2024 ANNUAL REPORT

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

Henry O. Briceño & Joseph N. Boyer

July 2025

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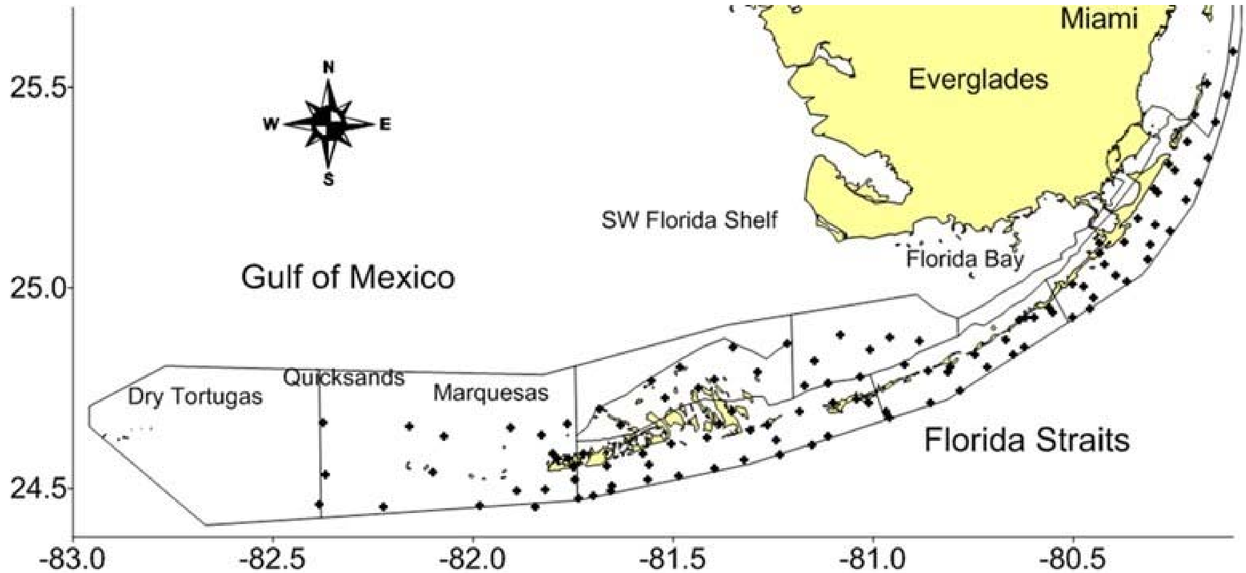

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EXECUTIVE SUMMARY

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 required the FKNMS to have a Water Quality Protection Plan (WQPP) thereafter developed by EPA and the State of Florida.

This report serves as a **30 year summary** of efforts to date in the execution of the Water Quality Monitoring Project for the FKNMS as part of the WQPP. The period of record for this report is Mar. 1995 – Dec. 2024 and includes data from 118 quarterly sampling events within the FKNMS over those 30 years.

For this year, field measurements and grab samples were collected from 112 fixed stations within the FKNMS boundary. Field measurements from each station (surface and bottom at most sites) included salinity, temperature (°C), dissolved oxygen (DO, mg l^{-1}), turbidity (NTU), and diffuse light attenuation coefficient (K_d, m^{-1}). Water quality variables included the dissolved nutrients nitrate (NO_3^-), nitrite (NO_2^-), ammonium (NH_4^+), and soluble reactive phosphorus (SRP). Total unfiltered concentrations included those of nitrogen (TN), organic carbon (TOC), phosphorus (TP), silicate (SiO_2) and chlorophyll *a* (CHLA, µg l^{-1}). Dissolved inorganic nitrogen (DIN) was calculated as NO_3^-+NO_2^-+NH_4^+ and total organic nitrogen (TON) as TN-DIN. All variables are reported in elemental mg l^{-1} (ppm) unless otherwise noted.

Strategic Targets

The EPA developed Strategic Targets for the Water Quality Monitoring Project (SP-47) which states that beginning in 2008, they shall annually maintain the overall water quality of the near shore and coastal waters of the FKNMS according to the 2005 baseline. For reef sites, CHLA should be less than or equal to 0.35 µg l^{-1} (ppb) and the K_d should be less than or equal to 0.20 m^{-1}. For all monitoring sites in the FKNMS, DIN should be less than or equal to 0.75 µM (10.5 ppb) and TP should be less than or equal to 0.25 µM (7.7 ppb).

The 2011 reduction of sampling sites in Tortugas/western FKNMS (Tortugas, 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 complications, we have not included the Tortugas or Shore stations in calculation of compliances after 2010.

The number of sites and percentage of total sites meeting and exceeding these Strategic Targets for the period of record to 2024 are shown in *Table i*. In addition, *Figure i* shows the graphs of percentage of sites meeting the targets in relation to baselines for CHLA, K_d. DIN, and TP.

For the six years prior to 2023, CHLA was elevated relative to the 2005 Target Baseline. 2023 and 2024 showed a return to lower CHLA across the region. TP was elevated for three of the last five years. These are indicators of creeping eutrophication and bear continued vigilance.

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

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 ppb	$K_d \leq 0.20\ m^{-1}$	DIN ≤ 10.5 ppb	TP ≤ 7.7 ppb
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%)
2021	123 of 172 (71.5%)	141 of 172 (82.0%)	611 of 688 (88.8%)	527 of 688 (76.6%)
2022	98 of 172 (57.0%)	129 of 171 (75.4%)	533 of 686 (77.7%)	458 of 688 (66.6%)
2023	129 of 170 (75.9%)	125 of 166 (75.3%)	624 of 684 (91.2%)	294 of 684 (43.0%)
2024	138 of 171 (80.7%)	127 of 169 (75.1%)	570 of 687 (83.0%)	584 of 688 (84.9%)

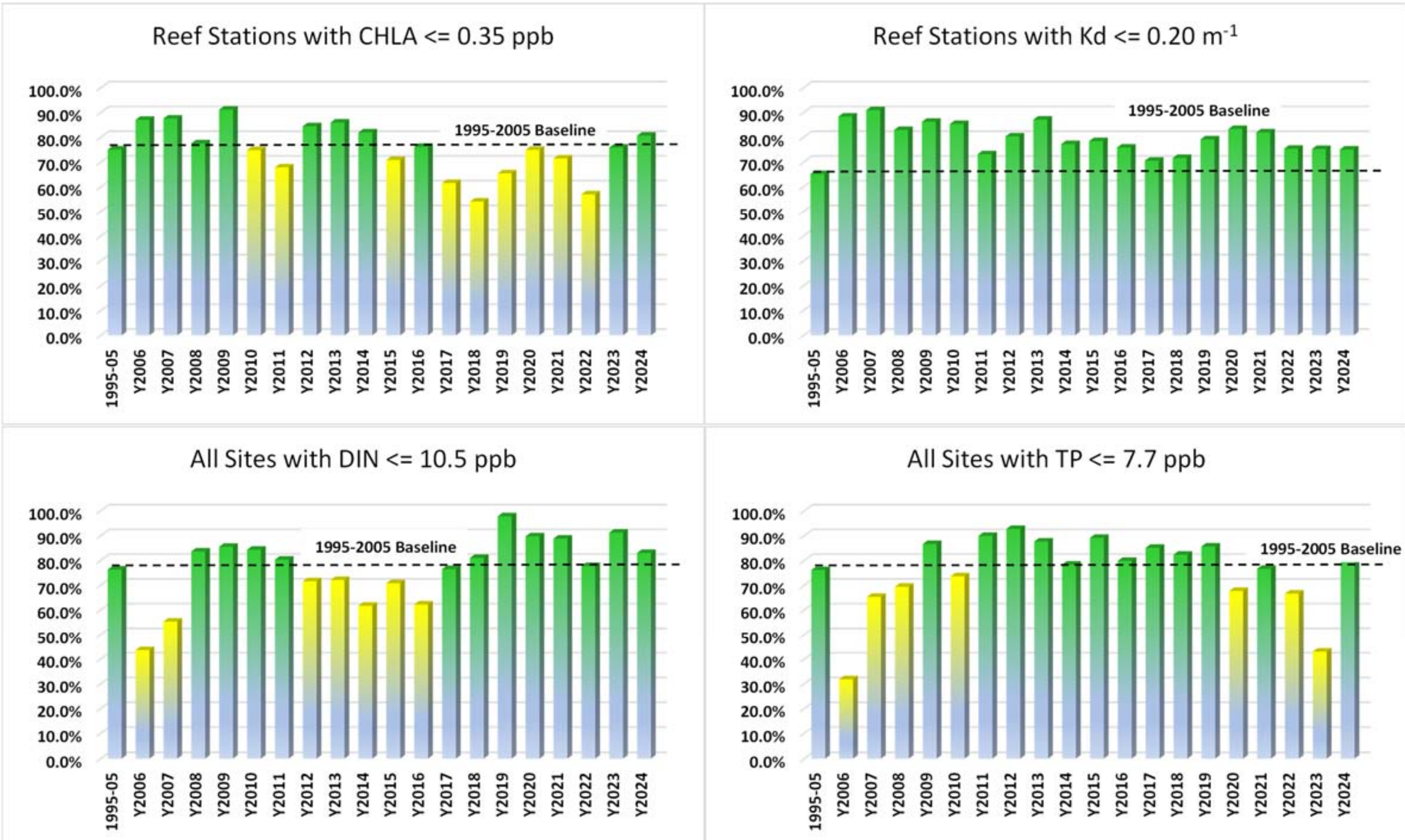

Figure i. *EPA targets expressed as percent of sites meeting baseline criteria by year.*

Trend Analysis – 30 years

The nonparametric Mann-Kendall Test was used to detect monotonic trends without the requirement that measurements be normally distributed. To quantify temporal trends, we used Sen slope regressions for each water quality variable over the period of record. Some of the Sen slopes were very small so to get a better idea of change over the period of record, the Sen slopes were multiplied by the number of years sampled and plotted as contour maps of potential total change in measured variable for the period of record (change maps). Only statistically significant M-K trends ($p<0.05$) were used to show directional tendencies in variables across the hydroscape (non-significant trends were coded as zero). We also included Shore stations located within the Halo Zone sampled since 2011.

The photosynthetic pigment, chlorophyll a, is a proxy measure of phytoplankton biomass. CHLA concentrations have increased in 35 of 112 sites in the FKNMS (*Fig. ii*). Significant increases ranged 0.08-0.19 ppb (median = 0.11 ppb) or ~39% increase over 1995 levels. Strongest increases seem to be associated with shallow stations near land but there were increases at offshore Reef sites and in major passes. Although ambient concentrations remain low relative to other coastal areas in the US, these increases are evidence of slow eutrophication of the FKNMS.

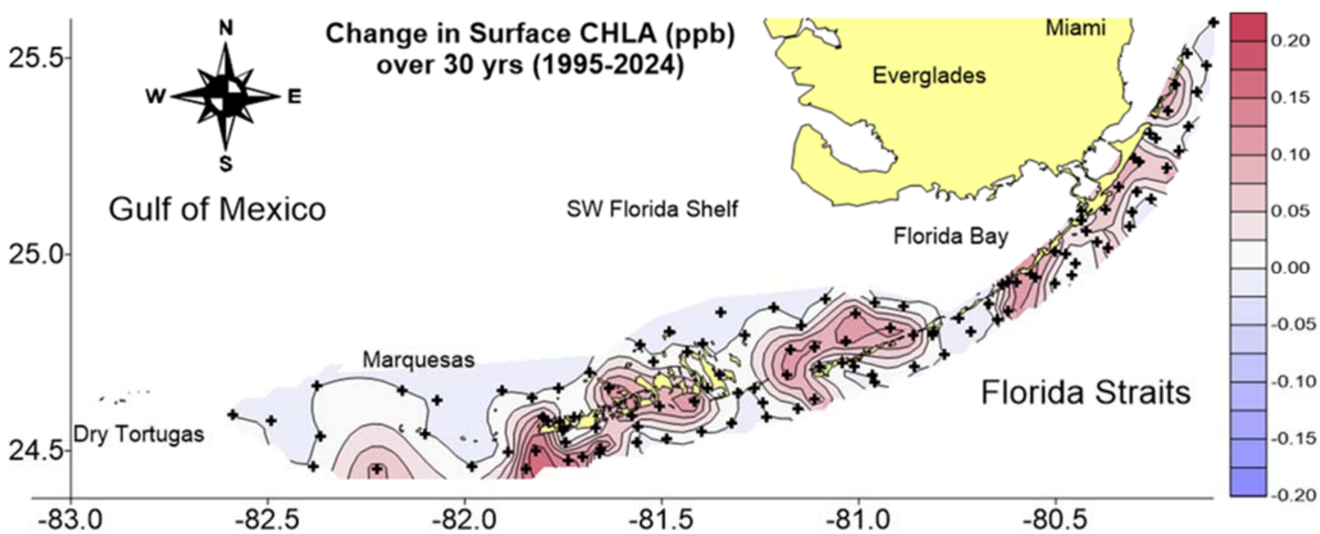

Figure ii. *Net change in CHLA in surface waters over the 30-year period.*

Total phosphorus (TP) is an important driver of primary production in South Florida inland and nearshore waters. Significant increases in TP (median = 0.002 ppm) occurred at 40 sites in the Keys primarily close to land, indicating potential terrestrial sources (*Fig. iii*). This is a 43.5% increase over 1995 levels. In contrast, TP declined in some of the deeper surrounding waters. Note the spatial similarity in changes in TP and CHLA (*Fig. ii*). These trends bear watching, given that we expect future TP concentrations to decline inshore in response to central sewer installation.

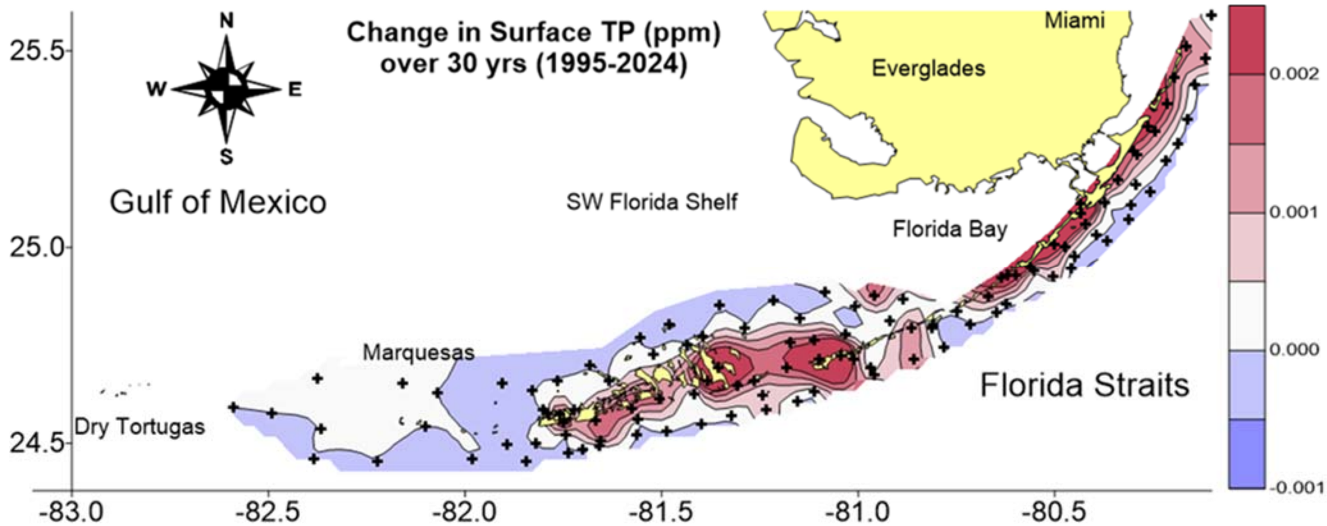

Figure iii. *Net change in surface TP over the 30-year period.*

Soluble reactive phosphorus (SRP) is the inorganic dissolved fraction of TP. SRP concentrations are generally an order of magnitude lower than TP in South Florida waters and may be below the kinetic threshold for uptake by phytoplankton. Contrary to TP, SRP concentrations have declined in the FKNMS (*Fig. iv*), which was not expected.

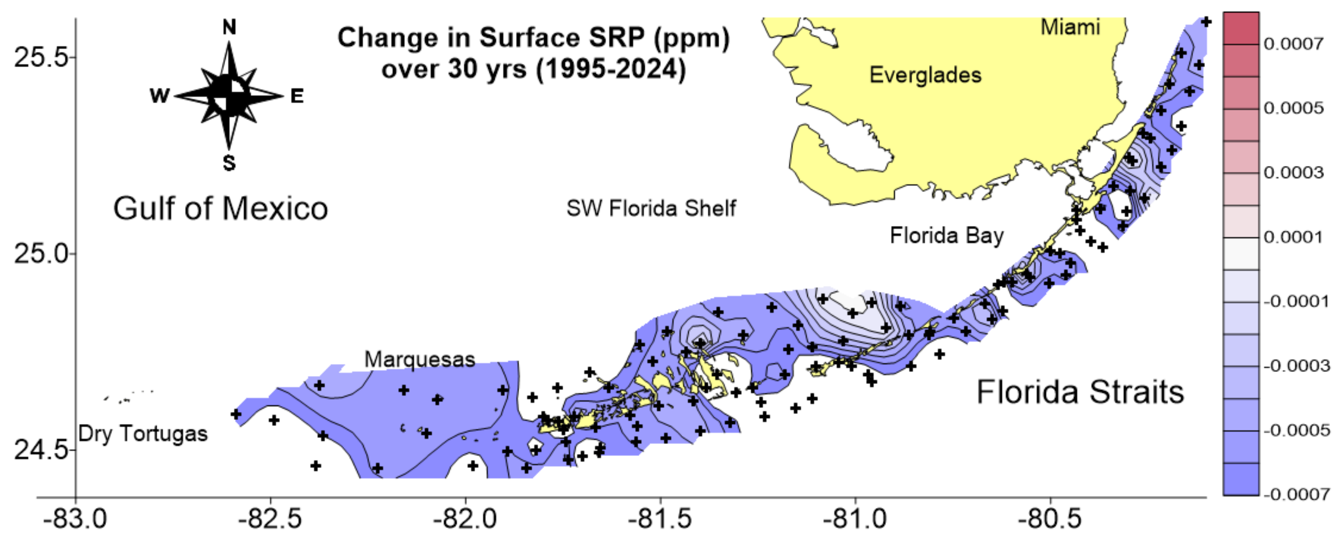

Figure iv. *Net change in surface SRP over the 30-year period.*

Keys-wide declining trends in DIN (NH_4^+, NO_2^-, NO_3^-) were small but widespread (*Fig. v*). Decreasing trends in NH4+ were observed across the FKNMS. Interestingly, these declines occurred at many of the same sites where TP increased. We are unsure if such trends are stoichiometrically related - whether increases in TP act to drive down NH_4^+ through biological uptake or whether declines in DIN allow more TP to be released to the water column.

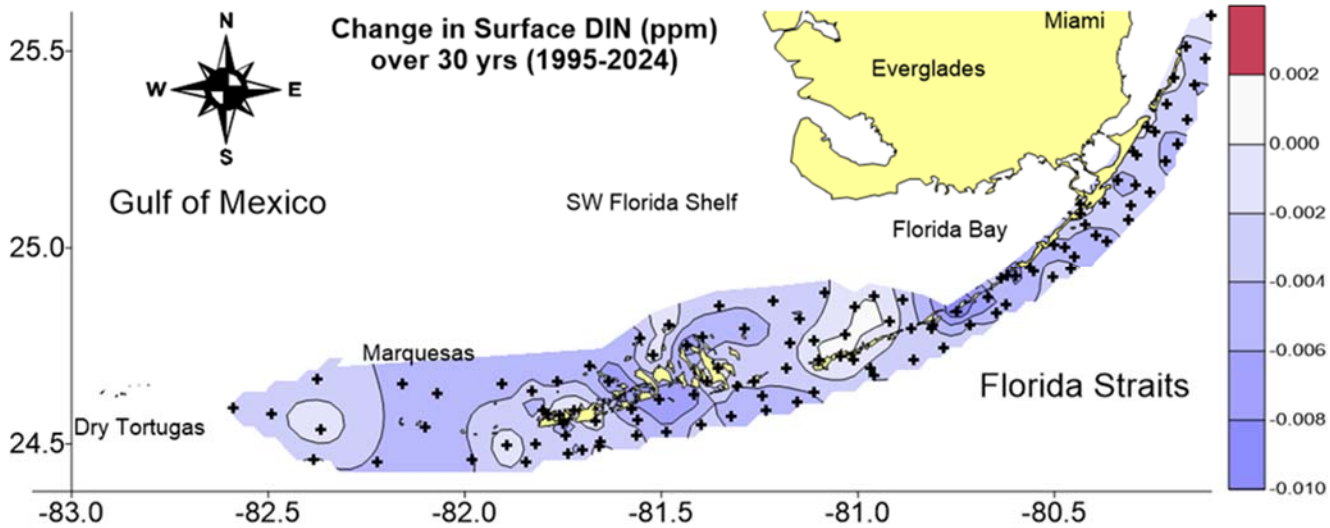

Figure v. *Net change in surface DIN over the 30-year period.*

The largest sustained monotonic trend has been the decline in surface TOC throughout the FKNMS (*Fig. vi*). This trend may be considered favorable given that TOC corresponds with CDOM (chromophoric dissolved organic matter), an important driver of light penetration. Declines in TOC are typically an indication of decreased terrestrial inputs to the region.

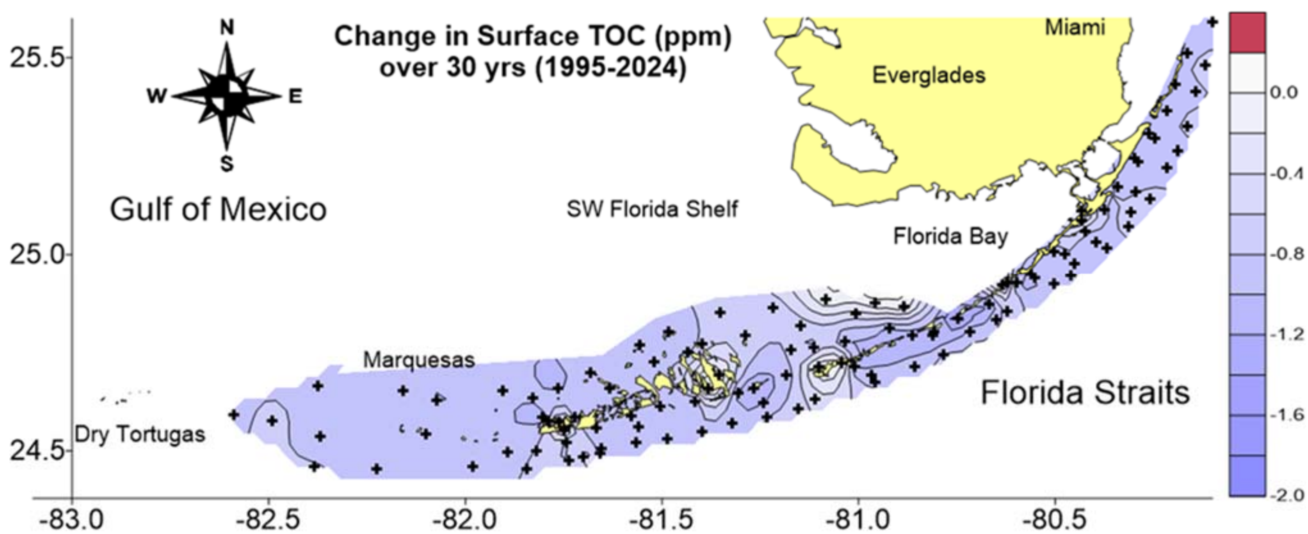

Figure vi. *Net change in TOC in surface waters over the 30-year period.*

Total nitrogen declined overall except for the Sluiceway region contiguous to Florida Bay (*Fig. vii*). Most of this is due to declines in the organic N fraction as it makes up ~96% of the TN pool.

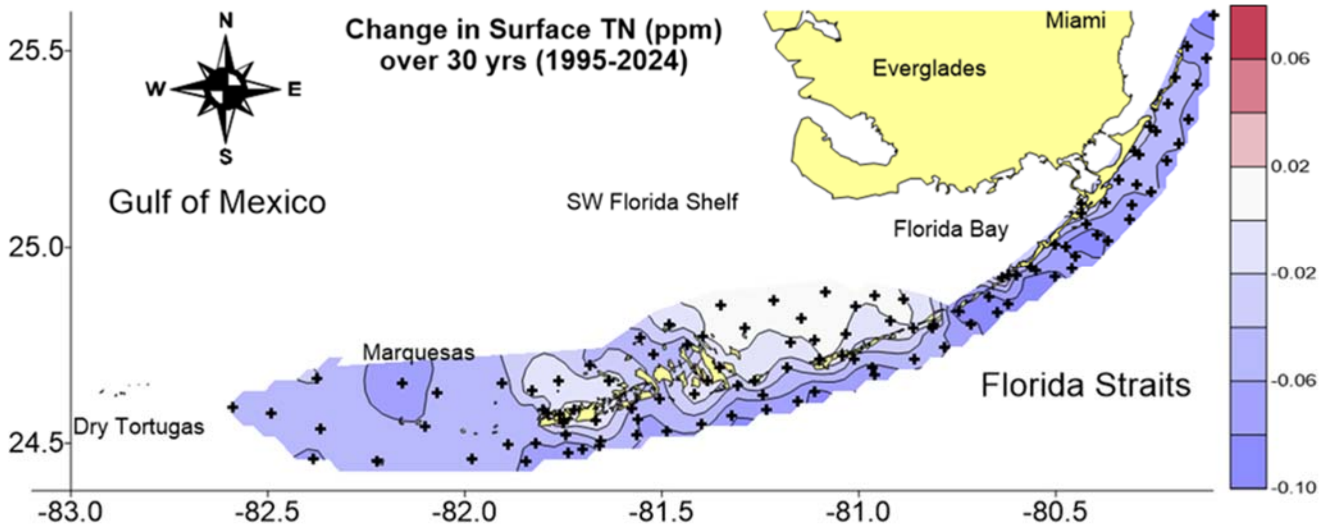

Figure vii. *Net change in TN in surface waters over the 30-year period.*

The TN:TP ratio (molar) is useful in assessing phytoplankton nutrient limitation (Redfield ratio). TN:TP declined in most areas (*Fig. viii*) implying that primary production is becoming less P-limited throughout the FKNMS. This trend is driven by concurrent minor declines in TN and significant increases in TP.

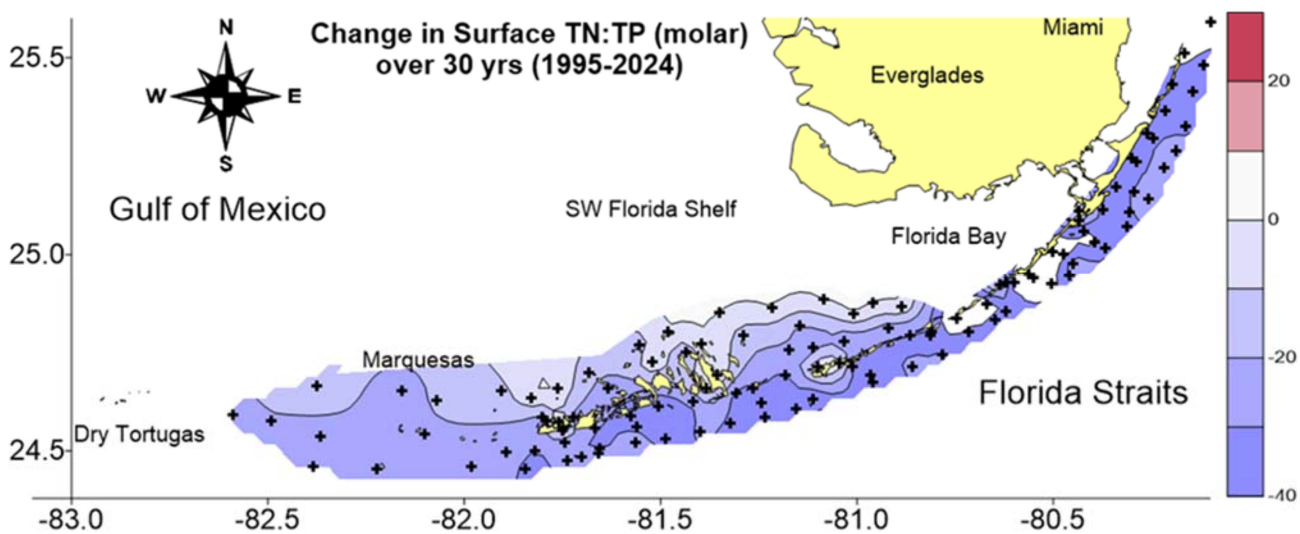

Figure viii. *Net change in TN:TP ratio in surface waters over the 30-year period.*

Diatoms require silicate to form their external frustules (shells). Si:DIN ratios >1 promote diatom growth in the phytoplankton community. Si:DIN <1 indicates growth limitation conditions for diatoms. The northern Sluiceway shows an increase towards fostering diatom community development (*Fig. ix*).

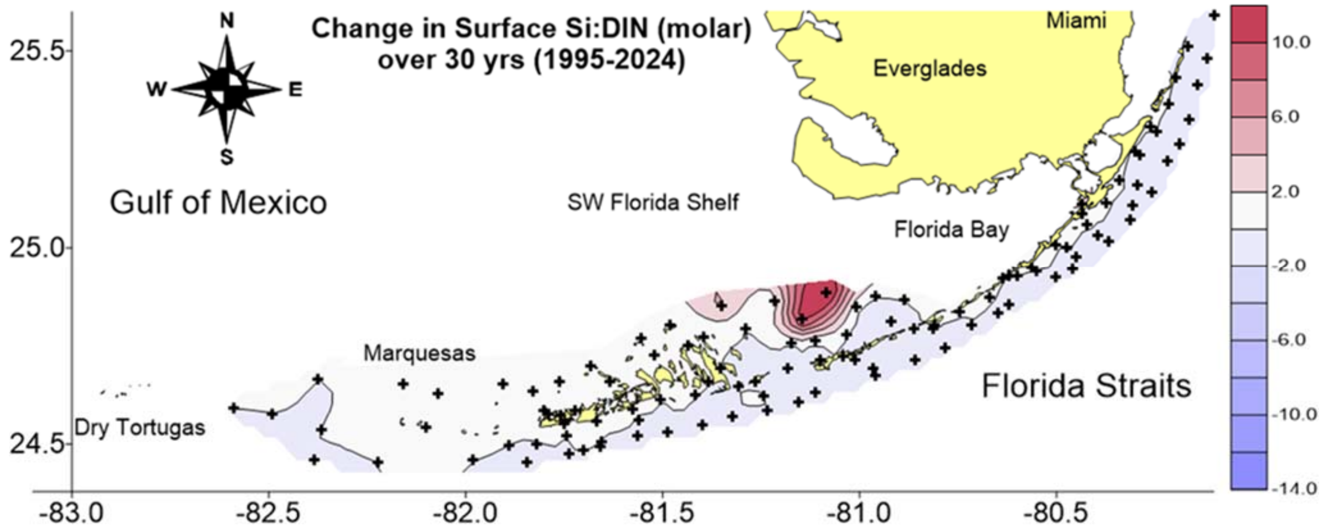

Figure ix. *Net change in Si:DIN ratio in surface waters over the 30-year period.*

No significant trends were observed in either surface or bottom salinity across the FKNMS (*Fig. x*).

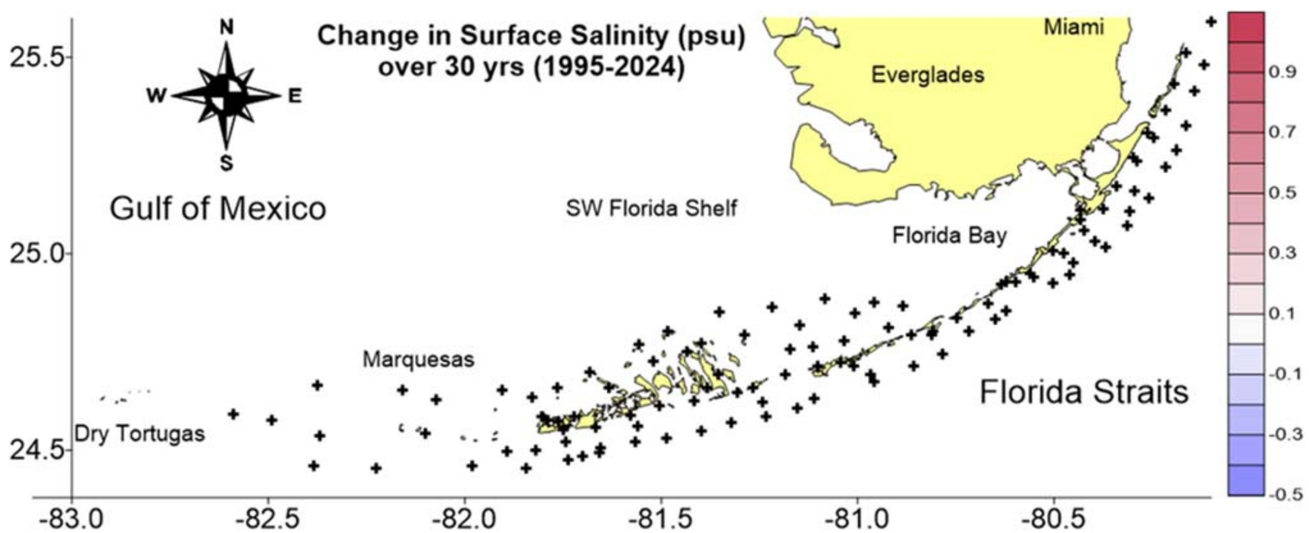

Figure x. *Net change in surface salinity over the 30-year period.*

Temperature displayed marginally significant long-term trends as well, but the change map does show some differences across regions (*Fig. xi*). The Bay zone and offshore areas tended to decline; only one Shore site off Marathon increased. Interestingly, with data from 2024, we observed increased surface temperature at three offshore reef sites. Quarterly collection of temperature over 30 years cannot be expected to resolve the small changes in subtropical water temperature expected under global climate change. Daily temperature measurements from three other research programs have shown that the waters of the Florida Keys have warmed ~0.8°C for the period 1878-2012 (Kuffner et al. 2015). However, there were generally increasing trends in water temperatures in the Backcountry, Bay, and Shore areas since 2011.

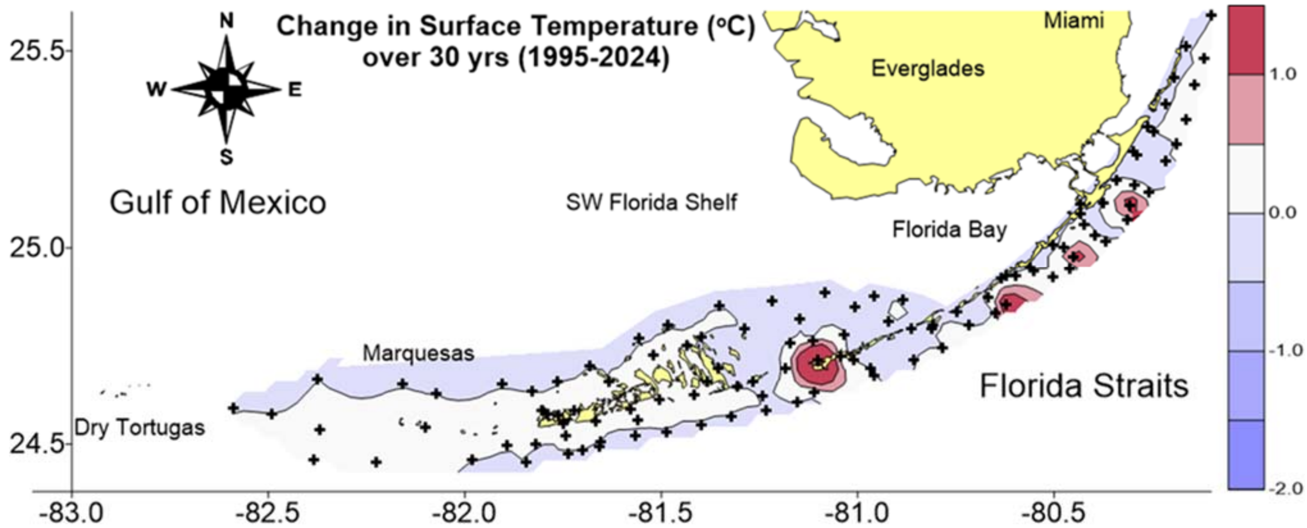

Figure xi. *Net change in surface temperature over the 30-year period.*

DO saturation increased at most sites in the FKNMS, which is generally considered a benefit to aquatic biota (*Fig. xii*). Measurements taken during daylight hours may be influenced by the amount of primary production in the water column and benthos and are offset by comparable drops at night. Greatest increases in DO_{sat} were observed offshore, indicating non-terrestrial influence. Some areas in the Sluiceway closest to Florida Bay and north Backcountry also showed small decreasing trends.

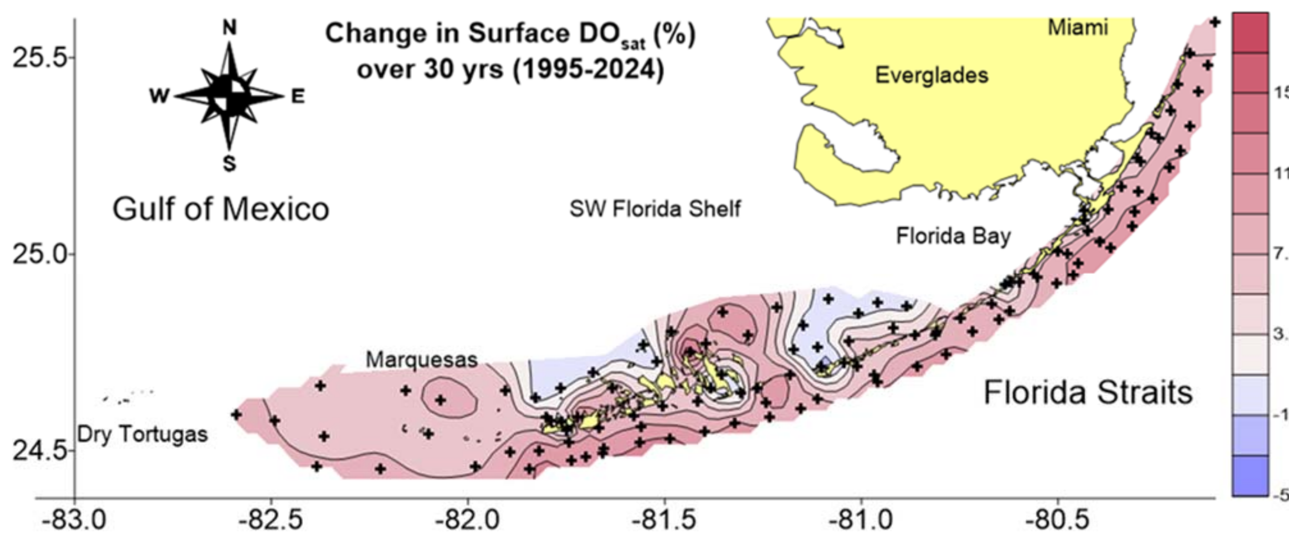

Figure xii. *Net change in surface DO saturation over the 30-year period.*

Water column turbidity declined throughout the FKNMS (a beneficial result, *Fig. xiii*). The largest declines occurred in northern Sluiceway/Backcountry and Marquesas. However, there were increases in surface turbidity at specific Shore sites in Upper Keys.

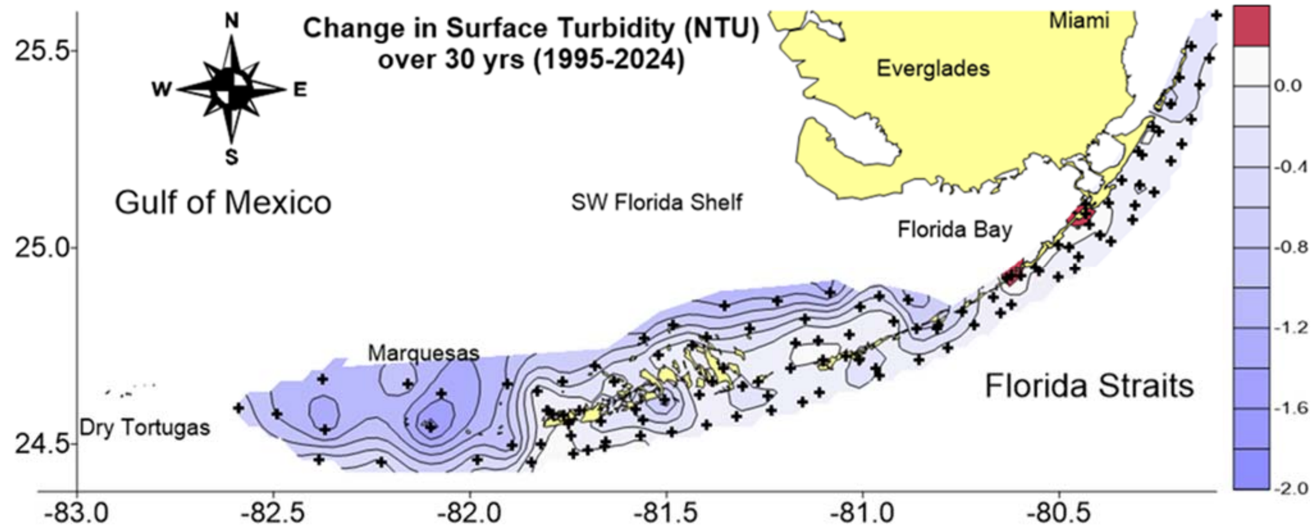

Figure xiii. *Net change in surface turbidity over the 30-year period.*

The diffuse light attenuation coefficient (K_d), a measure of light penetration, also declined (a beneficial result) in some offshore areas and Marquesas (*Fig. xiv*). There were isolated increases in the Backcountry, Sluiceway, and some Shore and Inshore sites.

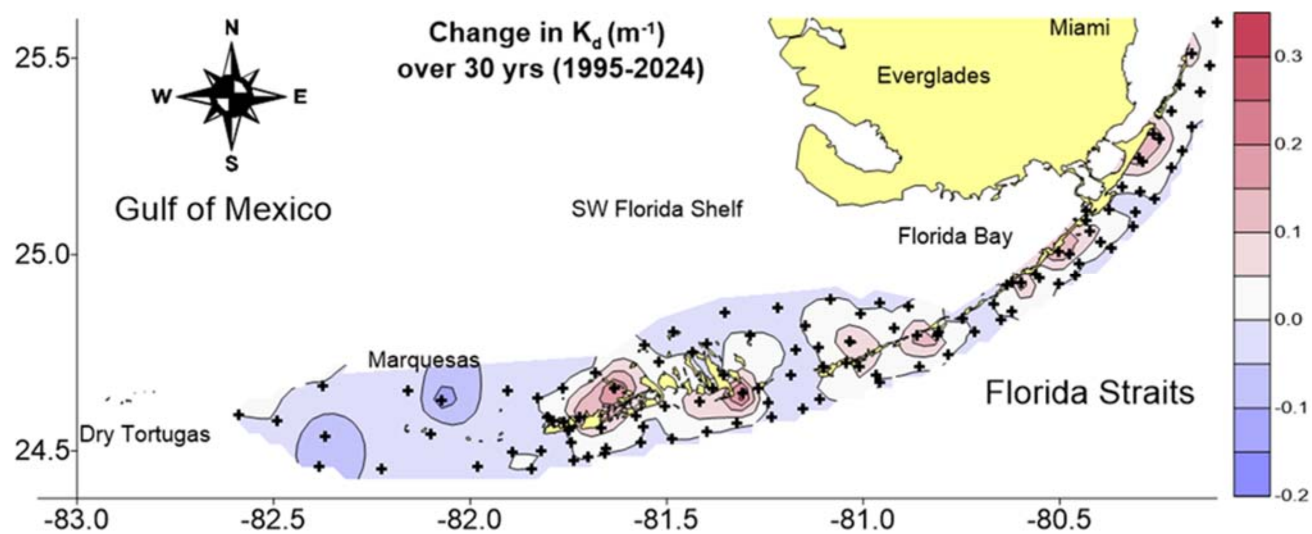

Figure xiv. *Net change in K_d over the 30-year period.*

Lower K_d tends to increase the proportion of surface irradiance reaching the bottom (I_o). More light on the bottom is beneficial to corals, seagrass, and algae. Increases in I_o were observed mostly in the Marquesas and isolated offshore Reef sites (*Fig. xv*). The Backcountry experienced decreases in I_o (with increases in K_d) resulting in less light penetrating to the bottom.

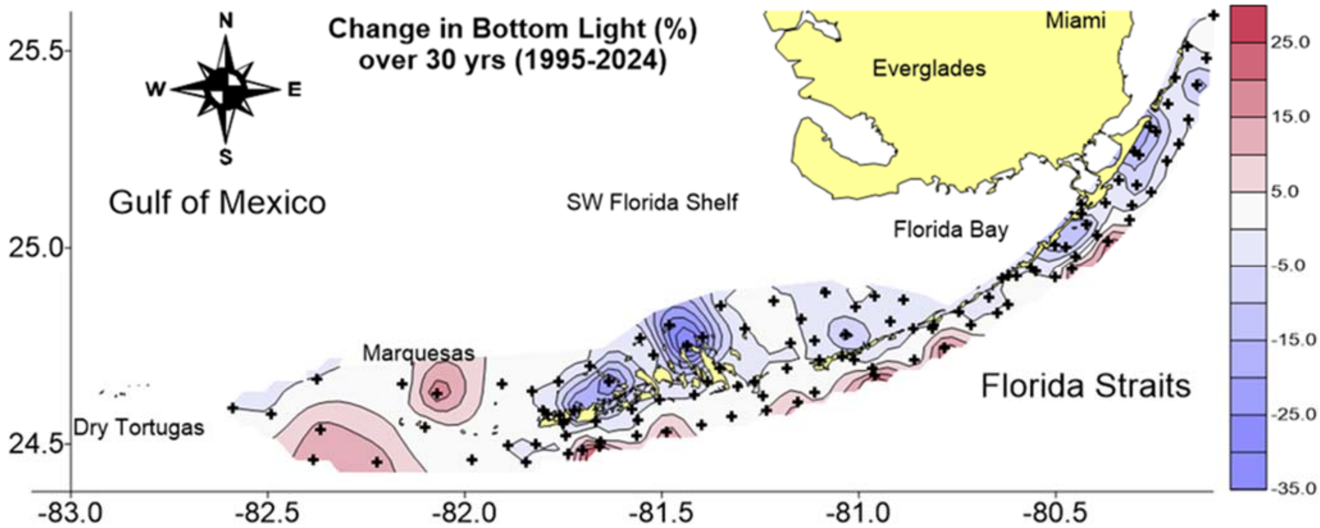

Figure xv. *Net change in incident bottom light over the 30-year period.*

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 FKNMS hydroscape. These results confirm the concept that monitoring is an important tool for addressing management questions and for developing new scientific hypotheses. We continue to maintain a website where data and reports from this project are accessible to the public, http://serc.fiu.edu/wqmnetwork/.

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 George H. 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.

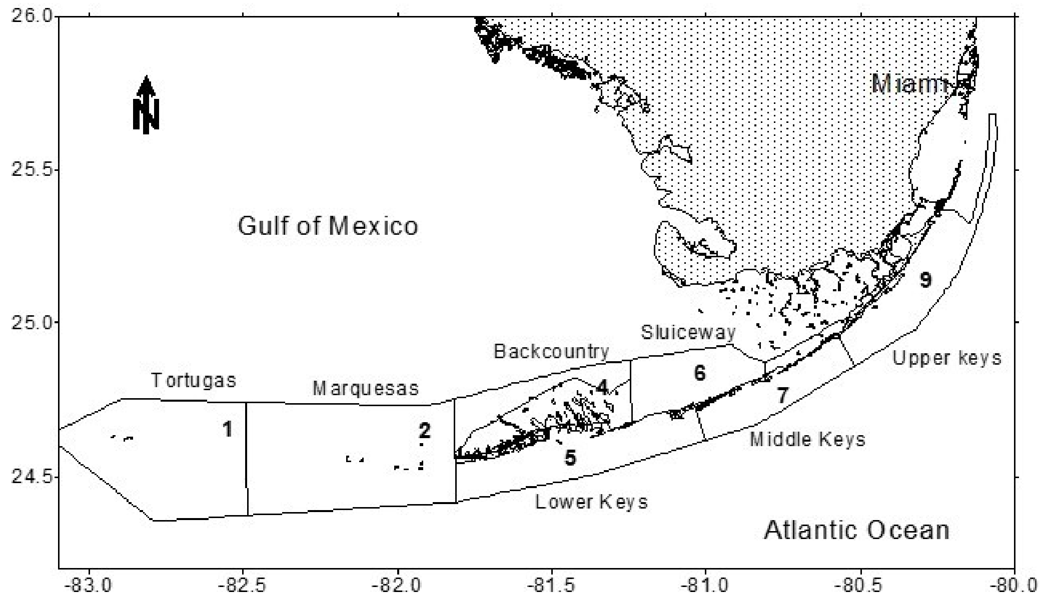

Figure 1*: Map of original FKNMS boundary including collapsed segment numbers and common names. Modified after Klein and Orlando (1994)*

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 Ocean 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. 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).

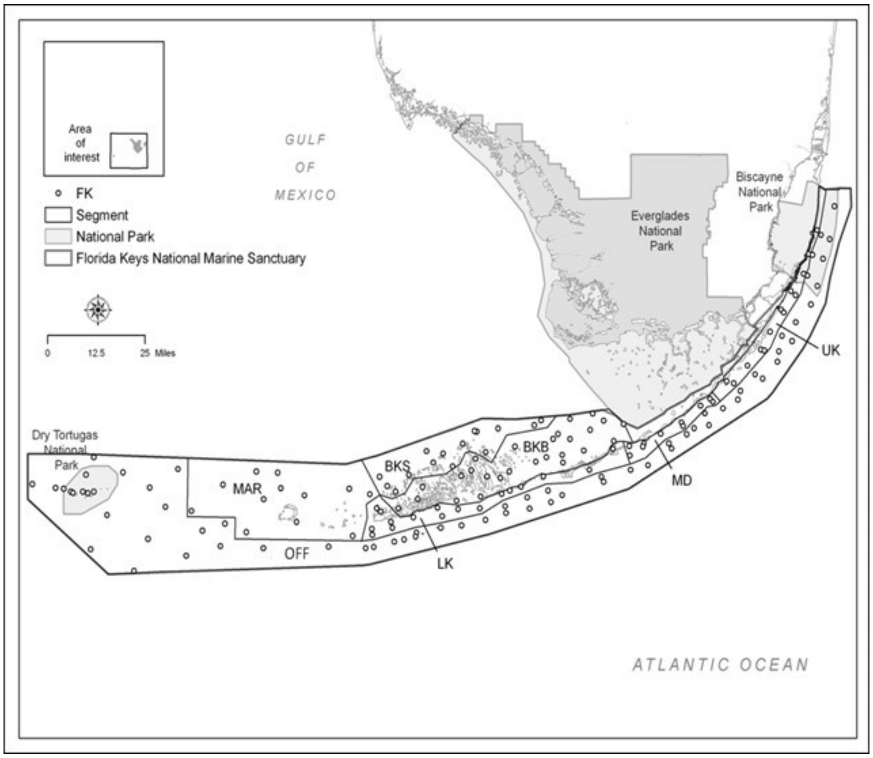

Figure 2: *The map of FKNMS showing segments derived from biogeochemical data: OFF=Offshore; MAR=Marquesas; BKS=Back Shelf; BKB= Back Bay; LK= Lower Keys; MK= Middle Keys; UK= Upper Keys*

Although the original quarterly sampling of 155 stations was reduced 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.

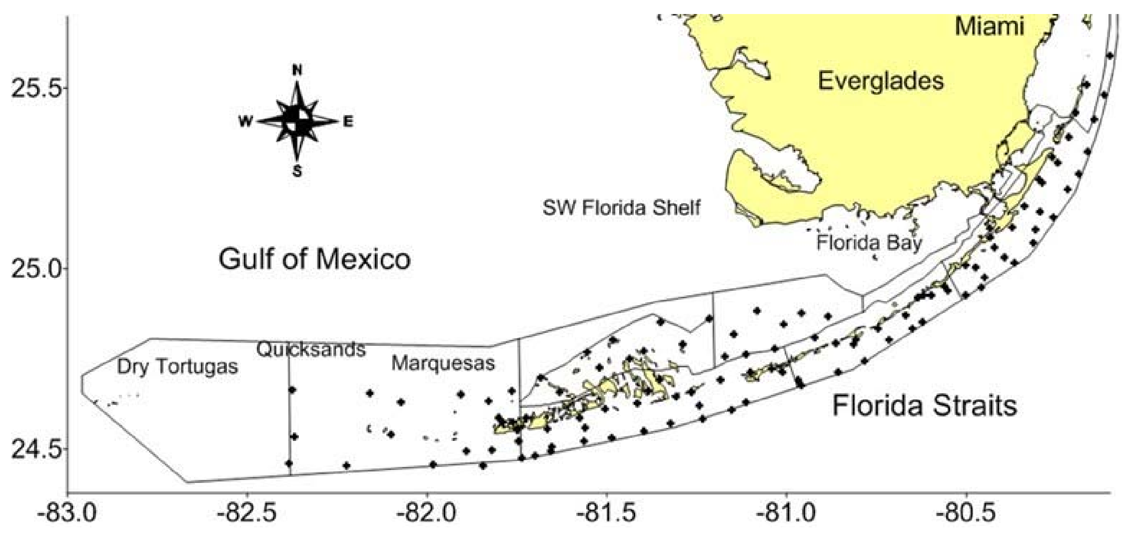

Figure 3*. The SERC Water Quality Monitoring Network showing the distribution of fixed sampling stations within the FKNMS for 2024 sampling.*

2. Methods

2.1. Field Sampling

The period of record of this study was March 1995 to December 2024, which included 118 quarterly sampling events. The 2011 reduction of sampling sites in Tortugas/western FKNMS (Tortugas, 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 Tortugas or Shore stations in calculation of compliances after 2010.

For 2024, field measurements and grab samples were collected from 112 fixed stations within the FKNMS boundary (Fig. 3). Depth profiles of temperature (°C), salinity, 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 an 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 Analyses

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 has 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). SiO_2 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 elemental 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 elucidate 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 of measuring change over time is useful for variables that change at a relatively continuous rate. The simplicity of this method makes it appealing to those who are tracking water quality, however, time series are often dominated by non-linear drivers and 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 30-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. To show the trend impact over time, trend contour maps report the total change over the 30-year period of record. Only statistically significant trends (p<0.05) were used to show directional tendencies in variables across the hydroscape.

While the Mann-Kendall Test informs us whether the overall trend is increasing or decreasing, it does not provide information about short-term changes 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 the shorter period of record.

3. Results

3.1. 2024: The Year in Brief

Weather has a significant impact on the short, mid and long-term water quality in the Florida Keys. High temperatures may cause low DO concentrations or seagrass die offs, especially in adjacent Florida Bay, whose waters move to the Florida Keys Sanctuary. Likewise, high rain rates increase freshwater contributions from the Everglades, as well as nutrient-laden stormwaters from the islands. Strong winds, on the other hand, cause defoliation and high organic matter contribution to the waters, cascading into low DO concentrations and nutrient increases in the water column. Storm surge and high winds from large hurricanes affect coastal communities and generate huge amounts of debris and pollution that end up in the Sanctuary.

The 2024 Atlantic hurricane season was an extremely active, destructive and costly season, featuring 18 named storms, 11 hurricanes and multiple major hurricanes, including five Cat 5 hurricanes. The 2024 Atlantic hurricane season in Florida was marked by three significant storms, including hurricanes Debby and Helene, which made landfall in the Big Bend of the peninsula, and Milton, which made landfall in Siesta Key, near Sarasota. The Florida Keys were spared from direct hits, and the storms' outer bands did not cause extreme rain. Nevertheless, both Helene and Milton caused significant damage to the Tampa Bay-Sarasota region, whose debris and tainted waters eventually moved south to the Florida Keys via Southwest Florida Shelf currents.

Annual precipitation as rain in the FKNMS during year 2024 at Key West (50.43") and at Key Largo (55.6") were significantly higher than annual average for Key West (40.22"; 1995-2023) and Key Largo (48.97"; 2000-2023).

Annual average air temperature in the Sanctuary at Key West and Key Largo reached 24.5 °C (76.3 °F) and 26.6 °C (79.8 °F) respectively, while the long-term average (1995-2023) for Key West was 25.8 C (78.5 °F) and during 2000-2023 in Key Largo it was 25.3 °C (77.5 °F).

Spinning fish events occurred in the Florida Keys throughout 2024, marking a continuation and escalation of an abnormal fish behavior phenomenon first noted in late 2023. Most of the reported events were in localities within the Florida Keys, **especially in the Lower Keys**, between **Boogie Channel and Bow Channel**. These events were characterized by fish loss of equilibrium, swimming in circles, and sometimes dying, with the most severe impact recorded among the critically endangered smalltooth sawfish. The peak of reports was in winter and spring of 2024, with a decline noted as temperatures rose into summer.

In total, there were over 233 reports of symptomatic fish behavior in 2024, with more than 80 species affected (https://myfwc.com/research/saltwater/health/spinningevent/updates/). The number of sawfish mortalities was unprecedented: 54 deaths were documented by October 2024. The event impacted a wide range of species, including: smalltooth sawfish (notably high mortality), tarpon, permit, bonefish, snook, mullet, pinfish, bigeye scad, ballyhoo, jack crevalle, yellow jack, blue runner, southern stingray, mutton snapper, mangrove snapper, cubera snapper, lane snapper, leatherjacket, yellowfin mojarra, scaled sardine, toadfish, goliath grouper, blue striped grunt, redfish, lemon shark, Atlantic sharpnose shark, spadefish, and many others.

The final cause of spinning has not been precisely identified, although neurotoxins from algae may be the culprit. In January 2024 a Working Group, including FWC, Monroe Co, NOAA, University of Alabama, Florida Gulf Coast University, Bonefish & Tarpon Trust, Lower Keys Guides Association, and Dolphin Island Sea Lab began coordinated work. At the time of finishing this annual report in June 2025, a significant number of tests on water, sediment and fish have been performed since December 2023. The Working Group reported the ongoing effort to the FKNMS Steering Committee:

- This was not a mass fish mortality event, although sawfish mortality was unprecedented.
- This was not a *Karenia brevis* or red algae tide.
- DEP testing of 250 chemicals indicated that concentrations were within limits.

- DO, salinity, pH and temperature were not suspected as causes of spinning.
- No pathologic viruses were detected.
- *Gambierdiscuss spp*., a benthic ciguatoxin producing dinoflagellate, was found in 58 out of 241 water samples, usually in high abundance. Other complex mixtures of benthic algal toxins were also detected. Most occurrences of this dinoflagellate have been observed in the Backcountry.

3.2. Overall Water Quality of the FKNMS in 2024

Summary statistics for all water quality variables from calendar year 2024 sampling events are shown in Table 1 as number of samples (*n*), minimum, maximum, and median. Overall, the region remains warm and euhaline with a median temperature of 28.6 °C and salinity of 36.3; DO_{sat} was relatively high at 96.6%. On this coarse scale, the FKNMS exhibited very good water quality with median NO_3^-, NH_4^+, TP, and SiO_2 concentrations of 0.002, 0.002, 0.006, and 0.025 mg l^{-1}, respectively. DIN comprised a small fraction (4.4%) of the TN pool (0.137 mg l^{-1}) with TON being the bulk (median 0.131 mg l^{-1}). SRP concentrations were very low (median 0.0001 mg l^{-1}) and comprised only 1.7% of the TP pool (0.008 mg l^{-1}). CHLA concentrations were also low overall (median 0.23 µg l^{-1}) but ranged from below 0.04 to 2.81 µg l^{-1}. Median TOC was 1.40 mg l^{-1}, a value higher than open ocean levels but consistent with coastal areas.

For 2024, median turbidity was (0.33 NTU) which influenced median K_d (0.247 m^{-1}). Overall, 34.9% of incident light (I_o) reached the bottom. Molar ratios of total N to P suggested a general P limitation of the water column (median TN:TP = 48.4) but this must be tempered by the fact that much of the TN may not be bioavailable. The potentially more usable ratio, DIN:TP, was 2.0 (median), indicating a stronger tendency for N limitation across the region.

Table 1. *Summary statistics for water quality variables for calendar year 2024 summarized by sampling depth as number of samples, minimum (Min.), maximum (Max.), and median.*

Variable	Depth	Count	Min.	Max.	Median
NO_3^-	Surface	448	0.0000	0.0310	0.0020
(mg l^{-1})	Bottom	279	0.0000	0.0250	0.0020
NO_2^-	Surface	448	0.0000	0.0080	0.0004
(mg l^{-1})	Bottom	279	0.0000	0.0030	0.0002
NH_4^+	Surface	448	0.0000	0.0420	0.0020
(mg l^{-1})	Bottom	279	0.0000	0.0250	0.0010
TN	Surface	448	0.0000	0.6070	0.1370
(mg l^{-1})	Bottom	280	0.0000	0.3850	0.1000
DIN	Surface	448	0.0000	0.0680	0.0060
(mg l^{-1})	Bottom	279	0.0000	0.0330	0.0040
TON	Surface	448	0.0000	0.5680	0.1310
(mg l^{-1})	Bottom	280	0.0000	0.3580	0.0930
TP	Surface	448	0.0000	0.0250	0.0060
(mg l^{-1})	Bottom	280	0.0000	0.0290	0.0060
SRP	Surface	447	0.0000	0.0040	0.0000
(mg l^{-1})	Bottom	278	0.0000	0.0030	0.0001
CHLA (μg l^{-1})	Surface	447	0.040	2.810	0.230
TOC	Surface	448	0.770	6.319	1.401
(mg l^{-1})	Bottom	280	0.798	3.116	1.146
SiO_2	Surface	448	0.0000	3.1630	0.0250
(mg l^{-1})	Bottom	280	0.0000	1.4190	0.0100
Turbidity	Surface	448	0.000	6.930	0.330
(NTU)	Bottom	281	0.000	7.640	0.320
Salinity	Surface	448	23.37	38.69	36.31
	Bottom	438	23.47	38.28	36.35
Temp.	Surface	445	19.75	33.31	28.65
(°C)	Bottom	438	19.63	33.32	28.81
DO	Surface	445	5.83	7.67	6.42
(mg l^{-1})	Bottom	438	5.83	7.67	6.41
K_d (m^{-1})		443	0.029	2.178	0.247
TN:TP	Surface	444	1.9	364.8	48.4
	Bottom	274	5.2	135.9	37.4
DIN:TP	Surface	438	0.0	22.7	2.0
	Bottom	267	0.0	15.1	1.6
Si:DIN	Surface	385	0.0	761.3	2.7
DO_{Sat}	Surface	445	91.9	117.7	96.6
(%)	Bottom	438	91.9	117.4	96.6
I_o (%)	Bottom	437	0.0	100.0	34.9
$\Delta\sigma_t$ (kg m^{-3})		438	-0.756	1.176	0.005

3.3. General Hydrological Drivers of Conditions

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 human intents for usage (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 challenging. Most of the important anthropogenic inputs are regulated and most likely controlled by land-based 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; Meyers et al 2024). Stormwater inputs have also been shown to be important for the halo zone (within 1,000 m of shore)(Lapointe & Matzie, 1996), 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/upwelling (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 demonstrate that these major sources of freshwater 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.

Recently, Julian et al. (2024) analyzed water column biogeochemical data from the freshwater Everglades, SW mangrove forests, SW Florida Shelf, Florida Bay, and FKNMS to understand how spatiotemporal changes varied across the ridge-to-reef hydroscape. The results demonstrated the need to look at biogeochemical patterns across the freshwater to marine gradient to fully understand the causes of biogeochemical changes.

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 (upwelling) as a breaking internal wave of sub-thermocline water.

3.4. 2024 Seasonal Surveys

Surface salinity distributions in 2023 showed the usual reduced salinity patterns in Sluiceway/Backcountry due to Florida Bay/Everglades inputs (Fig. 4). Hypersaline conditions developed in the Sluiceway during spring/summer, which was not typical as hypersalinity is usually a dry season condition. The magnitude of hypersalinity was small compared to some other years.

Surface temperature distributions (°C, Fig. 5) were relatively unremarkable except for low values in Marquesas offshore Lower Keys during late fall sampling. These temperatures coincided with lower salinity waters from the GOM transport event.

Salinity and temperature influence other water quality variables such as DO_{sat} (Fig. 6). Higher levels of DO_{sat} are generally beneficial for animal life. Lowest DO_{sat} conditions tended to develop in the Backcountry during warmest months and were mostly due to higher temperatures, salinities, and longer water residence time. This year, DO_{sat} was relatively high across the region throughout the year.

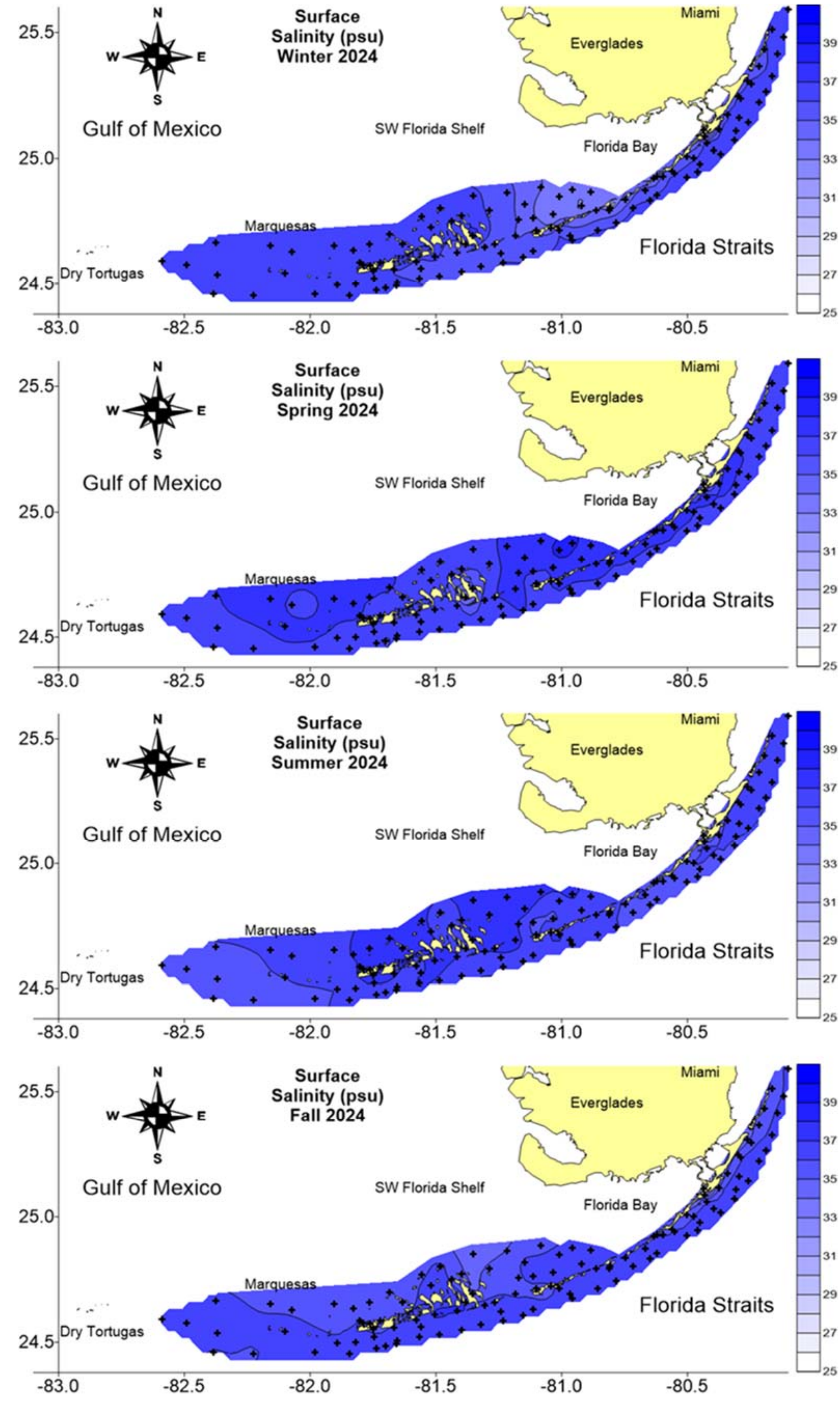

Figure 4. *Surface salinity distributions across the FKNMS during 2024.*

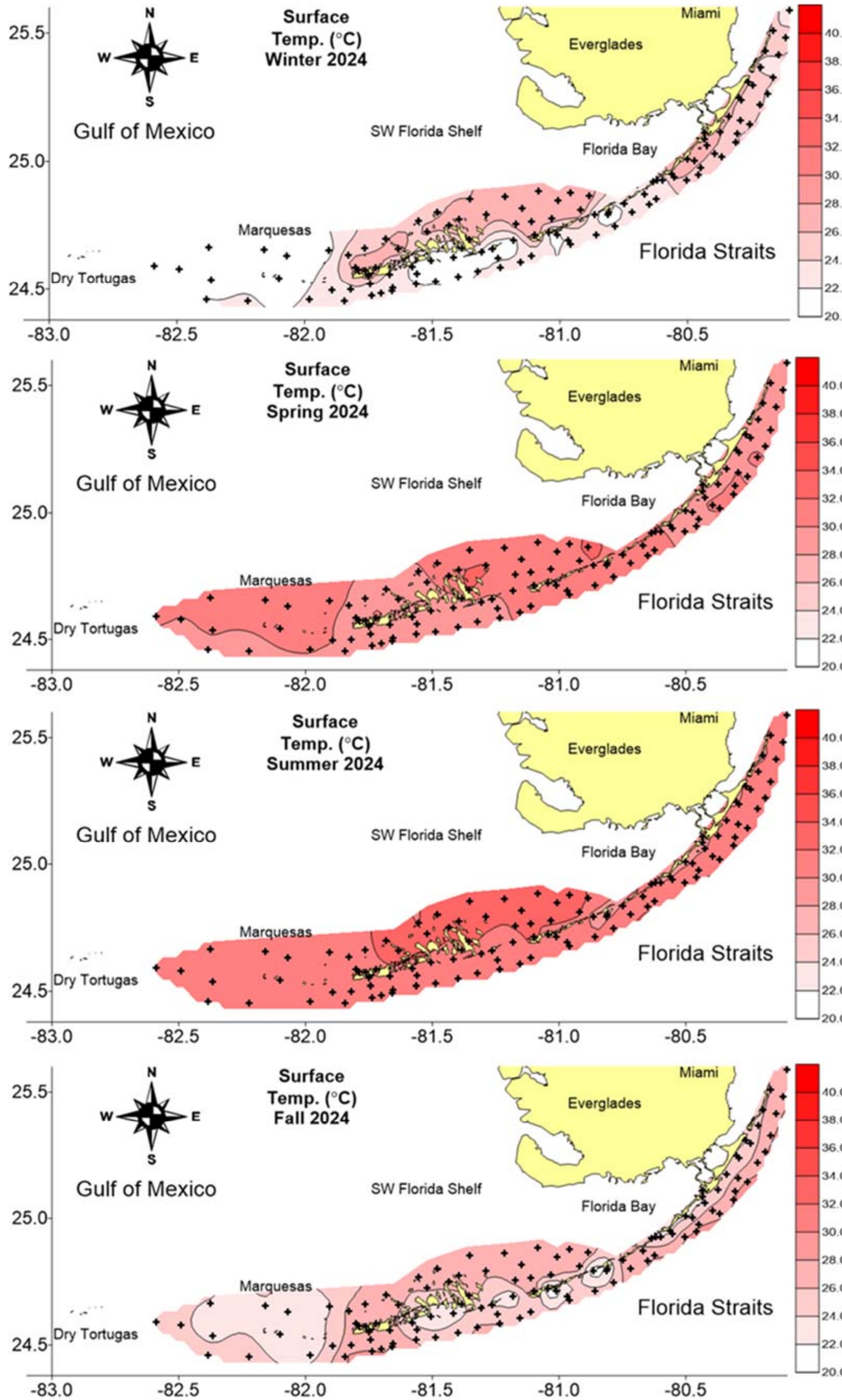

Figure 5. *Surface temperature distributions across the FKNMS during 2024.*

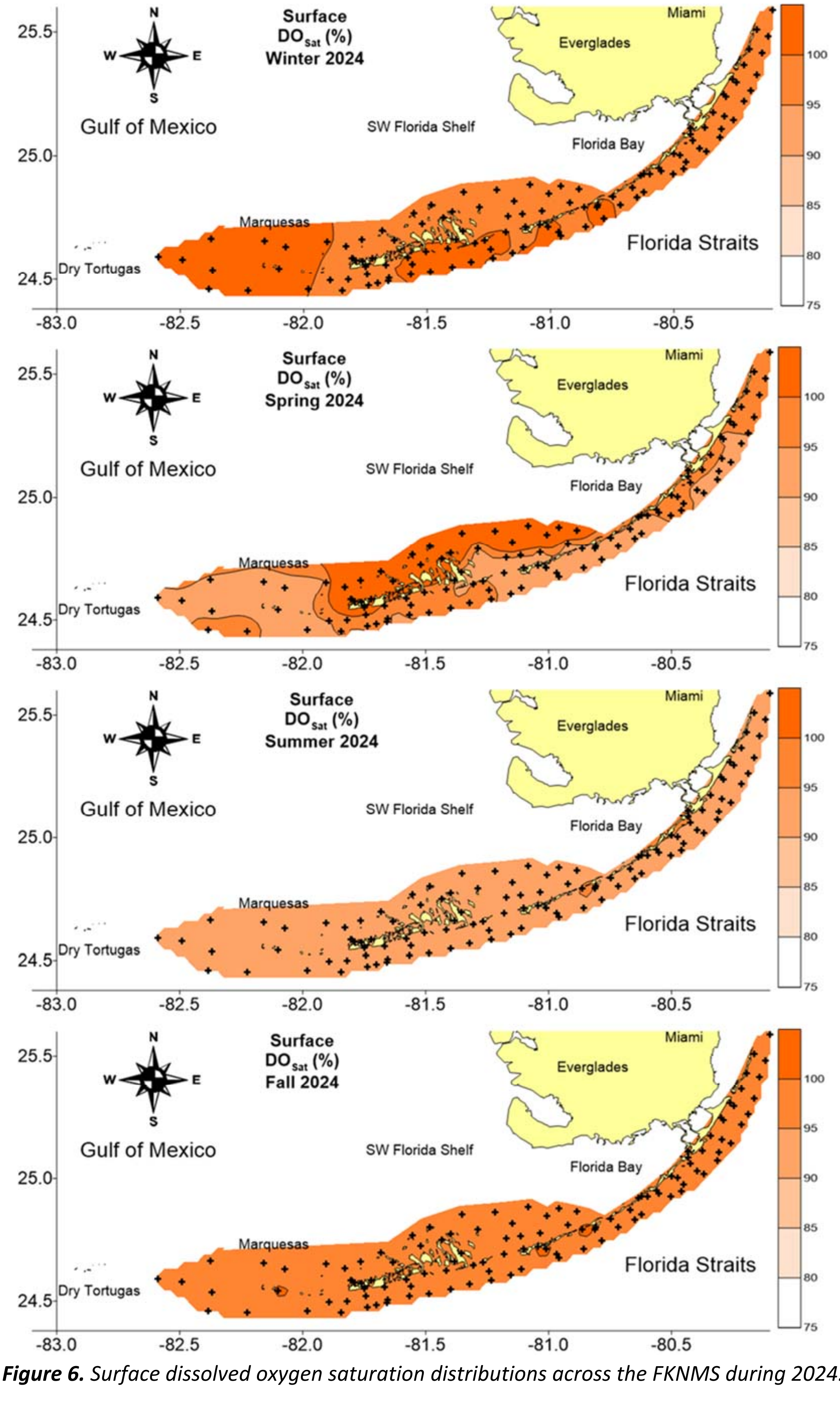

Figure 6. *Surface dissolved oxygen saturation distributions across the FKNMS during 2024.*

Independent water masses may be distinguished by differences in density (σ_t) between the surface and bottom ($\Delta\sigma_t$ in kg m^{-3}, Fig. 7). Density is usually driven more by salinity than temperature, so $\Delta\sigma_t$ may not always reflect differences between surface and bottom, even during upwelling events. However, decreased temperature of bottom waters from intrusion of deeper oceanic waters is often an indicator of elevated NO_3^- levels (Leichter and Miller 1999). These tidal bores impacting the reef tract often correspond to increased nutrient concentrations of NH_4^+, TP, and SRP in Keys bottom waters. Density stratification events are typically sporadic and widespread on the Atlantic side of the Keys and Marquesas. Temperature has more influence on σ_t when cold fronts quickly reduce surface water temperatures. In 2024, many reef sites experienced significant density stratification (elevated $\Delta\sigma_t$) during winter, spring, and a few in the fall (Fig. 7), indicating potential for tidal bores.

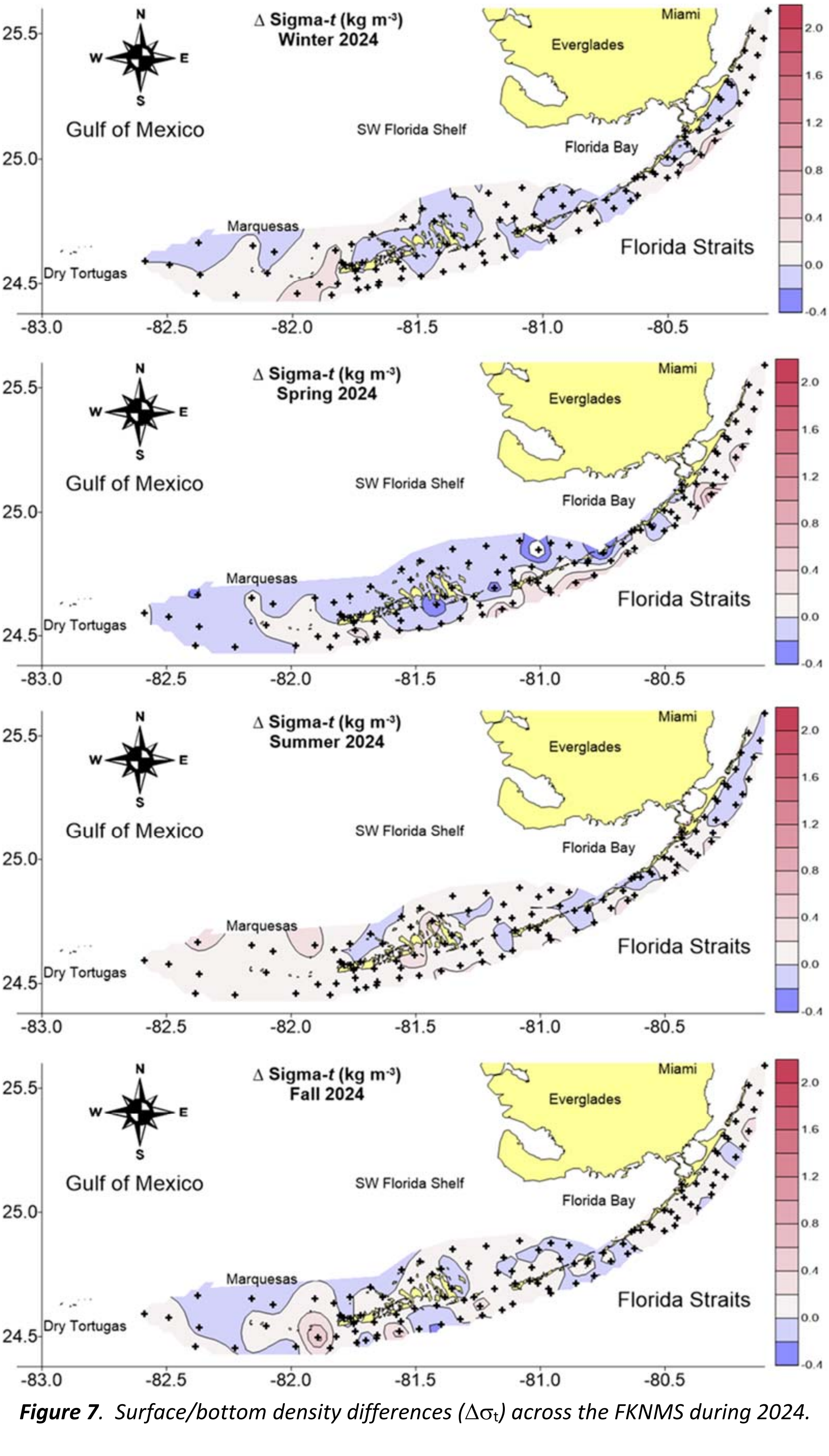

***Figure 7**. Surface/bottom density differences ($\Delta\sigma_t$) across the FKNMS during 2024.*

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 summer & fall 2024). Similar patterns of inshore-offshore gradients were observed in 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^-, ruling 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, resulting in relatively long water residence times. Salinities in this area are typically only 1-2 higher than local seawater and may be lower than surrounding areas during wet periods. 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).

For these reasons, we believe that sponge-mediated benthic flux may have the most significant influence on water quality in the Backcountry. Sponge population densities in Florida Bay range 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 DIN fluxes might be of comparable magnitude in this region.

During 2024 there were numerous areas and events of high NO_3^- water in the FKNMS, mostly occurring in summer and fall (Fig. 8). Surface and bottom water NO_3^- concentrations are not always coincident (Fig. 9). Some years we observed elevated NO_3^- in the bottom waters on the offshore reef tract which is 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. Examples may be identified by offshore to inshore nutrient concentration gradients. Surface NH_4^+ distributions are often similar to NO_3^- but are usually lower in magnitude (Fig. 10).

During 2024, intensification of NH_4^+ concentrations were patchy, mostly in the Backcountry during spring and fall. Bottom NH_4^+ concentrations were generally lower than surface meaning the main source was not from benthic flux/remobilization (Fig. 11).

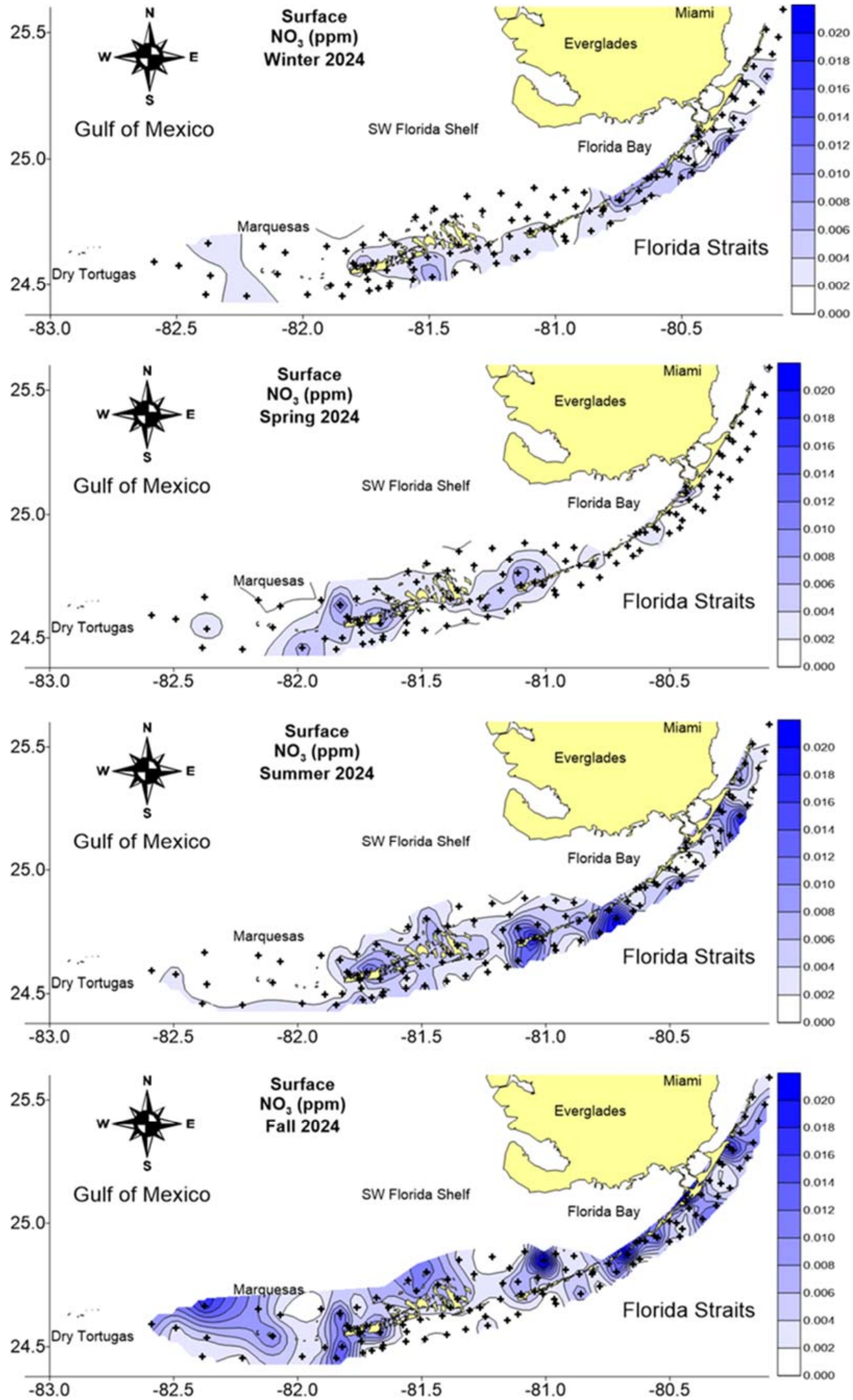

Figure 8. *Surface nitrate distributions across the FKNMS during 2024.*

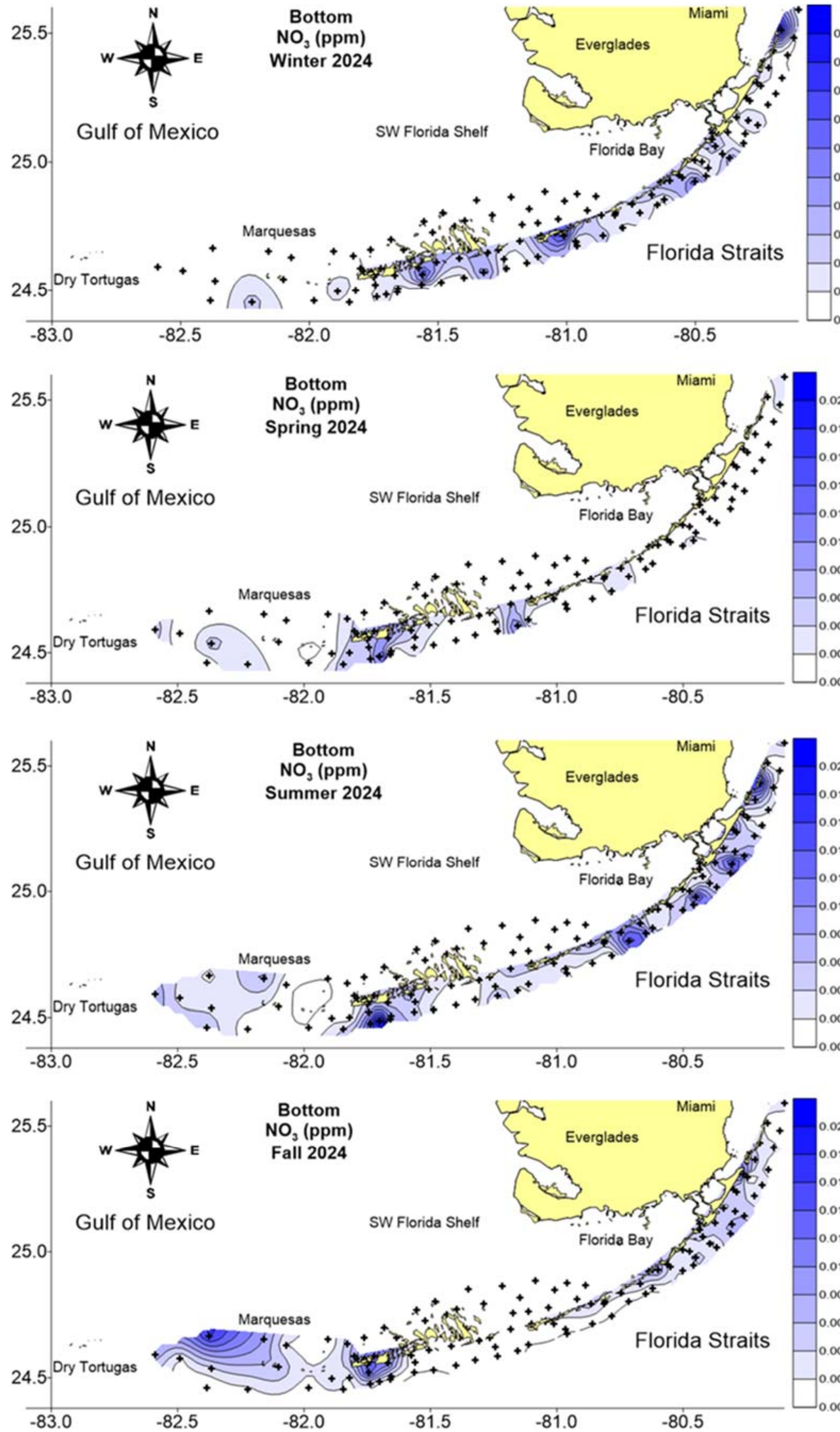

***Figure 9**. Bottom nitrate distributions across the FKNMS during 2024.*

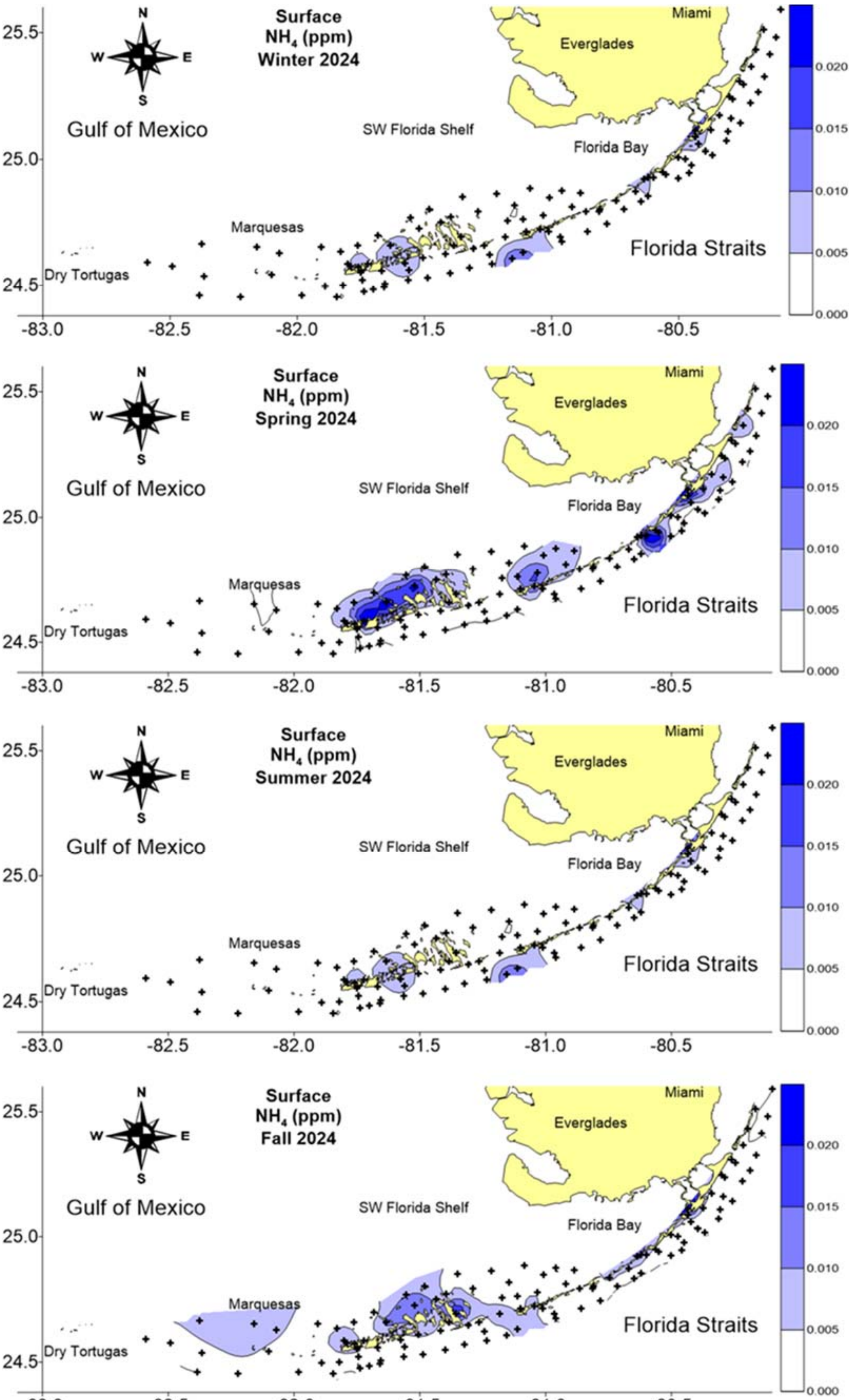

***Figure 10**. Surface ammonium distributions across the FKNMS during 2024.*

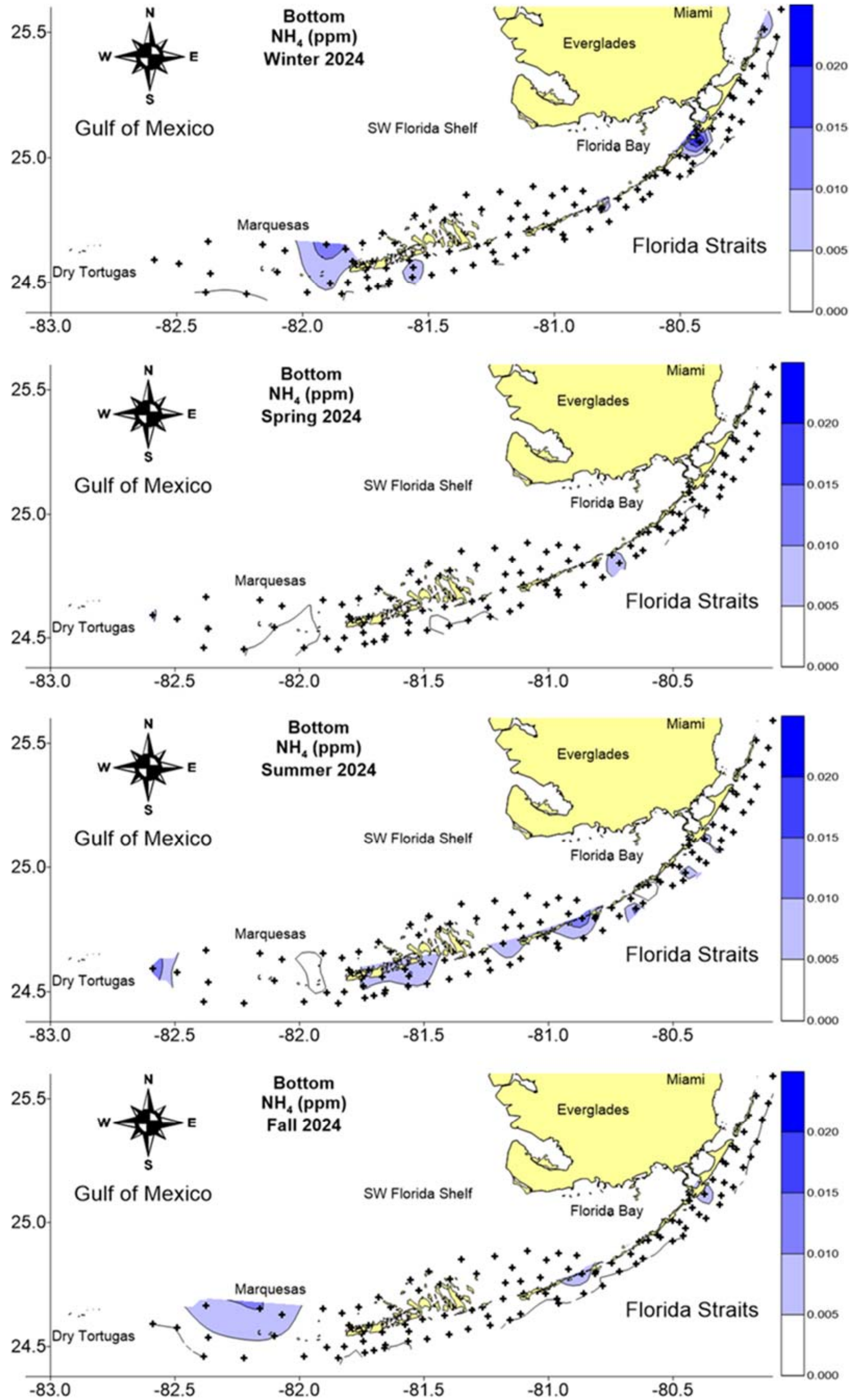

***Figure 11**. Bottom ammonium distributions across the FKNMS during 2024.*

Spatial patterns in TP in South Florida coastal waters are strongly driven by SW Coastal Everglades freshwater inputs 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 may even wrap around the Tortugas. TP gradients may also extend from western Florida Bay to the Middle/Lower Keys.

During 2024, surface TP concentrations were relatively low (<0.015 ppm) and uniform across the region (Fig 12). Bottom TP concentrations were also relatively uniform and similar to surface levels (Fig 13, note different scales). Slightly higher concentrations were observed in the Marquesas during fall.

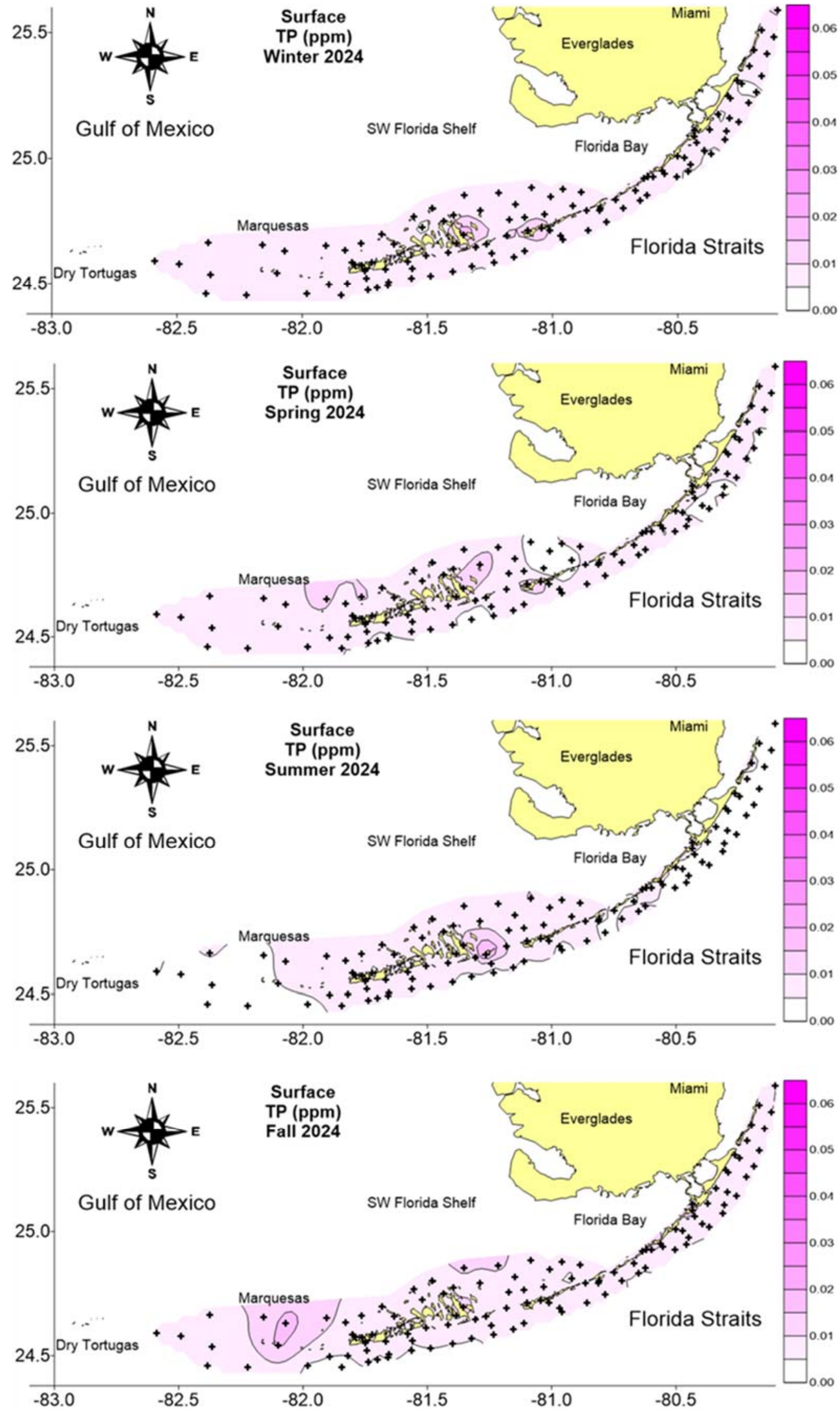

***Figure 12**. Distributions of surface total phosphorus across the FKNMS during 2024.*

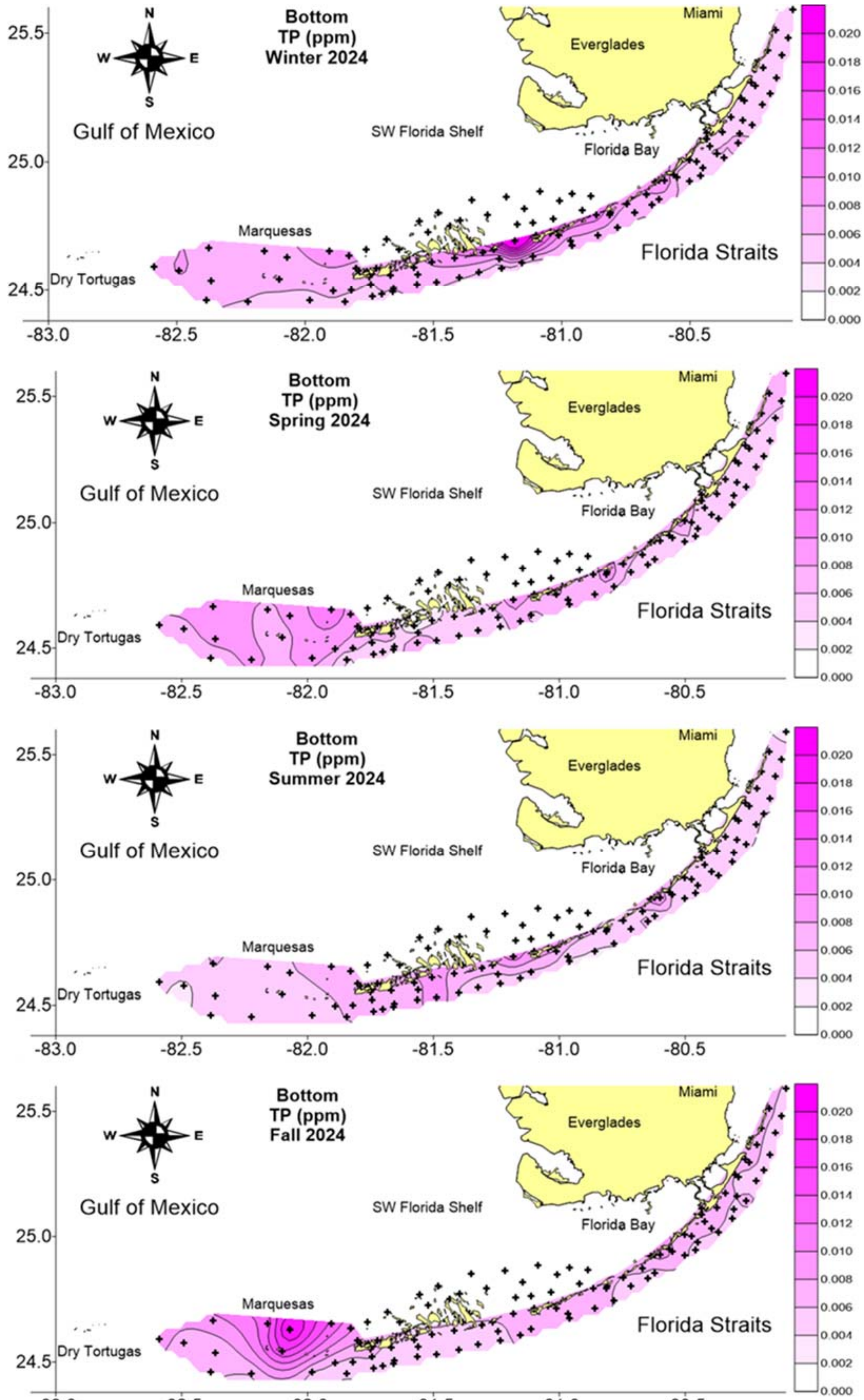

***Figure 13**. Distributions of bottom total phosphorus across the FKNMS during 2024.*

Concentrations of surface and bottom TOC (Fig. 14 & 15) and TON (Fig. 16 & 17) are usually similar in distribution pattern across the South Florida coastal hydroscape. This is because most TN occurs in organic form. Deviations from this common pattern are due to differences in sources of the dissolved organic matter. Previous 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 (dilution). 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. Offshore reef tract concentrations of TOC and TON were consistently the lowest in the FKNMS.

During 2024, patterns in surface TOC and TON concentrations were unremarkable (Figs. 14 & 16). Unlike some other years, both TOC and TON showed surface gradients from Florida Bay to Backcountry, probably as function of longer residence time in this region.

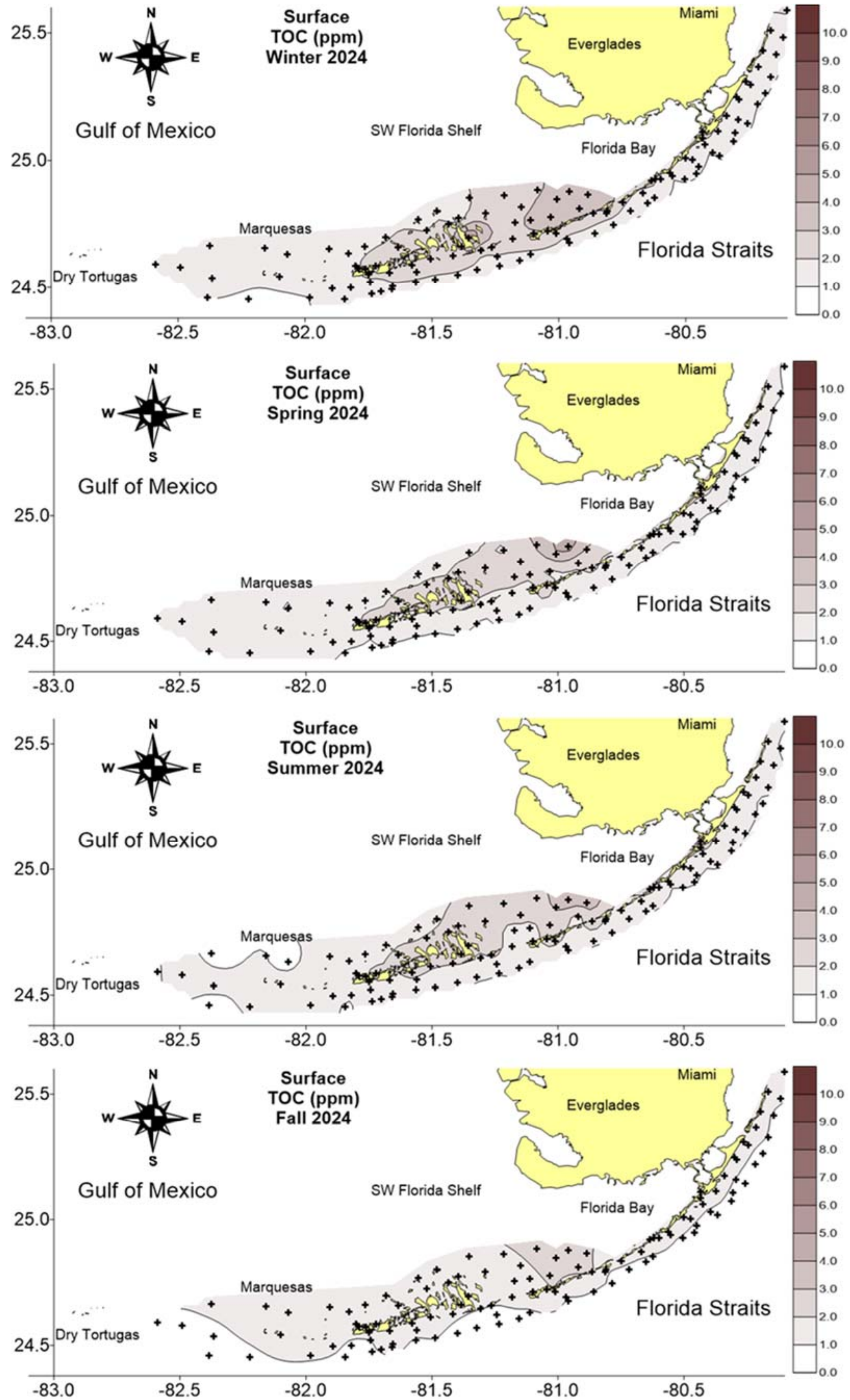

***Figure 14**. Distributions of surface total organic carbon across the FKNMS during 2024.*

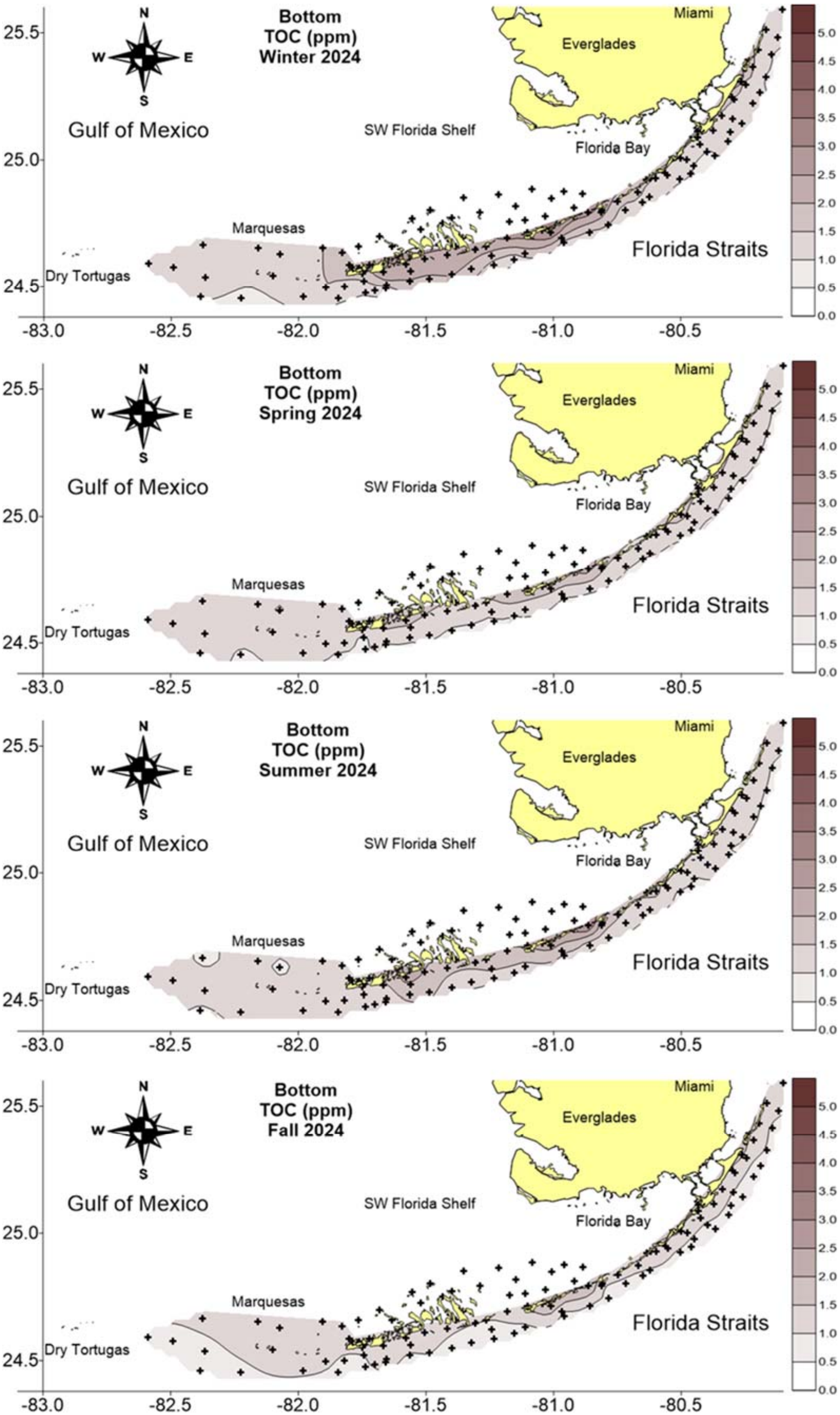

***Figure 15**. Distributions of bottom total organic carbon across the FKNMS during 2024.*

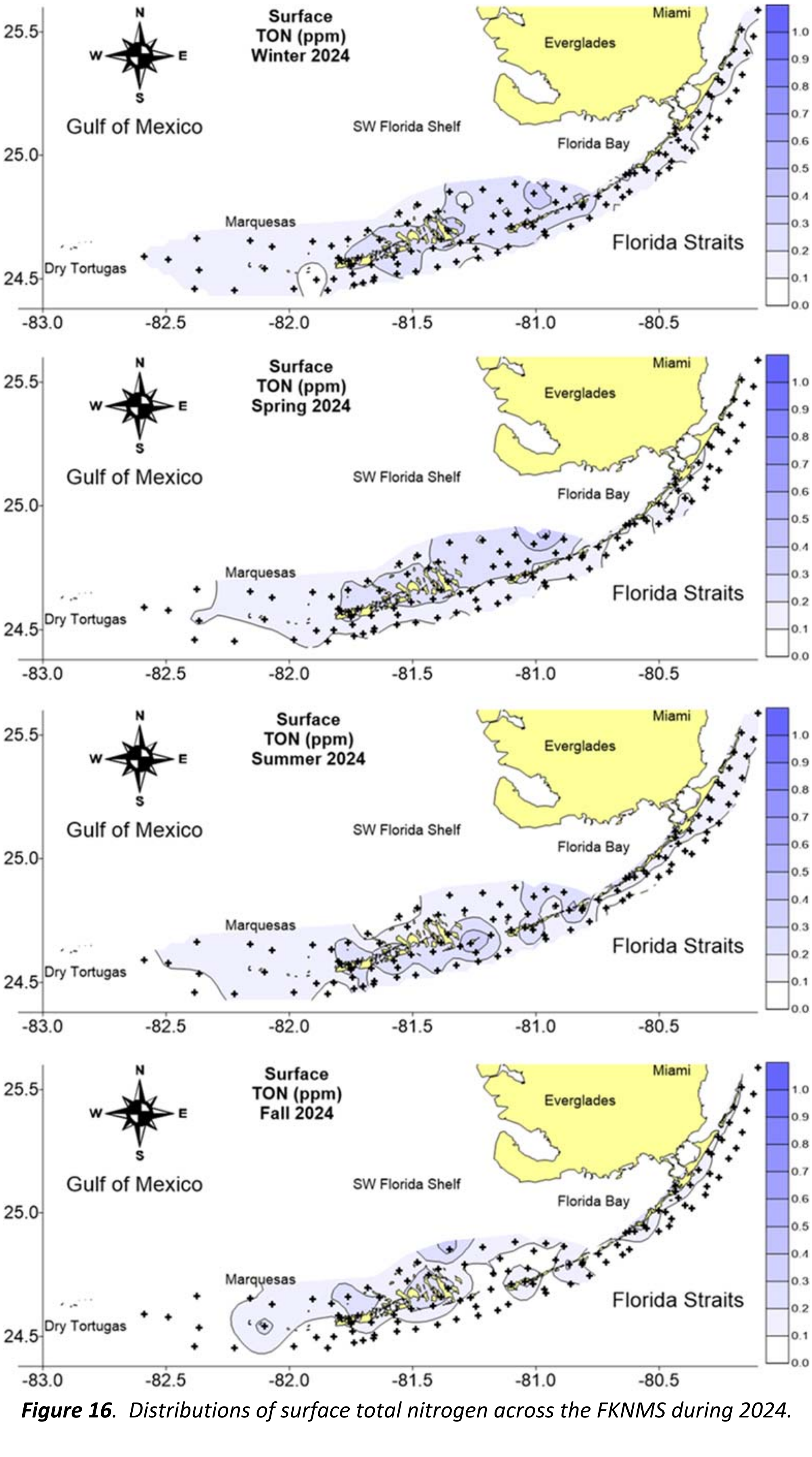

***Figure 16**. Distributions of surface total nitrogen across the FKNMS during 2024.*

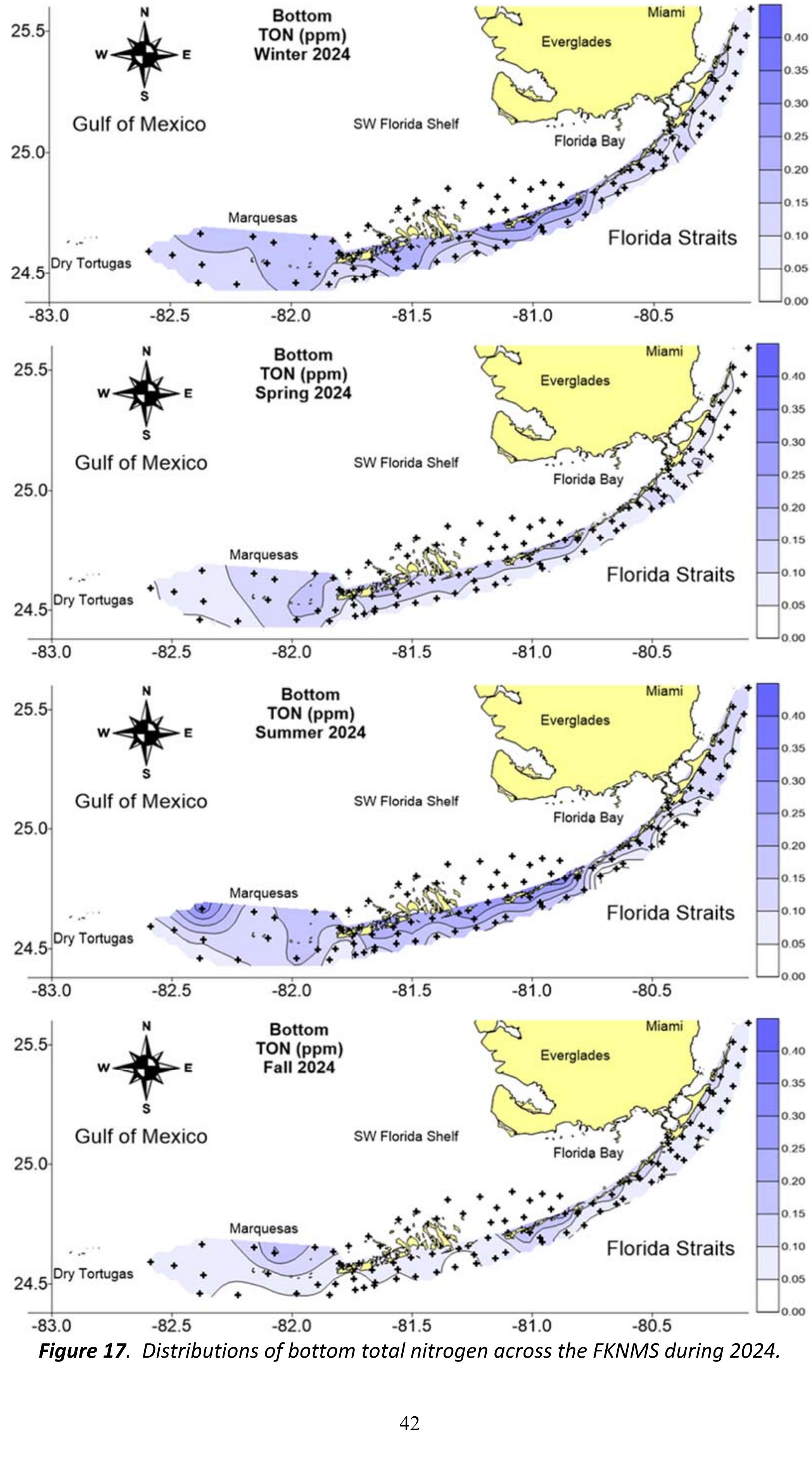

Figure 17. *Distributions of bottom total nitrogen across the FKNMS during 2024.*

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 usually 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, encompassing the historically rich Tortugas shrimping grounds. CHLA concentrations of 2.0 $\mu g\ l^{-1}$ 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 2024 were relatively low across the region (Fig. 18). A small elevation was observed in the Lower Keys during summer.

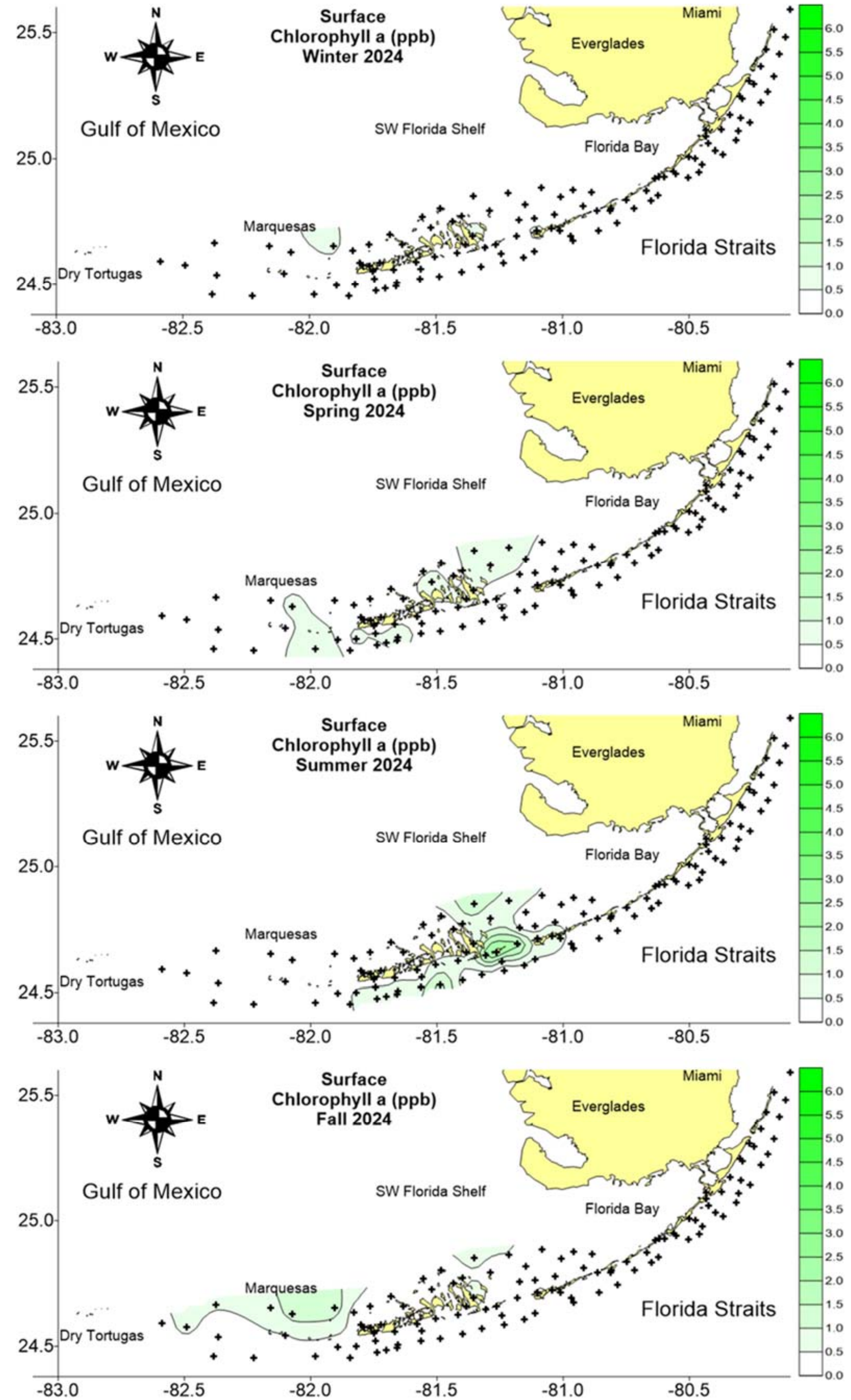

***Figure 18**. Distributions of surface chlorophyll a across the FKNMS during 2024.*

Along with TP and CHLA, turbidity is probably the next 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 2024, the highest turbidity values occurred in the shallow Backcountry along the northern boundary with the SW Shelf (Fig. 19). A significant turbidity increase was observed in the Marquesas during fall.

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 the 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 2024, K_d was generally under 0.05 m^{-1}. (Fig. 20), however higher K_d was observed in the Backcountry and coincided with fall CHLA increase in Lower Keys.

Turbidity and CDOM affect K_d, while site depth also affects I_o, the percentage of ambient light reaching the bottom (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 2024, lowest bottom light was observed in the deeper waters of the Marquesas during the winter and fall turbidity event. In addition, Io was lower during the fall CHLA increase in Lower Keys. This shows how the cumulative effect of very small increases in turbidity and K_d can affect light on the bottom at deeper sites.

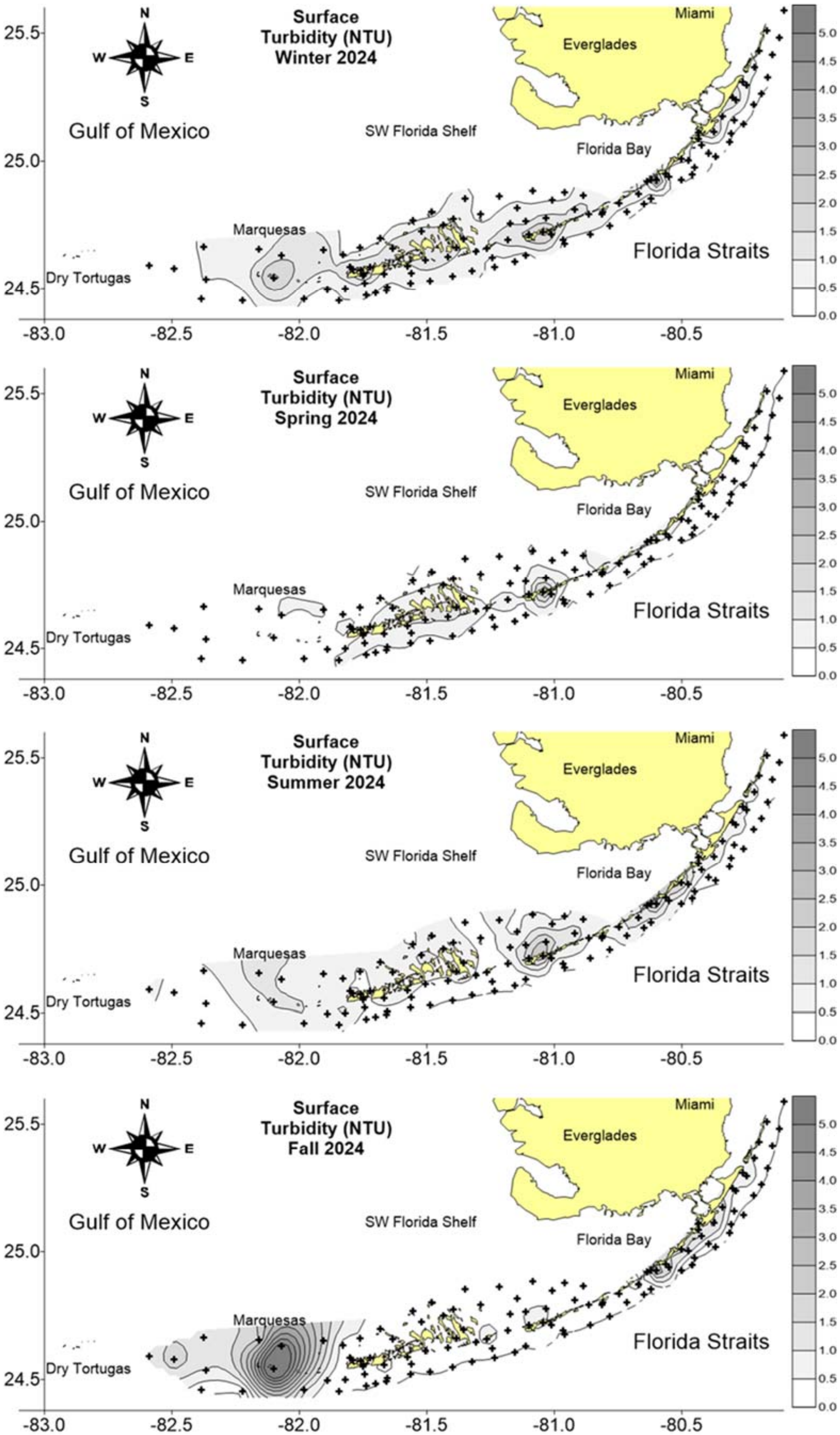

***Figure 19**. Distributions of surface turbidity across the FKNMS during 2024.*

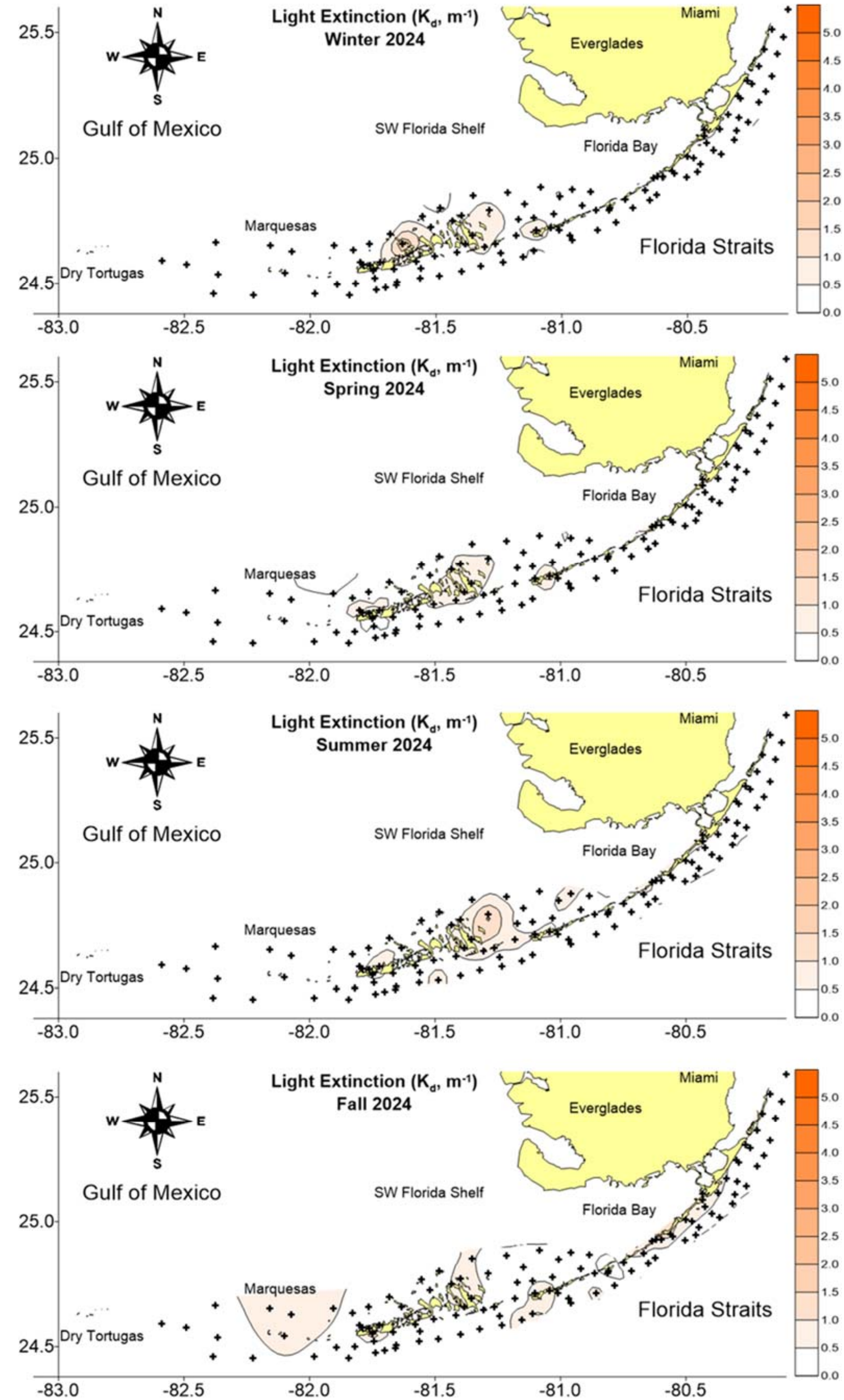

Figure 20. *Distributions of light extinction across the FKNMS during 2024.*

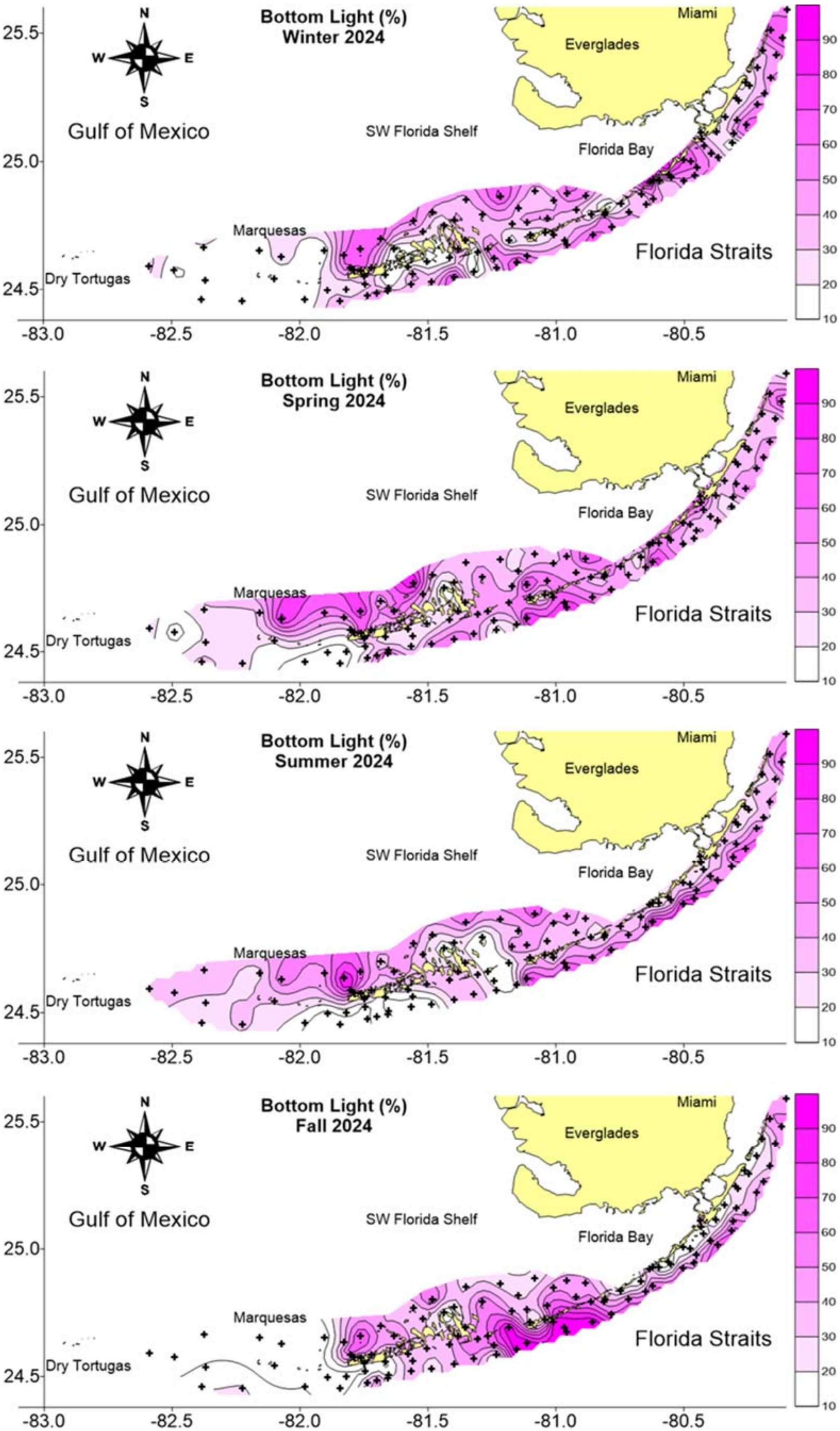

Figure 21*. Distributions of bottom light across the FKNMS during 2024.*

Surface SiO_2 concentrations usually exhibit patterns inverse to salinity. One source of SiO_2 in this area of carbonate rock and sediments is from freshwater, 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 are depleted mostly by mixing, allowing it to be used as a semi-conservative tracer of freshwater in this system (Ryther et al. 1967; Moore et al. 1986). In 2024, SiO_2 concentrations were low across the region but strong gradients from western Florida Bay/SW Florida Shelf through the Sluiceway were evident (Fig. 22).

The TN:TP ratio has been used as a relatively simple method of estimating potential nutrient limitation status of phytoplankton (Redfield 1967). The South Florida hydroscape generally 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 occurs in the southern Marquesas in fall and potentially along the Upper Keys reef tract. In 2024, TNTP ratios were relatively consistent across the region with the exception of spring in Sluiceway where elevated DIN forced drawdown of TP.

Most TN occurs in the form of organic N (TON), much of which is not bioavailable to phytoplankton. This contrasts with TP where most of the organic fraction 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). 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. In 2024, the DIN:TP ratio clearly reflects the imbalance between DIN and TP concentrations. Sometimes this is due to elevated occurrence of DIN, sometimes by low TP concentrations.

The Si:DIN ratio is used as an indicator of nutrient limitation in marine diatoms. Their growth becomes Si-limited when the Si:DIN ≤1 and the proportion of diatoms in the phytoplankton community is reduced. In 2024, Si:DIN ratios in northern Backcountry/Sluiceway and Marquesas were commonly >40, indicating higher propensity for diatom production (Fig. 25).

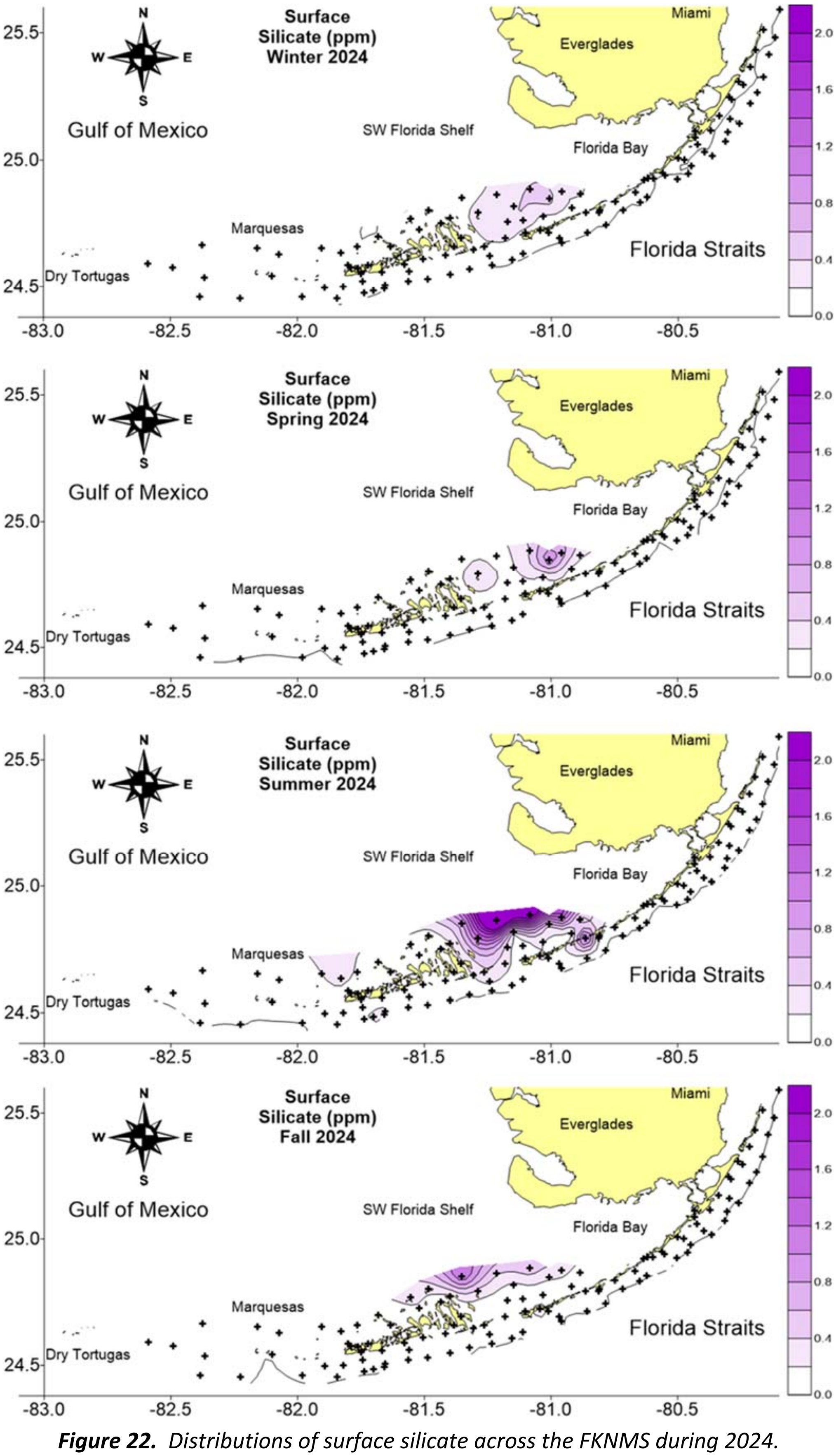

Figure 22. *Distributions of surface silicate across the FKNMS during 2024.*

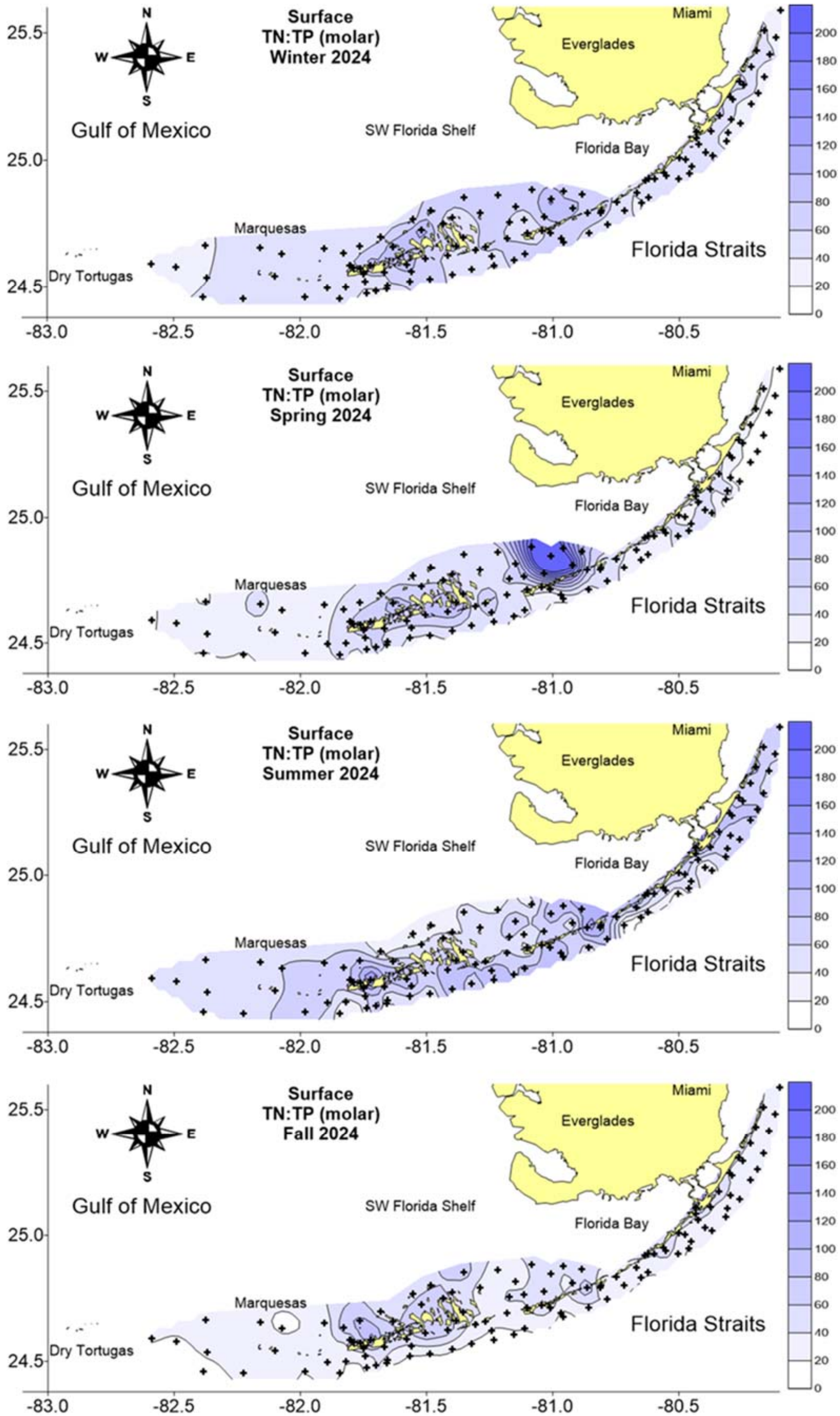

***Figure 23**. Distributions of surface TN:TP ratio across the FKNMS during 2024.*

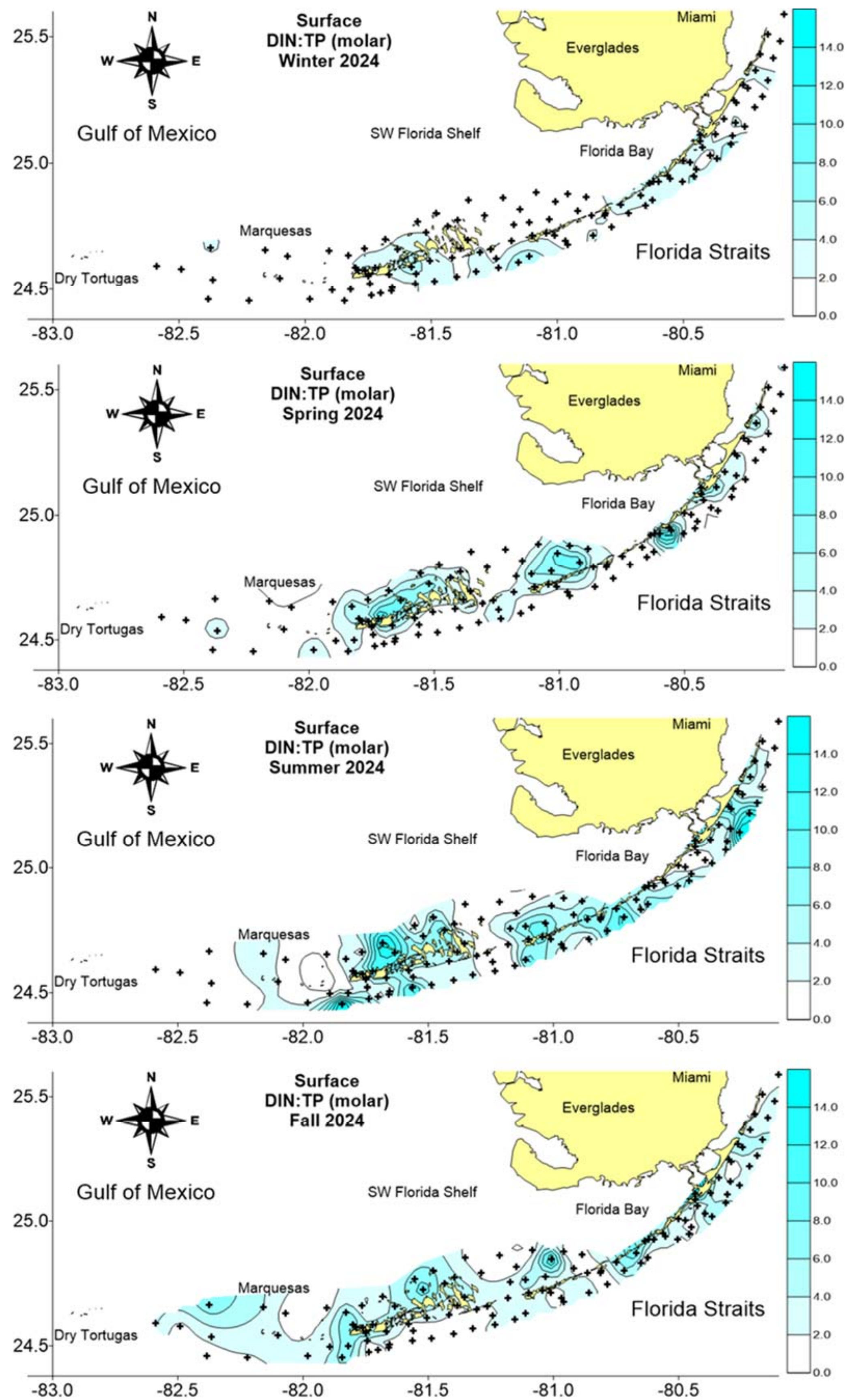

***Figure 24**. Distributions of surface DIN:TP ratio across the FKNMS during 2024.*

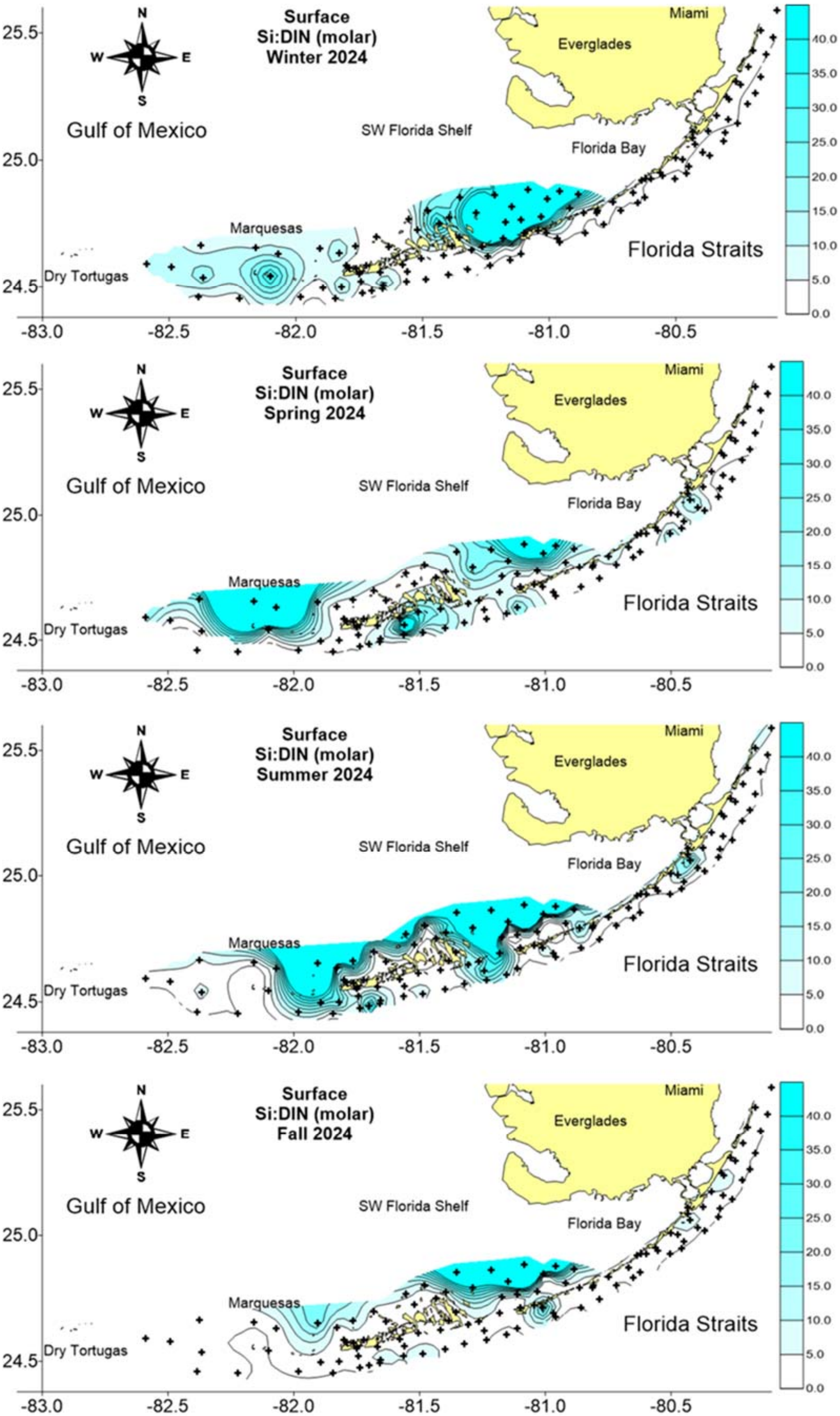

***Figure 25**. Distributions of surface Si:DIN ratio across the FKNMS during 2024.*

3.5. Temporal Trends and Dynamics – 30 Years

It is evident that there have been changes in the water quality of the FKNMS over time, and some sustained monotonic trends have been observed. However, we must remember that trends are primarily limited by the window of observation but may also be affected by the consistency of analytical methodology and limits of detection. In addition, when looking at what are perceived to be local trends, we may find that they are influenced by external, regional changes. This spatial autocorrelation in water quality is an inherent property of highly interconnected systems such as coastal and estuarine ecosystems because they are driven by hydrological and climate forcing. Clearly, some trends observed inside the FKNMS may be influenced by regional conditions and drivers occurring outside the Sanctuary boundaries.

As mentioned, time series analysis is limited to the window of observation, trends may change with continued data collection as future conditions vary. In addition, water quality in the Keys is largely driven by external influences and may vary according to climatic or disturbance events of long or short periodicity. Three main types of trends are typically observed in environmental systems: 1) monotonic (Fig. 26), 2) episodically driven with no net trend (Fig. 27), or 3) reversing/discontinuous with a change point (Fig. 28).

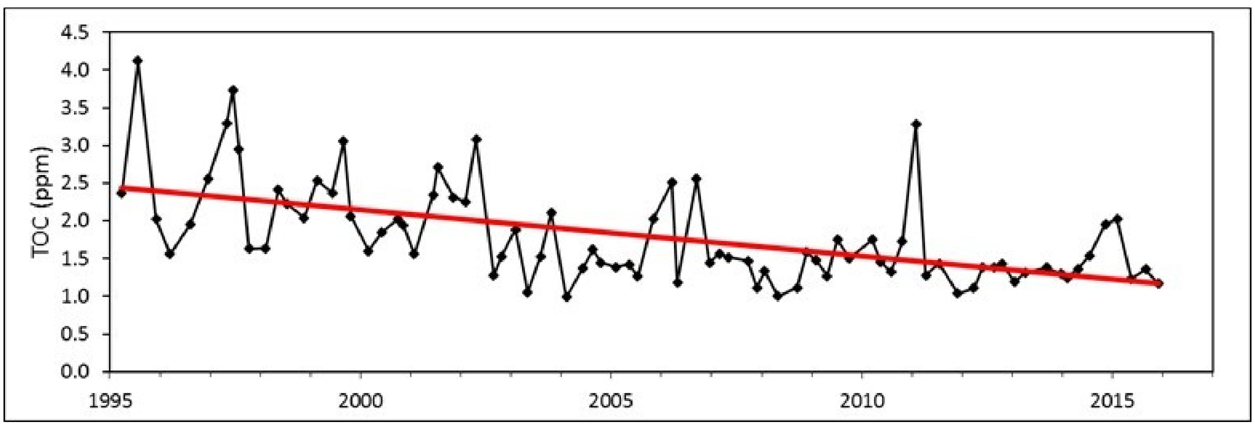

Figure 26. *Monotonic trend in TOC at Carysfort Reef.*

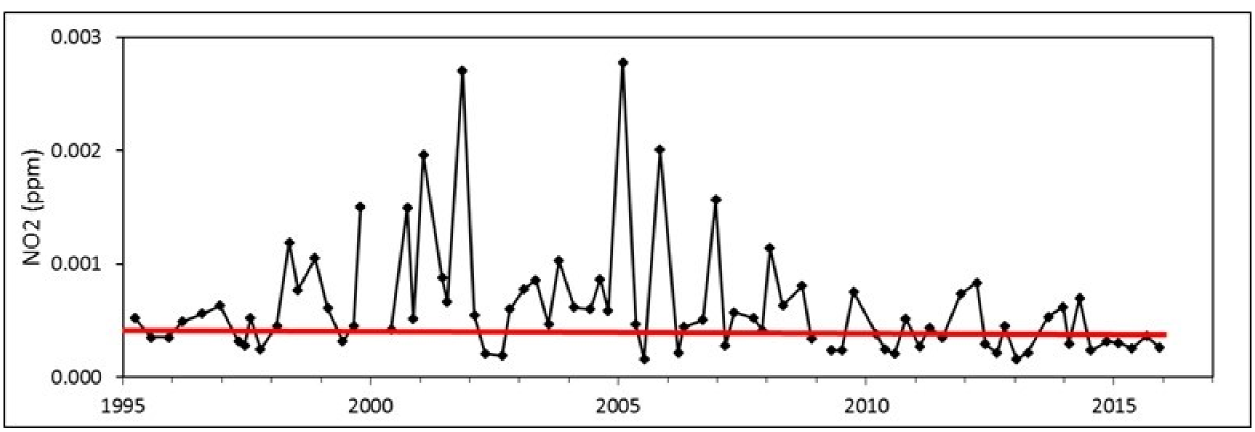

Figure 27. *Episodically driven pattern in NO_2^- with no net trend at Carysfort Reef.*

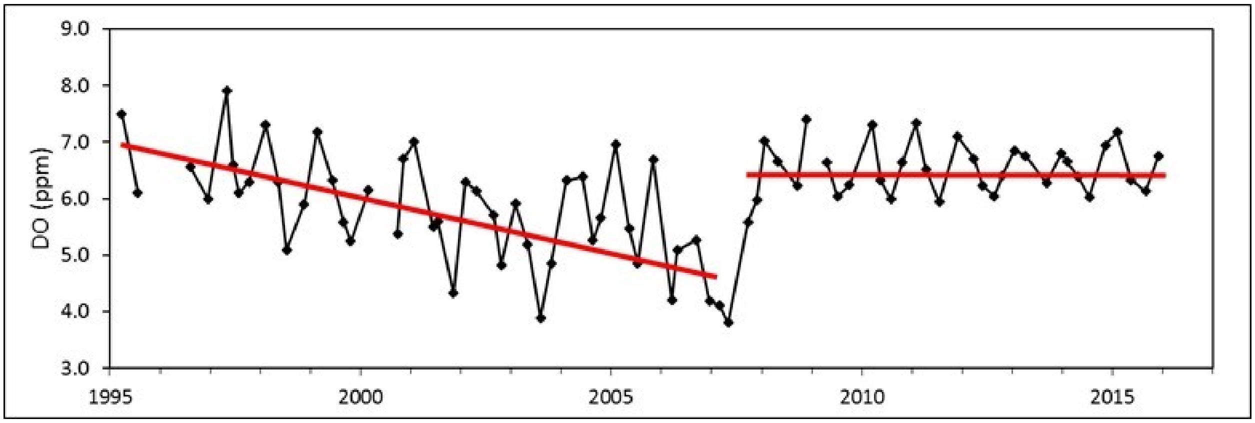

Figure 28. *Discontinuous trend in DO at Carysfort Reef.*

The least squares linear regression approaches shown above are not optimal for analyzing long term time series influenced by fluctuating conditions or disturbance events. Instead, nonparametric approaches and locally weighted regressions, such as LOESS (see Methods), are typically more useful for visualizing trend reversals and cycles (Fig 29).

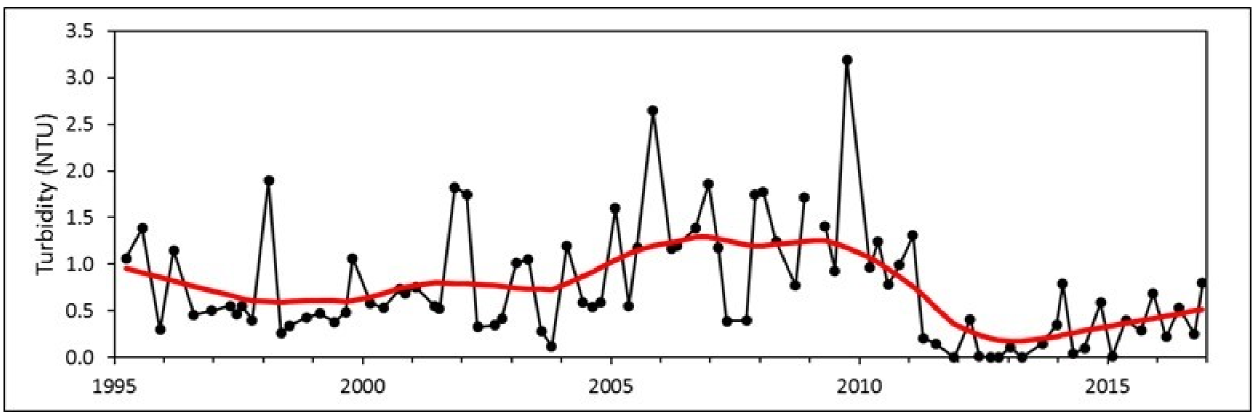

Figure 29. *LOESS fitting of trend in turbidity at Carysfort Reef.*

The nonparametric Mann-Kendall Test was used to detect monotonic trends without the requirement that measurements be normally distributed. To quantify temporal trends, we used Sen slope regressions for each water quality variable over the period of record. Some of the Sen slopes were very small, so to get a better idea of change over the period of record, the Sen slopes were multiplied by the number of years sampled and plotted as contour maps of potential net change in measured variable for the period of record. Only statistically significant M-K trends (p<0.05) were used to show directional tendencies in variables across the hydroscape (non-significant trends were coded as zero). We also included trends at Shore stations located within the Halo Zone even though they have only been sampled since 2011.

The photosynthetic pigment, chlorophyll *a*, is a proxy measure of phytoplankton biomass. CHLA concentrations have increased in 35 of 112 sites in the FKNMS (Fig. 30). Significant increases ranged 0.08-0.19 ppb (median = 0.11 ppb) or ~39% increase over 1995 levels. Strongest increases seem to be associated with shallow stations near land but there were increases at offshore Reef sites and in major passes. Although ambient concentrations remain low relative to other coastal areas in the US, these increases are evidence of slow eutrophication of the FKNMS.

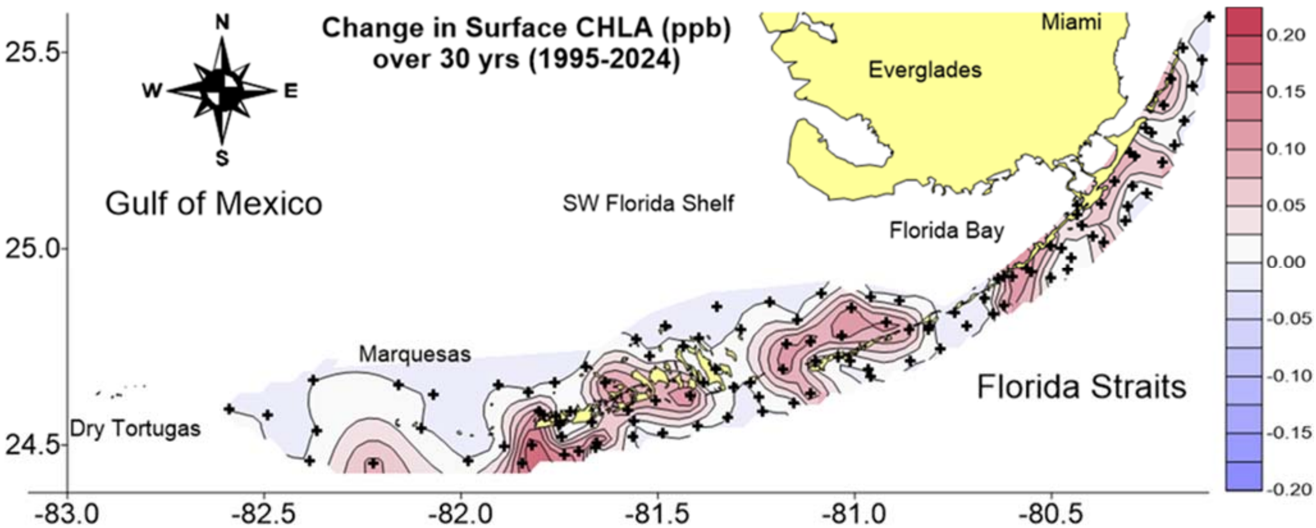

Figure 30. *Net change in chlorophyll a in surface waters over the 30-year period.*

The CHLA time series exhibited a strong elevation occurring during 1999-2000, coincident with peaks in NO_3^-, and SRP (Fig. 31 and later). Similar events occurred in the Marquesas during 2001-02 and 2005-06. The 2022-23 phytoplankton bloom is evident as upturns in the LOESS curves with recovery observed in 2024.

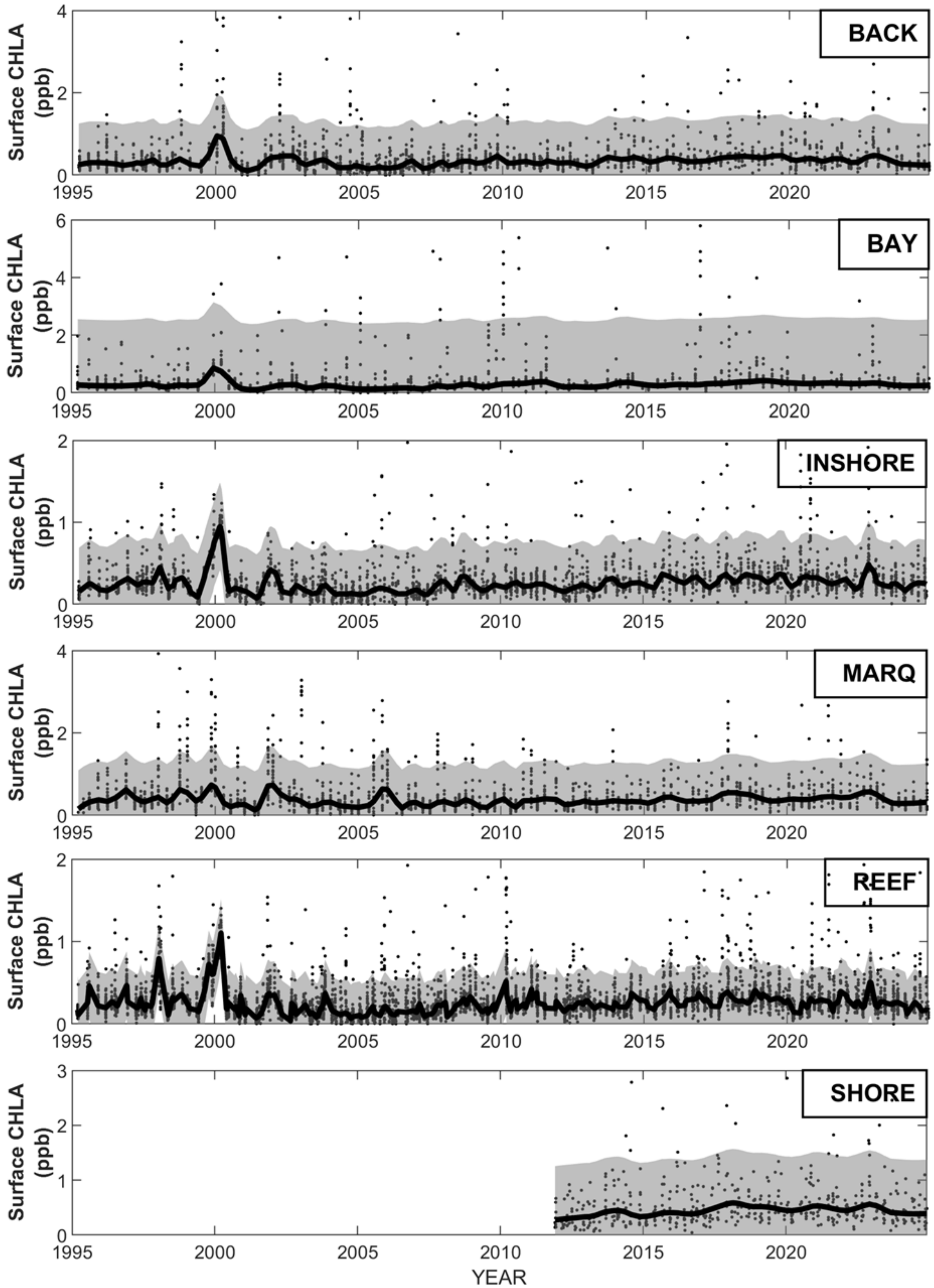

Figure 31. *Time series of surface Chlorophyll a by zone. The line is LOESS fit.*

Total phosphorus (TP) is an important driver of primary production in South Florida inland and nearshore waters. Significant increases in TP (median = 0.002 ppm) occurred at 40 sites in the Keys primarily close to land, indicating potential terrestrial sources (Fig. 32). This is a 43.5% increase over 1995 levels. In contrast, TP declined in some of the deeper surrounding waters. Note the spatial similarity in changes in TP and CHLA (Fig. 30). These trends bear watching, given that we expect future TP concentrations to decline inshore in response to central sewer installation.

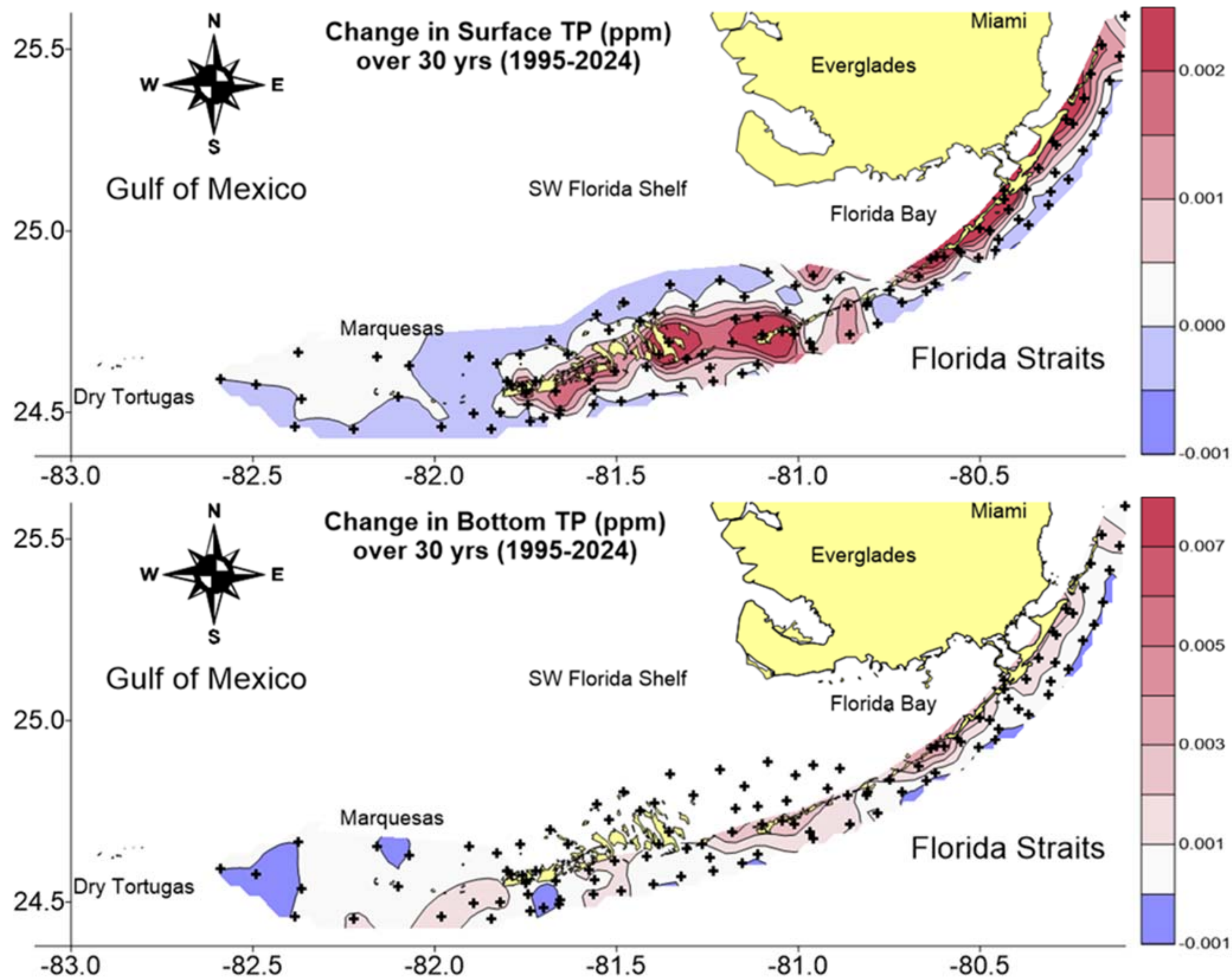

Figure 32. *Net change in surface and bottom TP over the 30-year period.*

The time series for TP (Fig. 33) shows some elevated periods in the record, especially during 2000 and 2006-7, which may be linked to major hurricane impacts during 1998-1999 and 2004-2005. We believe land-based and bay-wide disturbances from hurricanes Mitch (1998), Georges (1998), and Irene (1999) lasted until 2001, and those of Katrina-Rita-Wilma (2005) persisted until 2007 (Briceño & Boyer 2010). Significant reductions in TP occurred last year but were not enough to counteract the overall increasing trend.

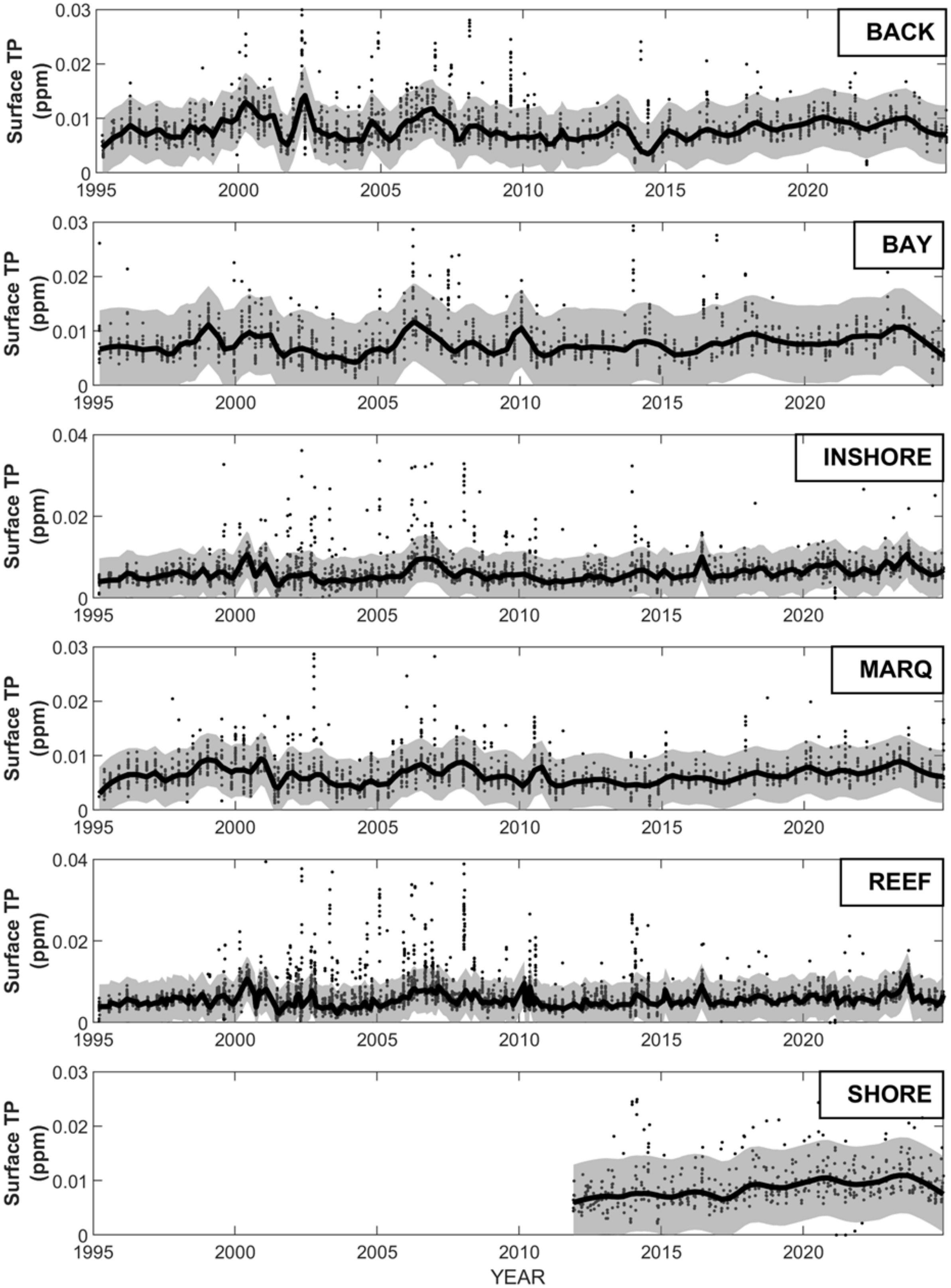

Figure 33. *Time series of surface TP by zone. The line is LOESS fit.*

Soluble reactive phosphorus (SRP) is the inorganic dissolved fraction of TP. SRP concentrations are generally an order of magnitude lower than TP in South Florida waters and may be below the kinetic threshold for uptake by phytoplankton. Contrary to TP, SRP concentrations have declined in the FKNMS (Fig. 34), which was not expected.

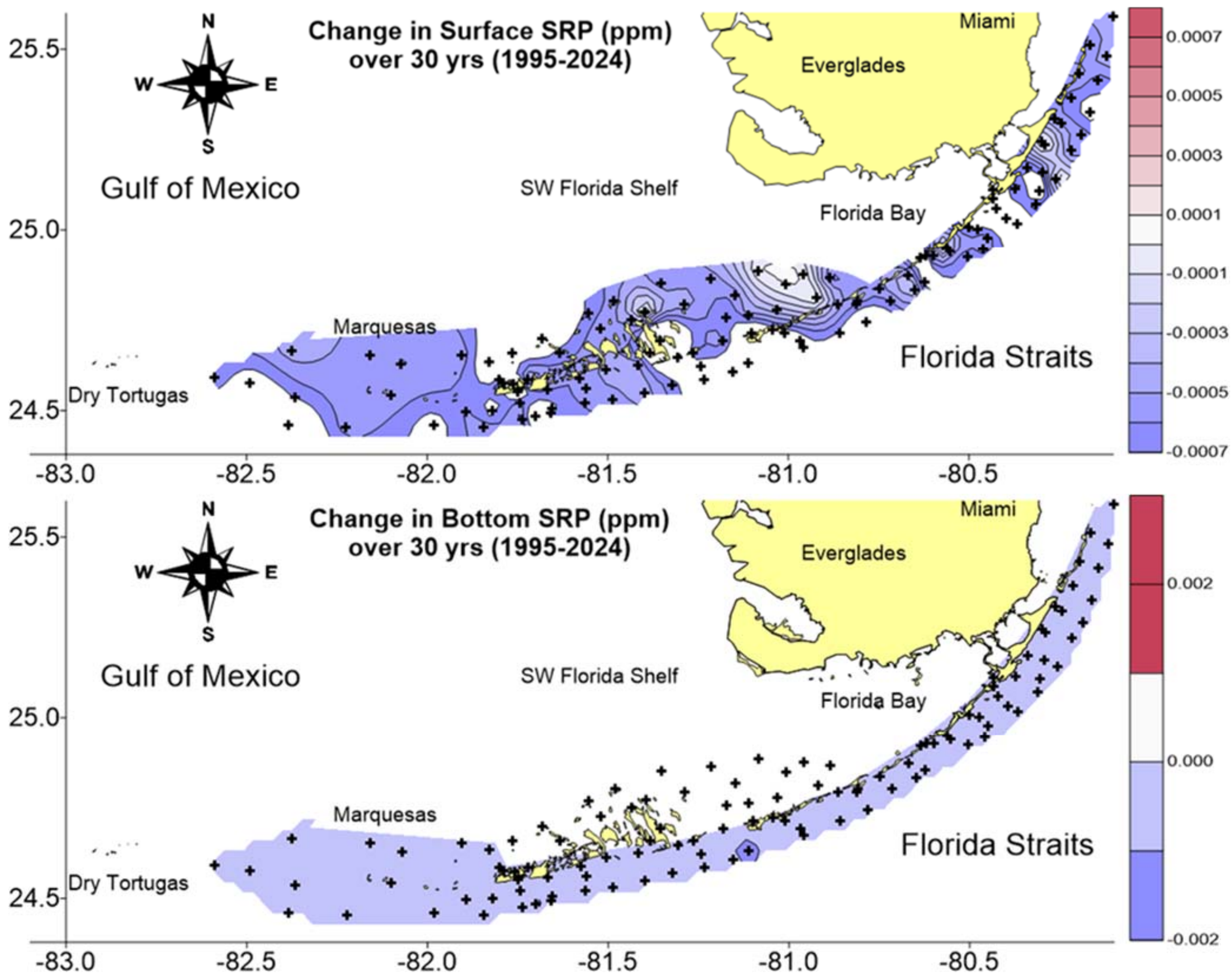

Figure 34. *Net change in surface and bottom SRP over the 30-year period.*

The SRP time series (Fig. 35) shows 2–3-year cyclical fluctuations in concentrations at Reef sites. However, the concentrations are very low and may not be biologically relevant. It appears that concentrations have declined in recent years.

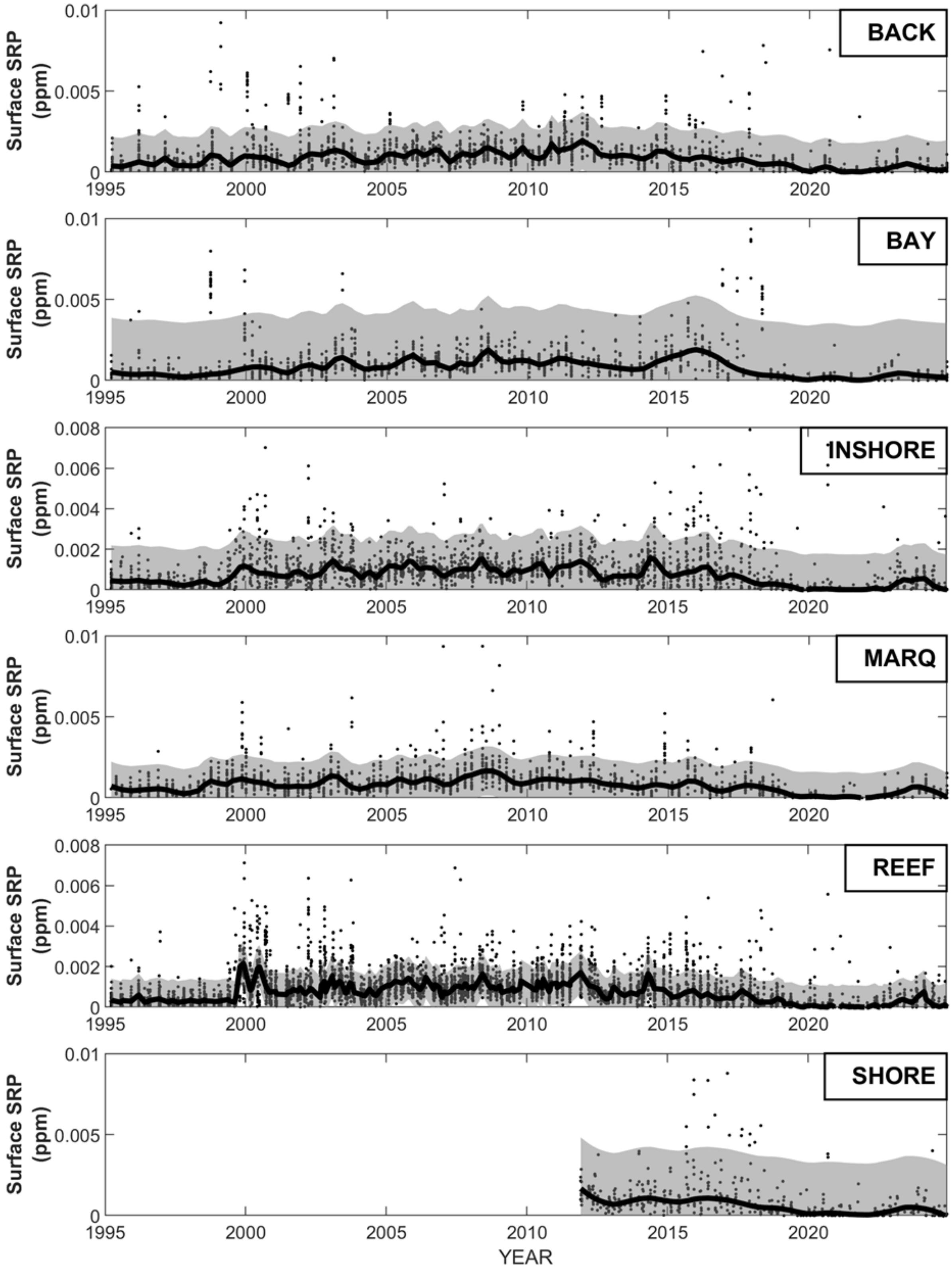

Figure 35. *Time series of surface SRP by zone. The line is LOESS fit.*

Some Keys-wide declining trends in NO_3^- were detected but the changes were minor (Fig. 36).

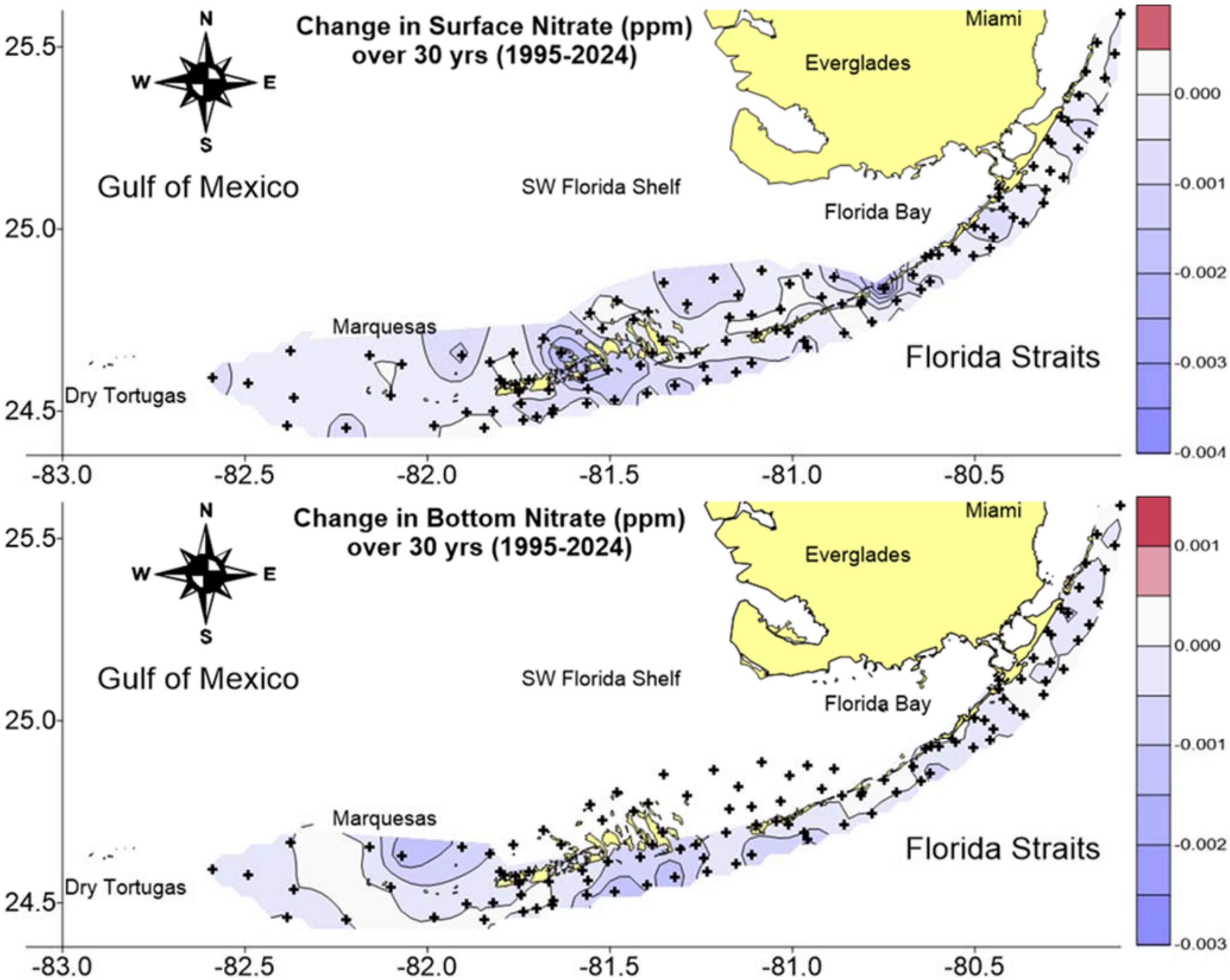

Figure 36. *Net change in surface and bottom NO_3^- over the 30-year period.*

Decreasing trends in NH_4^+ were also observed across the FKNMS (Fig. 37). Interestingly, these declines occurred at many of the same sites where TP increased. We are unsure if such trends are stoichiometrically related - whether increases in TP act to drive down NH_4^+ through biological uptake or whether declines in NH_4^+ allow more TP to be released to the water column.

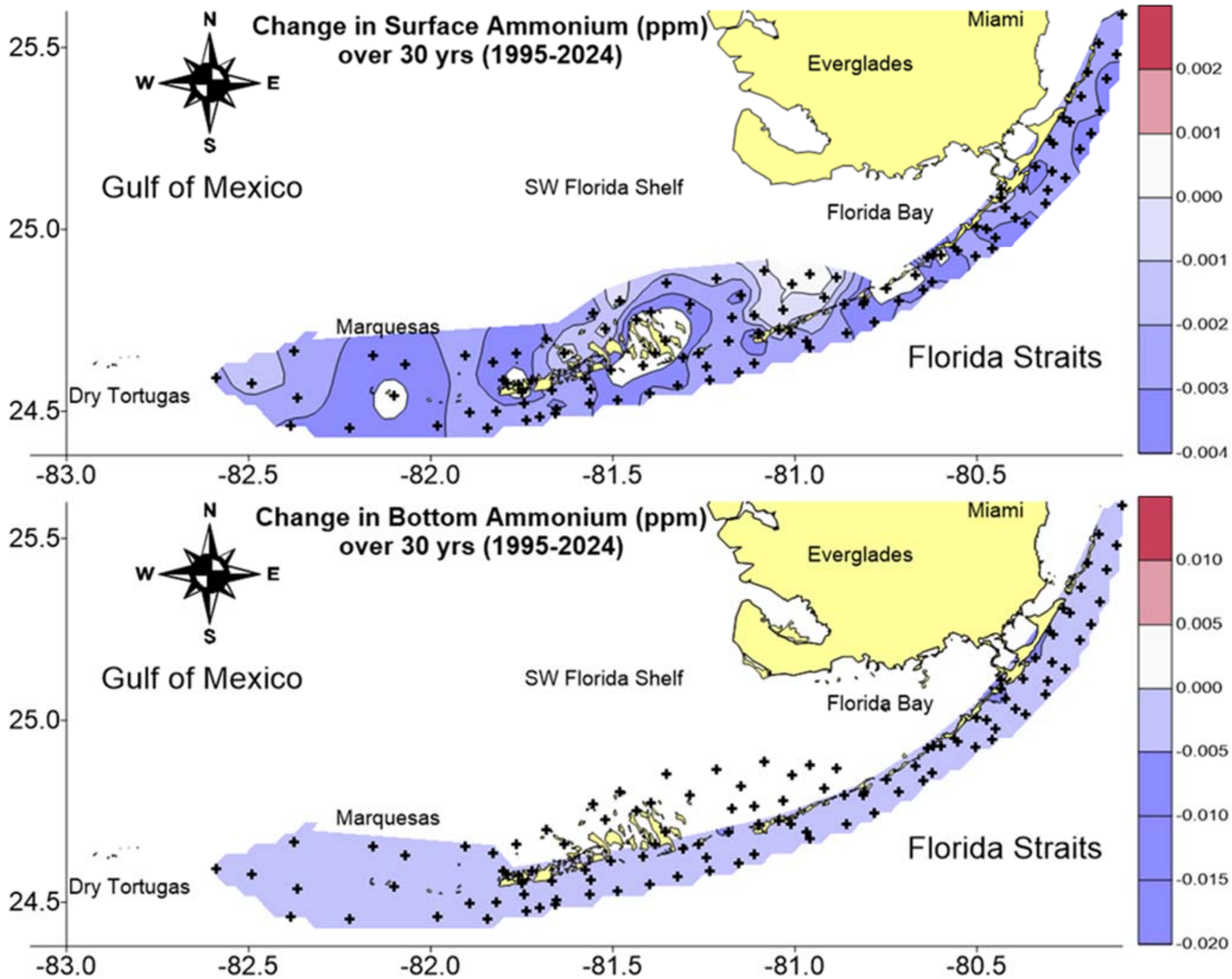

Figure 37. *Net change in surface and bottom NH_4^+ over the 30-year period.*

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. 38). The 1999-2000 NO_3^- 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). A recent uptick in NO_3^- for most regions has been observed.

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. 39). We believe the land-based disturbance from Katrina-Rita-Wilma events had a persistent effect on the FKNMS for the following two years. The effect in the Marquesas was more damped due to GOM circulation.

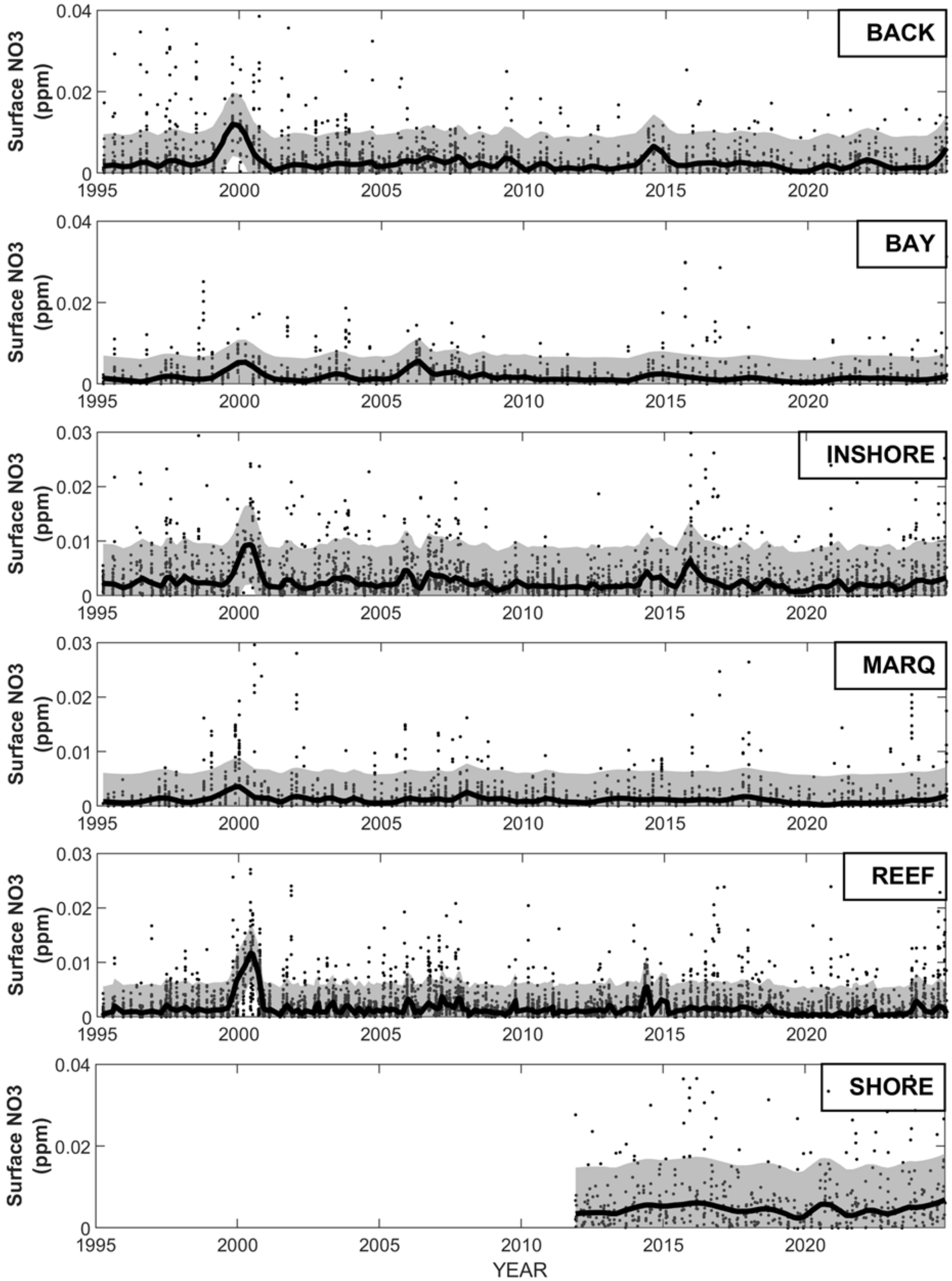

Figure 38. *Time series of surface NO_3^- zone. The line is LOESS fit.*

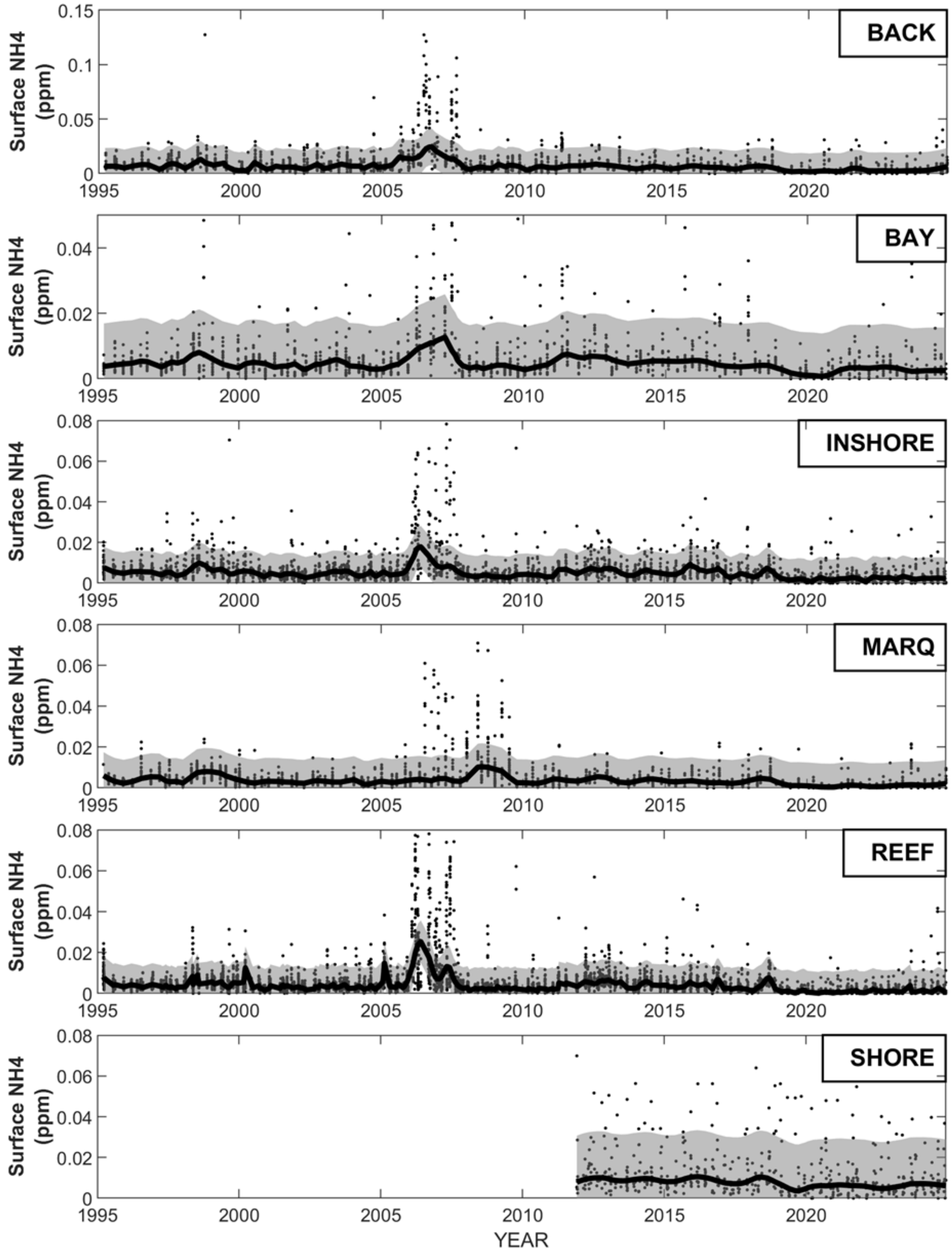

Figure 39. *Time series of surface NH_4^+ by zone. The line is LOESS fit.*

The largest sustained monotonic trend has been the decline in surface TOC throughout the FKNMS (Fig. 40). This trend may be considered favorable given that TOC corresponds with

CDOM (chromophoric dissolved organic matter), an important driver of light penetration. Declines in TOC are typically an indication of decreased terrestrial inputs to the region but see inshore-offshore gradients in bottom waters showing little to no decreases near land.

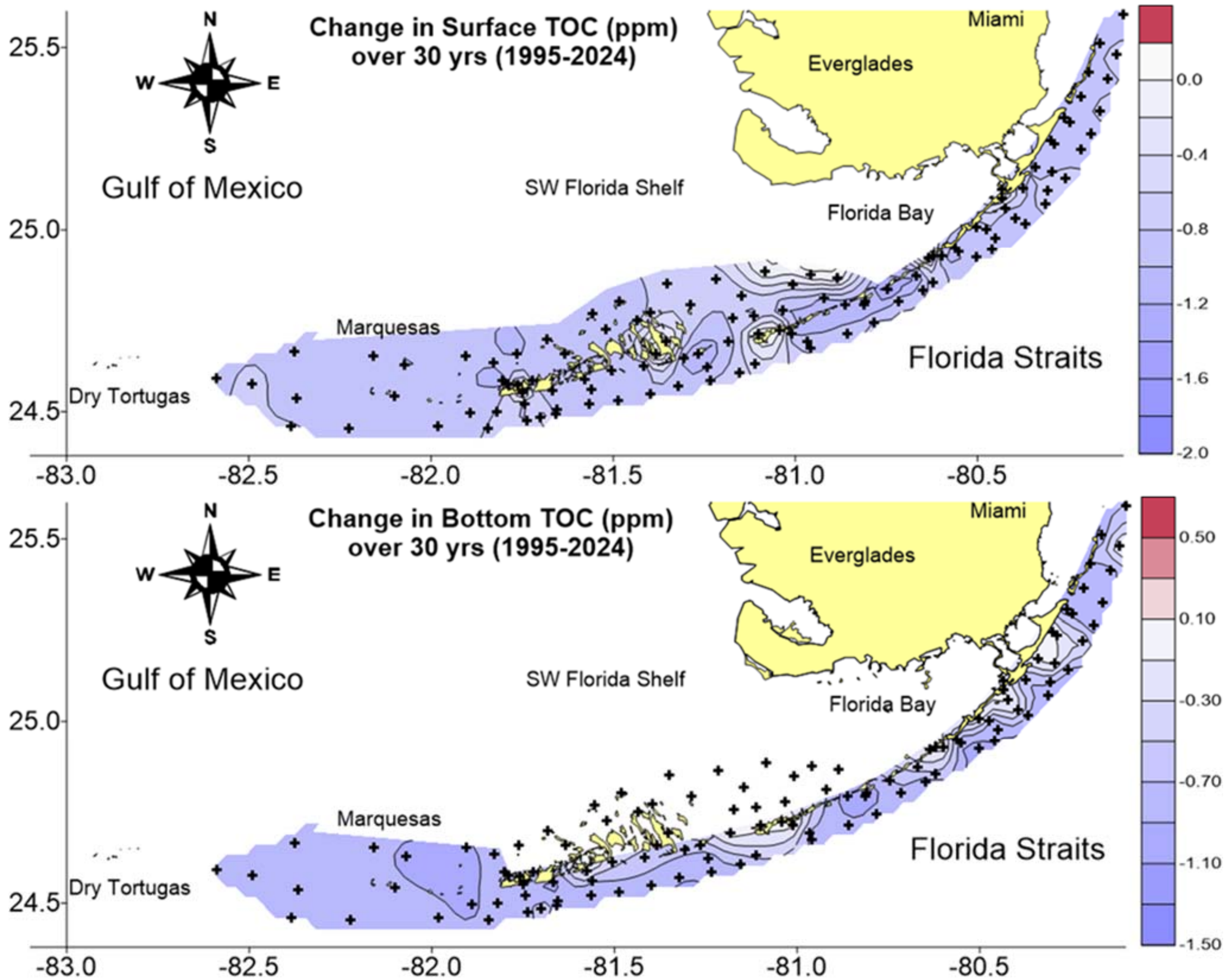

Figure 40. *Net change in surface and bottom TOC over the 30-year period.*

The TOC time series shows relatively steep declines early with a leveling out around 2005 (Fig. 41). 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 coincide with extended droughts in 2007 and 2010-2011. The rebound in TOC observed in the Bay zone has reversed.

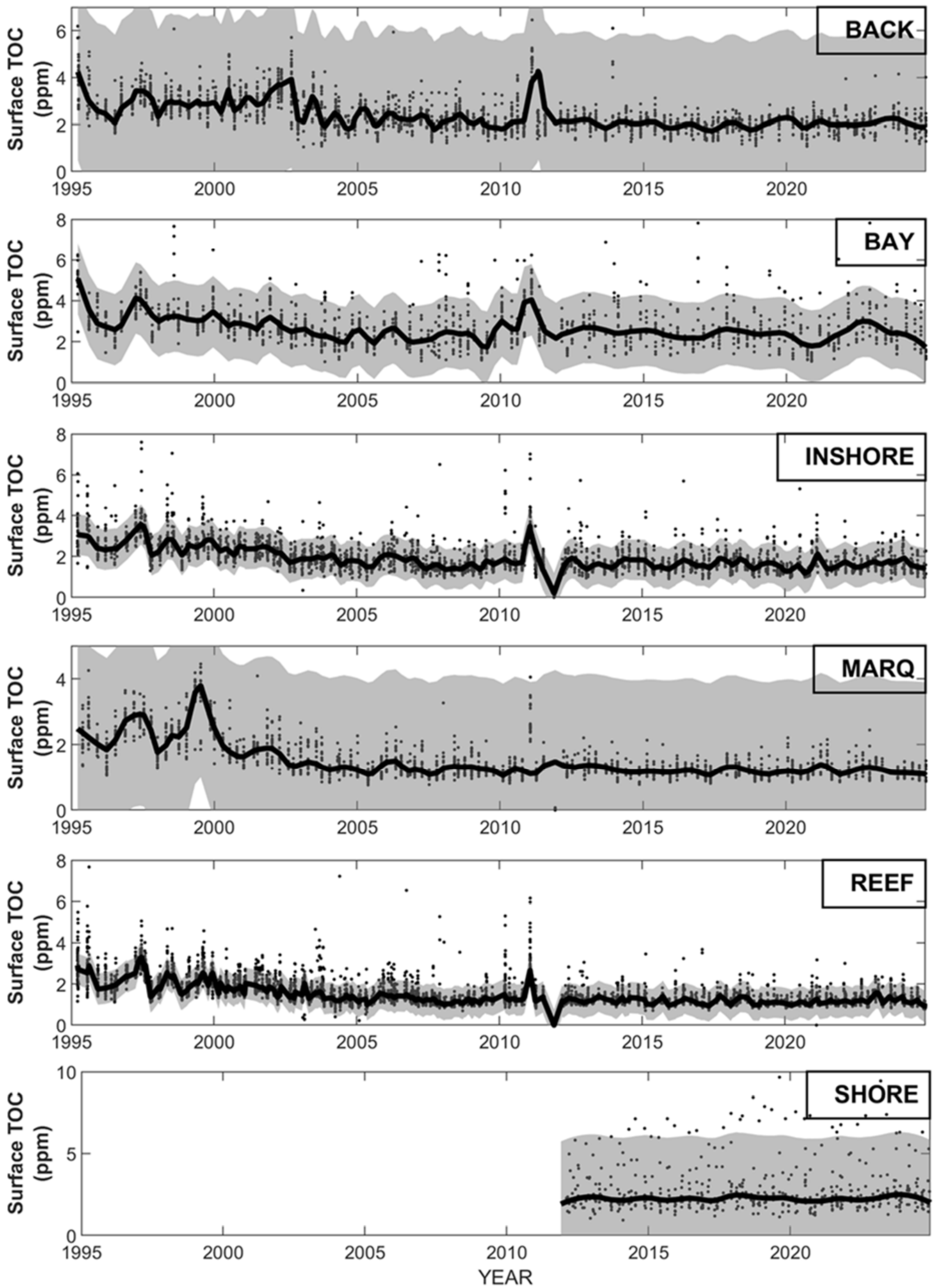

Figure 41. *Time series of surface TOC by zone. The line is LOESS fit.*

Total nitrogen declined overall except for the Sluiceway region contiguous to Florida Bay (Fig. 42). Most of this is due to declines in the organic N fraction as it makes up ~96% of the TN pool.

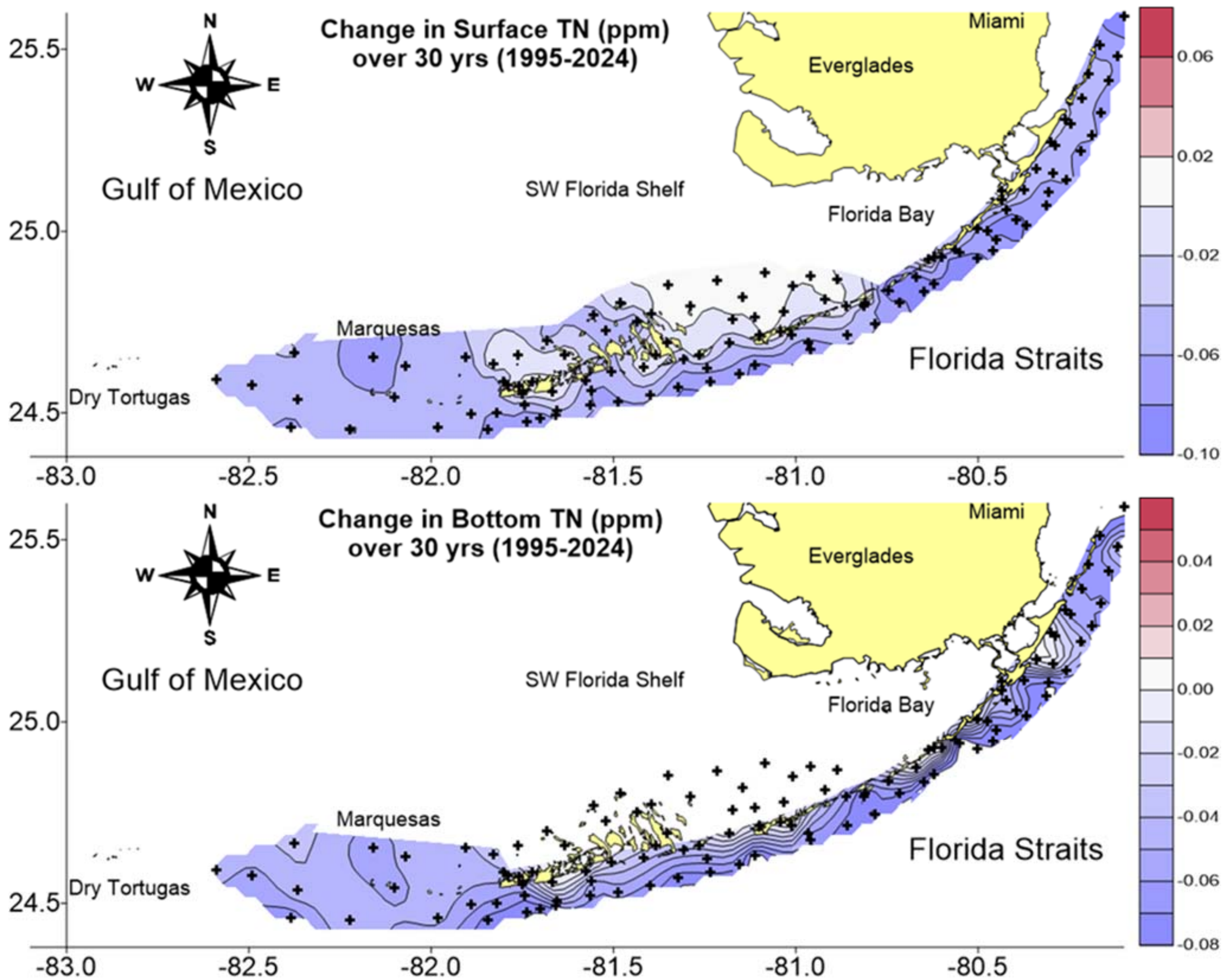

Figure 42. *Net change in surface and bottom TN over the 30-year period.*

The TN time series shows elevated concentrations across the region during 2003-4 and 2010 (Fig. 43). The long-term decline in TN is especially evident in Inshore waters of the Keys.

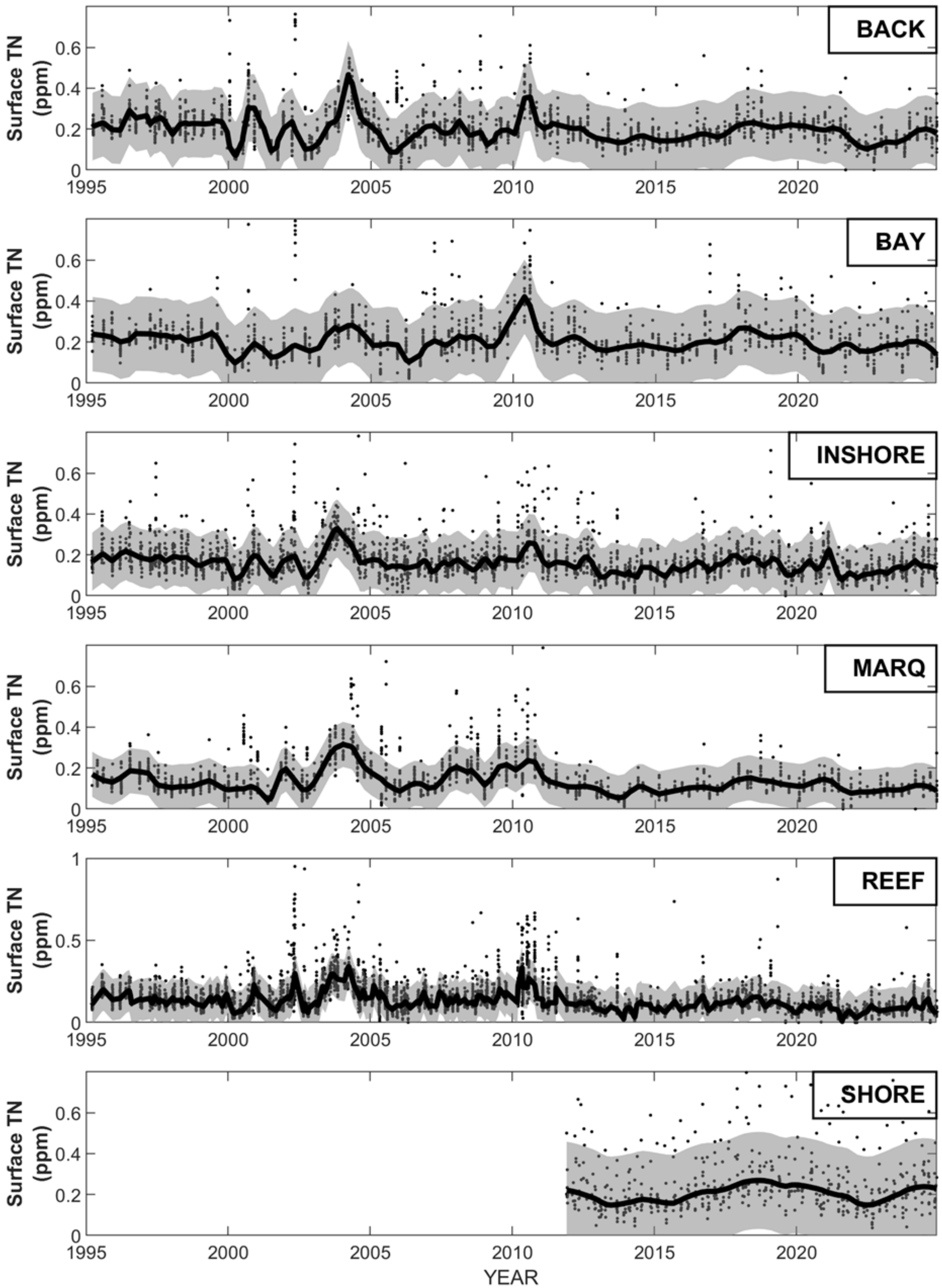

Figure 43. *Time series of surface TN by zone. The line is LOESS fit.*

The TN:TP ratio (molar) is useful in assessing phytoplankton nutrient limitation (Redfield ratio). TN:TP declined in most areas (Fig. 44) implying that primary production is becoming less P-limited throughout the FKNMS. This trend is driven by concurrent minor declines in TN and significant increases in TP.

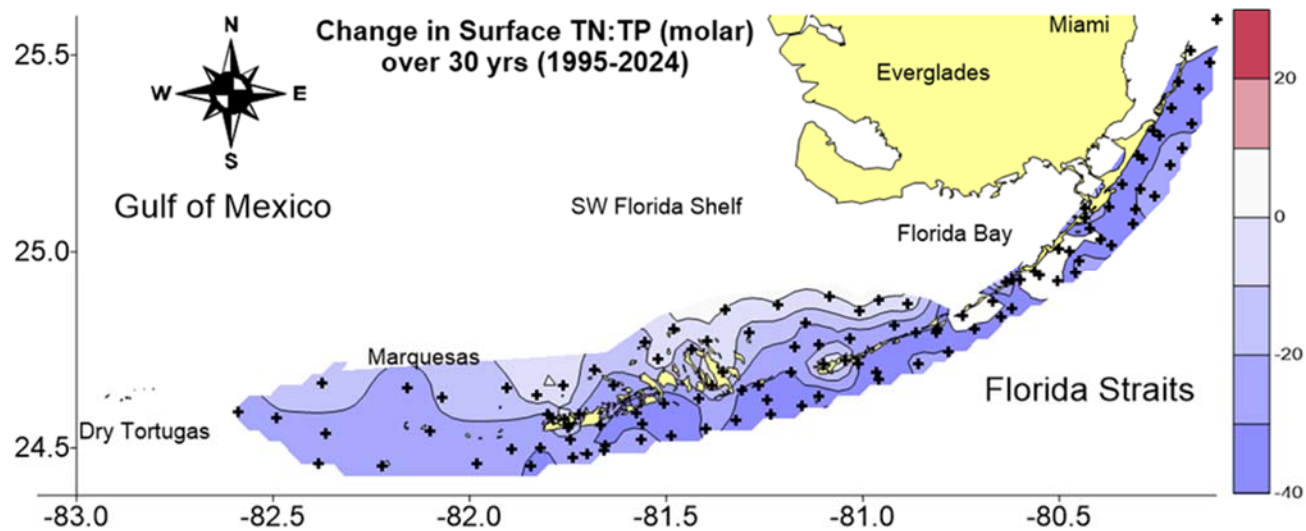

Figure 44. *Net change in TN:TP ratio in surface waters over the 30-year period.*

SiO_2 is an important nutrient for diatoms, a type of phytoplankton and an important food source for zooplankton and some fish. Minor declines in SiO_2 were observed throughout the FKNMS for the record (Fig. 45).

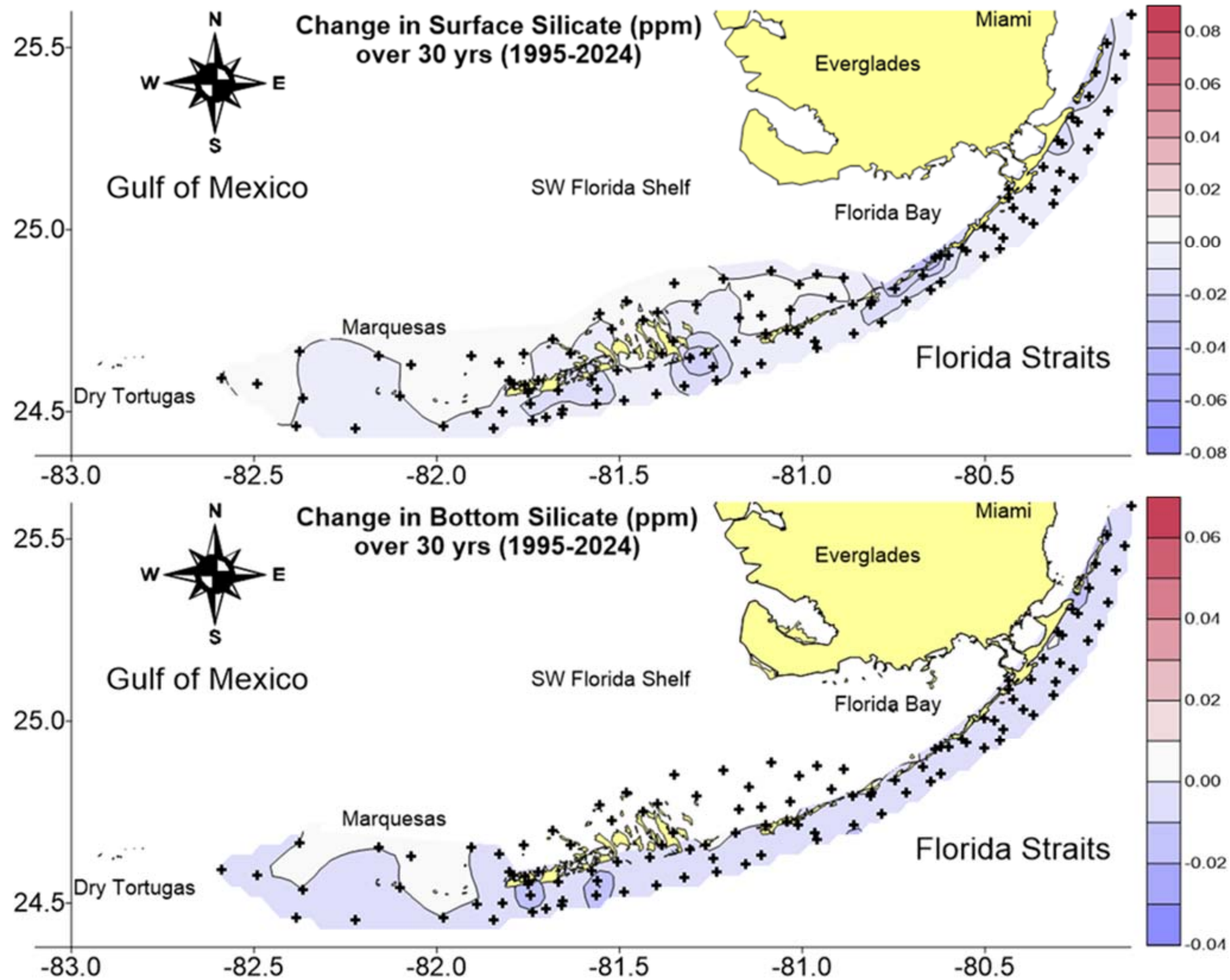

Figure 45. *Net change in surface and bottom SiO_2 over the 30-year period.*

The SiO_2 time series shows it to be relatively consistent across all regions, but with a current uptick occurring in the Backcountry (Fig. 46).

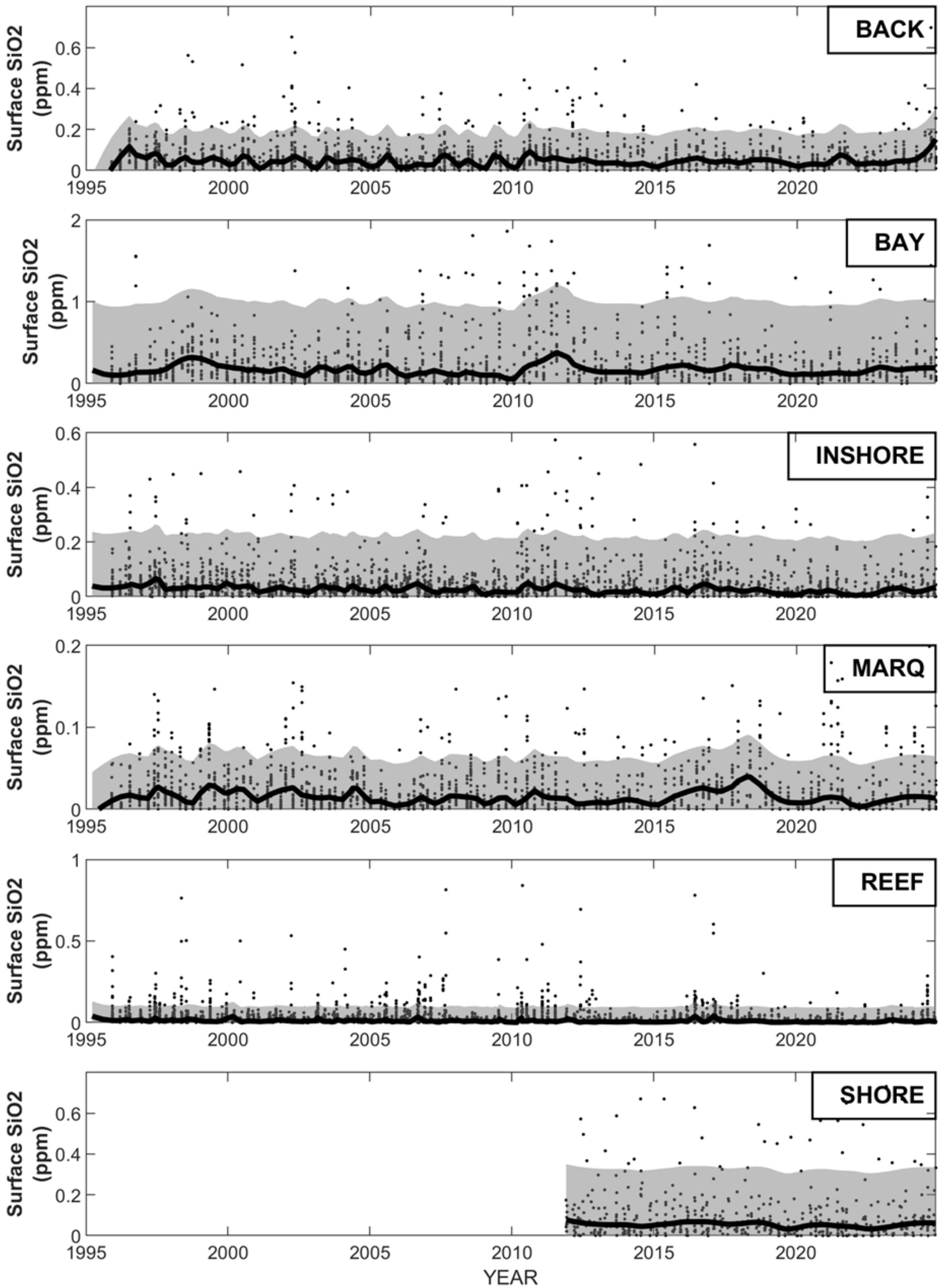

Figure 46. *Time series of surface SiO_2 by zone. The line is LOESS fit.*

Diatoms require silicate to form their external frustules (shells). Si:DIN ratios >1 promote diatom growth in the phytoplankton community. Si:DIN <1 indicates growth limitation conditions for diatoms. The norther Sluiceway shows an increase towards fostering diatom community development (Fig. 47).

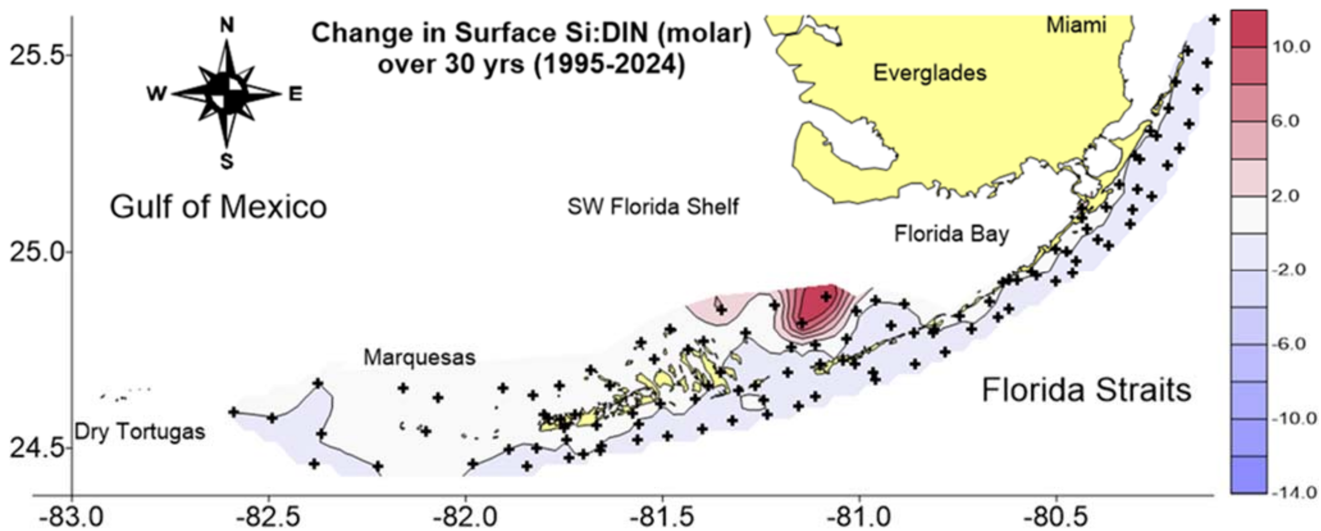

Figure 47. *Net change in Si:DIN ratio in surface waters over the 30-year period.*

No significant trends were observed in either surface or bottom salinity across the FKNMS (Fig. 48).

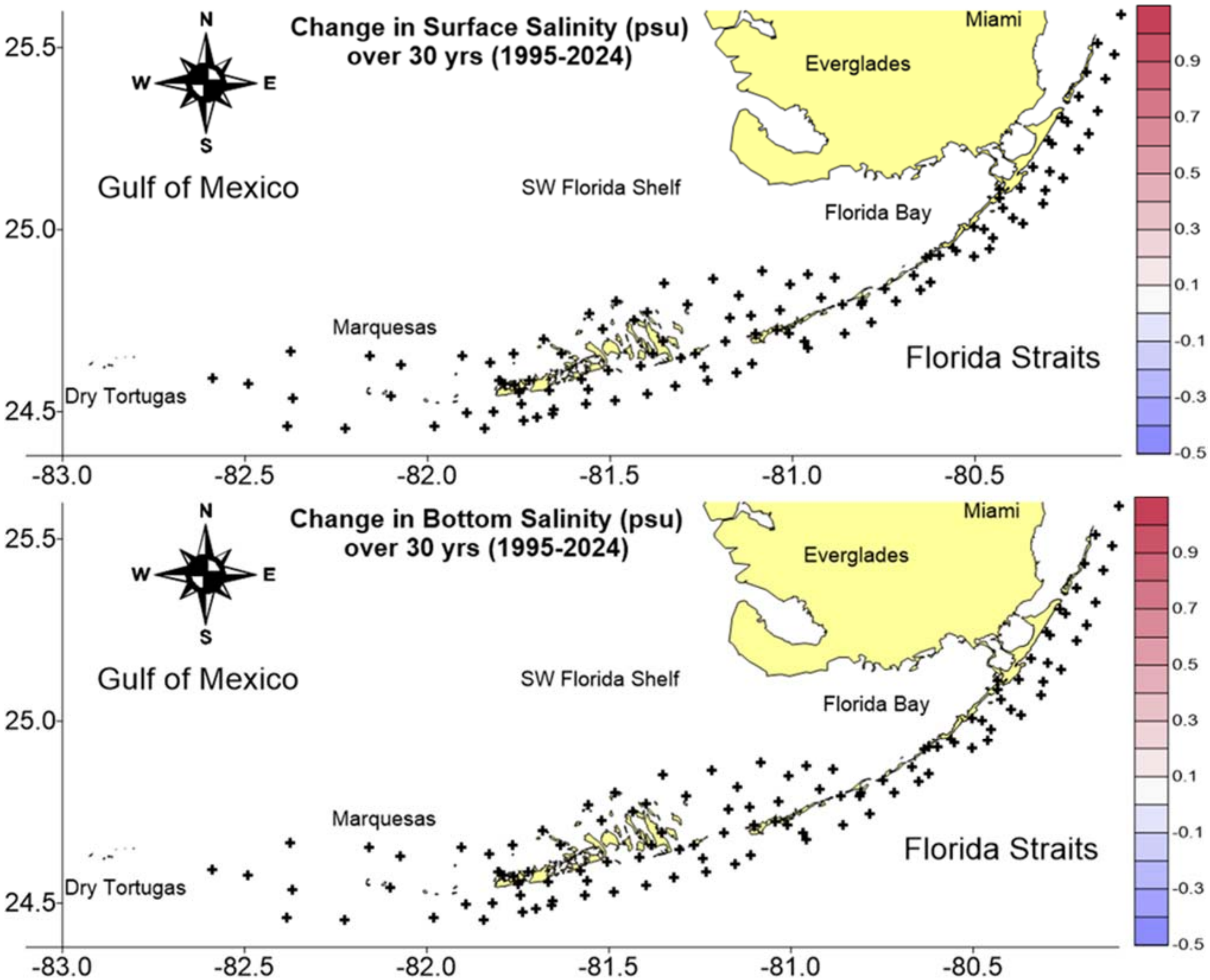

Figure 48. *Net change in surface and bottom salinity over the 30-year period.*

The time series of salinity on the Reef and Inshore areas was most congruent (Fig 49) with LOESS curve being smooth and consistent. Largest variations occurred in the Bay and Backcountry, areas that are most influenced by mainland freshwater and GOM 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. 49). Note the large depression in salinity in the Marquesas during 2005-07. We believe this was legacy of the 2005 hurricane season, which affected salinity in the GOM for an extended period afterwards (Briceño & Boyer 2010).

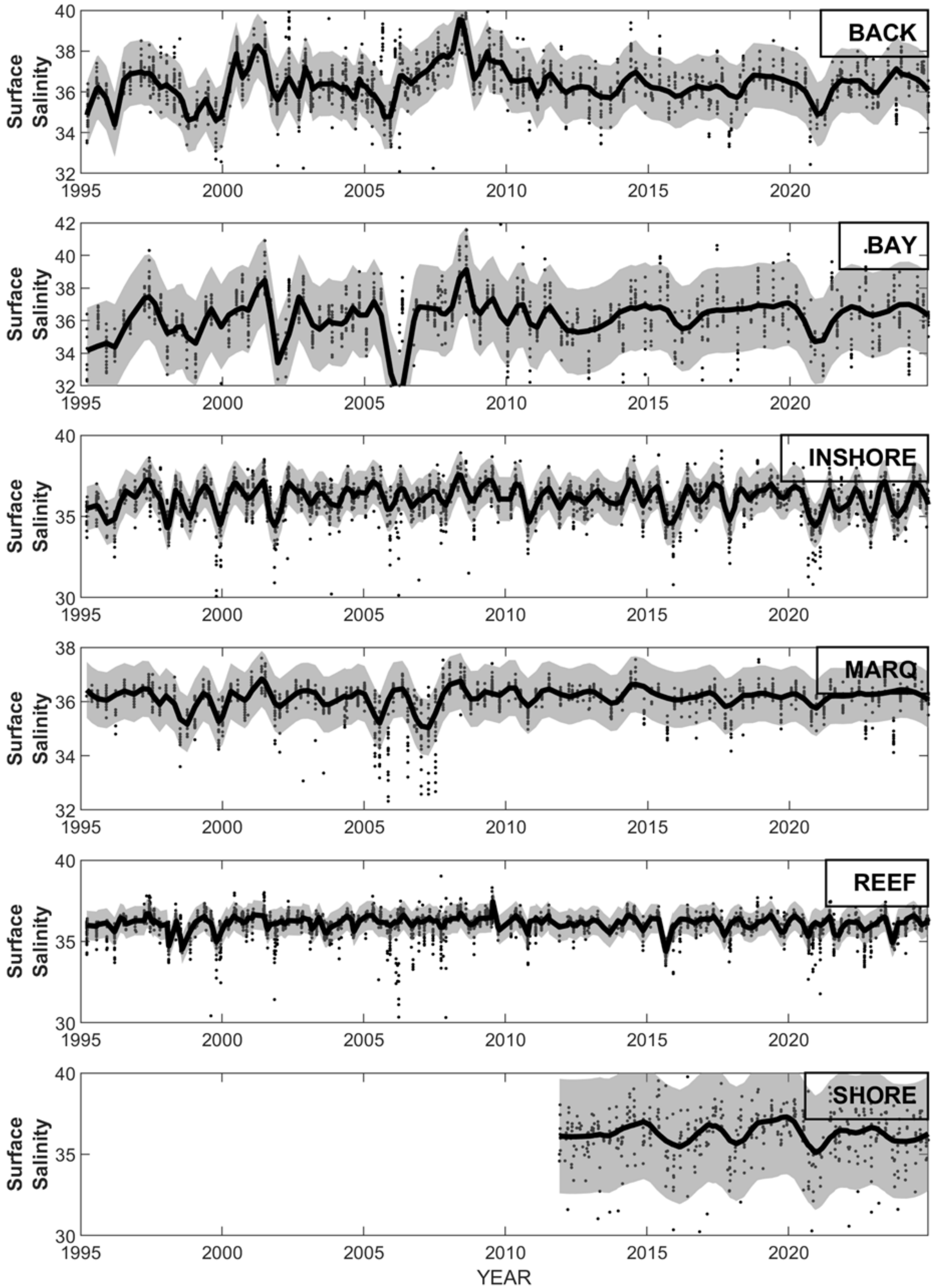

Figure 49. *Time series of surface salinity by zone. The line is LOESS fit.*

Temperature displayed marginally significant long-term trends as well, but the change map does show some differences across regions (Fig. 50). The Bay zone and offshore areas tended to decline; only one Shore site off Marathon increased. Interestingly, with data from 2024, we observed increased surface temperature at three offshore reef sites.

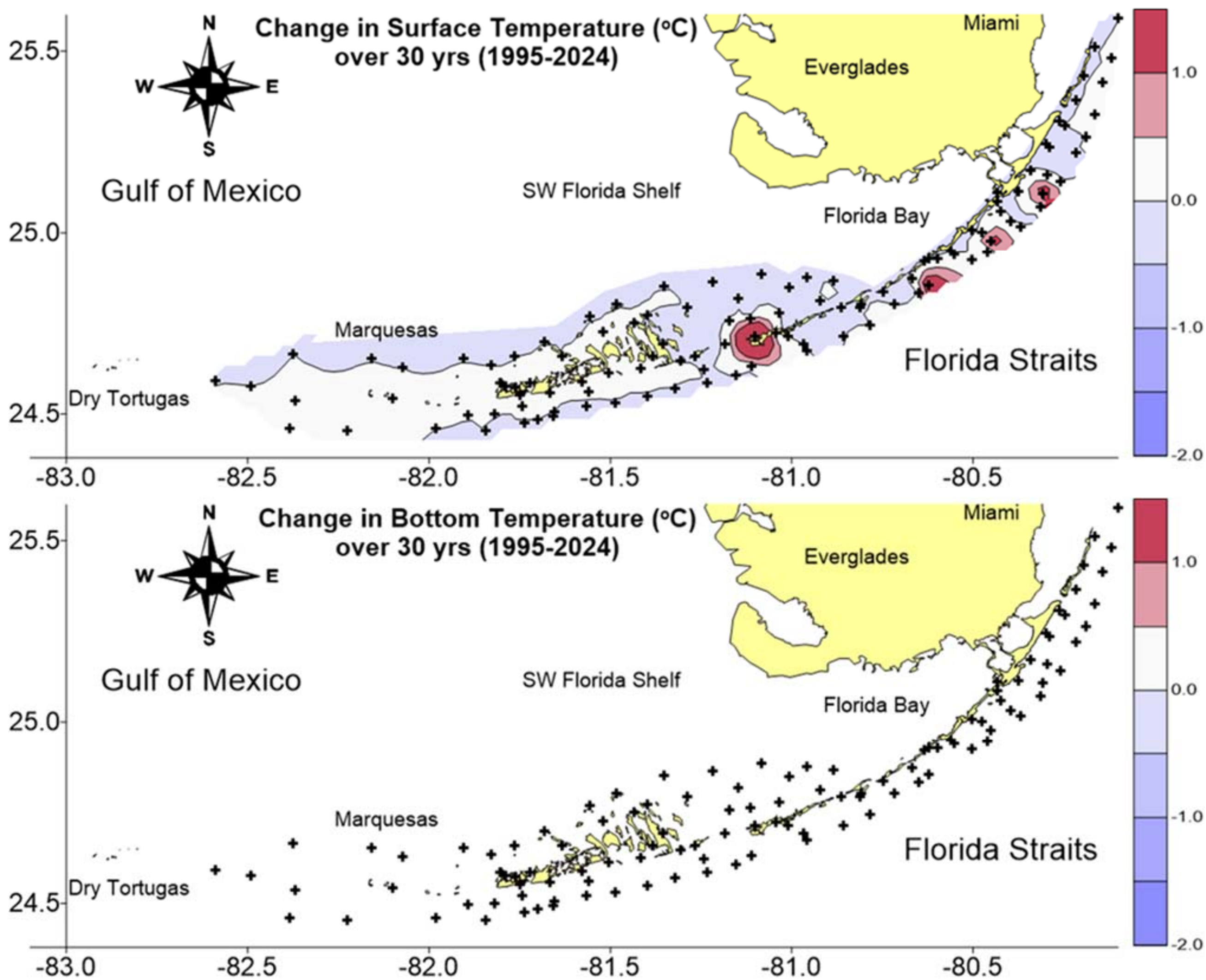

Figure 50. *Net change in surface and bottom temperature over the 30-year period.*

Quarterly collection of temperature over 30 years cannot be expected to resolve the small changes in subtropical water temperature expected under global climate change (Fig. 51). Daily temperature measurements from three other research programs have shown that the waters of the Florida Keys have warmed ~0.8°C for the period 1878-2012 (Kuffner et al. 2015). However, note the general increasing trends in water temperatures in the Backcountry, Bay, and Shore areas since 2011.

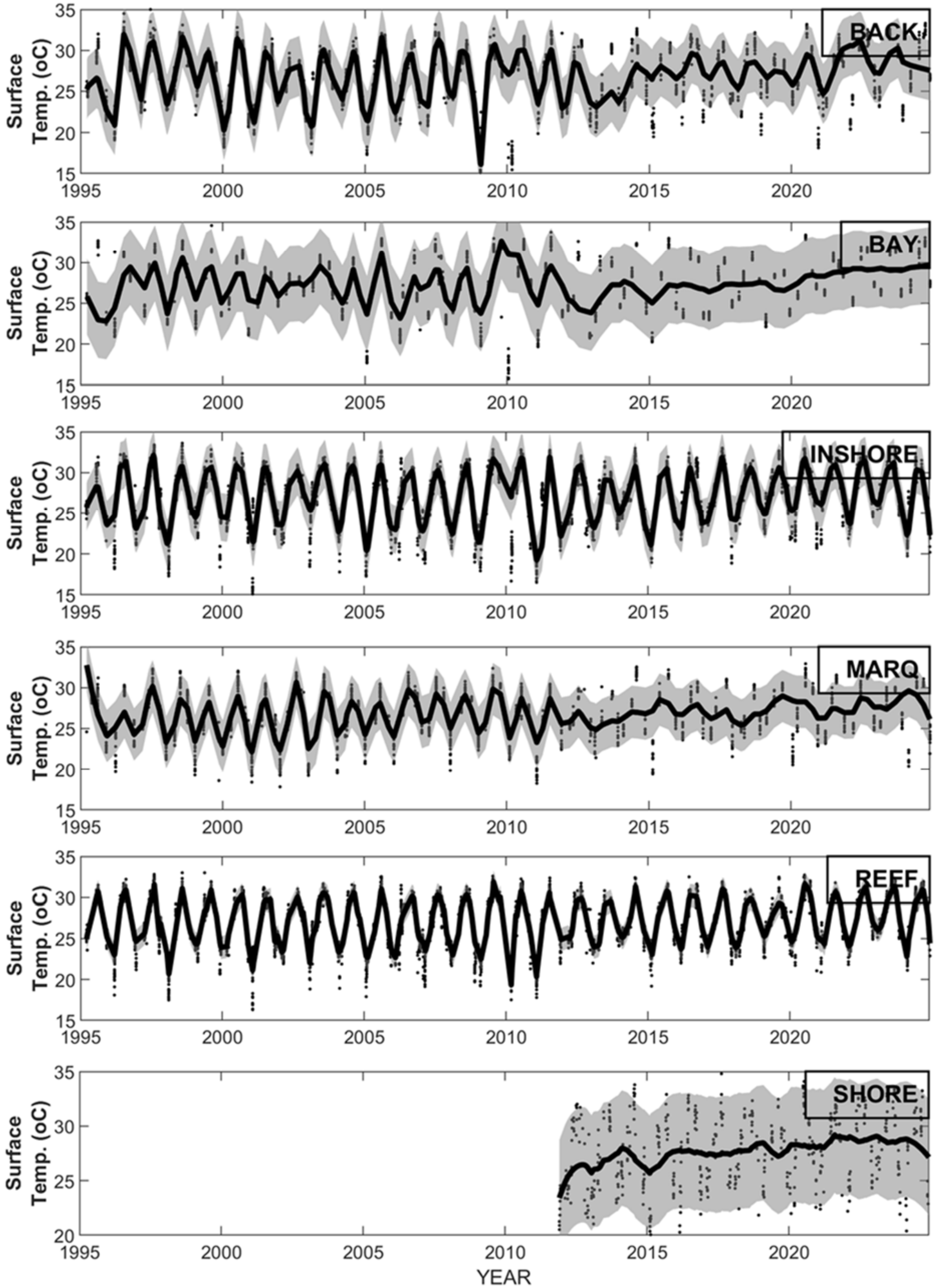

Figure 51. *Time series of surface temperature by zone. The line is LOESS fit.*

DO saturation increased at most sites in the FKNMS, which is generally considered a benefit to aquatic biota (Fig. 52). Measurements taken during daylight hours may be influenced primary production in the water column and benthos. Largest increases in DO_{sat} were observed offshore, indicating non-terrestrial influence. Some areas in the Sluiceway closest to Florida Bay and north Backcountry also showed small decreasing trends.

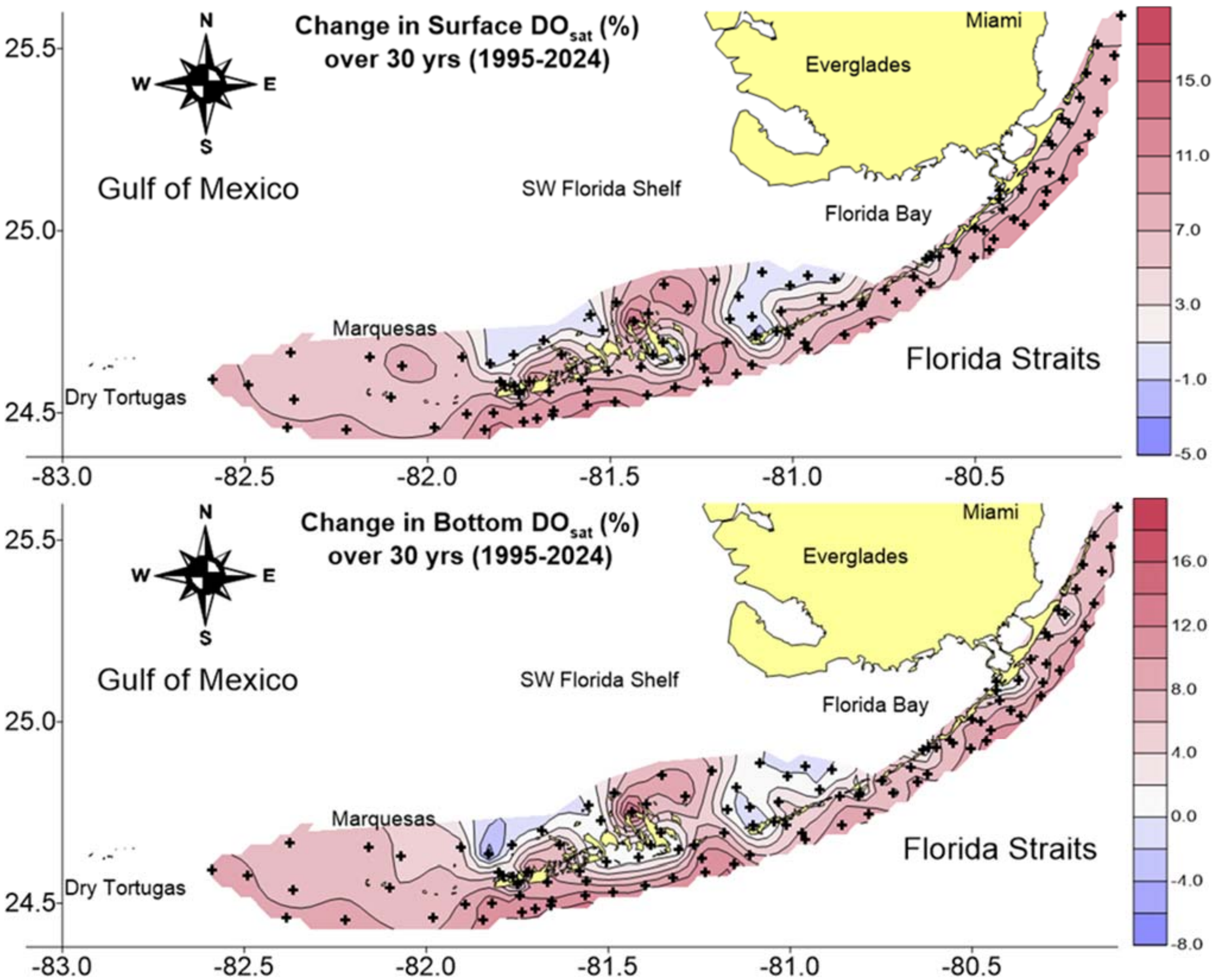

Figure 52. *Net change in surface and bottom DO saturation over the 30-year period.*

By looking at the map, one might assume that DO_{sat} has experienced a slow, incremental increase over the 30-year period. However, the LOESS regression of surface DO_{sat} showed a small decline in most zones (Fig. 53) and then a rapid decline from 2004 to early 2007 with a 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.

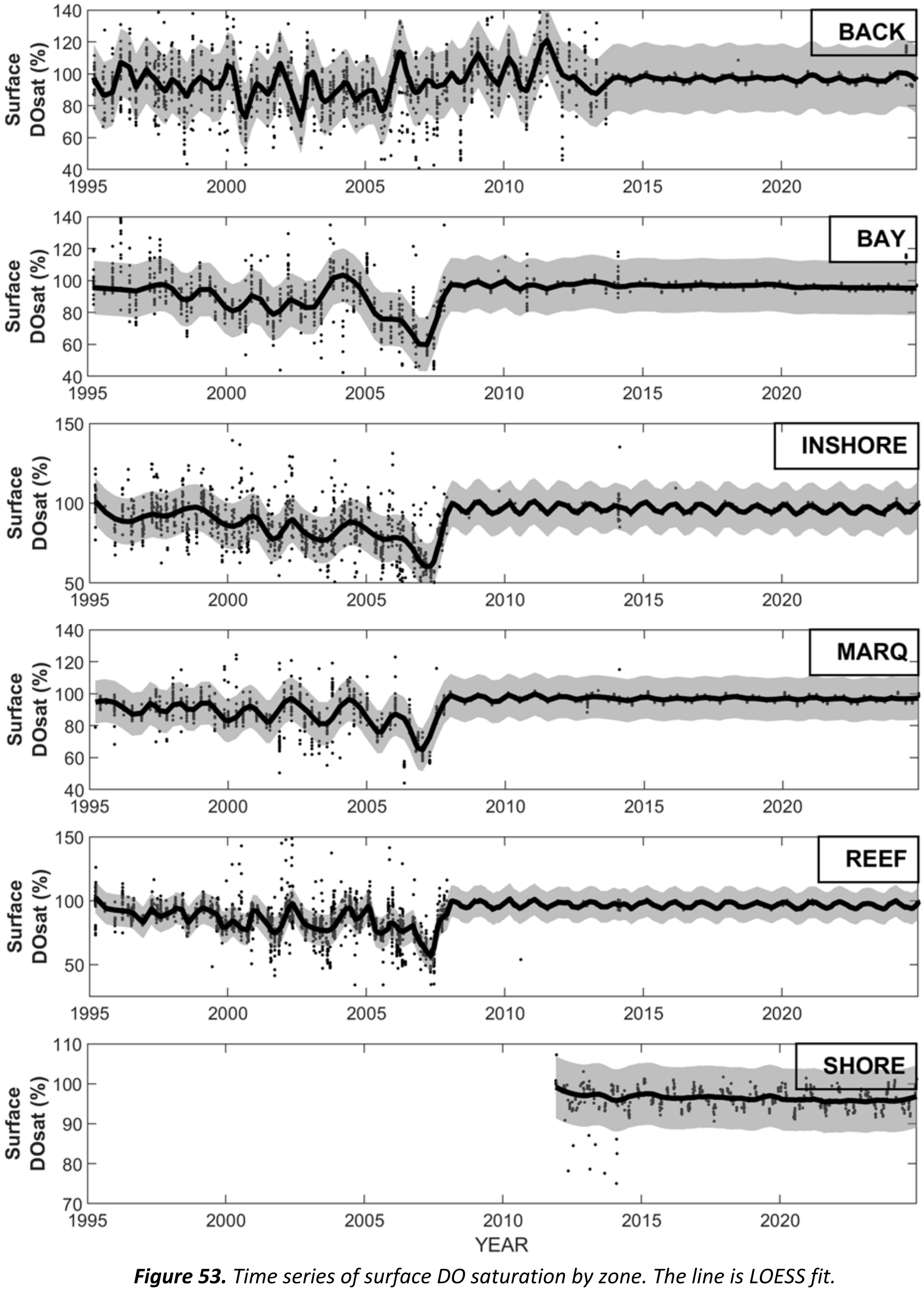

Figure 53. *Time series of surface DO saturation by zone. The line is LOESS fit.*

Water column turbidity declined throughout the FKNMS (a beneficial result, Fig. 54). The largest declines occurred in northern Sluiceway/Backcountry and Marquesas. However, there were increases in surface turbidity at specific Shore sites in Upper Keys.

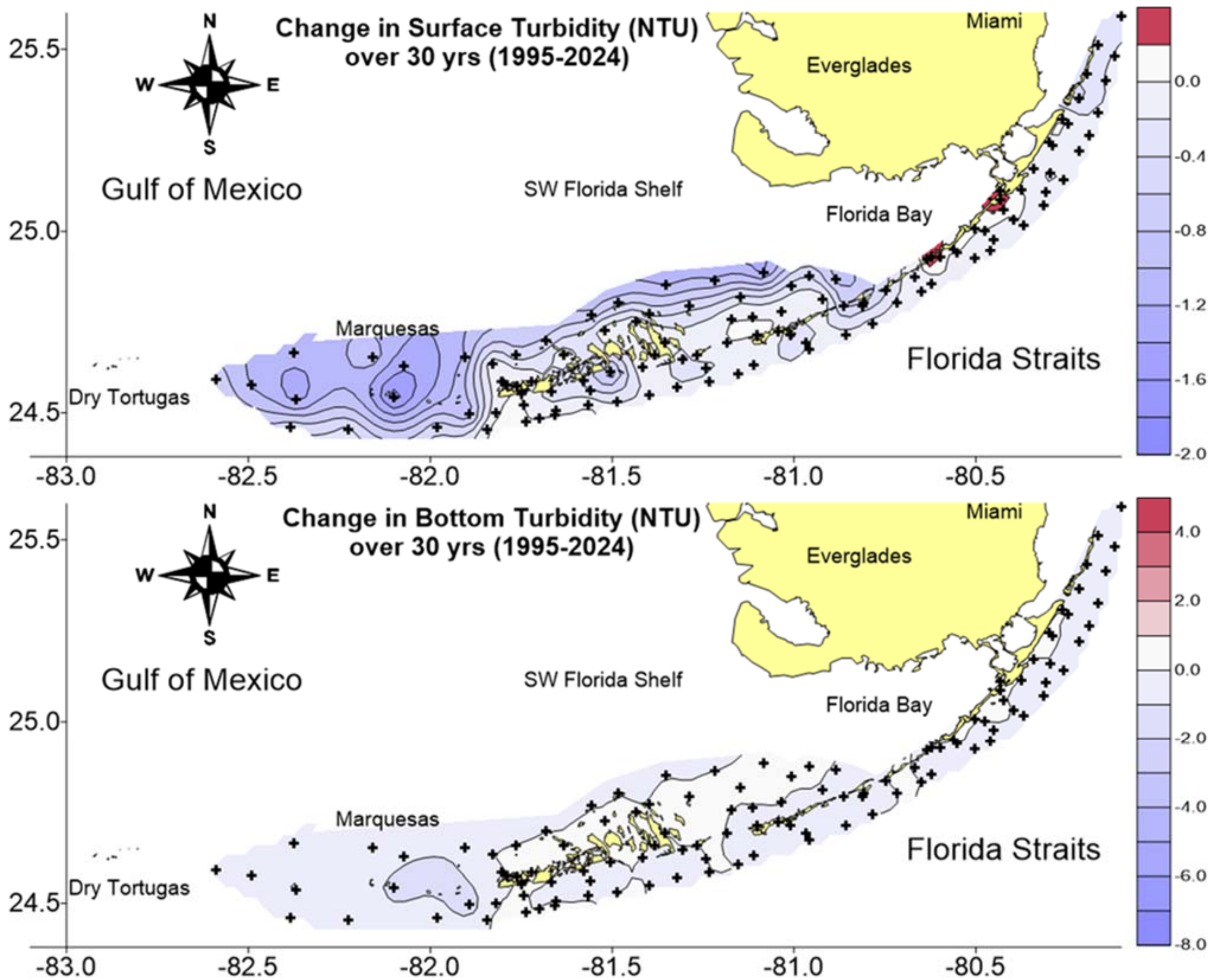

Figure 54. *Net change in surface and bottom turbidity over the 30-year period.*

The time series plots of surface turbidity (Fig. 55) gave more information on the nature of the trends. Turbidity was relatively consistent for the period 1995-2005, increased during the 2005 hurricanes, then rapidly returned to previous levels. Around 2010, turbidity across the region dropped to lower levels than before the 2005 disturbances and has remained so.

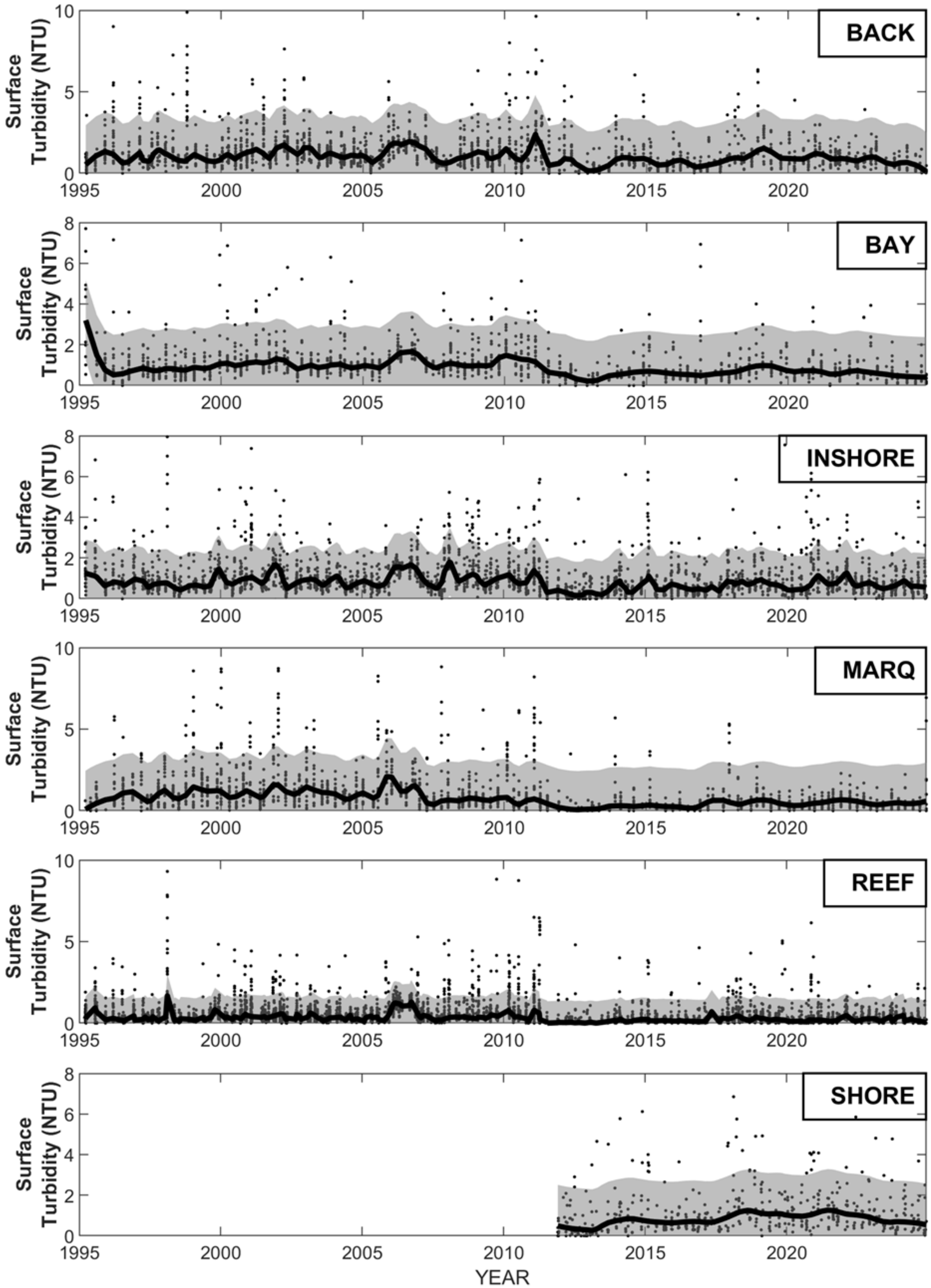

Figure 55. *Time series of surface turbidity by zone. The line is LOESS fit.*

The diffuse light attenuation coefficient (K_d), a measure of light penetration, also declined (a beneficial result) in some offshore areas and Marquesas (Fig. 56). However, there were isolated increases in K_d (less light penetration) in the Backcountry, Sluiceway, and some Shore and Inshore sites.

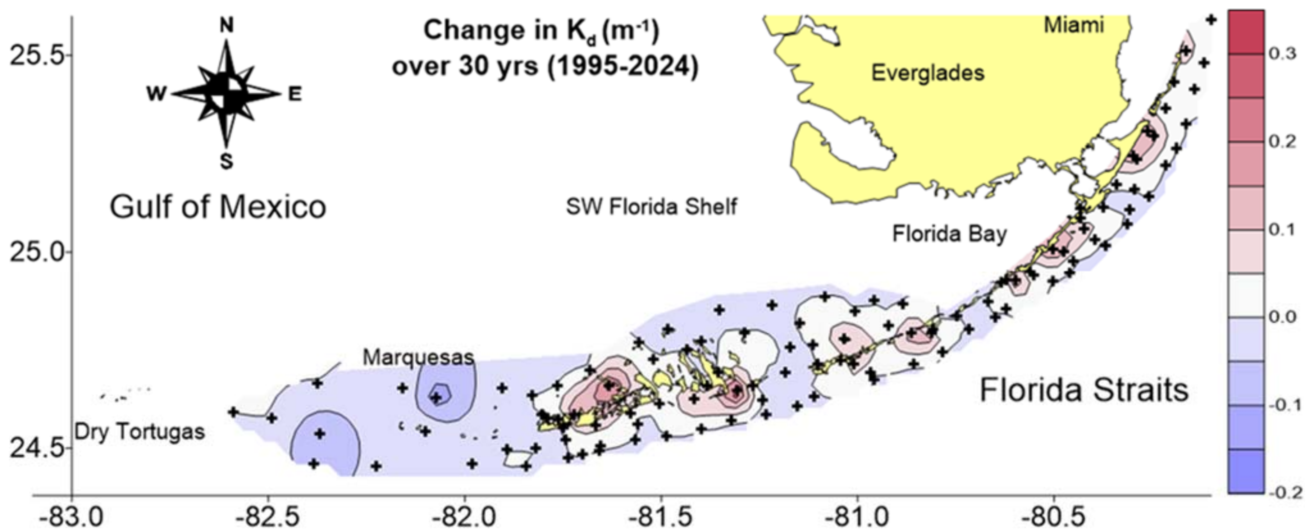

Figure 56. *Net change in K_d over the 30-year period.*

Lower K_d tends to increase the proportion of surface irradiance reaching the bottom (I_o). More light on the bottom is beneficial to corals, seagrass, and algae. Increases in I_o were observed mostly in the Marquesas and isolated offshore Reef sites (Fig. 57). The Backcountry experienced decreases in I_o (with increases in K_d) resulting in less light penetrating to the bottom.

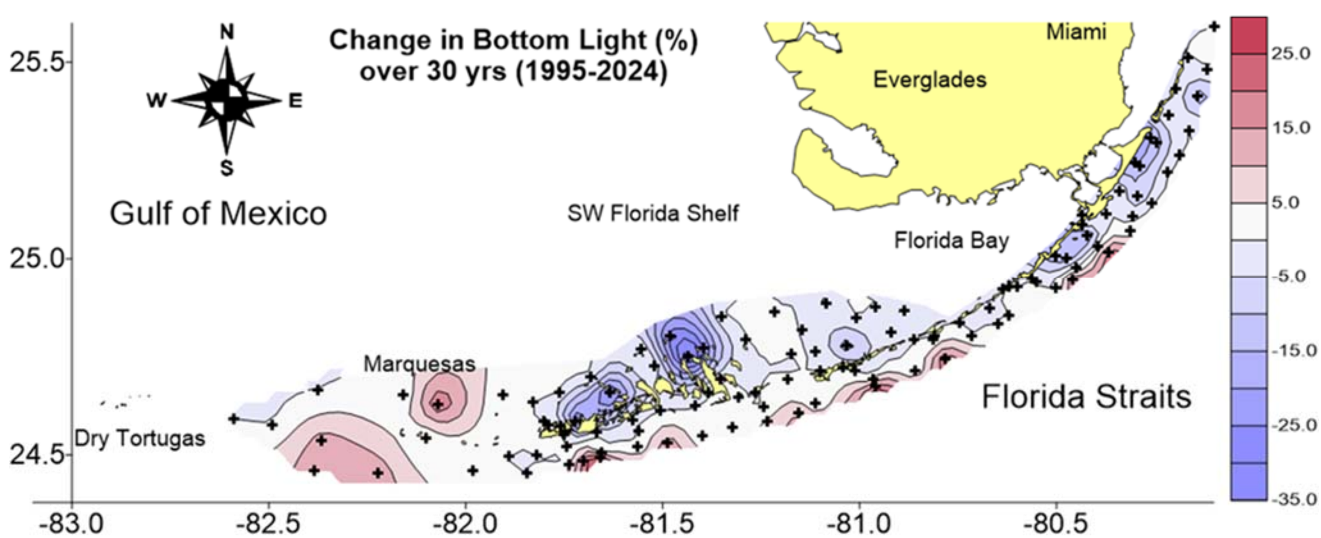

Figure 57. *Net change in bottom I_o over the 30-year period.*

The time series of K_d (Fig. 59) and I_o (Fig. 59) 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. Backcountry sites experienced a significant drop from 2006 to 2008.

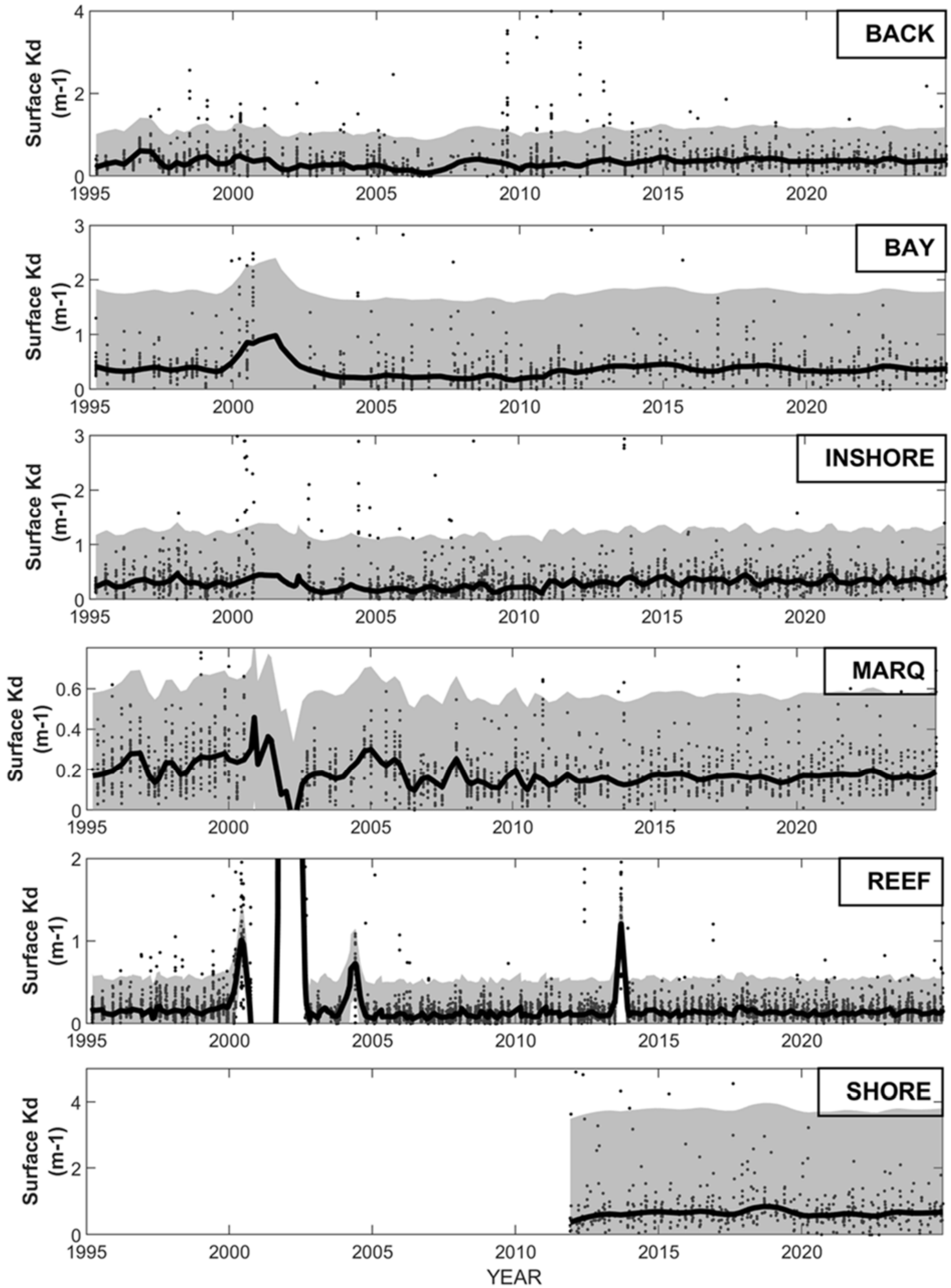

Figure 58. *Time series of Light Extinction (K_d) by zone. The line is LOESS fit.*

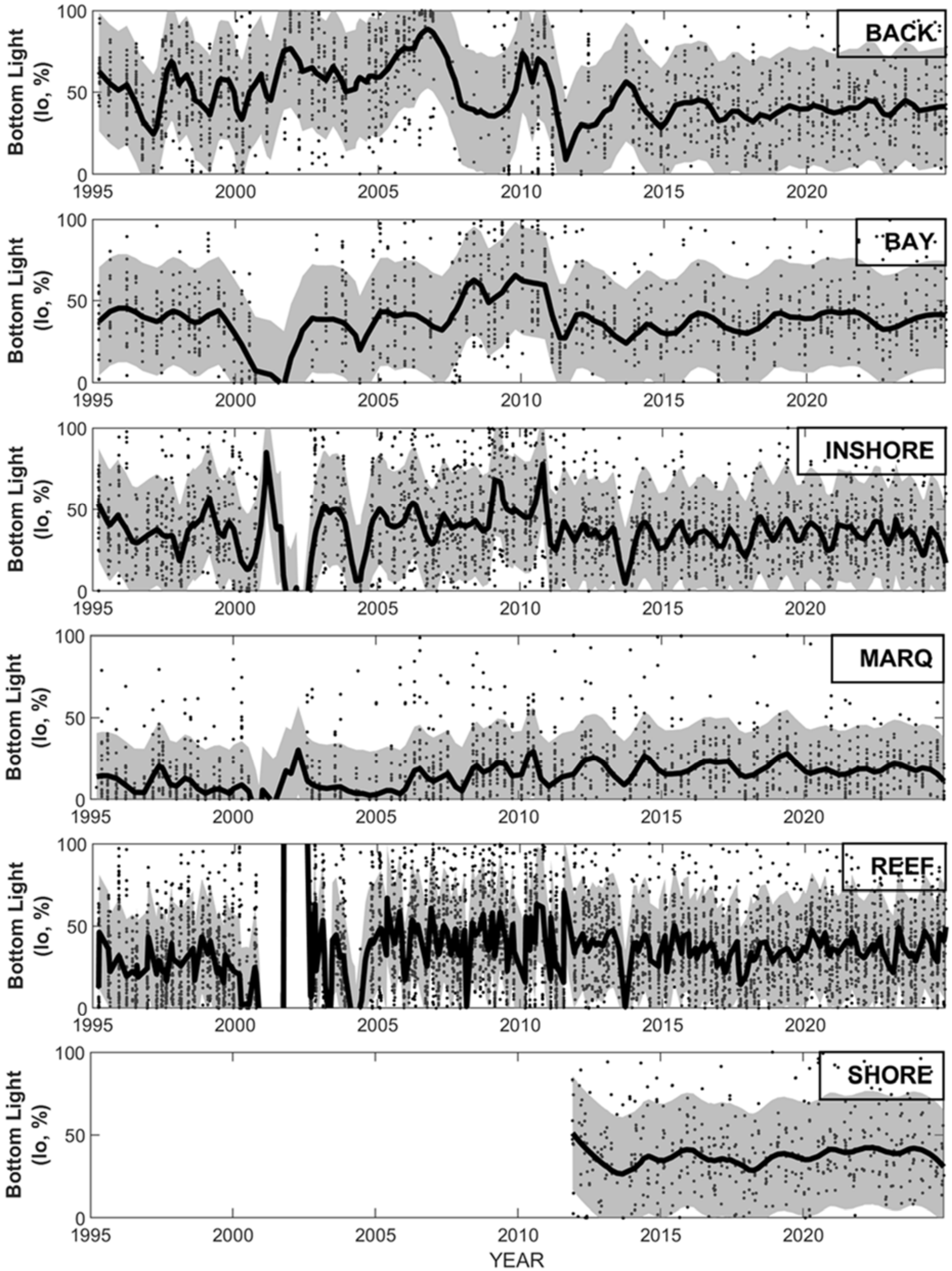

Figure 59. *Time series of % of surface light reaching the bottom (I_o) by zone. The line is LOESS fit.*

4. EPA Strategic Targets

The EPA developed Strategic Targets for the Water Quality Monitoring Project (SP-47) which states that beginning in 2008, they shall annually maintain the overall water quality of the near shore and coastal waters of the FKNMS according to the 2005 baseline. For reef sites, CHLA should be less than or equal to 0.35 $\mu g\ l^{-1}$ (ppb) and the K_d should be less than or equal to 0.20 m^{-1}. For all monitoring sites in FKNMS, DIN should be less than or equal to 0.75 µM (10.5 ppb) and TP should be less than or equal to 0.25 µM (7.7 ppb).

The 2011 reduction of sampling sites in Tortugas/western FKNMS (Tortugas, 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 complications, we have not included the Tortugas or Shore stations in calculation of compliances after 2010.

The number of sites and percentage of total sites meeting and exceeding these Strategic Targets for the period of record to 2024 are shown in Table 3. In addition, Figure 60 shows the graphs of percentage of sites meeting the targets in relation to baselines for DIN, TP, CHLA, and K_d.

For the six years prior to 2023, CHLA was elevated relative to the 2005 Target Baseline. 2023 showed a return to lower CHLA across the region and 2024 continued that trend. TP was elevated for three of the last four years but returned to below target for 2024. These are indicators of creeping eutrophication and bear continued vigilance.

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

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 ppb	$K_d \leq 0.20\ m^{-1}$	DIN ≤ 10.5 ppb	TP ≤ 7.7 ppb
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%)
2021	123 of 172 (71.5%)	141 of 172 (82.0%)	611 of 688 (88.8%)	527 of 688 (76.6%)
2022	98 of 172 (57.0%)	129 of 171 (75.4%)	533 of 686 (77.7%)	458 of 688 (66.6%)
2023	129 of 170 (75.9%)	125 of 166 (75.3%)	624 of 684 (91.2%)	294 of 684 (43.0%)
2024	138 of 171 (80.7%)	127 of 169 (75.1%)	570 of 687 (83.0%)	584 of 688 (84.9%)

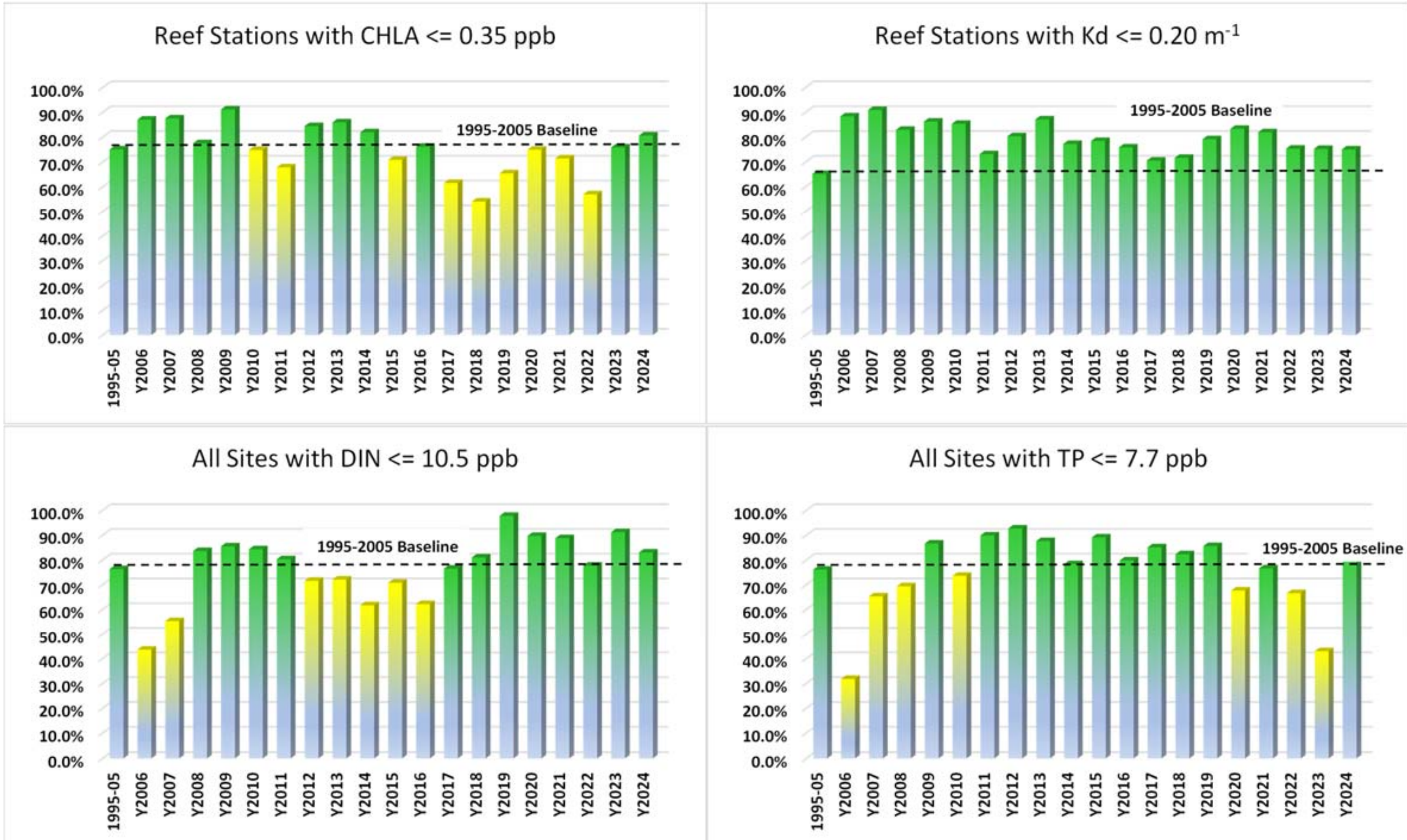

Figure 60. *EPA targets expressed as percent of sites meeting baseline criteria by year.*

This report serves as a **30 year summary** of efforts to date in the execution of the Water Quality Monitoring Project for the FKNMS as part of the WQPP. The period of record for this report is Mar. 1995 – Dec. 2024 and includes data from 118 quarterly sampling events within the FKNMS over those 30 years. 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 FKNMS hydroscape. These results confirm that monitoring may be viewed as a tool for answering management questions and developing new scientific hypotheses. We continue to maintain a website where data and reports from this project are accessible to the public, http://serc.fiu.edu/wqmnetwork/.

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