Seasonal Salinity Trends in Central and Southern Biscayne Bay (Florida, USA)

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for publication in
Journal of Hydrologic Engineering

Abstract

Salinity in estuaries varies naturally due to tides, weather, geomorphology, freshwater flow, climate, and sea-level. Before the 1950's, water management in Southern Florida focused on diverting freshwater to the ocean to make historic wetlands more amenable to development and to protect human life. However, current water management activities aim to restore wetlands and estuaries while maintaining flood control and drinking water for the human population. Due to anthropogenic alteration, the spatiotemporal variability in salinity within Biscayne Bay, Florida, is a significant concern for ecosystem restoration under the Comprehensive Everglades Restoration Plan (CERP). This study aims to analyze daily seasonal salinity trends within the Bay and quantify the change in salinity per year (salinity slope). Salinity data, collected at 30 stations within the central and southern regions of Biscayne Bay over 16 years (2005–2020), were examined for trends. The non-parametric Seasonal Kendall trend test, at a 0.05 significance level, was used for the analysis. Results of the trend analysis show salinity slopes were consistently positive (indicating increasing salinity over time) in the southern portion of the study area and negative (indicating decreasing salinity over time) in the northern portion of the study area. Throughout the study region, most salinity slopes were positive in the wet season and negative in the dry season. The study results show trends in seasonal salinity, which helps in understanding changes in this region. This study will aid future management efforts within Biscayne Bay.

Key words: Biscayne Bay, salinity, trend analysis, seasonal Kendall test, salinity slopes

Introduction

One of the defining characteristics of estuaries is the temporal and spatial variability in salinity (Torregroza-Espinosa et al. 2021). Drivers of the salinity in estuarine systems include natural and anthropogenic factors (NOAA 2021). Estuarine salinity is expressed as Practical Salinity Unit (PSU; UNESCO 1985). Estuarine salinity gradients impact physical processes and the distribution of organisms in ecosystems (Shellenbarger and Schoellhamer 2011). In South Florida, adverse and rapid salinity changes have impacted estuarine ecosystems (Bachman and Rand 2008).

Drivers of the salinity in South Florida’s estuarine systems have varied over the past 200 years (SFWMD 2023a). During the mid-1800s, natural habitats were impacted due to the extension of farms and ranch lands into the wild (NPS and OERI 2022). In the late 1800s, many wetlands in South Florida’s Everglades were drained or filled, and canals were dug to alter the natural freshwater flow regime (NPS and OERI 2022). In 1948, the Central and Southern Florida Flood Control Project drained half of the original Everglades through water management infrastructure (NPS and OERI 2022), allowing South Florida to develop into one of the most important economic regions in the country (USACE and USDOI 2015). Frequent hurricanes and floods in the early 20th century encouraged flood control measures to protect human life and economies in the region (OERI 2021). Freshwater that used to flow from Lake Okeechobee through the Everglades was slowly diverted to the coasts through an extensive and efficient network of canals (NPS and OERI 2022). These actions impacted estuarine habitat near canal mouths by creating rapid fluctuations in salinity (Browder et al. 2005) and declined the abundance and diversity of ecosystems within the Biscayne Bay ecosystem (SFNRC 2006).

The draining of the Everglades generated the need for restoration and resulted in the formulation of the Comprehensive Everglades Restoration Plan (CERP) (NPS and OERI 2022).

CERP was authorized in 2000 (OERI 2023) and is the largest hydrologic restoration project in the United States (National Academy of Sciences 2016). The goal of CERP is to reinstate the quantity, timing, quality, and distribution of freshwater in the ecosystem to gradually return to pre-development conditions (Marshall et al. 2009; NPS and OERI 2022; Wingard et al. 2022). The salinity in Biscayne Bay, located in South Florida, has been greatly influenced by the drainage of freshwater from the Florida Everglades through water management systems (Lirman et al. 2008).

Restoration efforts under CERP began in the early 2000s (USACE and USDOI 2015). In Biscayne Bay, these efforts are primarily implemented through the Biscayne Bay and Southeastern Everglades Ecosystem Restoration (BBSEER) and include the Biscayne Bay Coastal Wetlands (BBCW) phase I project (USACE 2023b). The BBCW phase I project was authorized in 2014 (USACE and USDOI 2015). The BBCW plan includes the construction of culverts, pumps, and associated wetlands to rehydrate wetlands by directing the fresh water that would otherwise enter the Bay through canals (RECOVER, 2019). Water will flow into the Bay through wetlands, reestablishing the connection between the wetlands and the Bay (RECOVER, 2019). The BBCW project covers 14,877 hectares and includes three components: the L-31E Culverts, Deering Estate, and Cutler Wetlands (SFWMD, South Florida Water Management District) 2018). Some BBCW components are completed, some are in progress, and the project will be nearly complete within the next 5 years (RECOVER, 2019).

Several studies have investigated changes in salinity in Southern Florida. A sediment core taken in 2002 indicated that salinity in Central Biscayne Bay has become increasingly marine over the last 100 years (Wingard et al. 2003). Another paleoenvironmental study on three cores collected in 2002 within Biscayne Bay (Wingard et al. 2003, 2004) showed a long-term salinity increase attributed to changing climate and anthropogenic activities (Wachnicka et al. 2013). Studies on more recent trends in Biscayne Bay's salinity and water quality have also been conducted. For example, studies have shown seasonal and spatiotemporal trends in nutrients, chlorophyll-a, and dissolved oxygen (Caccia and Boyer 2005, 2007; Millette et al. 2019) across the three regions of the Bay (North, Central, and South). Kelble et al. (2007) studied monthly salinities in Florida Bay, adjacent to Biscayne Bay, from 1998 to 2004 and observed a non-monotonic trend (i.e., highest and lowest monthly salinities in an annual cycle).

So far, there have been no peer-reviewed studies that have examined recent salinity trends in Biscayne Bay through the analysis of observational data. This is a critical gap in knowledge, given that restoration efforts are underway in the Bay to restore historical hydrology. The objective of this study is to (i) analyze seasonal Biscayne Bay salinity trends at individual stations within the study area between 2005 and 2020, a period that covers several years before restoration efforts were in place and after restoration had begun, (ii) evaluate the direction of the salinity slopes within the study region, and (iii) spatially interpolate the salinity slopes by kriging to provide a better visual representation of the data. Findings will aid in adaptive management and planning for future restoration efforts under climate change and accelerating sea-level rise. This study provides a novel framework for using trend analysis to study temporal and spatial variation in an estuarine system that may be experiencing change due to anthropogenic activities and climate.

Study Area

Biscayne Bay is a shallow tropical marine lagoon that has been impacted by natural and anthropogenic activities. The Bay covers an area of approximately 700 km^2 (270 mi^2) (Caccia and Boyer 2005) and includes Biscayne National Park, the largest marine park in the

U.S. National Park System (NPS and USDOI 2018; Wingard 2004). The salinity fluctuates spatially and seasonally in nearshore habitats of Biscayne Bay (Lirman et al. 2008). For the purpose of this study, nearshore and open bay stations are defined based on the observed salinity variations. Nearshore stations are considered closest to land on the Bay's western side, and open bay stations are considered further away from the mainland.

According to the Koppen classification (Peel et al. 2007), the climate in South Florida is a transition zone between sub-tropical (in the north) and tropical (in the south) and is influenced mainly by rainfall, storm events, temperature, and evaporation (Marshall et al. 2020). In addition to these variables, the climatic cycles Intertropical Convergence Zone (ITCZ) (Jones et al. 2019), El Niño- Southern Oscillation (ENSO), Atlantic Multidecadal Oscillation (AMO), and North Atlantic Oscillation (NAO) also influence the climate of South Florida (Wachnicka et al. 2013). The two predominant seasons of this region are the wet and dry seasons. The wet season extends from May to October and is characterized by warmer temperatures, frequent showers, and thunderstorms (NOAA 2023). The dry season extends from November to April and is characterized by cooler temperatures and less frequent precipitation (NOAA 2023). The wet season also corresponds to the hurricane season, when periodic storms can contribute large volumes of rainfall to the region over a short period (Marshall et al. 2020).

Material and Methods

(i) Dataset description

Time series of salinity data, from 30 stations across the central and southern regions of Biscayne Bay, were obtained from the DBHYDRO-SFWMD environmental database (SFWMD 2023c). These data were sampled by the Biscayne National Park and recorded using permanently or intermittently deployed sondes (SFWMD 2023b). The temporal resolution of the salinity data from the sondes is 15 minutes. The data were averaged daily, and a trend analysis was conducted at each station over the time period for which data was available. Twenty-three stations had data from 2005 to 2020, 6 stations only had data from 2011 to 2020, and 1 station had data from 2012 to 2020. Stations with truncated time series (n=7), were still considered in the analysis to augment the dataset. Daily salinity data were grouped into dry (November 1st to April 30th) and wet (May 1st to October 31st) seasons. Individual years over the study period, from January to December, were grouped seasonally. The data were not adjusted for unusual years where the dry or wet seasons may have been skewed. The rainfall variability during the study period between the wet and dry seasons is shown in Figure 1. Trend analyses were conducted on the daily salinity data for the wet season, dry season, and combined over both seasons. Details of the stations, their period of analysis, and missing data are listed in Table 1. The spatial distribution of stations is shown in Figure 2.

(ii) **Methodology**

a. Trend analysis

Seasonal salinity trends at individual stations were analyzed using the Seasonal Kendall (SK) test. The SK test is a modification of Kendall's trend test, allowing for seasonality in observations collected over time (Hirsch et al. 1982). The SK test is a non-parametric test widely used for trend detection in non-normally distributed data (Hirsch and Slack 1984). The function "kendallSeasonalTrendTest" from the EnvStats package in R, version 2.7.0 (Millard SP, 2013) was used to calculate trends within the seasonal data and to provide salinity slopes for each season. This function can test trends in two ways: (i) that allows for serial dependence; and (ii) that assumes serial independence. This study uses the trend test that allows for serial dependence. The function includes two tests: (i) the Van Belle-Hughes Heterogeneity Test for trend modified for serial dependence (HT); and (ii) the SK tests for trend modified for serial dependence (Millard SP, 2013). The SK test assumes that any monotonic trends present occur in the same direction (positive or negative). The SK test may not be appropriate if there are trends in different directions in one or more seasons (Hirsch and Slack 1984). This limitation of the SK test is overcome in the function "kendallSeasonalTrendTest" which tests for heterogeneity in trends among seasons by applying the HT test before applying the SK test (Millard SP, 2013). The HT is a heterogeneity test for trends in any direction (positive or negative) in any season (Belle and Hughes 1984). The HT statistic is approximately distributed as a chi-square random variable with p-1 degrees of freedom, where "p" is the number of seasons (Belle and Hughes 1984). Detailed descriptions of the HT are explained in (Belle and Hughes 1984).

The null hypothesis (H_0) for the SK test is that there is no constant trend for each of the seasons (wet and dry), and the alternate hypothesis (H_A) is that there is a trend in one or more seasons (Hirsch et al. 1982). The SK test calculates Kendall's tau, slope, and intercept for each season and an overall value for Kendall's tau, slope, and intercept combined over the seasons (Millard SP, 2013). The Kendall's tau ($\hat{\tau}$), slope ($\hat{\beta}_1$), and intercept ($\hat{\beta}_0$), for season j are computed as

$$\widehat{\tau_j} = \frac{2S_j}{n_j(n_j - 1)} \tag{1}$$

where

$$S_j = \sum_{i=1}^{N_j - 1} \sum_{k=i+1}^{N_j} sign\left[(X_{kj} - X_{ij})\,(Y_{kj} - Y_{ij})\right] \tag{2}$$

$$\hat{\beta}_{1_j} = Median\left(\frac{Y_{kj}-Y_{ij}}{X_{kj}-X_{ij}}\right); i < k;\ X_{kj} \neq X_{ik} \quad (3)$$

$$\widehat{\beta_{0_j}} = Y_{0.5_j} - \widehat{\beta_{1_j}}\, X_{0.5_j} \quad (4)$$

i=1,2,…n (n denotes the number of years), j= 1,2,..p (p denotes the number of seasons), k=i+1, X and Y denote two continuous random variables with bivariate distribution, N_j denotes the number of bivariate observations taken in the j^th season, $X_{0.5j}$ and $Y_{0.5j}$ denote the sample medians of X's and Y's respectively. Detailed descriptions of the SK test used in the function are explained in (Hirsch and Slack 1984).

The Z-statistic of the SK trend test is based on summing together the Kendall S-statistics for each season. The null hypothesis of the test is either accepted or rejected based on this statistic (Meals et al. 2011).

$$Z = \frac{\acute{S}}{\sqrt{var\ (\acute{S})}} \quad (5)$$

where

$$\acute{S} = \sum_{j=1}^{p} S_j \quad (6)$$

The Z-statistic indicates the direction of the trend. The p-value (alpha level = 0.05) indicates the significance of the trend. The function "kendallSeasonalTrendTest" used in this study calculates the Z-statistic and the associated p-value for the data combined over the seasons and not for each season. Kendall's tau ($\hat{\tau}$), is a correlation coefficient between two random variables, the slope ($\hat{\beta}_1$), is the rate of change of the variable over time, and the intercept ($\hat{\beta}_0$), is the point through which the estimated regression line passes. The overall tau (over the seasons) is the weighted average of the seasonal tau values, the overall slope is the median of all two-point slopes computed within each season, and the overall intercept is the median of the seasonal intercepts (Millard SP, 2013).

b. Spatial Interpolation

Salinity slopes were kriged for the dry, wet, and combined seasons using the gstat package, version 2.1-0 (Gräler et al. 2016; Pebesma 2004). Kriging is the most common and widely used spatial interpolation method (Haberlandt 1998), that uses semivariograms or covariances to help predict unknown variables from data at known locations (Pebesma and Wesseling 1998). Kriging was performed on the salinity slopes to provide a better visual representation of the data. Semivariograms were used in this study to depict the spatial autocorrelation of measured locations and were initially fit using various models (Sph, Exp, Gau, Mat) using the fit.variogram function in R software. Of the models tested, the exponential model resulted in the lowest Mean Squared Prediction Error (MSPE) for the wet, dry, and combined season data. The "eyeball method" was then used to further adjust the nugget, sill, and range parameters to further lower the MSPE for the exponential models. Leave One Out Cross-Validation (LOOCV) was performed on the kriging predictions to obtain mean prediction error (MPE), mean-squared prediction error (MSPE), and the coefficient of determination (R^2).

Results

This section presents the trend analysis of daily salinity data over the wet, dry, and combined wet and dry over seasons. The results of the spatial interpolation analysis are also presented in this section.

(i) **Trend analysis and salinity slopes combined over the wet and dry seasons**

The Z-statistic and the associated p-value (alpha = 0.05) of the SK trend test indicate statistically significant increasing trends (13 stations) outnumbering decreasing trends (10 stations) (Table 2).

The spatial distribution of the salinity slopes, combined over the seasons, at each station, is shown in Figure 2. Figure 2 shows that there are both increases (positive slopes) and decreases (negative slopes) in salinity within the study area. Positive salinity slopes were present in the central and southern areas of the study region. Negative salinity slopes were present in the northern, nearshore areas of the study area. The two most positive salinity slopes were at stations BISC00B (0.163 PSU/year, 2005 to 2020; Figure 3a) and BISCA2 (0.360PSU/year, 2011 to 2020; Figure 3b). The two most negative salinity slopes were at stations BISC52B (-0.138 PSU/year, 2005 to 2020; Figure 4a) and BISCD4 (-0.230 PSU/year, 2011 to 2020; Figure 4b). Stations with the most positive and negative salinity slopes are reported irrespective of the statistical significance. This is done to show the salinity variations within the study area.

(ii) **Seasonal salinity slopes**

a. Dry season

During the dry season, the majority of the stations (n=22) exhibit a negative salinity slope, and 8 stations exhibit a positive salinity slope (Table 3). Positive salinity slopes were present at all stations in the southern region during the dry season (Figure 5a). Negative salinity slopes were observed at most stations in the central and northern portions of the study area. The two most positive salinity slopes during the dry season were at stations BISC00B (0.204 PSU/year, 2005 to 2020) and BISCA4 (0.350 PSU/year, 2012 to 2020), and the two most negative salinity slopes were at stations BISC52B (-0.234 PSU/year, 2005 to 2020) and BISCD4 (-0.244 PSU/year, 2011 to 2020).

b. Wet season

During the wet season, the majority of stations (n=24) exhibit a positive salinity slope, while 6 stations exhibit a negative slope (Table 3). All the stations showing a negative salinity slope are located in the northern nearshore portion of the study area (Figure 5b). The two most positive salinity slopes were at stations BISC54B (0.160 PSU/year, 2005 to 2020) and BISCA2 (0.417 PSU/year (2011 to 2020), and the two most negative salinity slopes were at stations BISC62B (-0.042 PSU/year, 2005 to 2020) and BISCD4 (-0.213 PSU/year, 2011 to 2020). A box plot of salinity slopes from 30 stations shows that during the wet season, most salinity slopes are positive, and during the dry season, most salinity slopes are negative (Figure 6).

(iii) **Spatial interpolation analysis**

The salinity slopes were kriged to a prediction grid. The four southernmost stations (BISCA4, BISCA2, BISC00B, and BISC06B) were not included in the spatial interpolation because of their distance from the other stations (Figure 7a). Accordingly, 26 stations, including nearshore and open bay areas, were considered for the spatial interpolation analysis. The grid size of the prediction grid was 3.5 x 3.5 hectares.

The spatial interpolation analysis results are shown for (1) combined over the seasons, (2) the dry season, and (3) the wet season (Figures 7 b-d). Cross-validation results and fit statistics for the analysis are shown in Table 4. For all time periods: combined, dry, and wet seasons the salinity slope is negative in the north and positive in the south. For the dry season (Figure 7c), the salinity slope is negative in the nearshore, northern areas and increased to slightly positive in the open bay, southern areas. In the wet season, the salinity slope was positive across the study region except for the northernmost nearshore portion of the study area (Figure 7d). In addition to the prediction plots, standard deviation plots are also shown to quantify the uncertainty of the predictions (Figures 8b-d). For all the maps, prediction uncertainty is lower at the eastern portion of the mapped area near the coast, due to the higher density of sampling locations. The highest degree of uncertainty for all the maps is in the southeast portion of the mapped area where sampling density is lowest. The standard deviation maps show similar overall trends because the model parameters (nugget, sill, range) that best fit each data set were similar.

Discussion

In this study, we examined seasonal (wet and dry) salinity trends and the change in salinity per year (salinity slope) at 30 stations within central and southern regions of Biscayne Bay over 16 years (2005–2020). The non-parametric Seasonal Kendall trend test, at a 0.05 significance level, was used for the analysis. Salinity slopes were interpolated to a fine grid over the study area to provide a better visual representation of the data. Results of the trend test show mostly positive salinity slopes in the wet and mostly negative salinity slopes in the dry season. Spatial interpolation analysis results indicated negative salinity slopes along the nearshore areas of the northern portion of the study area and positive salinity slopes further south. In this section, we discuss the potential drivers of changing salinity slopes, including restoration, water management, climate change, changing rainfall patterns, climate variability, and sea-level rise.

Drivers responsible for changing salinity slopes may include restoration and water management practices. The BBCW restoration goal is to reduce point source freshwater flow to the Bay and Biscayne National Park (USACE 2021a) while improving salinity distribution near the shore of Biscayne Bay (SFWMD 2022). BBCW completed construction of the Deering Estate and portions of the L-31E Flow-way in the fall of 2012, and some phases of the L-31E Flow-way were completed in 2018 (USACE 2023a). Stations BISCD4 and BISC62B are both located near Deering Estate. Stations BISC40B and BISC28B are both located near the L-31 Flow-way. The restored wetland habitats are designed to absorb water in the wet season and slowly release it in a more natural pattern into the Bay (SFWMD 2022). In Biscayne Bay, water storage in the wet season and the gradual and sustained release of freshwater from storage in the dry season resulted in a more estuarine ecosystem in the nearshore areas (Stabenau et al. 2015). Within Florida Bay, the net freshwater flow suggests that the most substantial advantage would result from increasing dry-season inflows, especially in terms of reducing salinity fluctuations in the nearshore regions, Johnson (2012). In this study, stations BISCD4, BISC62B, BISC40B, and BISC28B (all nearshore stations) show a decreasing salinity slope, combined over the seasons and during the dry season (Figures 2 and 5a). We speculate that the management practices, such as restoration efforts, could account for the negative salinity slopes observed in these nearshore areas of the northern and central regions of the study area in the dry season. However, the BBCW phase I project is in progress. Further analysis is required to investigate the impacts of restoration efforts on the salinity slope.

Changes in the salinity slope could also be due to climate change and changing rainfall patterns. In South Florida, the traditional wet season runs from May through October. In our study, annual variation in the occurrence of the wet and dry seasons were not considered and the length of the wet and dry seasons did not change. If the wet season is becoming shorter, one would expect increases in salinity during what is traditionally known as the wet season. Obeysekera J. et al. (2011) showed that May rainfall decreased over time in Florida between

1950 and 2008, based on the influence of AMO. Abiy et al. (2019) conducted a trend analysis, revealing a decrease in October rainfall and an increase in August rainfall in Southeast Florida between 1906 and 2016. They indicated their findings might be due to the ongoing transition in the local rainfall pattern from a bimodal to a unimodal regime. Another study by Misra et al. (2018) investigated the start, end, and length of the wet seasons between 1948 and 2006 in Florida and observed a shorter wet season in urban areas relative to rural areas. They found the heterogeneity in the duration of the wet season as a response to changes in land cover. While these studies show different causes for changes in wet season duration, they agree that Biscayne Bay may be experiencing a decrease in the duration of the wet season. Indeed, our study shows that salinity is increasing in the wet season, which may be due to a decreased wet season duration as described in the findings from the above studies, and demonstrates how changes in rainfall and land cover may affect salinity trends in Biscayne Bay. However, more work is required to explore these causal relationships.

In addition to the changing rainfall patterns impacting salinity slopes, climate variability caused by ENSO cycles (El Nino, Neutral, and La Nina) may also impact salinity slopes. The ENSO cycles impact seasonal rainfall patterns in the Southeast U.S. (NOAA 2023a). The resulting freshwater variability influences seasonal salinity distribution (Schmidt et al. 2004). South Florida winters, which occur during the dry season, are warm and wet during El Niño conditions, while La Niña brings cool and dry conditions (NOAA 2023b). El Niño and La Niña cycles usually occur every 3 to 5 years. El Niño exists for 9 to 12 months, and La Nina exists for 1 to 3 years (NOAA 2023c). Our study period is from 2005 to 2020 (16 years) and includes at least three ENSO cycles. Wet season rainfall contributes to most of the annual rainfall in the study area (Figure 1a). Figure 1b shows that the ENSO cycles influence rainfall patterns within the study area. It appears that the negative phase of the ENSO cycle (the La Niña), is stronger than the positive phase of the ENSO cycle (the El Niño). Our study results indicate that during the dry season the salinity slopes are negative (Figure 5a) than the wet season (Figure 5b). We speculate that negative salinity slopes in the dry season may be due to increased rainfall patterns influenced by ENSO cycles.

Sea-level rise can also impact salinity over time. One would expect to see increases in salinity (positive salinity slope) over time in response to sea-level. The Intergovernmental Panel on Climate Change reported that the Global Mean Sea Level (GMSL) increased from 3.2 m per year over the period 1993–2015 to 3.6 mm per year over the period 2006–2015 (IPCC 2022). Several studies conducted globally, within the US, and within the region have investigated the impacts of sea-level rise on salinity (Du et al. 2018; Hauer 2017; Hilton et al. 2008; Liu and Liu 2014; Mills et al. 2021; Mulamba et al. 2019; Ross et al. 2015). Mills et al. (2021) used a hydrodynamic model to study the impacts of sea-level rise on salinity changes in the Guadiana Estuary, Spain. Their study showed an overall increase in salinity in the estuary in response to sea-level rise. Another modeling study in a tidal estuary in Taiwan showed that the rising sea-level rise will increase the distance of saltwater intrusion into the river, impacting water quality and fish habitat (Liu and Liu 2014). (Ross et al. 2015) used a statistical model and long-term salinity records to determine the response of salinity to rising sea-level in the Delaware estuary. Their study results indicated a positive correlation between rising sea-levels and increasing salinity. Hauer (2017) showed that Florida has the most exposure to sea-level rise throughout the United States. Southeast Florida’s low-lying elevation and porous geology are vulnerable to sea-level rise (Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact) 2020). A previous study in Biscayne Bay showed a long-term salinity increase in open-water areas due to rising sea-level, intensive urbanization of the southeast Florida coast, and associated reduction of freshwater discharges (Wachnicka et al. 2013). Our study shows that overall, throughout the seasons, the salinity slope is more positive in the open bay areas. Again, more work is required to explore these causal relationships.

This study shows the patterns in salinity slopes within Biscayne Bay and we speculate the complex and interconnected factors related to recent changes in salinity. The study results indicate the need for continued monitoring of salinity within Biscayne Bay to protect coastal ecosystems.

Conclusions

Understanding seasonal trends in salinity is vital for assessing restoration progress for adaptive management and future ecosystem restoration in Biscayne Bay under CERP. In this study, daily seasonal salinity trends at thirty stations were analyzed using non-parametric tests and spatial interpolation analysis. The results show an increase in daily average salinity over time in the southern portion of the Bay and a decrease in the northernmost part of the study site. Positive salinity slopes were present in the central and southern areas of the study region. Negative salinity slopes were present in the northern, nearshore areas of the study area. Seasonally, the change in salinity is more positive in the wet season and more negative in the dry season. Spatial analysis results indicated a negative salinity slope in the north and a positive salinity slope in the south for all time periods (combined, dry, and wet seasons).

Decreasing salinity (negative salinity slope) in the Deering Estate and L-31E Flow-way areas may be a result of restoration efforts under the BBCW phase I project. Conversely, increasing salinity (positive salinity slope) could be attributed to the sea-level rise and/or a decrease in the duration of the wet season. However, more analysis is required to understand how these factors impact spatial and temporal salinity trends within the Bay.

Data Availability Statement

Some or all data, models, or codes used during the study are available from the corresponding author upon reasonable request. Salinity data for the study area were obtained from the DBHYDRO - SFWMD environmental database (https://apps.sfwmd.gov/WAB/EnvironmentalMonitoring/index.html). The package used for SK trend tests is from the EnvStats package of R software, version 2.7.0 (Millard, SP 2013). The package used for spatial analysis is from the gstat package of R software, version 2.1-0 (Gräler et al. 2016, Pebesma and Wesseling 1998).

Acknowledgments

This research was funded by a NOAA/Atlantic Oceanographic and Meteorological Laboratory grant to the Northern Gulf Institute (award number NA210AR4320190). This research was also supported by the intramural research program of the U.S. Department of Agriculture, National Institute of Food and Agriculture (Hatch Accession Number 7004342).

Disclaimer

The authors declare no conflict of interest.

References

Abiy, A. Z., A. M. Melesse, W. Abtew, and D. Whitman. 2019. “Rainfall trend and variability in Southeast Florida: Implications for freshwater availability in the Everglades.” *PLoS One*, 14 (2). Public Library of Science. https://doi.org/10.1371/journal.pone.0212008

Bachman, P. M., and G. M. Rand. 2008. “Effects of salinity on native estuarine fish species in South Florida.” *Ecotoxicology*, 17 (7): 591–597. https://doi.org/10.1007/s10646-008-0244-7

Browder, J. A., R. Alleman, S. Markley, P. Ortner, and P. A. Pitts. 2005. “Biscayne Bay conceptual ecological model.” *Wetlands*, 25 (4): 854–869.

Caccia, V. G., and J. N. Boyer. 2005. “Spatial patterning of water quality in Biscayne Bay, Florida as a function of land use and water management.” *Mar Pollut Bull*, 50 (11): 1416–1429. https://doi.org/10.1016/j.marpolbul.2005.08.002

Caccia, V. G., and J. N. Boyer. 2007. “A nutrient loading budget for Biscayne Bay, Florida.” *Mar Pollut Bull*, 54 (7): 994–1008. https://doi.org/10.1016/j.marpolbul.2007.02.009

Du, J., J. Shen, Y. J. Zhang, F. Ye, Z. Liu, Z. Wang, Y. P. Wang, X. Yu, M. Sisson, and H. V. Wang. 2018. “Tidal response to sea-level rise in different types of estuaries: the importance of length, bathymetry, and geometry.” *Geophys Res Lett*, 45 (1): 227–235. Blackwell Publishing Ltd. https://doi.org/10.1002/2017GL075963

Gräler, B., E. Pebesma, and G. Heuvelink. 2016. “Spatio-temporal interpolation using gstat. ” *The R Journal*, 8 (1): 204–218.

Hauer, M. E. 2017. “Migration induced by sea-level rise could reshape the US population landscape.” *Nat Clim Chang*, 7 (5): 321–325. Nature Publishing Group. https://doi.org/10.1038/nclimate3271

Hilton, T. W., R. G. Najjar, L. Zhong, and M. Li. 2008. “Is there a signal of sea-level rise in Chesapeake Bay salinity?” *J Geophys Res Oceans*, 113 (9). Blackwell Publishing Ltd. https://doi.org/10.1029/2007JC004247

Hirsch, R. M., and J. R. Slack. 1984. “A nonparametric trend test for seasonal data with serial dependence.” *Water Resour Res*, 20 (6): 727–732. https://doi.org/10.1029/WR020i006p00727

Hirsch, R. M., J. R. Slack, and R. A. Smith. 1982. “Techniques of trend analysis for monthly water quality data.” *Water Resour Res*, 18: 107–121. https://doi.org/10.1029/WR018i001p00107

IPCC (Intergovernmental Panel on Climate Change). 2022. “Sea level rise and implications for low-lying islands, coasts and communities.” *The Ocean and Cryosphere in a Changing Climate*, 321–446. Cambridge University Press.

Johnson, R. 2012. “Foreword.” *Salinity and Hydrology of Florida Bay Status and Trends 1990-2009*, E. Stabenau and K. Kotun, eds., 1–39. Homestead, Florida: National Park Service, Everglades National Park, South Florida Natural Resources Center.

Jones, M. C., G. L. Wingard, B. Stackhouse, K. Keller, D. Willard, M. Marot, B. Landacre, and C. E. Bernhardt. 2019. "Rapid inundation of southern Florida coastline despite low relative sea-level rise rates during the late-Holocene." *Nat. Commun.*, 10 (1): 3231. https://doi.org/10.1038/s41467-019-11138-4

Kelble, C. R., E. M. Johns, W. K. Nuttle, T. N. Lee, R. H. Smith, and P. B. Ortner. 2007. "Salinity patterns of Florida Bay." *Estuar Coast Shelf Sci*, 71 (1–2): 318–334. https://doi.org/10.1016/j.ecss.2006.08.006

Lirman, D., G. Deangelo, J. Serafy, A. Hazra, D. Smith Hazra, J. Herlan, J. Luo, S. Bellmund, J. Wang, and R. Clausing. 2008. "Seasonal changes in the abundance and distribution of submerged aquatic vegetation in a highly managed coastal lagoon." *Hydrobiologia*, 596 (1): 105–120. https://doi.org/10.1007/s10750-007-9061-x

Liu, W.-C., and H.-M. Liu. 2014. "Assessing the impacts of sea level rise on salinity intrusion and transport time scales in a tidal estuary, Taiwan." *Water (Basel)*, 6 (2): 324–344. https://doi.org/10.3390/w6020324

Marshall, F. E., C. E. Bernhardt, and G. L. Wingard. 2020. "Estimating late 19th century hydrology in the Greater Everglades Ecosystem: An integration of paleoecologic data and models." *Front Environ Sci*, 8. Frontiers Media S.A. https://doi.org/10.3389/fenvs.2020.00003

Marshall, F. E., L. G. Wingard, and P. Pitts. 2009. "A simulation of historic hydrology and salinity in Everglades National Park: Coupling paleoecologic assemblage data with regression models." *Estuaries and Coasts*, 32: 37–53. https://doi.org/10.1007/s12237-008-9120-1

Meals, D. W., J. Spooner, S. A. Dressing, and J. B. Harcum. 2011. *Statistical Analysis for Monotonic Trends*. Fairfax.

Millard, S. P. 2013. *EnvStats : An R package for environmental statistics*. Springer, New York. ISBN 978-1-4614-8455-4, https://www.springer.com

Millette, N. C., C. Kelble, A. Linhoss, S. Ashby, and L. Visser. 2019. "Using spatial variability in the rate of change of chlorophyll a to improve water quality management in a subtropical oligotrophic estuary." *Estuaries and Coasts*, 42 (7): 1792–1803. https://doi.org/10.1007/s12237-019-00610-5

Mills, L., J. Janeiro, and F. Martins. 2021. "Effects of sea level rise on salinity and tidal flooding patterns in the Guadiana Estuary." *J. Water and Clim Change*, 12 (7): 2933–2947. https://doi.org/10.2166/wcc.2021.202

Misra, V., A. Mishra, A. Bhardwaj, K. Viswanathan, and D. Schmutz. 2018. "The potential role of land cover on secular changes of the hydroclimate of Peninsular Florida." *Climate and Atmospheric Science*, 1 (1). Nature Research. https://doi.org/10.1038/s41612-018-0016-x

Mulamba, T., P. Bacopoulos, E. J. Kubatko, and G. F. Pinto. 2019. “Sea-level rise impacts on longitudinal salinity for a low-gradient estuarine system.” *Clim Change*, 152 (3): 533–550. https://doi.org/10.1007/s10584-019-02369-x

National Academy of Sciences. 2016. “Progress toward restoring the Everglades.”

NOAA (National Oceanic and Atmospheric Administration). 2021. “What is an estuary?” Accessed April 15, 2023. https://oceanservice.noaa.gov/education/tutorial_estuaries/est01_whatis.html

NOAA (National Oceanic and Atmospheric Administration). 2023a. “Summer season.” Accessed April 15, 2023. https://www.weather.gov/mfl/summer_season

NOAA (National Oceanic and Atmospheric Administration). 2023b. “El Niño and its effect on the southeast U.S.” Accessed May 1, 2023. https://www.weather.gov/tae/enso

NOAA (National Oceanic and Atmospheric Administration). 2023c. “Climate page for South Florida.” Accessed May 8, 2023. https://www.weather.gov/mfl/winteroutlookforsouthflorida

NOAA (National Oceanic and Atmospheric Administration). 2023d. “National Weather Service, Climate Prediction Center.” Accessed May 1, 2023. https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensofaq.shtml#HOWOFTEN

NPS (National Park Service) and OERI (Office of Everglades Restoration Initiatives). 2022. “Restoring America’s Everglades.” Accessed April 15, 2023. https://storymaps.arcgis.com/stories/dfd3e4261602415683015a919dfbafec

NPS (National Park Service), and USDOI (US Department of the Interior). 2018. *Biscayne National Park Foundation Document*.

Obeysekera J., J. Park, M. Irizarry-Ortiz, P. Trimble, J. Barnes, J. VanArman, W. Said, and E. Gadzinski. 2011. *Past and Projected Trends in Climate and Sea Level for South Florida*. West Palm Beach, Florida OERI (Office of Everglades Restoration Initiatives). 2021. “Everglades History & Timeline.” Accessed April 7, 2023. https://storymaps.arcgis.com/stories/970b9663f9a84baaa26aff13573df4f2

OERI (Office of Everglades Restoration Initiatives). 2023. “Comprehensive Everglades Restoration Plan.” Accessed April 15, 2023. https://www.evergladesrestoration.gov/comprehensive-everglades-restoration-plan#:~:text=The%20CERP%2C%20authorized%20by%20the%20Water%20Resources%20Development,quantity%2C%20quality%2C%20timing%2C%20and%20distribution%20%28QQTD%29%20of%20water

Pebesma, E. J. 2004. “Multivariable geostatistics in S: The gstat package.” *Comput Geosci*, 30 (7): 683–691. https://doi.org/10.1016/j.cageo.2004.03.012

Pebesma, E. J., and C. G. Wesseling. 1998. “GSTAT: A program for geostatistical modelling, prediction and simulation.” *Comput Geosci*, 24 (1): 17–31.

Peel, M. C., B. L. Finlayson, and T. A. McMahon. 2007. “Updated world map of the Köppen-Geiger climate classification.” *Hydrol Earth Syst Sci*, 11 (5): 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

RECOVER. 2019. *2019 System Status Report*. Jacksonville and West Palm Beach, FL.

Ross, A. C., R. G. Najjar, M. Li, M. E. Mann, S. E. Ford, and B. Katz. 2015. “Sea-level rise and other influences on decadal-scale salinity variability in a coastal plain estuary.” *Estuar Coast Shelf Sci*, 157: 79–92. https://doi.org/https://doi.org/10.1016/j.ecss.2015.01.022

Schmidt, N., M. E. Luther, and R. Johns. 2004. “Climate variability and estuarine water resources: A case study from Tampa Bay, Florida.” *Coast. Manag*., 32 (2): 101–116. https://doi.org/10.1080/08920750490275895

SFNRC (South Florida Natural Resources Center). 2006. *Ecological & Hydrologic Targets for Western Biscayne National Park.*

SFWMD (South Florida Water Management District). 2018. *Annual Permit Report for the Biscayne Bay Coastal Wetlands Project. Appendix 2-3. Accessed October 4, 2023. https://apps.sfwmd.gov/sfwmd/SFER/2018_sfer_final/v3/appendices/v3_app2-3.pdf*

SFWMD (South Florida Water Management District). 2022. “SFWMD governing board approves last component of Biscayne Bay coastal wetlands project.” Accessed April 15, 2023. https://www.sfwmd.gov/news-events/news/sfwmd-governing-board-approves-last-component-biscayne-bay-coastal-wetlands

SFWMD (South Florida Water Management District). 2023a. “DBHYDRO timeseries.” Accessed May 8, 2023. https://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.show_dbkeys_matched?v_order_by=GROUP _NAME&v_js_flag=Y&v_data_type=SALI&v_county=DAD

SFWMD (South Florida Water Management District), E. M. 2023b. “SFWMD environmental monitoring.” Accessed May 8, 2023. https://apps.sfwmd.gov/WAB/EnvironmentalMonitoring/index.html

Shellenbarger, G. G., and D. H. Schoellhamer. 2011. “Continuous salinity and temperature data from San Francisco Estuary, 1982-2002: Trends and the salinity-freshwater inflow relationship TECHNICAL COMMUNICATIONS Continuous Salinity and Temperature Data from San Francisco Estuary, 1982-2002: Trends and the Salinity-Freshwater Inflow Relationship.” *Article in Journal of Coastal Research*. https://doi.org/10.2307/41315904

Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact). 2020. *Unified Sea Level Rise Projection Southeast Florida*. Accessed October 4, 2023. https://southeastfloridaclimatecompact.org/wp-content/uploads/2020/04/Sea-Level-Rise-Projection-Guidance-Report_FINAL_02212020.pdf

Stabenau, E., A. Renshaw, J. Luo, E. Kearns, and J. D. Wang. 2015. "Improved coastal hydrodynamic model offers insight into surface and groundwater flow and restoration objectives in Biscayne Bay, Florida, USA." *Bull Mar Sci*, 91 (4): 433–454. Rosenstiel School of Marine and Atmospheric Science. https://doi.org/10.5343/bms.2015.1017

Torregroza-Espinosa, A. C., J. C. Restrepo, J. Escobar, J. Pierini, and A. Newton. 2021. "Spatial and temporal variability of temperature, salinity and chlorophyll-a in the Magdalena River mouth, Caribbean Sea." *J South Am Earth Sci*, 105. Elsevier Ltd. https://doi.org/10.1016/j.jsames.2020.102978

UNESCO. 1985. *The International system of Units (SI) in Oceanography*. Paris.

USACE (US Army Corps of Engineers). 2021. *Biscayne Bay Coastal Wetlands Project*. Jacksonville District. Accessed on October 4, 2023. https://www.saj.usace.army.mil/BBCW/

USACE (US Army Corps of Engineers). 2023a. "Biscayne Bay coastal wetlands project." Accessed April 8, 2023. https://www.saj.usace.army.mil/BBCW/

USACE (US Army Corps of Engineers). 2023b. *Biscayne Bay Southern Everglades Ecosystem Restoration Project*. Jacksonville District.

USACE (US Army Corps of Engineers) and USDOI (US Department of the Interior). 2015. *Comprehensive Everglades Restoration Plan*. Jacksonville District. Accessed on October 4, 2023. https://www.saj.usace.army.mil/Portals/44/docs/Environmental/Report%20to%20Congress/FINAL_RTC_2015_01Mar16fin-WithLetters-WithCovers-508Compliant.pdf

Uwe, H. 1998. "Stochastic rainfall synthesis using regionalized model parameters." *J Hydrol Eng*, 3 (3): 160-168. American Society of Civil Engineers. https://doi.org/10.1061/(ASCE)1084-0699(1998)3:3(160)

van Belle, G., and J. P. Hughes. 1984. "Nonparametric tests for trend in water quality." *Water Resour Res*, 20 (1): 127–136. https://doi.org/10.1029/WR020i001p00127

Wachnicka, A., E. Gaiser, L. Wingard, H. Briceño, and P. Harlem. 2013. "Impact of Late Holocene climate variability and anthropogenic activities on Biscayne Bay (Florida, U.S.A.): Evidence from diatoms." *Palaeogeogr Palaeoclimatol Palaeoecol*, 371: 80–92. https://doi.org/10.1016/j.palaeo.2012.12.020

Wingard, G. L. 2004. *Changing Salinity Patterns in Biscayne Bay, Florida*. U.S. Geological Survey Fact Sheet 2004-3108. Accessed October 3, 2023. https://pubs.usgs.gov/fs/2004/3108/fs2004-3108.html

Wingard, G. L., T. M. Cronin, G. S. Dwyer, S. E. Ishman, D. A. Willard, C. W. Holmes, C. E. Bernhardt, C. P. Williams, M. E. Marot, J. B. Murray, R. G. Stamm, J. H. Murray, and C. Budet. 2003. *Ecosystem history of southern and central Biscayne Bay: Summary report on sediment core analyses*. Open-File Report 2003-375. Accessed on October 3, 2023. https://pubs.usgs.gov/publication/ofr03375

Wingard, G. L., T. M. Cronin, C. W. Holmes, D. A. Willard, G. S. Dwyer, S. E. Ishman, W. Orem, C. P. Williams, J. Albietz, C. E. Bernhardt, C. A. Budet, B. Landacre, T. Lerch, M. Marot, R. E. Ortiz, and U. S. G. Survey. 2004. *Ecosystem history of southern and central Biscayne Bay: Summary report on sediment core analyses - year two*. Open-File Report 2004-1312. Accessed on October 3, 2023. https://pubs.usgs.gov/of/2004/1312/ofr2004-1312.pdf

Wingard, G. L., B. L. Stackhouse, and A. M. Daniels. 2022. "Using mollusks as indicators of restoration in nearshore zones of south Florida's estuaries." *Bull Mar Sci*, 98 (3): 351-380. Rosenstiel School of Marine and Atmospheric Science. https://doi.org/10.5343/bms.2022.0004 617

Table 1. The list of stations considered for analysis, the period of analysis, the number of data points, and missing data points throughout the time series.

Station Number	Station	Period of analysis	Latitude	Longitude	Number of data points	Number of missing data points
1	BISC44B	Jan05-Dec20	25.52	-80.31	5689	155
2	BISC46B	Jan05-Dec20	25.53	-80.3	5606	238
3	BISC48B	Jan05-Dec20	25.52	-80.28	5433	411
4	BISC52B	Jan05-Dec20	25.55	-80.31	5710	134
5	BISC54B	Jan05-Dec20	25.55	-80.29	5606	238
6	BISC56B	Jan05-Dec20	25.56	-80.31	5821	23
7	BISC60B	Jan05-Dec20	25.56	-80.28	5589	255
8	BISC62B	Jan05-Dec20	25.61	-80.31	5765	79
9	BISC64B	Jan05-Dec20	25.61	-80.3	5662	182
10	BISC66B	Jan05-Dec20	25.6	-80.29	5520	324
11	BISC70B	Jan05-Dec20	25.64	-80.25	5537	307
12	BISCD2	Jan11-Dec20	25.62	-80.30	3615	38
13	BISCD4	Jan11-Dec20	25.62	-80.29	3612	41
14	BISCD6	Jan11-Dec20	25.62	-80.3	3653	0
15	BISCD8	Jan11-Dec20	25.47	-80.21	3501	152
16	BISC00B	Jan05-Dec20	25.25	-80.41	5702	142
17	BISC06B	Jan05-Dec20	25.28	-80.4	5113	731
18	BISC10B	Jan05-Dec20	25.4	-80.24	5422	422
19	BISC12B	Jan05-Dec20	25.44	-80.3	5648	196
20	BISC18B	Jan05-Dec20	25.48	-80.31	5664	180
21	BISC20B	Jan05-Dec20	25.47	-80.28	5710	134
22	BISC22B	Jan05-Dec20	25.49	-80.34	5755	89
23	BISC26B	Jan05-Dec20	25.49	-80.33	5793	51
24	BISC28B	Jan05-Dec20	25.5	-80.34	5784	60
25	BISC34B	Jan05-Dec20	25.49	-80.31	5417	427
26	BISC36B	Jan05-Dec20	25.49	-80.28	5603	241
27	BISC40B	Jan05-Dec20	25.51	-80.34	5738	106
28	BISCA2	Jan11-Dec20	25.32	-80.35	3606	47
29	BISCA4	Jan12-Dec20	25.34	-80.32	2361	927
30	BISCA6	Jan11-Dec20	25.45	-80.33	3653	0

Table 2. Daily trends and trend magnitudes of salinity slopes combined over the seasons. From the SK test results, for a 95% confidence interval, the computed p-value of less than 0.05 indicates the presence of a statistically significant trend.

		Test statistics and p-values						**Combined over the seasons**		
Station Number	**Station**	Chi-square (HT)	p-value (HT)	Z-statistic (SK test)	p-value (SK test)	Kendall's Tau	Salinity slope	Lower Confidence Interval	Upper Confidence Interval	Intercept
1	BISC46B	32.25	<0.001	2.93	0.003	0.025	0.044	0.015	0.073	-70.621
2	BISC52B	58.54	<0.001	-7.83	<0.001	-0.069	-0.138	-0.173	-0.104	262.333
3	BISC54B	51.72	<0.001	4.20	<0.001	0.038	0.056	0.030	0.081	-96.119
4	BISC56B	35.13	<0.001	-3.74	<0.001	-0.033	-0.061	-0.092	-0.029	112.062
5	BISC60B	38.36	<0.001	-0.28	0.779	-0.002	-0.004	-0.031	0.023	25.596
6	BISC62B	43.62	<0.001	-8.62	<0.001	-0.077	-0.124	-0.152	-0.096	243.832
7	BISC64B	16.38	<0.001	-5.97	<0.001	-0.054	-0.081	-0.108	-0.055	177.620
8	BISC66B	38.73	<0.001	-4.30	<0.001	-0.038	-0.052	-0.075	-0.028	109.995
9	BISC70B	57.65	<0.001	-5.85	<0.001	-0.053	-0.057	-0.076	-0.038	139.337
10	BISCD2	10.37	0.001	-2.16	0.031	-0.024	-0.059	-0.113	-0.005	177.626
11	BISCD4	1.27	0.260	-8.15	<0.001	-0.090	-0.230	-0.287	-0.173	488.555
12	BISCD6	14.11	<0.001	-1.66	0.096	-0.018	-0.044	-0.095	0.008	151.339
13	BISC44B	53.17	<0.001	1.60	0.110	0.013	0.024	-0.005	0.053	-41.263
14	BISC48B	18.21	<0.001	3.45	0.001	0.031	0.039	0.017	0.061	-46.217
15	BISCD8	11.80	0.001	1.04	0.296	0.012	0.011	-0.010	0.032	6.767
16	BISC00B	11.99	<0.001	9.33	<0.001	0.082	0.163	0.129	0.197	-289.833
17	BISC06B	2.73	0.098	2.84	0.005	0.026	0.051	0.016	0.086	-69.082
18	BISC10B	10.79	0.002	10.02	<0.001	0.090	0.042	0.034	0.050	-46.785
19	BISC12B	45.18	<0.001	4.15	<0.001	0.037	0.049	0.026	0.071	-55.204
20	BISC18B	57.45	<0.001	2.29	0.022	0.019	0.029	0.004	0.054	-32.368
21	BISC20B	5.24	0.022	1.55	0.121	0.014	0.016	-0.004	0.035	2.105
22	BISC22B	34.68	<0.001	0.57	0.569	0.004	0.012	-0.029	0.053	-40.727
23	BISC26B	62.84	<0.001	-0.84	0.401	-0.007	-0.014	-0.047	0.019	25.444
24	BISC28B	50.05	<0.001	-2.29	0.022	-0.020	-0.048	-0.089	-0.007	71.623
25	BISC34B	33.09	<0.001	7.38	<0.001	0.064	0.100	0.074	0.127	-166.652
26	BISC36B	59.91	<0.001	2.93	0.003	0.026	0.027	0.009	0.045	-21.096
27	BISC40B	42.30	<0.001	-2.75	0.006	-0.024	-0.056	-0.096	-0.016	84.638
28	BISCA2	3.84	0.050	13.59	<0.001	0.150	0.360	0.310	0.409	-696.754
29	BISCA4	0.69	0.406	13.05	<0.001	0.178	0.338	0.292	0.386	-647.985
30	BISCA6	1.46	0.226	-0.22	0.824	-0.003	-0.009	-0.092	0.073	41.320

Table 3. Kendall's tau, salinity slope, and intercept for the dry and the wet season from the SK test. Note: The SK test does not give test statistics and p-values for each season.

		Dry Season			**Wet Season**		
Station Number	**Station**	Kendall's Tau	Slope	Intercept	Kendall's Tau	Slope	Intercept
1	BISC46B	-0.027	-0.040	108.303	0.074	0.137	-249.546
2	BISC52B	-0.136	-0.234	497.281	-0.001	-0.003	27.385
3	BISC54B	-0.025	-0.035	100.628	0.104	0.160	-292.866
4	BISC56B	-0.085	-0.130	288.768	0.018	0.043	-64.643
5	BISC60B	-0.057	-0.084	198.566	0.053	0.087	-147.374
6	BISC62B	-0.136	-0.174	377.964	-0.019	-0.042	109.701
7	BISC64B	-0.091	-0.114	258.780	-0.018	-0.035	96.461
8	BISC66B	-0.093	-0.107	247.955	0.018	0.029	-27.966
9	BISC70B	-0.122	-0.122	279.833	0.015	0.017	-1.158
10	BISCD2	0.012	0.026	-23.140	-0.059	-0.175	378.392
11	BISCD4	-0.102	-0.244	521.567	-0.078	-0.213	455.544
12	BISCD6	0.024	0.047	-65.511	-0.059	-0.170	368.189
13	BISC44B	-0.051	-0.078	184.713	0.077	0.146	-267.239
14	BISC48B	-0.008	-0.010	52.739	0.068	0.089	-145.174
15	BISCD8	-0.026	-0.024	83.974	0.051	0.053	-70.441
16	BISC00B	0.113	0.204	-381.570	0.052	0.113	-198.097
17	BISC06B	0.011	0.021	-11.762	0.041	0.078	-126.402
18	BISC10B	0.061	0.031	-25.497	0.117	0.052	-68.074
19	BISC12B	-0.023	-0.033	97.734	0.096	0.121	-208.142
20	BISC18B	-0.049	-0.067	165.020	0.085	0.130	-229.757
21	BISC20B	-0.007	-0.008	48.984	0.034	0.040	-44.774
22	BISC22B	-0.048	-0.097	216.998	0.056	0.158	-298.453
23	BISC26B	-0.077	-0.133	294.409	0.062	0.135	-243.520
24	BISC28B	-0.083	-0.167	358.029	0.041	0.117	-214.782
25	BISC34B	0.011	0.015	0.531	0.111	0.182	-333.835
26	BISC36B	-0.043	-0.044	122.459	0.095	0.099	-164.650
27	BISC40B	-0.080	-0.159	340.603	0.034	0.094	-171.328
28	BISCA2	0.128	0.307	-585.727	0.173	0.417	-807.780
29	BISCA4	0.165	0.350	-670.957	0.191	0.327	-625.012
30	BISCA6	-0.016	-0.058	143.481	0.011	0.045	-60.841

Table 4. Cross-validation results and fit statistics for salinity slope.

Data	**Mean Absolute Error (MAE)**	**Mean Squared Prediction Error (MSPE)**	**Coefficient of Determination (R^2)**
Wet season	0.0630	0.0067	0.7617
Dry season	0.0700	0.0086	0.7146
Combined over the seasons	0.0566	0.0058	0.7541

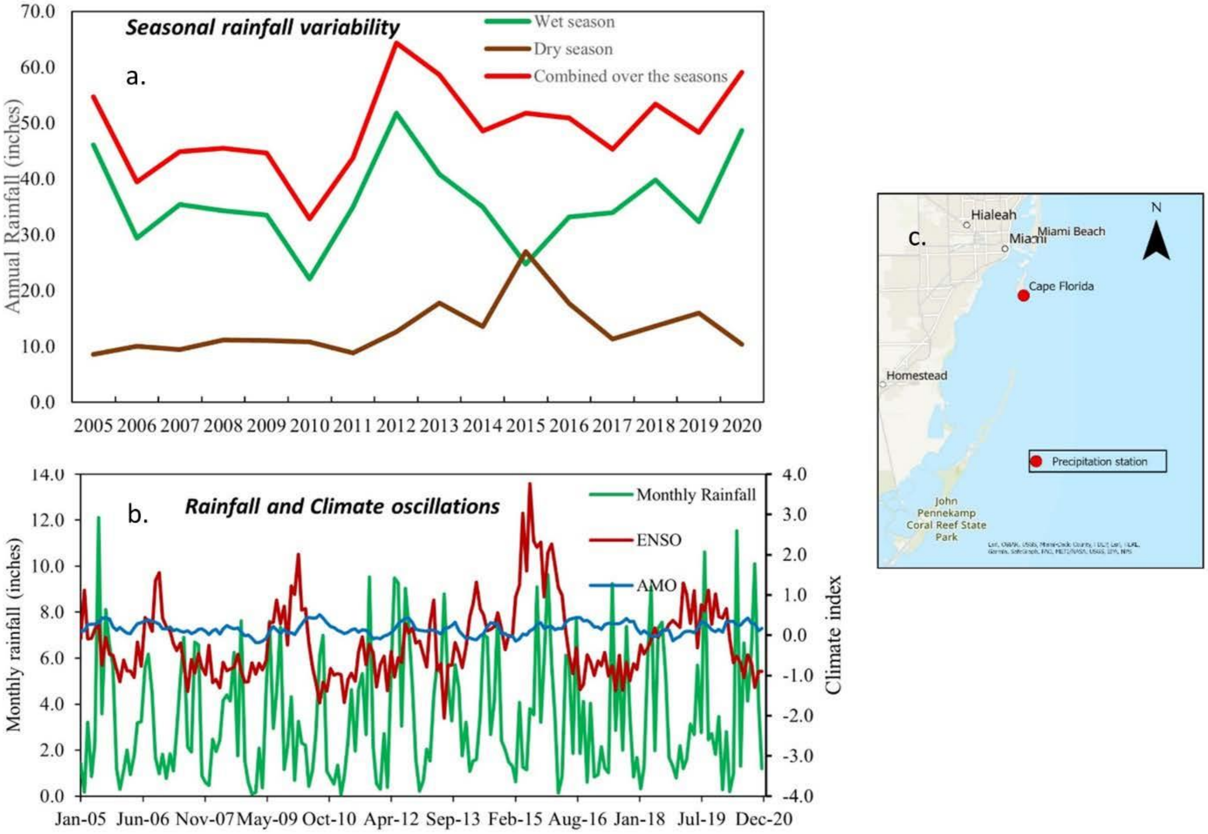

Figure 1. (a) Annual rainfall variability between the wet and dry seasons over the study period (200-2020), (b) Monthly rainfall and climate oscillations (ENSO and AMO), and (c) the location of the rainfall station within the study area. Spatial distribution of stations indicating positive and negative salinity slopes combined over the seasons.

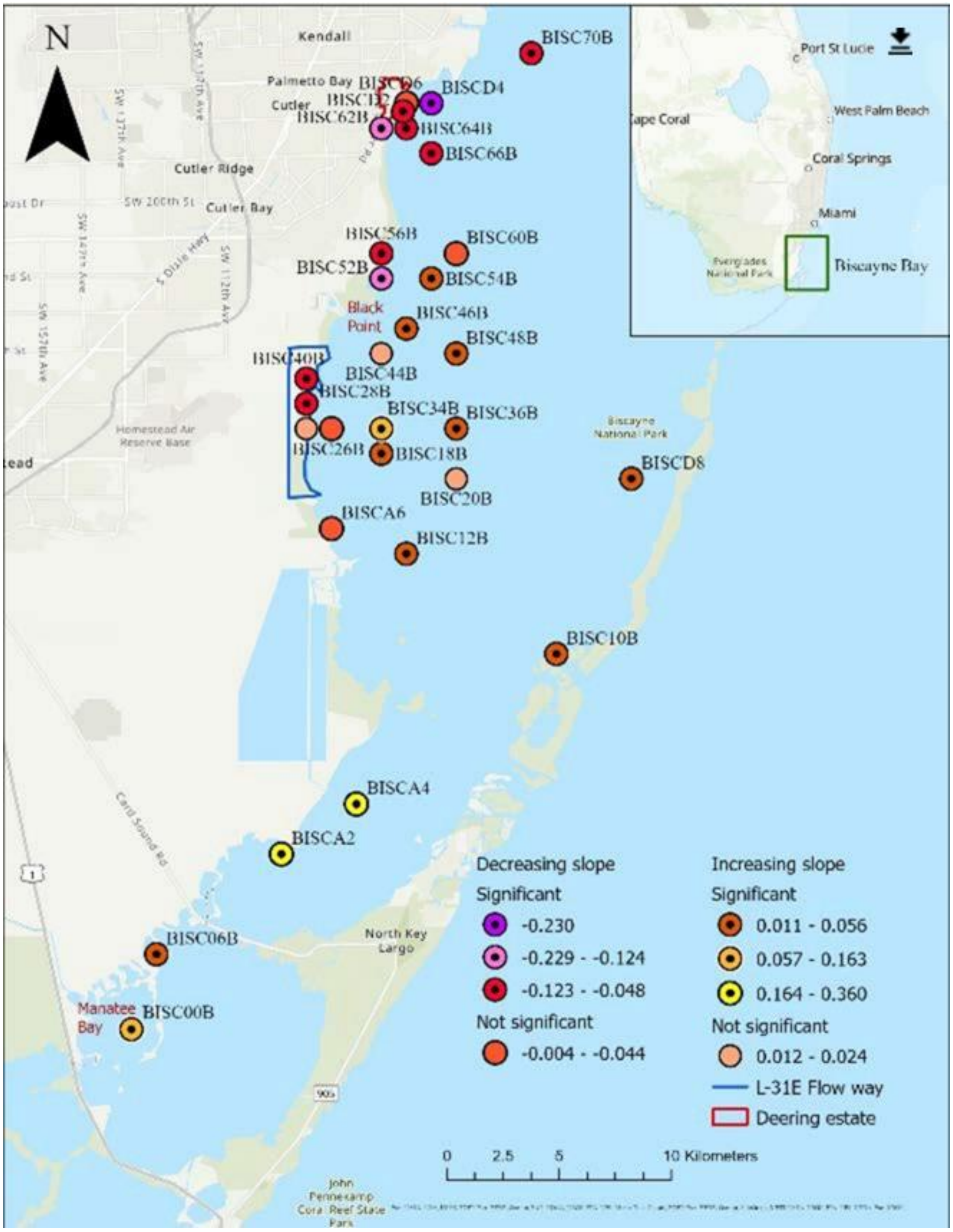

Figure 2. Spatial distribution of stations (combined over the stations) over the study area. Circles with black dots represent salinity slopes at stations where trends are statistically significant.

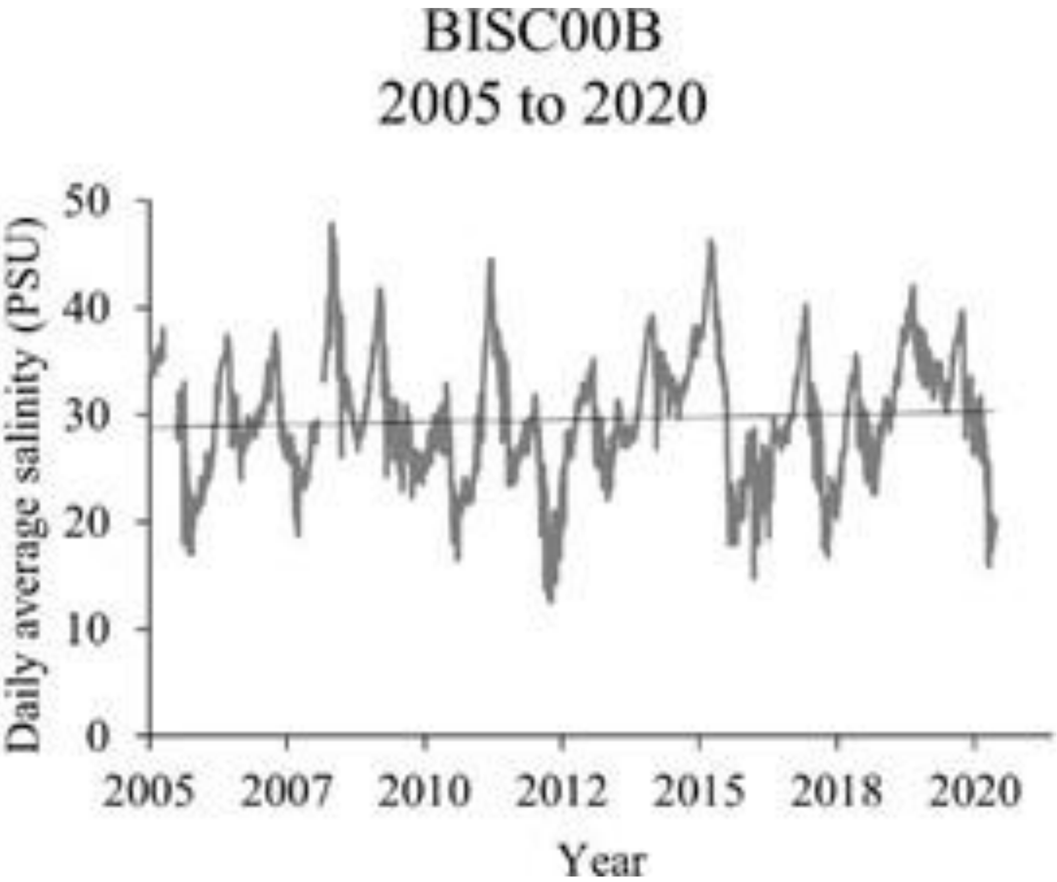

Figure 3a. Time series plot of southernmost station BISC00B from 2005 to 2020.

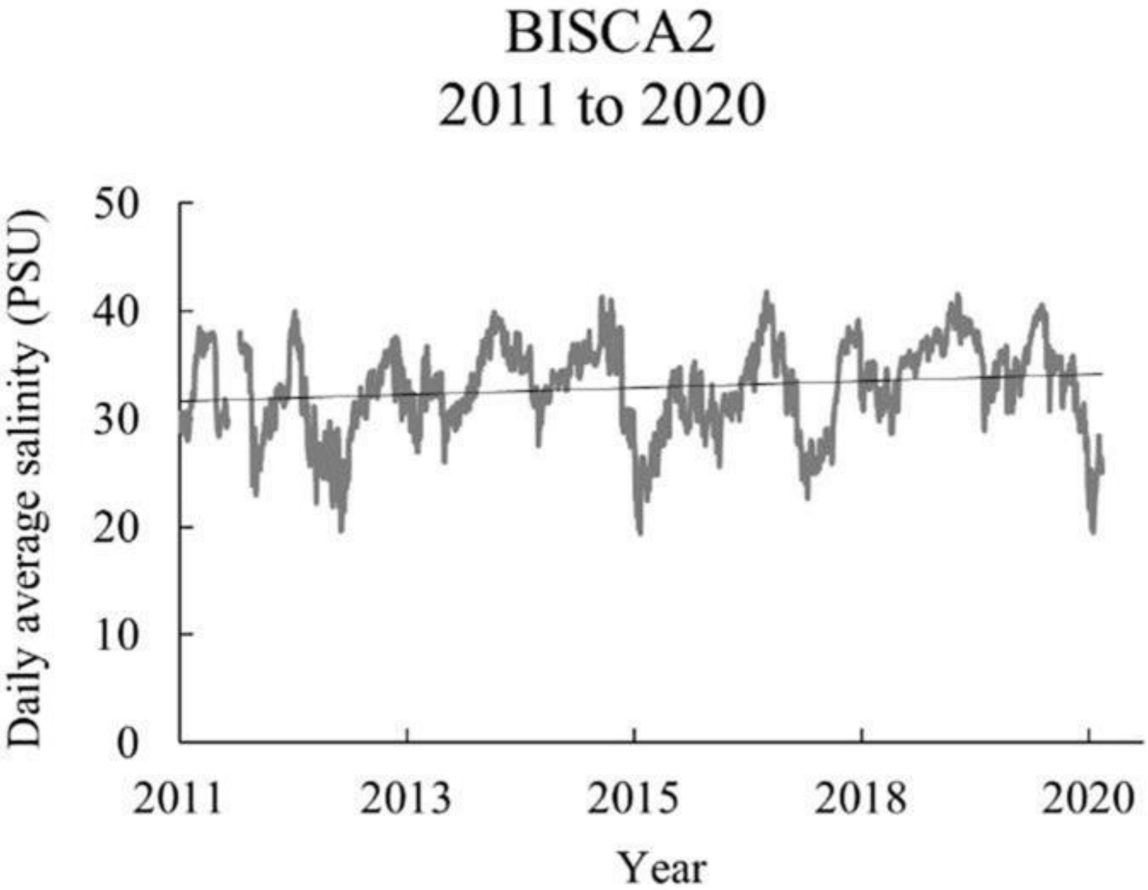

Figure 3b. Time series plot of station BISCA2 north of Manatee Bay from 2011 to 2020.

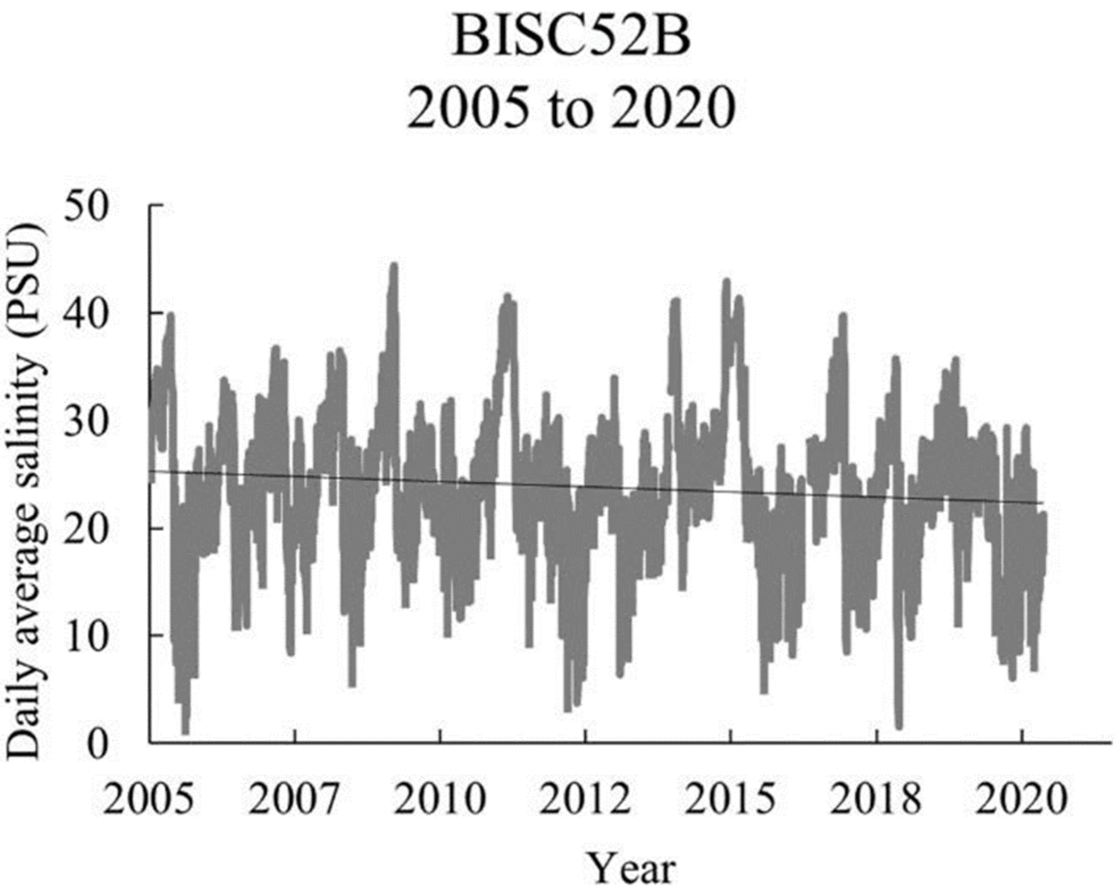

Figure 4a. Time series plot of station BISC52B from just north of Black Point, from 2005 to 2020.

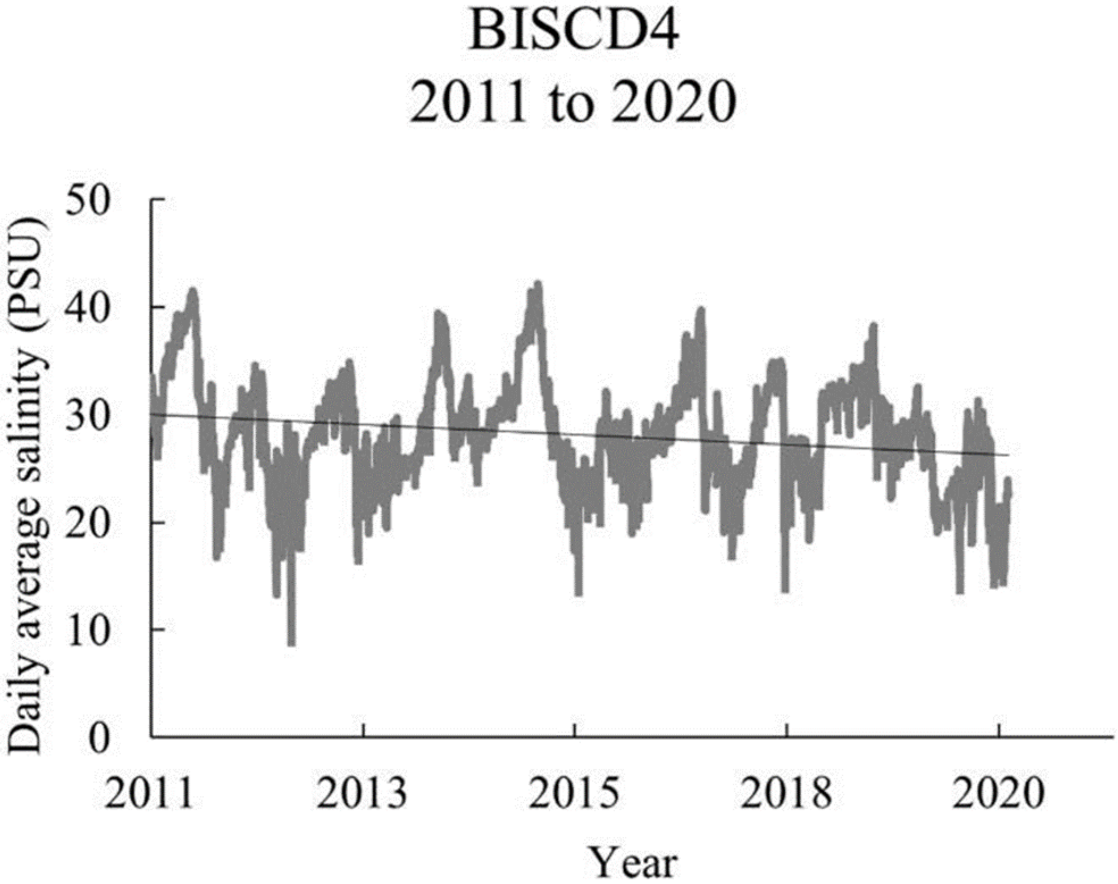

Figure 4b. Time series plot of station BISCD4 near Deering Estate, from 2011 to 2020.

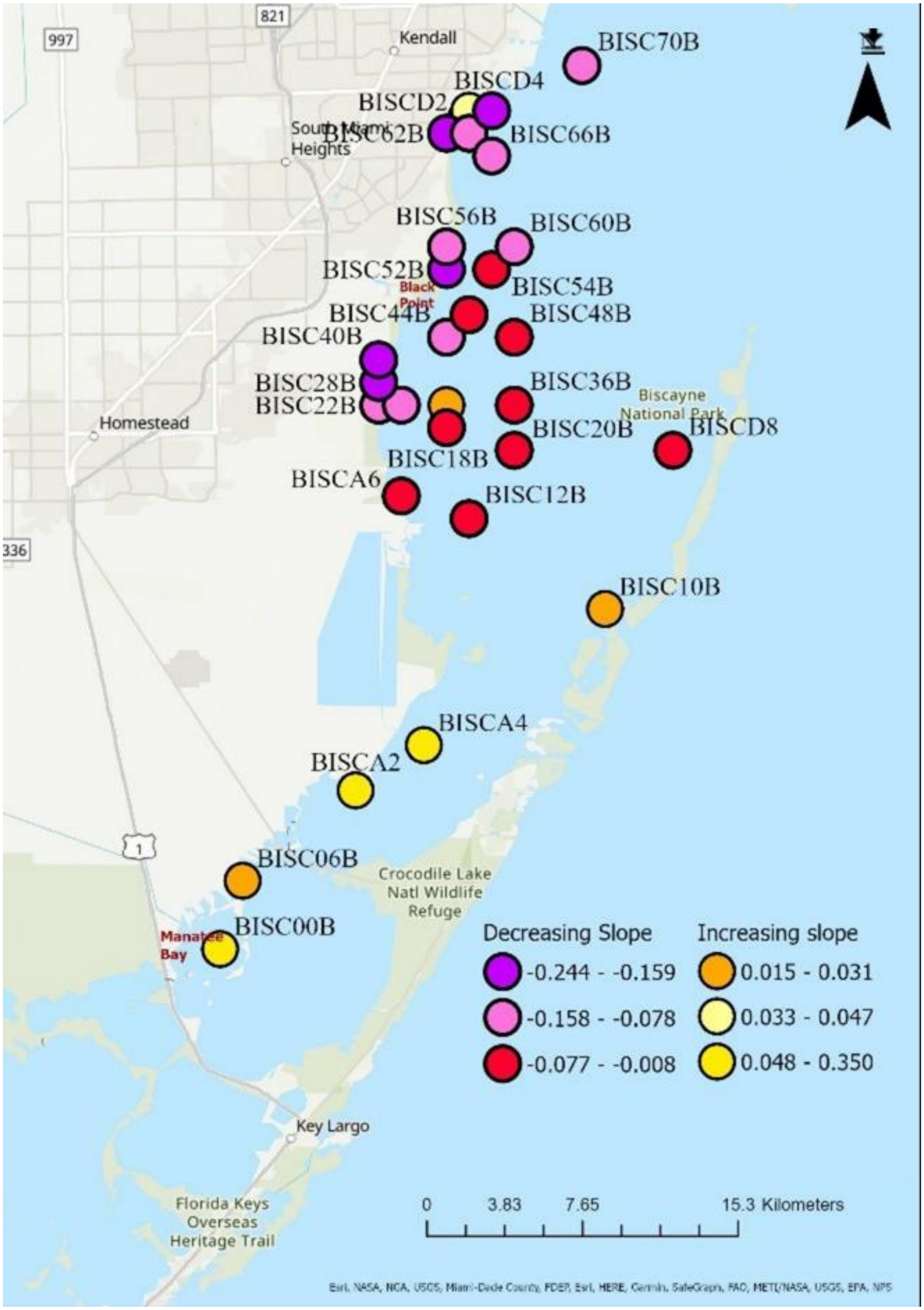

Figure 5a. Spatial distribution of stations indicating positive and negative salinity slopes for the dry season.

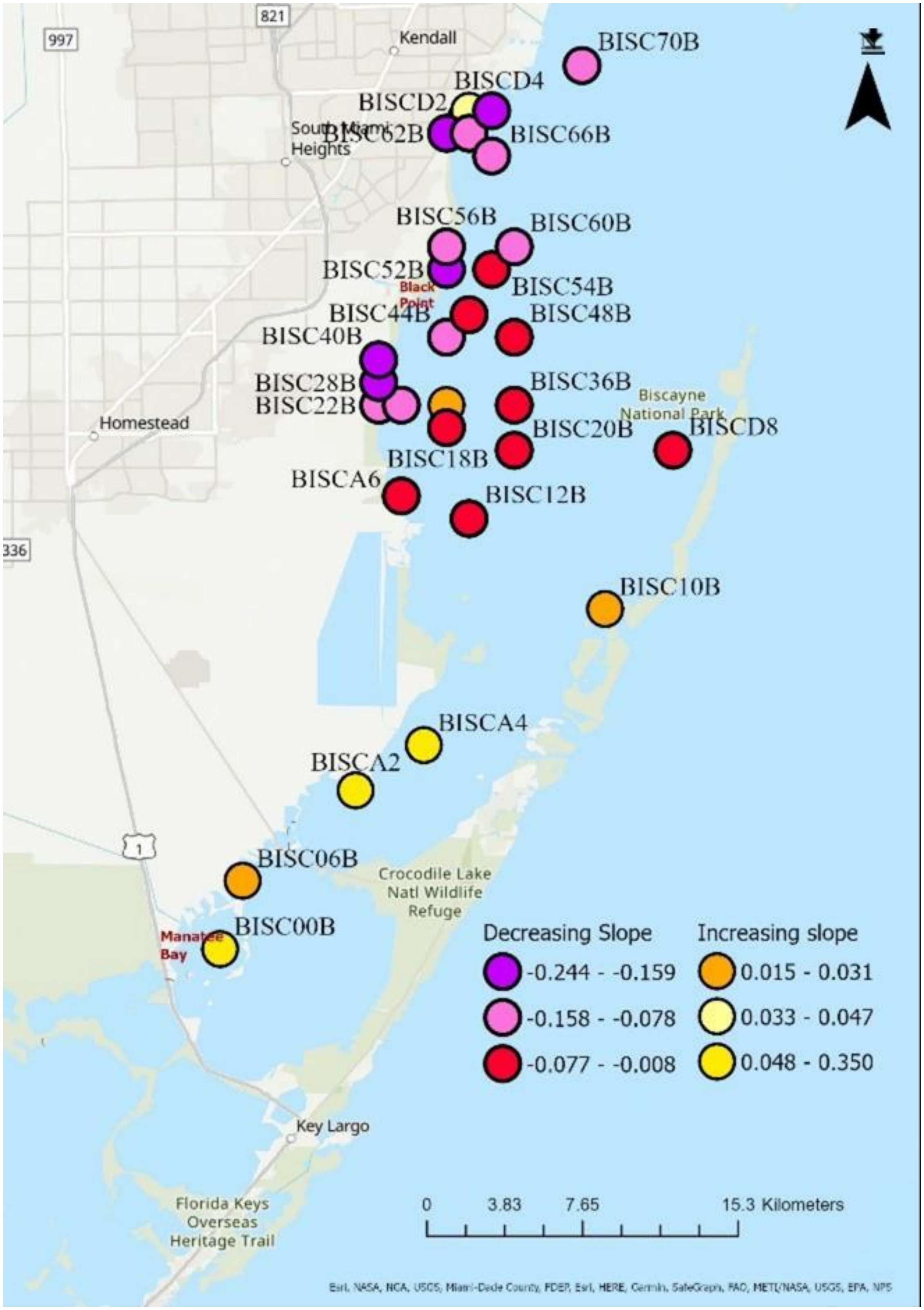

Figure 5b. Spatial distribution of stations indicating positive and negative salinity slopes for the wet season.

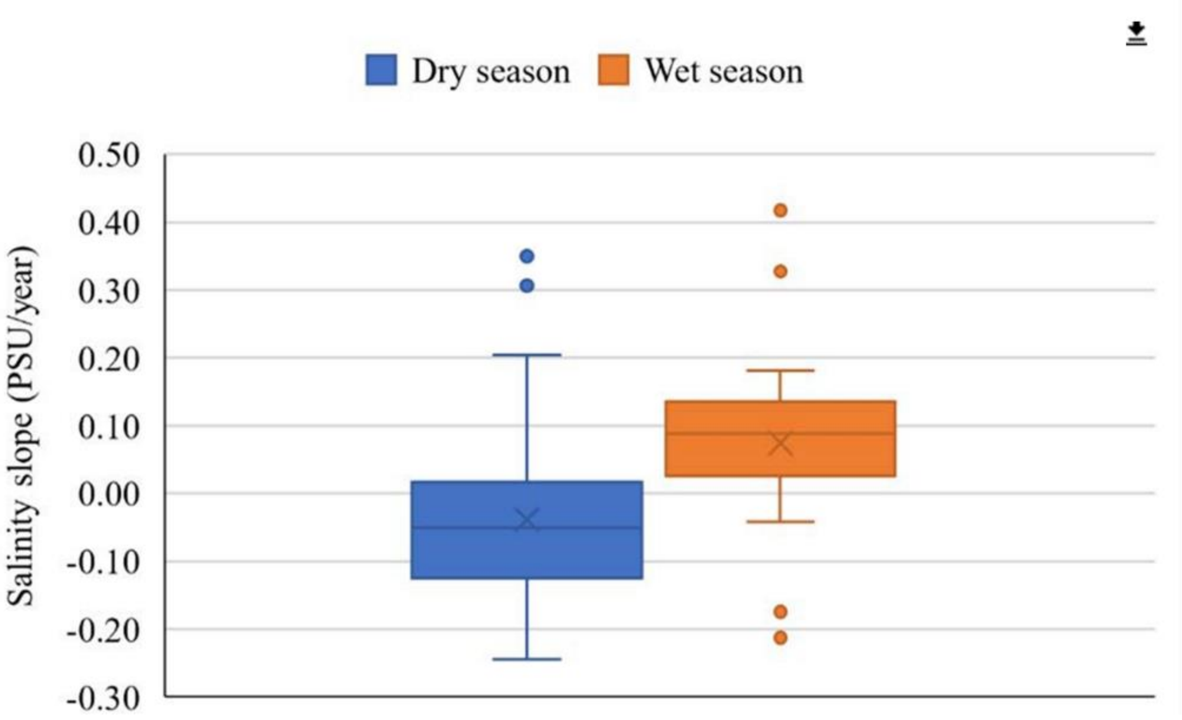

Figure 6. Box plot showing the mean, median, and quartiles of salinity slope in the dry and wet seasons.

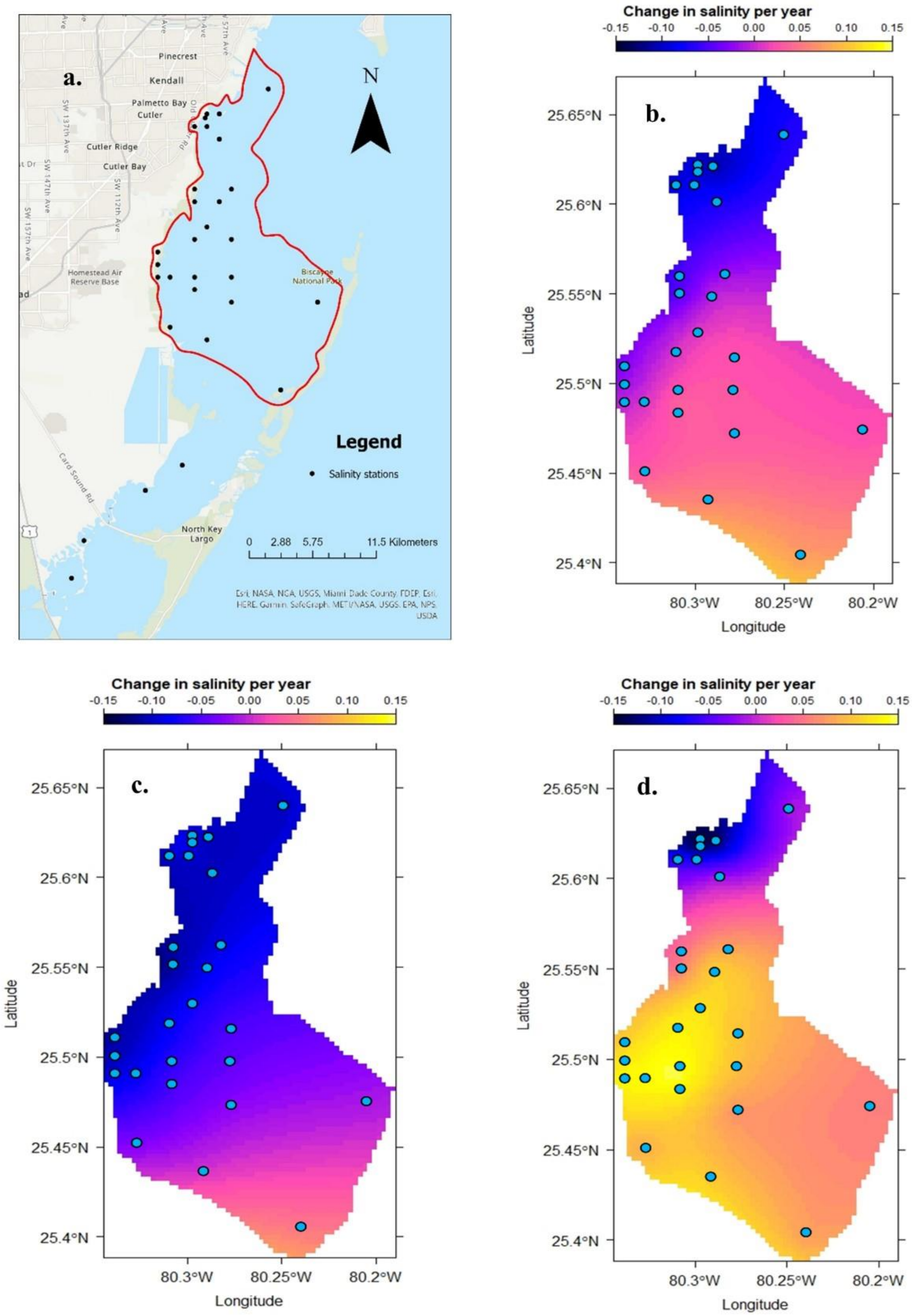

Figure 7. Stations included in the spatial analysis: (a) Spatial analysis for salinity slope; (b) combined over the seasons; (c) dry season; and (d) wet season.

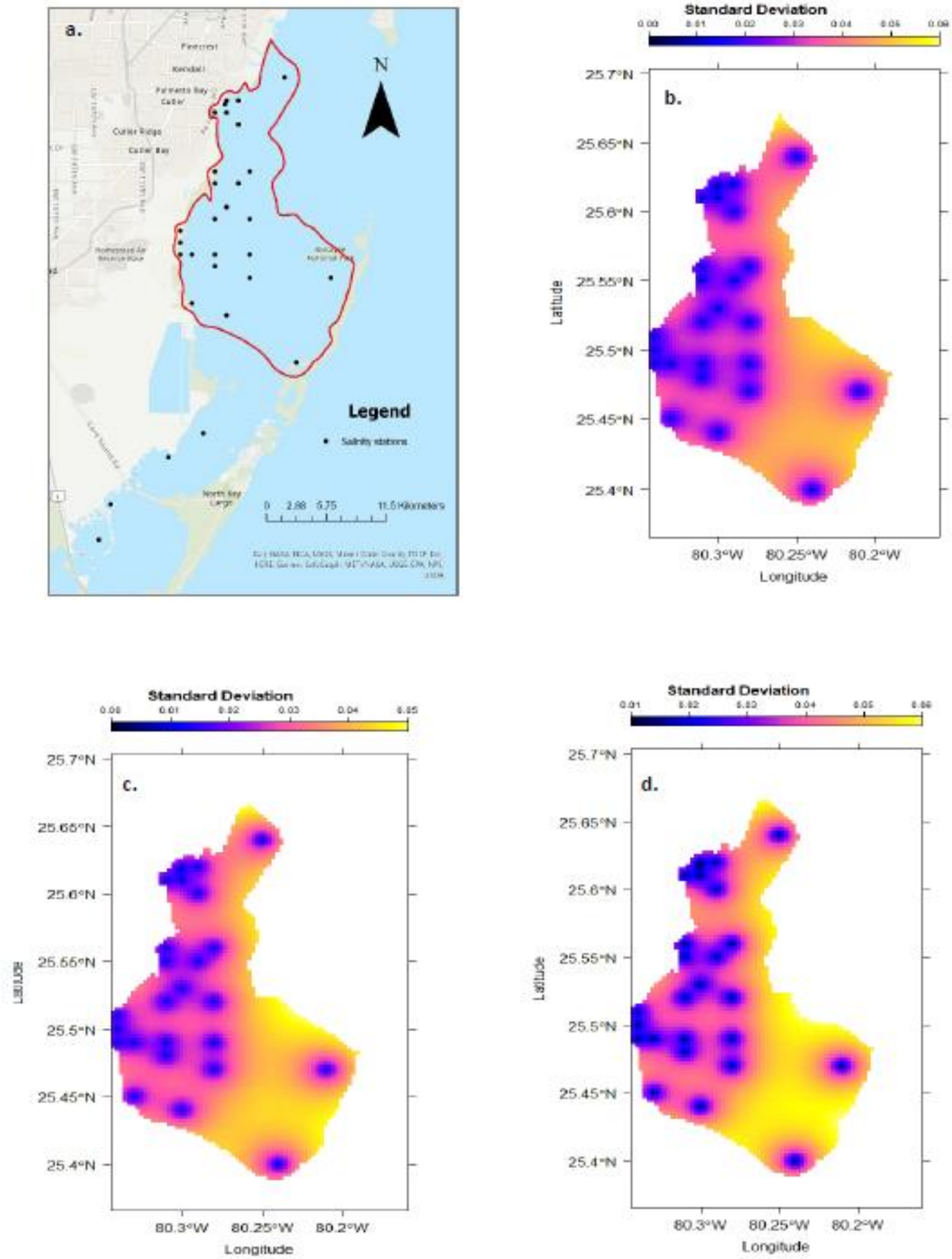

Figure 8. Prediction grid boundaries are shown in red line: (a) standard deviation plots for (b) combined over the seasons, (c) dry season, and (d) wet season.