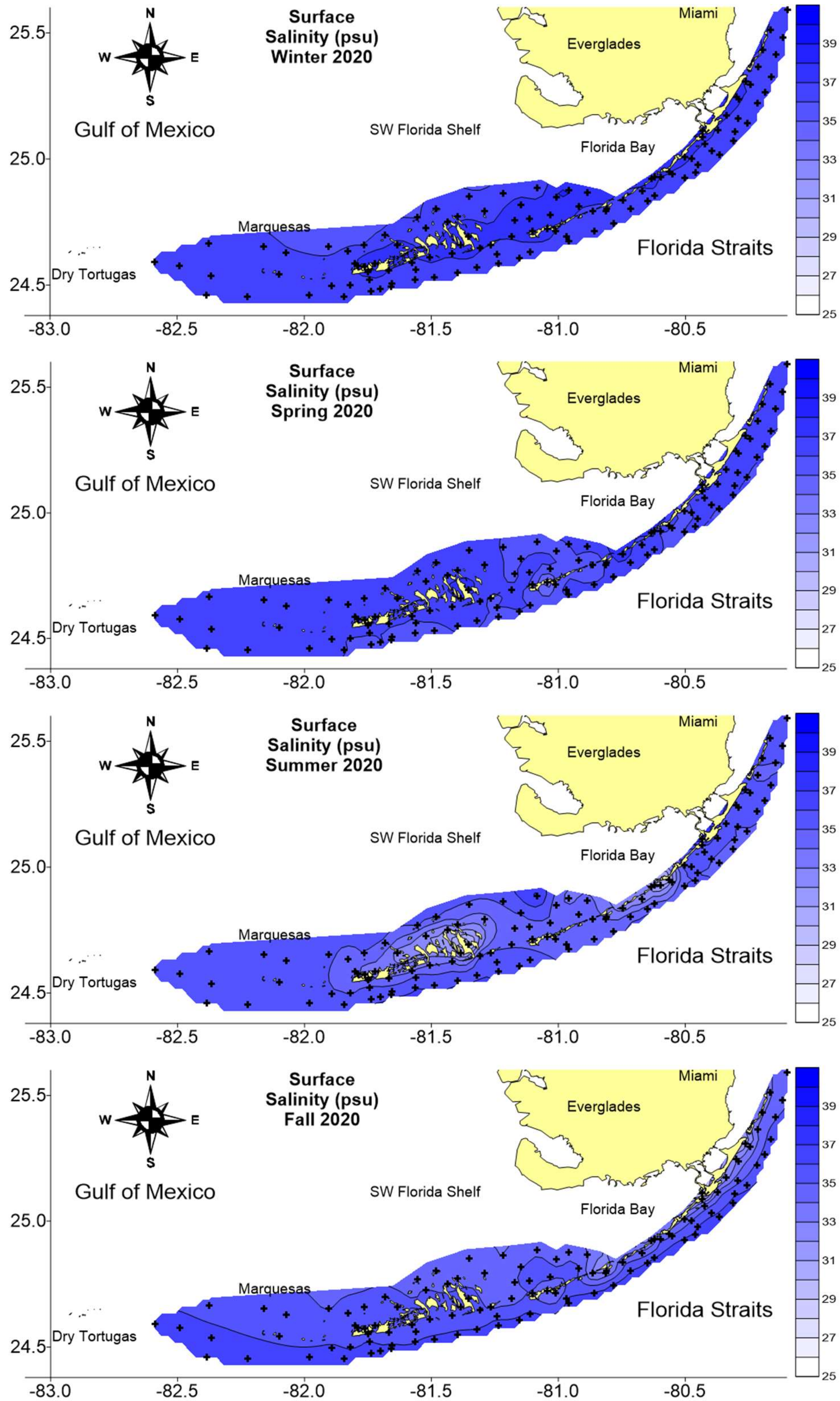

Figure 4*. Surface salinity distributions across the FKNMS during 2020.*

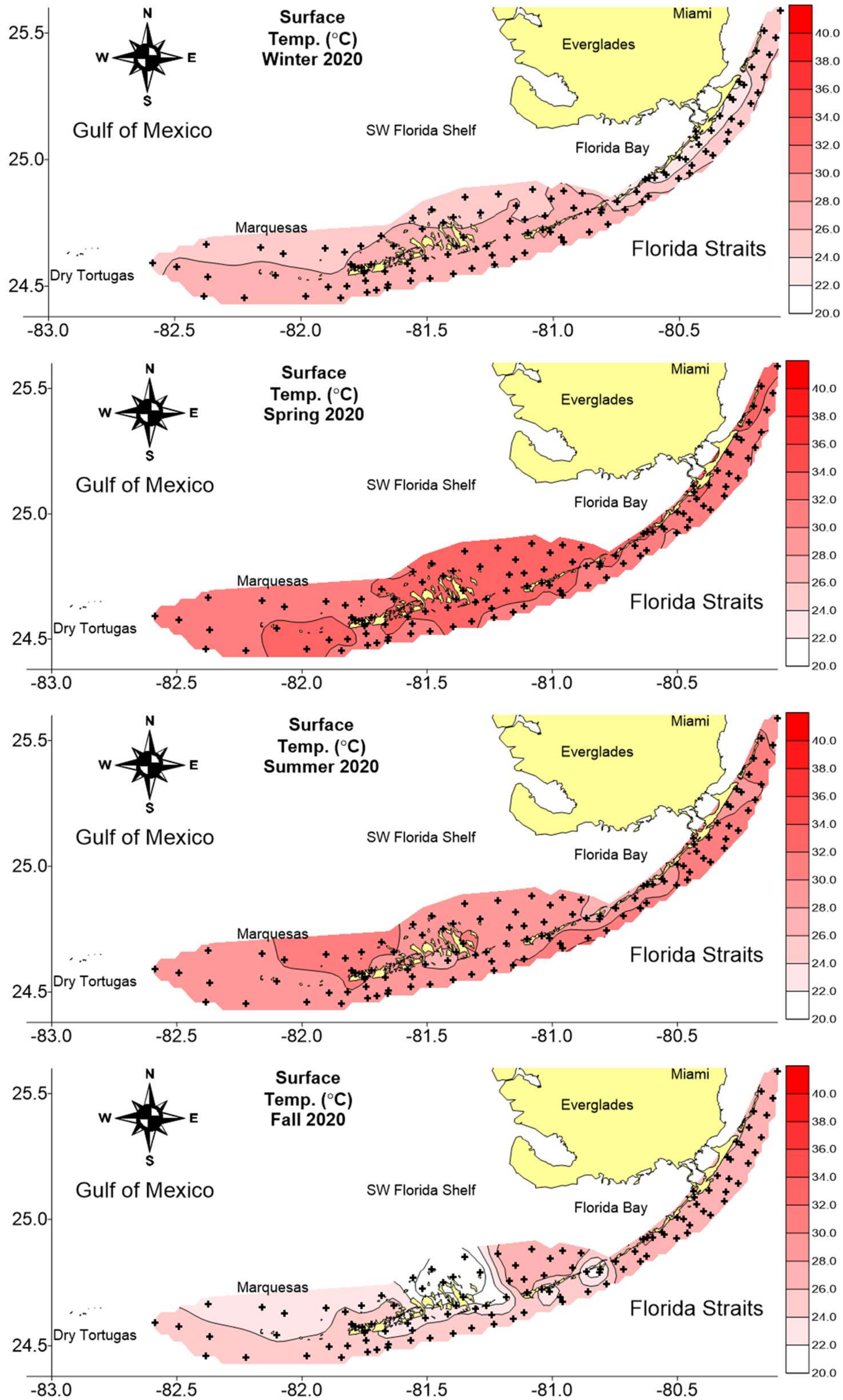

***Figure 5**. Surface temperature distributions across the FKNMS during 2020.*

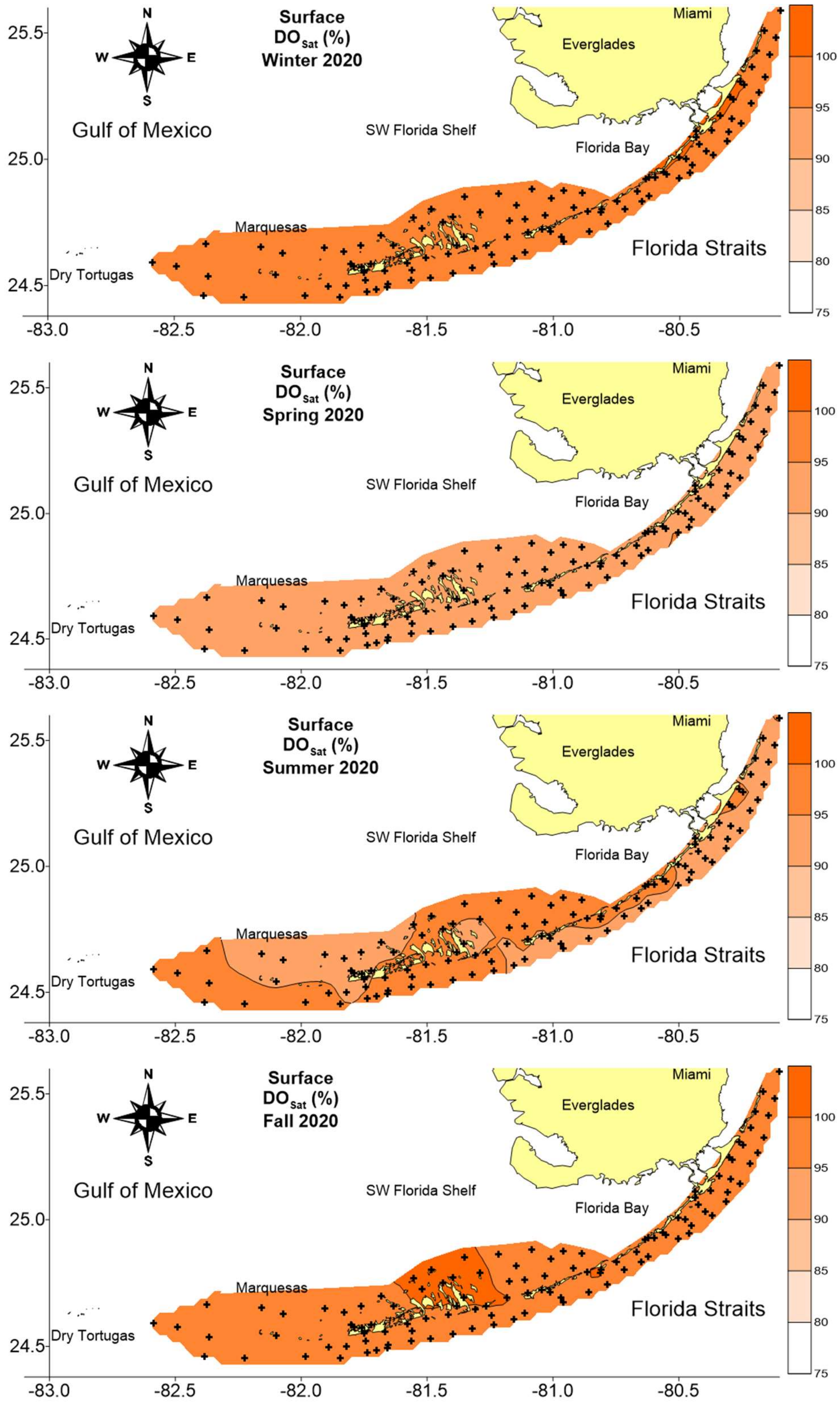

Figure 6. *Surface dissolved oxygen saturation distributions across the FKNMS during 2020.*

In many situations, independent water masses may be distinguished by difference in density (delta sigma-*t* or $\Delta\sigma_t$ in kg m^{-3}) between surface and bottom (Fig. 7). Since density is driven more by salinity than temperature, we do not always observe differences in σ_t between surface and bottom during upwelling events. However, decreased temperature of bottom waters from intrusion of deeper oceanic waters is often an indicator of elevated NO_3^- levels. These upwelling events also affect other nutrient species such as NH_4^+, TP, and SRP in bottom waters as well. Temperature will have influence on σ_t when cold fronts come through ad quickly reduce surface water temperatures.

Stratification events are typically sporadic and widespread on the Atlantic side of the Keys and Marquesas. This year the Marquesas and offshore Lower Keys had slightly elevated $\Delta\sigma_t$ during spring, summer, and fall (Fig 7) with many reef sites experiencing significant density stratification.

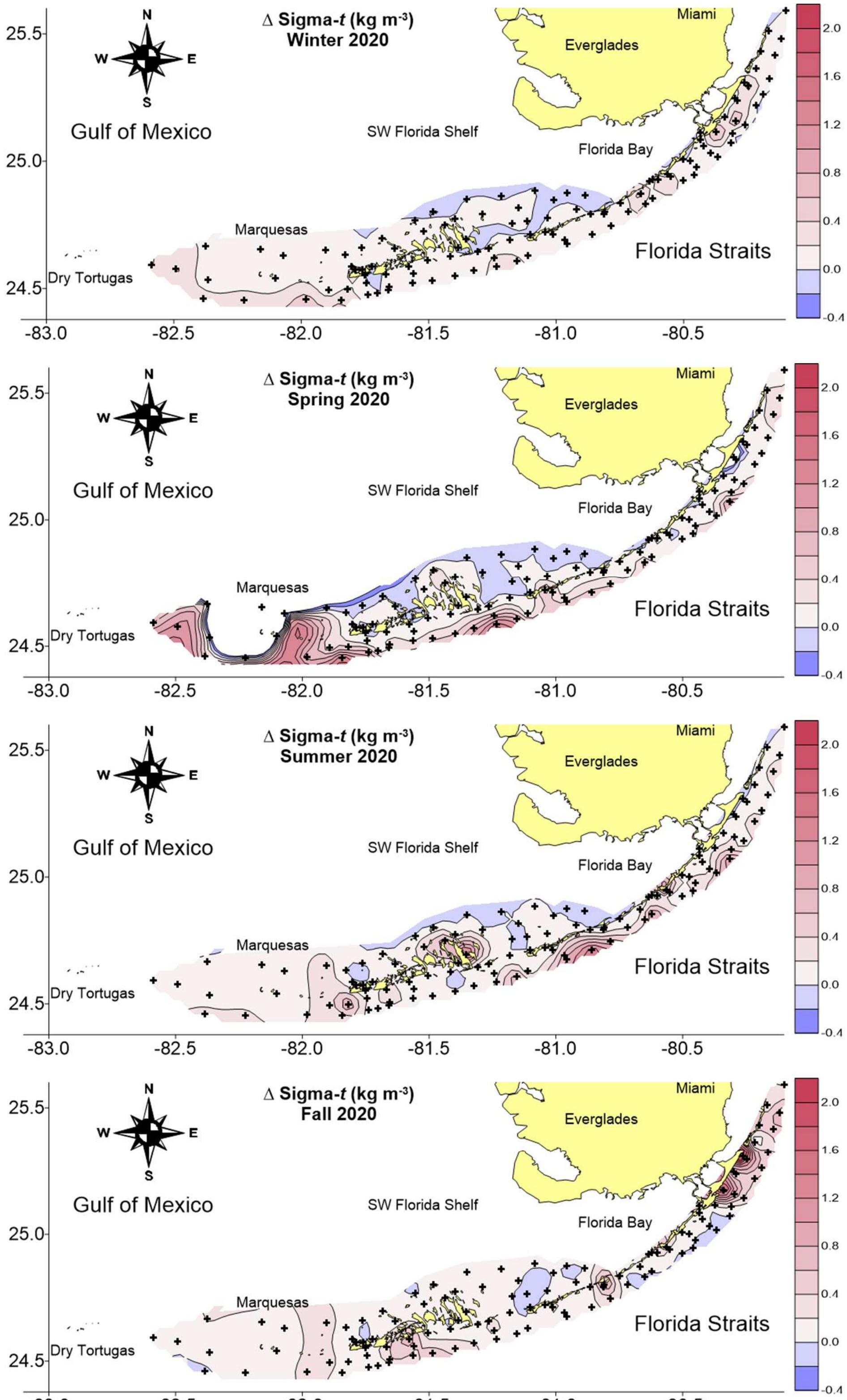

***Figure 7**. Surface/bottom density differences ($\Delta\sigma_t$) across the FKNMS during 2020.*

Visualization of spatial patterns of DIN concentrations over South Florida waters provides an extended view of source gradients over the region (Fig. 8-11). The oceanside transects off the uninhabited Upper Keys (off Biscayne Bay) typically exhibit the lower NO_3^- compared to the Middle and Lower Keys (Fig. 8), but this is not always the case (see fall 2020). Similar patterns inshore-offshore gradients was observed in a previous transect surveys from these areas (Szmant and Forrester 1996).

Intensification of NO_3^- often occurs in the Backcountry region which we believe is due to a combination of anthropogenic loading, extended water residence time, benthic N_2 fixation, and most importantly, sponge-mediated benthic flux (Hoer et al. 2018). The local sources of NO_3^-, e.g., septic systems and stormwater runoff around Big Pine Key have been implicated (Lapointe and Clark 1992), however, there are uninhabited areas that also exhibit high NO_3^- which rules out the premise of septic systems being the only source of NO_3^- in this area. The Backcountry area is very shallow (~0.5 m) and hydraulically isolated from the SW Shelf and Atlantic Ocean which results in a relatively long water residence time. However, the effect of increased water residence time in DIN concentration is probably small. Salinities in this area are typically only 1-2 higher than local seawater and may actually be lower than surrounding during wet periods. Additionally, NO_3^- concentration usually declines for salinities above ~35.3 region-wide. Benthic N_2 fixation may also contribute some $NH_4^+$to the Backcountry but much of this is used by seagrass to balance their N demand (Capone & Taylor 1980).

Sponge-mediated benthic flux may have the most significant influence on water quality in the Backcountry. Sponge population densities in Florida Bay ranged from 0.08 to 21 individuals m^{-2} with biomass as high as 4.4 L sponge m^{-2} (Hoer et al. 2019). They estimated an average DIN contribution from sponge biomass of 8.3 mg L^{-1} N m^{-2} d^{-1}, with peak N fluxes of 49.0 mg L^{-1} N m^{-2} d^{-1}. The Backcountry exhibits a similar sponge density (Boyer et al. 2005) therefore, we expect that benthic fluxes might be of comparable magnitude in this region.

Surface and bottom water NO_3^- concentrations are not always coincident (Fig. 9). In some years we observed elevated NO_3^- in the bottom waters on the offshore reef tract. This has been attributed to “upwelling” (internal tidal bores) of deep water onto the reef tract (Leichter et al. 2003). This deep ocean water transport is a regular and persistent phenomenon which can deliver high nutrient waters to the offshore reef tract independent of any terrestrial source.

Interestingly, during fall 2020, intensification of NO_3^- concentrations in the Upper Keys bottom waters was from deep ocean tidal bore while high concentrations in surface waters were most probably from either stormwater runoff or southern transport from Biscayne Bay. The SHORE sites around Marathon were also elevated, probably the result of direct runoff or groundwater inputs.

Surface NH_4^+ concentrations are often distributed in a similar manner as NO_3^- but are usually lower in magnitude (Fig. 10). During 2020, intensification of NH_4^+ concentrations, similar to NO_3^-, occurred alongshore in the Upper Keys and in SHORE sites around Marathon in summer (Fig. 11).

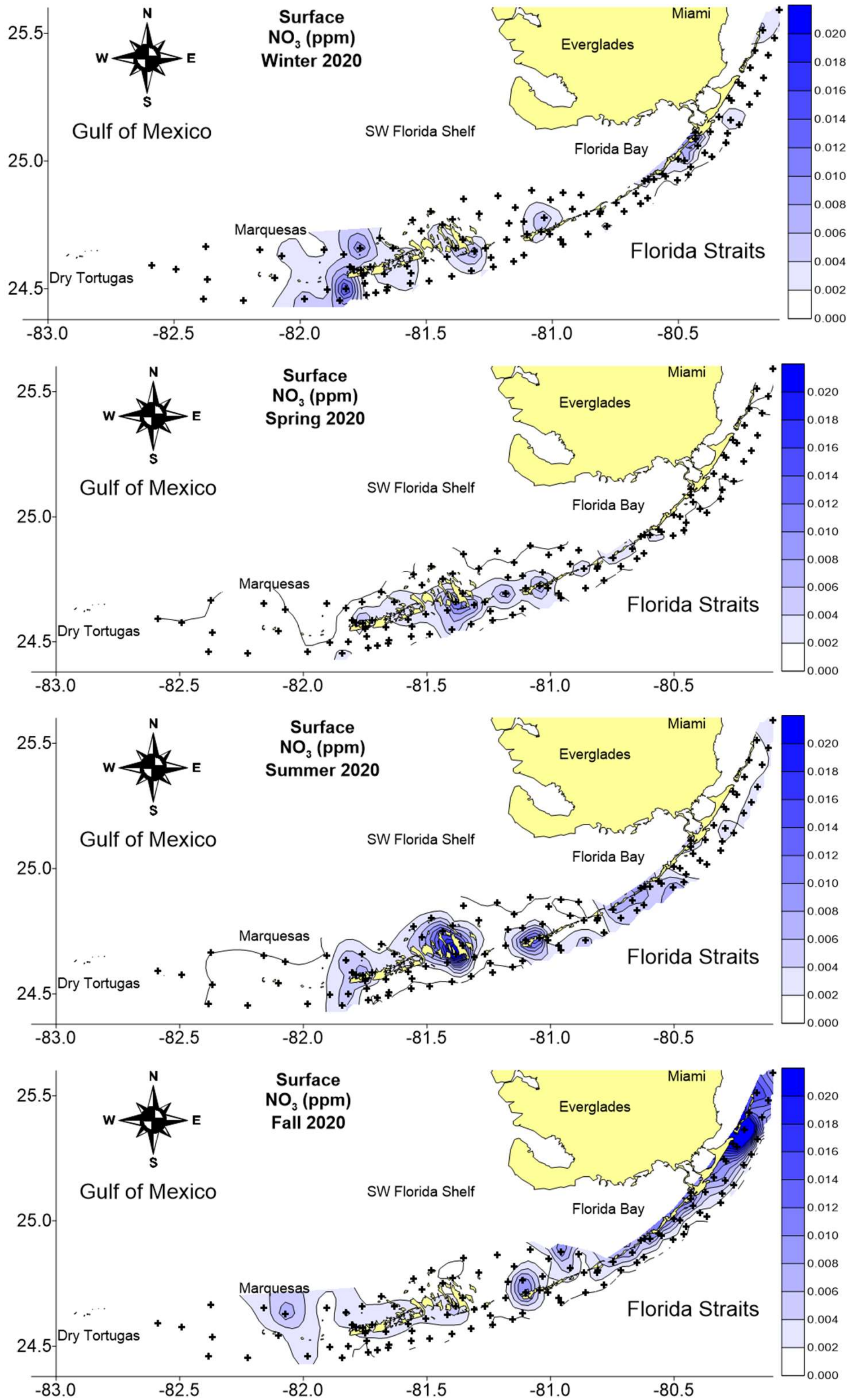

***Figure 8**. Surface nitrate distributions across the FKNMS during 2020.*

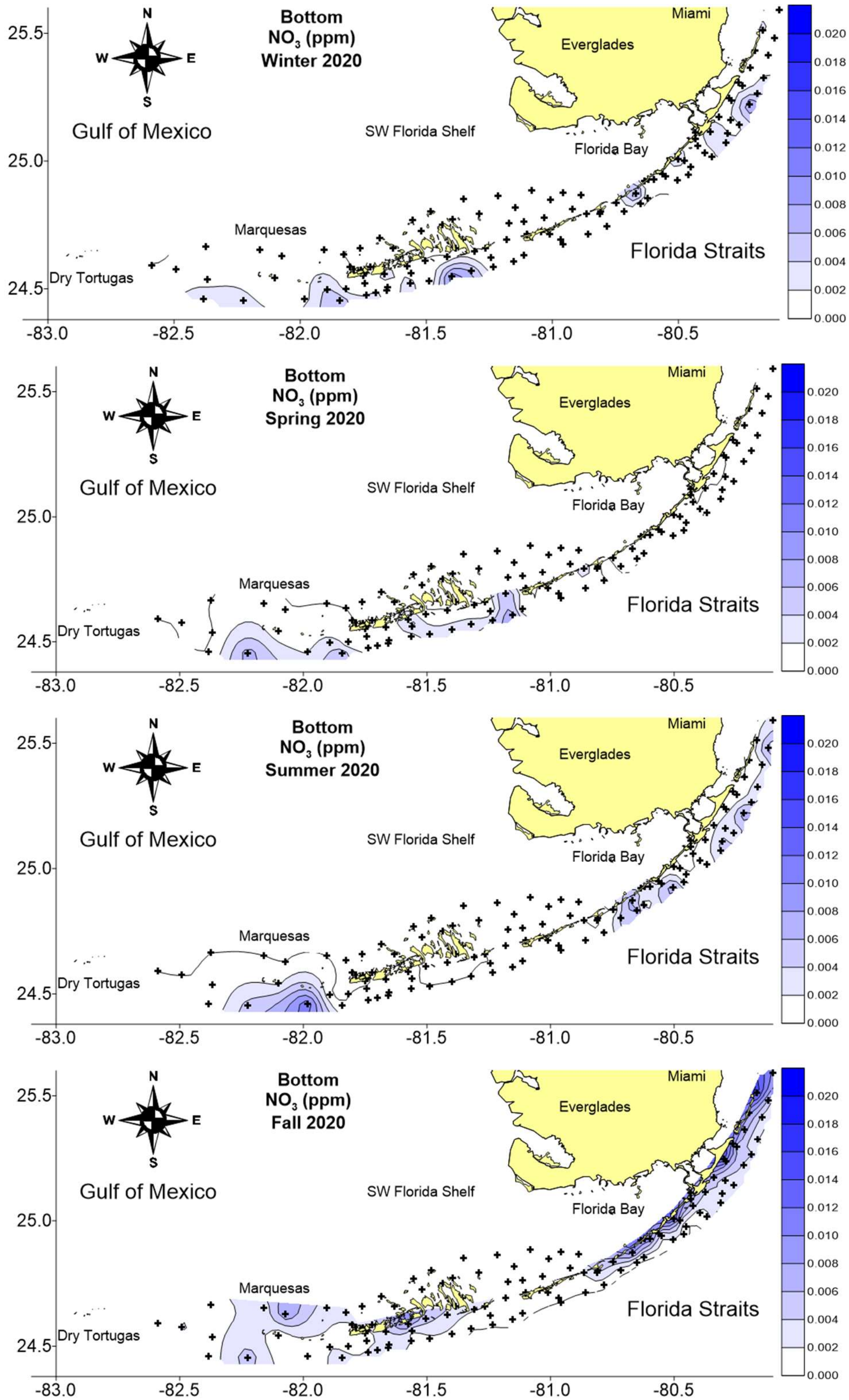

Figure 9. *Bottom nitrate distributions across the FKNMS during 2020.*

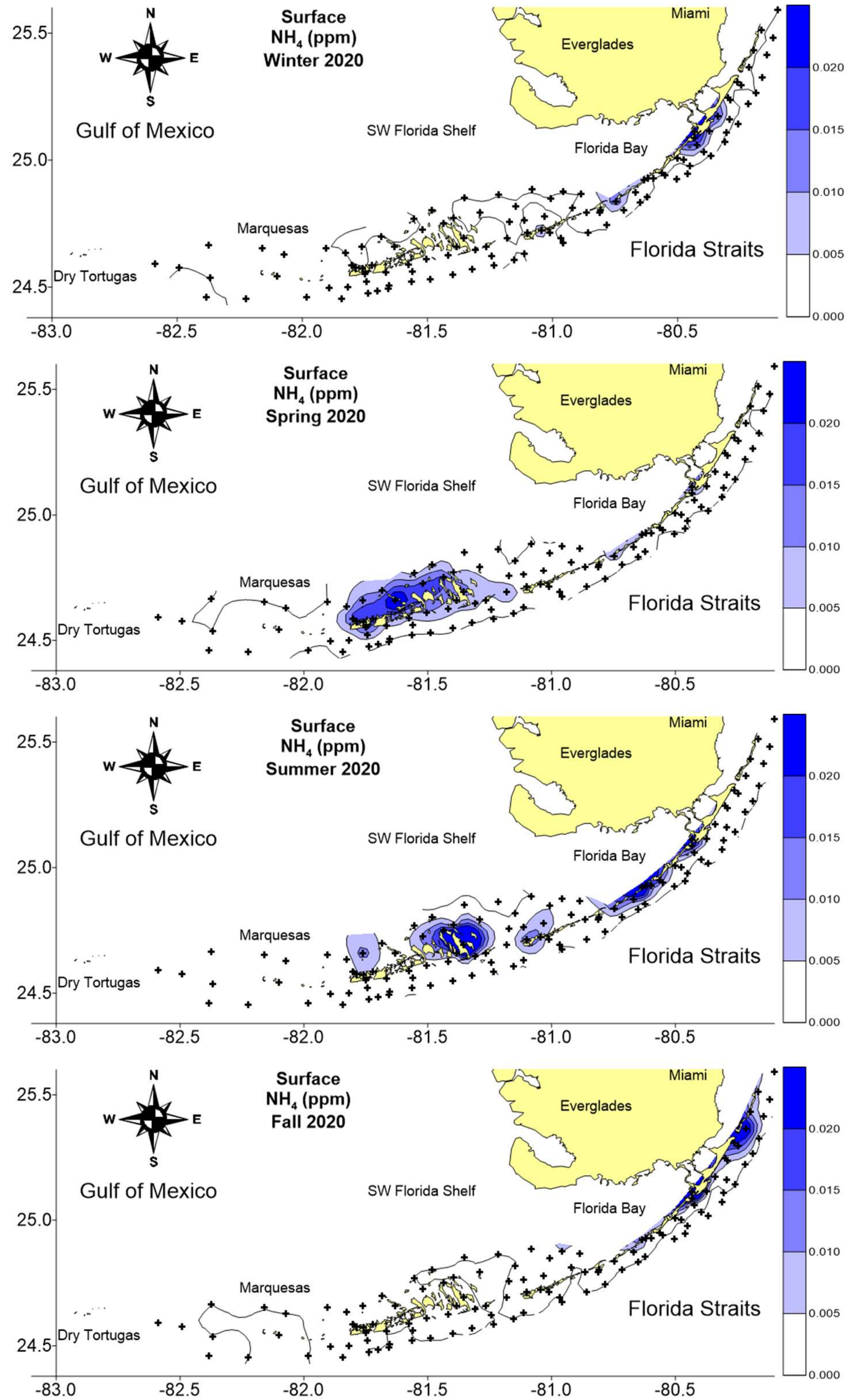

***Figure 10**. Surface ammonium distributions across the FKNMS during 2020.*

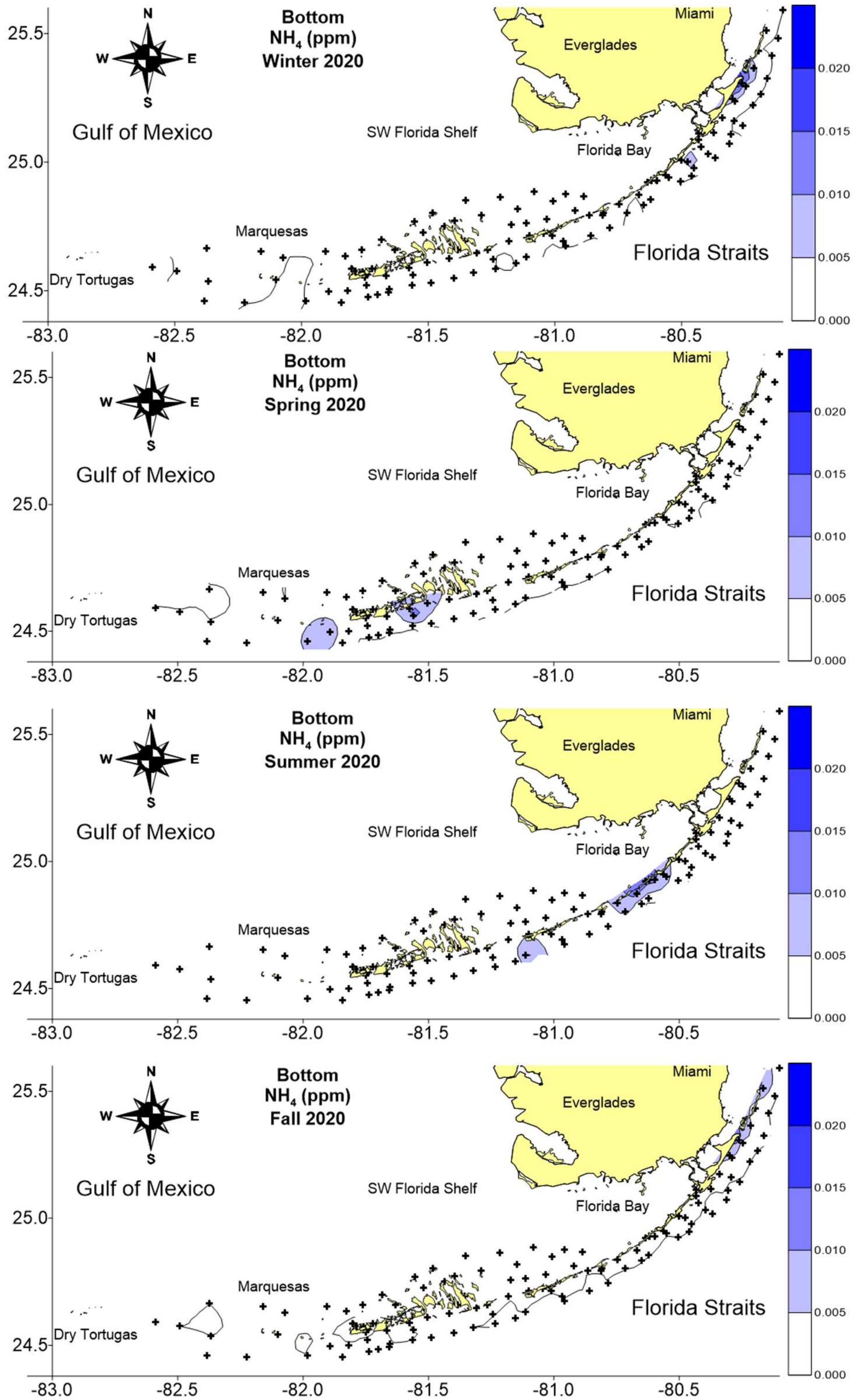

***Figure 11**. Bottom ammonium distributions across the FKNMS during 2020.*

Spatial patterns in TP in South Florida coastal waters are strongly driven by SW Coastal Everglades and GOM sources (Boyer and Briceño 2007, 2011). A gradient in TP typically extends from the inshore waters of Whitewater Bay - Ten Thousand Islands mangrove complex out onto the SW Shelf and Tortugas. Gradients also usually extend from western Florida Bay to the Middle/Lower Keys. The spatial distribution of TP on the SW Shelf is driven by freshwater inputs from mangrove rivers and transport of Gulf of Mexico waters through the region. No significant evidence of significant groundwater sources exists (Corbett et al. 2000).

During 2020, highest TP concentrations occurred mostly along the northern boundary of the Sluiceway, and Marquesas with occasional hits at individual offshore sites (Fig 12). Bottom TP was generally less than 0.02 ppm although there was slight intensification in Marquesas and one site in northernmost Keys during winter/spring (Fig 13, note different scale than surface TP).

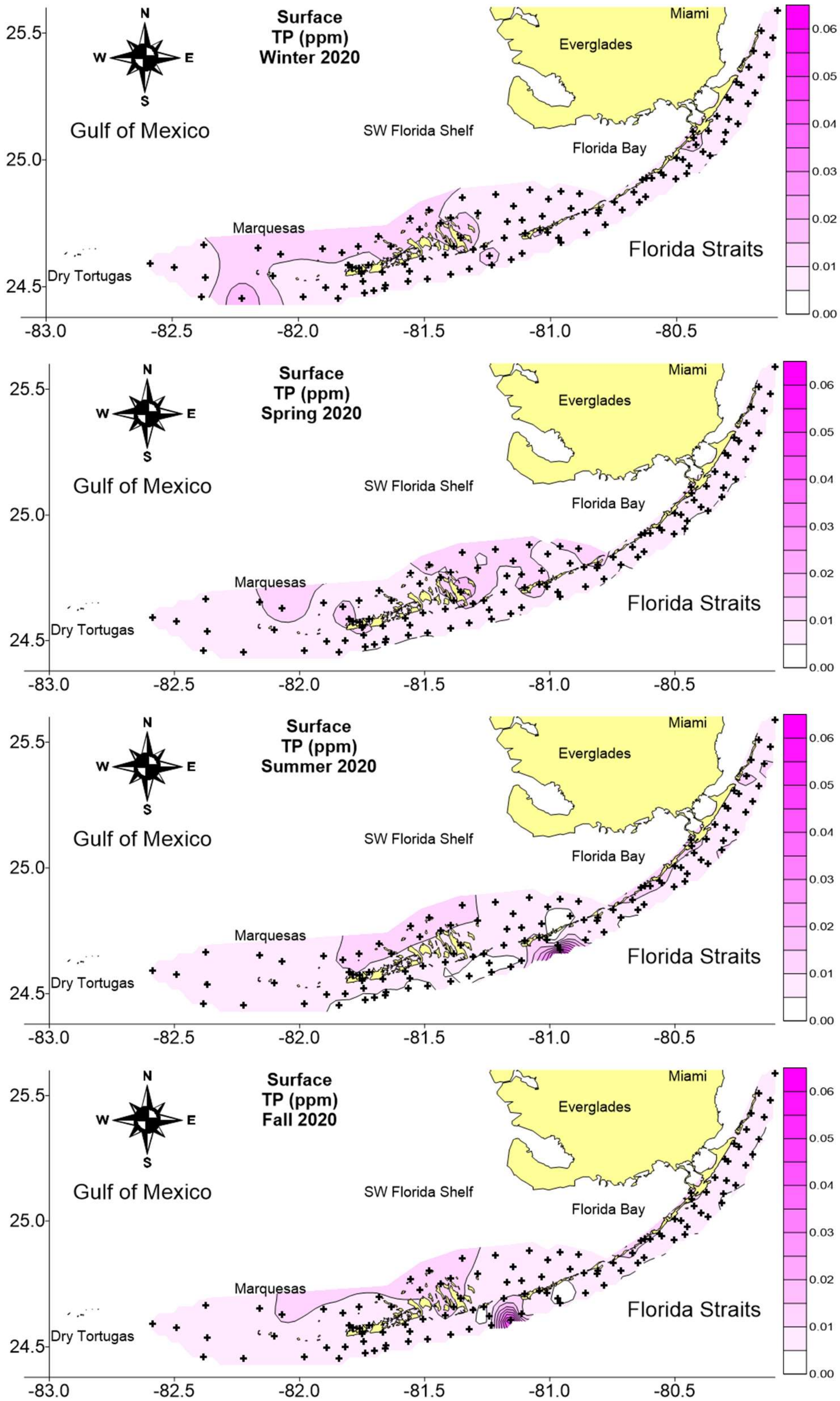

Figure 12. *Distributions of surface total phosphorus across the FKNMS during 2020.*

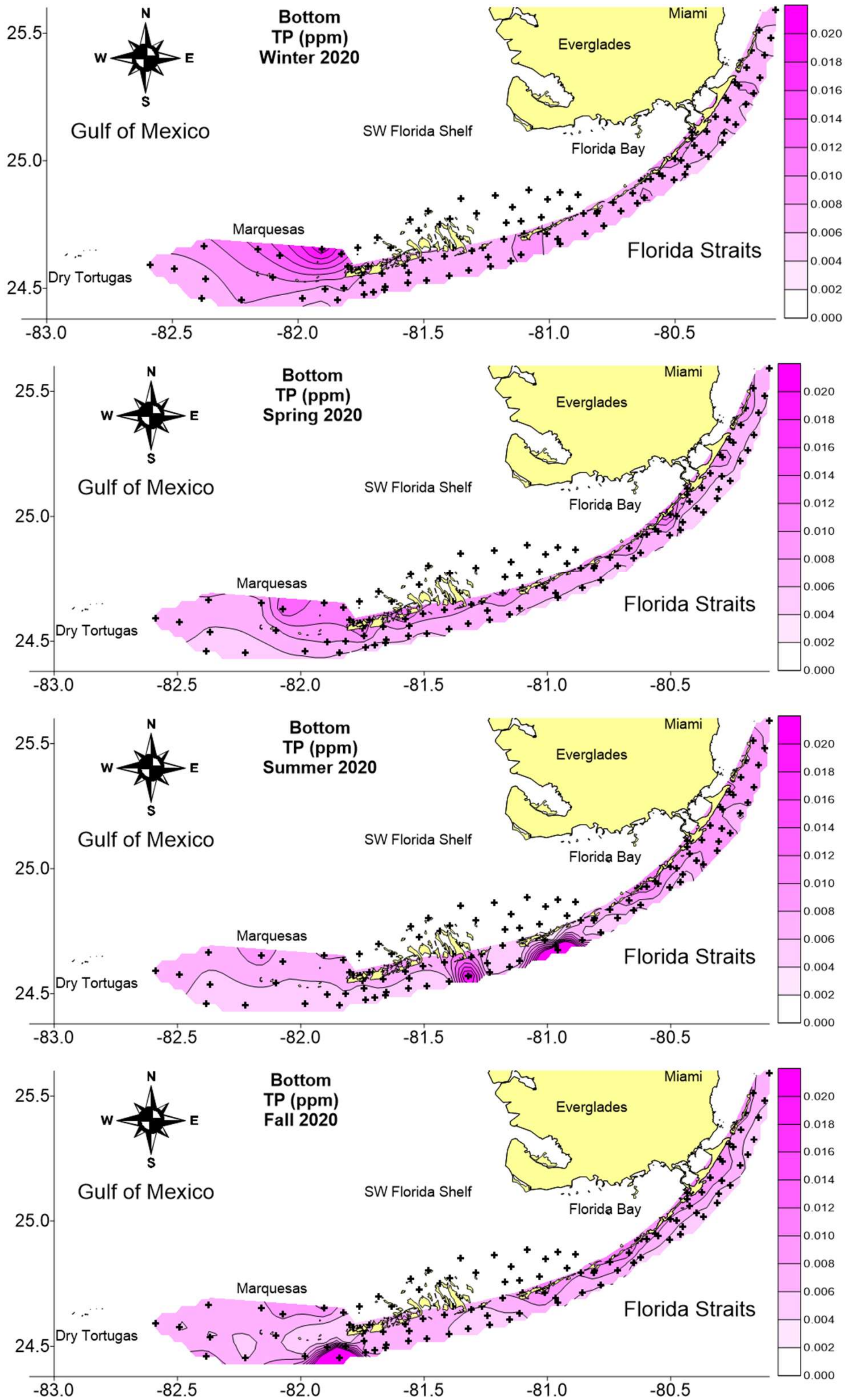

***Figure 13**. Distributions of bottom total phosphorus across the FKNMS during 2020.*

Concentrations of surface and bottom TOC (Fig. 14 & 15) and TON (Fig. 16 & 17) are similar in pattern of distribution across the South Florida coastal hydroscape. Most of the TN is organic in nature so we expect this. Deviations from this common pattern are due to differences in sources of dissolved organic matter. Our past data from this area showed that concentrations of TOC and TON increase from the Everglades headwaters through the mangrove zone and then decrease with distance offshore. The high concentrations of TOC and TON in Florida Bay were due to a combination of terrestrial loading (Boyer and Jones, 1999), in situ production by seagrass and phytoplankton, and evaporative concentration (Fourqurean et al. 1993, Boyer et al. 1997).

Advection of SW Shelf and Florida Bay waters through the Sluiceway and passes accounted for this region and the inshore area of the Middle Keys as having highest TOC and TON of the FKNMS. Strong offshore gradients in TOC and TON existed for all mainland Keys segments. The higher concentrations of TOC and TON in the inshore waters of the Keys may have a terrestrial source (anthropogenic) or may be derived from decomposition of seaweed rack rather than simply benthic production and sediment re-suspension. Main Keys reef tract concentrations of TOC and TON were consistently the lowest in the FKNMS.

During Fall 2020, elevated TON was observed in one surface station and multiple bottom stations in the oceanside Islamorada area. We are not sure what caused this anomaly but the fact that it was most extensive in bottom waters implicates a benthic source.

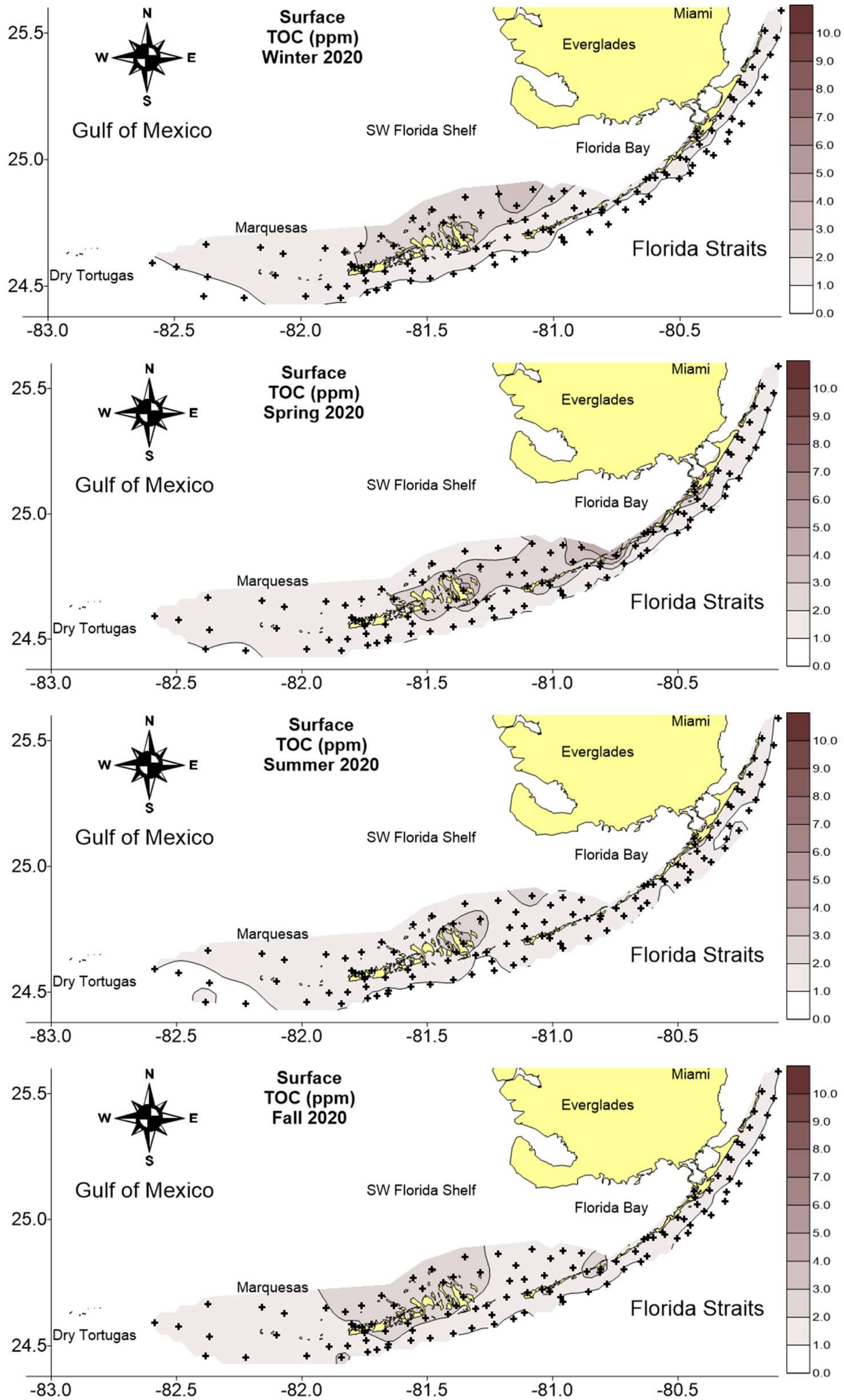

***Figure 14**. Distributions of surface total organic carbon across the FKNMS during 2020.*

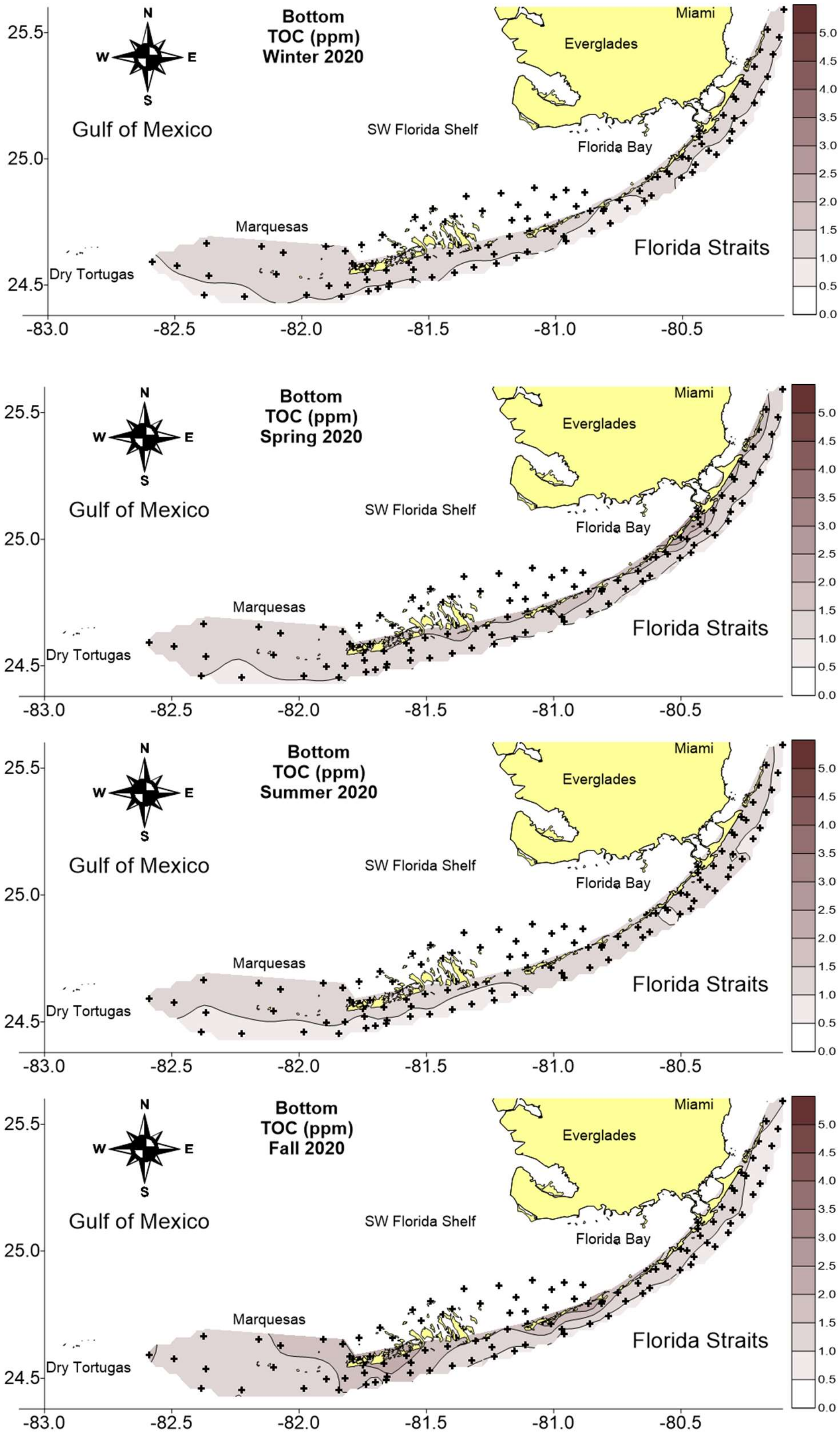

***Figure 15**. Distributions of surface total organic carbon across the FKNMS during 2020.*

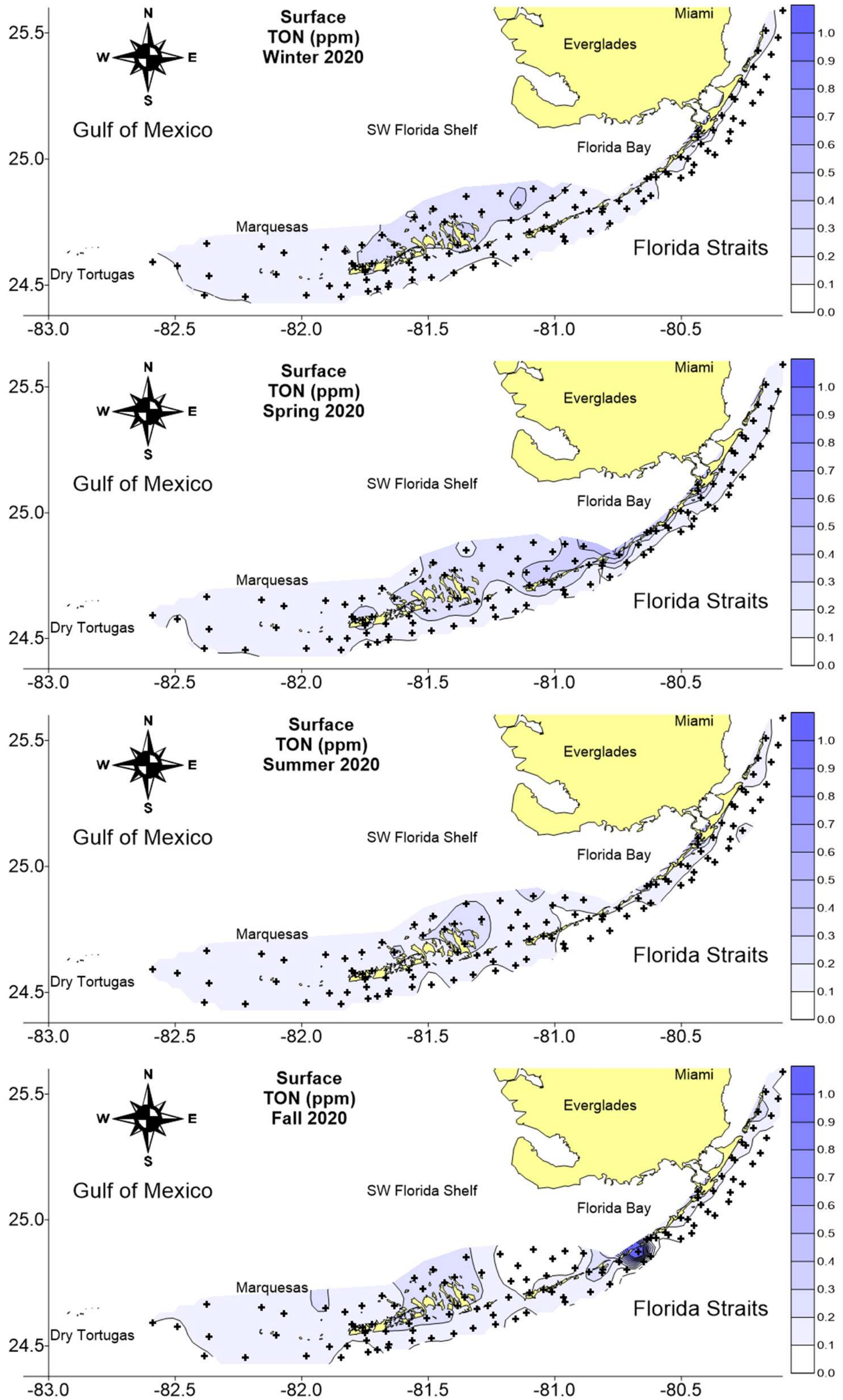

***Figure 16**. Distributions of surface total nitrogen across the FKNMS during 2020.*

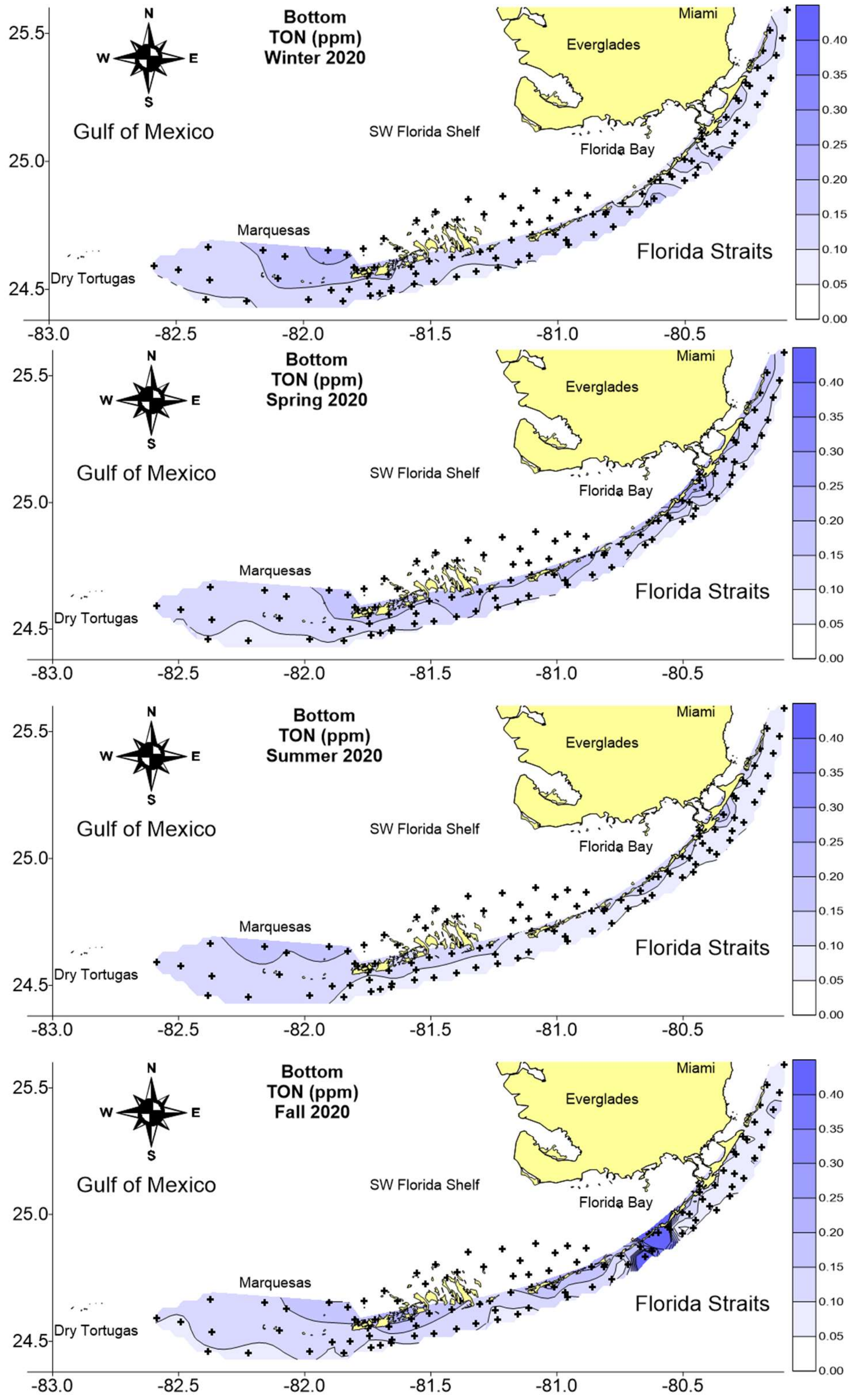

Figure 17. *Distributions of bottom total nitrogen across the FKNMS during 2020.*

Much emphasis has been placed on assessing the impact of episodic phytoplankton blooms in Florida Bay on the offshore reef tract environment. In the past, spatial patterns of CHLA concentrations showed that the SW Shelf, Northern Florida Bay, and the Ten Thousand Islands exhibited higher CHLA levels relative to the FKNMS. The oceanside transects in the Upper Keys exhibited the lowest overall CHLA concentrations of any area in the FKNMS. Transects off the Middle and Lower Keys showed that a drop in CHLA occurred at reef tract sites; there was no linear decline with distance from shore. Inshore and Hawk Channel CHLA concentrations among Middle Keys, and Lower Keys sites were not significantly different.

Historical data also showed that CHLA concentrations were typically higher in the Marquesas than in other areas of the FKNMS. When examined in context with the whole South Florida ecosystem, it is obvious that the Marquesas zone should be considered a continuum of the SW Shelf rather than a separate management entity. This shallow sandy area (often called the Quicksands) acts as a physical mixing zone between the SW Shelf and the Atlantic Ocean and is a highly productive area for other biota as well as it encompasses the historically rich Tortugas shrimping grounds. CHLA concentrations of 2 $\mu g\ l^{-1}$ in the water column of a reef tract might be considered an indication of eutrophication, but a similar CHLA level in the Quicksands indicates a productive ecosystem which feeds a valuable shrimp fishery.

CHLA levels during 2020 were relatively low, highest CHLA values occurred mostly along the northern boundary of the Backcountry and Lower Keys, suggesting an important contribution from the SW Shelf (Fig. 18). In addition, spring 2020 saw a short CHLA elevation around Big Pine Key.

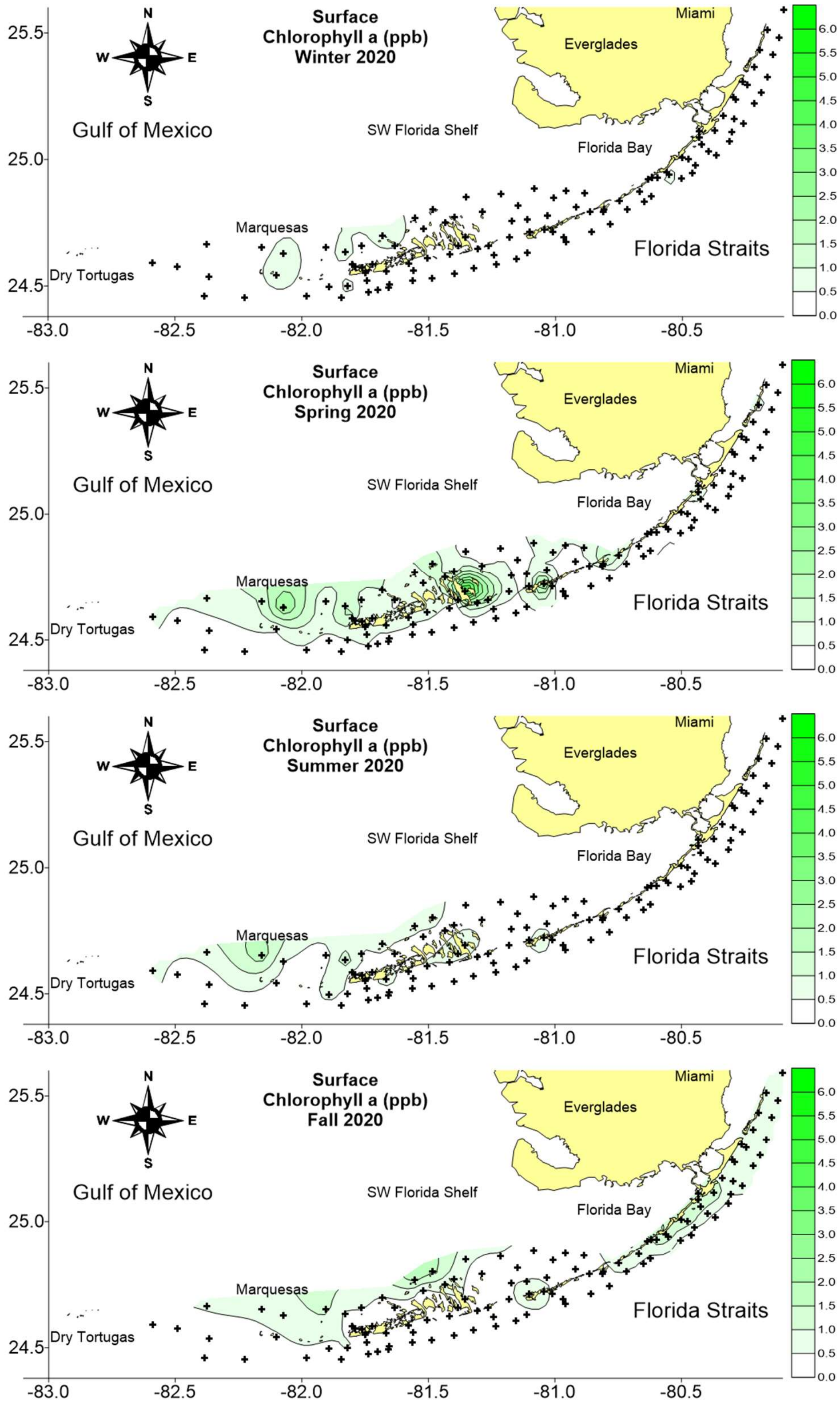

Figure 18. *Distributions of surface chlorophyll a across the FKNMS during 2020.*

Along with TP and CHLA, turbidity is probably the second most important determinant of local ecosystem health. The fine grained, low density carbonate sediments are easily re-suspended, rapidly transported, and have high light scattering potential. Sustained high turbidity indirectly affects benthic community structure by decreasing light penetration and thereby limiting seagrass and coral growth. Regional-scale observations of turbidity clearly show patterns of onshore-offshore gradients which extend out onto the SW Shelf to the Marquesas (Stumpf et al. 1999). Strong turbidity gradients have been observed on the SW Shelf but reef tract levels remain remarkably low regardless of inshore levels. Elevated turbidity in the Backcountry is most probably due to the shallow water column being easily re-suspended by wind and wave action. In 2020, highest turbidity values typically occurred in the Backcountry during the and mostly along the northern boundary with the SW Shelf (Fig. 19). There was also a large turbidity event in the Islamorada area during fall which may have been the cause of elevated TON as described previously.

Light extinction (K_d) is typically highest alongshore where waters are easily stirred up and loaded w/ colored dissolved organic matter (CDOM) from plant decomposition and improves with distance from land as water column becomes deeper and land-based sources are diluted. In Keys waters, CDOM may be a more important driver of light penetration than turbidity, thus the saying by divers that the visibility is "clean and green". For 2020, K_d was generally under 0.01 m^{-1}. (Fig. 20), however some high, site-specific K_d observations mostly in the Backcountry tended to obscure low level patterns on the contour maps. Surprisingly, the high turbidity event around Islamorada did mot manifest as increased light extinction, as expected.

Turbidity and CDOM affect K_d , while site depth also affects the percent of ambient light reaching the bottom (I_o, Fig. 21). More light on the bottom is beneficial to corals, seagrass, and algae. Even when the water column is clear, the deeper the water depth, the less light there will be relative to surface. For 2020, lowest bottom light was observed in the deeper waters of the Marquesas. Interestingly, the low I_o levels in fall corresponded with the elevated turbidity event around Islamorada.

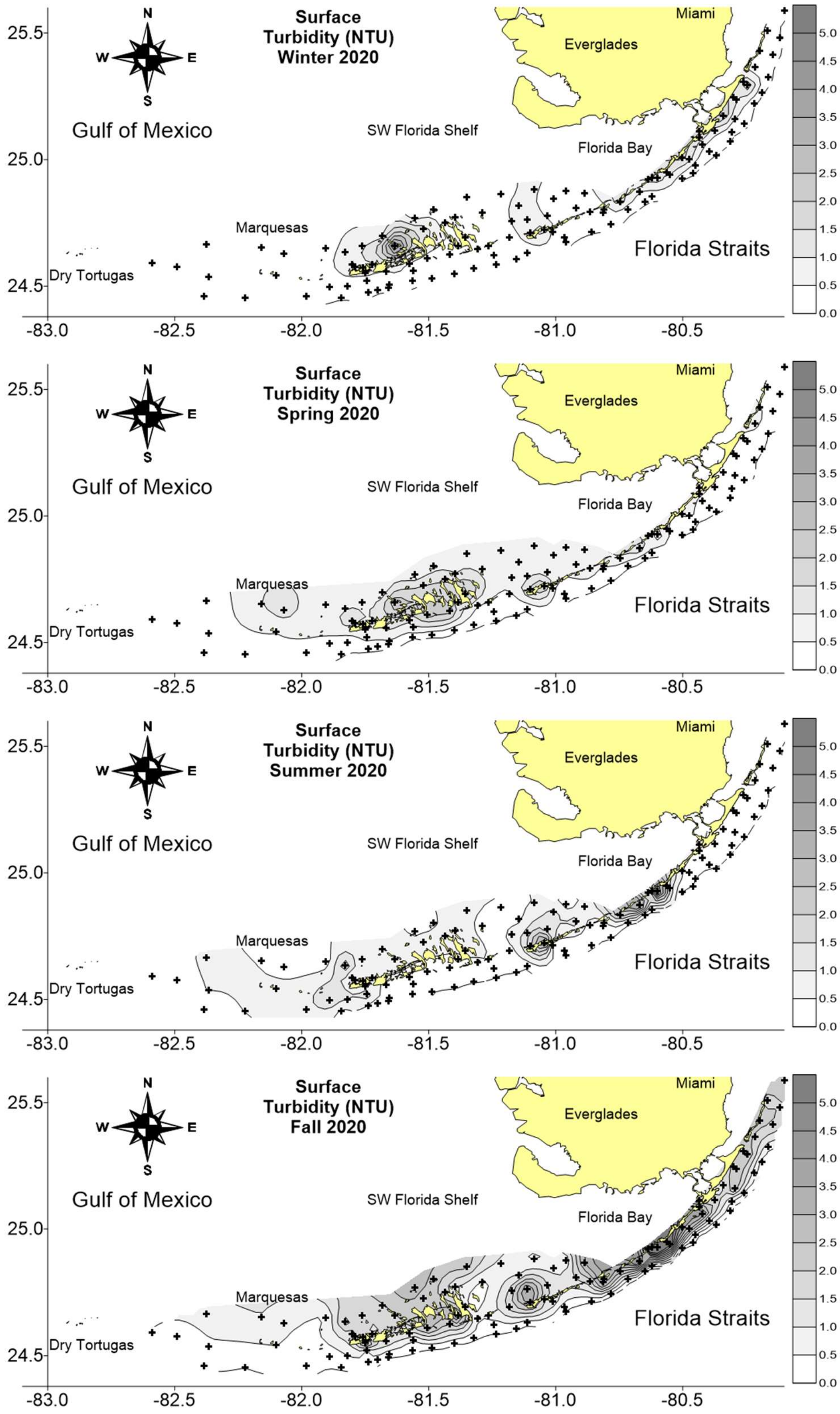

***Figure 19**. Distributions of surface turbidity across the FKNMS during 2020.*

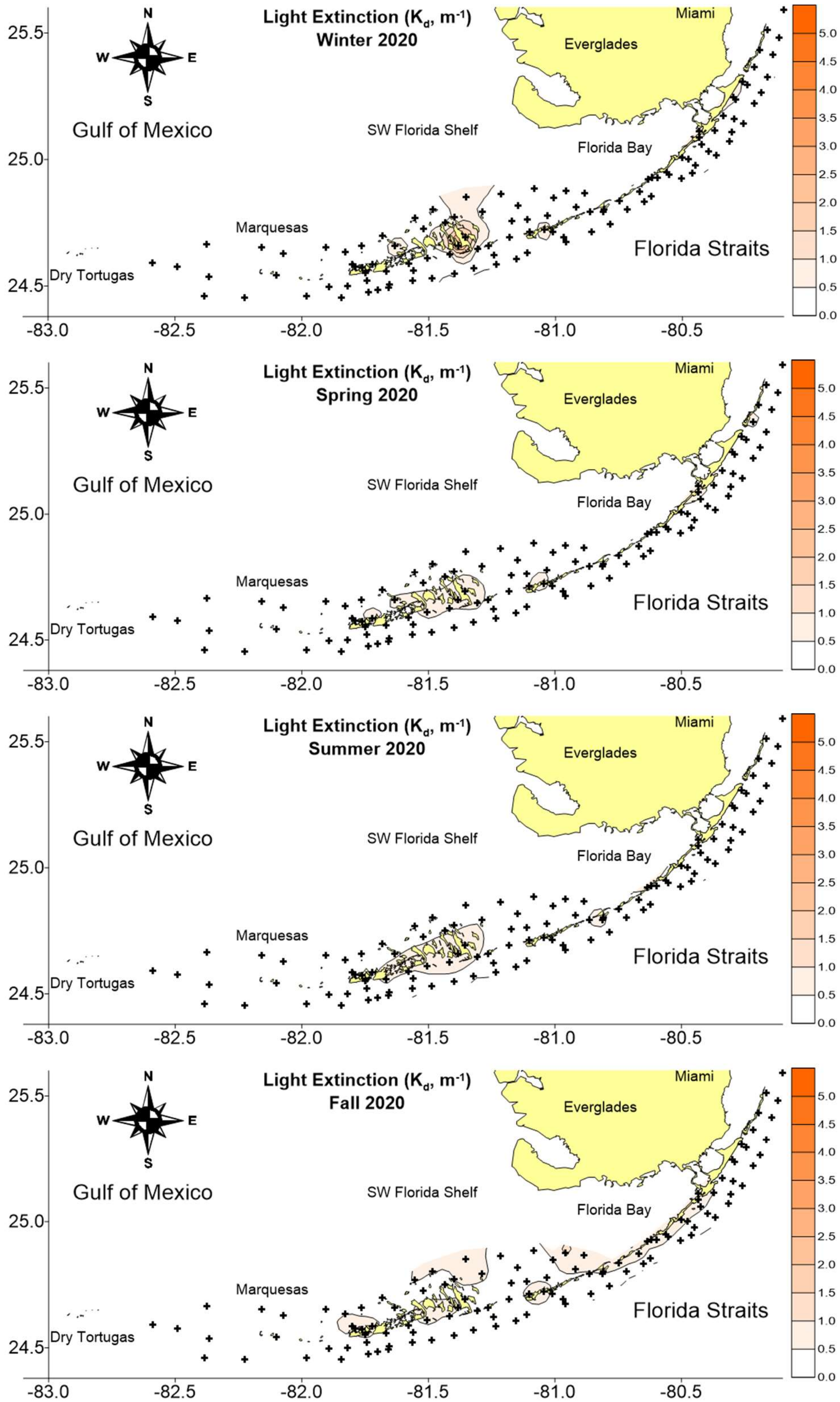

***Figure 20**. Distributions of light extinction across the FKNMS during 2020.*

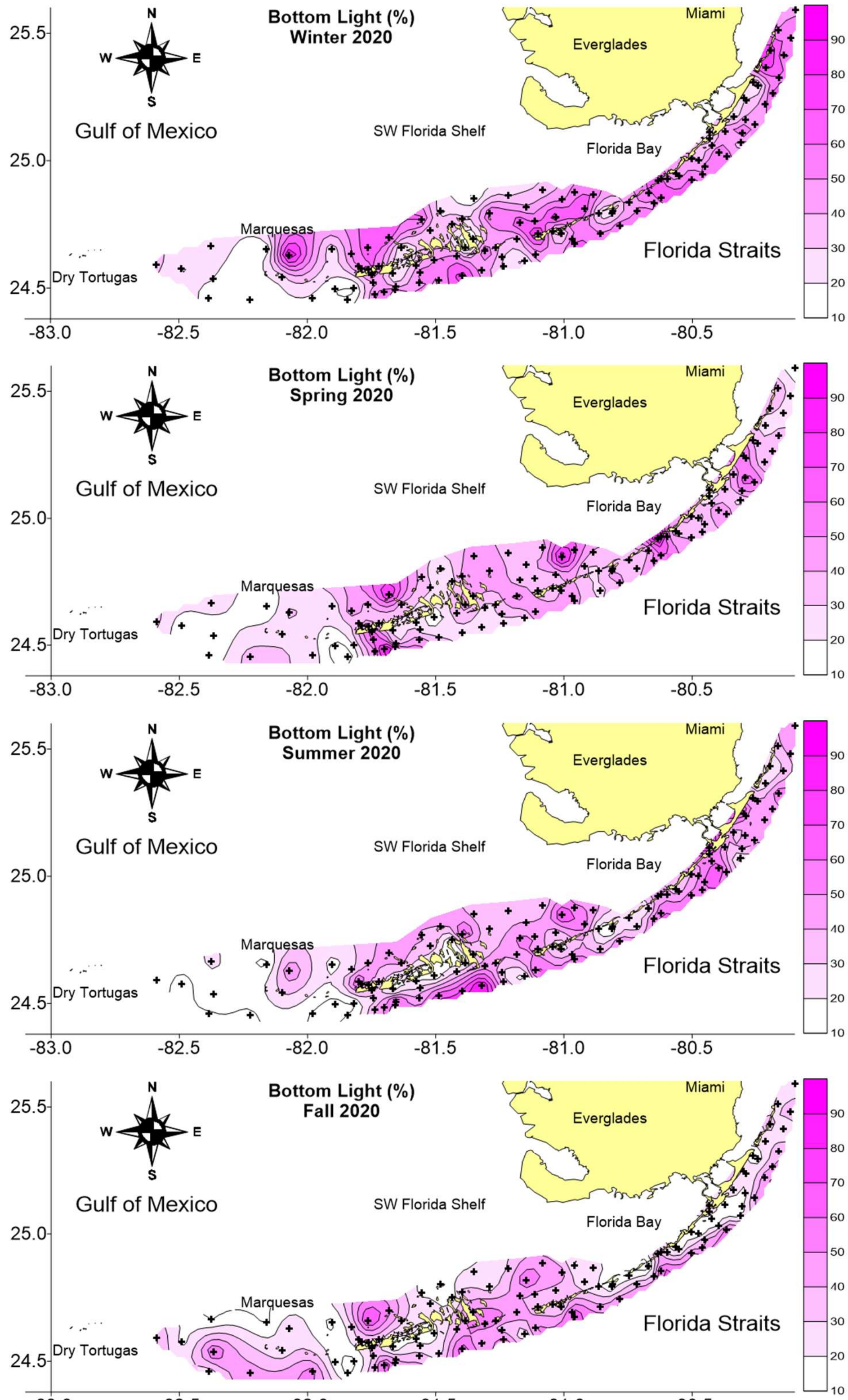

***Figure 21**. Distributions of bottom light across the FKNMS during 2020.*

Surface SiO_2 concentrations usually exhibit a pattern similar to salinity. The source of SiO_2 in this geologic area of carbonate rock and sediments is from siliceous periphyton (diatoms) growing in the Shark River Slough, Taylor Slough, and C-111 basin watersheds. Unlike the Mississippi River plume with CHLA concentrations of 76 $\mu g\ l^{-1}$ (Nelson and Dortch 1996), phytoplankton biomass on the SW Shelf (1-2 $\mu g\ l^{-1}$ CHLA) was not sufficient to account for the depletion of SiO_2 in this area. Therefore, SiO_2 concentrations on the SW Shelf are depleted mostly by mixing (although we no longer have data from the SW Shelf), allowing SiO_2 to be used as a semi-conservative tracer of freshwater in this system (Ryther et al. 1967; Moore et al. 1986). In 2020, SiO_2 concentrations were very low, relative to other years with no coherent pattern. (Fig. 22).

The TN:TP ratio has been used as a relatively simple method of estimating potential nutrient limitation status of phytoplankton (Redfield 1967). Most of the South Florida hydroscape has TN:TP values >> 16:1, indicating the potential for phytoplankton to be limited by P in most of the FKNMS (Fig. 23). Potential N limitation typically occurrs in the southern Marquesas in fall and potentially along the Upper Keys reef tract. Note the high fall 2020 TN:TP around Islamorada as a result of episodic TON/turbidity event.

Most TN occurs in the form of organic N (TON) and is not bioavailable to phytoplankton while much of the organic fraction of TP is labile (as ester-bonded P). Therefore, the TN:TP ratio overestimates P limitation and should be recognized as such. A better estimate of phytoplankton nutrient limitation may be the DIN:TP ratio (Fig. 24) which assumes that most of the TON is refractory and that all TP is bioavailable. Given these assumptions, the FKNMS would be considered more of an N-limited system (<16), notwithstanding the DIN pulse in the Upper Keys during fall 2020. This becomes moot when the ambient nutrient concentrations are lower than biological kinetic thresholds for uptake, which often occurs. It is also important to recognize that ambient nutrient concentrations are the result of competing processes: advection, biological uptake, and remineralization. Barring external source/sink, nutrient levels increase when remineralization exceeds uptake and vice versa.

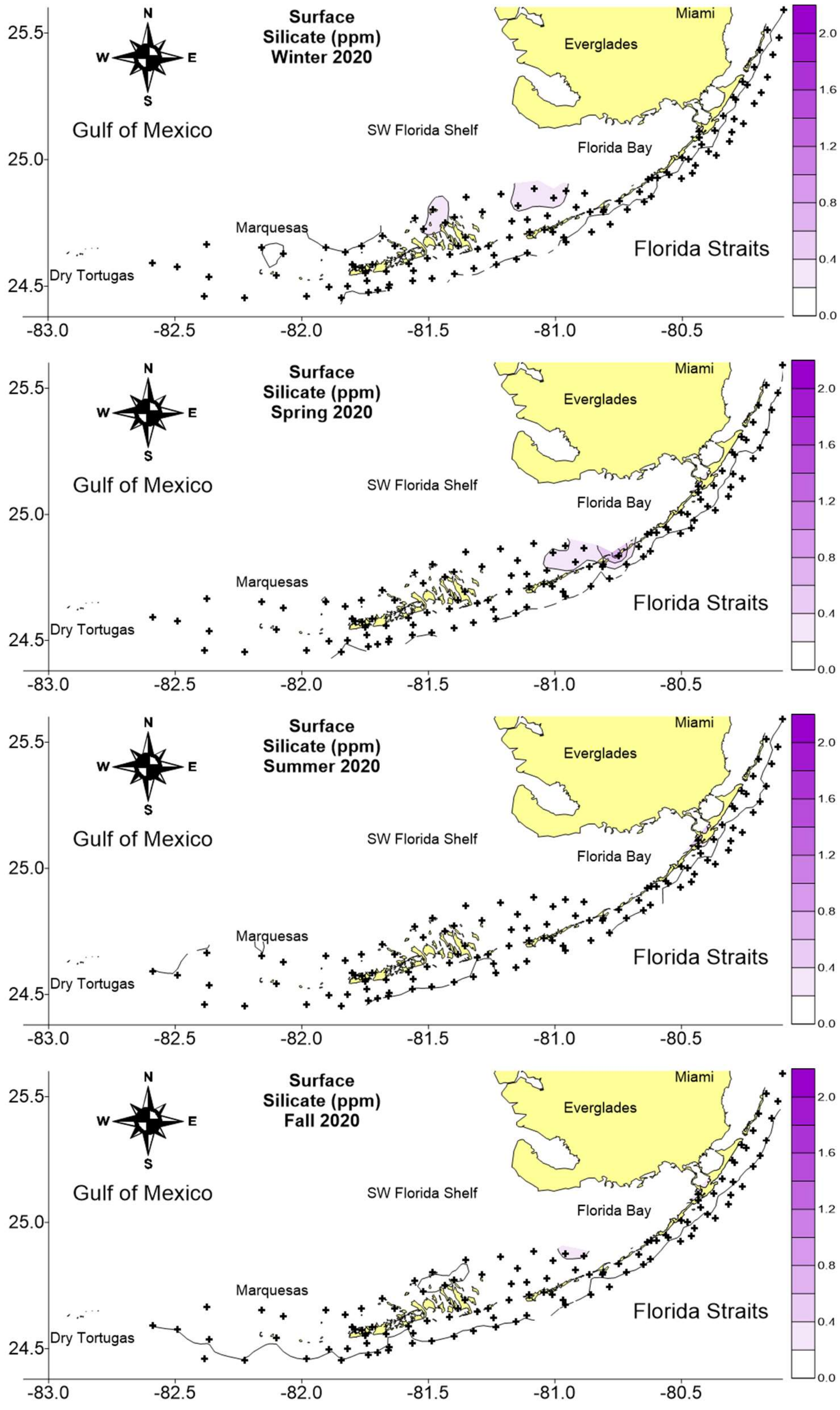

Figure 22. *Distributions of surface silicate across the FKNMS during 2020.*

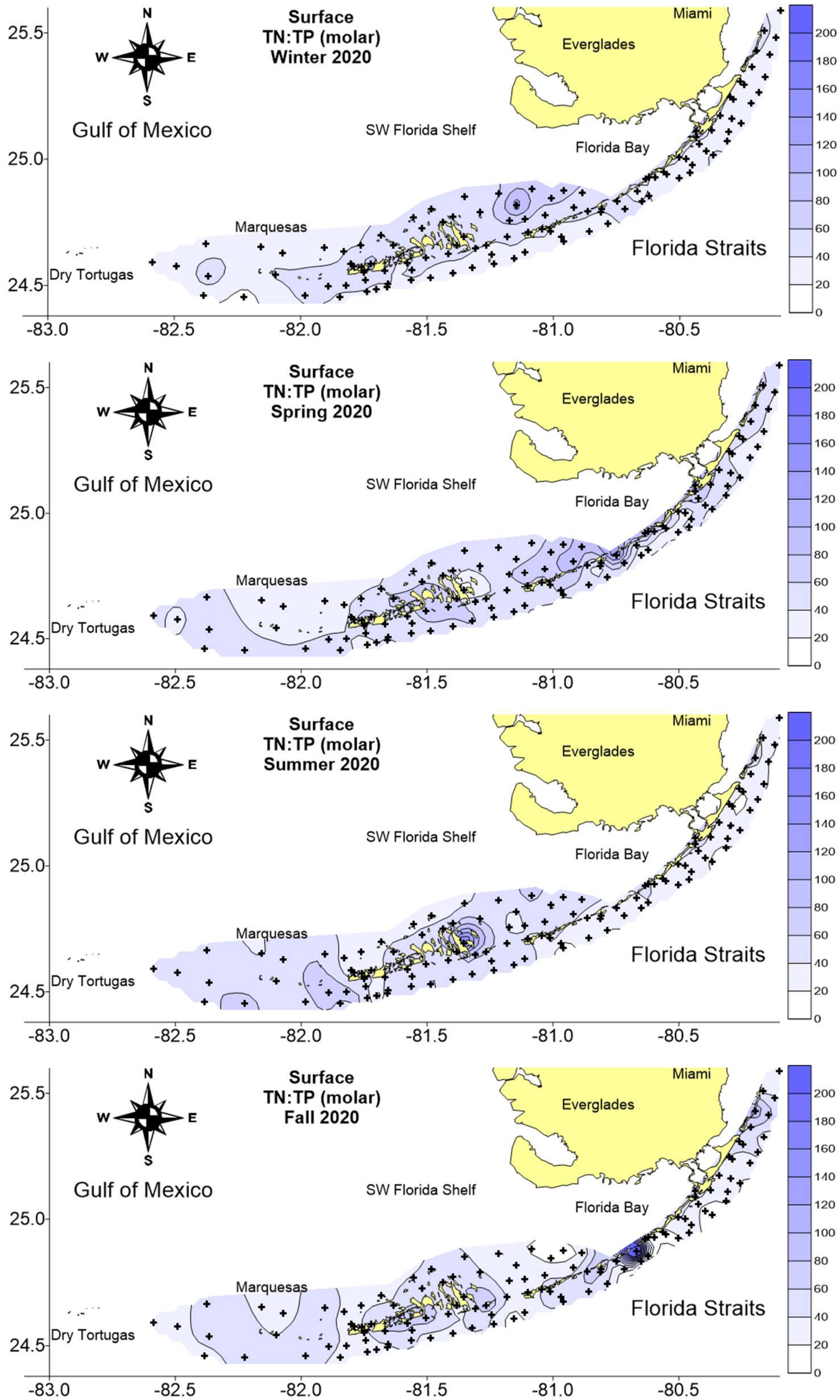

Figure 23. *Distributions of surface TN:TP ratio across the FKNMS during 2020.*

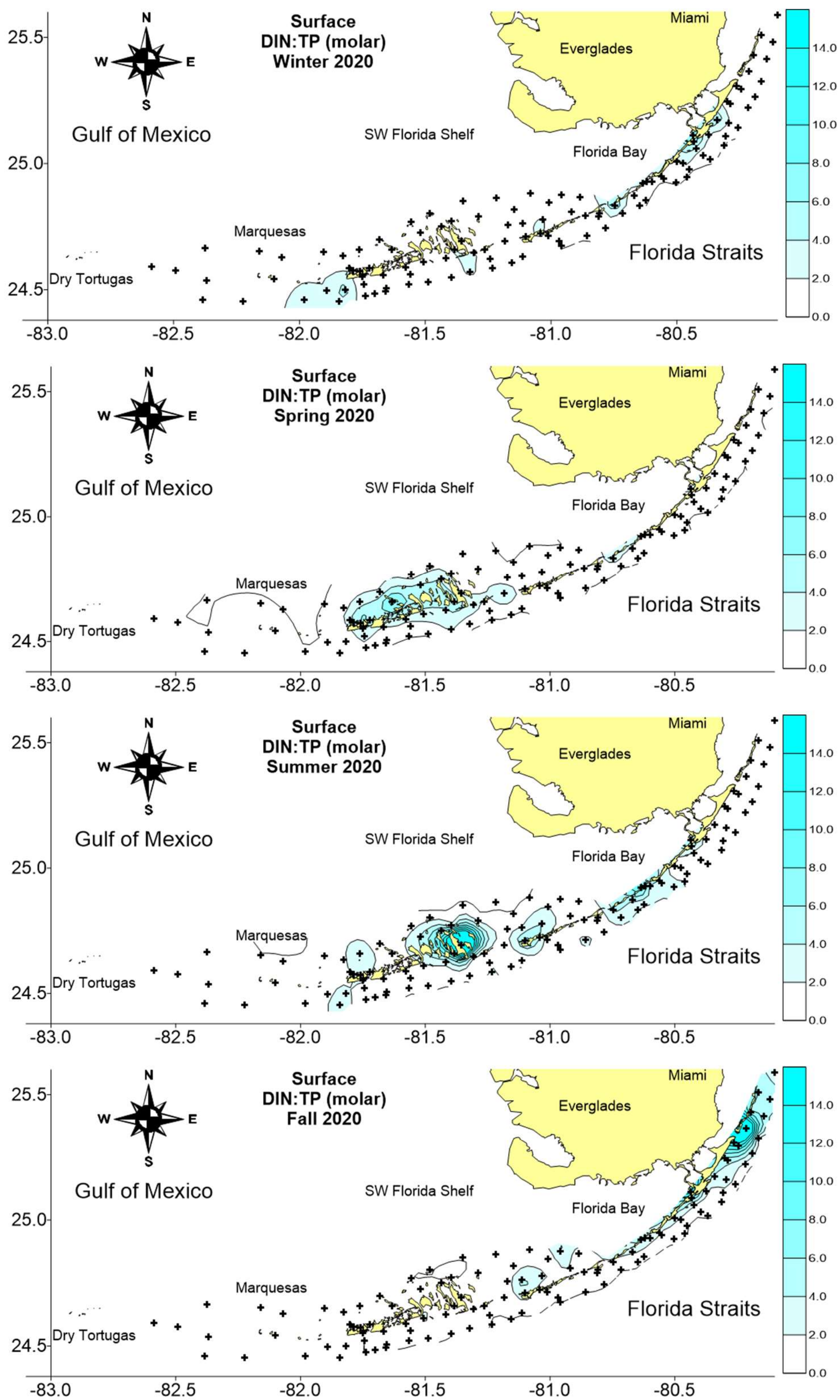

Figure 24. *Distributions of surface DIN:TP ratio across the FKNMS during 2020.*

3.4. Temporal Trends and Dynamics

Clearly, there have been changes in the FKNMS water quality over time, some sustained monotonic trends have been observed. However, we must always keep in mind that trend analysis is limited to the window of observation and method of analysis. In addition, when looking at what are perceived to be local trends, we may find that they occur across the whole region at more subtle levels. This spatial autocorrelation in water quality is an inherent property of highly interconnected systems such as coastal and estuarine ecosystems driven by similar hydrological and climate forcing. Clearly, trends observed inside the FKNMS are influenced by regional conditions and by drivers from outside the Sanctuary boundaries.

As mentioned, time series analysis is limited to the window of observation and trends may change with continued data collection. In addition, water quality in the Keys is largely driven by external influences and may fluctuate according to climatic or disturbance events of long or short periodicity. Examples of the types of trends observed in environmental systems shown below are 1) monotonic (Fig. 25), 2) episodically driven with no net trend (Fig. 26) and 3) reversing or discontinuous with change point (Fig. 27).

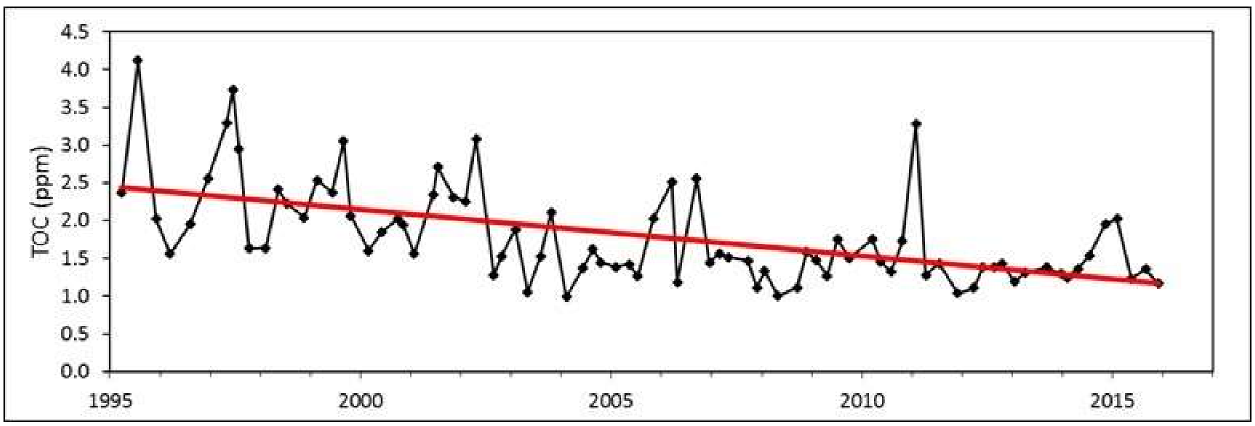

Figure 25. *Monotonic trend in TOC at Carysfort Reef.*

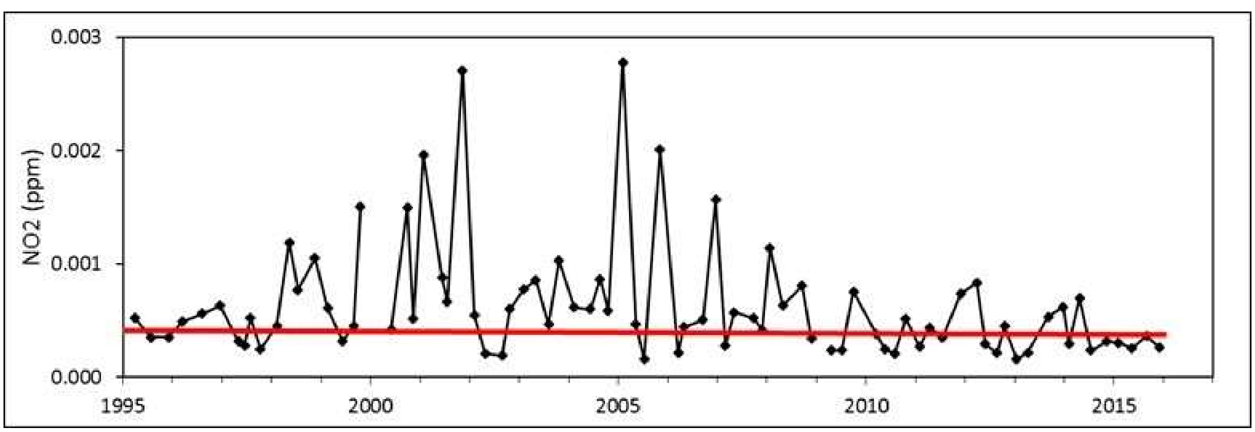

Figure 26. *Episodically driven pattern in NO_2^- with no net trend at Carysfort Reef.*

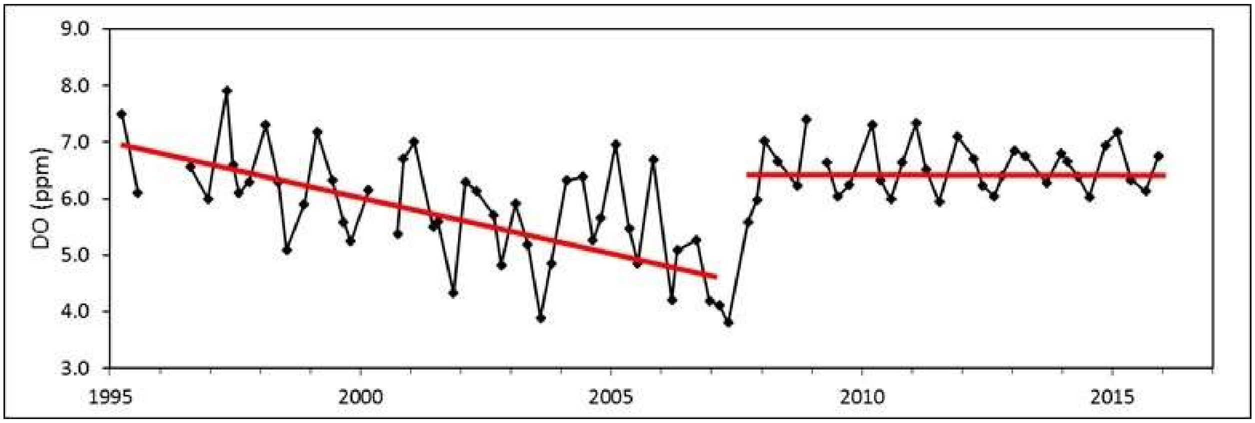

Figure 27. *Discontinuous trend in DO at Carysfort Reef.*

Linear regression approaches shown above may not be optimal for analyzing long term time series influenced by fluctuating conditions or disturbance events. Instead, locally weighted regressions, such as LOESS, are more useful for visualizing trend reversals and cycles in those time series (Fig 28).

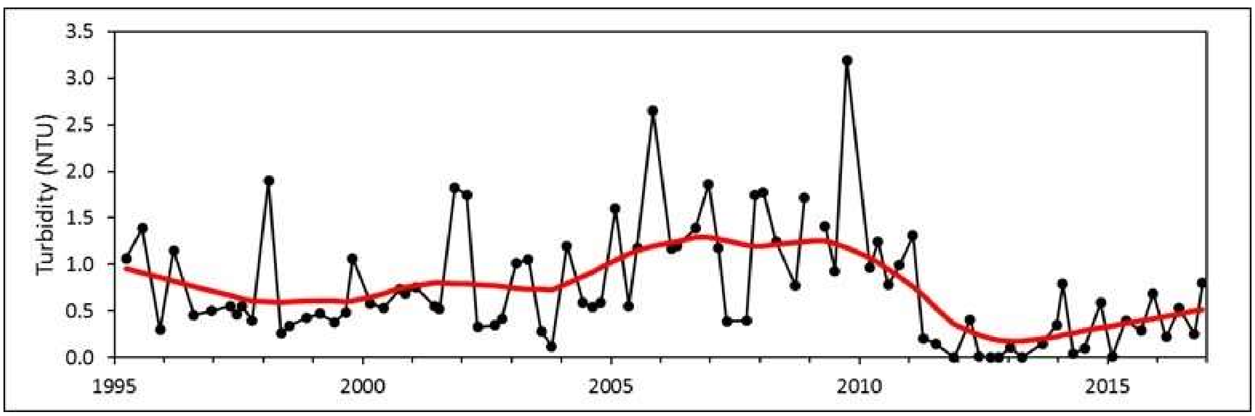

Figure 28. *LOESS fitting of trend in turbidity at Carysfort Reef.*

To quantify trends, we used Sen slope regressions for each water quality variable for the 25-year period of record. Statistical significance was tested using the nonparametric Mann-Kendall τ_b. Some of the Sen slopes were very small, so to get a better idea of change over the period of record, the annualized slopes were multiplied by the number of years sampled and plotted as contour maps of <u>total change</u> for the record. For the 26-year period of record, most variables exhibited some significant trends but not at all sites. <u>We chose to map all the projected total changes regardless of significance</u> in order to show directional tendencies in variables across the FKNMS. A table of all variable trends by station, showing statistical significance, is provided in Appendix A.

Surface salinity did not exhibit many significant long-term trends, nonetheless, the change maps (Fig. 29) show differences among regions. Both surface and bottom salinity in the bayside area of the Middle Keys and oceanside Upper Keys increased over time, while the Oceanside

Lower Keys declined. The time series of salinity on the Reef and Inshore areas was most consistent (Fig 30) with LOESS curve being smooth and consistent. Largest variations occurred in the Bay and Backcountry, areas that are most influenced by mainland freshwater sources and because of their shallow waters are more sensitive to high evaporation rates (salinity increase) or heavy rains (salinity decrease). The Backcountry displayed some salinity cycles lasting 4-5 years (Fig. 30). Note the large depression in salinity in the Marquesas during 2005-7. We believe this was legacy of the 2005 hurricane season, which affected salinity in the Gulf of Mexico for an extended period afterwards (Briceño & Boyer 2010).

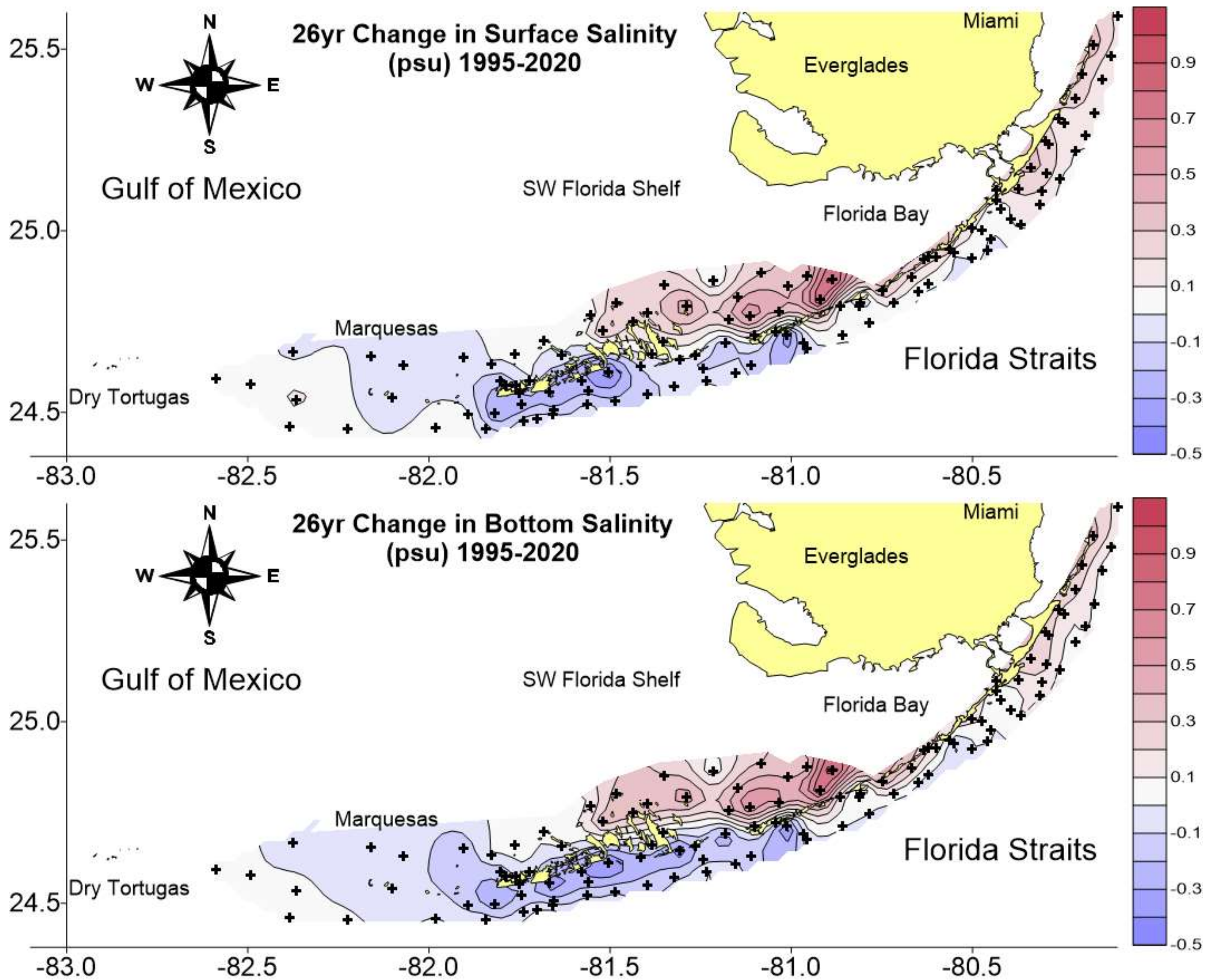

Figure 29. *Total change in surface and bottom salinity for 26-year period.*

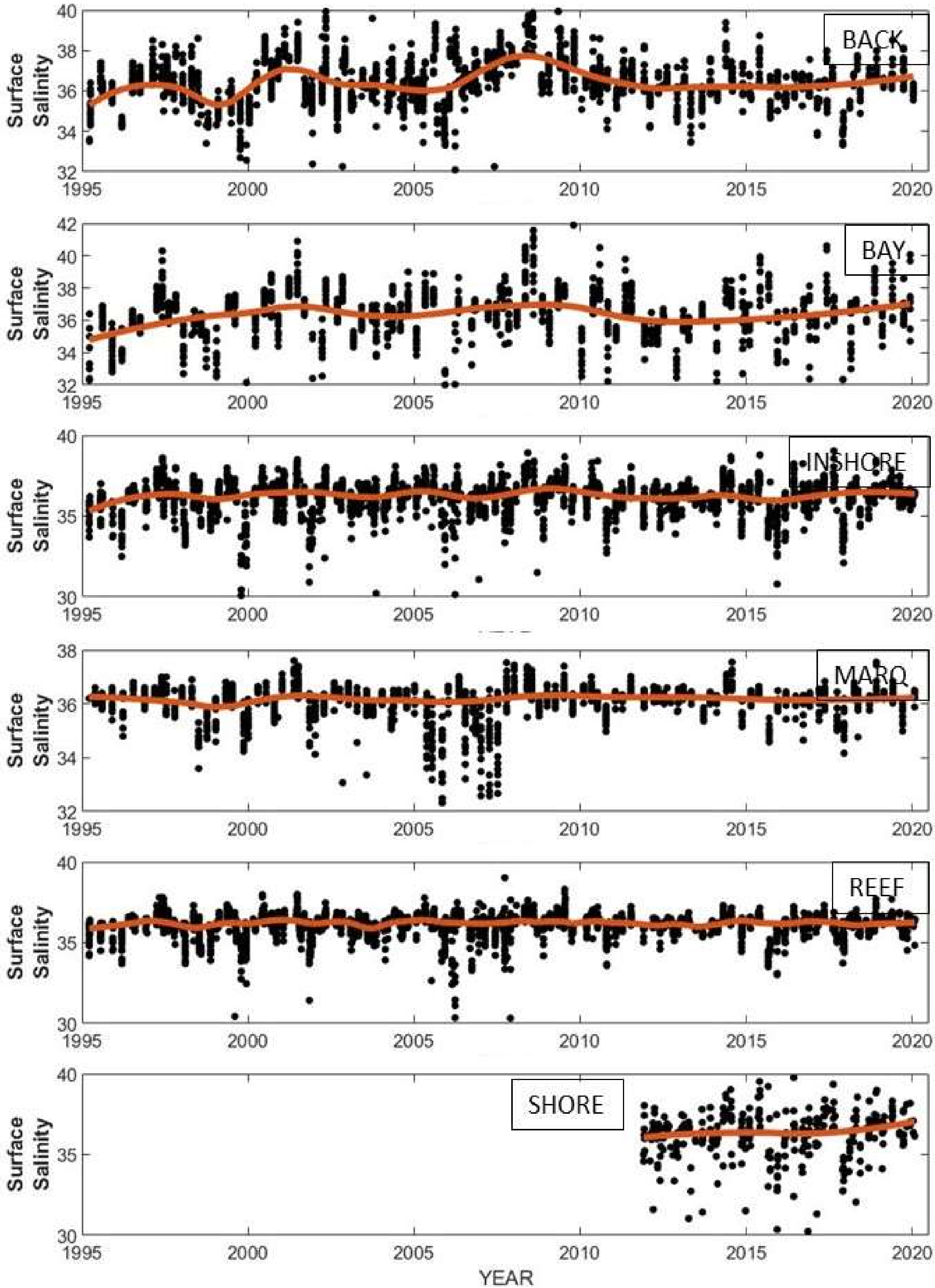

Figure 30. *Time series of surface salinity by zone. The line is LOESS fit.*

Temperature also did not exhibit a statistically significant long-term trends but the change maps show relative differences in direction of tendency across regions (Fig. 31). The Bay and Backcountry zones tended to decline while the oceanside Upper Keys and Marquesas tended to increase. The temperature time series also show that the most variability occurred in the shallowest areas such as the Backcountry and Bay (Fig. 32).

Quarterly collection of temperature over 26 years cannot be expected to resolve the small changes in subtropical waters expected under global climate change. Daily temperature measurements from three separate programs have shown that the waters of the Florida Keys have warmed ~0.8°C for the period 1878-2012 (Kuffner et al. 2015).

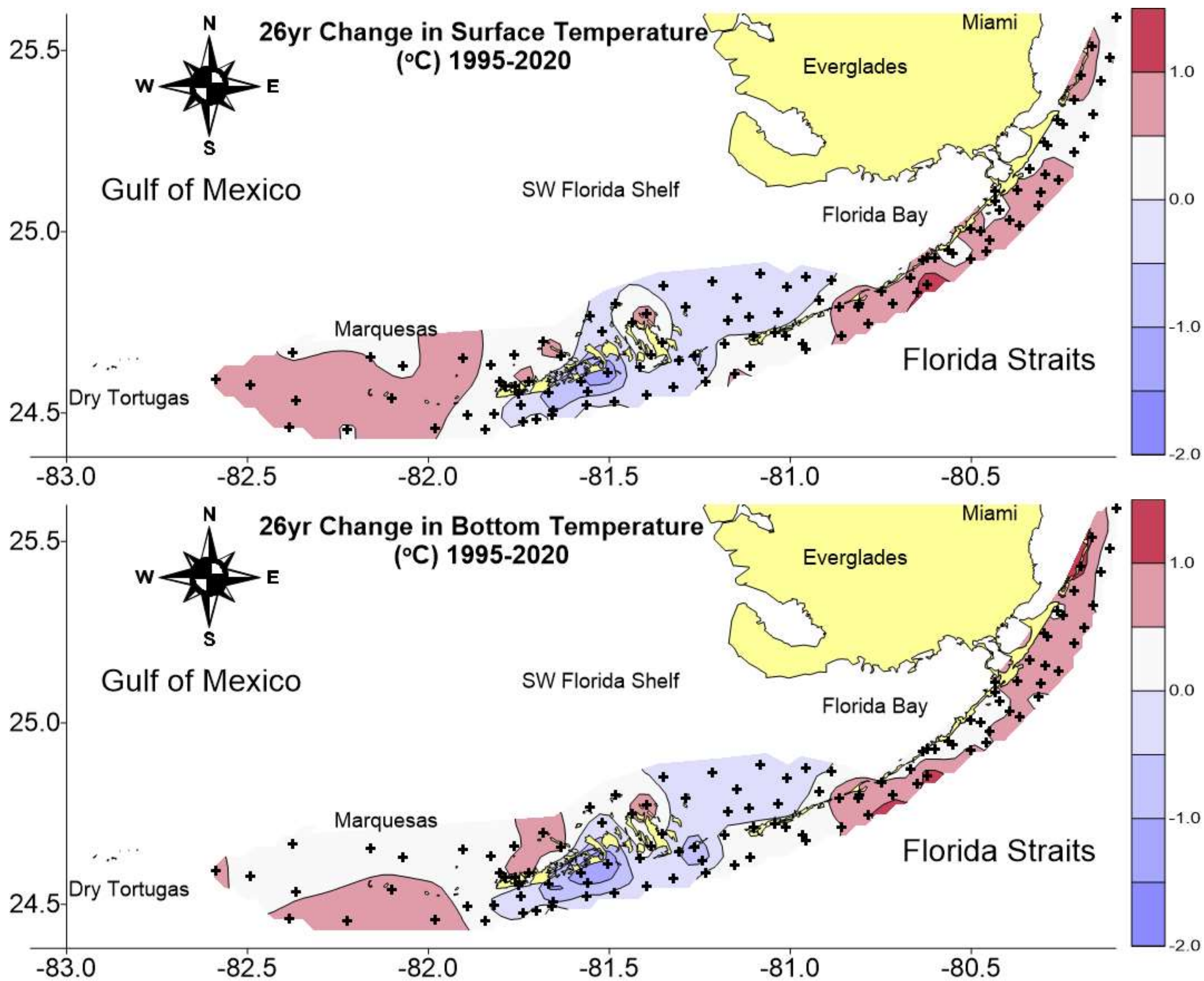

Figure 31. *Total change in surface and bottom temperature for 26-year period.*

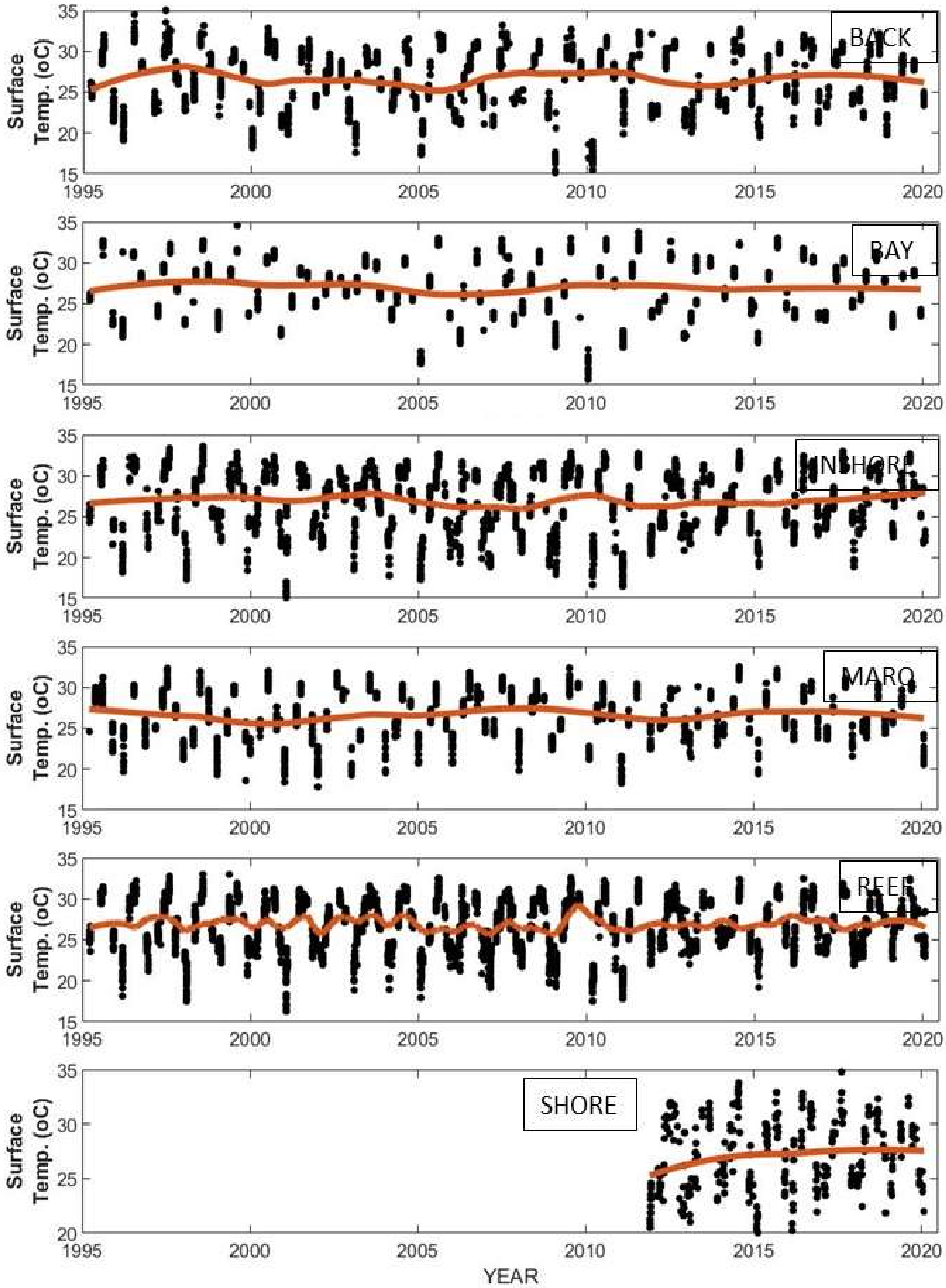

Figure 32. *Time series of surface temperature by zone. The line is LOESS fit.*

Surface DO saturation increased at most sites the FKNMS (Fig. 33). Increased DO_{sat} is beneficial for animal life. Greatest increases in DO_{sat} were generally observed on the Atlantic side of the Keys. A few sites in the Sluiceway areas closest to Florida Bay and north Backcountry sites showed decreasing trends. Trends in bottom DO_{sat} were similar to surface sites.

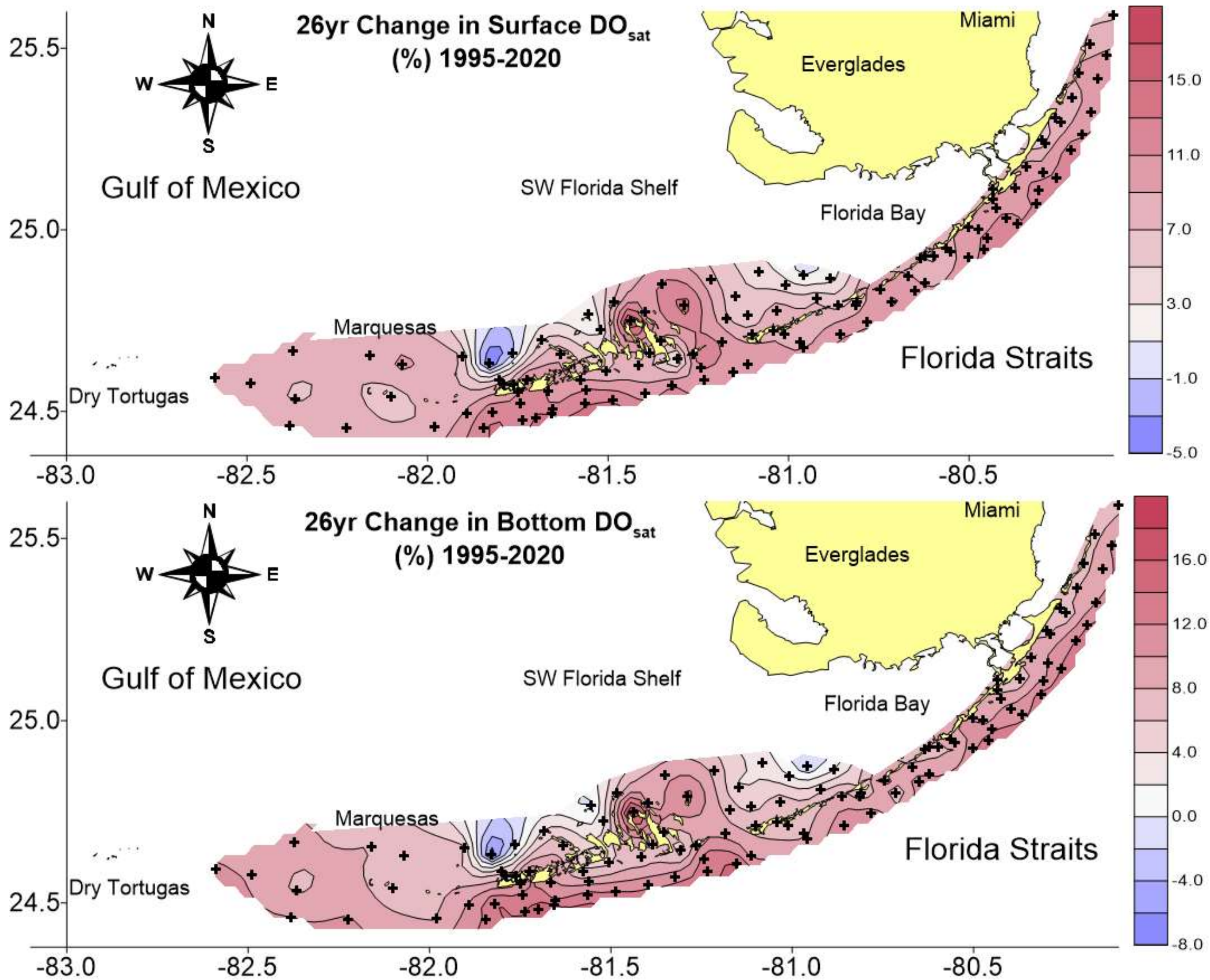

Figure 33. *Total change in surface and bottom DO saturation for 26-year period.*

By looking at the map, one might assume that DO_{sat} has experienced a slow, incremental increase of over the 26-year period. However, the LOESS regression of surface DO_{sat} showed a small decline in most zones (Fig. 34) and then a rapid decline from 2004 to early 2007 with strong rebound in late 2007 to levels slightly higher than pre-2004. The DO_{sat} drop seems to be linked to eight major hurricane impacts during 2004 (Charley, Frances, Ivan and Jeanne) and 2005 (Dennis, Katrina, Rita, and Wilma) whose effects lasted until 2007. Interestingly, DO_{sat} in the Backcountry was relatively stable for the period of record and was not affected like other areas. Net DO_{sat} changes over the 26-year period were small but significant; the range of internal variability during those impacted years was larger and significant.

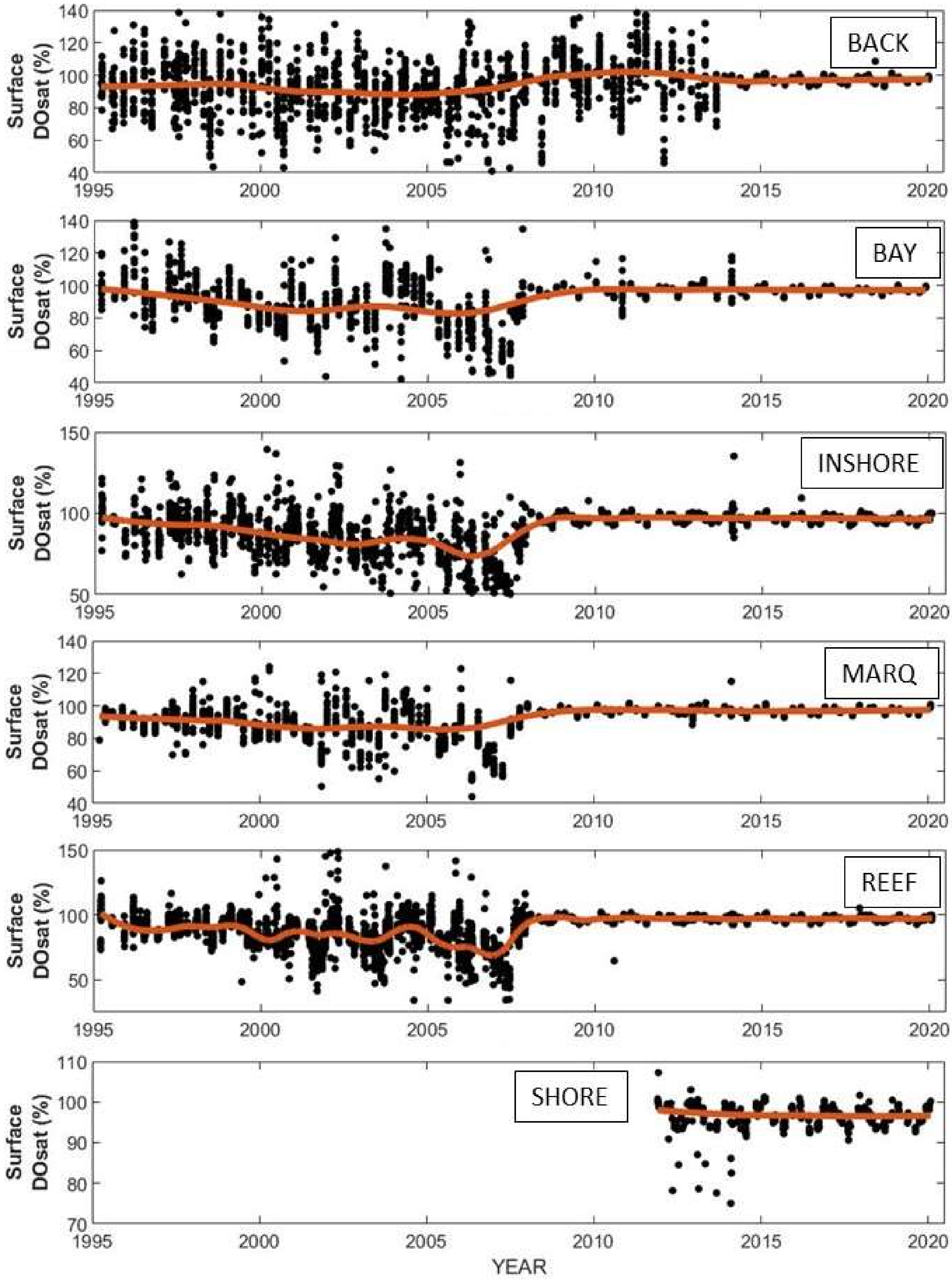

Figure 34. *Time series of surface DO saturation by zone. The line is LOESS fit.*

Water column turbidity declined throughout the FKNMS (a beneficial result) during the 26-year period (Fig 35). The largest declines in turbidity occurred in western Florida Bay and Marquesas. There were small increases in bottom water turbidity at sites along northern boundary of Sluiceway and Backcountry.

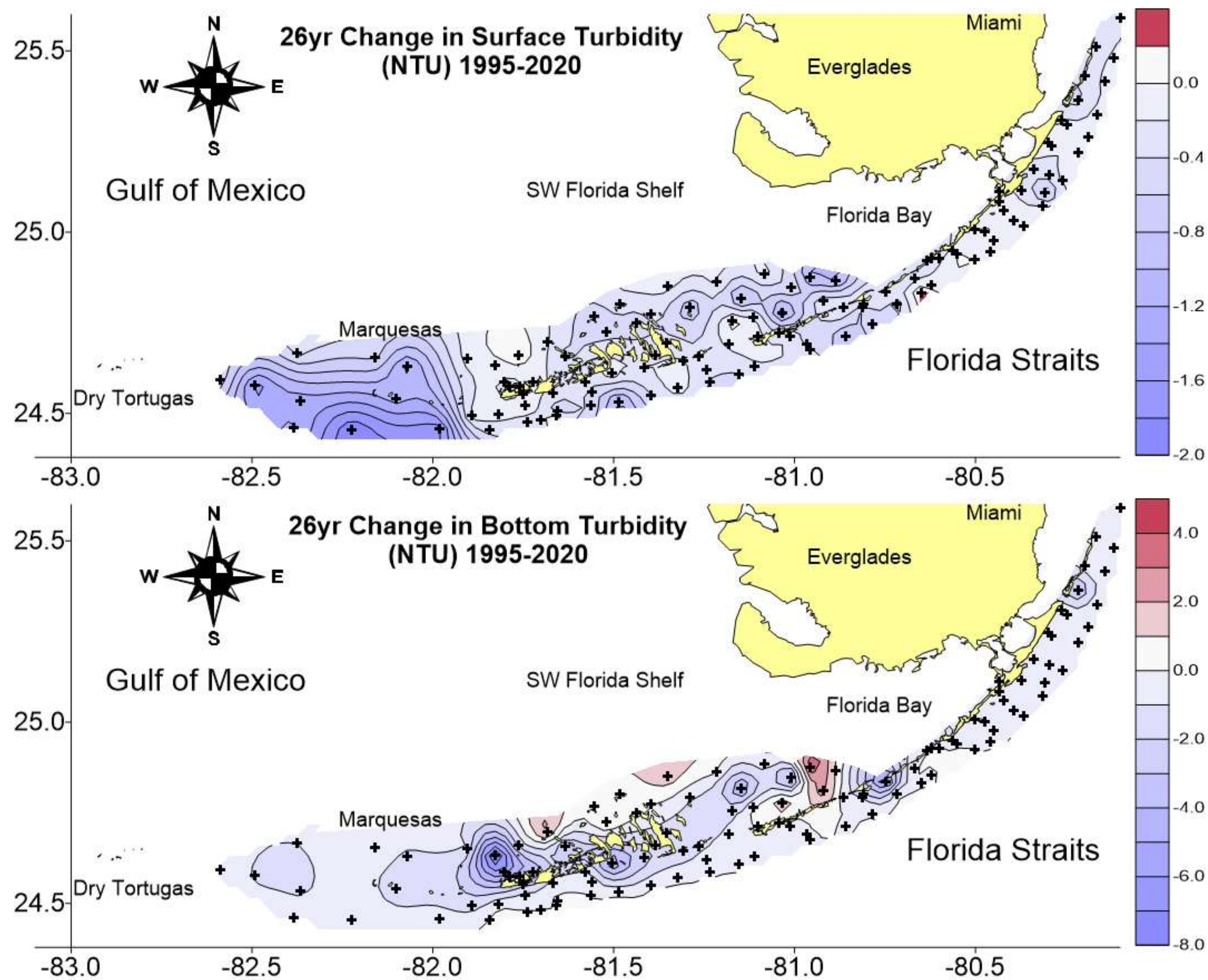

Figure 35. *Total change in surface and bottom turbidity for 26-year period.*

The time series plots of surface turbidity (Fig. 36) gives more information on the nature of the trend. Turbidity was relatively consistent for the period 1995-2005, increased during the 2005 hurricane, then rapidly returned to previous levels. Around 2010, turbidity across the region had dropped to lower levels than before the 2005 disturbances and have remained so.

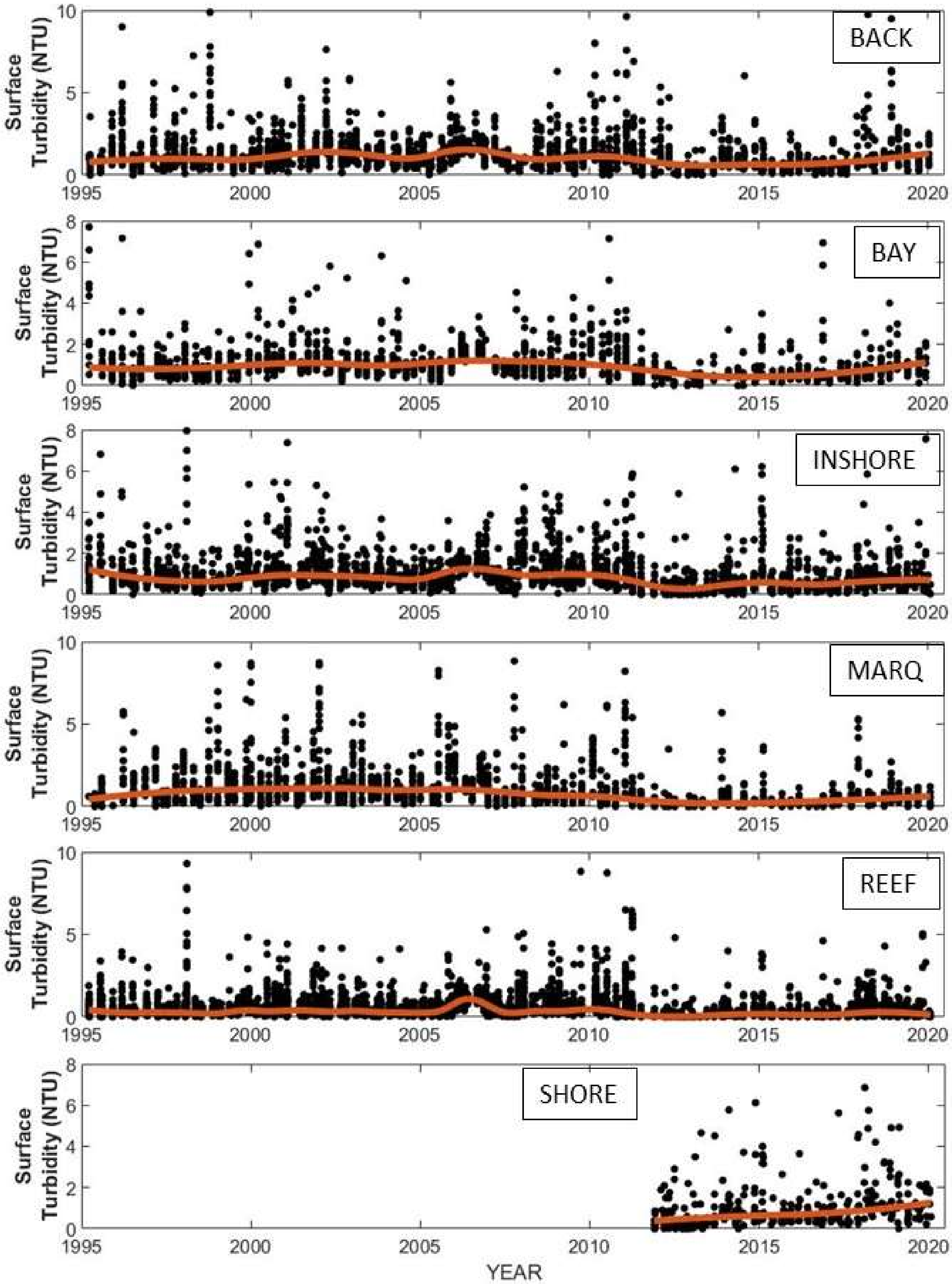

Figure 36. *Time series of surface turbidity by zone. The line is LOESS fit.*

Light extinction (K_d) also showed significant declining trend, a positive result, offshore and in the Marquesas but increased in the Backcountry, Sluiceway, and inner Upper Keys (Fig. 37). Lower K_d tends to increase the amount of light reaching the bottom (I_o in %). More bottom light is beneficial to corals, seagrass, and algae. I_o increased mostly at offshore reef sites throughout the Keys but decreased inshore and in the Upper Keys (Fig. 38). The Backcountry also experienced increases in K_d with decreases in I_o, resulting in less light on the bottom.

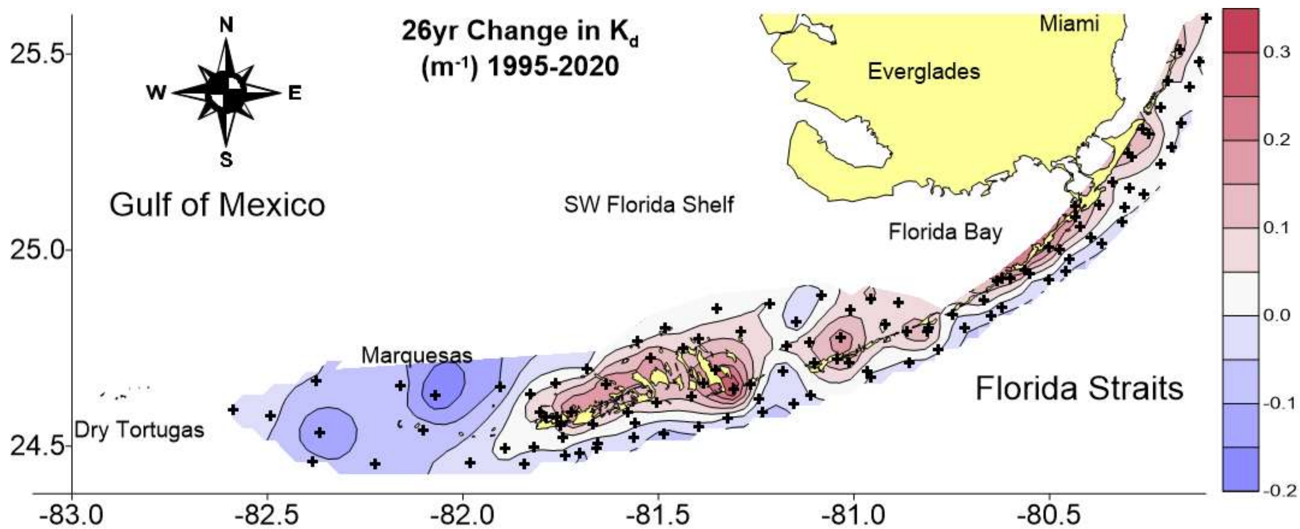

Figure 37. *Total change in bottom K_d for 26-year period.*

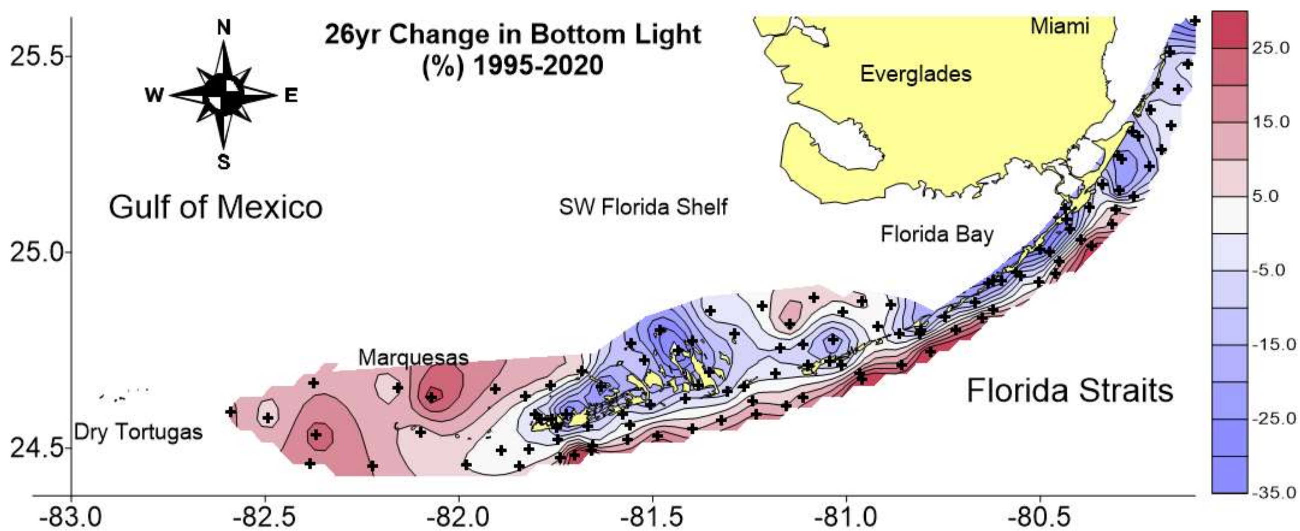

Figure 38. *Total change in bottom I_o for 26-year period.*

The time series of K_d (Fig. 39) and I_o (Fig. 40) show a region-wide and sustained increase in I_o since 2004, except for Marquesas where values have remained relatively constant since 2007. Light reaching bottom I_o has oscillated widely, experiencing a strong decline in 1999-2000 and a sharp increase in 2001-2002, especially in REEF, INSHORE and BAY sites. BACK sites experienced a significant drop from 2006 to 2008. Finally, MARQ sites increased markedly their I_o in 2011.

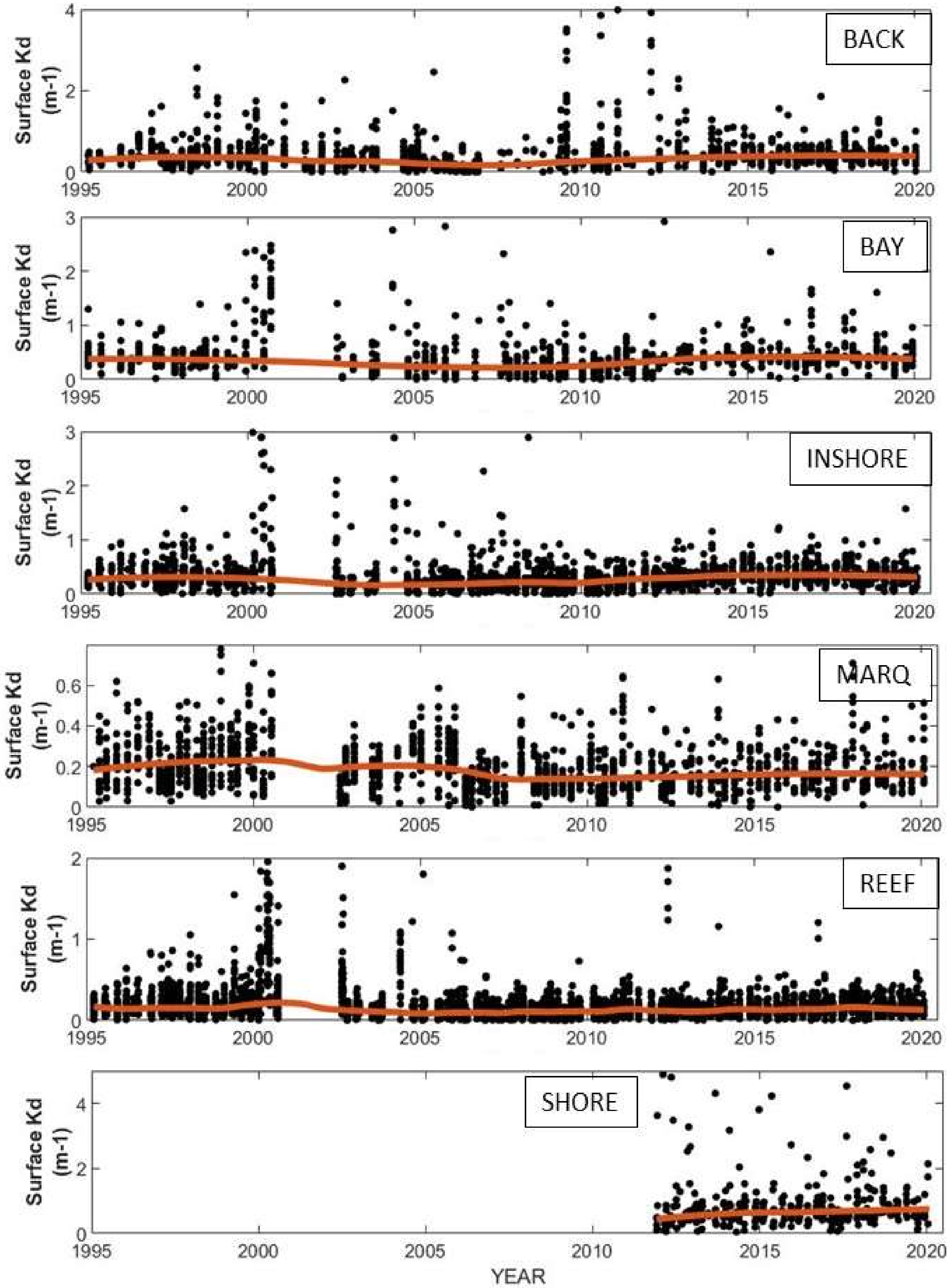

Figure 39. *Time series of Light Extinction (K_d) by zone. The line is LOESS fit.*

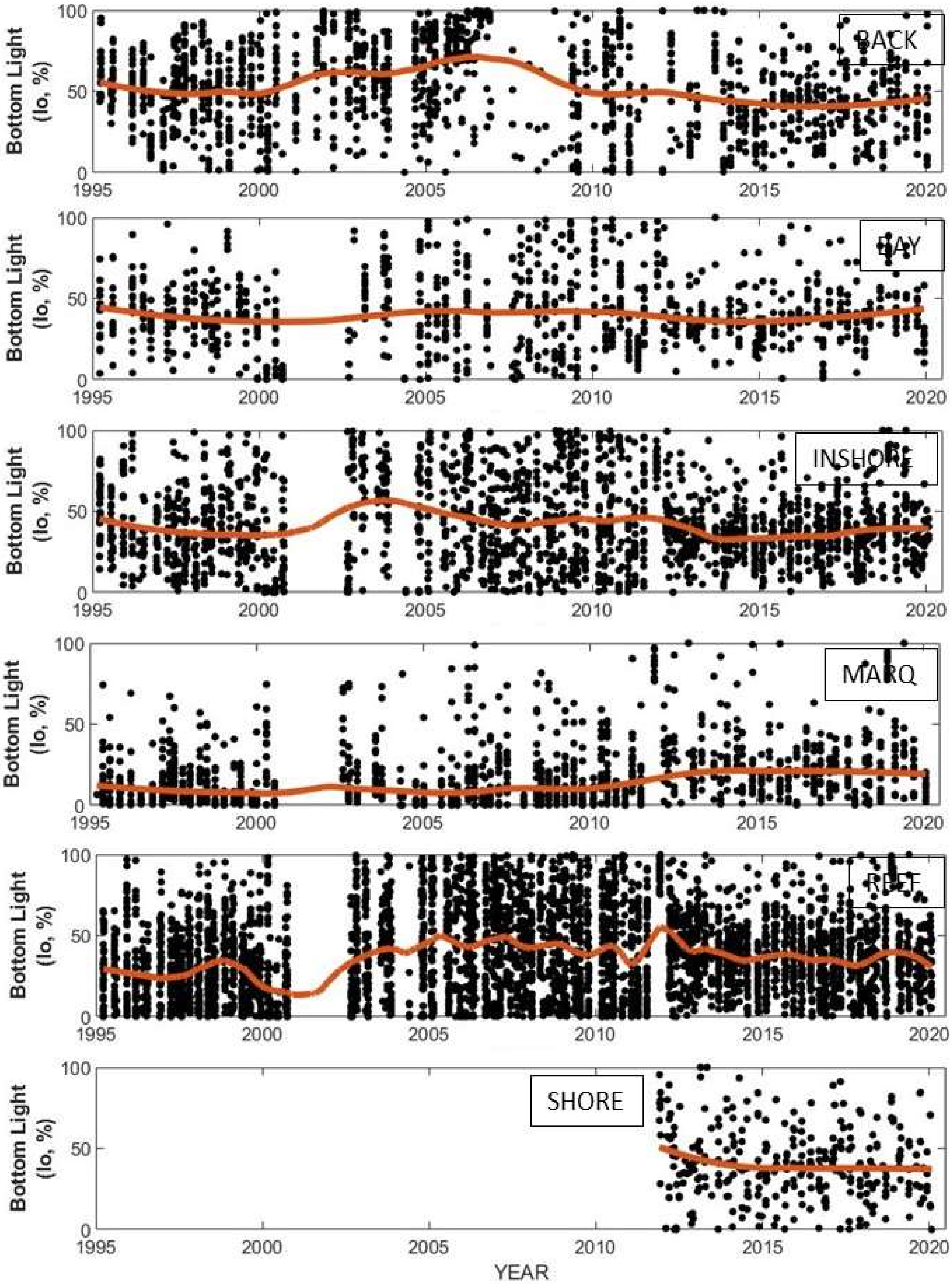

Figure 40. *Time series of % of surface light reaching the bottom (I_o) by zone. The line is LOESS fit.*

Small declining trends in TP were observed in surface waters of the Marquesas (Fig. 41) but increases in TP occurred in all other areas of the FKNMS. These trends need to be watched as we expected TP to decline inshore as in response to recent central sewering. Even greater trends in TP were observed in bottom waters.

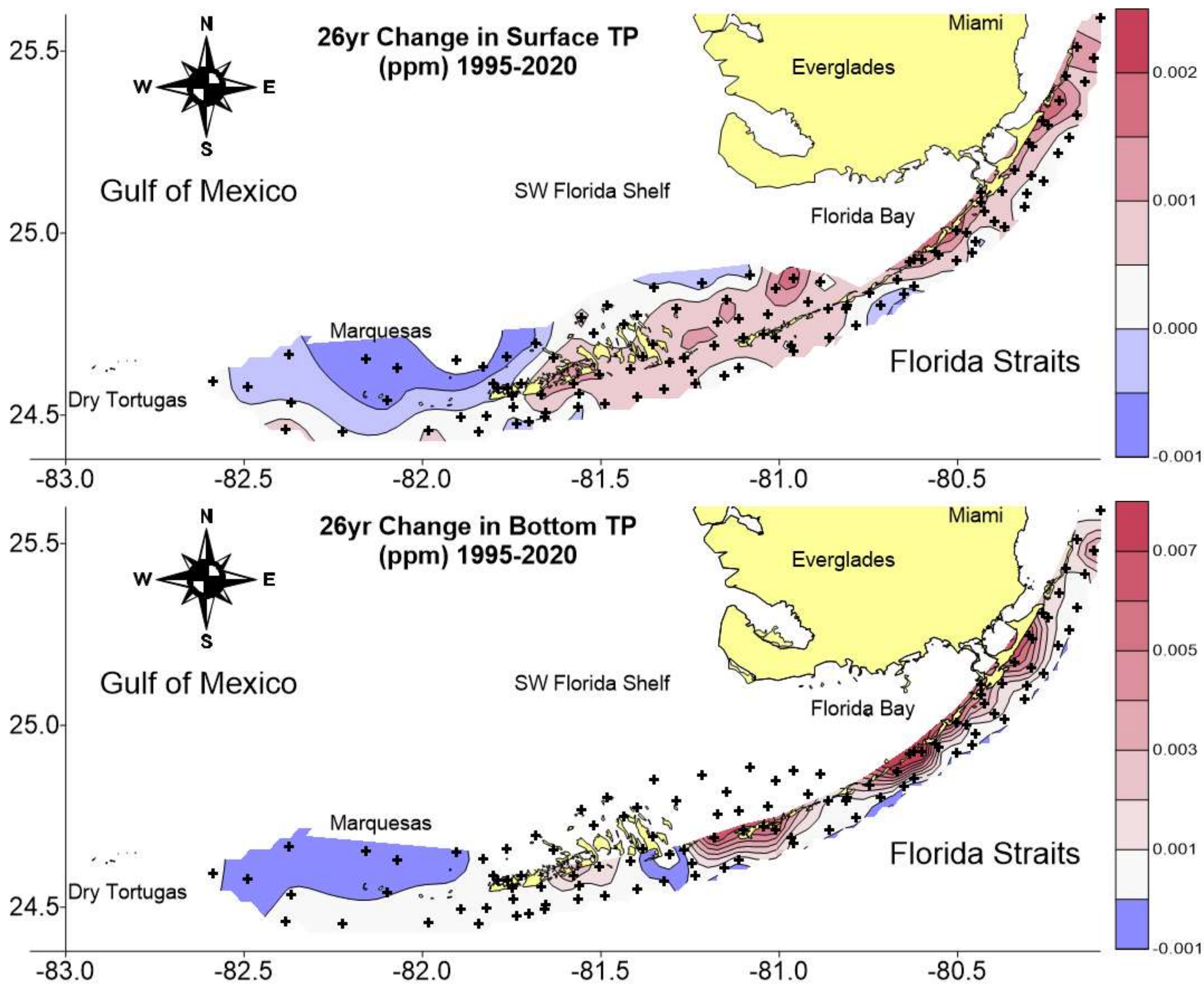

Figure 41. *Total change in surface and bottom TP for 26-year period.*

The TP time series (Fig. 42) shows some elevated periods in the record, especially during 2000 and 2006-7 time period. As described for DO_{sat} changes, TP positive deviations seems to be linked to major hurricane impacts during 1998-1999 and 2004-2005 whose effects lasted until 2000 and 2007 respectively. We believe the bay and land-based disturbance from hurricanes Mitch and Georges (1998) and Irene (1999) lasted until 2001, and those of Katrina-Rita-Wilma persistent until 2007 (Briceño & Boyer 2010). Otherwise, TP is consistently low (<0.01 ppm).

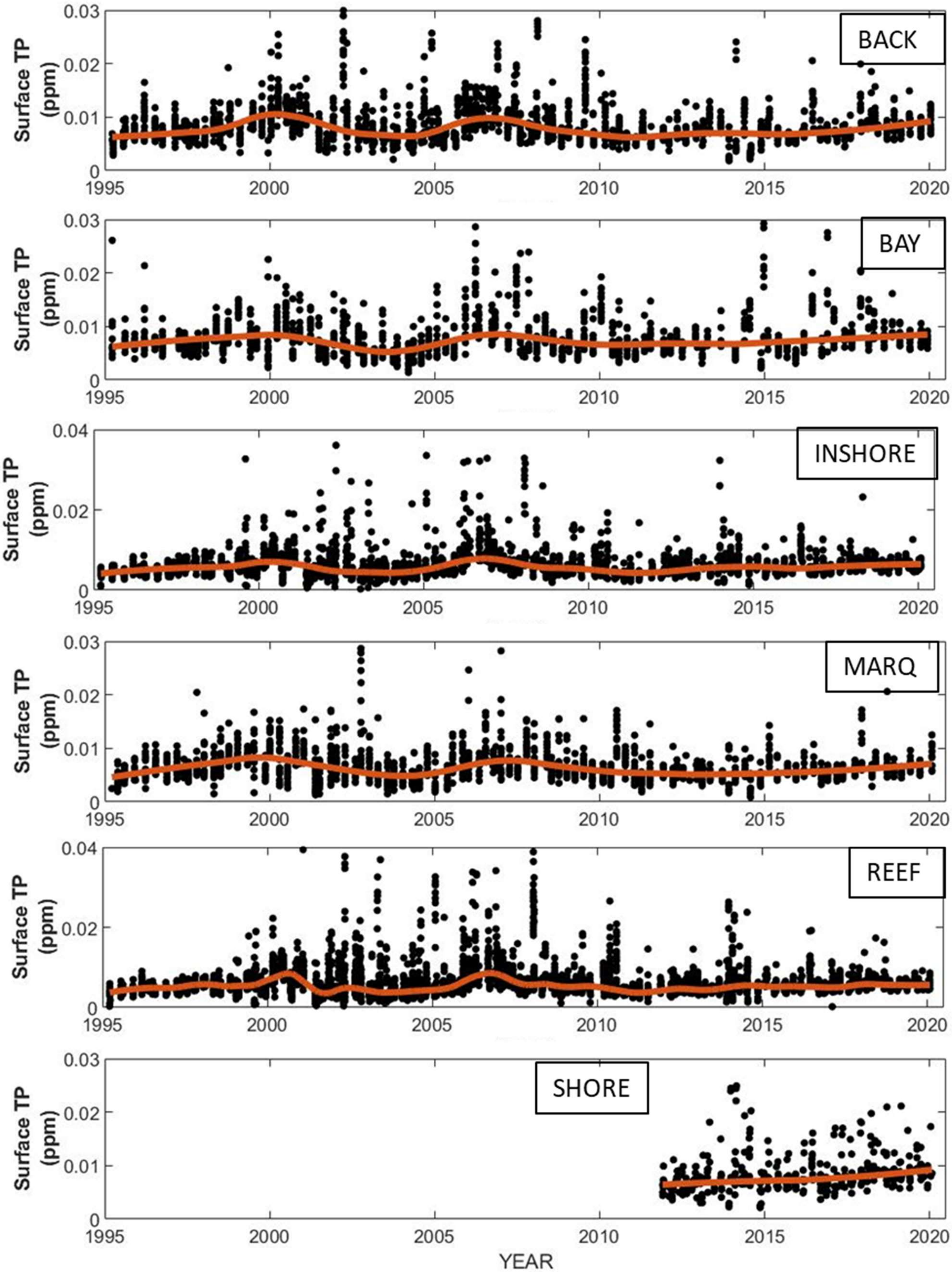

Figure 42. *Time series of surface TP by zone. The line is LOESS fit.*

Very small decreases in SRP were observed (Fig. 43) but these trends were not statistically significant. Concentrations of SRP are generally an order of magnitude lower than TP and may be below the threshold of kinetic uptake for phytoplankton, meaning that not all SRP is accessible to phytoplankton.

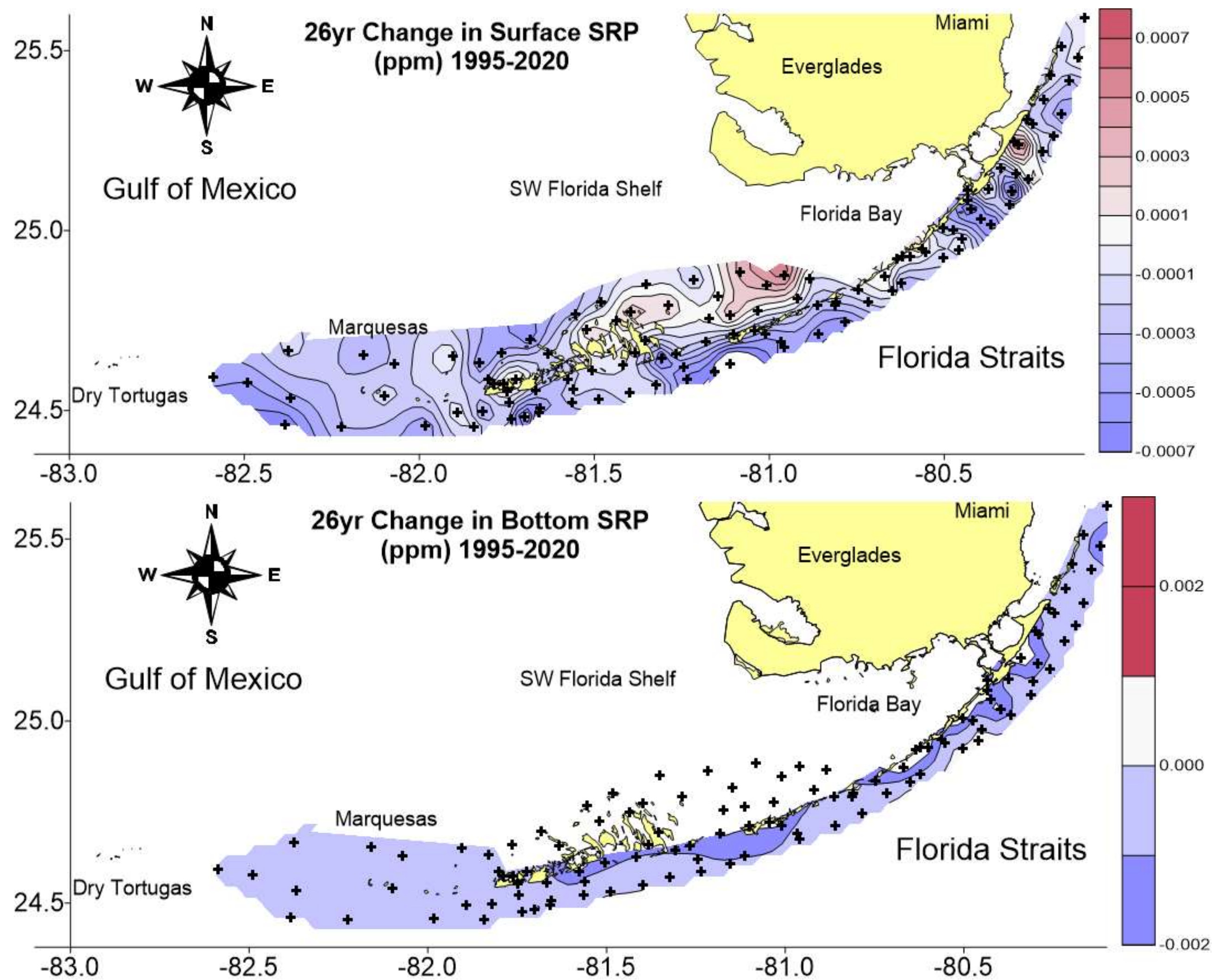

Figure 43. *Total change in surface and bottom SRP for 26-year period.*

The SRP time series (Fig. 44) shows 2-3 year cyclical fluctuations in concentrations at REEF sites. However, the concentrations are very low and may not be biologically relevant.

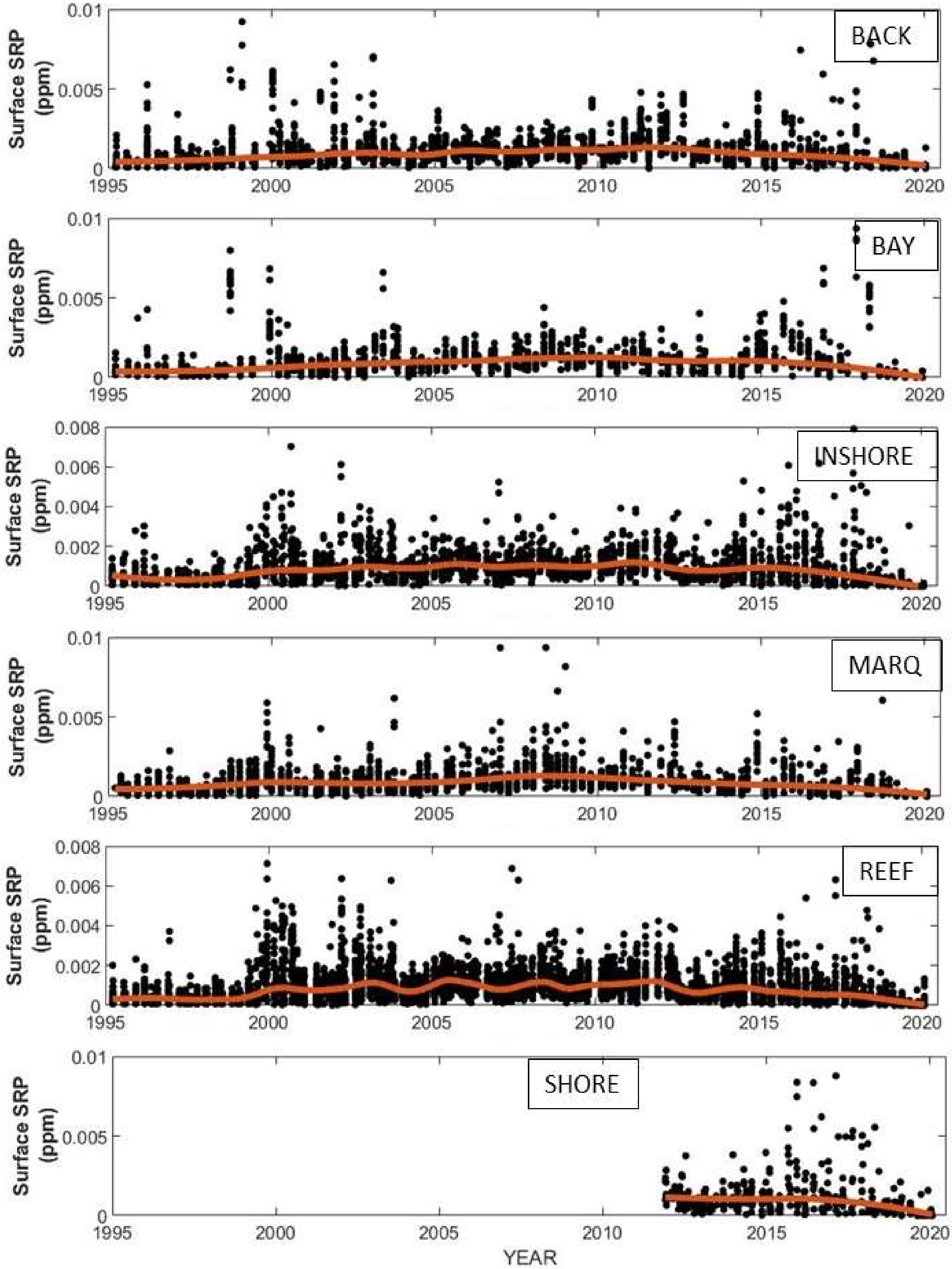

Figure 44. *Time series of surface SRP by zone. The line is LOESS fit.*

Nitrate showed small declines over most of the FKNMS for the record, a beneficial result (Fig. 45). The increase observed in bottom NO_3^- in Islamorada area was influenced by the 2020 episode.

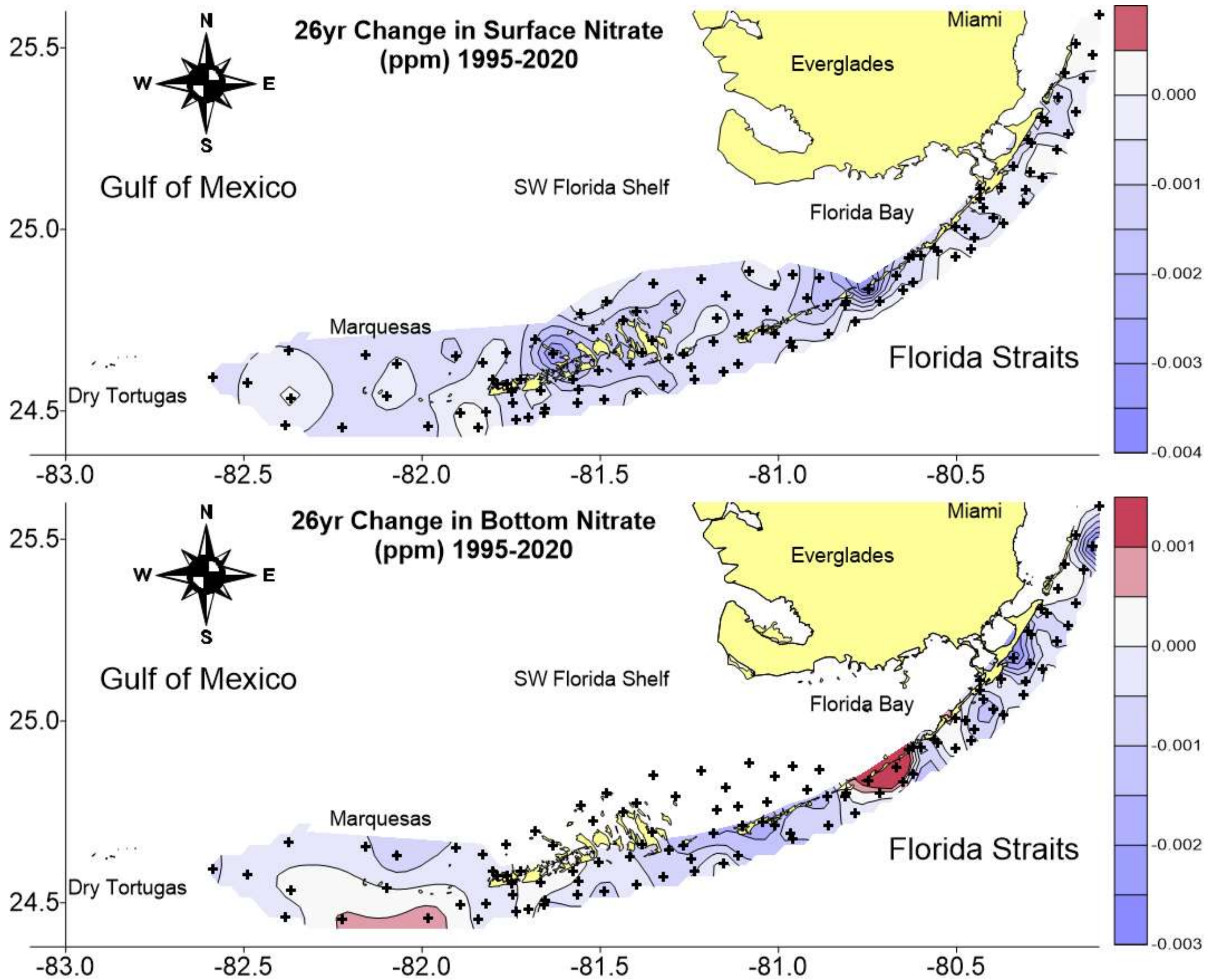

Figure 45. *Total change in surface and bottom NO_3^- for 26-year period.*

Decreasing trends in NH_4^+ were also small but wide-ranging across the FKNMS (Fig. 46). Interestingly, the larger, decreasing trends in bottom NH_4^+ were observed at many of the same oceanside inshore sites off the Upper and Middle Keys where TP was increasing. We are not sure if such trends are stoichiometrically related or not. Did increases in TP drive down NH_4^+ through biological uptake? Or did declines in NH_4^+ allow TP to be released to the water column?

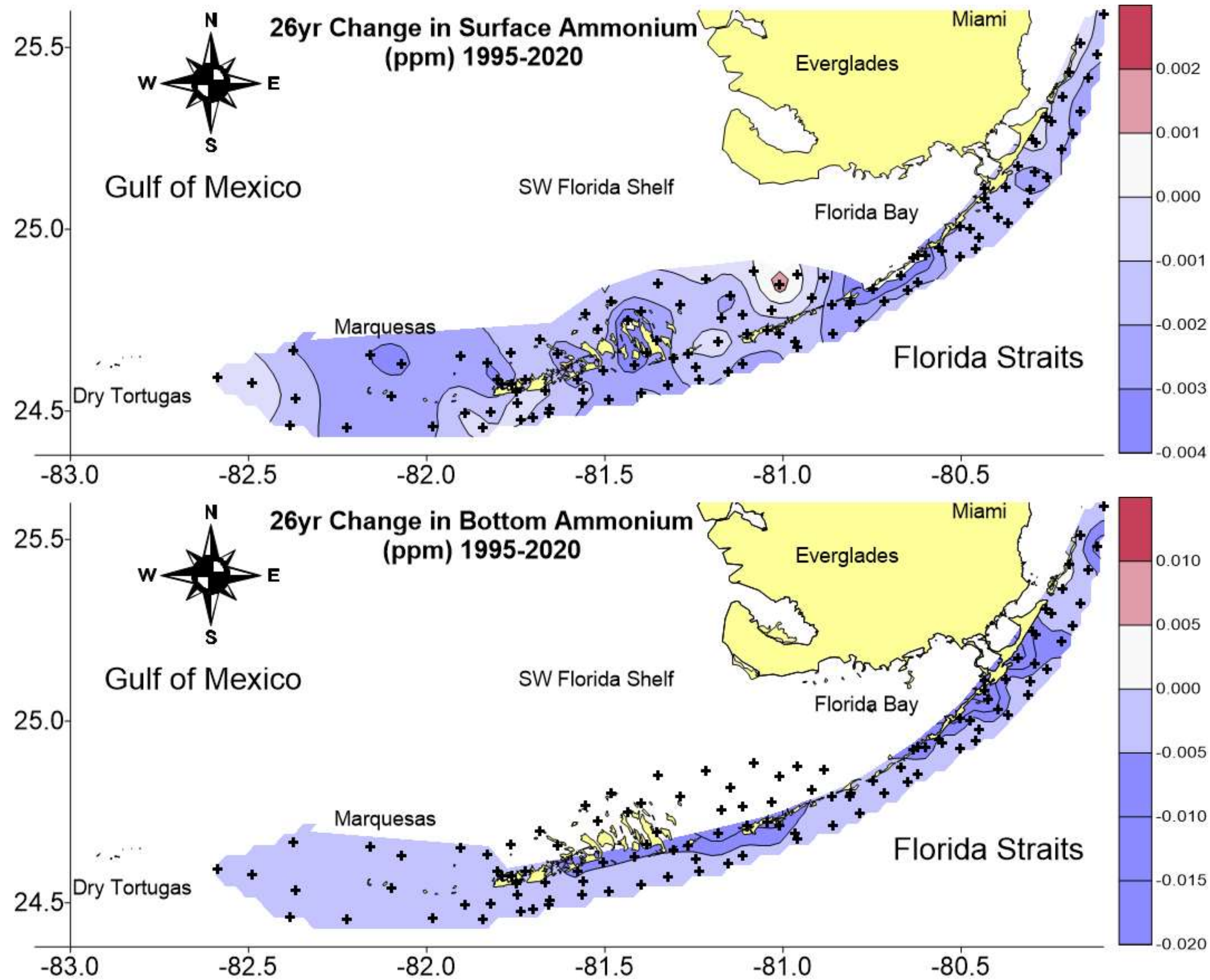

Figure 46. *Total change in surface and bottom NH_4^+ for 26-year period.*

The NO_3^- time series was relatively consistent with a distinct elevation across the FKNMS during 2000 and smaller ones during 2003-4 and 2006-7 (Fig. 47). The 1999-2000 NO_x high coincides with elevated concentrations in Florida Bay, which have been linked to hurricane Irene impacts, exacerbated by extreme freshwater discharges (Briceño and Boyer 2010).

The NH_4^+ time series was interesting as it showed large elevation in concentrations during 2006-7, the year following the Fall 2005 hurricane season (Fig. 47). We believe the land-based disturbance from Katrina-Rita-Wilma had a persistent effect on the FKNMS for the following two years. Interestingly, the effect in the Marquesas did not show up possibly as dampening due to GOM circulation.

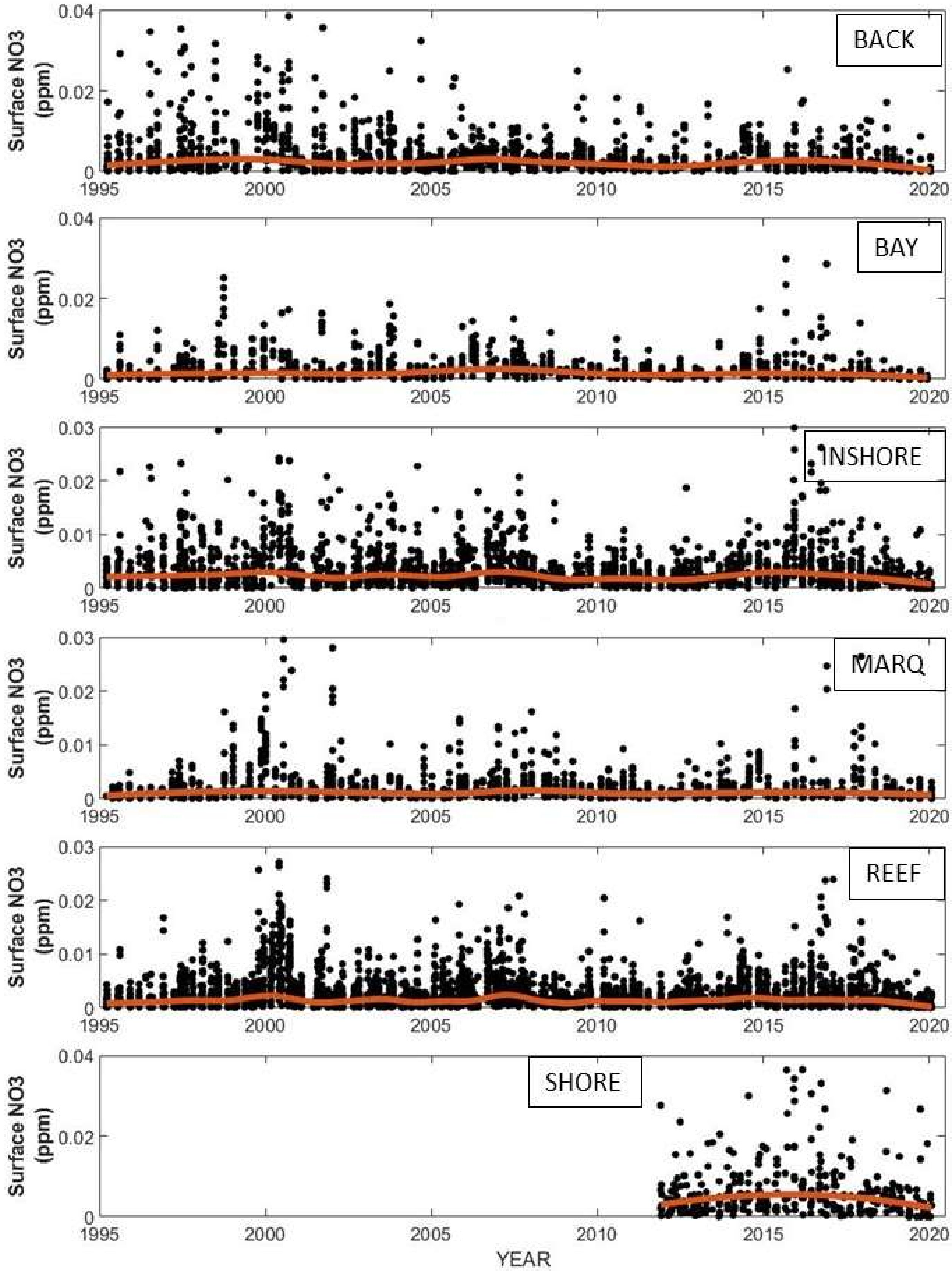

Figure 47. *Time series of surface NO_3^-+NO_2^- by zone. The line is LOESS fit.*

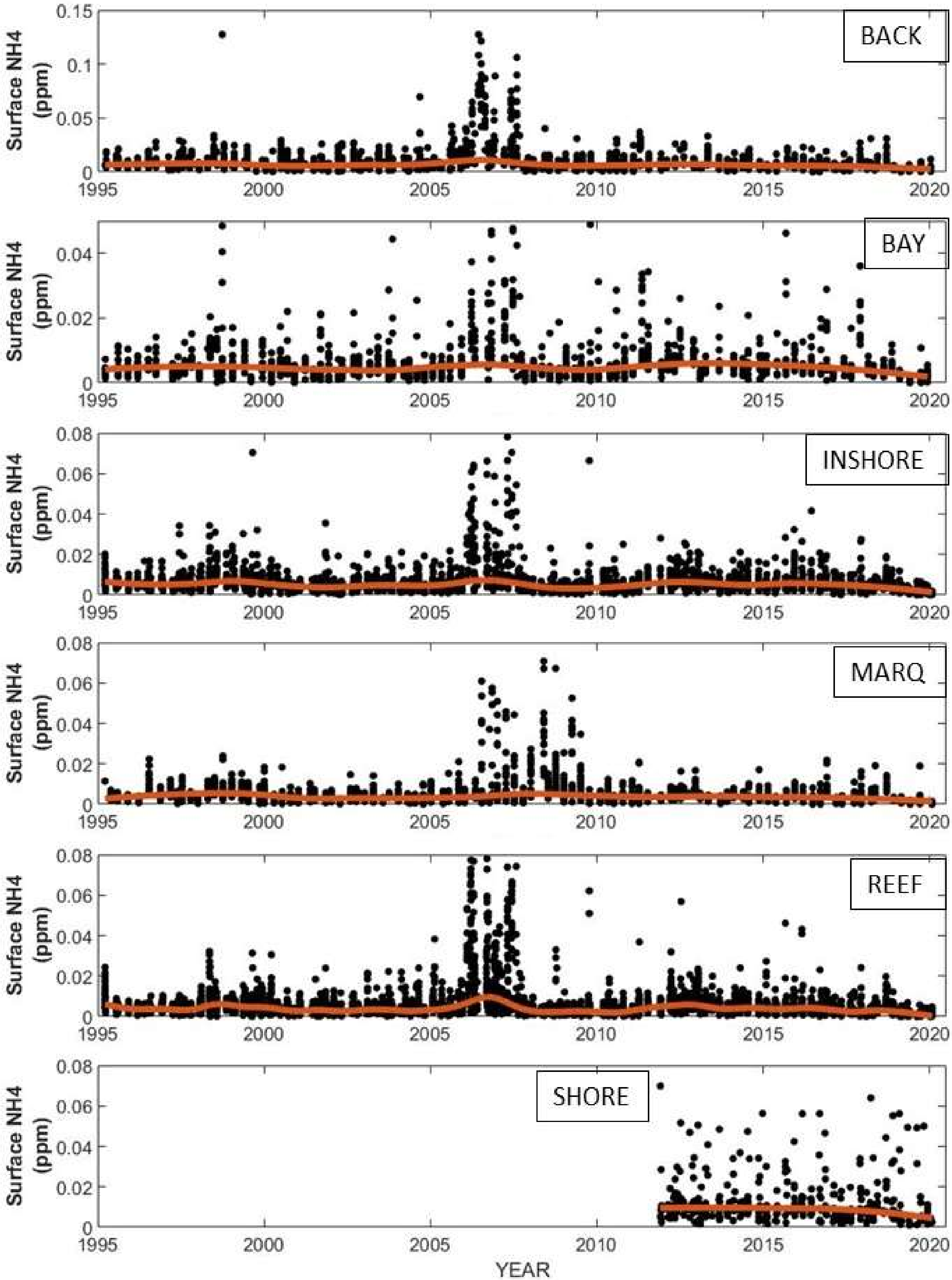

Figure 48. *Time series of surface NH_4^+ by zone. The line is LOESS fit.*

Total nitrogen continued to decline overall with exception of Sluiceway contiguous to Florida Bay (Fig. 49). Most of this is due to decline in the organic N fraction as it makes up ~96% of the TN pool.

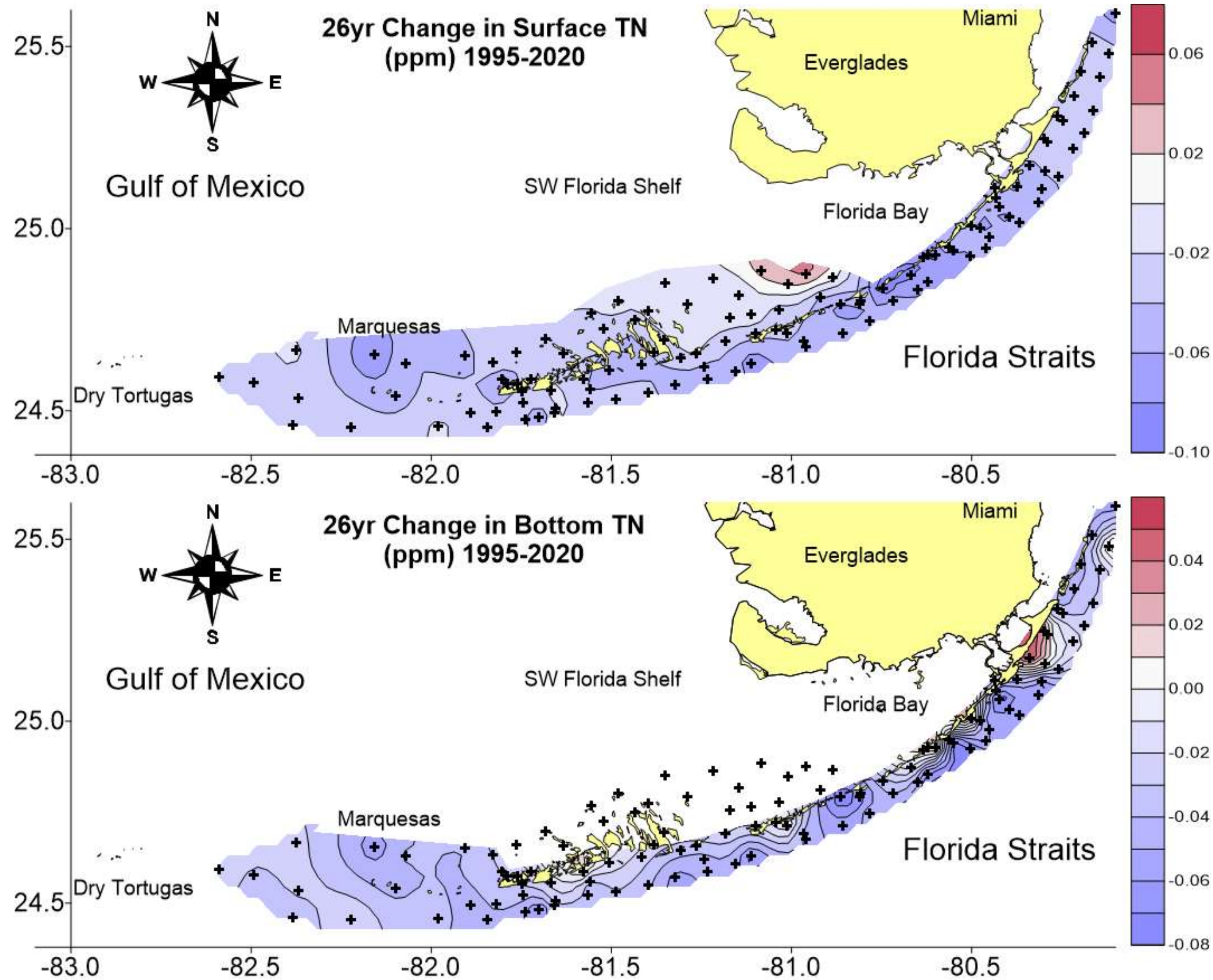

Figure 49. *Total change in surface and bottom TN for 26-year period.*

The TN time series shows elevated concentrations across the region during 2003-4 and 2010 (Fig. 50). The long-term decline in TN is especially evident in inshore waters of the Keys.

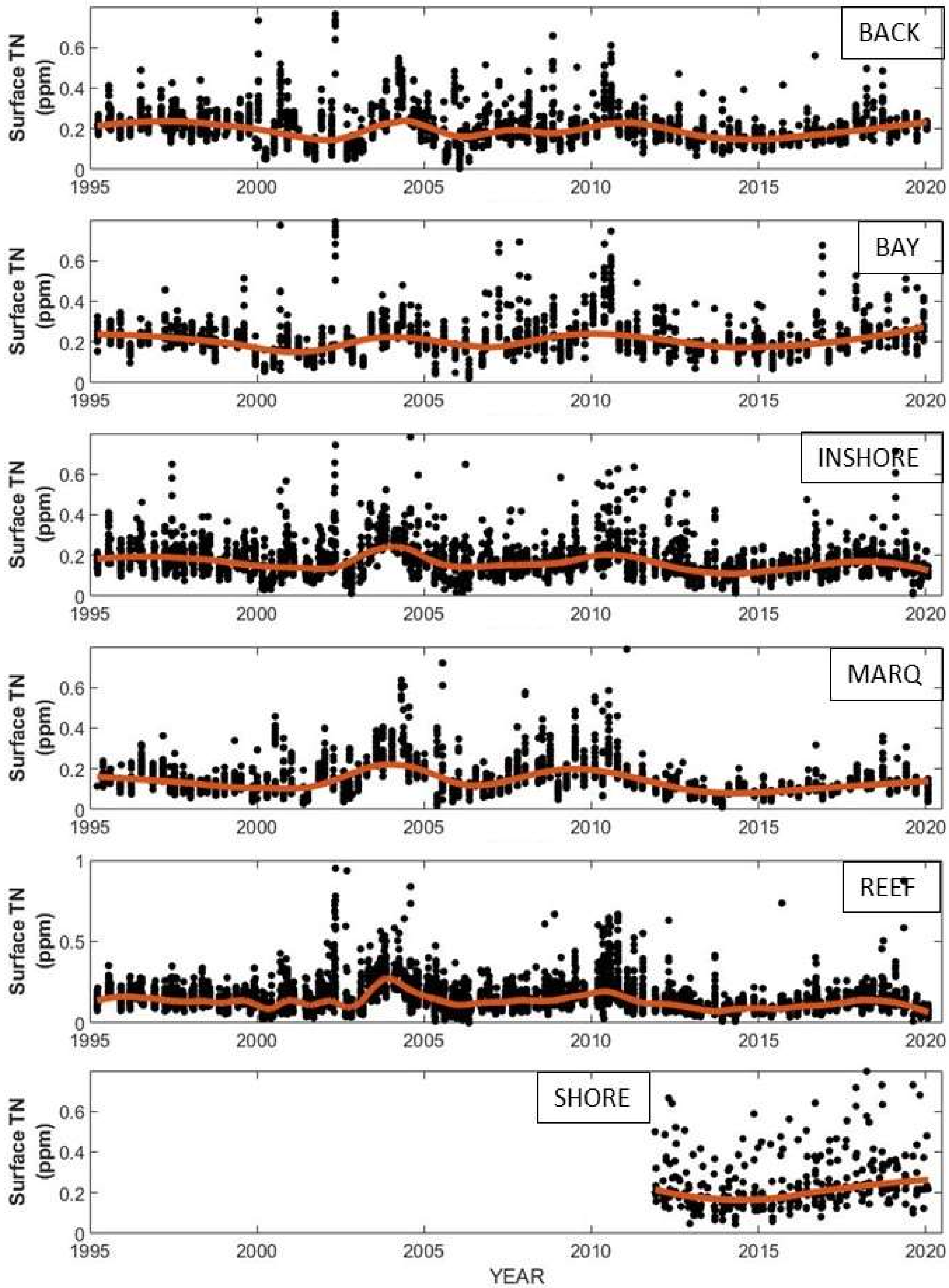

Figure 50. *Time series of surface TN by zone. The line is LOESS fit.*

The largest sustained monotonic trend has been the decline in surface TOC concentration throughout the FKNMS (Fig. 51). This decline could be considered favorable given that TOC corresponds with CDOM (an important driver of light penetration) but may also be an indication of decreased terrestrial inputs to the region.

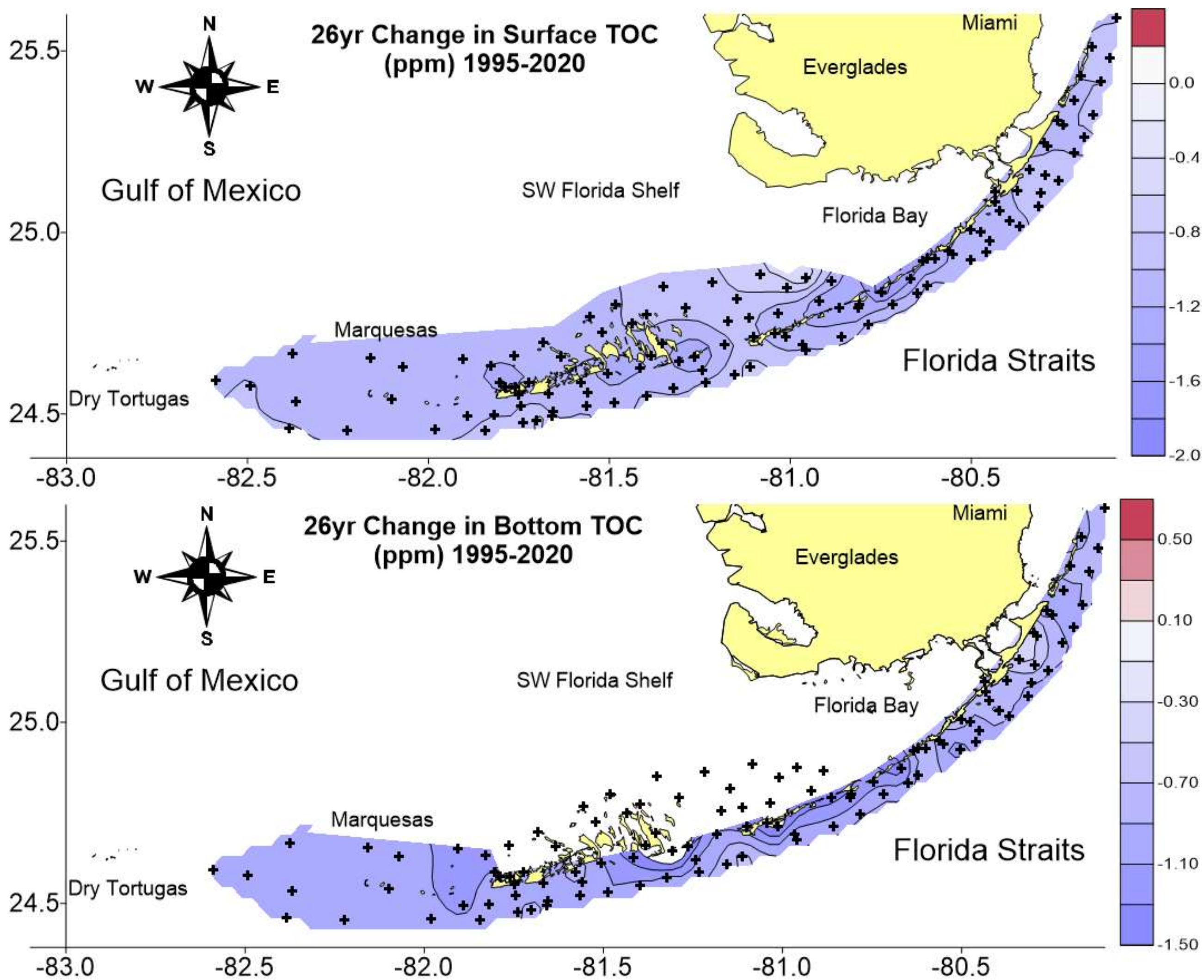

Figure 51. *Total change in surface and bottom TOC for 26-year period.*

The TOC time series show relatively steep declines in the beginning with a leveling out around 2005 (Fig. 52). This declining trend has been observed also on SW Shelf, west coast mangrove estuaries and Florida Bay (Briceño and Boyer 2007), highlighting the importance of a regional contribution of organic matter from the Everglades to Florida Bay and SW Shelf. Regier et al. (2016) found that dissolved organic carbon (DOC) fluxes from the Everglades were primarily controlled by hydrology but also by seasonality and long-term climate patterns (AMO) as well as episodic weather events. Lowest DOC concentrations in water coincide with extended droughts in 2007 and 2010-2011.

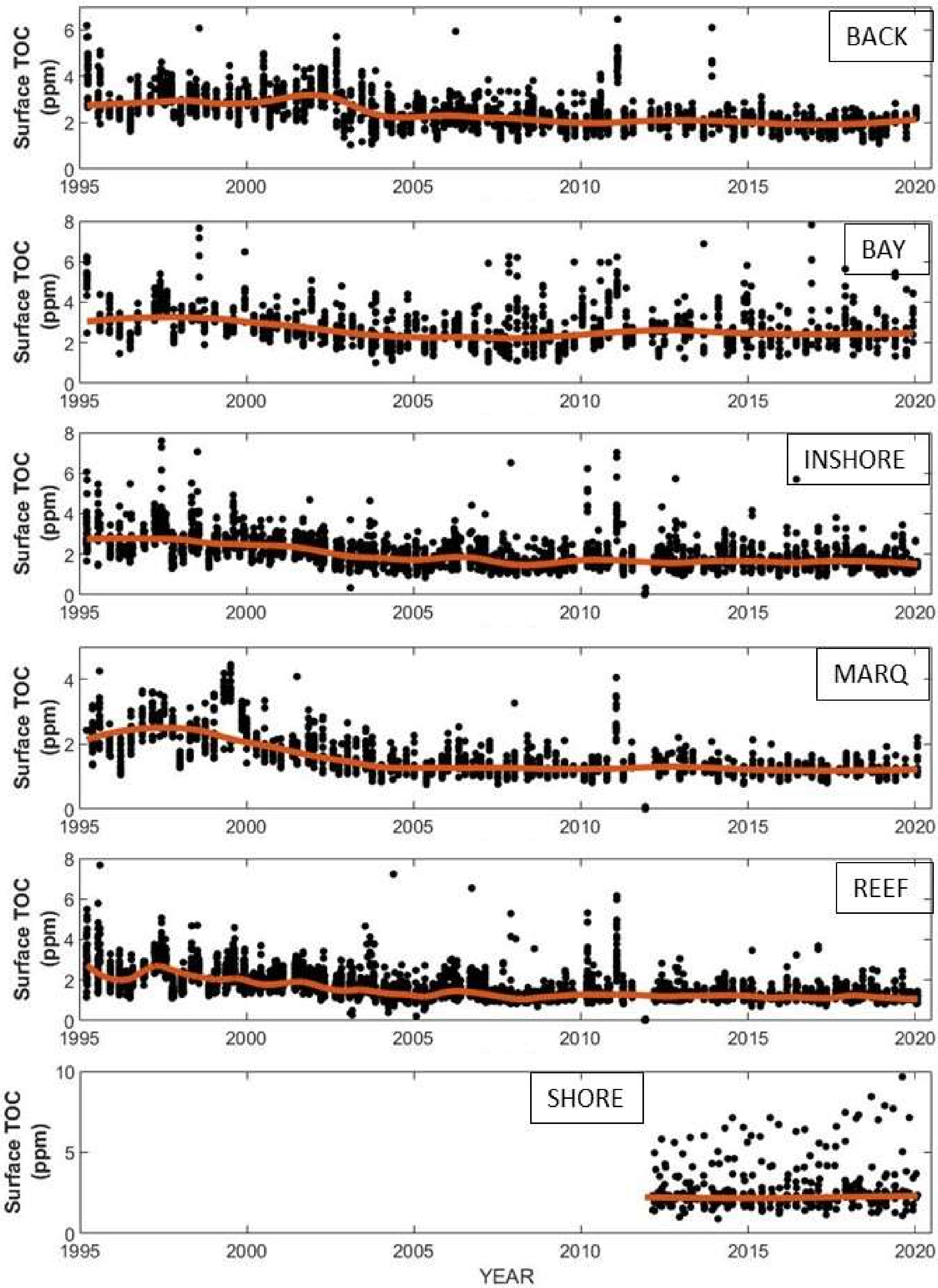

Figure 52. *Time series of surface TOC by zone. The line is LOESS fit.*

SiO$_2$ declined throughout the FKNMS except at two sites in the Sluiceway adjacent to Florida Bay (Fig. 53). We expect these increases are from a more Bay-wide trend but do not have data to show this. The SiO$_2$ time series shows small declines in the beginning with bump around 2010 for most regions (Fig. 54).

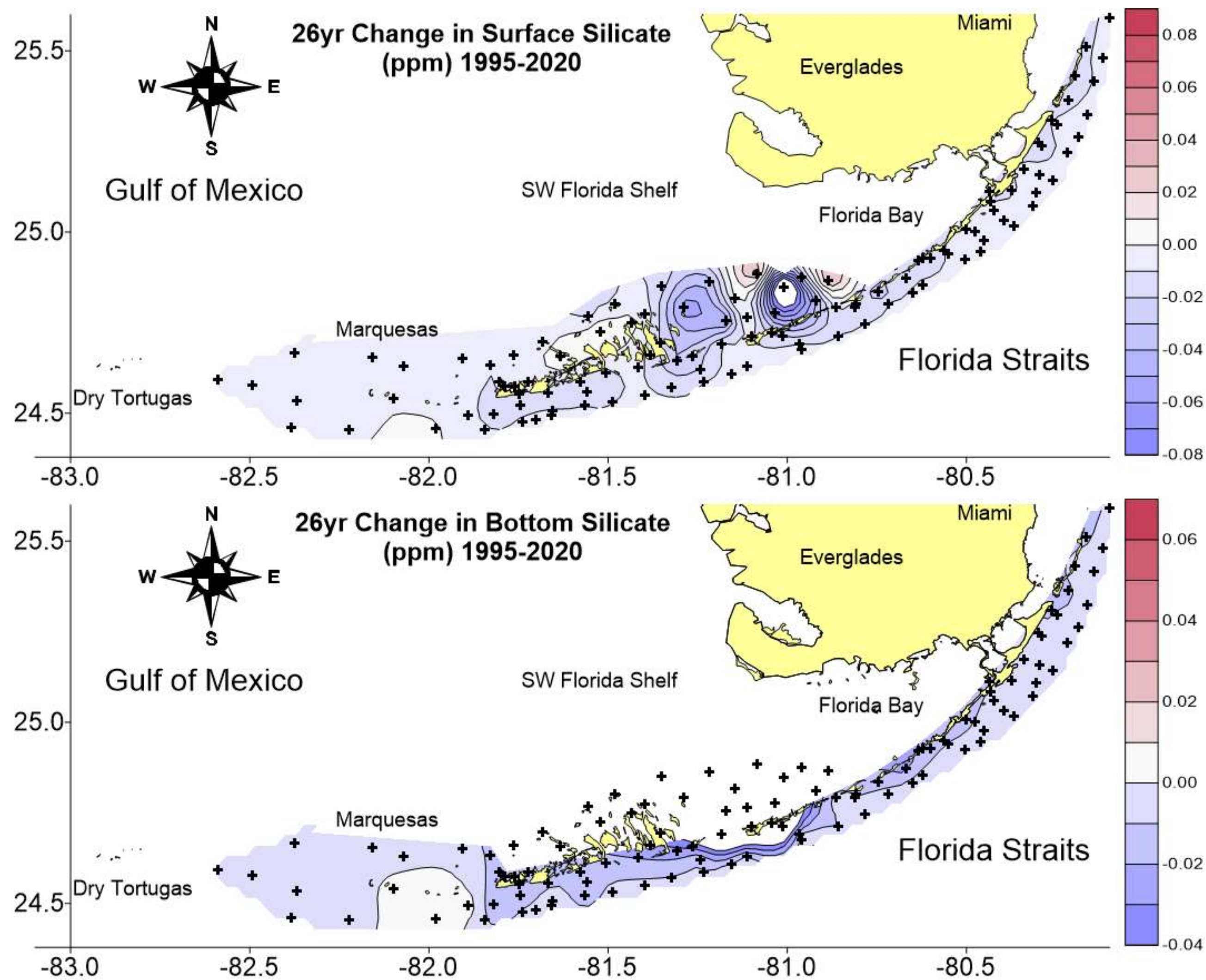

Figure 53. *Total change in surface and bottom SiO2 for 26-year period.*

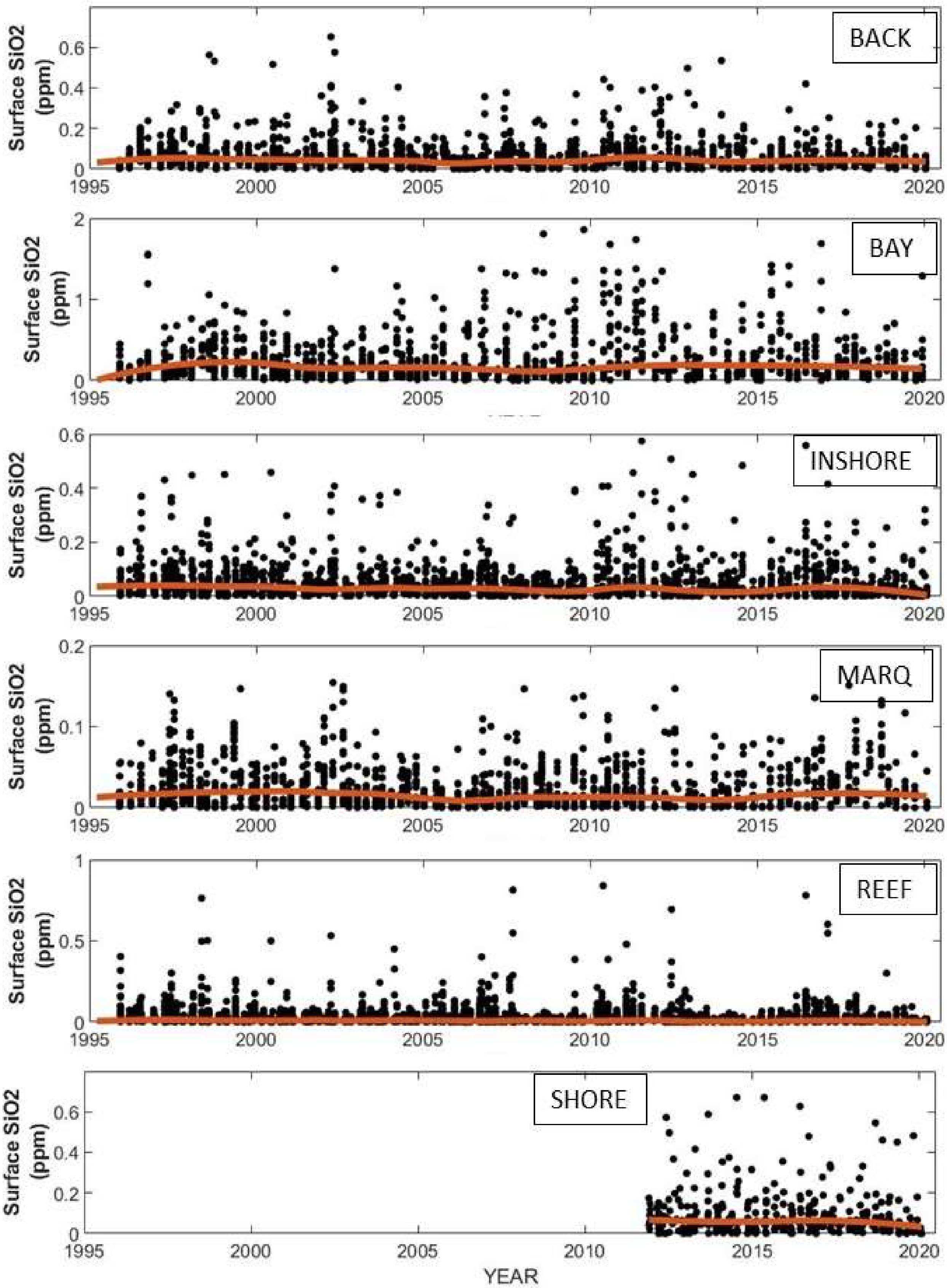

Figure 54. *Time series of surface SiO_2 by zone. The line is LOESS fit.*

CHLA concentrations increased across much of the Keys (Fig. 55), many of which showed statistical significance (Appendix A). Significant increases for the 26-year record ranged from 0.083 0.279 ppb or 28-68% increase. Some declines in CHLA were observed in the Marquesas but were not significant.

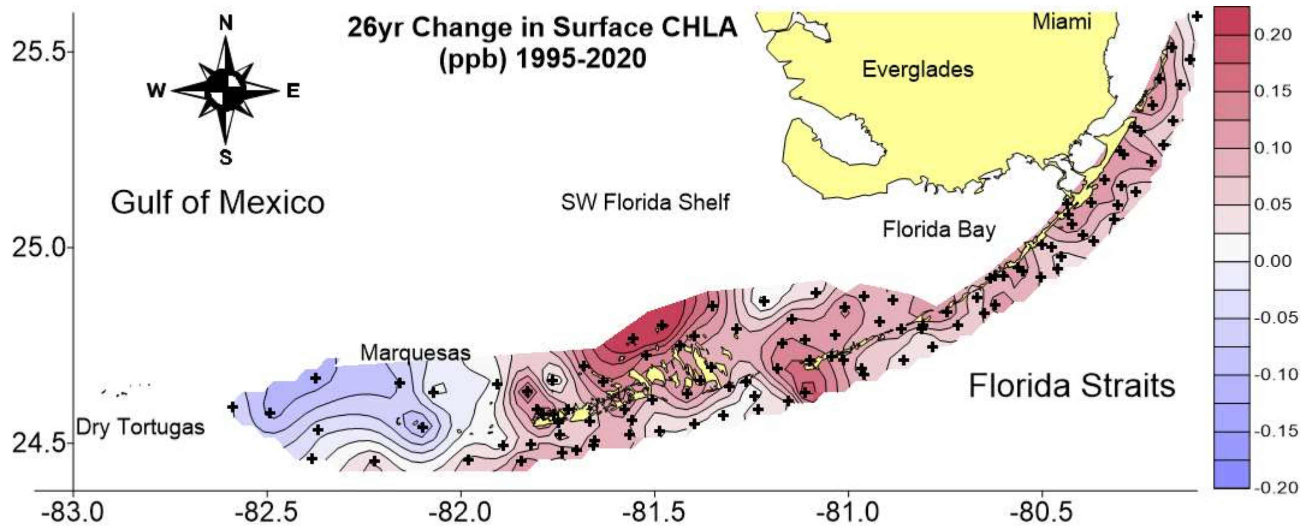

Figure 55. *Total change in chlorophyll a in surface waters for 26-year period calculated from trends.*

Additionally CHLA exhibited a common perturbation marked by elevated CHLA concentrations occurring during 1999-2000, coincident with peaks in NO_3, and SRP (Fig. 56). Similar events occur in Marquesas during 2001-2002 and 2005-2006.

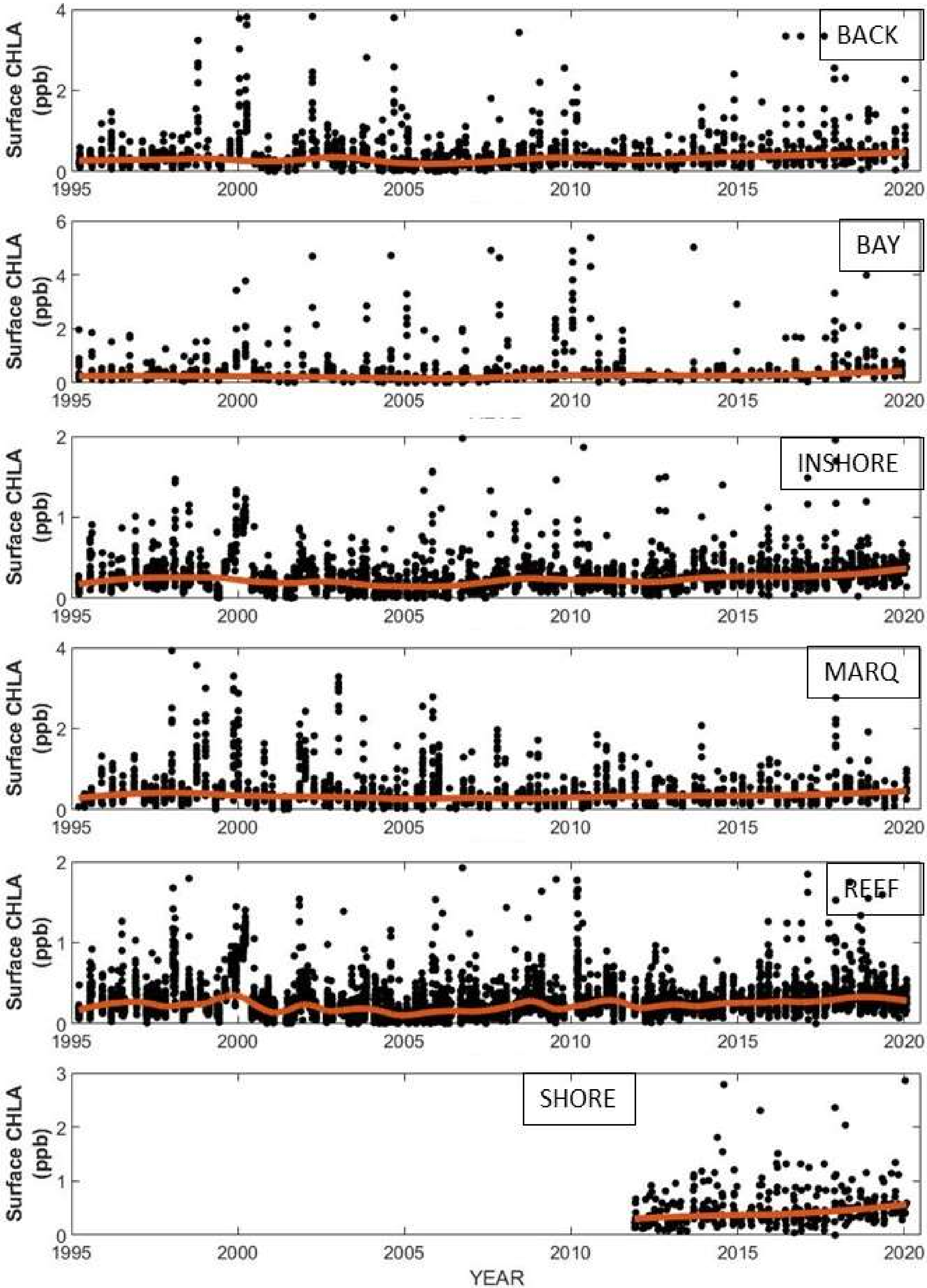

Figure 56. *Time series of surface Chlorophyll a by zone. The line is LOESS fit.*

4. Strategic Targets

The EPA developed Strategic Targets for the Water Quality Monitoring Project which state that beginning in 2008, to annually maintain the overall water quality of the near shore and coastal waters of the FKNMS according to 2005 baseline. For reef sites, chlorophyll *a* should be less than or equal to 0.2 micrograms/l and the vertical attenuation coefficient for downward irradiance (K_d, i.e., light attenuation) should be less than or equal to 0.13 per meter. For all monitoring sites in FKNMS, dissolved inorganic nitrogen should be less than or equal to 0.75 µM (0.010 mg l^{-1}) and total phosphorus should be less than or equal to 0.2 µM (0.0077 mg l^{-1}). Table 3 shows the number of sites and percentage of total sites exceeding these Strategic Targets for the period of record to 2019. In addition, Figure 57 shows the percent of sites meeting the targets in relation to baseline for DIN, TP, CHLA, and K_d.

Table 3: EPA WQPP Water Quality Targets derived from 1995-2005 Baseline

For reef stations, chlorophyll less than or equal to 0.35 micrograms liter^{-1} (ug l^{-1}) and vertical attenuation coefficient for downward irradiance (K_d, i.e., light attenuation) less than or equal to 0.20 per meter; for all stations in the FKNMS, dissolved inorganic nitrogen less than or equal to 0.75 µM and total phosphorus less than or equal to 0.25 µM; water quality within these limits is considered essential to promote coral growth and overall health. The number of samples and percentage exceeding these targets is tracked and reported annually. Values in green are those years with % compliance greater than 1995-2005 baseline. Values in yellow are those years with % compliance less than 1995-2005 baseline.

EPA WQPP Water Quality Targets				
	REEF Stations		All Stations (excluding SHORE sites)	
Year	CHLA ≤ 0.35 µg l^{-1}	K_d ≤ 0.20 m^{-1}	DIN ≤ 0.75 µM (0.010 mg l^{-1})	TP ≤ 0.25 µM (0.008 mg l^{-1})
1995-05	1778 of 2367 (75.1%)	1042 of 1597 (65.2%)	7826 of 10254 (76.3%)	7810 of 10267 (76.1%)
2006	196 of 225 (87.1%)	199 of 225 (88.4%)	432 of 990 (43.6%)	316 of 995 (31.8%)
2007	198 of 226 (87.6%)	202 of 222 (91.0%)	549 of 993 (55.3%)	635 of 972 (65.3%)
2008	177 of 228 (77.6%)	181 of 218 (83.0%)	836 of 1,000 (83.6%)	697 of 1,004 (69.4%)
2009	208 of 228 (91.2%)	189 of 219 (86.3%)	858 of 1,003 (85.5%)	869 of 1,004 (86.6%)
2010	170 of 227 (74.9%)	176 of 206 (85.4%)	843 of 1,000 (84.3%)	738 of 1,003 (73.6%)
2011	146 of 215 (67.9%)	156 of 213 (73.2%)	813 of 1,012 (80.3 %)	911 of 1,013 (89.9 %)
2012	142 of 168 (84.5%)	135 of 168 (80.4%)	489 of 683 (71.6 %)	634 of 684 (92.7 %)
2013	148 of 172 (86.0%)	150 of 172 (87.2%)	496 of 688 (72.1 %)	603 of 688 (87.6 %)
2014	141 of 172 (82.0%)	133 of 172 (77.3%)	426 of 690 (61.7%)	540 of 690 (78.3%)
2015	122 of 172 (70.9%)	135 of 172 (78.5%)	487 of 688 (70.8%)	613 of 688 (89.1%)
2016	131 of 172 (76.2%)	129 of 170 (75.9%)	427 of 687 (62.2%)	549 of 688 (79.8%)
2017	106 of 172 (61.6%)	120 of 170 (70.6%)	440 of 575 (76.5 %)	581 of 683 (85.1 %)
2018	92 of 170 (54.1%)	108 of 152 (71.7%)	558 of 689 (81.0 %)	573 of 689 (82.3 %)
2019	112 of 171 (65.5%)	133 of 168 (79.2%)	669 of 684 (97.8 %)	587 of 686 (85.6 %)
2020	129 of 172 (75.0%)	141 of 169 (83.4%)	617 of 688 (89.7%)	466 of 688 (67.7%)

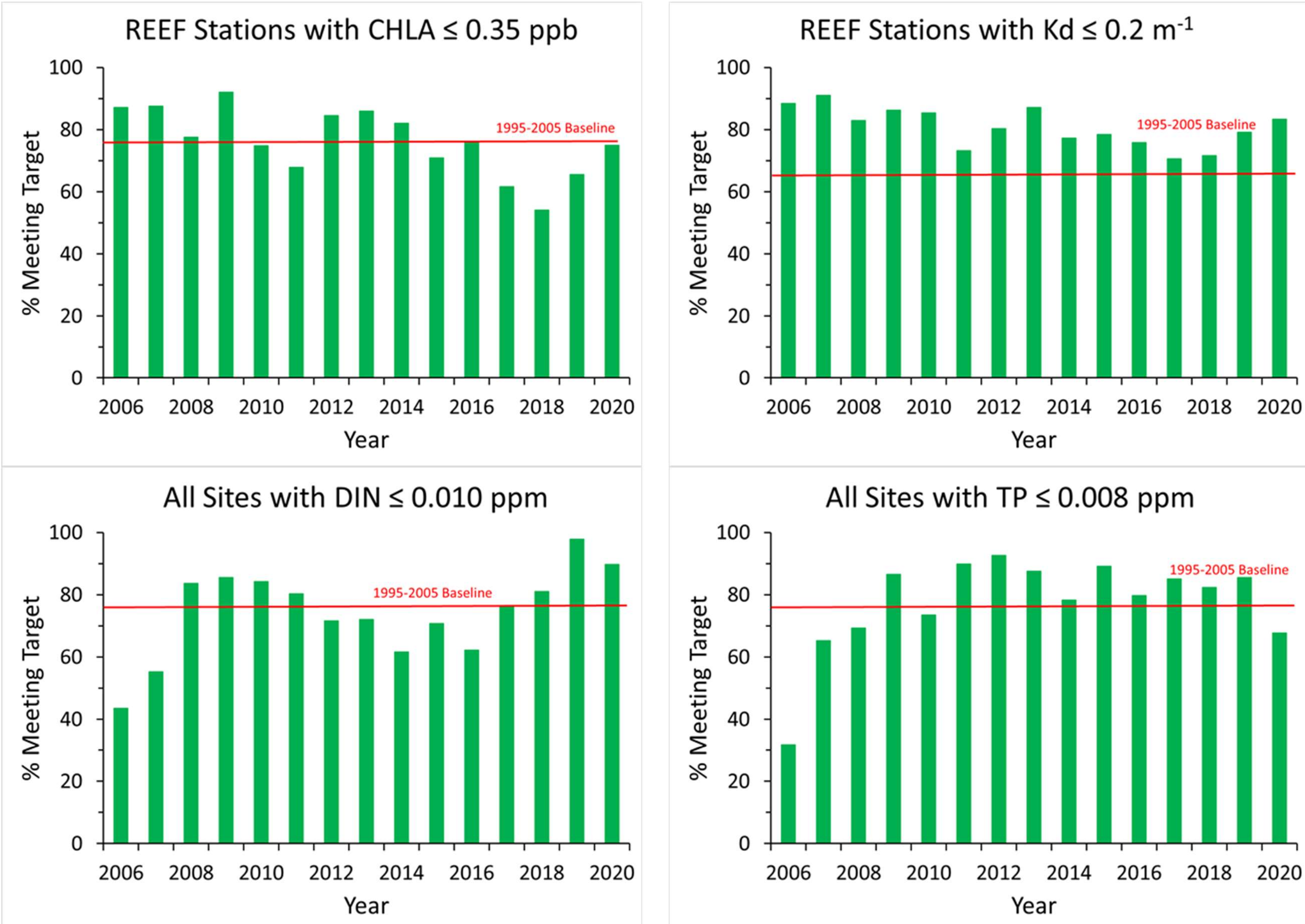

Figure 57. *EPA targets expressed as percent of sites meeting baseline criteria by year.*

5. Acknowledgements

We thank all the many field and laboratory technicians involved with this project over the past 25 years. Special thanks go out to Pete Lorenzo, Jeff Absten, Tom Frankovich, Mark Kershaw, Rafael Gonzales-Collazo, Pierre Sterling, Scott Kaczynski, Sandro Stumpf, Pura Rodriguez de la Vega, Ruth Justiniano, Dania Sancho, Frank Tam, Omar Beceiro, Bill Gilhooly, Breege Boyer, Ingrid Ley, and Milagros Timiraos. Kudos to Steve Blackburn, and the FKNMS Steering Committee for continued support and funding. Finally, we thank Fred McManus, Billy Causey, and Ron Jones for kickstarting the whole enchilada. This project was possible due to continued funding by the FIU/US-EPA Agreement #X7-00049716-0. This is contribution number XXX-T from the Southeast Environmental Research Center in the Institute of the Environment at Florida International University

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7. Appendix A. – Total Change in Measured Variables for 1995-2020

Time series trends were analyzed for all variables by station using Mann-Kendall *t* test. Sen Slope estimates (unit/yr) were multiplied by number of years sampled to give total changes over the period of record. Significant trends ($p < 0.05$) are highlighted in **green** for beneficial trends, **red** for degrading trends, and **blue** for trends in nondeterminate variables, such as N:P ratios. Variable names appended with **-S** denote surface sampling while those with **-B** were collected on the bottom.