Estuaries Vol. 25, No. 5, p. 976–984 October 2002

ENSO Impacts on Salinity in Tampa Bay, Florida

NANCY SCHMIDT* AND MARK E. LUTHER

College of Marine Science, University of South Florida, 140 Seventh Avenue South, St. Petersburg, Florida 33701

ABSTRACT: Estuarine salinity distributions reflect a dynamic balance between the processes that control estuarine circulation. At seasonal and longer time scales, freshwater inputs into estuaries represent the primary control on salinity distribution and estuarine circulation. El Niño-Southern Oscillation (ENSO) conditions influence seasonal rainfall and stream discharge patterns in the Tampa Bay, Florida region. The resulting variability in freshwater input to Tampa Bay influences its seasonal salinity distribution. During El Niño events, ENSO sea surface temperature anomalies (SSTAs) are significantly and inversely correlated with salinity in the bay during winter and spring. These patterns reflect the elevated rainfall over the drainage basin and the resulting elevated stream discharge and runoff, which depress salinity levels. Spatially, the correlations are strongest at the head of the bay, especially in bay sections with long residence times. During La Niña conditions, significant inverse correlations between ENSO SSTAs and salinity occur during spring. Dry conditions and depressed stream discharge characterize La Niña winters and springs, and the higher salinity levels during La Niña springs reflect the lower freshwater input levels.

Introduction

Tampa Bay is the largest estuary in Florida and is one of the most biologically diverse subtropical estuarine areas in the United States. It supports a wide variety of marine organisms, including over 250 macroalgae species, 250 fish species, and 1,200 species of macro-invertebrates (e.g., scallops, sponges, crabs, and shrimp; Harwell et al. 1995). This diversity, combined with its role as nursery habitat for many species, makes Tampa Bay a vital habitat for Gulf of Mexico fish and shellfish populations.

Recreational and commercial use of the Tampa Bay estuary system contributes greatly to the local economy, and its ecological health is an issue of great concern (DelCharco 1998). Because many regulatory and management decisions that impact estuaries and their watersheds (such as Tampa Bay) are based on circulation patterns and flow, it is essential to understand and expand the knowledge of estuarine dynamics.

Estuarine circulation is controlled by a suite of factors that vary over a range of time scales from tidal (diurnal to semi-diurnal) to annual and longer. The primary controls include density differences, astronomical tides, and winds. Large-scale weather patterns as well as synoptic wind events may increase or decrease flows out of or into estuaries. For example, on time scales of days, persistent winds associated with winter frontal passages have a strong impact on residence time in Tampa Bay (Burwell 2001). Density-driven circulation within estuaries is controlled by horizontal salinity gradients and is influenced by the net freshwater supply into estuaries. Freshwater input is the sum of runoff, stream flow, groundwater discharge, and direct precipitation minus evaporation from the estuary. Salinity patterns in an estuary result from a dynamic steady state in which the advective flux of salt into or out of the estuary, which is driven by the net freshwater supply, is balanced by the dispersive flux from the exchange of water by tides and other hydrodynamic mixing processes (Pritchard 1956).

Freshwater inputs into estuaries vary on many time scales. For example, seasonal precipitation patterns such as wet summer and dry winter seasons may have a pronounced influence on estuarine salinity distributions. At interannual time scales, climate variability such as El Niño-Southern Oscillation (ENSO) has well documented influences on precipitation and stream discharge, which dominate freshwater inputs into estuaries. In terms of characterizing ENSO impacts on estuarine systems, most research has focused on individual El Niño or La Niña events and their influences on water quality and biological and physical parameters (Peebles 1999; Lipp et al. 2001a; Matheson unpublished data). This paper describes the impact of ENSO on salinity distribution in Tampa Bay, Florida from the period of 1974 through 1999. Understanding ENSO-related variability in salinity has important implications for water resources management in the Tampa Bay area. Natural salinity variability may reinforce or diminish the impacts

* Corresponding author; current address: Institute for the Study of Planet Earth, The University of Arizona, 715 North Park Avenue, Tucson, Arizona 85721; tele: 520/792-8712; e-mail: nschmidt@mail.arizona.edu.

of human-caused changes in salinity in the bay, with implications for not only the estuarine ecosystem but also the economy and welfare of its human residents.

Implications of Variability in Salinity Distribution

Variability in salinity levels within an estuary has implications for both its physical and biological components. The longitudinal salinity distribution controls the residual or density-driven circulation in an estuary, therefore, anything that affects the salinity gradient from the head to the mouth of an estuary impacts estuarine circulation and flushing. Because the distribution of water quality parameters such as chlorophyll a and dissolved oxygen are often affected by the same physical processes that determine salinity distribution (for example, tides, precipitation, and evaporation), their levels are related to salinity in many estuaries (Rutherford et al. 1995; Boyer et al. 1997; Bendis 1999). Many organisms in estuaries have optimal salinity ranges, and changes in salinity distributions due to both natural and human causes have the potential to impact biological resources (Zarbock et al. 1995; Boler 1998).

Coastal and estuarine areas in the United States are experiencing unprecedented population growth. Hand-in-hand with burgeoning coastal populations comes the necessity of managing and maintaining coastal waters that are increasingly stressed by human impacts. Increased wastewater originating from treatment plants and septic tanks and higher volumes of urban nonpoint runoff both result from population growth in coastal communities (NOAA 1998). Urbanization will continue to alter coastal watersheds and freshwater flows to estuaries, such as Tampa Bay, as rural lands are converted to housing developments and stream flows are diverted to meet the freshwater needs of the growing population. Within this context, it is important to understand the role of natural climate variability, through its impacts on precipitation and stream discharge, on salinity distributions in order to assess effectively and accurately the impacts of human alterations.

ENSO and Florida

El Niño-Southern Oscillation (ENSO) refers to a global climate fluctuation that originates in the equatorial Pacific Ocean through large-scale interaction between the ocean and atmosphere. During El Niño (warm) events, the waters of the eastern equatorial Pacific are anomalously warm and sea level pressure lowers in the eastern Pacific Ocean and rises to the west. This is accompanied by a weakening of the low-latitude easterly trade winds and increased heating of the tropical atmosphere over the central and eastern Pacific Ocean. The associated impacts on atmospheric conditions include strengthening of jet streams and steering of extratropical storms and frontal systems along paths that are significantly different from normal. During La Niña (cold) events, the waters of the equatorial Pacific are anomalously cool, with strengthened easterly trade winds and higher sea level pressure in the eastern Pacific Ocean (Rasmusson and Carpenter 1982; Trenberth 1991; Dawson and O'Hare 2000). Teleconnections for both El Niño and La Niña events include temperature and precipitation anomalies in many regions of the world (Rasmusson and Wallace 1983; Ropelewski and Halpert 1986). In Florida, ENSO teleconnections include elevated rainfall during El Niño fall and winter seasons and low rainfall levels during La Niña winter and spring seasons. Impacts on stream discharge demonstrate similar patterns, although streamflow response may be delayed by several months depending on drainage basin characteristics (Schmidt et al. 2001).

Materials and Methods

Site Characteristics

Tampa Bay, the largest estuary in Florida, covers about 1,031 km^2, stretches about 53 km in length (Fig. 1), and has a watershed of 6,483 km^2 (Southwest Florida Water Management District 1998). Most of the bay is shallow, with an average depth of only 3.7 m, but the navigational channels reach depths of up to 13 to 14 m (Zervas 1993). The tides in Tampa Bay are small in amplitude—the diurnal range is 70 cm (Goodwin and Michaelis 1976)—and are mixed semi-diurnal and diurnal. Tidal constituents account for only 52% of sea-level fluctuations in Tampa Bay (Zhang 1994), with coastal set-up and synoptic scale set-up contributing significantly to error in sea-level prediction. The strongest tidal currents occur in the deepest, dredged parts of the bay and are on the order of 1 m s^{-1}. Residual circulation in Tampa Bay varies from about 0.05 to 0.1 m s^{-1} in the navigational channel in the middle of the bay.

The principal rainy season is from June to September, the result of local afternoon thunderstorms and the occasional tropical storm. Due to synoptic-scale winter storms, February and March also may show secondary precipitation peaks (Winsberg 1990). Maximum rainfall levels occur in the summer (averaging about 50 cm) and minimum levels in the fall (averaging about 15 cm). Interannual variations in precipitation are common in the Tampa Bay area and may be related to climate variability such as ENSO (Schmidt et al. 2001). Annual rainfall averages 140 cm. During El

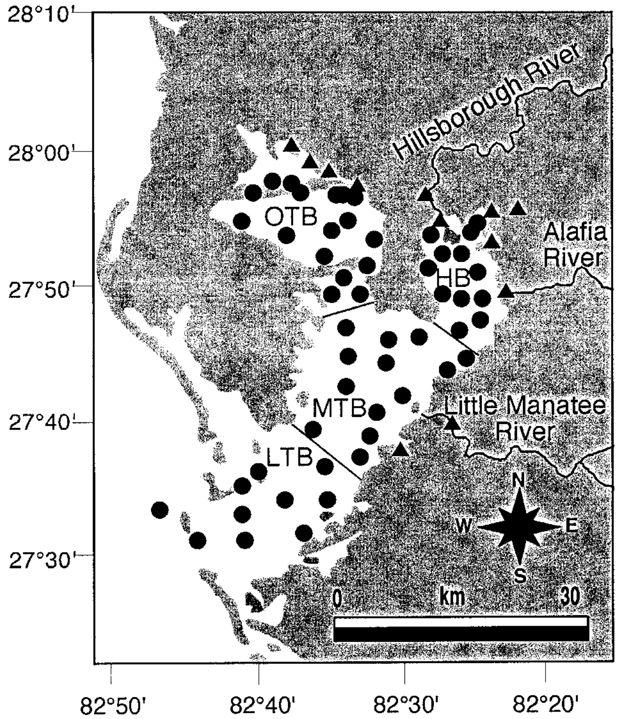

Fig. 1. Map of Tampa Bay area with estuarine salinity stations indicated by circles and tributary stations indicated by triangles. The geographic subdivisions in Tampa Bay are Old Tampa Bay (OTB), Hillsborough Bay (HB), middle Tampa Bay (MTB), and lower Tampa Bay (LTB).

Niño years, there may be an additional 40–50 cm of precipitation while during La Niña years there may be as much as 90 cm less precipitation (Schmidt et al. 2001).

Freshwater input to the bay comprises direct precipitation (43%; Zarbock et al. 1995) and surface water sources (discharge from several rivers, mostly along the east side of the bay, and direct runoff; 41%; Zarbock et al. 1995), with smaller contributions from domestic point sources, groundwater, springs, and industrial point sources. Peak stream flow occurs in August–September, with a secondary peak in February–March. This seasonal stream discharge pattern corresponds to the seasonal rainfall distribution with lags up to a month or two. Due to the small drainage area, mean annual freshwater flow is small, averaging only 95 $m^3 s^{-1}$ for the period 1985–1991 (Zarbock et al. 1995) with approximately 35–39 $m^3 s^{-1}$ from stream flow (Flannery 1989; based on gauged rivers; Zarbock et al. 1995). There is considerable interannual variability in stream flow. During the period 1974–1994, Bendis (1999) finds that annual combined flows for Tampa Bay's four largest drainages (Hillsborough, Alafia, Little Manatee, and Manatee Rivers) are up to five times higher during wet years such as 1979 and 1983 than during dry years such as 1990. These four rivers drain approximately 75% of the bay's watershed and account for up to 82% of the total stream flow into the bay. Most of Tampa Bay's freshwater inflow is into Hillsborough Bay, which is located in the northern, more industrial and urban part of the bay. Flannery (1989) catalogues 44 minor tributaries, most of which are ungauged and less than 28 km long. Many of the small tidal creeks have been substantially modified by channelization, bank hardening, urban runoff, industrial discharges, and flow alteration during the past 50 years. The Hillsborough River has been dammed 18 km from its mouth to create a reservoir for the City of Tampa's drinking water supply.

Salinities in Tampa Bay vary from highs of 35 or more at the mouth to lows of 22 or less in the upper portions of the bay, and this gradient occurs during both relatively dry and wet years (Squires et al. 1995). Squires et al. (1995) and Galperin et al. (1991) both conclude that horizontal density gradients are significant in driving the circulation of the bay. Because of its shallow depth, relatively small freshwater inflows, small tidal range, and winds, Tampa Bay is typically vertically well mixed (DelCharco 1998). Salinity throughout the bay typically is inversely related to stream flow, with high values baywide during the winter and late spring and low values in the summer (Bendis 1999). These patterns are most pronounced in the upper portions of the bay (Tampa Bay National Estuary Program 1995). In terms of freshwater inputs and estuarine circulation, proposed freshwater diversions and concentrate discharges from a desalination plant are two pertinent alterations to Tampa Bay's fresh water inputs and circulation. Both of these have as yet unknown interactions with climate variability.

Based on analyses of water quality data (Lewis and Whitman 1985; Rutherford et al. 1995; Bendis 1999) and of residence time (Burwell 2001), Tampa Bay can be divided into four bay segments that are delineated by the combined effects of fresh water input, morphology, and tidal forcing (Fig. 1). Lower Tampa Bay flushes very quickly and is dominated by tidal influences, especially along the deep navigational channel. The Sunshine Skyway Bridge causeway and irregularities in the bay's morphology cause the circulation to be slower on the sides of the bay in this section. Middle Tampa Bay typically has the largest salinity gradients and is not dominated by any single mechanism; both freshwater input and wind stress dominate in this section (Burwell 2001). Most of the bay's freshwater input enters into Hillsborough Bay, and this section flushes relatively quickly. Burwell (2001) finds Old Tampa Bay, which is shallow and has restricted flows due to constrictions and causeways, to have very long residence times and circulation that is dominated by tidal forcing. Both Burwell (2001) and Bendis (1999) find that the northernmost parts of Old Tampa Bay are influenced by freshwater flow from several small tidal creeks in this area.

Data

El Niño-Southern Oscillation

Monthly Niño-3.4 sea surface temperature anomaly (SSTA) values for the period 1974–1999 were obtained from the Climate Prediction Center (CPC) and used to evaluate ENSO conditions. El Niño (La Niña) months were defined as those whose SSTA exceeds 0.4°C (is less than −0.4°C). Months were considered neutral when SSTA fell between ± 0.4°C. This methodology is in agreement with previous research on the impacts of climate variability in Florida (Lipp et al. 2001b; Schmidt et al. 2001). This approach to classifying ENSO events was chosen because there is no single generally accepted classification scheme, this scheme captures the most widely recognized and accepted ENSO events, and application of this classification scheme to the SSTA data is straight-forward.

Salinity

Monthly salinity data (1974–1999) were obtained for Tampa Bay and its tidal tributaries from the Environmental Protection Commission of Hillsborough County (HEPC), which maintains the most extensive database of its kind for Tampa Bay. Over the period of record, salinity was measured once a month at mid-depth for 11 tributary and 52 estuarine stations (Fig. 1). Tributary stations average 78% data coverage and estuarine stations average 99% data coverage for mid-depth salinity over the period of record. Seventeen estuarine stations are located in Old Tampa Bay, 12 in Hillsborough Bay, 12 in middle Tampa Bay, and 11 in lower Tampa Bay. Four tidal tributary stations are located in Old Tampa Bay, 5 in Hillsborough Bay, and 2 in middle Tampa Bay.

The HEPC samples on a monthly basis over a three-week period during which roughly one-third of the stations are sampled on one day in each of three consecutive weeks (Boler et al. 1991). This sampling regime is not synchronized to tidal cycle. Because depths in Tampa Bay and its tributaries vary from over 10 meters in the shipping channel to less than 2 meters over seagrass flats, mid-depth is not the same water depth at different stations. Interpretation of these data must take into account that they were collected under variable conditions. Despite the asynoptic monthly sampling strategy, salinity data from the Tampa Bay area are suitable for answering the questions posed in this research.

Analyses

The approach used in this study was to analyze the statistical correlation between salinity and ENSO SSTAs for 63 tidal tributary and estuarine stations in Tampa Bay, Florida from 1974 through 1999. For each station, mid-depth salinity was correlated with ENSO SSTAs in several different ways: over the entire period of record; for all months corresponding to El Niño conditions; for all months corresponding to La Niña conditions; and seasonally for months corresponding to El Niño and La Niña ENSO SSTA values. The latter correlations attempt to take into account the non-linearity of ENSO-related teleconnections and impacts that might affect salinity so that the question asked, for example, might be: If it is an El Niño winter, is there a correlation between the strength of the El Niño and salinity in Tampa Bay?

Approximate randomized correlations were used in all analyses to test the null hypothesis that there is no relationship between ENSO SSTAs and salinity in Tampa Bay. This computer-intensive test generates the probability distribution of the test statistic by recomputing it for many (10,000) artificially constructed data sets and is used to assess significance under minimal assumptions. The observations that are tested do not need to meet the normal distribution criteria of conventional parametric statistics and do not need to be a random sample. Approximate randomized tests maximize the ability to discriminate between hypotheses because the sampling distribution is known (Noreen 1989).

Results

Results for the correlation analyses are discussed in sections corresponding to ENSO state. Correlation values (r-values) for the approximate randomized correlations are considered significant if the probability of the correlation arising by chance is less than or equal to 5%.

Salinity and ENSO SSTAs

The relationship between monthly ENSO SSTAs and salinity in the Tampa Bay area was examined in several ways, the results of which are summarized in Table 1. No significant correlations exist between salinity and ENSO SSTAs over the entire period of record (all months) or when only seasonal values are considered.

Salinity, El Niño, and La Niña

The relationship between mid-depth salinity and El Niño and La Niña conditions was examined over

TABLE 1. Mean r-value for correlations between monthly salinity data and ENSO SSTA for the period 1974–1999.

	Middle Salinity	
	Tidal Tributary	Estuarine
All months	−0.095	−0.061
Winter (JFM)	−0.154	−0.073
Spring (AMJ)	−0.194	−0.249
Summer (JAS)	−0.020	−0.013
Fall (OND)	−0.057	0.014

TABLE 2. Mean r-value for correlations between mid-depth salinity and El Niño or La Niña months for the period 1974–1999.

	El Niño		La Niña	
	Tributary	Estuarine	Tributary	Estuarine
All months	−0.156*	−0.311***	−0.082	0.032
Winter (JFM)	−0.105	−0.401**	−0.123	0.223
Spring (AMJ)	0.000	−0.407***	−0.444**	−0.384**
Summer (JAS)	−0.057	−0.235	−0.109	0.059
Fall (OND)	−0.324*	−0.341**	−0.020	0.110

* Correlation values that are significant at the 90% level.
** Correlation values that are significant at the 95% level.
*** Correlation values that are significant at the 99% level.

the entire period of record (all months corresponding to either El Niño or La Niña conditions) as well as seasonally. Significant correlations between El Niño SSTAs and mid-depth salinity are documented for estuarine stations over the entire period of record and for all seasons except summer (Table 2). Significant correlations for La Niña SSTAs and mid-depth salinity are found only during spring months. Overall, mid-depth salinity varies negatively with both El Niño and La Niña ENSO SSTA values.

Spatiotemporal Variability of Salinity and El Niño/La Niña Correlations

Correlation results for El Niño and mid-depth salinity exhibit spatial variability, with decreasing correlation values and significance from head to mouth for all seasons except spring (Table 3; Fig. 2). Stations in Old Tampa Bay (OTB) have the largest mean correlation value and significance level, whereas stations in lower Tampa Bay (LTB) have the lowest mean correlation value and significance level. This spatial trend is reversed for spring months. For La Niña conditions, only the spring season mid-depth salinity has significant correlations with ENSO SSTAs. This inverse relationship is strongest at the head of the bay and weakens towards the mouth (Table 4, Fig. 3).

Discussion

Salinity and ENSO

The connection between salinity and ENSO is a complicated chain of impacts from ENSO SSTAs to global weather patterns to local precipitation effects to spatially variable discharge and runoff patterns within the Tampa Bay drainage area to salinity distribution. Various factors influence this chain of impacts, including nonlinearities in ENSO teleconnections. Recent research into the differences in timing and impacts of El Niño and La Niña teleconnections has shown that they are not necessarily equal and opposite (Hoerling et al. 1997). This has been documented for ENSO impacts on Florida's seasonal precipitation, with increased rainfall associated with El Niño falls and winters and drier conditions associated with La Niña winters and springs (Schmidt et al. 2001). With respect to the results of the correlation analyses for salinity and ENSO SSTAs (Table 1), it is not surprising that the correlation values are low and insignificant.

Mid-depth salinity in Tampa Bay is significantly and inversely correlated to El Niño SSTAs (Table 2; Fig. 2). The increased precipitation and elevated discharge levels associated with El Niño events (positive ENSO SSTAs) in Florida result in lower

TABLE 3. Mean r-value for significant correlations between mid-depth salinity and El Niño months from Table 2, broken out by each bay section for the period 1974–1999.

	Winter (JFM)	Spring (AMJ)	Summer (JAS)	Fall (OND)
All estuarine stations	−0.401**	−0.407***	−0.235	−0.341**
OTB	−0.513***	−0.353**	−0.341**	−0.418***
HB	−0.369**	−0.381**	−0.071	−0.324**
MTB	−0.395**	−0.444***	−0.231	−0.348**
LTB	−0.272**	−0.480***	−0.255	−0.231
All tidal tributary stations	−0.105	0.000	−0.057	−0.324*
OTB	−0.047	0.039	−0.148	−0.429***
HB	−0.085	−0.040	0.023	−0.301***
MTB	−0.275**	0.022	−0.075	−0.171

* Correlation values that are significant at the 90% level.
** Correlation values that are significant at the 95% level.
*** Correlation values that are significant at the 99% level.

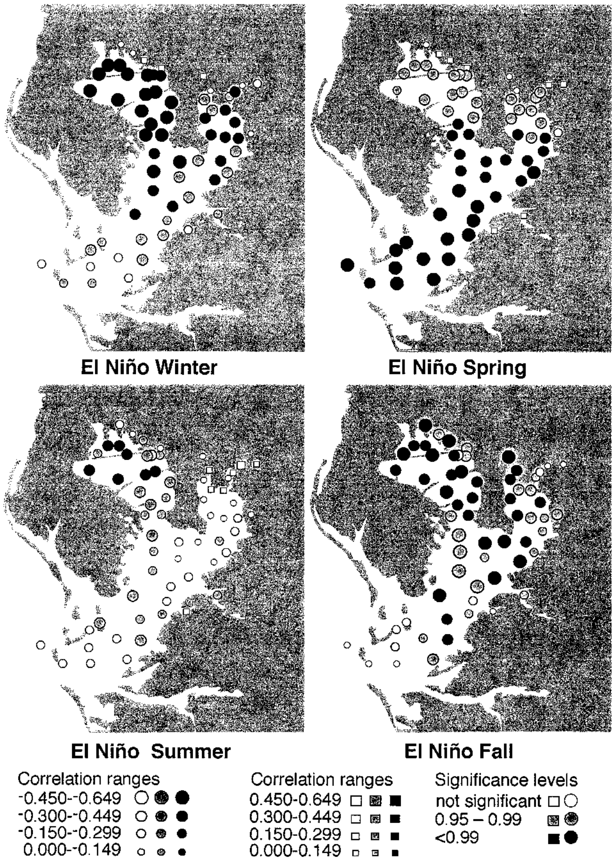

Fig. 2. Maps of Tampa Bay showing, for each season, the sign, strength, and significance of correlations between ENSO SSTA and mid-depth salinity for the four bay sections for El Niño conditions.

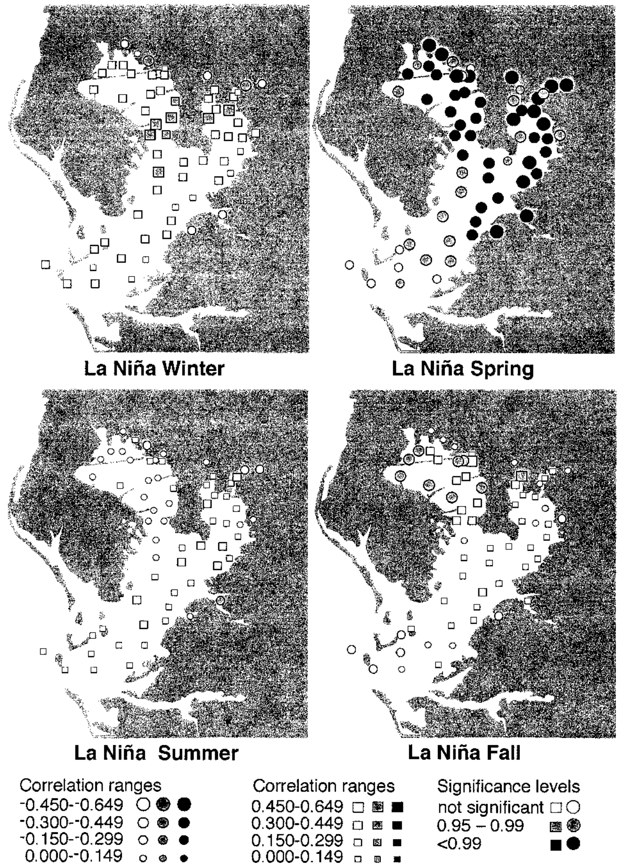

Fig. 3. Maps of Tampa Bay showing, for each season, the sign, strength, and significance of correlations between ENSO SSTA and mid-depth salinity for the four bay sections for La Niña conditions.

mid-depth salinity values in Tampa Bay. This relationship is strongest in the winter and spring, reflecting the prolonged response of discharge to the elevated precipitation levels in fall and winter. Summer salinity patterns are not influenced by ENSO state but instead are dominated by the impact of highly localized, convective storms and their runoff. Salinity during fall exhibits significant relationships with El Niño conditions but not as strong as during the winter season. This is consistent with the weaker and less significant relationships found between El Niño conditions and both precipitation and stream discharge during the fall season (Schmidt et al. 2001).

TABLE 4. Mean r-value for significant correlations between mid-depth salinity and La Niña months from Table 2, broken out by each bay section for the period 1974–1999.

	Winter (JFM)	Spring (AMJ)	Summer (JAS)	Fall (OND)
All estuarine stations	0.223	−0.385*	0.059	0.110
OTB	0.266	−0.405**	−0.034	0.301
HB	0.218	−0.434**	0.105	0.052
MTB	0.217	−0.392*	0.102	0.078
LTB	0.169	−0.292	0.106	−0.085
All tidal tributary stations	−0.123	−0.444*	−0.109	−0.020
OTB	−0.156	−0.435*	−0.102	−0.027
HB	−0.062	−0.439*	−0.085	0.018
MTB	−0.212	−0.47**	−0.184	−0.101

* Correlation values that are significant at the 95% level.

** Correlation values that are significant at the 99% level.

La Niña impacts on the Tampa Bay, Florida area include lower precipitation levels and depressed stream discharge rates during winter and spring (Schmidt et al. 2001). Mid-depth salinity in Tampa Bay during spring is elevated significantly in response to these local La Niña conditions (Table 2). Other seasons do not exhibit significant relationships between salinity and La Niña SSTAs.

Salinity levels in the tidally influenced tributaries of Tampa Bay exhibit no significant relationships to either El Niño or La Niña ENSO SSTAs with the exception of La Niña spring (Tables 2 and 4). In the tidal portions of the rivers, higher salinity water is located farther upstream during drier La Niña conditions, accounting for the inverse relationship.

Spatiotemporal Variability in ENSO Impacts on Salinity

Tampa Bay is divided into several, distinct geographical sections, based on analyses of water quality data (Lewis and Whitman 1985; Bendis 1999) and residence times (Burwell 2001), whose characteristics are determined by different processes and influences. The results of the analyses of El Niño conditions and mid-depth salinity in Tampa Bay corroborate these divisions. The spatial patterns are most evident in winter and spring, when the relationships between El Niño conditions and salinity are strongest (Table 3; Fig. 2). Freshwater inputs from small creeks and runoff have the greatest influence on salinity distribution in Old Tampa Bay due to its restricted tidal exchange and long residence times. As a result, Old Tampa Bay responds quickly to elevated precipitation and discharge levels associated with El Niño in the fall and winter and has significant correlations between El Niño SSTAs and mid-depth salinity in all seasons (Fig. 2). Hillsborough Bay receives most of Tampa Bay's stream input and has residence times on the order of weeks (Burwell 2001). Increased freshwater input into Hillsborough Bay during El Niño falls and winters is reflected in the overall negative and significant relationship between mid-depth salinity and ENSO SSTAs (Fig. 2).

Middle and lower Tampa Bay are dominated by tidal exchange and mixing due to wind events; salinity in these sections is not significantly correlated with El Niño ENSO SSTA during summer, fall, and winter (Fig. 2). In both these bay sections in the spring, the correlations between mid-depth salinity and El Niño ENSO SSTAs are negative and highly correlated at all stations. This pattern may represent the flushing of low salinity waters that accumulated during the winter from Old Tampa Bay, which has residence times on the order of several months (Burwell 2001).

La Niña conditions are correlated significantly and inversely with mid-depth salinities at most stations in Tampa Bay only during spring (Table 4; Fig. 3). During spring, larger and more highly significant correlations are found at stations near the head of Tampa Bay (in Old Tampa Bay, Hillsborough Bay, and middle Tampa Bay). Stations in lower Tampa Bay have lower correlations, and only half of the stations have significant correlations. Both rainfall and stream discharge are depressed during La Niña winters and springs; this is reflected in the inverse relationship between salinity and ENSO SSTAs.

Management and Monitoring Implications

We have demonstrated significant correlations between ENSO state and mid-depth salinity in Tampa Bay, Florida. Salinity in an estuary is determined by a suite of dynamically variable influences, and climate variability such as ENSO may impact salinity distributions through teleconnections with precipitation and stream discharge. Documented El Niño (La Niña) impacts in the Tampa Bay area include elevated (depressed) rainfall and stream discharge during fall and winter (winter and spring) with resulting depressed (elevated) estuarine salinity levels. In terms of assessing the impacts of human influences on estuarine areas, it is important to understand the natural variability of estuarine circulation and salinity distribution.

In Tampa Bay, both imminent changes in freshwater withdrawal schedules and concentrated discharge generated by desalination have the potential to impact the estuarine system, with possible consequences to both natural and human estuarine assets. The environmental impacts associated with increasing groundwater use and a growing population have resulted in the adoption of a Master Water Plan, which has been charged with developing new water supply sources (Tampa Bay Water 2000). As a result, a desalination plant was built on Tampa Bay and surface water withdrawal schedules have been developed for the Hillsborough and Alafia Rivers (Fig. 1) to supplement existing water supplies and to decrease groundwater withdrawals. In order to detect and monitor potential impacts of surface withdrawals on the hydrology and ecology of the associated tidal river segments, a comprehensive Hydrobiological Monitoring Program (HBMP) was developed. Inherent in the HBMP is the recognition that surface water withdrawals are linked to potential changes in salinity patterns, as well as associated water quality constituents and biological communities (Coastal Environmental/PBS&J, Inc. 1998). The HBMP began in spring 2000 and will operate for three years before initiation of new surface water withdrawals and for three years afterwards. Documenting impacts on salinity patterns based data from a 3-yr base period are possible only with respect to an accurate understanding of the role of natural variability, including interannual influences such as ENSO, on the bay's dynamics. The results presented here have direct relevance to the ability of the HBMP to meet its goal of determining whether or not significant post-withdrawal changes in hydrology, water quality, biota, habitat, and vegetation constitute an unacceptable adverse impact.

Acknowledgments

The authors would like to thank Sid Flannery of the Southwest Florida Water Management District for his assistance throughout the course of this research. This work is funded in part by the Greater Tampa Bay Marine Advisory Council Physical Oceanographic Real-Time System, Inc., by the National Oceanic and Atmospheric Administration Office of Global Programs, and by the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) program. Although the research described in this article has been funded in part by the U.S. Environmental Protection Agency's STAR program through grant R 825197-01-0, it has not been subjected to any EPA review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

Literature Cited

Bendis, B. 1999. Water quality trends in Tampa Bay, Florida. M.S. Thesis, University of South Florida, Tampa, Florida.

Boler, R. N. 1998. Surface water quality: 1995–1997, Hillsborough County, Florida. Enivornmental Protection Commission, Tampa, Florida.

Boler, R. N., R. C. Molloy, and E. M. Lesnett. 1991. Surface water quality monitoring by the Environmental Protection Commission of Hillsborough County, p. 111–135. *In* S. Treat and P. Clark (eds.). Proceedings of the Tampa Bay Area Scientific Information Symposium 2. Tampa, Florida.

Boyer, J. N., J. W. Fourqurean, and R. D. Jones. 1997. Spatial characterization of water quality in Florida Bay and Whitewater Bay by multivariate analyses: Zones of similar influence. *Estuaries* 20:743–758.

Burwell, D. B. 2001. Modeling residence times: Eulerian vs. Langrangian. Ph.D. Dissertation, University of South Florida, Tampa, Florida.

Coastal Environmental/PBS&J, Inc. 1998. Cumulative Impact analysis for Master Water Plan Projects. Final Report prepared for the West Coast Regional Water Supply Authority, Clearwater, Florida.

Dawson, A. G. and G. O'Hare. 2000. Ocean-atmosphere circulation and global climate: The El Niño–Southern Oscillation. *Geography* 85:193–208.

DelCharco, M. J. 1998. Tidal Flow in Selected Areas of Tampa Bay and Charlotte Harbor, Florida, 1995–1996. U.S. Geological Survey Water-Resources Investigations Report 97-4265. Tallahassee, Florida.

Flannery, M. S. 1989. Tampa and Sarasota Bays' watersheds and tributaries, p. 18–48. *In* E. D. Estevez (ed.). NOAA Estuary-of-the-Month, Seminar Series No. 11. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Estuarine Programs Office, Washington D.C.

Galperin, B., A. F. Blumberg, and R. H. Weisberg. 1991. A time-dependent three-dimensional model of circulation in Tampa Bay, p. 77–98. *In* S. Treat and P. Clark (eds.). Proceedings of the Tampa Bay Area Scientific Information Symposium 2. Tampa, Florida.

Goodwin, C. R. and D. M. Michaelis. 1976. Tides in Tampa Bay, Florida: June 1971 to December 1973. United States Geological Survey Open File Report FL75004. Tallahassee, Florida.

Harwell, M. A., J. S. Ault, and J. H. Gentile. 1995. Comparison of the Ecological Risks to the Tampa Bay Ecosystem from Spills of Fuel Oil #6 and Orimulsion. Comparative Ecological Risk Assessment, Volume 1. Center for Marine and Environmental Analyses, University of Miami, Miami, Florida.

Hoerling, M. P., A. Kumar, and M. Zhong. 1997. El Niño, La Niña, and the nonlinearity of their teleconnections. *Journal of Climate* 10:1769–1786.

Lewis, III, R. R. and R. L. Whitman, Jr. 1985. A new geographic description of the boundaries and subdivisions of Tampa Bay, p. 10–18. *In* S. F. Treat, J. L. Simon, R. R. Lewis, III, and R. L. Whitman, Jr. (eds.). Proceedings of the Tampa Bay Area Scientific Information Symposium. Tampa, Florida.

Lipp, E. K., R. Kurz, R. Vincent, C. Rodriquez-Palacios, S. R. Farrah, and J. B. Rose. 2001a. The effects of seasonal variability and weather on microbial fecal pollution and enteric pathogens in a subtropical estuary. *Estuaries* 24:266–276.

Lipp, E. K., N. Schmidt, M. E. Luther, and J. B. Rose. 2001b. Determining the effects of El Niño–Southern Oscillation events on coastal water quality. *Estuaries* 24:491–497.

Noreen, E. W. 1989. Computer Intensive Methods for Testing Hypotheses. John Wiley and Sons, New York.

Peebles, E. 1999. An Assessment of the Effects of Freshwater Inflows on Fish and Invertebrate Habitat Use in the Manatee River, Braden River, Peace River, and Shell Creek Estuaries, Volume I: Monthly Monitoring. Report prepared for Southwest Florida Water Management. Tampa, Florida.

Pritchard, D. W. 1956. The dynamic structure of a coastal plain estuary. *Journal of Marine Research* 15:33–42.

Rasmusson, E. M. and T. H. Carpenter. 1982. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño. *Monthly Weather Review* 110:354–384.

Rasmusson, E. M. and J. M. Wallace. 1983. Meteorological aspects of the El Niño/Southern Oscillation. *Science* 222:195–202.

Ropelewski, C. F. and M. S. Halpert. 1986. North American precipitation and temperature patterns associated with the El Niño Southern Oscillation (ENSO). *Monthly Weather Review* 114:352–362.

Rutherford, E. H., B. J. Bendis, G. A. Vargo, and K. A. Fanning. 1995. Review of historical Tampa Bay water quality data. *Florida Scientist* 58:67–81.

Schmidt, N., E. K. Lipp, J. R. Rose, and M. E. Luther. 2001. ENSO influences on seasonal rainfall and river discharge in Florida. *Journal of Climate* 42:615–628.

Southwest Florida Water Management District (SWFWMD). 1998. Comprehensive Watershed Management Plan, Tampa Bay/Anclote River, Volume I: Assessment. Tampa, Florida.

Squires, A. P., G. A. Vargo, R. H. Weisberg, K. A. Fanning, and B. Galperin. 1995. Review and synthesis of historical Tampa Bay water quality data. *Florida Scientist* 58:228–233.

Tampa Bay National Estuary Program (TBNEP). 1995. Current and historical freshwater inflows to Tampa Bay, Florida. Technical Publication #01-94. St. Petersburg, Florida.

Tampa Bay Water. 2000. New Water Plan. Quarterly Report, September 2000, prepared for the Southwest Florida Water Management District. Clearwater, Florida.

Trenberth, K. E. 1991. General characteristics of El Niño-Southern Oscillation, p. 13–42. *In* M. H. Glantz, R. W. Katz, and N. Nicholls, (eds.). Teleconnections Linking Worldwide Climate Anomalies. Cambridge University Press, New York.

Winsberg, M. D. 1990. Florida Weather. University of Central Florida Press, Orlando, Florida.

Zarbock, H., A. Janicki, D. Wade, D. Heimbuch, and H. Wilson. 1995. Current and Historical Freshwater Inflows to Tampa Bay. Tampa Bay National Estuary Program, St. Petersburg, Florida.

Zervas, C. E. (ed.). 1993. Tampa Bay Oceanography Project: Physical Oceanographic Synthesis. NOAA Technical Report NOS OES 002. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Silver Springs, Maryland.

Zhang, M. 1994. Predictability of sea level and currents of Tampa Bay. M.S. Thesis, University of South Florida, St. Petersburg, Florida.

Sources of Unpublished Materials

Matheson, Jr., R. E. unpublished data. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute, 100 8th Avenue SE, St. Petersburg, Florida 33701.

National Oceanic and Atmospheric Administration (NOAA). 1998. Population: Distribution, density and growth. NOAA's State of the Coast Report. URL: http://state_of_coast.noaa.gov/bulletins/html/pop_01/pop.html

Received for consideration, May 11, 2001
Accepted for publication, April 5, 2002