NOAA Technical Report NOS CO-OPS 041

# NORTH CAROLINA BATHYMETRY/TOPOGRAPHY SEA LEVEL RISE PROJECT: DETERMINATION OF SEA LEVEL TRENDS

Silver Spring, Maryland

May 2004

noaa National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF COMMERCE
National Ocean Service
Center for Operational Oceanographic Products and Services

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Chris Zervas

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## INTRODUCTION

NOAA's Center for Sponsored Coastal Ocean Research (CSCOR) recently initiated a program entitled "Ecological Impacts of Sea Level Rise". This program is intended to evaluate the potential impact of long-term sea level rise on a specific coastal region, 25 to 50 years in the future. An initial goal of the project is to generate a digital elevation model (DEM) for the bathymetry and topography of the North Carolina coastal region, with all elevations tied to a common datum. Present-day sea level trends will be extended into the future, raising the tidal datums and thereby shifting the position of the shoreline. For North Carolina, the shoreline is defined as the mean high water (MHW) tidal datum (NOS, 2001). Maps will be generated indicating which low-lying areas of the coastal region will be submerged. A prerequisite for this project is the accurate determination of sea level trends using historic data at as many coastal locations as possible.

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) holds historic North Carolina water level data tied to established tidal bench marks. These records extend as far back as 1933 for Southport and 1935 for Wilmington. Eight stations have data spanning a period of at least 20 years and therefore are good candidates for the determination of mean sea level (MSL) trends with reasonable confidence intervals (Table 1).

The stations at Duck, Cape Hatteras, Atlantic Beach, and Yaupon Beach are located directly on the Atlantic Ocean (Figure 1). The stations at Oregon Inlet Marina, Beaufort, and Southport are located behind barrier islands a short distance from the ocean. The station at Southport is at the entrance to the Cape Fear River. The station at Wilmington is located on the Cape Fear River approximately 40 km from the ocean.

CO-OPS has recently adopted a new National Tidal Datum Epoch of 1983-2001 (NOAA, 2003). New tidal datums are now available which supercede the 1960-1978 tidal datums. The level of the new MSL datum relative to the North American Vertical Datum of 1988 (NAVD 88) is given in Table 1 for the five stations that are connected to NAVD 88.

The monthly mean sea levels at Wilmington for the period 1935-2002 are shown in Figure 2 relative to the recently established 1983-2001 MSL datum. The stations at Duck, Cape Hatteras, Beaufort, and Wilmington do not have any long periods without data (Table 1). Oregon Inlet Marina, Atlantic Beach, Southport, and Yaupon Beach have large gaps in their data records. Confidence intervals for the trends at the latter stations may be narrowed by difference comparisons with stations having more complete data records.

A recent study of tidal ranges at CO-OPS coastal water level stations with over 25 years of data (Zervas, 2003) indicated that only four out of 116 stations had large and statistically significant increases in tidal range. Two of these stations, Wilmington and Beaufort, were in North Carolina. The other two were Philadelphia, PA, and Anchorage, AK. The increasing tidal ranges at Wilmington and Beaufort may be attributed to the continual deepening of the navigational channels to these ports by the U.S. Army Corps of Engineers. Because of these increases in tidal range, trends calculated for the tidal datums of mean higher high water (MHHW), mean high water (MHW), mean low water (MLW), and mean lower low water (MLLW) were significantly different from each other and/or from the MSL trend. In this report, trends in the mean range of tide (Mn) and the great diurnal range of tide (Gt) will be calculated for all of the eight North Carolina stations. For any station showing a large increase in tidal range, trends will be obtained for each of the tidal datums (i.e., MHHW, MHW, MLW, and MLLW).

**Table 1. CO-OPS water level stations in North Carolina with data spanning over 20 years**

| Station Number | Station Name | Periods of Data | 1983-2001 MSL relative to NAVD 88 (meters) |
|---|---|---|---|
| 8651370 | Duck | 1978-2002 | -0.128 |
| 8652587 | Oregon Inlet Marina | 1977-1980, 1994-2002 | -0.026 |
| 8654400 | Cape Hatteras | 1978-2002 | -0.135 |
| 8656483 | Beaufort | 1973-2002 | N/A |
| 8656590 | Atlantic Beach | 1977-1983, 1998-2000 | N/A |
| 8658120 | Wilmington | 1935-2002 | 0.01 |
| 8659084 | Southport | 1933-1954, 1976-1988 | -0.141 |
| 8659182 | Yaupon Beach | 1977-1978, 1996-1997 | N/A |

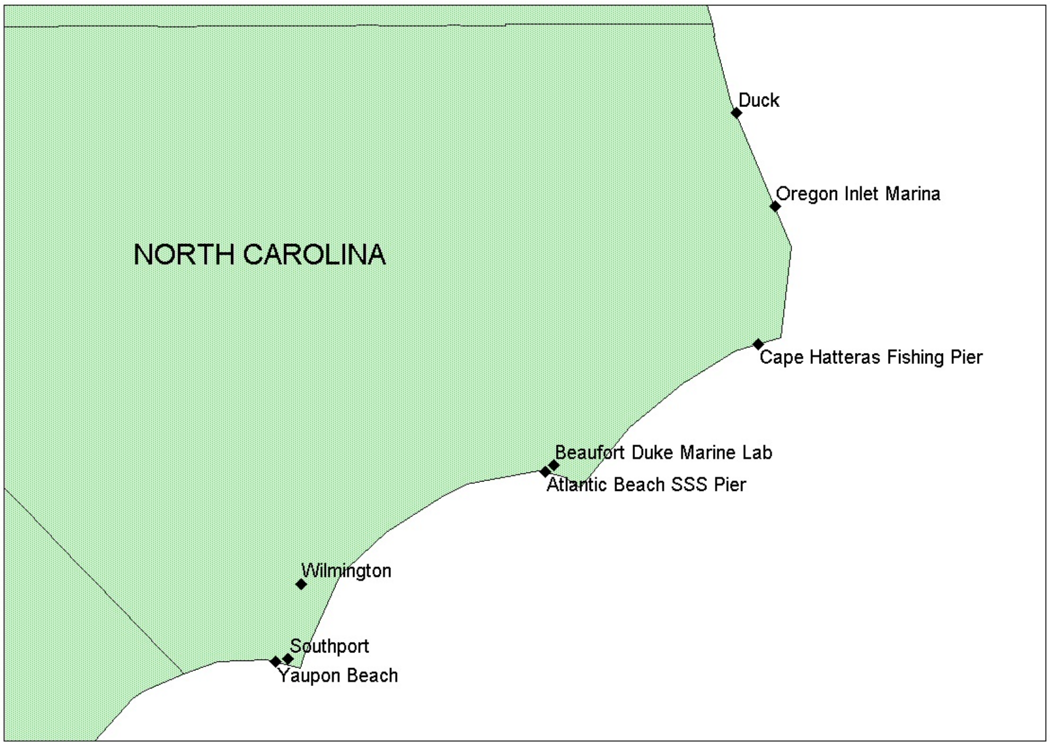


**Figure 1**. Location of eight CO-OPS water level stations in North Carolina with long term data sets.

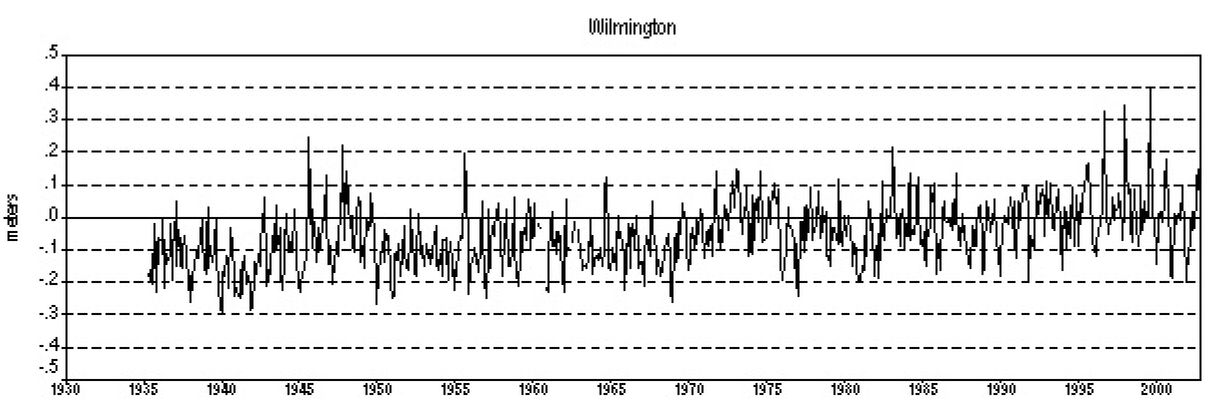


**Figure 2**. Monthly mean sea level for Wilmington, NC relative to the 1983-2001 mean sea level datum.

## MEAN SEA LEVEL TRENDS

The trend for a monthly water level time series is obtained by means of a linear regression with an autoregressive coefficient and a seasonal cycle as described in Zervas (2001). The seasonal cycle is accounted for by twelve parameters, one for each month. The autoregressive coefficient is included to account for the serial correlation of the residual time series. It has little effect on the value of the trend, but results in a more accurate estimate of the uncertainty of the trend. All results will be displayed with a 95% confidence interval which is +/- 1.96 times the standard error.

Mean sea level trends calculated for the eight North Carolina stations are displayed in Figure 3 and Table 2. The stations with the longest data intervals (68 years at Wilmington and 56 years at Southport) have the narrowest confidence intervals. The trends range from 2.04 mm/yr at Southport to 4.27 mm/yr at Duck. The average for all eight North Carolina stations is 2.88 mm/yr. There appears to be a regional gradient with the trends increasing from south to north. This implies that the land is sinking more rapidly along the northern portion of the coastline.

In an effort to obtain better-constrained MSL trends for Oregon Inlet Marina, Atlantic Beach, Southport, and Yaupon Beach, the monthly water level differences between these stations and the stations at Beaufort and Wilmington were analyzed. The seasonal and interannual water level variations are highly correlated along the Atlantic coastline (Zervas, 2001). Therefore, water level differences between two stations have much less variability than the water level time series at any

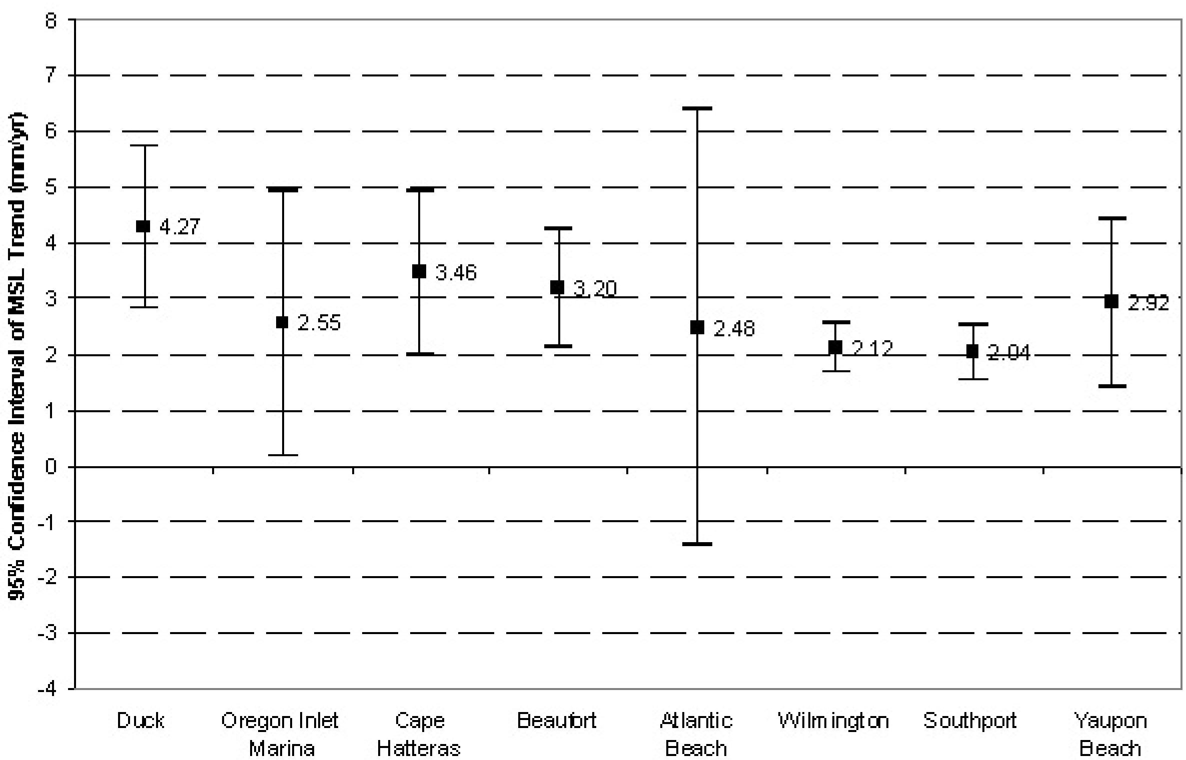


**Figure 3**. Mean sea level trends and 95% confidence intervals for North Carolina water level stations from north (Duck) to south (Yaupon Beach).

one station. A determination of the trend in a water level difference time series should produce a well-constrained estimate of the difference in trend between the two stations. Then the difference in trend can be added to the trend determined from the longer data record to get the trend at the station with the shorter data record (Mitchell et al., 1994). The water level difference trends are determined by the same method described for determining water level trends (i.e., linear regression with an autoregressive coefficient and a seasonal cycle). The trend standard error at the station with the shorter data record is the square root of the sum of the squares of the trend standard errors at the station with the longer record and the water level difference.

**Table 2. Mean sea level trends for North Carolina water level stations in mm/yr**

| Station Number | Station Name | Based on water level | | Based on water level differences | | |
|---|---|---|---|---|---|---|
| | | MSL Trend | Standard Error | Differenced from | MSL Trend | Standard Error |
| 8651370 | Duck | 4.27 | 0.74 | | | |
| 8652587 | Oregon Inlet Marina | 2.55 | 1.21 | Beaufort | 3.11 | 0.91 |
| 8654400 | Cape Hatteras | 3.46 | 0.75 | | | |
| 8656483 | Beaufort | 3.2 | 0.54 | | | |
| 8656590 | Atlantic Beach | 2.48 | 1.99 | Beaufort | 1.93 | 1.29 |
| 8658120 | Wilmington | 2.12 | 0.23 | | | |
| 8659084 | Southport | 2.04 | 0.25 | Wilmington | 2.21 | 0.3 |
| 8659182 | Yaupon Beach | 2.92 | 0.77 | Beaufort | 1.79 | 0.76 |

The better-constrained MSL trends from water level difference analysis for the stations with shorter data records were compared with the MSL trends for the stations with longer data records (Table 2 and Figure 4). The best estimates for the trends at Oregon Inlet Marina, Atlantic Beach, and Yaupon Beach were from difference comparisons with Beaufort. The older data at Southport (1933-1954) could only be differenced with Wilmington; the resulting trend standard error was greater than that obtained with the Southport data alone. The trends range from 1.79 mm/yr at Yaupon Beach to 4.27 mm/yr at Duck. The average for all eight North Carolina stations is 2.74 mm/yr. These trends are similar to those obtained at other stations on the U.S. east coast (Zervas, 2001), but are less than the rapidly rising MSLs observed in Louisiana (9 to 10 mm/yr) and eastern Texas (5 to 8 mm/yr).

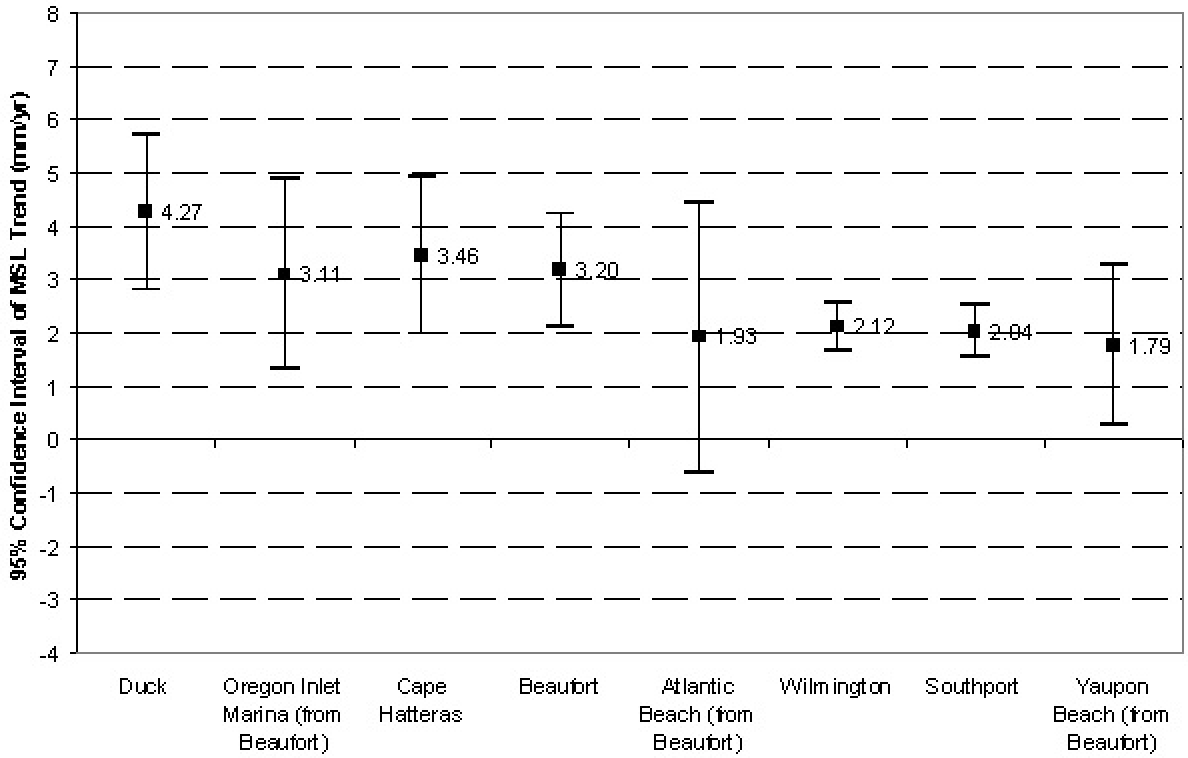


**Figure 4**. Mean sea level trends and 95% confidence intervals for North Carolina water level stations with trends for Oregon Inlet Marina, Atlantic Beach, and Yaupon Beach based on water level differences with Beaufort.

## AVERAGE SEASONAL CYCLE

In obtaining the mean sea level trends discussed in the previous section, the average seasonal cycle is also produced. The average monthly MSLs for the North Carolina water level stations are displayed in Figures 5-12. For most stations, the data used were relative to the 1983-2001 MSL datum. However, for Atlantic Beach and Yaupon Beach, the 1983-2001 MSL datums were not available and the seasonal cycles are presented relative to the arbitrary station datums.

It can be seen that the seasonal cycle is very similar at all stations with the highest monthly water levels of the year occurring in September and October and the lowest monthly water levels of the year occurring in January and February (December and January for Wilmington). Atlantic Beach and Yaupon Beach have large confidence intervals because of limited data. The seasonal cycle for Yaupon Beach is based on only 26 months of data.

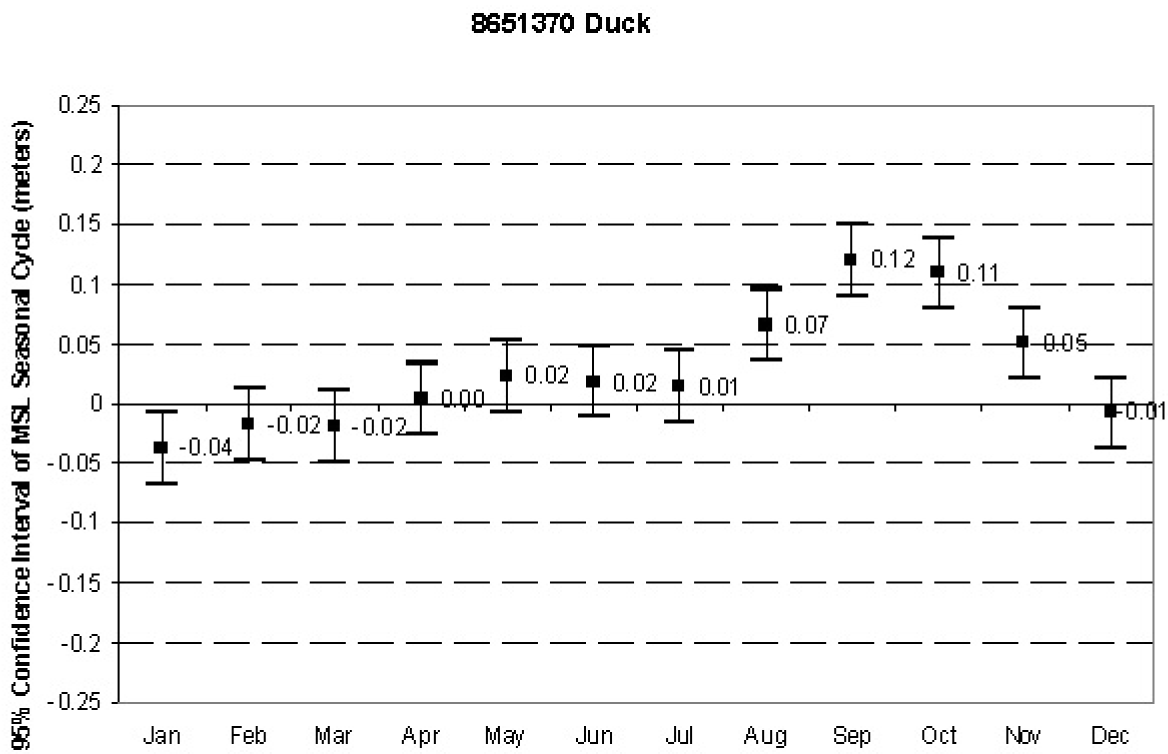


**Figure 5**. Average seasonal cycle of mean sea level for Duck in meters.

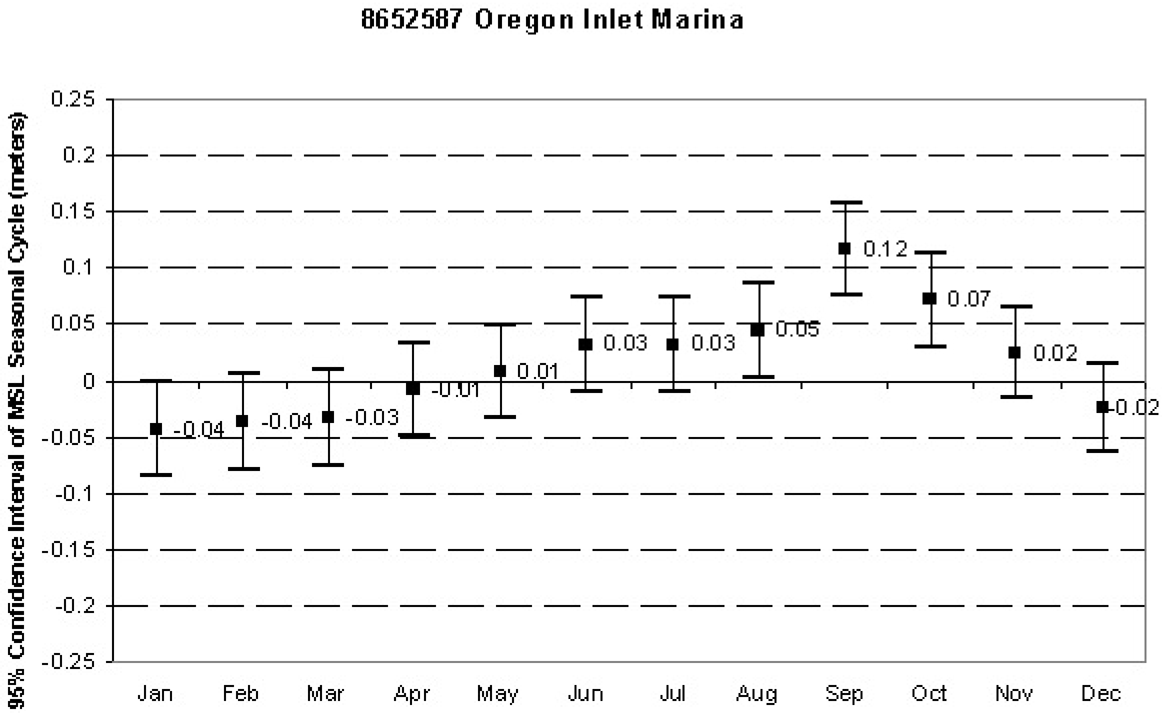


**Figure 6**. Average seasonal cycle of mean sea level for Oregon Inlet Marina in meters.

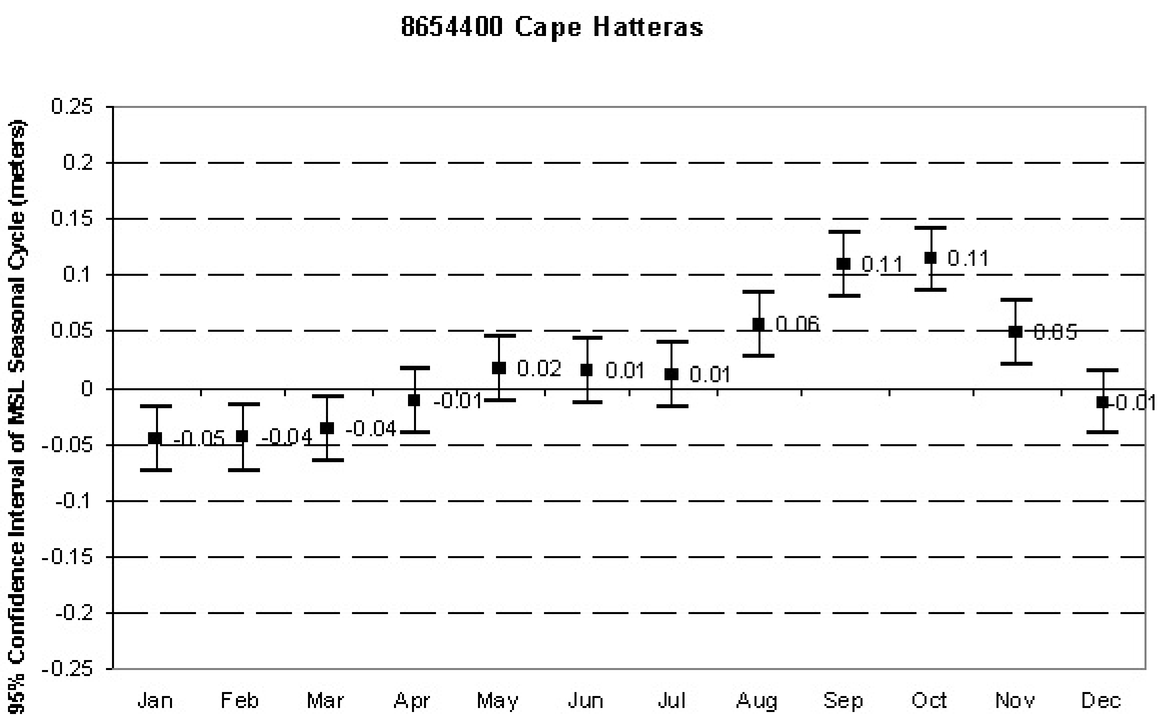


**Figure 7**. Average seasonal cycle of mean sea level for Cape Hatteras in meters.

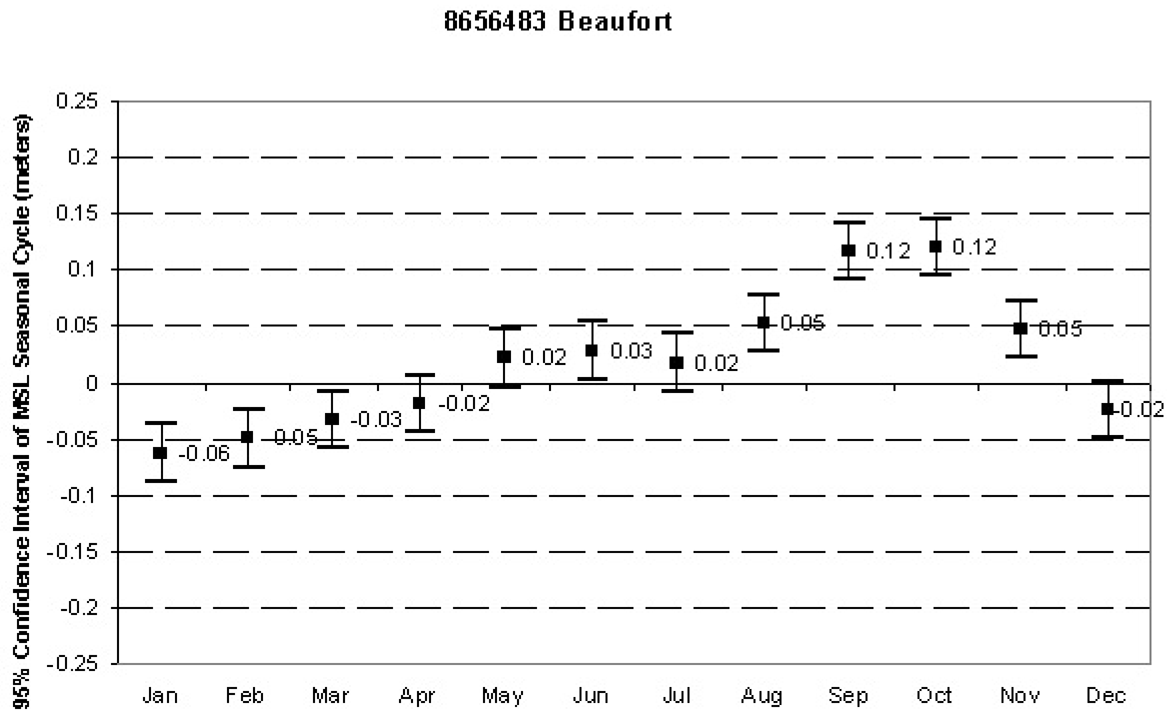


**Figure 8**. Average seasonal cycle of mean sea level for Beaufort in meters.

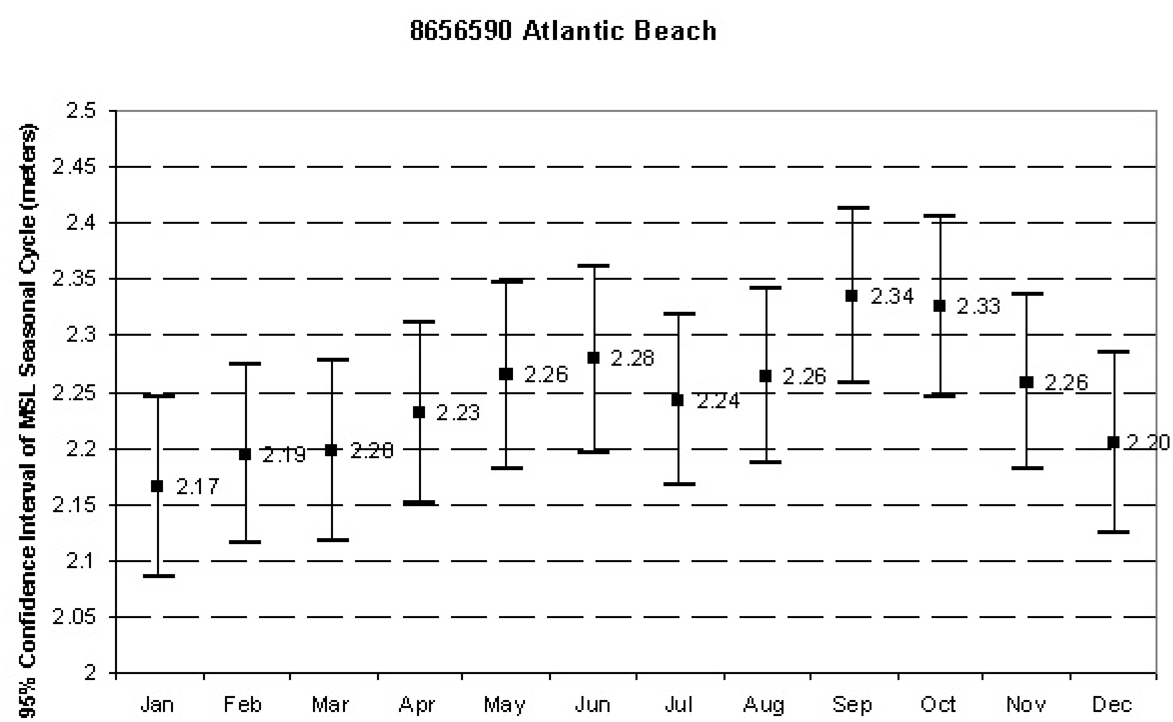


**Figure 9**. Average seasonal cycle of mean sea level for Atlantic Beach in meters.

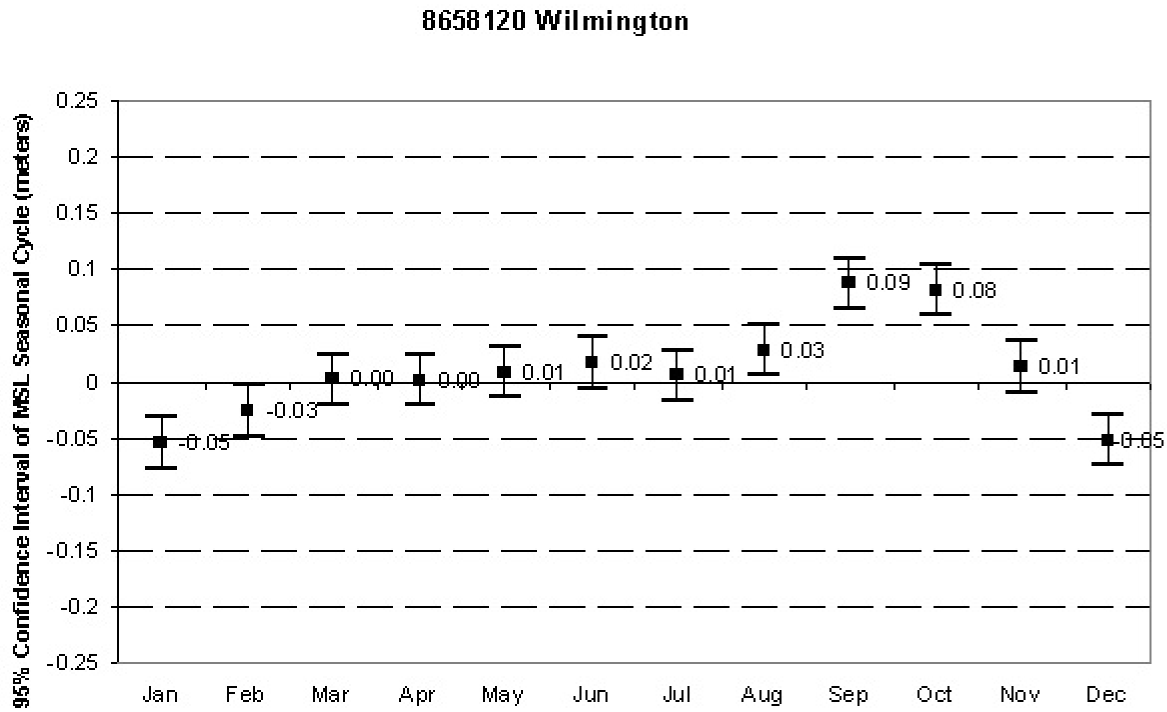


**Figure 10**. Average seasonal cycle of mean sea level for Wilmington in meters.

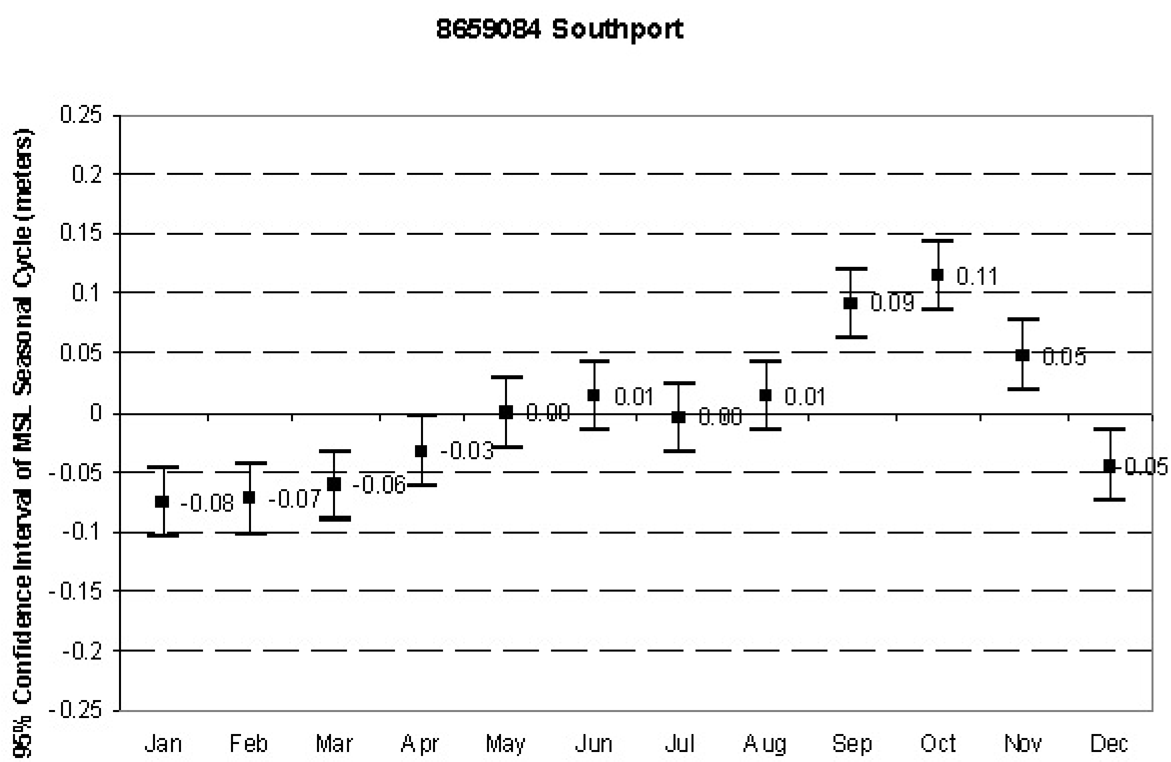


**Figure 11**. Average seasonal cycle of mean sea level for Southport in meters.

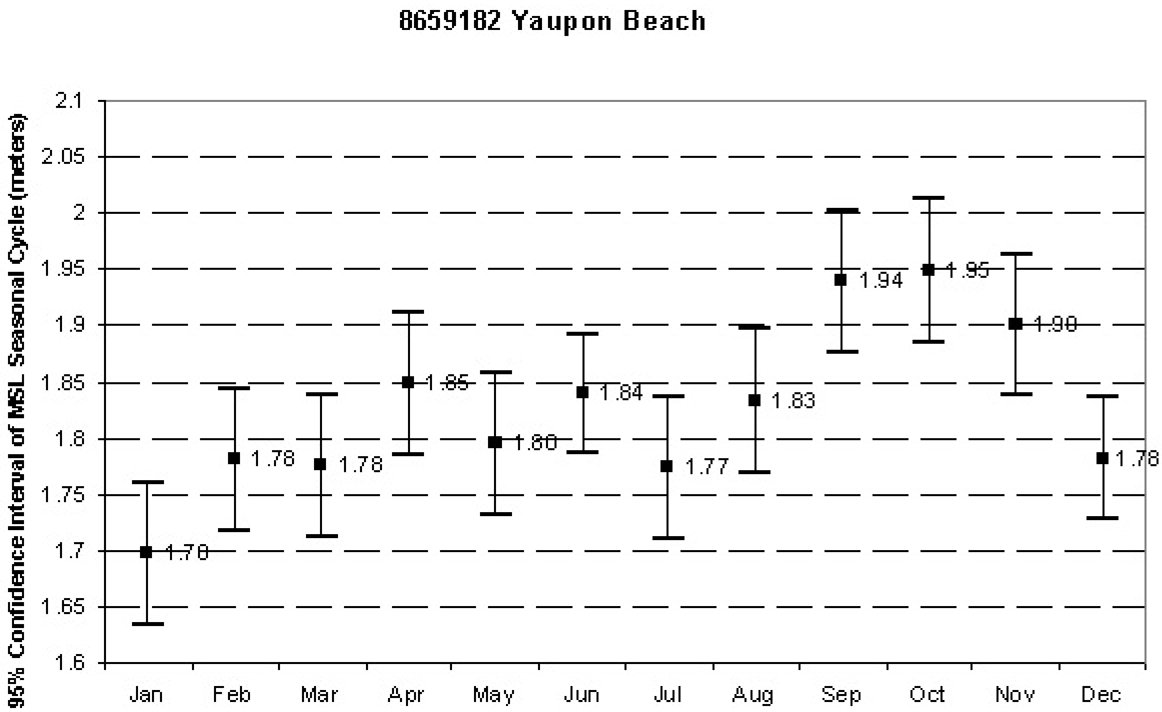


**Figure 12**. Average seasonal cycle of mean sea level for Yaupon Beach in meters.

## VARIABILITY OF 50-YEAR MEAN SEA LEVEL TRENDS AT WILMINGTON

Since the data record at Wilmington is 68 years long, the 95% confidence interval for the mean sea level trend is small (less than 1 mm/yr). In order to determine whether any decadal variations in trend may have occurred over that period, mean sea level trends were calculated for overlapping 50-year subsets of the data. These results are shown in Figure 13. Although there is some variability in the trends obtained, due to several years of anomalously high water levels in the late 1940s, the 95% confidence intervals indicate that the differences are not statistically significant.

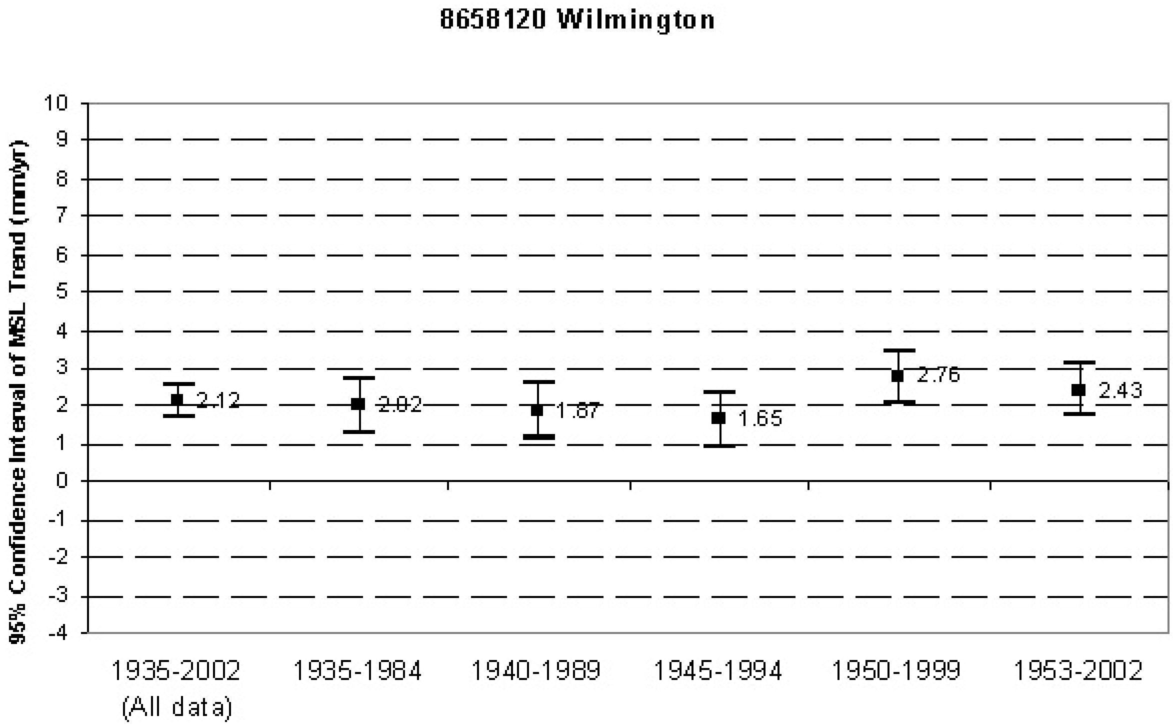


**Figure 13**. Mean sea level trends for Wilmington based on the entire data set (1935-2002) and for selected 50-year periods.

## CHANGES IN TIDAL RANGE

In most cases, it can be assumed that there will be no significant differences between the trend of the mean sea level and the trends of all the tidal datums such as MHHW, MHW, MLW, MLLW. However, a recent study (Zervas, 2003), shows that both Wilmington and Beaufort have undergone significant increases in tidal range since the stations were installed. Both stations are at some distance from the ocean, and the navigational channels connecting these ports to the ocean have been widened and deepened over the years by the U.S. Army Corps of Engineers. At this time, the Cape Fear River, connecting Wilmington to the ocean, is being deepened from 38 feet to 42 feet and the ocean bar and entrance channel is being deepened from 40 feet to 44 feet (Hackney, 2002). The mean range of tide (Mn = MHW - MLW) and the great diurnal range of tide (Gt = MHHW - MLLW) will be analyzed for the eight North Carolina CO-OPS stations to determine whether any of the other stations are also being affected by increasing tidal ranges.

The Mn and Gt data have a prominent 18.6-year astronomical tidal cycle related to the obliquity of the moon's node (Figure 14). Any calculated trend for tidal range should be based on data spanning at least one nodal cycle. Fortunately, all of the stations except Southport have data from the late 1970s and the late 1990s when the positive effect of the nodal cycle on semidiurnal tidal constituents was the greatest. Southport has Mn data available from 1933-1954 spanning an entire nodal cycle. The trends for the tidal ranges are obtained by linear regression with an autoregressive coefficient, a 12-month seasonal cycle, and the 18.6-year astronomical cycle.

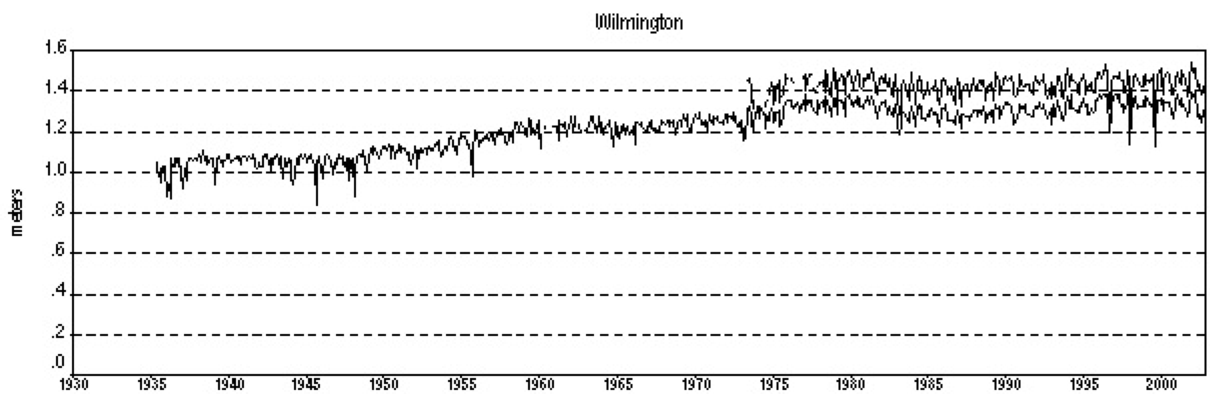


**Figure 14**. Monthly mean range of tide (lower line) and great diurnal range of tide (upper line) for Wilmington, NC.

Figure 15 shows the Mn trends. The three stations with large and statistically significant increases in the mean range of tide are Oregon Inlet Marina, Beaufort, and Wilmington (greater than 3 mm/yr). The stations directly on the Atlantic Ocean (Duck, Cape Hatteras, Atlantic Beach, and Yaupon Beach) do not have large changes in the mean range of tide. Southport, just inside the entrance to the Cape Fear River, has had only a small increase in Mn tidal range.

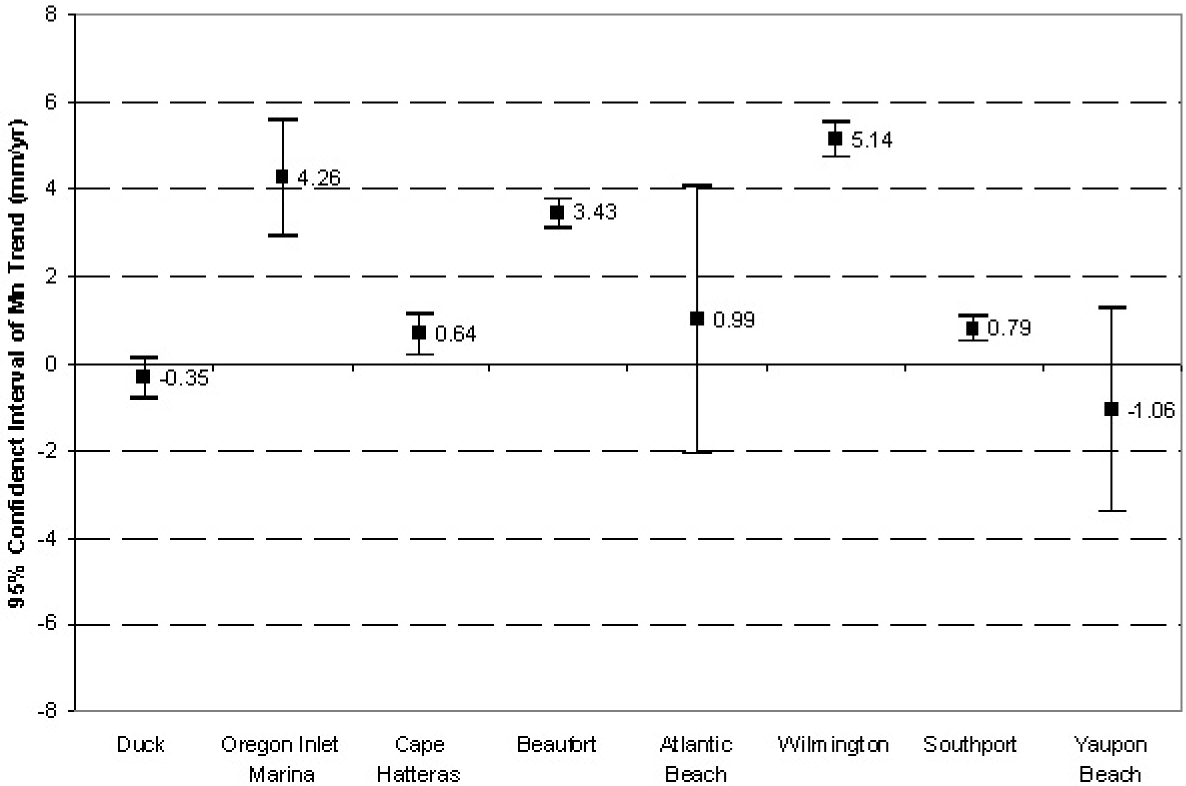


**Figure 15**. Trends (mm/yr) in mean range of tide for North Carolina water level stations.

Figure 16 shows the Gt trends. The only large and statistically significant trends are at Oregon Inlet Marina and Beaufort. Duck, Cape Hatteras, Atlantic Beach, and Yaupon Beach, all directly on the Atlantic Ocean, show no significant change in Gt. Southport is not shown because Gt values (or MHHW and MLLW values) were not tabulated for U.S. east coast stations before the 1970s and the data ends in 1988. For Wilmington, the Gt values only go back to 1973. The calculated Gt trend for Wilmington is small and barely significant. This is explained by the Mn record for Wilmington (Figure 14), which shows a non-linearly increasing tidal range with most of the increase taking place before the 1970s, followed by an apparent leveling off in the trend since the 1970s. The ongoing dredging project in the Cape Fear River is expected to lead to further increases in tidal range (Hackney, 2002).

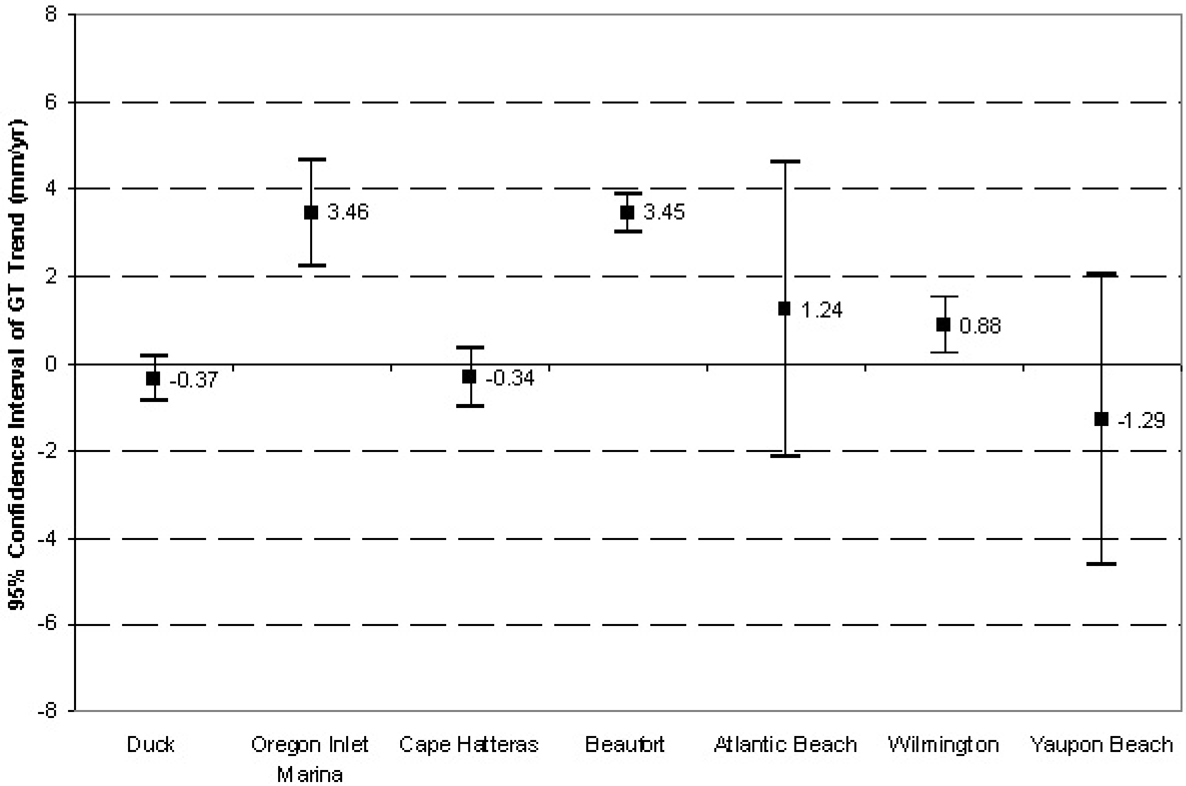


**Figure 16**. Trends (mm/yr) in great diurnal range of tide for North Carolina water level stations.

## CHANGES IN THE M2 TIDAL CONSTITUENT

The M2 semidiurnal tidal constituent, with a period of 12.42 hours, is the largest amplitude tidal constituent at U.S. east coast water level stations. It can be obtained by the harmonic analysis of hourly water level data. The resulting tidal amplitudes are adjusted for the timing of the analyzed data within the 18.6-year astronomical tidal cycle. Harmonic analyses were carried out for hourly data near the installation dates of seven of the stations and for the most recent data to verify that the large increases in Mn and/or Gt at Oregon Inlet Marina, Beaufort, and Wilmington are caused by increased tidal amplitudes. No hourly water level data were available for Southport from 1933-1954. The increases in the amplitude of M2 are shown in Table 3. An estimate of the rate of change per year in the M2 tidal range (which is twice the amplitude) is also derived. These values are comparable to the rates of increase in Mn since the stations were installed (Figure 15).

**Table 3. Changes in amplitude and range of the M2 tidal constituent**

| Station | Harmonic Analysis Period | M2 Amplitude (m) | Change in M2 Range (m) | Rate of Change (mm/yr) |
|---|---|---|---|---|
| Duck | 6/1/78 - 5/31/79 | 0.477 | 0 | 0 |
| | 1/1/02 - 12/31/02 | 0.477 | | |
| Oregon Inlet Marina | 5/7/79 - 1/31/80 | 0.071 | 0.12 | 5.22 |
| | 1/1/02 - 12/31/02 | 0.131 | | |
| Cape Hatteras | 1/1/79 - 12/31/79 | 0.435 | -0.004 | -0.17 |
| | 1/1/02 - 12/4/02 | 0.433 | | |
| Beaufort | 1/1/78 - 12/31/78 | 0.418 | 0.092 | 3.83 |
| | 1/1/02 - 12/31/02 | 0.464 | | |
| Atlantic Beach | 2/16/78 - 2/15/79 | 0.547 | 0.002 | 0.1 |
| | 1/1/99 - 12/31/99 | 0.548 | | |
| Wilmington | 1/1/36 - 12/31/36 | 0.441 | 0.366 | 5.55 |
| | 1/1/02 - 12/31/02 | 0.624 | | |
| Yaupon Beach | 1/7/78 - 7/6/78 | 0.694 | 0.002 | 0.11 |
| | 5/16/96 - 1/31/97 | 0.695 | | |

These results indicate that increasing tidal range can be accurately estimated by performing harmonic analyses on limited segments of hourly water level data separated by long data gaps. Numerous locations on the North Carolina coastline have hourly water level data available from the 1970s. Collection of several months of new water level data at these sites could further delineate regions where tidal ranges have changed significantly.

## TIDAL DATUM TRENDS

Since there are large and significant increases in tidal range at Oregon Inlet Marina, Beaufort, and Wilmington, trends were obtained for the MHHW, MHW, MLW, and MLLW tidal datums at these stations (Table 4). The trends were calculated by linear regression with an autoregressive coefficient, a 12-month seasonal cycle, and the 18.6 year astronomical tidal cycle described previously. The trends and the 95% confidence intervals are shown in Figures 17-19.

For Oregon Inlet Marina, the high water trends are over 6 mm/yr while the low water trends are below 3 mm/yr. There is a small overlap of the confidence intervals. A large data gap between 1980 and 1994 results in the large trend uncertainties. For Beaufort, the high water trends are above 4.5 mm/yr while the low water trends are below 2.5 mm/yr. The high water trends are statistically different than the low water trends, although some of the confidence intervals overlap with the MSL trend confidence interval.

The monthly MHHW and MLLW were not tabulated for U.S. east coast stations until the 1970s. Therefore, for Wilmington, the MHW and MLW trends were calculated for the entire 1935-2002 period and for the 1973-2002 period for comparison with the MHHW and MLLW trends. Figure 14 suggests that the tidal range at Wilmington increased steadily until the 1970s and then appeared to level off. The trends based only on data from 1973-2002 have high uncertainties and are not statistically different than the MSL trend (Figure 19). For the entire 1935-2002 period, however, the MHW trend is above 4 mm/yr while the MLW trend is negative and both are significantly different than the MSL trend.

**Table 4. Tidal datum trends for North Carolina water level stations (in mm/yr)**

| Station Number | Station Name | MHHW | | MHW | | MLW | | MLLW | |
|---|---|---|---|---|---|---|---|---|---|
| | | Trend | Std. Error | Trend | Std. Error | Trend | Std. Error | Trend | Std. Error |
| 8652587 | Oregon Inlet Marina | 6.28 | 1.04 | 6.71 | 1.01 | 2.62 | 1.26 | 2.86 | 1.23 |
| 8656483 | Beaufort | 5.92 | 0.59 | 4.91 | 0.54 | 1.5 | 0.56 | 2.47 | 0.61 |
| 8658120 | Wilmington (1935-2002) | | | 4.18 | 0.21 | -0.96 | 0.28 | | |
| 8658120 | Wilmington (1973-2002) | 2.43 | 0.69 | 2.38 | 0.65 | 1.68 | 0.86 | 1.53 | 0.9 |

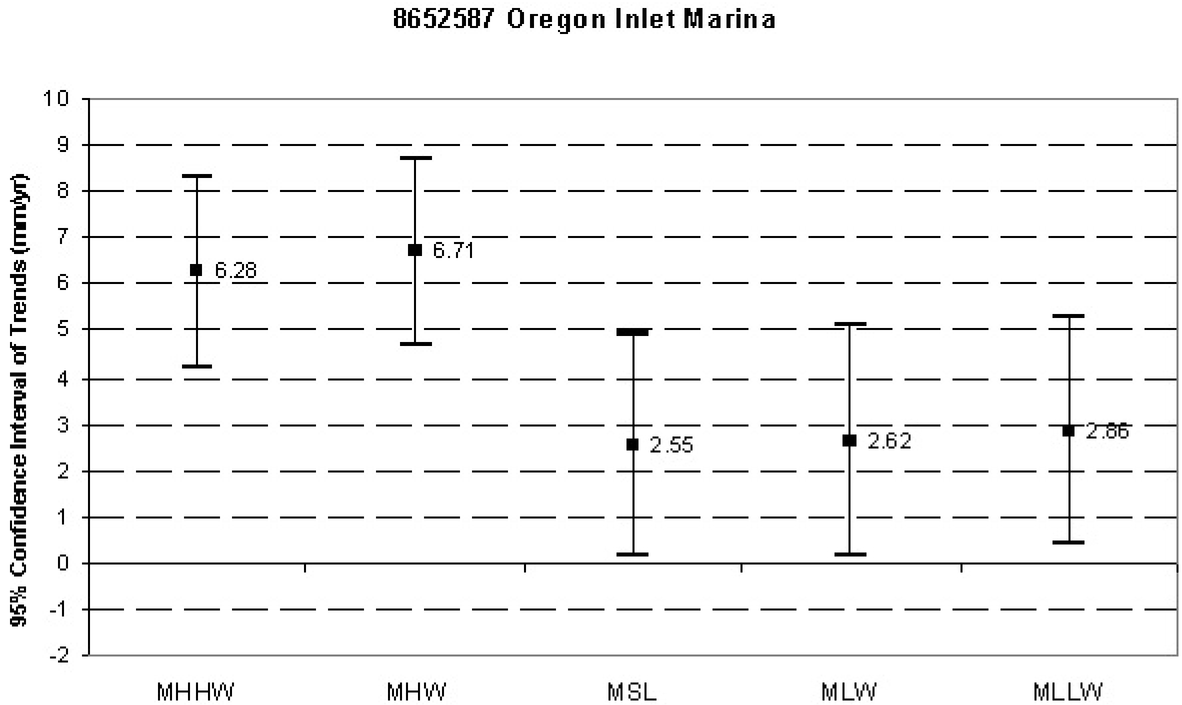


**Figure 17**. Comparison of trends for tidal datums at Oregon Inlet Marina based on data from 1977-2002 with a large gap from 1980 to 1994.

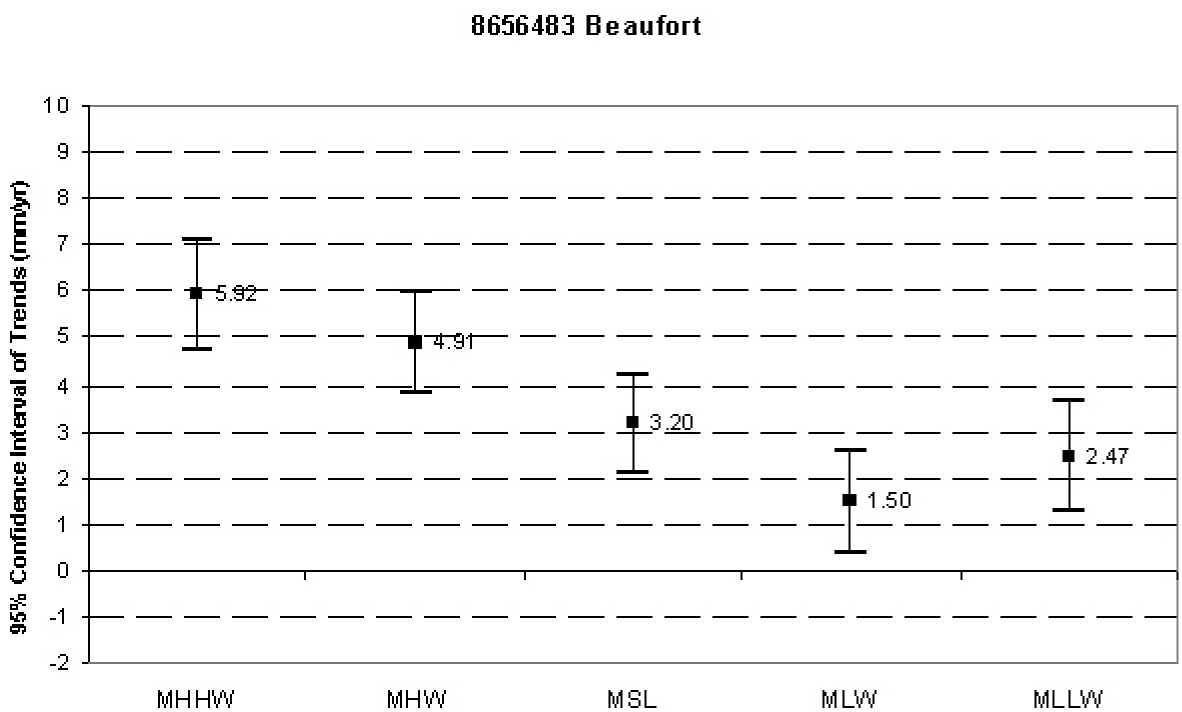


**Figure 18**. Comparison of trends for tidal datums at Beaufort. MHW, MSL, and MLW trends are based on data from 1973-2002. MHHW and MLLW trends are based on data from 1976-2002.

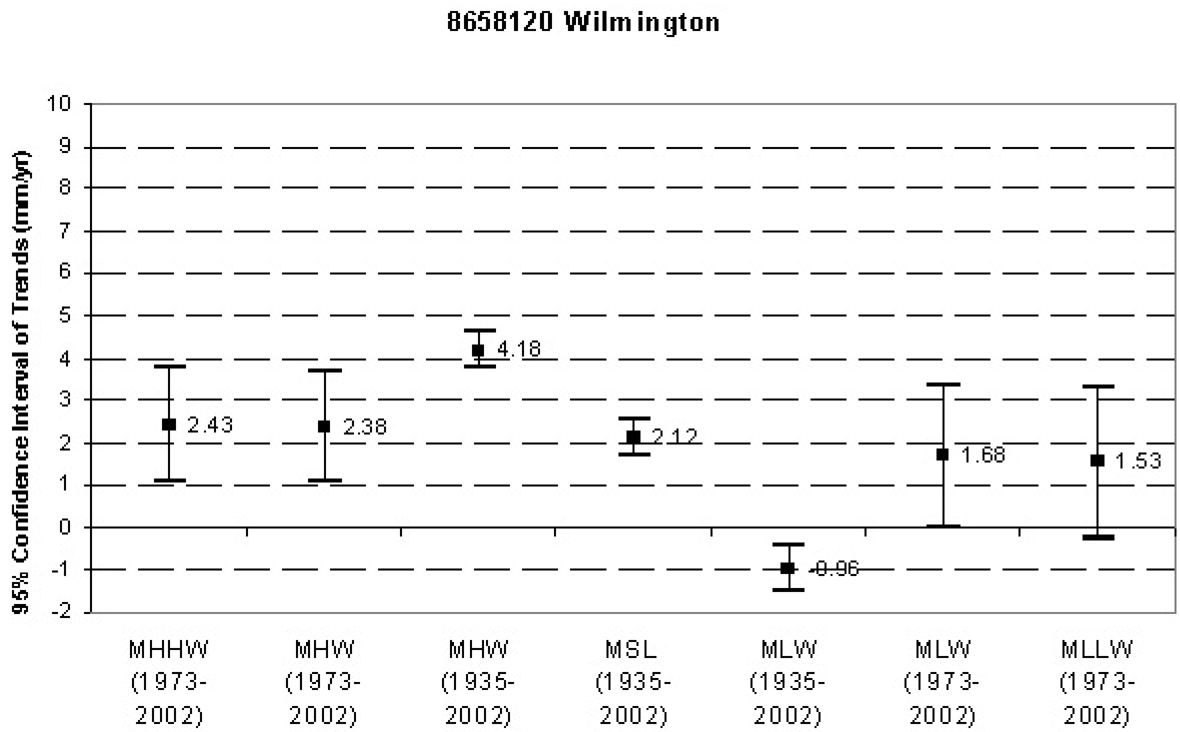


**Figure 19**. Comparison of trends for tidal datums at Wilmington showing MHW, MLW, and MSL trends based on data from 1935-2002 and MHHW, MHW, MLW, and MLLW trends based on data from 1973-2002.

## SUMMARY

This analysis of historical North Carolina water level data was carried out in preparation for the North Carolina Bathymetry/Topography Sea Level Rise Project. MSL and tidal datum trends will be applied to a coastal DEM for North Carolina in order to predict shoreline movements and to map submerged zones, 25 to 50 years in the future. MSL trends were obtained from monthly data from eight CO-OPS water level stations (Duck, Oregon Inlet Marina, Cape Hatteras, Beaufort, Atlantic Beach, Wilmington, Southport, and Yaupon Beach). Water level difference comparisons for the stations with large data gaps were made with the stations with more complete records to narrow the trend confidence intervals. The calculated MSL trends increase from south (1.79 mm/yr at Yaupon Beach) to north (4.27 mm/yr at Duck), with an overall average of 2.74 mm/yr. Average seasonal cycles were similar for all stations, with the highest monthly water levels in early fall and the lowest monthly water levels in winter. The longest time series (68 years at Wilmington) shows no significant changes in 50-year trends.

The mean ranges (Mn) and great diurnal ranges (Gt) were analyzed to determine any long term changes in tidal range. Oregon Inlet Marina, Beaufort, and Wilmington have large and statistically significant increases in Mn and/or Gt (greater than 3 mm/yr). Stations located directly on the Atlantic Ocean had no such increase in tidal range. Harmonic analyses were carried out for a period near the installation date of each station and for the most recent data. The observed increases in the amplitude of the largest tidal constituent (M2) agree with the calculated increases in tidal range. For the stations at Oregon Inlet Marina, Beaufort, and Wilmington, the MHHW, MHW, MLW, and MLLW trends were obtained. Continual dredging of the channels connecting these stations to the ocean has resulted in variation in the trends of different tidal datums. In some locations, the high water datums have been rising at a rate significantly faster than the MSL trend. Whether or not this difference in trend continues, depends on future dredging activity and on the opening or closing of inlets in North Carolina's chain of barrier islands.

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## REFERENCES

Hackney, Courtney T., 2002. Monitoring effects of a potential increased tidal range in the Cape Fear River ecosystem due to deepening Wilmington Harbor, North Carolina, Year 1: August 1, 2000 - July 31, 2001, Dept. of Biological Sciences, Univ. Of North Carolina at Wilmington, (http://people.uncw.edu/hackney/capefearriver.htm).

Mitchell, Clifton E., P. Vincent, R. J. Weldon II, and M. A. Richards, 1994. Present-day vertical deformation of the Cascadia margin, Pacific Northwest, United States, *Journal of Geophysical Research*, Vol. 99, No. B6, 12257-12277.

NOAA, 2003. Notice of change to the nation's tidal datums with the adoption of a new National Tidal Datum Epoch period of 1983 through 2001, Federal Register/Notices, Vol. 68, No. 102, Wednesday, May 28, 2003.

NOS, 2001. Tidal datums and their applications, NOAA Special Publication, NOS CO-OPS 1, National Ocean Service, NOAA, 111 pp.

Zervas, Chris E., 2001. Sea level variations of the United States 1854-1999, NOAA Tech. Rep. NOS CO-OPS 36, National Ocean Service, NOAA, 186 pp.

Zervas, Chris E., 2003. Long term changes in tidal response associated with the deepening of navigational channels, *Proceedings, Coastal Zone 03: Coastal zone management through time*, Baltimore, MD, July 13-17, 2003, NOAA Coastal Services Center.