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Determining the Effects of El Niño–Southern Oscillation Events on Coastal Water Quality

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ABSTRACT: The importance of the El Niño–Southern Oscillation (ENSO) on regional-scale climate variability is well recognized, although the associated effects on local weather patterns are poorly understood. Little work has addressed the ancillary impacts of climate variability at the community level, which require analysis at a local scale. In coastal communities water quality and public health effects are of particular interest. Here we describe the historical influence of ENSO events on coastal water quality in Tampa Bay, Florida (USA) as a test case. Using approximate randomized statistics, we show significant ENSO influences on water quality, particularly during winter months, with significantly greater fecal pollution levels during strong El Niño winters and significantly lower levels during strong La Niña winters as compared to neutral conditions. Similar significant patterns were also noted for El Niño and La Niña fall periods. The success of the analyses demonstrates the feasibility of assessing local effects associated with large-scale climate variability. It also highlights the possibility of using ENSO forecasts to predict periods of poor coastal water quality in urban regions which local agencies may use to make appropriate preparations.

Introduction

The link between climate and health was recognized as early as Hippocrates and through the 16th century (Rees 1996). Without knowledge of disease-causing agents, many believed that strange weather patterns caused a variety of health problems, resulting in the adage, ''under the weather'' (Rees 1996, p. 35). While it has long been realized that ''wind-borne poisons (called miasmas)'' (Rees 1996, p. 35) do not cause disease, in recent years there has been increased scientific recognition that climate variability contributes to the distribution, growth, and survival of certain pathogenic microorganisms and affects public health (Colwell 1996; National Oceanic and Atmospheric Administration 1999; Checkley et al. 2000). Both local weather patterns and climate variability play a role in the dispersion of pathogenic microorganisms. Events such as extreme rainfall and floods often overwhelm water treatment facilities and onsite disposal systems and increase storm water runoff, all of which may result in the introduction of high levels of enteric pathogens to nearby surface waters and wells. Interannual climate variability due to El Niño–Southern Oscillation (ENSO) events and other phenomena can also affect water quality and public health both directly and indirectly by resulting in poor sanitation due to floods (Gueri et al. 1986) or promoting favorable conditions for growth/survival of certain pathogens, i.e., *Vibrio cholerae* (Colwell 1996). Given the importance of nonpoint sources of pollution in the United States and elsewhere, heavy or prolonged rains may contribute to pollutant loading, including pathogenic microorganisms, from urban and agricultural runoff and on-site sewage disposal (O'Shea and Field 1992; Paul et al. 1997). Exposure to the public during these events occurs from the contamination of drinking water, recreational water, and shellfish (Rose 1997).

Short-term predictive models forecast ENSO events with varying success rates and research has effectively demonstrated a strong relationship between regional precipitation patterns and ENSO events (Ropelewski and Halpert 1986; Schmidt et al. 2001). In addition to the importance and utility of regional-scale models, an understanding of anomalies in local weather patterns is an important and immediate concern. There has been little work to demonstrate statistically significant weather patterns or determine the ancillary effects of these anomalies related to ENSO events at the local scale. This contribution builds upon previous research by the authors on the topic of ENSO influence on local variability in seasonal rainfall and river discharge in Florida (Schmidt et al. 2001). Using an approximate randomized difference of means test, Schmidt et al. (2001) demonstrated significant seasonal responses of rainfall and streamflow to El Niño and La Niña conditions in south central Florida. They also found significant season-

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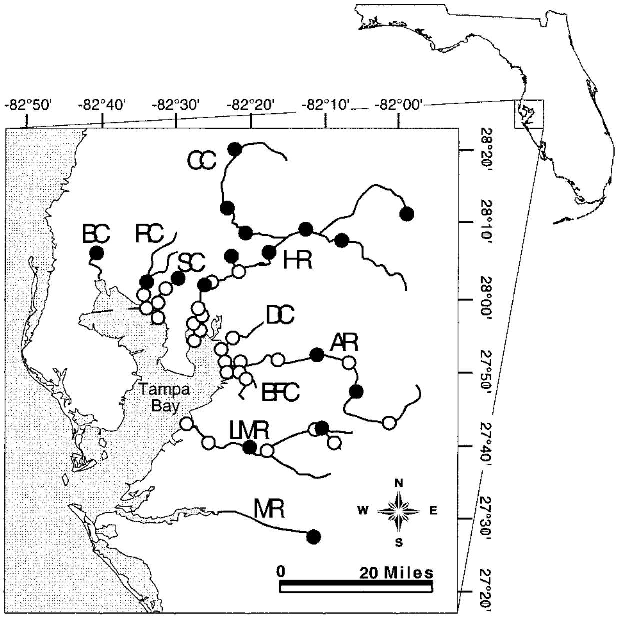

Fig. 1. Map of Tampa Bay watersheds. Filled circles represent river gage stations, open circles represent water quality stations. BC: Brooker Creek, RC: Rocky Creek, SC: Sweetwater Creek, CC: Cypress Creek, HR: Hillborough River, DC: Delaney Creek, AR: Alafia River, BFC: Bullfrog Creek, LMR: Little Manatee River, and MR: Manatee River.

al variability in rainfall within the state of Florida, with distinct patterns noted particularly between the panhandle and southernmost Florida.

We hypothesize that a statistical relationship may exist between ENSO events and water quality, based on reported relationships between the ENSO, precipitation, and river discharge (Sun and Furbish 1997; Zorn and Waylen 1997) and the subsequent relationship between water quality and both rainfall and discharge (Barbé and Francis 1995; Lipp et al. 2001). Using historical data, we analyzed the relationship between microbiological water quality and ENSO events in south central Florida, a region that is known to experience anomalous precipitation and river flow associated with ENSO phases (El Niño and La Niña) (Schmidt et al. 2001). The strength of these relationships and seasonal changes were evaluated with analyses of continuous and categorical data. We demonstrate a simple approach to define the role of particular modes of climate variability (i.e., ENSO events) on coastal water quality by focusing on temporal and spatial scales that are important to public health decisions at local levels using Tampa Bay, Florida (USA) as a test case.

Materials and Methods

Description of Study Site

Historical changes in water quality and their relationship to the ENSO were assessed in Tampa Bay, Florida. Tampa Bay is the second largest Gulf Coast estuary and the largest estuary in Florida. The entire watershed contains 35,500 km^2, which are drained by 31 major basins (Southwest Florida Water Management District 1998). We studied 7 drainage basins (Fig. 1), which are qualitatively described in terms of major land-use patterns and other sources of pollution in Table 1. Within the entire Tampa Bay watershed 56% of the land is developed; 40% of the built-up areas are urban and 16% include agricultural and pasture lands (Southwest Florida Water Management District 1998).

ENSO Indices

The state of the ENSO was measured using the Climate Prediction Center's Niño Region 3.4 monthly Sea Surface Temperature anomaly (SSTA) indices, which are based on recorded temperatures from 5°N to 5°S and 170°W to 120°W in the equatorial Pacific Ocean. Seasons from 1974–1998 were classified as extreme (El Niño or La Niña) or neutral. Climatology indicates that Florida winters begin in January (Winsberg 1990), therefore seasons were defined as follows: winter

TABLE 1. Description of Tampa Bay drainage basins.

Basin	Drainage Area (acres)	Major Land Use	Notes
Hillsborough River	431,742	Agriculture (32% north and central); Urban and Industrial (25% south)	Springs in upper and lower reaches (1 each), dam and drinking water reservoir
Alafia River	270,000	Agriculture (68% south); Phosphate Mining (east); Urban and Industrial (north and west)	2 springs; >91% of watershed is developed or altered
Bullfrog Creek	25,758	Agriculture (50% east); Urban and Residential (12% west)	
Rocky Creek	30,008	Urban (41% south); Agriculture (north)	Several lakes up to 93 acres
Sweet Water Creek	23,896	Urban (69%)	2 large lakes (191 and 283 acres)
Delaney Creek	15,161	Urban (55%)	
Little Manatee River	135,046	Forest (38%); Agriculture (84%)	

TABLE 2. Classification of ENSO events between seasons, based on period of record available for water quality (1974–1998).

Season	Extreme El Niño	Neutral	Extreme La Niña
Winter	1983, 1987, 1992, 1995, 1998	1979, 1981, 1982, 1990, 1991, 1994, 1997	1974, 1976, 1985, 1989
Spring	1982, 1983, 1987, 1992, 1993, 1997	1976, 1977, 1978, 1979, 1980, 1981, 1984, 1986, 1990, 1994, 1995, 1996, 1998	1988 (1974, 1975, 1985, 1989)[a]
Summer	1982, 1987, 1991, 1997	1978, 1979, 1980, 1981, 1983, 1984, 1985, 1989, 1990, 1992, 1995, 1996	1975, 1988, 1998
Fall	1976, 1977, 1982, 1986, 1987, 1991, 1994, 1997	1978, 1980, 1981, 1985, 1989, 1992, 1996	1975, 1984, 1988, 1995, 1998

[a] Weak La Niña events (Niño 3.4 SSTA −0.4 to −0.69) are included in parentheses.

included January, February, and March; spring included April, May, and June; summer included July, August, and September; and fall included October, November, and December. Extreme ENSO seasons were defined to occur when the 5-mo running average, centered on the season, of the Niño Region 3.4 SSTA exceeded ± 0.7°C. Neutral ENSO seasons were defined to occur when the 5-mo running average, centered on the season, fell between ± 0.4°C (Table 2). There is no generally accepted scheme to define ENSO events; our classification agrees well with other published literature (Gershunov and Barnett 1998b; Hoerling et al. 1997) and includes the most widely recognized and accepted ENSO events. Application of this scheme to the SSTA data is straightforward. Our thresholds excluded questionable ENSO events while providing an adequate number of cases for analyses for all ENSO phase seasons except extreme La Niña spring. Where data were available there was often a significant signal noted in extreme La Niña springs. For those cases where insufficient data existed for extreme La Niña, all La Niña springs (≤ −0.40°C) were tested.

Monthly water quality data (1974–1998) were obtained for Tampa Bay and its tributaries from the Hillsborough County Environmental Protection Commission (HEPC). Water quality was quantitatively assessed using concentrations of fecal coliform bacteria (colony forming units (CFU)/100 ml) at 29 stations. By convention, concentrations for each sample were transformed by the equation, $\log_{10}$ ((CFU/100 ml) + 1). When concentrations were below detectable limits (< 1 to < 100 CFU/100 ml), a value of zero was used for statistical analyses. Samples were collected only once per month from each station. Stations were combined in individual watersheds to mitigate small-scale events that might dominate a local area during the monthly sampling but would not be indicative of an entire drainage basin. Adequate data coverage was available at 7 of the 31 drainage basins, and included an average of 4.1 stations per watershed. A maximum of 7 and a minimum of 2 stations were used per drainage basin.

Approximate randomized statistics were used in all analyses. These computer-intensive tests generate the probability distribution of the test statistic by recomputing it for many (> 100) artificially constructed data sets and can be 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; they need not constitute a random sample. In addition to avoiding the assumptions required of parametric statistics, approximate randomized tests maximize the ability to discriminate between hypotheses because the sampling distribution is known (Noreen 1989).

Monthly anomalies in fecal coliform levels were obtained by subtracting the basin-averaged mean monthly value (over the data record) from individual basin-averaged monthly values and were correlated against Niño region 3.4 monthly SSTA. Significance of the Pearson correlation coefficients was determined by comparing the r-value of the observed correlation to that of the distribution of the correlation under the null hypothesis. This distribution was generated by randomly shuffling the SSTA values against fecal coliform anomaly values and recalculating the r-value 10,000 times. Correlations were run against the entire data record, with a lag of 0 to 3 mo between monthly Niño Region 3.4 SSTA and monthly water quality anomalies to allow the detection of any delayed responses.

The correlation test provides information regarding the significance of the relationship between SSTA associated with the ENSO and fecal coliform levels but does not reveal details concerning the relative importance of particular seasons. The differences in mean fecal coliform concentrations between extreme El Niño, neutral, and extreme La Niña events for each season were analyzed using an approximate randomized difference of means test (Noreen 1989). Log-transformed basin-averaged seasonal fecal coliform concentrations for extreme El Niño and La Niña events were tested against the seasonal fecal coliform levels for neutral periods. The observed difference in means was compared to the distribution of the randomly generated difference under the null hypothesis. As in the correlation analysis, recalculating the difference in means 10,000 times generated the distribution. Given the high level of noise inherent in the fecal coliform data set and the need to average over time and space, results were considered to be statistically significant at an α level of 0.10 rather than 0.05.

Results

Correlation Analysis

Work by Schmidt et al. (2001) indicates that both precipitation and streamflow in south central Florida are significantly related to ENSO events. Given that water quality often deteriorates during periods of high precipitation and river discharge, we hypothesized that a direct relationship may exist between ENSO events and water quality. Fecal coliform bacteria were used as a proxy for water quality, as they are the most commonly used indicator of poor water quality due to fecal pollution and potential health risks worldwide. Correlation analyses were used to provide an initial assessment of whether any relationship existed between Niño 3.4 SSTA and changes in fecal coliform levels (water quality) in Tampa Bay.

Analysis of monthly anomalies in fecal coliform levels with monthly Niño 3.4 SSTA revealed a significant and positive correlation in 5 of the 7 watersheds examined over the 25-yr period of record. Even for significant correlations, coefficients were low ($r = 0.088$ to 0.23). These values were similar to those obtained for comparisons between Niño 3.4 SSTA and both precipitation and streamflow in Florida (Schmidt unpublished data). The majority of basins with strong correlations were located in the eastern portion of the Tampa Bay watershed. In this region, land use includes broad areas devoted to agriculture and pasture, and there is substantial land application of sewage sludge in some areas (Southwest Florida Water Management District 1998; Table 1). Land use appears to be an important factor in relating changes in water quality to the strength of the ENSO event.

Seasonal Analysis

The importance of the ENSO to variability in factors such as rainfall and streamflow in Florida, and elsewhere, varies with season (Schmidt et al. 2001). Given the significant relationship for most of the studied watersheds between fecal coliform levels and Niño 3.4 SSTA, we expanded our ex-

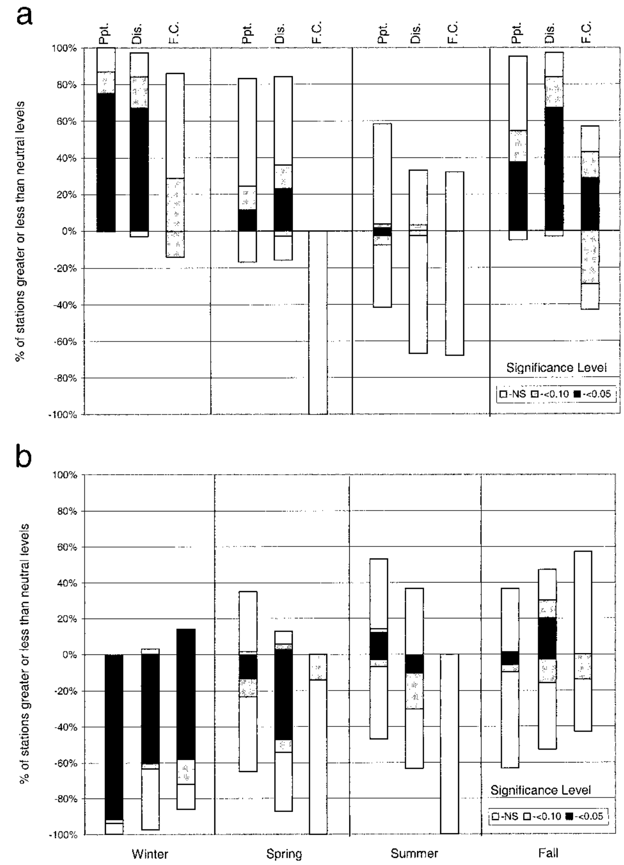

Fig. 2. Chart shows the percentage of stations (or basins) with fecal coliform (F.C.), precipitation (Ppt.), or discharge (Dis.) values that were greater than or less than that of neutral seasons for extreme El Niño (A) and extreme La Niña (B) events. Shading indicates significance levels. For spring, all La Niña events were used as there was only one extreme La Niña event within the period of record. Significance results from Schmidt et al. (2001) include statewide precipitation stations and streamflow for south central Florida (Charlotte Harbor and Tampa Bay) for 1950 to 1998.

amination to assess the seasonal differences in fecal coliform levels between extreme ENSO phases (El Niño and La Niña; Table 2) and neutral conditions to better define the relationship between ENSO events and water quality. Basin-averaged fecal coliform values were compared between seasons and ENSO phase.

Winter

Fecal coliform levels were compared between neutral winters and both extreme El Niño and extreme La Niña winters (Fig. 2). For extreme El Niño winters, there was an overall increase in fecal coliform levels as compared to neutral winters. With the exception of Delaney Creek, where the percent deviation was -20.4 ($p = 0.087$), the deviations in fecal coliform levels from neutral winters ranged between 7.6% and 18.7%. Only at Rocky and Sweetwater Creeks were the fecal coliform levels significantly greater than neutral values ($p < 0.10$). During extreme La Niña winters, there was an overall decrease in fecal coliform levels as compared to neutral winters. With the exception of Rocky Creek, where the percent deviation from neutral was 36.8 ($p = 0.034$), the deviations in fecal coliform levels from neutral ranged between −16.2% and −45.5%. Fecal coliform levels at Bullfrog Creek, Delaney Creek, Hillsborough River, and Sweetwater Creek were significantly below neutral values ($p < 0.05$). Fecal coliform levels at Little Manatee River were significantly lower than neutral at $p < 0.10$. Although Alafia River fecal coliform values showed a negative deviation during extreme La Niña winters, the difference from neutral winters was not significant.

Spring

For extreme El Niño springs, the average fecal coliform levels were lower than those found during neutral springs (Fig. 2). Percent deviations from neutral ranged between −4.6 and −20.1; however, differences were not significant in any watershed. For the one case of an extreme La Niña spring, fecal coliform levels in all basins were significantly below neutral values ($p < 0.10$). Deviations from neutral ranged from −0.9% to −46.0%. Given the lack of data during extreme La Niña spring events, deviations from neutral were also examined for all 5 spring La Niña events. For the more general La Niña springs cases, levels in all basins were lower than during neutral spring (−2.1% to −47.4% deviation). The differences were not significantly different from neutral values.

Summer

Fecal coliform levels during extreme El Niño summers showed a varied response with neutral summers (Fig. 2). None of the fecal coliform concentrations were significantly different than levels found in neutral summers and percent deviations ranged from −13.7 to 11.8. For extreme La Niña summers, percent deviations were consistently negative (−0.1% to −45.1%). However, the differences from neutral values were not significant.

Fall

Fecal coliform concentrations during extreme El Niño falls were generally greater than that found during neutral periods (Fig. 2). Although fecal coliform values at Bullfrog Creek, Delaney Creek, and Little Manatee River were less than that found during neutral fall, the differences were not significant. The remaining stations all showed greater than neutral fecal coliform concentrations, with deviations between 8.2% and 25.3%. The difference from neutral fall was only significant for Hillsborough River (25.3% deviation) and Rocky Creek (22.3% deviation). Patterns during extreme La Niña falls showed both positive and negative deviations from neutral falls. The only drainage with significant differences from neutral values was the Little Manatee River, where levels were 17.5% below neutral values.

Discussion

Extreme weather conditions including droughts and floods can dramatically affect communities at many levels. Although direct effects may include crop damage, property damage, destruction of homes, and loss of life, even moderate changes in climate can affect water resources in both quantity and quality and indirectly affect public health. Although research has demonstrated regional-scale climate variability during ENSO events, particularly relating to changes in temperature and precipitation (Ropelewski and Halpert 1986; Livezey et al. 1997; Gershunov and Barnett 1998a; Livezey and Smith 1999), it is at the local level where economic and public health impacts are felt and where decisions regarding public policy must be made. There is a need to better predict and understand the effects of climate variability at the local scale. To our knowledge this is the first study to examine the ancillary or indirect effects of ENSO on fecal pollution in coastal waters as it relates to recognized changes in precipitation and streamflow.

The extreme El Niño conditions observed in 1997 and early 1998 spurred investigations into the effects of climate variability on human health (National Oceanic and Atmospheric Administration 1999). During this time, the role of rainfall and streamflow in the introduction and transport of indicators of fecal pollution and human enteroviruses to coastal waters was demonstrated in southwest Florida (Lipp et al. 2001). Higher than average precipitation and river discharge were found in the winter months (1997–1998) along with lower water temperatures. Those patterns, which are typical of El Niño winters in Florida, provided a mechanism for transport of enteric contaminants by runoff and discharge into coastal waters and increased survival due to lower salinity and temperature (Barbé and Francis 1995; Wyer et al. 1995; Weiskel et al. 1996; Sun and Furbish 1997; Lipp et al. 2001).

Throughout Florida and in the Tampa Bay area, population growth in the last 20 years has been accompanied by an increased volume of wastewater discharged to coastal waters. Nonpoint sources (from septic systems and stormwater runoff) constitute a major cause of coastal pollution. Agricultural lands, land application of sewage sludge, septic systems, and wildlife contribute to high levels of coastal fecal pollution when transport mechanisms, such as high precipitation and river discharge, are in operation. The consequences of such pollution include closures of recreational and shellfish propagating waters and potential exposure to human pathogens (Lipp and Rose 1997).

The predictable, or normal, seasonal nature of rainfall in Florida has lead to specific water management strategies. The majority of rainfall in southern and central Florida occurs in the summer months, while spring and fall are relatively dry. In the southern part of the state winter storms account for less than 15% of the average annual precipitation (Nese and Grenci 1996). Similar to the larger-scale patterns noted for the southeastern U.S. (Ropelewski and Halpert 1986) precipitation and consequently streamflow along the south central Gulf coast of Florida are strongly related to ENSO (Schmidt et al. 2001). The seasonal ENSO effect results in precipitation patterns that are superimposed upon the normal seasonal trends. Significant correlations between Niño 3.4 SSTA and fecal coliform levels at the majority of basins analyzed demonstrate that Tampa Bay water quality also may be broadly linked to the ENSO state via teleconnections that results in anomalous precipitation and river discharge. Significantly increased fecal pollution, relative to neutral conditions, was most dramatic for extreme El Niño winter months. ENSO development tends to peak in the winter; the strongest weather patterns are also noted during that time (Ropelewski and Halpert 1986). Significant increases in wintertime precipitation and discharge in Florida during extreme El Niño events (Zorn and Waylen 1997; Schmidt et al. 2001) may exacerbate conditions and result in greater than average levels of indicator organisms or introduction of enteric pathogens (Lipp et al. 2001). Below average precipitation and discharge (Schmidt et al. 2001) lead to depressed fecal coliform levels during extreme La Niña winters. A significant ENSO signal was also often noted in the fall, and the signal was generally variable, although not significant, in the spring. The ENSO signal was ambiguous in the summer. In general, these observations follow patterns noted for both precipitation and river discharge in south central Florida (Fig. 2; Schmidt et al. 2001). The lack of significant associations in all basins studied is most likely related to watershed characteristics, including the type of waste disposal, extent of development and industry, and the presence of dams and diversions. This type of climate information combined with in-depth analyses of watersheds will be useful in proactively tailoring water quality monitoring and control programs in the Tampa Bay region.

Conclusions

Changes in water quality (using fecal coliform bacteria) in Tampa Bay, Florida were shown to vary with ENSO phases. We have previously shown a significant relationship between ENSO events and precipitation and discharge (Schmidt et al. 2001) and between water quality and rainfall and discharge in Florida (Lipp et al. 2001), and now report that a direct association between fecal pollution and ENSO events can be measured. Despite an inherently noisy data set, significant trends between fecal coliform levels and Niño 3.4 SSTA were noted for the majority of the Tampa Bay watersheds we examined. This study provides a baseline to initiate the development of water quality forecast models, ultimately using factors such as the ENSO and other climatic variables combined with land-use characteristics to predict periods of poor water quality. This will further the development of public policies for monitoring, assessing, and managing important bays and coastlines for recreation, industry, and fisheries.

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