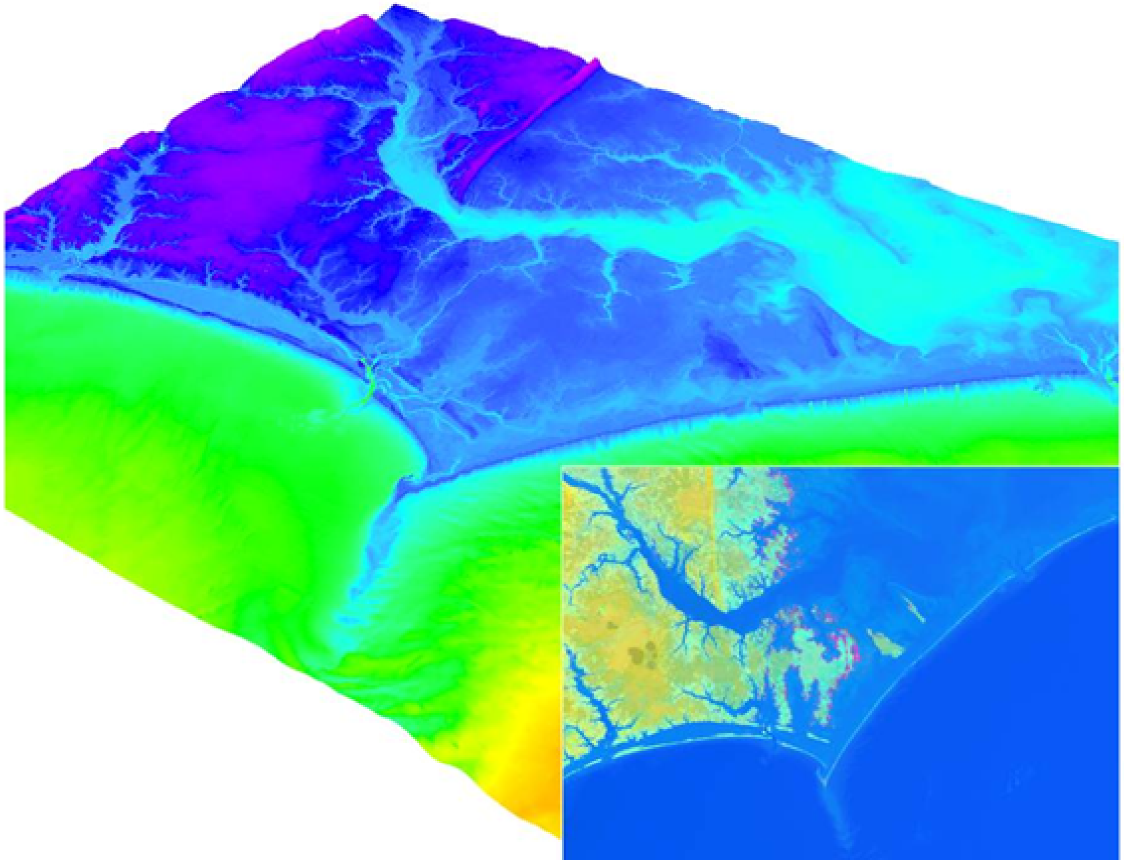
NOAA Technical Report NOS 2010-01

Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment



September 2010

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service

NOAA Technical Report NOS 2010-01

Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment

NOAA Center for Operational Oceanographic Products and Services
Richard Edwing, Director
http://www.tidesandcurrents.noaa.gov

NOAA Coastal Services Center
Margaret Davidson, Director
http://www.csc.noaa.gov/

NOAA National Geodetic Survey
Juliana Blackwell, Director
http://www.ngs.noaa.gov/

NOAA Office of Coast Survey
Captain John Lowell, Director
http://www.nauticalcharts.noaa.gov/

Acknowledgments:

A special thank you to the writing team: Allison Allen (lead), Stephen Gill, Doug Marcy, Maria Honeycutt, Jerry Mills, Mary Erickson, Edward Myers, Stephen White, Doug Graham, Joe Evjen, Jeff Olson, Jack Riley, Carolyn Lindley, Chris Zervas, William Sweet, Lori Fenstermacher, Dru Smith.

And to those who reviewed the document: W. Michael Gibson, Gretchen Imahori, Paul Scholz, Mary Culver, Jeff Payne.

Technical editor: Helen Worthington, NOAA Center for Operational Oceanographic Products and Services.

September 2010

U.S. DEPARTMENT OF COMMERCE
Gary Locke, Secretary

National Oceanic and Atmospheric Administration
Dr. Jane Lubchenco, Undersecretary of Commerce for Oceans and Atmosphere and NOAA Administrator

National Ocean Service
David Kennedy, Acting Assistant Administrator

Table of Contents

List of Figures

List of Tables

Executive Summary

Understanding trends in sea level, as well as the relationship between global and local sea level, provides critical information about the impacts of the Earth's climate on our oceans and atmosphere. Changes in sea level are directly linked to a number of atmospheric and oceanic processes. Changes in global temperatures, hydrologic cycles, coverage of glaciers and ice sheets, and storm frequency and intensity are examples of known effects of a changing climate, all of which are directly related to, and captured in, long-term sea level records. Sea levels provide an important key to understanding the impact of climate change, not just along our coasts, but around the world. By combining local rates of relative sea level change for a specific area based on observations with projections of global sea level rise (IPCC 2007), coastal managers and engineers can begin to analyze and plan for the impacts of sea level rise for long-range planning.

This document is intended to provide technical guidance to agencies, practitioners, and coastal decision-makers seeking to use and/or collect geospatial data to assist with sea level change assessments and mapping products. There is a lot of information available today regarding sea level change and navigating this information can be challenging. This document seeks to clarify existing data and information and provide guidance on how to understand and apply this information to analysis and planning applications by directing readers to specific resources for various applications.

There is no single approach to sea level change mapping and assessment. The specific data and information requirements of any user are unique depending on their application, location, and need. It is important to understand what to look for and what questions to ask when applying existing information or collecting new data.

The discussion in this document is structured around four key questions to address the required technical considerations:

- What is sea level change and how is it measured?
- What are the considerations for sea level applications with respect to data standards?
- How can users understand and apply geospatial data and information to support sea level rise mapping and assessment and aid in coastal decision making?
- What are the limitations and gaps with respect to sea level measurement, and what are the implications of those gaps?

The document is divided into eight distinct chapters to assist readers in quickly locating the most relevant information:

- The Introduction and General Information chapters pose the key questions to ask when approaching mapping/analysis amidst sea level change, and provide background information on past and projected sea level trends.

- Chapter 2 provides details about the definition of sea level change, the status of sea level research and data today, how to use this information, and how geospatial data are related to sea level applications.

- Chapter 3 discusses existing types and sources of geospatial data available for sea level mapping projects.

- Chapter 4 addresses more specific types of data sets, how to acquire them, and how they can serve multiple uses.

- Chapter 5 provides details on error and uncertainty within the data, and how to use specialized tools such as VDatum, as well as how to integrate data products for maximum utility.

- Chapter 6 outlines the array of applications for sea level change data, including various models (DEM), and using those applications to measure and quantify changes in sea levels, as well as ecosystems and wetlands.

- Chapter 7 presents case studies that deal with extreme events and anomalies and offers insights from workshops and conferences.

- Chapter 8 offers a wide range of additional resources for the user who wishes to delve deeper into the subject of sea level change.

In summary, this document amasses the most up-to-date and useful information from NOAA and others to provide the user with access to a wide range of potential solutions to assist with planning for sea level change.

Chapter 1.0 Introduction

This document is designed to support the climate community in conducting sea level rise assessments, as well as communities involved in coastal development and restoration, habitat assessment and protection, coastal hazard planning and mitigation, and more. Critical products affected by sea level considerations include: navigational, National Shoreline and National reference system, marine boundaries, integrated bathymetric/topographic (bathy/topo) models, and other geospatial products and tools that support a variety of practical application and research projects. With this resource, users can assess the utility of existing data and inform the acquisition of new data against standards of the National Oceanic and Atmospheric Administration (NOAA). The document provides links to NOAA standards for bathymetry, topography, and vertical control as defined by NOAA's National Ocean Service (NOS).

Four NOAA NOS Program Offices collaborated to produce this document: the Center for Operational Oceanographic Products and Services (CO-OPS), the Coastal Services Center (CSC), the Office of Coast Survey (OCS), and the National Geodetic Survey (NGS).

Approach

This technical document pulls from and links together existing standards and documents and incorporates additional appropriate documents and reference material. The document provides a series of technical references with executive summary-level syntheses to link them together and facilitate their use. The references include elements of bathymetry, topography, and vertical control as they relate to sea level measurement, mapping, assessment, and the impacts of sea level change.

Key Questions

The discussion is structured around four key questions to address the required technical considerations:

- What is sea level change and how is it measured?
- What are the considerations for sea level applications with respect to data standards?
- How can users understand and apply geospatial data and information to support sea level rise mapping and assessment and aid in coastal decision making?
- What are the limitations and gaps with respect to sea level measurement, and what are the implications of those gaps?

Chapter 2.0 General Information

The purpose of this chapter is to provide fundamental background in understanding sea level change, appropriate terminology for describing sea level variations at local and global scales, and basic concepts of reference datums critical for assessing impacts of sea level change. Some considerations of accuracy and for datum transformation are also included to lay the foundation for subsequent chapters.

2.1 What is Sea Level Change?

2.1.1 Global and Relative Sea Level Change

The level of the sea observed along the coast changes in response to a wide variety of astronomical, meteorological, climatological, geophysical, and oceanographic forcing mechanisms. From the highest frequency wind waves and sea swell to tsunamis and local seiches, to the daily tides, to monthly, seasonal, and annual variations, to decadal and multi-decadal variations, and finally, to changes over hundreds of millions of years, sea level is constantly changing at any given location.

For purposes of this document, the time scales of concern with respect to sea level change include the monthly through the multi-decadal time frames. Multi-decadal change in sea level is often described as indicated by long-term sea level trends or shorter time periods, or monthly sea level anomalies, both of which are discussed in this document. Sea level change has geospatial and temporal variations such that sea level can be rising or falling depending upon location and time scale. Therefore, this document focuses on sea level change in general, rather than sea level rise, which is a specific type of sea level change.

In addition, there is a subtle, but significant distinction to make when discussing sea level change and the context for which estimation of the change is required. This distinction is one between global sea level change and relative sea level change (Williams et al. 2009).

- **Global (Eustatic) sea level change** is often caused by the global change in the volume of water in the world's oceans in response to three climatological processes: 1) ocean mass change associated with long-term forcing of the ice ages ultimately caused by small variations in the orbit of the earth around the sun; 2) density changes from total salinity; and most recently 3) heat content of the world's ocean, which recent literature suggests may be potentially accelerating due to global warming. Global sea level change can also be caused by basin changes, through such processes as seafloor spreading. Thus global sea level, also sometimes referred to as global mean sea level, is the average height of all the world's oceans[1]. Global sea level rise is a specific type of global sea level change

---

[1] Note that rates of global sea level change vary per region as discussed in later sections of Chapter 2.

that climate models are forecasting to occur at an accelerated rate and is the topic of much of the discussion in this document.

- **Relative sea level change** is the local change in sea level relative to the elevation of the land at a specific point on the coast. Relative sea level change is a combination of both global and local sea level change due to changes in estuarine and shelf hydrodynamics, regional oceanographic circulation patterns, hydrologic cycles (river flow) and local and/or regional vertical land motion (subsidence or uplift). Thus, relative sea level change is variable along the coast depending upon the local and regional factors previously described. Relative sea level rise is a specific type of sea level change that affects many applications, since the contribution to the local relative rate of rise from global sea level rise is expected to increase. Some areas, as discussed later in this chapter, are experiencing relative sea level fall, which can also have ecological and societal impacts. Some localized areas exhibit a more dramatic relative sea level change trend than is generally observed globally unless data are filtered to account for local geophysical anomalies.

2.1.2 Geologic History of Sea Level

Figure 2.1 shows large variations in global mean sea level elevation over the last 400,000 years resulting from four natural glacial and interglacial cycles. Global mean sea level was approximately 4 meters (m) to 6 m higher than it was during the last interglacial warm period 125,000 years ago and 120 m lower during the last Ice Age, approximately 21,000 years ago.

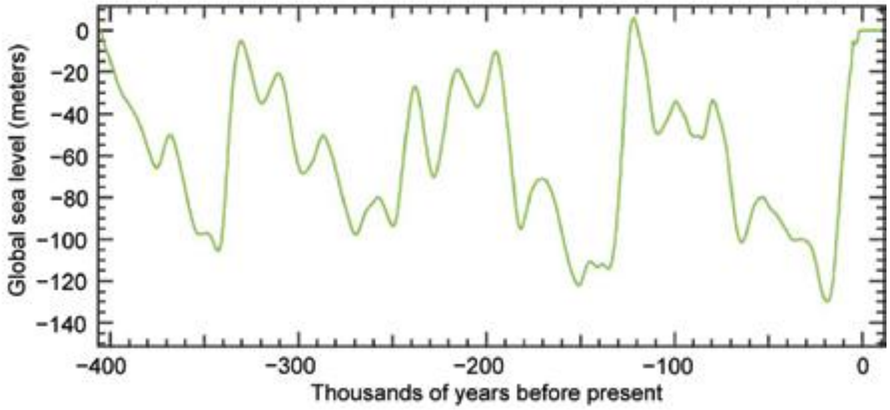


Figure 2.1. Global sea level change from 400,000 years ago to the present (Williams et al. 2009).

The generalized plot in figure 2.2 illustrates the rise in global mean sea level at variable rates over the last 18,000 years as the Earth moved from a glacial period to the present interglacial warm period. The rise was rapid but highly variable, slowing about 3,000 years ago. Recent acceleration is not noticeable at this scale. All human development has occurred in the last 3,000 years, when the average rate of global sea level rise has been relatively flat. We are not used to witnessing significant changes in rates of global sea level rise, but these changes necessitate adaptation and mitigation planning.

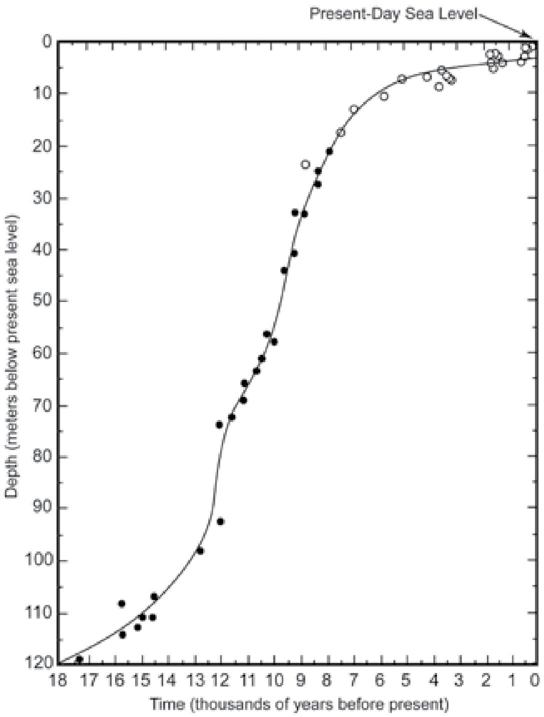


Figure 2.2. The rise in global mean sea level over the last 18,000 years (Williams et al. 2009).

2.1.3 Present Day Global Sea Level

Figure 2.3, taken from the Intergovernmental Panel on Climate Change's (IPCC) 2007 report, shows annual averages of global mean sea level in millimeters (mm). The red curve shows sea level variation from tide gauge observations since 1870 (updated from Church and White 2006); the blue curve displays adjusted tide gauge data from Holgate and Woodworth (2004), and the black curve is based on satellite observations from Leuliette et al. (2004). The red and blue curves represent deviations from their averages for 1961 to 1990, and the black curve is a deviation from the average of the red curve for the period 1993 to 2001. Vertical error bars show 90% confidence intervals for the data points. The estimated trend over the past century, based on analyses of tide gauge records around the globe, is 1.7 mm/yr - 1.8 mm/yr.

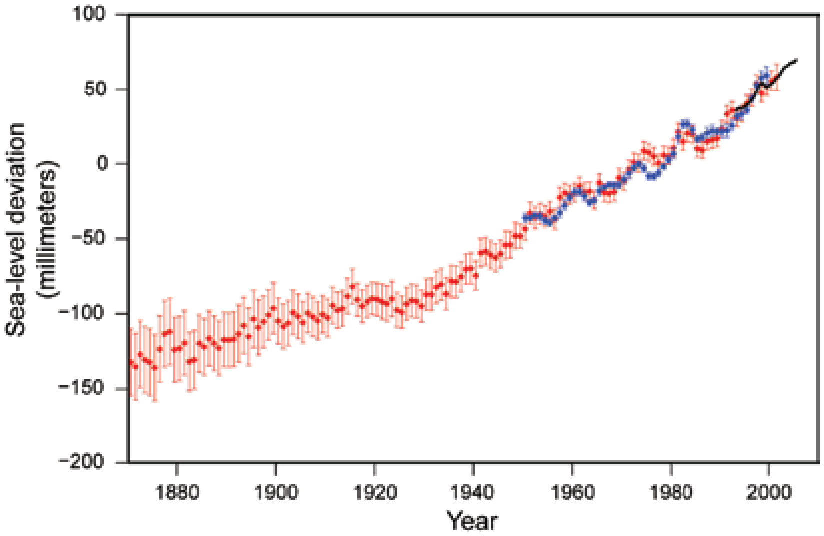


Figure 2.3. Global mean sea level change since 1860 (Williams et al. 2009).

2.1.4 The Latest 16-Year Trends in Global Mean Sea Level from Satellite Altimetry

Figure 2.4 shows an estimate of the present trend in global sea level rise based on a series of overlapping satellite altimeter missions performed since 1992, capturing a rate of 3.0 mm/yr for the global oceans (http://ibis.grdl.noaa.gov/SAT/SLC/index.php), implying an acceleration of the rates compared to the last century. A description of sea level measurements from altimetry is found in subsequent sections (section 3.1).

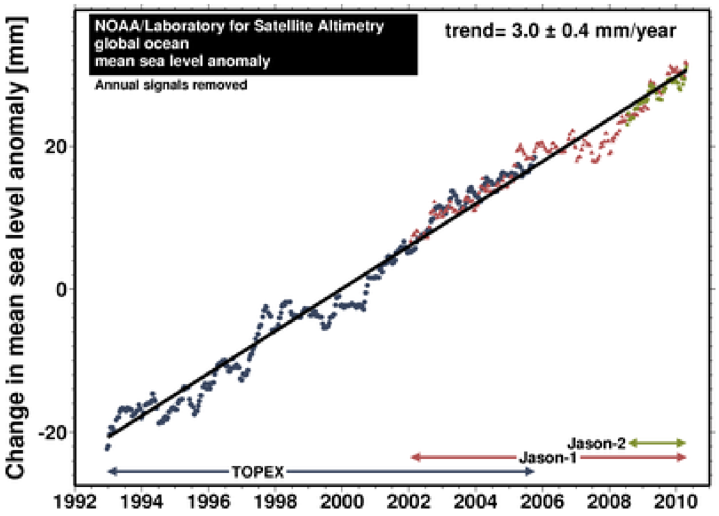


Figure 2.4. The estimated rate of global sea level rise since 1992 using satellite altimeter data.

Figure 2.5 illustrates the significant geospatial variability of the global sea level trends around the world (http://ibis.grdl.noaa.gov/SAT/SLC/index.php). Although the composite global trend in sea level change is 3.0 mm/yr from 1993 to the present, regional trends show variations from over 10 mm/yr to less than −10 mm/yr. It is important to understand this regional variability in the global signal when estimating local and regional rates. These regional patterns and the limited duration of the time series may reflect decadal variability rather than long-term trends. Note, for instance, the obvious geographic pattern similar to that observed during normal to La Niña conditions. See section 3.1 for additional discussion on how satellite altimeters measure sea level.

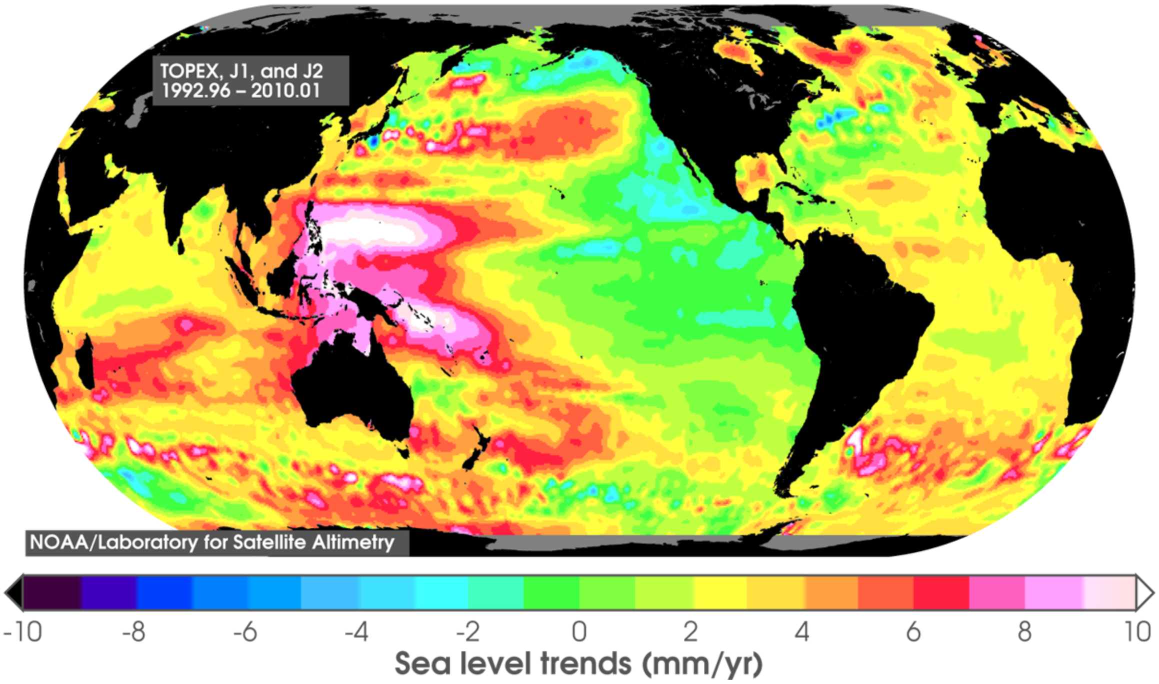


Figure 2.5. Regional rates of sea level change from overlapping satellite altimeter missions**.**

2.1.5 Projected Acceleration in Global Mean Sea Level

Figure 2.6 shows a plot of the recent rise in global sea level and the estimated acceleration in the rate of global sea level rise from several future sea level projections to the year 2100 based on various computer models. The blue shaded area represents the sea level rise projection by Meehl et al. (2007), which corresponds to the A1B emissions scenario and is part of the basis for the IPCC (2007) estimates. The higher gray-and-dashed-line projections are from Rahmstorf (2007) and consider the factors used in the IPCC estimates, but they also include effects of potential increased ice flow rates and associated melting of ice sheets in Greenland and Antarctica.

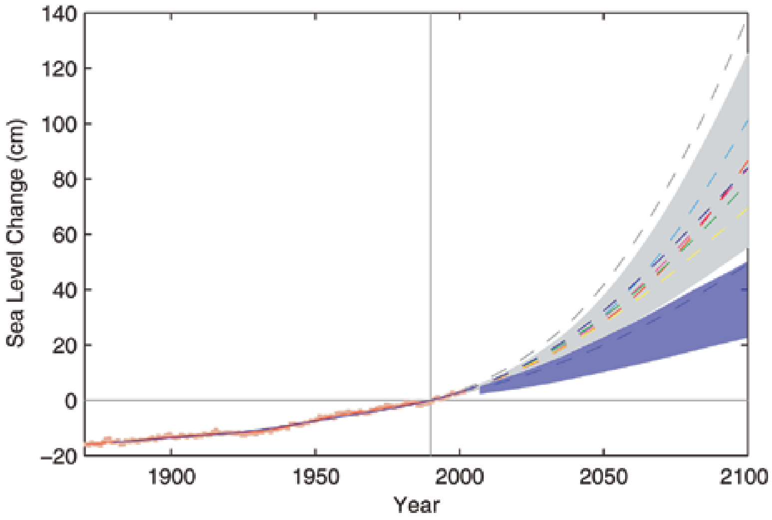
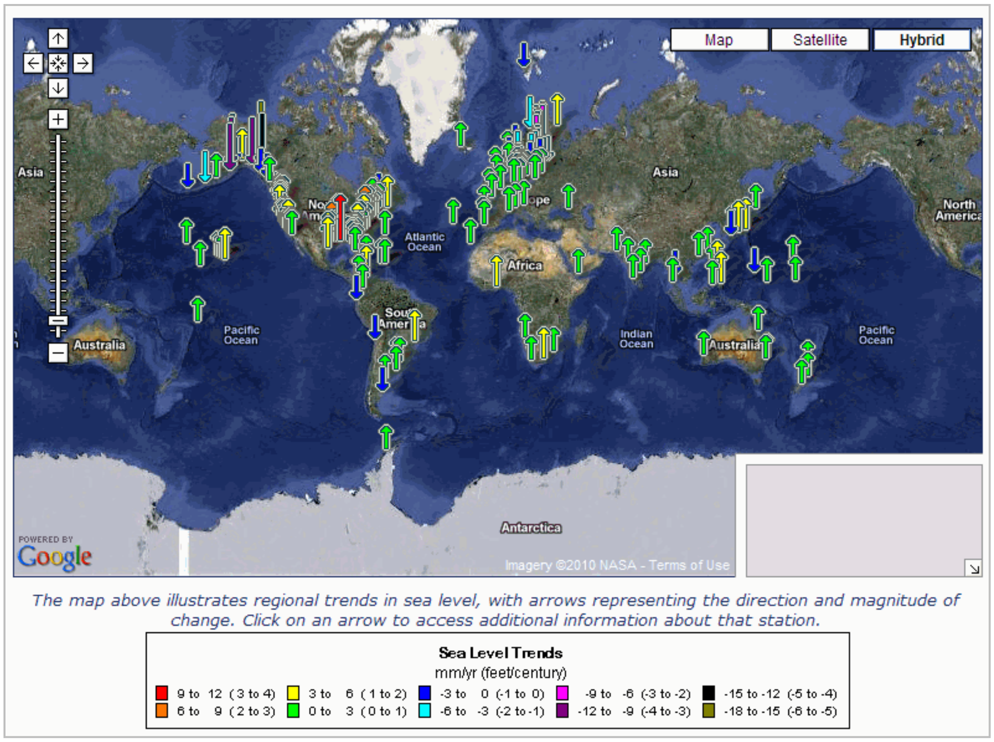


Figure 2.6. Observed and projected sea level rise since the late 1800s (Williams et al. 2009).

2.1.6 Present-Day Trends in Relative Mean Sea Level

Rates of relative sea level change are highly variable along the coasts because they are the combination of many effects (in addition to those from global sea level change) and have significant contributions from local and regional rates of vertical land motion. Local trends in relative sea level are estimated using long-term tide gauge records (Zervas 2009). A discussion of tide gauge data used for local mean sea level determination is found in section 3.1.3. The important point is that tide gauges measure variations of the water relative to the land, thus providing key information on the land-water interface required for many applications. Although tide gauge records are considered key data sources for developing sea level trends world-wide, special consideration must be given to gauge zeros, datums, and the fact that gauges are typically connected directly to land and land-based monumentation. The records alone cannot distinguish among components whether changes are due to global sea level change or land movement but do provide rates of actual change relative to the land. Figure 2.7 shows NOAA's Sea Levels Online website, depicting the relative sea level trends around the globe based on tide gauge records (http://tidesandcurrents.noaa.gov/sltrends/index.shtml). The various lengths, colors, and directions of the arrows illustrate the variability of the sea level trends around the globe. Extreme rates of relative sea level rise are found in the northern Gulf of Mexico due to regional and local land subsidence. Extreme rates of relative sea level fall are found in the Gulf of Alaska, where there is local rebound of the land due to loss of the land-based glaciers and/or uplift response to plate tectonics (including large earthquakes).



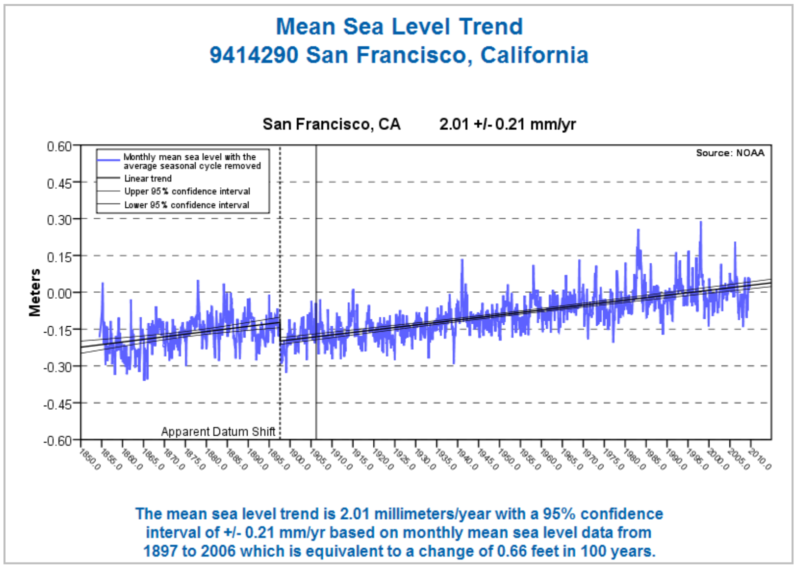
The map above illustrates regional trends in sea level, with arrows representing the direction and magnitude of change. Click on an arrow to access additional information about that station.

Sea Level Trends
mm/yr (feet/century)

🟥 9 to 12 (3 to 4)	🟨 3 to 6 (1 to 2)	🟦 -3 to 0 (-1 to 0)	■ -9 to -6 (-3 to -2)	⬛ -15 to -12 (-5 to -4)
🟧 6 to 9 (2 to 3)	🟩 0 to 3 (0 to 1)	■ -6 to -3 (-2 to -1)	🟪 -12 to -9 (-4 to -3)	■ -18 to -15 (-6 to -5)

Figure 2.7. Relative sea level trends around the globe computed from tide gauge records. NOAA website at: http://tidesandcurrents.noaa.gov/sltrends/index.shtml.

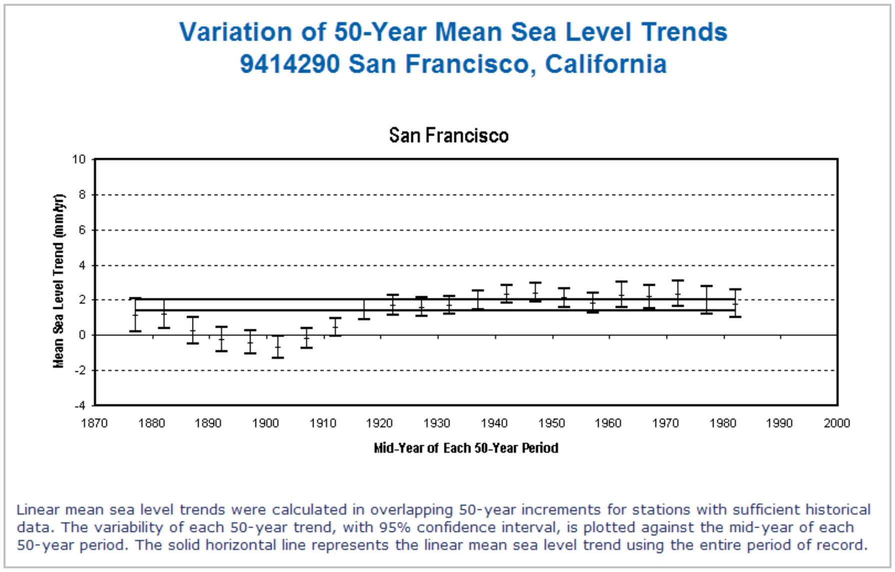
Figure 2.8 provides an example of a long-term tide gauge record and the computed relative mean sea level trends for San Francisco, CA, which is the longest continuously-operating tide gauge in the U.S. Note that the 95% confidence interval trend lines are also depicted. Trend calculations are decoupled for discrete events such as major earthquakes and station relocations so that the observations prior to the specific disturbance are not computed into the long-term trend.



The mean sea level trend is 2.01 millimeters/year with a 95% confidence interval of +/- 0.21 mm/yr based on monthly mean sea level data from 1897 to 2006 which is equivalent to a change of 0.66 feet in 100 years.

Figure 2.8. The long-term relative mean sea level trend for San Francisco.

Relative mean sea level trends are typically computed at a tide gauge using the longest record available without known discontinuities. For climate applications, the variability of sea level trends is also of interest, and the records are being analyzed for evidence of acceleration of the trends. Figure 2.9 shows the variability of overlapping 50-year trends for the record at San Francisco. Using this methodology, the latest 50-year segment was centered 25 years ago; however, the nature of the variability is still of interest.



Variation of 50-Year Mean Sea Level Trends
9414290 San Francisco, California

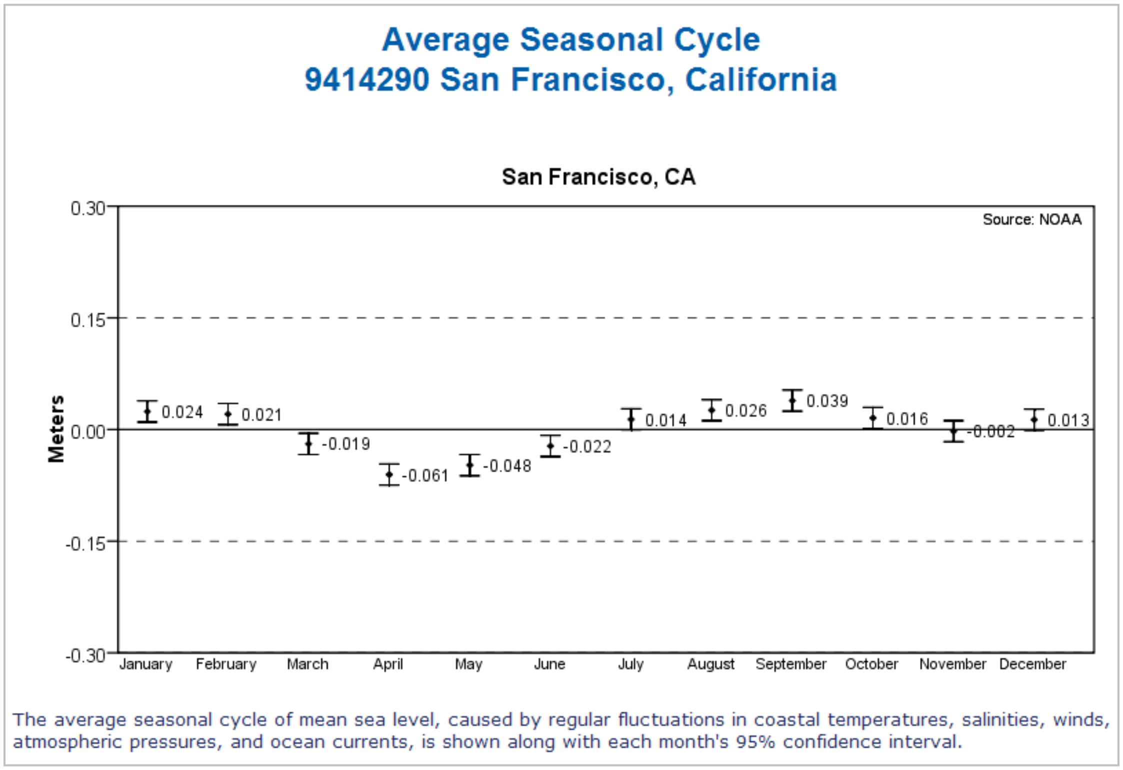
Linear mean sea level trends were calculated in overlapping 50-year increments for stations with sufficient historical data. The variability of each 50-year trend, with 95% confidence interval, is plotted against the mid-year of each 50-year period. The solid horizontal line represents the linear mean sea level trend using the entire period of record.

Figure 2.9. The variability of relative mean sea level trends over a long period record using over lapping 50-year segments.

2.1.7 Annual and Decadal Sea Level Variations

Understanding annual and decadal sea level variations can also be important for context and correct application to a particular coastal zone project. Several factors affect the water level measured at a tide station over various time scales. For shorter time scales, these include local and regional wind stress, changes in barometric pressure, and astronomical tidal forcing. At seasonal time scales, the larger-scale seasonal changes in atmospheric pressure, wind, river discharge, water density, and seasonal changes in circulation patterns have a greater impact. It is important to distinguish which factors are contributing to the sea level trends and account for those that are seasonal, tidal, or meteorological. Whereas some signals, such as astronomical tide, can be eliminated from the long-term record, others are not as easy to distinguish and remove properly. Depending on the region of study, there may be greater impacts on water level from physical forcing than the astronomical tide. Some areas are more significantly affected by wind-driven circulation and storm surge, which are harder to predict or account for. On a longer time scale, sea level observations also exhibit interannual and decadal variations, which are often difficult to remove because they can be intertwined with seasonal variations as well as ocean-atmospheric interactions. However, if a sea level series from which a trend is being computed begins or ends in a significant crest or trough of an interannual “event” (e.g., El Niño Southern

Oscillation, ENSO), calculated trends can become biased. Interannual and decadal trends are typically not removed from monthly mean sea level records (monthly averages of hourly sea level heights), but should be recognized, and short-term records should be avoided, as they do not sufficiently capture long-term trends and therefore create bias (Parker 1992). The relationship between water level and atmospheric processes makes sea level records an important part of understanding global teleconnections. The NOAA Sea Levels Online website (http://tidesandcurrents.noaa.gov/sltrends/index.shtml) is also a source for annual and decadal variation information using long-term tide gauge records. For example, figure 2.10 shows the average annual variability in monthly mean sea level (computed over the period of record, 1897-2006) using San Francisco with high sea levels in January, February, August, September, and October of each year.

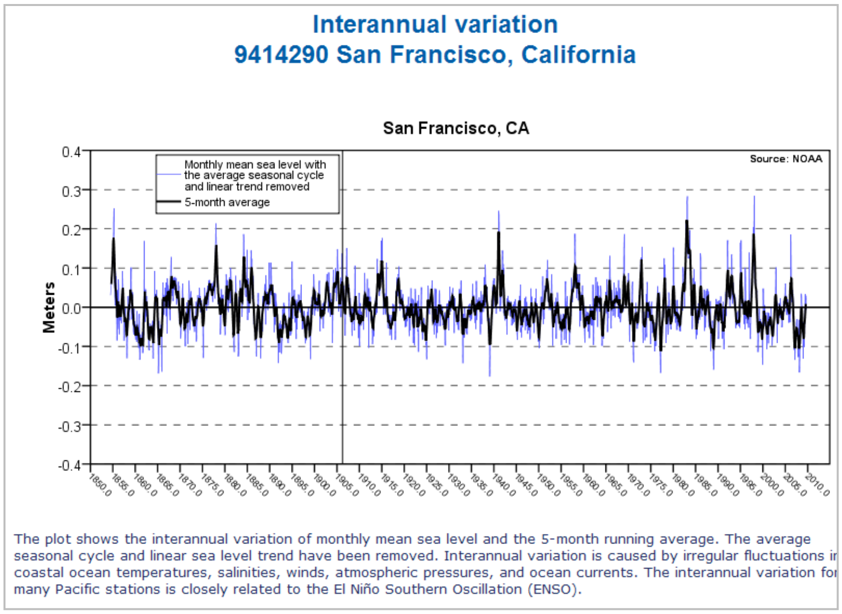


Average Seasonal Cycle
9414290 San Francisco, California

The average seasonal cycle of mean sea level, caused by regular fluctuations in coastal temperatures, salinities, winds, atmospheric pressures, and ocean currents, is shown along with each month's 95% confidence interval.

Figure 2.10. Average annual variation in monthly mean sea level at San Francisco.

Figure 2.11 shows the interannual variability in mean sea level for San Francisco. This analysis first subtracts the annual seasonal cycle from the record and removes the linear sea level trend so that the resulting sea levels can be examined for anomalous time periods. The anomalously high sea levels are found during the El Niño periods (e.g., 1982-1983 and 1997-1998).


Interannual variation
9414290 San Francisco, California

The plot shows the interannual variation of monthly mean sea level and the 5-month running average. The average seasonal cycle and linear sea level trend have been removed. Interannual variation is caused by irregular fluctuations in coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The interannual variation for many Pacific stations is closely related to the El Niño Southern Oscillation (ENSO).

Figure 2.11. The interannual variation in monthly mean sea level at San Francisco

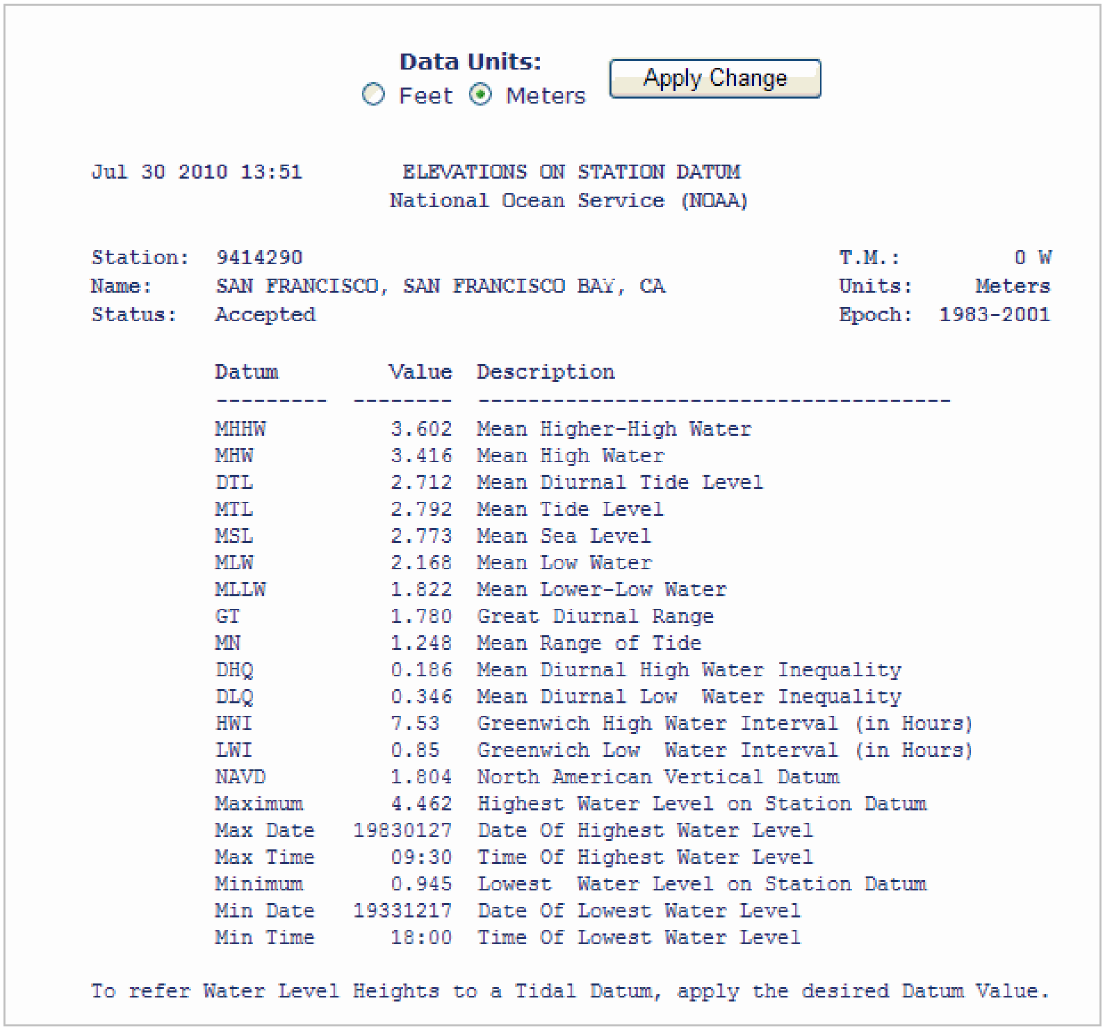
2.2 Considerations for Sea Level Applications

2.2.1 Datums

Tidal Datums and the National Tidal Datum Epoch (NTDE)

Generally, a datum is a base elevation used as a reference from which to reckon heights or depths. A tidal datum is a standard elevation defined by a certain phase of the tide. Tidal datums are used as references to measure local sea levels near the tide gauge at which the measurements were collected and should not be extended into areas with differing oceanographic characteristics without substantiating measurements. So that they may be recovered when needed, such datums are referenced to fixed monuments known as bench marks near the tide gauge. Tidal datums are also the basis for establishing marine boundaries, delineating privately-owned land, state-owned land, territorial sea, exclusive economic zone, and high seas boundaries.

Tidal datums are based on averaged stages of the tide, such as mean high water (MHW) and mean lower low water (MLLW). To minimize all the significant daily, monthly, and yearly sea level variations, a tidal datum such as MHW is defined as the average of all the high water elevations tabulated over an 18.6-year period (rounded to 19 years to obtain closure on the annual cycle). The 19-year period encompasses all significant variations in the mean range of tides due to variations in lunar and solar orbits, including the 18.6-year regression of the moon’s nodes. It also averages out most meteorological effects on water level, which could bias a tidal datum computed from a shorter length data time series. The National Tidal Datum Epoch (NTDE) is a specific 19-year period defined by NOAA. Water level observations obtained during this cycle are used to calculate official tidal datums. The present Epoch is the 1983-2001 NTDE. Figure 2.12 shows the accepted 1983-2001 NTDE tidal datum elevations relative to an arbitrary station datum at San Francisco, CA. This Web-based presentation also includes the elevation of the geodetic North American Vertical Datum of 1988 (NAVD 88) relative to the same station datum and includes the tabulated highest and lowest tides of record. NOAA reference manuals on applications of tidal datums (NOAA 2001) and computation of tidal datums from short series of measurements (NOAA 2003) provide more detail. See also http://tidesandcurrents.noaa.gov/ for products and information.



```
Jul 30 2010 13:51        ELEVATIONS ON STATION DATUM
                        National Ocean Service (NOAA)

Station:  9414290                                         T.M.:        0 W
Name:     SAN FRANCISCO, SAN FRANCISCO BAY, CA            Units:    Meters
Status:   Accepted                                        Epoch: 1983-2001

          Datum         Value   Description
          ---------  --------   -------------------------------------
          MHHW          3.602   Mean Higher-High Water
          MHW           3.416   Mean High Water
          DTL           2.712   Mean Diurnal Tide Level
          MTL           2.792   Mean Tide Level
          MSL           2.773   Mean Sea Level
          MLW           2.168   Mean Low Water
          MLLW          1.822   Mean Lower-Low Water
          GT            1.780   Great Diurnal Range
          MN            1.248   Mean Range of Tide
          DHQ           0.186   Mean Diurnal High Water Inequality
          DLQ           0.346   Mean Diurnal Low  Water Inequality
          HWI           7.53    Greenwich High Water Interval (in Hours)
          LWI           0.85    Greenwich Low  Water Interval (in Hours)
          NAVD          1.804   North American Vertical Datum
          Maximum       4.462   Highest Water Level on Station Datum
          Max Date   19830127   Date Of Highest Water Level
          Max Time      09:30   Time Of Highest Water Level
          Minimum       0.945   Lowest  Water Level on Station Datum
          Min Date   19331217   Date Of Lowest Water Level
          Min Time      18:00   Time Of Lowest Water Level

To refer Water Level Heights to a Tidal Datum, apply the desired Datum Value.
```

Figure 2.12. Accepted 1983-2001 NTDE datums for San Francisco, CA. From: http://tidesandcurrents.noaa.gov/. NAVD refers to the North American Vertical Datum of 1988.

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) periodically updates the Nation's tidal datum elevations to new NTDE periods. The most recent such update was in April 2003 in which the 1983-2001 NTDE superseded the 1960-1978 NTDE. The NOS policy is to revise the NTDE every 20-25 years to account for changes in relative mean sea level due to global sea level change and long-term local and regional vertical land mass movements. The new NTDE calculations provide the most accurate up-to-date tidal datum information required to support essential Federal, state, and private sector coastal zone management projects including navigation safety, storm surge monitoring, coastal engineering, ecosystem research, hazard mitigation, and other critical issues confronting coastal communities. Previous tidal epochs were determined for the periods 1924-1942, 1941-1959, and 1960-1978 (figure 2.13). New NTDEs are adopted so that all tidal datums throughout the United States are based on one (and most recent) specific common reference period. The NDTEs do not need to be consecutive 19-year periods without gaps. The change in relative mean sea level drives the timing. The latest NTDE update was officially announced in the Federal Register on May 28, 2003 (volume 68, Number 102).

It should be noted, however, that in areas experiencing high rates of relative sea level change, datums must be updated more frequently than the national NTDE. NOAA has adopted a “Modified Tidal Datum Epoch” procedure for updating datums in areas of rapid sea level change due to rapid subsidence and uplift. Instead of using a full 19 years of monthly mean sea level, datums computed from the modified epoch are based on the most recent 5 years of data and are not the same as the standard NTDE datums. However, the procedure still adheres to the NTDE concept, since the monthly mean ranges of tide are computed using the full 19 years of data. Long-term variations in monthly mean sea level are due to oceanographic change and vertical land motion, while variations in range of tide are due to the changing moon’s declination and nodal cycle. Special care must be taken in describing these areas on a station-by-station basis and care must be taken in the use of them for controlling the development of 19-year equivalent datums at nearby short-term stations. Example areas where the Modified Tidal Datum Epoch is used are in southeast Alaska, where recent glacial melt has resulted in rapid local land rebound or uplift and relative sea level fall, and in the Louisiana Mississippi Delta area, where regional and local land subsidence have resulted in rapid sea level rise. Rates of relative sea level change in these areas are typically greater than 7-8 mm/yr.

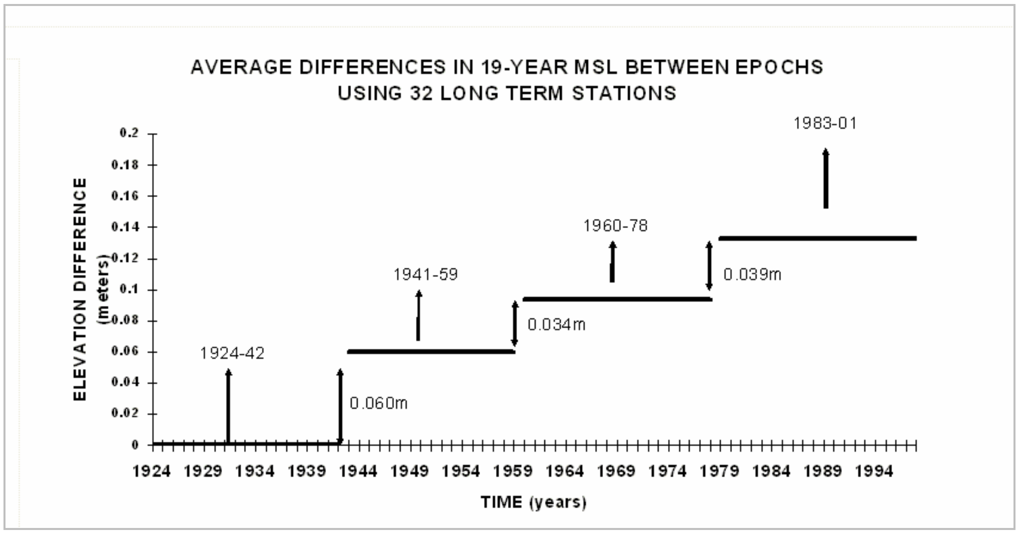


Figure 2.13. History of updates to the National Tidal Datum Epoch due to sea level change.

Geodesy and Geodetic Datums

Geodesy is the branch of applied mathematics concerned with determination of the size and shape of the Earth, its gravity field, the precise determination of positions on the Earth's surface and the measurement of geodynamic phenomena, such as the motion of the magnetic poles, tides and tectonic plate motion. The National Geodetic Survey (NGS) defines a geodetic datum as: "A set of constants used for calculating the coordinates of points on the Earth." Generally, a datum is a reference from which measurements are made (such as a surface of zero elevation for referencing heights or the origin and orientation of a Cartesian coordinate frame used to reference Cartesian coordinates, as well as latitudes and longitudes, if an ellipsoid model is also included). Traditionally, horizontal datum describes a datum in which latitude and longitude are referenced. A vertical datum references elevations or heights.

Types of Vertical Datums:

There are three primary types of vertical datums in use in United States. These are orthometric, ellipsoidal, and dynamic. Other types of datums (such as "normal" and "normal orthometric") also exist in other countries, but will not be discussed further. Dynamic datums are generally used only in large landlocked bodies of water (such as the Great Lakes) but do not have a significant role in this document and will not be further discussed. The remaining two, orthometric and ellipsoidal, are outlined in the following paragraphs.

However, before proceeding, a primer on certain terminology is helpful.

Geoid: The geoid is the surface of constant gravity potential which best fits (in the least squares sense) global mean sea level. By this definition, at any given point in time, which represents a given distribution of mass on Earth (and in the Universe), there is one and only one geoid.

Ellipsoid: Usually meaning an "ellipsoid of revolution," it is a three-dimensional surface that would be described by the rotation of an ellipse about its semi-minor axis. An ellipsoid, being an arbitrary shape (defined by only 2 variables) is non-unique, and various groups have adopted different ellipsoids of reference for various reasons.

Plumb Line: A curved line in space that is always tangent to the local direction of gravity. It is also perpendicular to any surface of constant gravity potential (an equipotential surface) through which it passes.

Ellipsoidal Normal: A straight line perpendicular to the surface of an ellipsoid.

Geoid Undulation: The distance along the ellipsoidal normal from a chosen ellipsoid to the geoid. If the reference ellipsoid is chosen so as to "fit the geoid", the magnitude of geoid undulations ranges from approximately −100 to +100 meters (m), globally.

Orthometric Datums

Orthometric datums are used for referencing orthometric heights. An orthometric height is the distance between the geoid and a point on the Earth's surface (measured along the plumb line). In general, orthometric heights are impossible to determine through a direct measurement, since this would require full knowledge of both the plumb line and the geoid, which are generally within Earth's crust. As such, a variety of approximations are used estimate orthometric heights. One of the most common is called a "Helmert orthometric height" and relies solely on surface leveling measurements and surface gravity measurements.

Also, orthometric heights are colloquially, but incorrectly, called heights above mean sea level (MSL). Oceanographic MSL, however, departs from the geoid through both periodic effects (such as tides) and non-periodic effects (such as western boundary currents). Furthermore, MSL is defined over the surface of the oceans only, whereas the geoid is a continuous surface, approximating the ocean's surface over the oceans, but slicing under the continents at land areas. As such, heights "above mean sea level" are meaningless over land. **North American Datum of 1988 (NAVD 88):** The current official vertical datum for all surveying and mapping activities of the Federal government. The datum is *defined* as the surface of equal gravity potential to which orthometric heights shall refer in North America, and which is 6.271 m (along the plumb line) below the geodetic mark at "Father Point/Rimouski" (PID TY5255 in the NGS Integrated Database). However, it is *realized* (i.e., its primary method of access is) through over 500,000 geodetic bench marks across North America with published Helmert orthometric heights, most of which were originally computed from a minimally constrained adjustment of leveling and gravity data, holding the geopotential value at "Father Point/Rimouski" fixed.

National Geodetic Vertical Datum of 1929 (NGVD29)

The predecessor of NAVD 88, the National Geodetic Vertical Datum of 1929 (NGVD29) served as the official vertical datum for all surveying and mapping activities of the Federal Government for the U.S. until it was superseded. It was defined as the surface of equal gravity potential, to which orthometric heights shall refer in North America, and which is 0.000 m above mean sea level at 26 chosen tide gauges on the East and West Coasts of the United States and Canada (below the geodetic mark at "Father Point/Rimouski" (PID TY5255 in the NGS Integrated Database). However, it was *realized* (i.e., its primary method of access was) through the National network of geodetic bench marks across North America with published normal orthometric heights, most of which were originally computed from a constrained adjustment of leveling data, holding the mean sea level heights at 29 tide gauges as fixed to be zero in NGVD 29. A superseded synonym for NGVD29 was Sea-level Datum of 1929.

Both NAVD 88 and NGVD29 were "fixed" and did not take into account the changing stands of sea level or vertical land motion (except in sporadic cases of re-leveling). Because there are many variables affecting sea level, and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and local mean sea level is not consistent from one location to another in either time or space.

Ellipsoidal Datums/Geometric Reference Frames

Ellipsoidal datums (or, more recently "geometric reference frames") have become important with the development of GPS. They often include an origin and orientation of a Cartesian coordinate system, overlain with an ellipsoid that approximates the geoid. Ellipsoidal heights are the distances along the ellipsoidal normal to a point on the Earth's surface. While GPS is a purely Cartesian (i.e., *XYZ*) system, the introduction of a simple ellipsoid model allows for the fast determination of latitude, longitude, and ellipsoid height indirectly from GPS observations. There are various geometric reference frames in use, but for scientific applications, especially sea level change, the International Terrestrial Reference Frame (ITRF) is preferred. The ITRF is a regularly updated (e.g. ITRF2000, ITRF2005, ITRF2008) realization of the International Terrestrial Reference System (ITRS), produced under the auspices of the International Earth Rotation and Reference Frame Service (IERS). Each ITRF is purely Cartesian, therefore any convenient ellipsoid may be superimposed to convert to latitude, longitude, and ellipsoid height. The convention most frequently used is the ellipsoid known as GRS-80 (http://www.ncgs.state.nc.us/pdf/FAQs_for_NAD_83_NSRS2007.pdf).

It is critical to understand the geometric reference frame in use, as its origins and varied ellipsoids will directly impact height measurements, such as those used in SLC detection. For example, the official geometric reference frame (still frequently called a horizontal datum) for the U.S. is NAD83, whose origin is known to be offset from ITRF2008 by approximately 2.2 m.

National Reference Systems

The NGS defines, maintains, and provides access to the National Spatial Reference System (NSRS) that is a nationally consistent coordinate system for determining latitude, longitude, height, scale, gravity, and Earth orientation parameters. See: http://www.ngs.noaa.gov/INFO/OnePagers/NSRSOnePager.pdf.

The NSRS also tracks how these parameters change with time. The major components of NSRS are:

- A consistent, accurate, and up-to-date National Shoreline
- The National CORS, a set of GNSS Continuously Operating Reference Stations meeting NOAA geodetic standards for installation, operation, and data distribution
- A network of passive control monuments including the Federal Base Network (FBN), the Cooperative Base Network (CBN), and the User Densification Network (UDN)
- A set of accurate models describing dynamic geophysical processes affecting spatial measurements

2.2.2 Datum Transformations

There are numerous horizontal and vertical datums used for a variety of geospatial applications. Topographic maps (e.g., from USGS) generally have elevations referenced to orthometric datums, either the NAVD 88 or to the older NGVD29. Source engineering documents and maps are typically referenced to a variety of horizontal and vertical datums, depending upon agency and surveyor. All GPS positioning data are referenced to one of several 3-D/ellipsoid datums. Depths on NOAA's nautical charts are typically referenced to MLLW, while bridges and overhead obstructions are referenced to MHW. In estuaries that are described as non-tidal (no tide or no significant tide compared to non-tidal hydrodynamic influences) local water level datums are determined from mean water level measurements and are augmented by safety factors for low and high water datum references for similar practical charting applications. The legal shoreline in the U.S., the shoreline represented on NOAA's nautical charts, is defined as the MHW shoreline; that is, the land-water interface when the water level is at an elevation equal to the MHW datum. Caution is advised in the use of shoreline data because, in reality, due to sea level variability and the frequency with which tidal datums are updated as well as limitations in survey technologies, the charted shoreline may not represent the true land-sea interface at the elevation of the 19-year epoch MHW for all areas or points along the shoreline data set. The MLLW line is also the nautical chart datum depicted on NOAA's charts. Lidar data are collected using GPS vertical control (thus referenced to the ellipsoid) and are converted to NAVD 88 referenced elevations for many applications, though for charting applications, a relationship to local tidal datums, such as MLLW and MHW, must also be established.

For application to climate change scenarios and to inundation analyses and modeling, it is critical that all elevations and depths be referenced to the same datum, regardless of source. Thus, integrating data that are referenced to different datums from multiple sources requires appropriate datum transformation tools. Historically, differences between datums were available only at a particular location or point at a bench mark or at a tide station, where an actual survey had been performed using leveling techniques or static GPS observations. Manual interpolation of datum relationships between observation locations is often extremely difficult and the results inaccurate, depending upon the location and the spatial variability of the parameter being interpolated. NOAA's National Ocean Service provides two unique tools, NADCON (North American Datum Conversion) and VDatum, for transformation across horizontal and vertical datums, respectively.

To convert data between NAD27 and NAD83, the NGS developed NADCON, a program that uses minimum curvature to relate coordinate differences between the two systems. Visit the NGS NADCON Web page at http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html Tidal datum elevations vary significantly with horizontal (geographic) distance, especially in shallower waters and usually vary more rapidly than the horizontal variation in orthometric or 3-D/ellipsoid vertical datums. The variations are often correlated with spatial changes in the range of tide and type of tide. These changes can occur within a short distance in the more complex tidal hydrodynamic estuaries and river systems.

NOS developed a vertical datum transformation tool called VDatum (http://vdatum.noaa.gov/) to facilitate the easy transformation of elevation data between any two vertical datums among a choice of 36 orthometric, tidal and ellipsoid vertical datums (See chapter 5 discussion on VDatum). The transformations within VDatum employ models (such as a geoid or a tidal model) to deliver the transformations. VDatum offers point location and batch file output, which can be put into a gridded model output or a GIS file thus providing interpolated information away from the observation locations.

The decision to use either a transformation tool or a more direct measurement depends upon the application and the desired accuracy. The published point elevations from NGS for geodetic datums at bench marks and from CO-OPS at tide stations offer the most accurate elevations. Performing a new static GPS survey, leveling between existing bench marks in the survey area, establishing a new tide station and computing new tidal datums, or performing a new bathymetric or shoreline survey may be the only ways to meet the most stringent accuracy requirements for a local project. That decision interplay between transformation models and observations requires understanding of project accuracy requirements, as well as uncertainties and limitations of the interpolation and transformation tools being used. A discussion of datum uncertainties and datum transformation uncertainties can be found on the NOAA VDatum website at http://vdatum.noaa.gov/docs/est_uncertainties.html.

2.3 Accuracy Needed For Various Sea Level Applications

The best way to address accuracy very much depends upon the application. How are the data to be used and in what context? In most instances, the user must determine the total accuracy requirements of the final product and how certain he or she needs to be to make a decision or assume a significant amount of risk in final statements and conclusions?

There are a few basic statements on accuracy of relative sea level trends that can be made, however. For instance, the accuracy of relative sea level trends computed from tide gauge records is highly dependent upon the record length as detailed by Zervas (2009). Figure 2.14 shows the relationship of the 95% confidence level (an expression of uncertainty) in a sea level trend with record length. The confidence limits of a 20-year record have almost a 3.0 mm/yr uncertainty, while a trend from a 40-year record has only a 1.0 mm/yr uncertainty. For most applications, the uncertainty of the trend is much less than the value of the actual trend itself. NOAA publishes relative trends in mean sea level for only those stations with greater than 30 years of record.

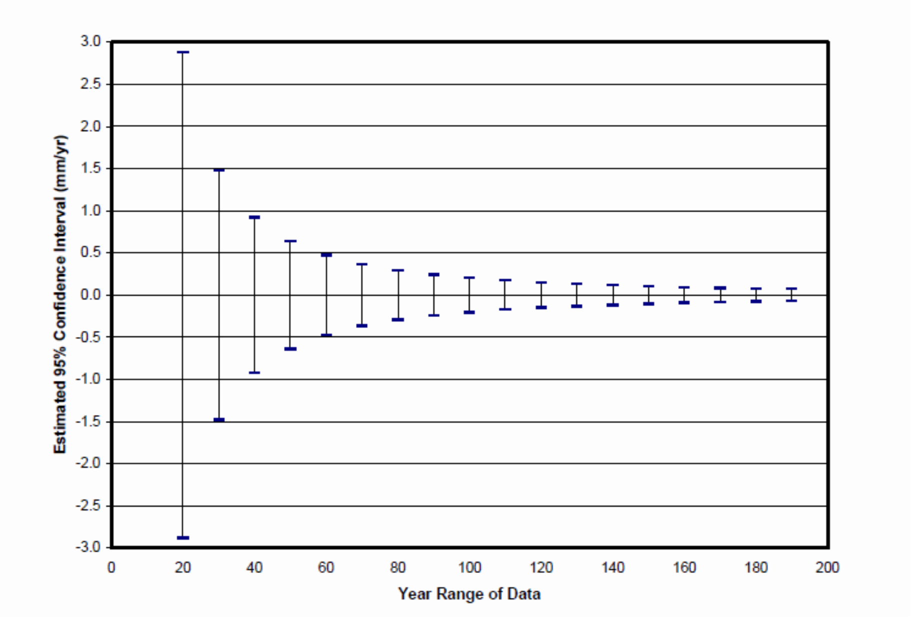


Figure 2.14. A 95% confidence interval for linear mean sea level trend versus series length (Zervas 2009).

If it is found that shorter record lengths are required, then the trend must always be presented with an estimate of its uncertainty. When trends among a region are compared, the trends from greater than 30 years of record should be used. When comparing trends using shorter record lengths, it is important to use trends determined from simultaneous time periods.

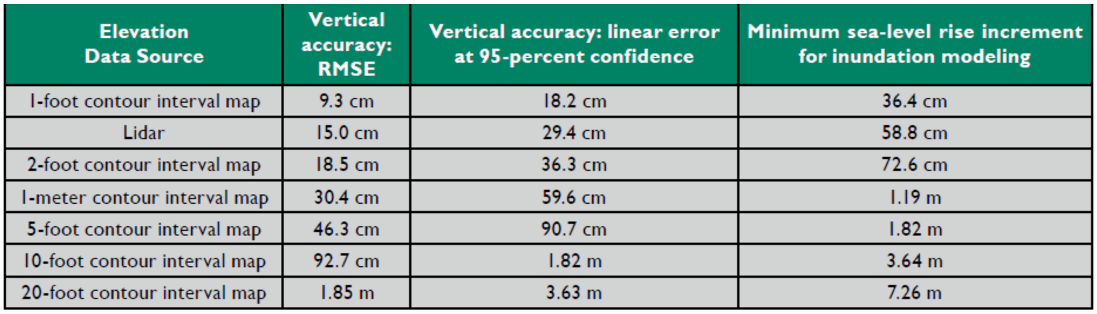
There are also some basic statements that can be made on the accuracy required for topographic elevations when merging them with sea level rise trends or scenarios. CCSP 4.1 (Gesch et al. 2009) found that in many instances, users showing impacts of sea level rise on elevation surfaces were overextending their findings because they ignored the underlying accuracy of the source elevation data and reported results in increments that could not be supported by the data. Some of the CCSP4.1 findings were:

> The accuracy with which coastal elevations have been mapped directly affects the reliability and usefulness of sea level rise impact assessments. Although previous studies have raised awareness of the problem of mapping and quantifying sea level rise impacts, the usefulness and applicability of many results are hindered by the coarse resolution of available input data. In addition, the uncertainty of elevation data is often neglected.
>
> Existing studies of sea level rise vulnerability based on currently available elevation data do not provide the degree of confidence that is optimal for local decision making.
>
> There are important technical considerations that need to be incorporated to improve future sea level change impact assessments, especially those with a goal of producing vulnerability maps and statistical summaries that rely on the analysis of elevation data. The primary aspect of these improvements focuses on using

high-resolution, high-accuracy elevation data, and consideration and application of elevation uncertainty information in development of vulnerability maps and area statistics.

Studies that use elevation data as an input for vulnerability maps and/or statistics need to have a clear statement of the absolute vertical accuracy. There are existing national standards for quantifying and reporting elevation data accuracy.

Figure 2.15 provides CCSP4.1 guidance on the minimum sea level rise increment supportable by various accuracies of source elevation data. Topographic lidar data are being increasingly used; however, 15.0 cm Root Mean Square Error (RMSE) accuracy is often ignored when applying it to various incremental rates of sea level rise or for any inundation mapping purposes.



Elevation Data Source	Vertical accuracy: RMSE	Vertical accuracy: linear error at 95-percent confidence	Minimum sea-level rise increment for inundation modeling
1-foot contour interval map	9.3 cm	18.2 cm	36.4 cm
Lidar	15.0 cm	29.4 cm	58.8 cm
2-foot contour interval map	18.5 cm	36.3 cm	72.6 cm
1-meter contour interval map	30.4 cm	59.6 cm	1.19 m
5-foot contour interval map	46.3 cm	90.7 cm	1.82 m
10-foot contour interval map	92.7 cm	1.82 m	3.64 m
20-foot contour interval map	1.85 m	3.63 m	7.26 m

Figure 2.15. Table 2.4 from Gesch et al. (2009).

Figure 2.16 further explains the on-the-ground difference various uncertainties in source elevation can make. The more accurate lidar-derived DEM (±0.3 m at 95% confidence) results in a delineation of the inundation zone with much less uncertainty than when the less accurate topographic map-derived DEM (±2.2 m at 95% confidence) is used. Depending on the slope of the topography, that uncertainty can translate into a significant horizontal distance. Care must be taken not to overstate the resolution of area impacts of inundation for given sources of data.

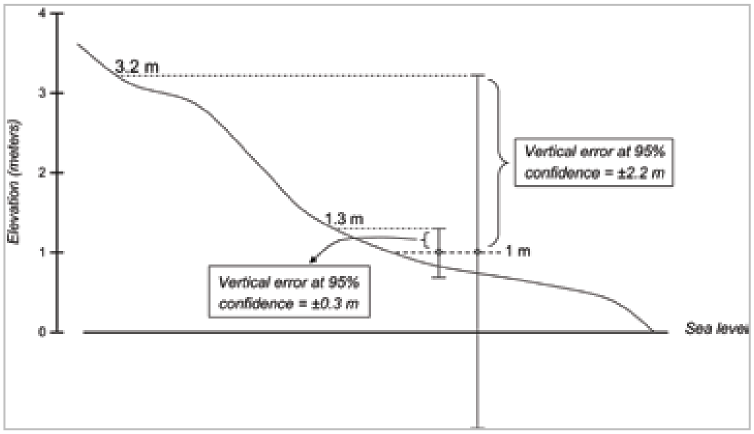


Figure 2.16. How a sea level rise of 1 m is mapped onto the land surface using two digital elevation models with differing vertical accuracies, from figure 2.2 in Gesch et al. (2009).

2.4 Use of Sea Level Rise Information

Understanding trends in sea level, as well as the relationship between global and local sea level, provides critical information about the impacts of the Earth's climate on our oceans and atmosphere. Changes in sea level are directly linked to a number of atmospheric and oceanic processes. Changes in global temperatures, hydrologic cycles, coverage of glaciers and ice sheets, and storm frequency and intensity are examples of known effects of a changing climate, all of which are directly related to, and captured in, long-term sea level records. Sea levels provide an important key to understanding the impact of climate change, not just along our coasts, but around the world. By combining local rates of relative sea level change for a specific area based on observations with projections of global sea level rise (IPCC 2007), coastal managers and engineers can begin to analyze the impacts of sea level rise for long-range planning**.**

The sea level change information, along with the fundamental water level and geodetic data sources described in this document, can be used to:

1) Obtain a basic understanding of how sea level rise affects the physical environment:

- Shoreline change and erosion or deposition (sediment transport)
- Coastal flooding impacts of coupling with storm events (frequency and duration)
- Coastal wetland sustainability
- Effects on coastal habitats
- Local and regional vertical land motion
- Adequacy/accuracy of existing navigational charts
- Proper use of historical nautical charts, which are compiled from various surveys, typically conducted over several decades.

2) Understand potential societal impacts of sea level rise, such as:

- Shore protection and retreat
- Impacts on population, land use planning and infrastructure
- Public access
- Floodplain management and coastal zone management

3) Perform vulnerability studies and risk assessments on impacts of sea level rise, for example:

- USGS/Coastal Vulnerability Index Maps (Theiler et al. 2009)
- EPA/Coastal Elevations at Risk Maps (EPA 2009)
- U.S. Army Corps of Engineers (USACE)/ Engineering Planning and Design Guidance (USACE 2009)
- DOT/Impacts on Transportation Infrastructure (DOT 2008)

4) Perform basic research in estimating global sea level rise (Douglas et al. 2001 and Church and White 2006).

The present relative mean sea level trends derived from tide gauge records are often used as baseline rates for addressing future impacts as if there would be no acceleration in present day rates of global sea level rise.

The global climate models (IPCC 2000) are used to project the increased elevation in global mean sea level by a certain time (2100) and do not use estimates of changing rates. The USACE (2009) estimates the change in the rates of global sea level rise using a mathematical curve for practical application to get interim values.

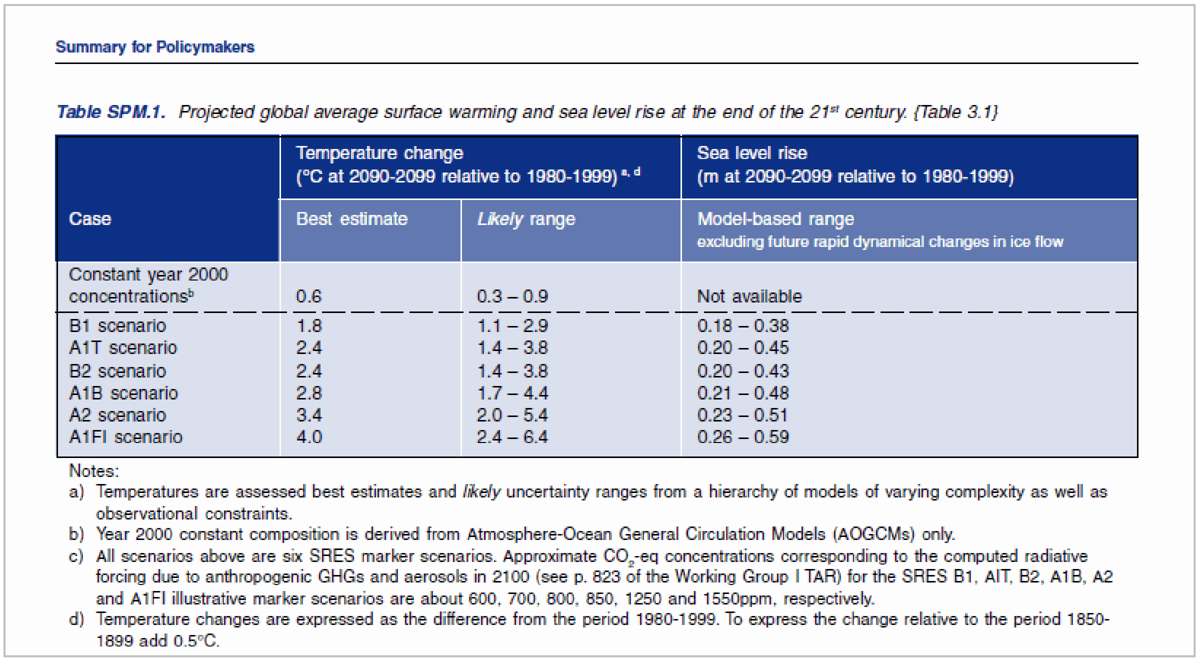
Sea level change information in the form of existing trends, projected trends, existing and projected extremes, and the nature of the time and spatial variability of the information can be used in a variety of applications. Chapter 6 describes many of these applications in more detail.

2.5 Projection of Future Sea Level Trends

2.5.1 Background Discussion

If the period of interest in projected sea level change is only from one to five years from now (2010), then the linear trends in relative mean sea level computed from tide station records probably suffice as a baseline estimate for most applications (see other chapters of this document). Climate models project accelerated contributions to global warming and global sea level rise from 10 years out to the end of the century. If projections for longer time scales are required, then information from the ongoing climate research needs to be applied and integrated with actual present day trends.

Projection of future global sea level change is dependent upon climate change models that predict the impacts of various scenarios for greenhouse gas emissions. The series of efforts underway by Intergovernmental Panel on Climate Change (IPCC) provides the latest scientific consensus on impacts of global warming. The latest report (IPCC 2007) made projections of sea level rise for various climate model scenarios. Ongoing research in climate modeling and in global sea level rise has continued since the 2007 report and will be included in the next IPCC assessment. A table from the IPCC (2007) report (figure 2.17) shows the relationship of projected average surface warming and sea level rise from 1980-1999 to 2090-2099 for various climate model scenarios. The table also shows a range of temperature change scenarios resulting in several sea level rise scenarios, from 0.18 m to 0.59 m by 2100. Note that the uncertainty in the model results is expressed by a range of values for each scenario.



Summary for Policymakers

Table SPM.1. Projected global average surface warming and sea level rise at the end of the 21st century. {Table 3.1}

Case	Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d]		Sea level rise (m at 2090-2099 relative to 1980-1999)
	Best estimate	*Likely* range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations[b]	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:

a) Temperatures are assessed best estimates and *likely* uncertainty ranges from a hierarchy of models of varying complexity as well as observational constraints.

b) Year 2000 constant composition is derived from Atmosphere-Ocean General Circulation Models (AOGCMs) only.

c) All scenarios above are six SRES marker scenarios. Approximate CO$_2$-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the Working Group I TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550ppm, respectively.

d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5°C.

Figure 2.17. Projected temperature change and global sea level rise by 2100 from IPCC (2007).

The IPCC is careful to caveat these results and explain their limitations. The results do not contain full effects of ice sheet flow because published peer reviewed literature was not available at the time of the report. Thus, the upper values for each scenario are not necessarily the upper bounds for potential sea level rise. A significant amount of research to determine rates of sheet flow that would increase the ocean volume is ongoing, and the next IPCC report could be expected to have new rates that explicitly include such effects. In the mean time, researchers have published their individual estimates of sea level rise that include increased contribution from melting of the land-based ice masses. For instance, Rahmstorf (2007) used results from the IPCC 2007, as well as increased rates of melting of the ice sheets in Greenland and Antarctica, to show their effect in comparison to the published IPCC results (figure 2.18). Upper bounds scenarios for sea level rise by 2100 are over 1 m.

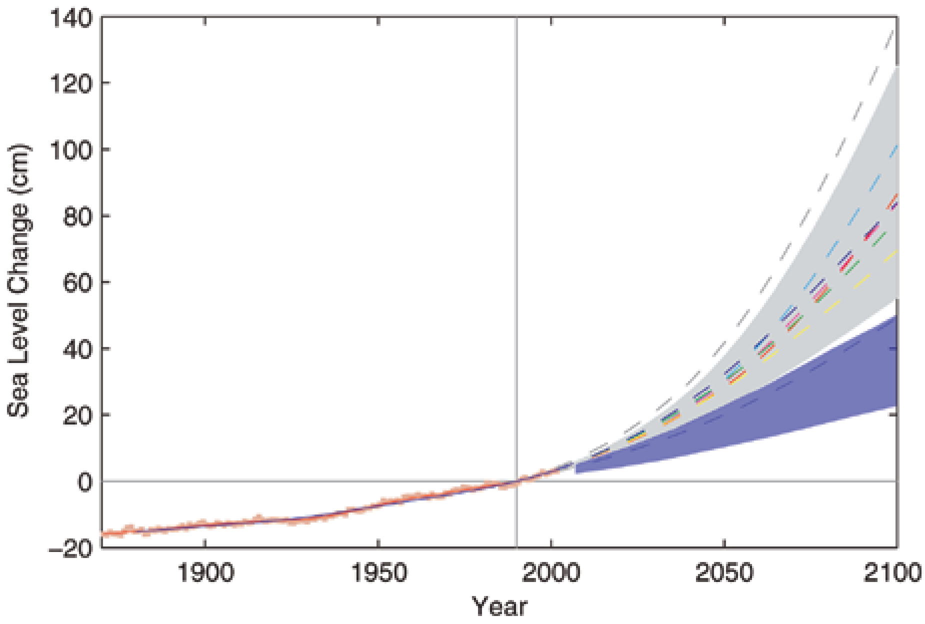


Figure 2.18. Composite of sea level rise scenarios from IPCC 2007 and Rahmstorf (2007). Blue curve is the A1B scenario from IPCC 2007, and the grey curve is from Rahmstorf after including accelerated ice flow (Williams et al. 2009).

Also important to note is that IPCC (2007) did not include graphics of sea level rise showing exponential curves of sea level rise until 2100. They simply provide values at 2100 with no values implied or inferred before that time. The report did indicate that the climate models, not the time resolution of the impacts, allowed for inferring such a curve. There is no scientific basis for inferring an exponential function with the curvatures shown. Figure 2.19 uses curves for graphical comparison and visual understanding to make a point. Users should interpolate values with caution and allow for uncertainty. The U.S. Army Corps of Engineers (USACE, 2009) issued an interim guidance document for incorporating projected sea level change into engineering planning and design. That document uses sea level rise scenario curves established in a National Research Council (NRC) report several years ago (NRC 1987) as a best estimate for practical application to their requirements for planning and design.

2.5.2 Integration of Projections and Scenarios

The USACE guidance document (previously referenced) uses the present local rate of sea level change from the tide station network as an initialization point to estimate future sea level rise using the formulas describing each curve. USACE uses a curve equation modified from NRC (1987) to account for a more recent estimate of global sea level rise, even with the caveats described earlier, because most coastal engineering project lifetimes are 50 years in length, and interim information is required prior to 2100, which is all that IPCC (2007) provides. Figure 2.19 compares the NRC modified curves to two of the IPCC 2007 scenarios. The modified NRC-III curve approximates the updated curves suggested by Rahmstorf (2007) in figure 2.18 and the text in USACE (2009) describing the equations is excerpted as follows:

Using the current estimate of 1.7 mm/year for global mean sea level change as presented by the IPCC (IPCC 2007) results in this USACE modified equation:

$$E(t) = 0.0017t + bt^2 \quad (2)$$

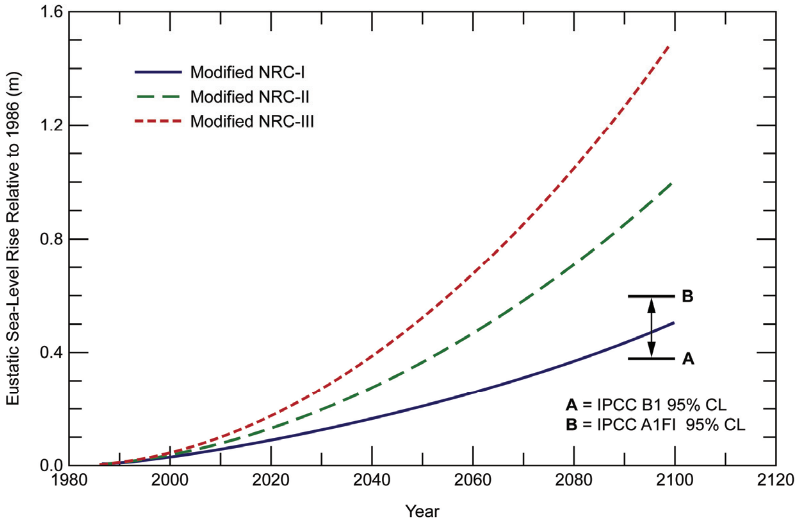


Figure 2.19. Taken from USACE (2009) comparing the modified NRC (1987) curves compared to the IPCC (2007) model results.

The three scenarios proposed by the NRC result in global (eustatic) sea level rise values of 0.5 m, 1.0 m, and 1.5 m by the year 2100. Adjusting the equation to include the historic global mean sea level change rate of 1.7 mm/yr updates the values for the variable *b* being equal to 2.36E-5 for modified NRC Curve I, 6.20E-5 for modified NRC Curve II, and 1.005E-4 for modified NRC Curve III.

Another method, but just as arbitrary, is to construct discrete rates of sea level rise for different periods as opposed to a smoothly varying function, as shown in figure 2.20 (Gill, 2010).

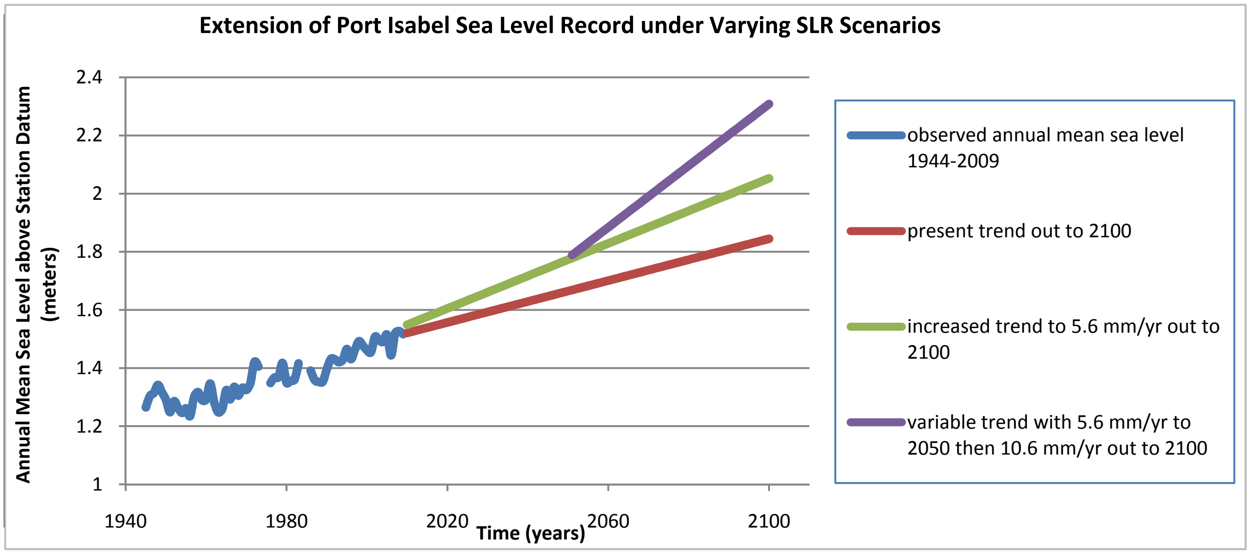


Figure 2.20. Extension of present relative sea level trends using various accelerated global sea level rates of rise.

For many applications, the time dimension may not be required. In these instances, a value of projected sea level rise is used to demonstrate a particular effect, such as an inundation map. This value could help to answer questions of potential risk, for instance, “Will my sewage treatment plant infrastructure become inundated if there is a 0.5 m sea level rise?”

Notably, all of the climate models project global sea level to rise over the next century, with some projections with very high increases of over 1.0 m. There is a considerable amount of recent research examining historical tide gauge records for evidence of acceleration in sea level rise and in reconciling the altimeter trends with global trends determined from tide gauges. This has proven difficult because water level records from tide gauges capture variability from many different types and geographic scales of physical oceanographic and meteorological forcing with a wide variety of overlapping time dimensions (Church and White 2006). For local application, assumptions on the local and regional rates of vertical land movement need to be made. Typically, regional land motion rates change slowly and can be assumed to be linear over century time scales; however, the local rates may change significantly over time if due to local ground water or oil withdrawal or after major earthquakes..

Long-term tide gauge records have been used over the last few decades to estimate rates of 20th century sea level rise, primarily based on the historical tide gauge data (Douglas 2001). Tide gauges measure the height of the sea surface relative to coastal land-based bench marks. However, these measurements include a signal from large spatial-scale secular trends in glacial isostatic adjustment (GIA) and possibly also regional and local tectonic motions. To estimate the change in eustatic sea level (i.e., changes in the volume of the ocean), the tide gauge records must be corrected for ongoing GIA and tectonic motions. This correction uses geological data to infer long-term motions or geophysical models to estimate the GIA. Selected tide gauges with the best long-term records located on fairly stable landforms are used. The global distribution of these records is significantly biased toward the northern hemisphere, however. Once adjusted for vertical land motion, the residual trends are compiled to produce a composite estimate of global sea level rise. Rates using this methodology are approximately 1.8 mm/yr for the twentieth century.

Snay et al. (2009) uses local rates of local vertical land motion as estimated from Continuously Operating Reference Stations (CORS), which is a nationwide network of GPS stations. Using CORS located near tide stations, the report cites a composite trend of approximately 1.8 mm/yr as well. The CORS data suffer from relatively short record lengths (less than 10 years for most), as the GPS technology is relatively new.

2.6 Relevance of Geospatial Data to Sea Level Applications

Geospatial data are especially relevant to sea level applications for describing impacts of sea level rise in a visual and practical sense. The time series plots of variations in sea level from tide gauges and altimeter systems provide valuable information but do not immediately provide the “so what.” The examples shown in previous sections of the CCSP4.1 report attempt to explain this “so what.” Amounts and impacts of sea level change need to be put in terms that the users can understand and put into the context of their "language." Thus, for the USACE, as described earlier, sea level projection curves were developed with a mathematical description for practical application to engineering planning life cycles. CCSP4.1 attempts to provide information on potential risk to the population and the economy. Maps with sea level scenarios and visualizations are among the most effective ways to communicate risk. However, having the best possible baseline and source data and having accurate geospatial information to show their distribution are extremely important. Having an inaccurate depiction for the sake of an attention-getting show is dangerous and bad science. Realistic geospatial depictions can still be attention-getting, along with a clear statement of the uncertainty bounds and caveats of the material.

In particular, the geospatial information of the following parameters could be required for many sea level applications:

- Water level data and datum elevations, water level extremes, and derived sea level trends
- Geodetic data, geoid, ellipsoid, orthometric elevations, gravity, topography
- Vertical land motion, subsidence, uplift
- Other geophysical data, such as hydrology and river flow/stage
- Coastal water temperature and density
- Coastal meteorological data
- Bathymetry

In addition to fundamental point sources of this information listed above, gridded geospatial data fields are extremely useful but typically require modeling of the parameters, as is explained for transformation tools such as VDatum.

References Cited:

Church, J.A. and N.J. White, 2006: A 20th Century acceleration in global sea level rise. *Geophysical Research Letters*, 33(1), L01602, doi:10.1029/2005GL024826.

DOT, 2008: The potential impacts of global sea level rise on transportation infrastructure, Part1: Methodology, U.S. DOT Center for Climate Change and Environmental Forecasting, accessed 8/2010 at: http://climate.dot.gov/impacts-adaptations/sea_level_rise.html.

EPA, 2009: Chapter 1. Coastal Elevations in the Mid-Atlantic. In: *Background documents supporting Climate Change Science Program Synthesis and Assessment Product 4.1*, J.G, Titus and E.M. Strange, eds., U.S. Environmental Protection Agency, FPA 430-R-07-004.

Gesch, D.B., B.T. Guiterezz, and S.K.Gill, 2009: Coastal Elevations. In: *Coastal Sensitivity to Sea level Rise: A Focus on the Mid-Atlantic Region.* A report by the U.S. Climate Change Science Program, and the Subcommittee on Global Change Research, U.S. Environmental Protection Agency, Washington, DC, pp25-42.

Gill. S.K., 2010: Sea level measurement, determination, and application in the Gulf of Mexico, presentation at the Sea Level Rise 2010 Conference, Corpus Christi, TX, March 1-3, 2010.

Gill, S.K., et al. 2009: Population, land use, and Infrastructure. In: *Coastal Sensitivity to Sea level Rise: A Focus on the Mid-Atlantic Region.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Environmental Protection Agency, Washington DC, pp105-116.

Holgate, S.J. and P.L. Woodworth, 2004: Evidence for enhanced sea level rise during the 1990's. *Geophysical Research Letters,* 31, L07305, doi:10.1029/2004GL019626.

IPCC, 2007: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge U.K. and New York, 996pp.

Leuliette, E. W., R.S. Nerem, and G.T. Mitchum, 2004: Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Marine Geodesy,*27(1-2), 79-94.

Meehl, G.A. *et al*, 2007: Global climate projections. In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K. and New York, pp. 747-845.

NOAA, 2003: Computational Techniques for Tidal Datums Handbook, NOAA Special Publication NOS CO-OPS 2, NOAA National Ocean Service, Center for Operational Oceanographic Products and Services, 90pp.

NOAA, 2001: Tidal Datums and Their Applications, NOAA Special Publication NOS CO-OPS 1, S.K. Gill and J.R. Schultz, eds. NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 111pp.

NRC, 1987: Responding to Changes in Sea Level, Engineering Implications. Committee on Engineering Implications of Changes in Mean Sea Level, marine Board, Commission on Engineering and technical Systems, National Research Council. National Academy Press, Washington, D.C. 1987.

Parker, B.P., 1991: Sea level as an indicator of climate and global change. *Marine Technology Society Journal*, Vol. 25, No. 4.

Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea level rise. *Science,* 315(5810), 368-370.

Thieler, E.R. et al, 2009: National Assessment of Coastal Vulnerability to Sea level Rise. Fact sheet accessed at: http://woodshole.er.usgs.gov/project-pages/cvi/ in August 2010. USGS Woods Hole Field Center, MA.

USACE, 2009: Water Resource Policies and Authorities, Incorporating Sea level Change Considerations in Civil Works Programs, EC 1165-2-211, Expires July 2011, CECW-CE Circular No. 1165-2-211, Department of the Army, U.S. Army Corps of Engineers, Washington, DC, 1 July 2009.

Williams et al. 2009: Sea level rise and its effects on the coast. In: *Coastal Sensitivity to Sea level Rise: A Focus on the Mid-Atlantic Region.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Environmental protection Agency, Washington, DC, pp 25-42.

Zervas, C., 2009: Sea Level Variations of the United States 1854-2006, NOAA Technical Report NOS CO-OPS 053, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 78pp.

Chapter 3.0 Existing Data and Access

As outlined in chapters 1 and 2, sea level change (SLC) mapping and assessment projects rely on a wide variety of datasets that reflect existing physical conditions, as well as projections of future conditions and impacts. This chapter focuses on geospatial data needed to accurately determine SLC impacts, including references to existing data sources and further technical guidance.

3.1 Important Types of Geospatial Data Used for Sea Level Change Mapping and Assessment Projects

The primary datasets needed to accurately map and assess the impacts of SLC can be broadly grouped into the following types (summarized from NRC 2009):

Base Surface Elevation

Two types of base surfaces are important to sea level change projects: land surface elevation (topography) and its underwater equivalent (bathymetry). Topography is expressed as the height of a location above the geodetic datum and is in most cases a positive value. Bathymetry is expressed as the depth of the land surface below rivers, lakes, and oceans; positive depth implies negative elevation. Subsequent sections in this chapter provide more detail on the different types of topographic and bathymetric data (including shorelines), as well as where to access them.

Water Surface Elevation

SLC projects are concerned with examining the impacts of differing water levels on the base surface. Therefore, the final primary data type needed is information about water bodies, particularly the location of the air/water boundary surface relative to the base surface elevations. At a coastal tide gauge, this data type is “sea level” for mapping and assessment purposes. The height of water surfaces is measured with stream and tide gauges. The location and elevation of the gauges themselves must be determined accurately to correctly relate water surface measurements to other elevations. Later sections provide more detail on accurately measuring water surface heights.

Elevation Reference

Before elevation can be measured or the data used in engineering analysis, a measurement system must be established. The location of “zero” elevation (in other words, a vertical datum) and a method of measuring heights relative to that zero elevation must be established on the Earth, where it can be used for all types of height measurements. Chapter 2.2.1 describes the three different types of vertical datums in use, while this chapter (section 3.1.3) explains the types of data that contribute to establishing and monitoring these datums. More information on how to select an appropriate reference frame for SLC projects is available in chapter 6.4.

While not a stand-alone dataset, metadata are vital to ensuring the accuracy and utility of SLC mapping and assessment products. A key way to locate and discover the origin and quality of a particular dataset is to refer to its metadata—that is, data about the data. Metadata should be regarded as a critical component of any dataset. Generally, metadata contains the dataset's definition, structure, and administration of data files, with all contents provided in context to facilitate data use and archive. For geospatial datasets, metadata should contain information sufficient to answer the following questions:

- Who created the data?
- Who maintains it?
- When were the data collected? When were they published?
- Where is the geographic location?
- What is the content of the data? The structure?
- Why were the data created?
- How were they produced (data acquisition and processing methodologies)?
- Where are the data stored?
- What are the vertical and horizontal datums/reference systems?
- How are accuracy, precision, and uncertainty (total propagated error for vertical and horizontal) defined?

Before investing significant time and effort in obtaining or applying dataset that pertains to SLC, users should critically review the metadata. If metadata are incomplete or absent, or there is no readily apparent way to collect the missing information from the data originator(s), users may reconsider use of that dataset or qualify their project results accordingly.

3.1.1 Base Surface Elevation: Topographic Data and How Shorelines Are Related To Topographic Datasets

Topography is defined as the general shape or form of the land surface, determined by analyzing the elevation of the land. Topography specifically involves recording the relief or terrain, which is the three-dimensional quality of the surface, and identifying specific landforms. This involves generation of elevation data in electronic form, including graphic representation of landforms on a map by a variety of techniques, including contour lines and relief shading.

Topography is a crucial dataset for determining the impacts of sea level change because the shape of the physical landscape influences the direction that water flows over it, where it accumulates, and how and where it drains. The accuracy with which coastal topography has been mapped directly affects the reliability and usefulness of SLC impact assessments (CCSP 2009), and is the most important factor in determining accuracy of flood maps (NRC 2009). In coastal areas characterized by flat topography, small changes in sea level cause greater changes in the extent of areas inundated by sea level rise or exposed by sea level fall.

As the boundary between water and dry land, shorelines are an important component of SLC projects. Changes in shoreline position are, in large measure, driven by changes in water levels (see section 3.1.3 for further explanation), and shoreline movement is one of the effects of SLC that is most readily understandable and easy to communicate to a wide range of audiences. Because delineation of shorelines is often done through analysis of elevation data (topographic or bathymetric, sometimes both), information about shorelines is provided in the context of topographic data throughout this document.

Topographic Data Types

Topographic data are available in several different forms (raw points, rasters, triangular irregular networks, contours, regularly gridded digital elevation models) and can be collected using different sensors and methods. Among the more common sources of topographic data are:

Land Survey (captures centimeter-scale elevation changes)

Land surveying is the technique and science of accurately determining the terrestrial or three-dimensional position of points and the distances and angles between them. These points are usually on the surface of the Earth, and they are often used to establish land maps and boundaries for ownership or governmental purposes. Land surveying involves using traditional surveying equipment such as levels and theodolites. More recent instruments include total stations that combine leveling, ranging, and angle measurement. Today, most survey-grade equipment uses Global Positioning System (GPS) data in a kinematic differential mode to obtain relative ellipsoidal or orthometric heights precise to 30 mm-40 mm (root mean square error or RMSE), in areas of a few tens of kilometers in radius. GPS is the most accurate way to obtain heights but can only be done one point at a time, which is very labor intensive and costly.

Aerial Image (Photogrammetry) (10 cm)

Stereo aerial imagery is and has commonly been used to derive elevations for use in generating digital elevation models (chapter 5.3). The technique provides accurate information and is used extensively in highway and road projects. However, it is less cost effective when working on larger areas, and its accuracy suffers in areas of dense vegetation. This method can yield elevations with vertical accuracy on the order of 10 cm (RMSE).

Topographic Lidar (10 cm)

Lidar (light detection and ranging) is an active sensor, similar to radar, which transmits laser pulses to a target and records the time it takes for the pulse to return to the sensor receiver. This technology is currently being used for high-resolution topographic mapping by mounting a lidar sensor, integrated with GPS and inertial measurement unit (IMU) technology, to the bottom of aircraft and measuring the pulse return rate to determine surface elevations. Lidar yields vertical accuracy of 10 cm (RMSE).

IfSAR (1 m)

Interferometric Synthetic Aperture Radar (IfSAR or InSAR) is an aircraft or satellite-mounted sensor designed to measure surface elevation, though its primary strength is in measuring elevation *change*. IFSAR derives a surface height by correlating two coherent radar images, which are acquired by two antennae separated by a known distance. The radar images are derived from electromagnetic energy returned to each antenna from the first surface it encounters. An interferogram that represents the phase difference of the corresponding pixels of the two radar images is generated. The height of the pixel is calculated from this phase difference and the airborne navigation information. IfSAR generally only yields 1m (RMSE) vertical accuracy, though it can detect elevation change on the order of millimeters (see http://www.csc.noaa.gov/digitalcoast/data/coastalifsar/index.html).

National Elevation Dataset (NED) (varying accuracy based on geography)

A derived topographic dataset that is nationally available is the USGS National Elevation Dataset (NED) (http://ned.usgs.gov/) has been developed by merging the highest-resolution, best quality elevation data available across the U.S. into a seamless raster format. NED has a consistent projection (geographic) and elevation units (meters). Nationwide coverage is available for data at a 1 arc-second (30-meter [m]) post spacing; there also is substantial coverage at 1/3 arc-second (10-m) post spacing. The horizontal datum is NAD83, except for AK, which is NAD27. The vertical datum is NAVD 88, except for AK, which is NAVD29. NED is a living dataset updated bimonthly to incorporate the “best available” DEM data. As more 1/9 arc-second (3 m) post spacing data covering the U.S. is available, it will be added to the seamless dataset.

Shoreline Data

As stated earlier, a shoreline can most simply be defined as a linear boundary that marks the transition from water to dry land. In practice, given the variety of datums in use (chapter 2.2) and the data sources and delineation methods available, identifying and using shorelines in SLC mapping and assessment projects require careful work.

The National Shoreline

NOAA’s National Geodetic Survey (NGS) sustains a Coastal Mapping Program with the goal of providing the National Shoreline for the U.S. and its territories (http://shoreline.noaa.gov/). NGS and its predecessors have conducted shoreline mapping activities since the original “Survey of the Coast” in 1807 (Shalowitz 1964), and the shoreline depicted on National Ocean Service (NOS) nautical charts is treated as the legal shoreline by many U.S. agencies (Graham et al. 2003). In addition to its primary use on nautical charts to assist in safe navigation, the National Shoreline also serves numerous other purposes, ranging from determination of legal boundaries to coastal management and environmental applications, such as climate change studies (Morton et al. 2004; Scavia et al. 2002; Titus and Richman 2001).

Universally-accepted methodologies and definitions for a standard shoreline do not currently exist. Indeed, numerous indicators or proxies for shoreline position have been used in shoreline mapping and described in the literature, including: vegetation lines; dune lines; dune toes; bluff or cliff lines; beach scarps; berm crests; the high water line (HWL), interpreted as the wet/dry line from the last high tide; coastal structures, such as seawalls or bulkheads; in addition to datum-based shorelines (e.g., Boak and Turner 2005; Crowell et al. 1991; Leatherman 2003; Moore 2000; Moore et al. 2006; Morton 1991; Morton and Speed 1998; Pajak and Leatherman 2002).

Historically, the shoreline depicted on NOS topographic sheets (T-Sheets) was an interpreted HWL (Boak and Turner 2005; NRC 2004; Moore et al. 2006). After the 1930s, the component of the U.S. Coast and Geodetic Survey that later became the NOS/NGS Remote Sensing Division adopted procedures for shoreline mapping from tide-coordinated aerial photography (Smith 1981). The current procedures are designed to produce lines representing the intersection of the land (at the specific time of data acquisition) and the water surfaces of the mean high water (MHW) and mean lower low water (MLLW) tidal datums (NRC 2004). These procedures entail compiling the land/water interface in stereo photography flown within a time window calculated from the predicted or observed (via water level stations) time of MHW or MLLW plus or minus a specified vertical tolerance, which is a function of the tidal range (Graham et al. 2003). However, consideration must also be given to the effects of the vertical profile of the beach or shoreline, which will impact the horizontal shoreline accuracy.

While the photogrammetric procedures remain NGS' primary methodology for mapping the National Shoreline, over the course of the past decade NGS has worked with numerous partners to develop, test, and refine new airborne light detection and ranging (lidar) shoreline mapping procedures. One of the main benefits of using lidar is that the tide-coordination requirements are not as intensive during survey as with the photogrammetric procedure; it is typically only necessary to acquire the data below a certain stage of the tide, rather than within a very narrow tide window. Thus, the efficiency of data acquisition is increased greatly. Furthermore, the lidar-based procedures assist in eliminating some of the subjectivity associated with the manual photogrammetric compilation methods and providing multi-use data that can benefit other coastal projects and programs (Scott et al. 2009; White 2007). It should be noted that lidar still requires tide control; however, with advanced acquisition of water level data and the development of an ellipsoid to tidal datum transformation (such as VDatum) prior to lidar survey, the tide requirements are often addressed prior to survey data collection.

Other Shoreline Sources

While the National Shoreline serves as a nationally consistent dataset that is used for a variety of applications, anyone with access to the necessary computing technology (e.g., Geographic Information System [GIS] software) and suitable source data (e.g., high-resolution topographic and bathymetric data, aerial imagery, GPS-aided surveying data) can "map" a shoreline. The graphic in figure 3.1 shows one such example. Shorelines may be made publicly available by a wide range of sources, such as academic/research institutions, government agencies, or private consultants. When considering such data for use in an SLC mapping project, it is vitally important to obtain the accompanying metadata. The metadata provides information on how the shoreline was developed, by whom, when, and most importantly, what elevation the line represents (e.g., HWL).

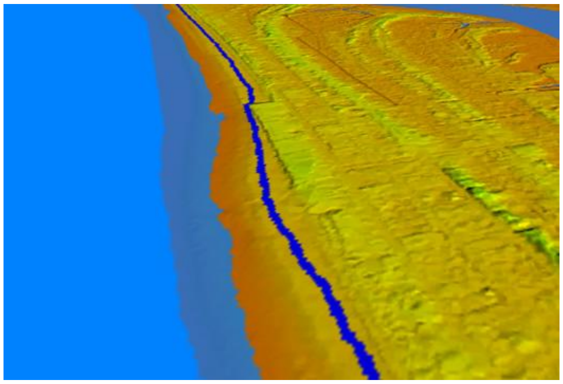


Figure 3.1. This image shows high-resolution lidar data with an extracted shoreline in blue. As opposed to aerial photography, where a shoreline would be derived based on visual identity of a feature (such as the wet/dry line), lidar data provides the advantage of deriving a true datum-based shoreline (such as the mean high water line or specific elevation contours). Note: To derive a true-datum-based line, accurate, consistent geospatial determinations of ellipsoid to reference datums must be derived across the extents of the survey.

3.1.2 Base Surface Elevation: Bathymetric Data

Bathymetry is the general configuration of the seafloor represented by depth data, or the underwater equivalent of topographic data. Nautical charts from hydrographic surveys support safety of surface or subsurface navigation and usually show seafloor relief or terrain as contour lines (called depth contours or isobaths) and selected depths (soundings), and also provide surface navigational information. Bathymetric maps (a more general term where navigational safety is not necessarily a concern) may also use a Digital Terrain Model (DTM) and artificial illumination techniques to illustrate the depths being portrayed.

Bathymetric data are crucial in determining SLC impacts for several reasons. First, the shape and depth of the seafloor influence how water moves onto the topographic surface. For example, coastal areas with a flatter, shallower continental shelf experience higher tidal ranges due to SLC. Coastal areas with concave shorelines and shallow bathymetry are more vulnerable to higher storm surges as well; with SLC, the areas vulnerable to high surges may change over time. Bathymetry also directly influences wave patterns, which can cause increased wave energy on certain portions of the coast, leading to enhanced coastal erosion. Last, bathymetric data are needed to examine the effects of dropping water levels. For example, if sea level falls (as is expected for the Great Lakes), bathymetric information is needed to identify the future location and configuration of the shoreline.

Common bathymetric data types include the following:

Lead Line Surveying
Early techniques used pre-measured heavy rope or cable lowered over a ship's side. The greatest limitation of this technique is that it measures the depth only a single point at a time, and so is

inefficient. It is also subject to movements of the ship and currents moving the line out of true plumb and therefore is inaccurate.

Sound Navigation and Ranging (SONAR)

The data used to make bathymetric maps today typically come from an echosounder (sonar) mounted beneath or over the side of a boat, "pinging" a beam of sound downward at the seafloor or from remote sensing lidar or Laser Detection and Ranging (ladar) systems. The amount of time it takes for the sound or light to travel through the water, bounce off the seafloor, and return to the sounder is what the equipment uses to calculate the distance to the seafloor.

> ***Single-Beam SONAR*** collects discrete points along track lines. The data coverage is sparse and requires a greater degree of interpolation between transects. Since the early 1930s and more commonly from the 1940s onward, the occasional pings of a single-beam sounder might be averaged to create a map.
>
> ***Multibeam SONAR*** collects continuous point data throughout survey area. The data coverage is greater than single-beam and has higher resolution. The coverage is limited in shallow waters. Multi-beam collection features hundreds of narrow adjacent beams arranged in a fan-like swath of perhaps 90 degrees to 170 degrees across. The tightly packed array of narrow individual beams provides high angular resolution and accuracy. The wide swath, which is depth dependent, generally allows a boat to map more seafloor in less time than a single-beam echosounder by making fewer passes.

A number of different outputs are currently generated, including a subset of the original measurements that satisfy some conditions (e.g., most representative likely soundings, shallowest in a region, etc.) or integrated DTMs (e.g., a regular or irregular grid of points connected into a surface). Historically, selection of measurements was more common in hydrographic applications, while DTM construction was used for engineering surveys, geology, flow modeling, etc. Since 2003-2005, DTMs have become more accepted in hydrographic practice.

Bathymetric Lidar

Bathymetric lidar systems operate in a manner similar to their topographic lidar counterpart, with one notable exception. Bathymetric systems transmit two light waves, one in the infrared and one in the green spectrum, and are capable of detecting two returns that delineate the water surface and seabed. The infrared band is quickly absorbed and is therefore used to detect the water surface, while the green band is used as the optimum light frequency to achieve maximum penetration in shallow water. Lidar bathymetry systems operate at a much slower rate, currently around 1000 soundings per second, due to the requirements for a much longer laser pulse and higher power. Bathymetric lidar mapping can be conducted in clear water in depths up to 50 m. This is a function of water clarity, and performance will decrease with increased water turbidity.

Satellite Altimetry

Satellites are also used to measure deep-sea bathymetry. Satellite radar data are used to model deep-sea topography of the ocean bottom by detecting the subtle variations in sea level caused by the gravitational pull of undersea mountains, ridges, and other masses, and inferring the size and location of these features. Sea level is generally higher over sea mounts and ridges than abyssal plains and trenches.

Users obtaining historical nautical chart products must not only be aware of the various technologies used to obtain bathymetric soundings, but must also be aware of the various reference datum changes over time. For instance, as noted in previous sections, tidal datum NTDE periods are updated over time to account for sea level change, and soundings taken during one period may have a different NTDE reference than later soundings. In addition, formal datum changes have taken place, for instance the change from mean low water (MLW) to mean lower low water (MLLW) back for the East Coast in the 1980s. Thus, depending upon the accuracy desired, users cannot assume the depths from a particular nautical chart were taken at the same time using the same technologies and reference datum.

3.1.3 Water Surface Elevation

Measurement of Water Levels and Determination of Sea Level Trends

Water level measurements for most coastal applications are made at a water level station. They are typically called tide stations when located in an area in which the tide dominates the daily rise and fall of the water level and simply called water level stations when located in non-tidal areas such as the Great Lakes.

For application to climate studies and research, especially in estimating relative mean sea level trends, long-term continuous measurements are required. The networks should have characteristics of a true “end-to-end” system that includes data collection through data delivery to and application by the user community. To ensure this application, NOAA long-term water level networks have been configured to ensure long-term sustained measurements.

Water level stations consist of a water level sensor(s), any required ancillary sensors (i.e., water density to correct pressure sensor data), a data collection platform (DCP), a data transmission system (satellite radio, line-of-sight radio, telephone, internal recording device), and a network of local reference points (bench marks) surveyed into the water level sensor (leveled in). Backup sensors and DCPs are also used. NOAA water level stations collect and distribute 6-minute interval water level elevations relative to documented reference zeros (arbitrary station datum) or datum elevations (such as MLLW or NAVD 88) (NOAA 2001). NOAA water level stations also have geodetic datum connection to geodetic reference systems using either direct leveling to geodetic marks or static GPS surveys.

Starting in the early 1990s, the Next Generation Water Level Measurement System replaced the older technology systems that largely went unchanged since the mid-1800s (http://celebrating200years.noaa.gov/transformations/tides/welcome.html#is). Water level measurement sensor systems were changed from the float/wire stilling well systems to newly-engineered air acoustic and pressure systems that reduced known error sources of the old systems. The new system configuration underwent extensive laboratory and field testing prior to implementation and side-by-side operation with the old systems prior to their independent operation. This testing ensured continuity of the long-term tidal record. The new water level sensors are directly leveled to local survey marks, so local observers are no longer needed to manually observe and record independent tide staff readings for controlling the automatic tide gauge. The new systems contain an electronic data acquisition system. Instead of paper tape, the data are now stored in computer memory chips. These systems were designed to operate unattended for a full year without requiring maintenance. Additionally, the systems collect a wide variety of environmental measurements, such as wind speed, air /water temperature, barometric pressure, and conductivity. Figure 3.2 shows a schematic of a NGWLMS station.

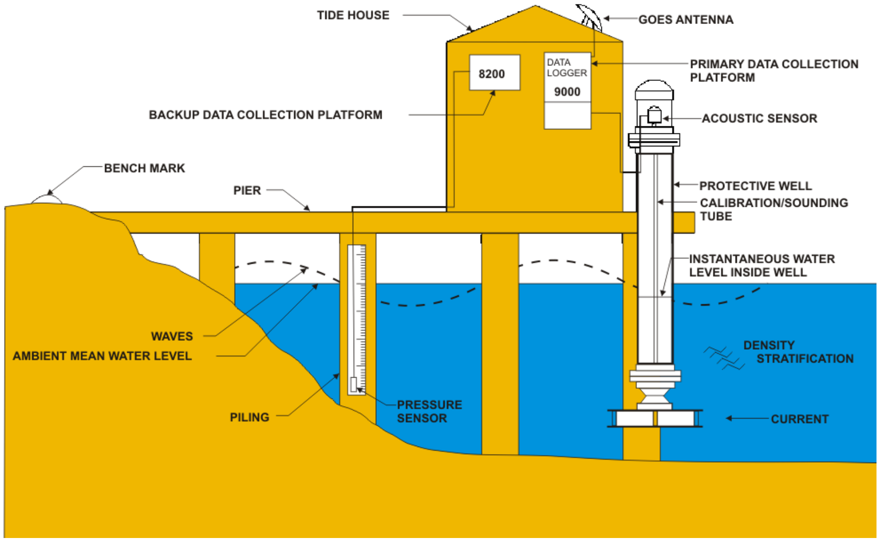


Figure 3.2. Schematic of a modern water level station

Another major advancement with this system is the method for sending water level data to NOAA headquarters for processing. Instead of mailing a data tape once a month, data are transmitted over the Geostationary Operational Environmental Satellite (GOES) system every 6 minutes. Headquarters automatically receives the satellite transmissions just minutes after it is transmitted from the gauge. Data quality control and processing are automated, eliminating the manually intensive and time-consuming review of strip charts and the punch paper tapes that required conversion to digital format.

For information on how other countries measure sea level, the Intergovernmental Oceanographic Commission (IOC) Manual on Sea Level Measurement and Interpretation (IOC 2006) reviews several different types of water level sensors and their configurations, including the new technology radar gauges and GPS buoy technology, in a series of manuals and discusses the requirements of long-term sustained measurements of sea level. Figure 3.3 shows new NOAA tide station installations in the Gulf of Mexico, specifically hardened and configured to withstand storm surges and high winds during storm events, thus ensuring long-term sustained operation without major gaps in data. These stations contain backup sensors and data collection modes, local networks of bench marks that are leveled to every year, and have ongoing sensor calibration checks and active continuous data quality control.

Calcasieu Pass, LA **Corpus Christi, TX**

Figure 3.3. NOAA tide station installations at (left) Calcasieu Pass, LA and (right) Corpus Christi, TX hardened to withstand major storm surge for continuous long-term operation.

Use of Water-Level Measurements to Determine Relative Sea Level Trends

Relative sea level trends are computed from carefully compiled observations at long-term tide stations. Monthly mean sea level values are computed from the observed hourly heights over each calendar month. Time series of monthly mean sea levels are created, quality controlled, and referenced to a documented reference datum for the entire time series.

The monthly data can also be used to obtain the average seasonal cycle for each station represented as 12 mean values. The residual time series after the trend has been removed contains valuable information about the correlation of the interannual variability between stations, which is better defined by a monthly residual series than by an annual residual series. Trends derived from monthly mean sea level (MSL) data also have smaller standard errors as was shown in Zervas (2009). The NOAA sea level trends are computed using the methodology found in section 3.2.3 on derivation of MSL trends found in Zervas (2009). The least squares solution incorporates knowledge of the average seasonal cycle.

A simple least squares linear regression gives an accurate MSL trend but can substantially underestimate the standard error or uncertainty of that trend. The reason is that, for sea level data, the residual time series is serially auto-correlated even after the average seasonal cycle is removed. Each month is partially correlated with the value of the previous month and the value of the following month. There are actually fewer independent points contributing to the standard error of a linear regression, which assumes a series of independent data. Therefore, following Zervas (2009), the monthly MSL data are characterized as an auto-regressive process of order 1. This is the recommended treatment for computing relative sea level trends from long-term monthly mean sea level data form tide gauge observations.

Each calculated linear trend has an associated 95% confidence interval that is primarily dependent on the year range of data for each station. A derived inverse power relationship indicates that 50-60 years of data are required to obtain a trend with a 95% confidence interval of ±0.5 mm/yr. This dependence on record length is caused by the interannual variability in the observations.

Figure 3.4, the calculated trend for San Diego California, shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend is also shown, including its 95% confidence interval. The plotted values are relative to the most recent NTDE mean sea level (1983-2001).

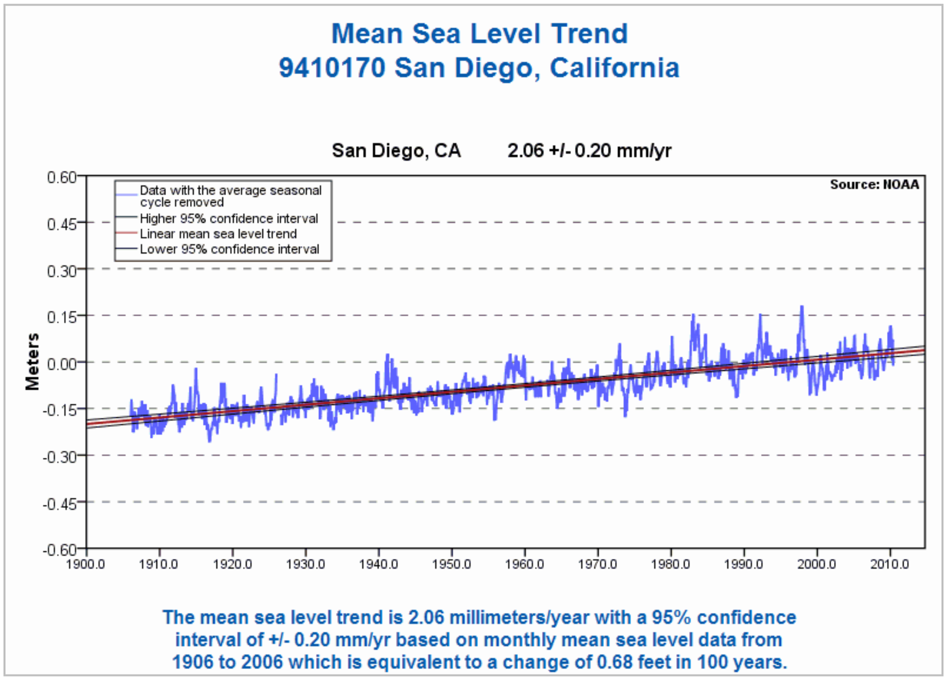
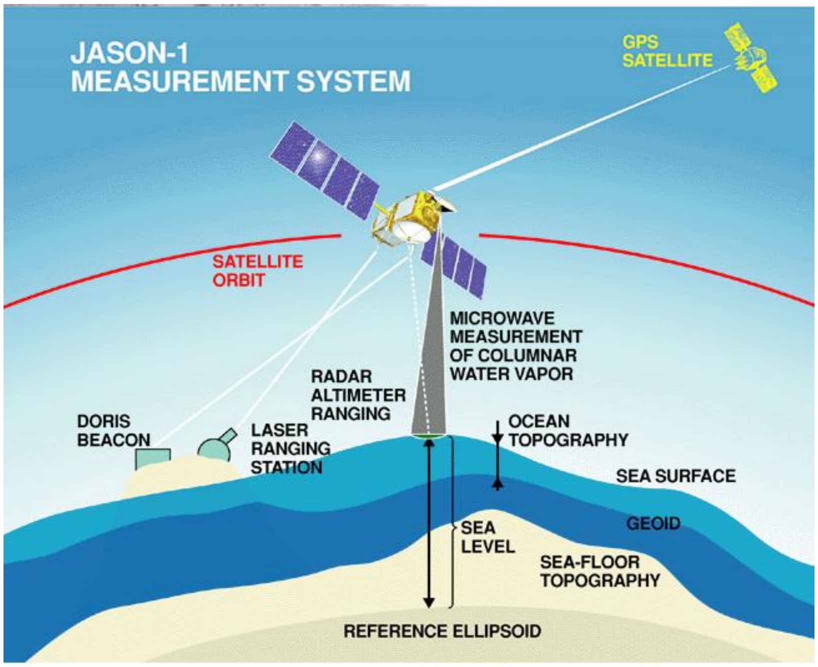


Figure 3.4. The relative mean sea level trend for San Diego, CA

Use of Satellite Data to Determine Sea Level Trends

Whereas tide stations provide point coverage of relative sea level variability over long time periods, they must be combined in a global network mode with appropriate corrections for vertical land motion in order to generate spatial estimates of global sea level variations (Douglas 2001). Satellite altimetry provides significant spatial coverage of the world's oceans due to the satellite orbital confirmations and repeat cycles. Continuous coverage of the oceans in the latitude band ±66 degrees has been in place since the launch of the *TOPEX/Poseidon* mission in late 1992, using overlapping missions with the Jason series of altimeter missions. For climate applications, the overriding drawback is the relatively short duration of the continuous, uninterrupted altimeter record (17 years), which is much shorter than the tide gauge records that go back a century or more and the record length is somewhat close to known major decadal cycles such as ENSO, thus making it difficult to estimate long-term global trends in sea level.

As shown in figure 3.5, satellite altimeters basically determine the distance from the satellite to a target surface by measuring the satellite-to-surface round-trip time of a radar pulse. The satellite orbits must be accurately tracked and the satellite position is determined relative to an arbitrary reference surface, an ellipsoid. The sea surface height is the range from the sea surface to a reference ellipsoid. The magnitude and shape of the echoes (or waveforms) also contain information about the characteristics of the surface that caused the reflection. The best results are obtained over the ocean, which is spatially homogeneous and has a surface that conforms to known statistics. Surfaces that are not homogeneous, which contain discontinuities or significant slopes, such as some ice, rivers or land surfaces, make accurate interpretation more difficult. The *TOPEX/Poseidon* and *Jason* altimeters used 10-day repeat cycles, thus giving time series measurements at every point along a track. Figure 3.6 shows the ground track coverage of the *Jason-1* altimeter. Note that the coverage does not extend to the polar oceans (although other altimeter missions, particularly, *ERS-1* and *ERS-2* did extend into those regions).



(Photo courtesy of CNES-website, http://www-aviso.cnes.fr)

Figure 3.5. Schematic of a satellite altimeter configuration.

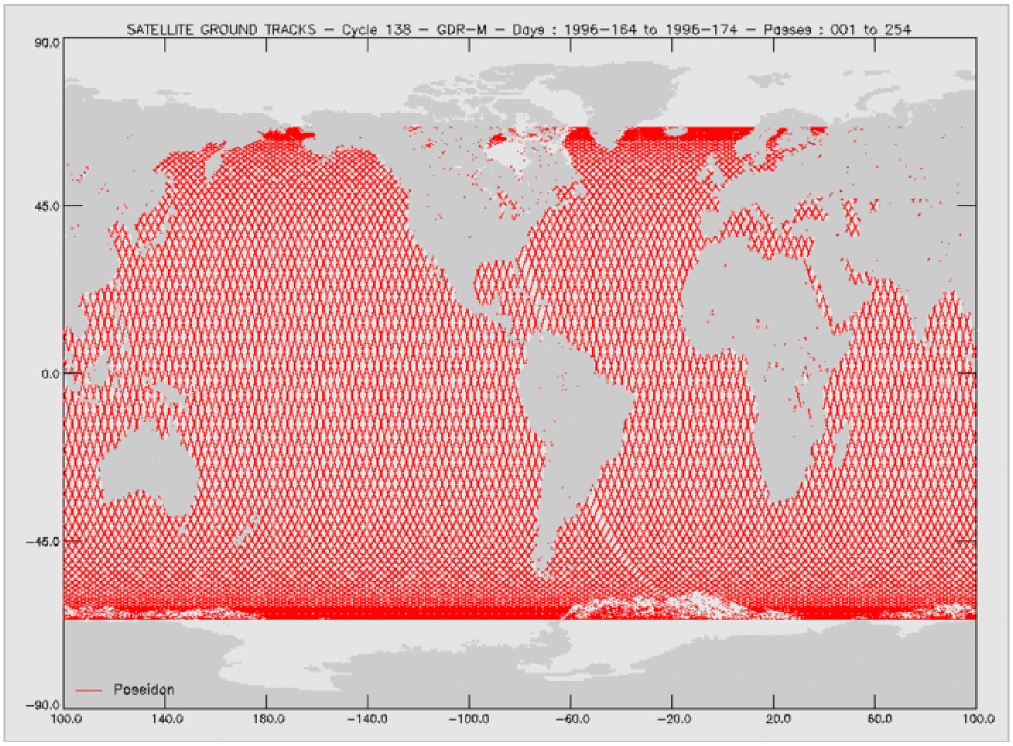


Figure 3.6. The ground track coverage for the *Jason*-1 satellite altimeter mission

Satellite altimeters rely upon ongoing point source verification (calibration) using tide stations located directly under the ground tracks (Saxena 1995) and ongoing calibration and estimates of altimeter drift using a global network of tide gauges (Mitchum 2000).

To be useful for sea level applications, numerous corrections are systematically made to the altimeter data to account for the effects of various physical phenomena:

1) propagation corrections: the altimeter radar wave is affected during atmosphere crossing:
    - ionospheric correction
    - wet tropospheric correction
    - dry tropospheric correction
2) ocean surface correction for the sea state which directly affects the radar wave: electromagnetic bias
3) geophysical corrections for the tides (ocean, solid earth, polar tides, loading effects)
4) atmospheric corrections for the ocean's response to atmospheric dynamics: inverse barometer correction (low frequency), atmospheric dynamics correction (high frequency)

To calculate global mean sea level, the global or basin mean sea level time series must be distinguished from the regional maps of mean sea level slopes. In both cases, these calculations are available for the period of each mission being considered, or by combining several altimetry missions covering the entire altimetric period.

For each mission (*TOPEX*/*Poseidon*, *Jason*-1, *Jason*-2), a mean grid of sea level anomalies for a 2°×2° grid is first calculated for each cycle (approximately 10 days) to distribute the measurements equally across the surface of the oceans. Sea level anomalies are computed by subtracting the gridded mean sea levels for each cycle from a mean sea reference surface. The global or basin mean for each grid is calculated by weighting each box according to its area, to give less significance to boxes at high latitudes, which cover a smaller area. This then gives the time series per cycle, which is then filtered with a low-pass filter to remove signals of less than 2 months or 6 months. The annual and semi-annual periodic signals are also adjusted. The slope in mean sea level is deduced from this series using a least squares method.

The global mean sea level for the entire altimetric period is calculated by combining the time series from all three *TOPEX/Poseidon*, *Jason-1* and *Jason-2* missions before filtering out the periodic signals. The three missions are linked together during the verification phases of the *Jason-1* and *Jason-2* missions to calculate precisely the bias in global MSL between these missions. The global MSL reference series is obtained by filtering out the periodic signals for the entire altimetric period.

The regional slopes in MSL for each mission are estimated using sea level anomaly grids for each cycle and each mission as previously defined for the time series. The regional slopes are estimated using the least squares method at each grid point after adjusting the periodic signals (annual and semi-annual). The map of these points is deduced from the slope grid, as well as the map of the corresponding formal adjustment error. Figure 2.4 is the multi-mission map of the overall global mean sea level anomaly since 1992, clearly showing the upward trend on nearly 3.0 mm/yr. Figure 2.5 is the global map showing the high degree of spatial variability of the regional trends that go into the make-up of the global trend.

Use of Very Long Baseline Interferometry to Study Long-Term Sea Level Variations

Very Long Baseline Interferometry (VLBI) also plays a role in studying global sea level changes. From Robertson (2002):

> VLBI is a novel observing technique for measuring the relative positions of widely separated points on the surface of the Earth with centimeter-level accuracy. Such accuracy is two or three orders of magnitude better than was available with classical techniques only a few decades ago. This enormous improvement in accuracy has opened up for study a broad new spectrum of geophysical phenomena. The new measurements allow direct observation of the tectonic motions and deformations of the Earth's crustal plates, observations of unprecedented detail of the variations in the rotation of the Earth, and direct measurement of the elastic deformations of the Earth in response to tidal forces. These new measurements have placed significant constraints on models of the interior structure of the Earth; for example, measurements of the variations in the Earth's rotation have been shown to be particularly sensitive to the shape of the

core-mantle boundary. The VLBI measurements, coupled with other space-based geodetic observing techniques such as the Global Positioning System, allow construction of a global reference frame accurate at the centimeter level. Such a frame will be essential to studying long-term global changes, especially those changes related to sea-level variations as recorded by tide gauge measurements.

3.1.4 Reference elevation: How it Factors Into Sea Level Change Projects

As described at the start of this chapter, SLC projects relying on elevation datasets (including topographic, bathymetric, and water-level data, primarily collected for navigation, boundaries, engineering and other practical uses) must have established the location of "zero" and a physical reference for elevation zero (i.e., a vertical datum must be both defined and accessible) for all types of height measurements. Chapter 2, section 2.2 provides detail on the different types of vertical datums that are available, while this section discusses methods to accurately determine and monitor these datums, including how to accurately measure elevations of marsh surfaces.

Continuously Operating Reference Stations (CORS): How They Tie Elevation-Related Datasets into the National Spatial Reference System

NOAA's National Geodetic Survey (NGS) manages a network of Continuously Operating Reference Stations (CORS) that provide Global Navigation Satellite System (GNSS) data, consisting of carrier phase and code range measurements to support three dimensional positioning, meteorology, space weather, and geophysical applications throughout the United States, its territories, and a few foreign countries.

Surveyors, GIS users, engineers, scientists, and the public at large who collect GPS data can use CORS data to improve the precision of their positions. CORS-enhanced, post-processed coordinates are within a few centimeters of accuracy within the National Spatial Reference System (NSRS), both horizontally and vertically.

The CORS network is a multi-purpose cooperative endeavor involving government, academic, and private organizations. The sites are independently owned and operated. Each agency shares its data with NGS, and NGS in turn analyzes and distributes data free of charge. As of May 2010, the CORS network contains over 1,450 stations contributed by over 200 different organizations, and the network continues to expand.

For additional information on CORS, see http://www.ngs.noaa.gov/CORS/Articles/, particularly the following entries:

> Snay, R., et al. 2007. Using global positioning system-derived crustal velocities to estimate rates of absolute sea level change from North American tide gauge records, *J. Geophys. Res.*, 112(B04409), 1-11 http://www.ngs.noaa.gov/CORS/Articles/Snay-et-al-JGR2007.pdf.

Schenewerk, M.J., et al. 2001. Vertical ocean-loading deformation derived from a global GPS network, *J. Geodetic Soc. of Japan*, 47(1) http://www.ngs.noaa.gov/GRD/GPS/Projects/OLT/Ets.00aug31/ets.html.

Schwarz, C.R., et al. 2009. Accuracy assessment of the National Geodetic Survey's OPUS-RS utility, *GPS Solutions*, 13(2), 119-132 http://www.ngs.noaa.gov/CORS/Articles/SchwarzetalGPSSOL09.pdf

GravD and Its Role in the Future of Elevation Referencing

NOAA's NGS is leading the GRAV-D project (http://www.ngs.noaa.gov/GRAV-D/), an effort to model and monitor Earth's geoid (a surface of the gravity field, closely related to global mean sea level) to serve as a zero reference surface for all orthometric heights in the nation.

The GRAV-D project has a decadal-scale gravity monitoring component, which is directly related to two components of climate-driven changes to sea level. First, the GRAV-D project aims to comprehensively re-survey the entire gravity field of the United States, enabling the modeling of the geoid to 1 centimeter of accuracy in much of the United States. Such a model, mixed with approximately 1 centimeter of GNSS ellipsoid height accuracy, would allow users in much of the U.S., particularly coastal regions, to access orthometric heights through a GNSS receiver to below 2 cm of accuracy. Second, the primary shape of the ocean's surface is driven by Earth's gravity field, with tides and currents having almost two orders of magnitude less impact. As such, changes to the sea surface are directly linked to changes to the gravity field. As NGS monitors changes to the gravity field, these changes reflect sea level change.

In addition, climate change affects more than sea level. For instance, changes to water tables have been seen through their small but measurable changes to the local gravity field. Therefore, basin-scale changes to freshwater resources are potentially detectable through the monitoring aspect of GRAV-D. These data could be used to analyze both the climate-driven impacts of the change and its long-term implications.

Use of Surface Elevation Tables (SETs) to Establish a Reference Surface in Marshes to Measure Elevations

Surface Elevation Tables (SETs) are portable measuring instruments deployed atop wetland vertical bench marks, allowing millimeter-level changes in surface elevation and occurring at one point to be measured over time (figure 3.7). SETs integrate both surface and subsurface processes that affect elevation change down to the depth of the bench mark (typically 3-20 m). They have been used for over a decade by coastal ecologists to investigate processes leading to wetland development, sustainability, or loss. NGS has recently developed guidelines to tie SET bench marks to the National Spatial Reference System (NSRS) and is working on projects to incorporate SETs into a system of high accuracy vertical control in coastal wetland settings (http://www.ngs.noaa.gov/PUBS_LIB/ProceduresForConnectingSETBMsToTheNSRS.pdf).

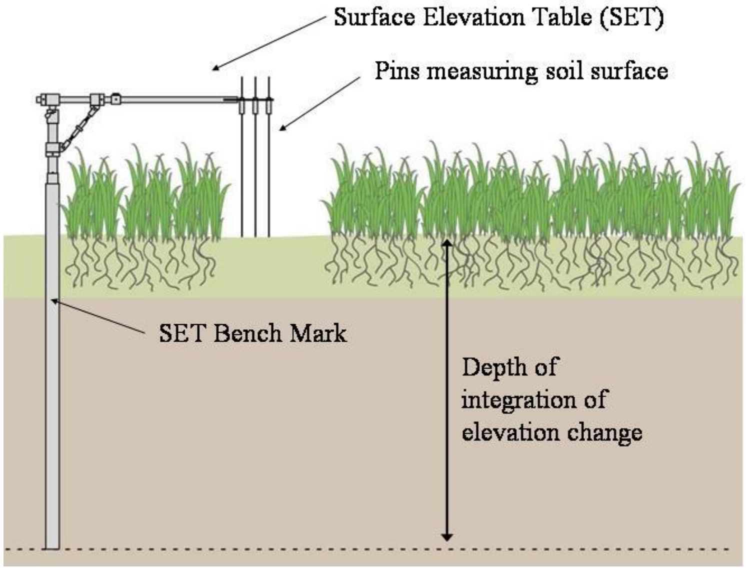


Figure 3.7. Surface Elevation Table conceptual diagram, courtesy of Don Cahoon, USGS.

One benefit of tying SETs to the NSRS is the ability to monitor local changes in sea level at the local coastal intertidal level. Until now, estimates of local SLC were based solely on tide gauges, which are connected to land elevation through a series of upland bench marks. However, most coastal intertidal surfaces are highly dynamic, and many are affected by shallow-depth subsidence. SETs provide a measure of the elevation change over such shallow depths; combining SET data with local sea level data gives a more accurate picture of locally-expressed sea level within the dynamic intertidal zone. Obtaining accurate heights on SET bench marks also allows the stability of the wetland bench marks themselves to be monitored, which is very important to calibrate observations over long periods of time, providing an estimate of deep subsidence (figure 3.8).

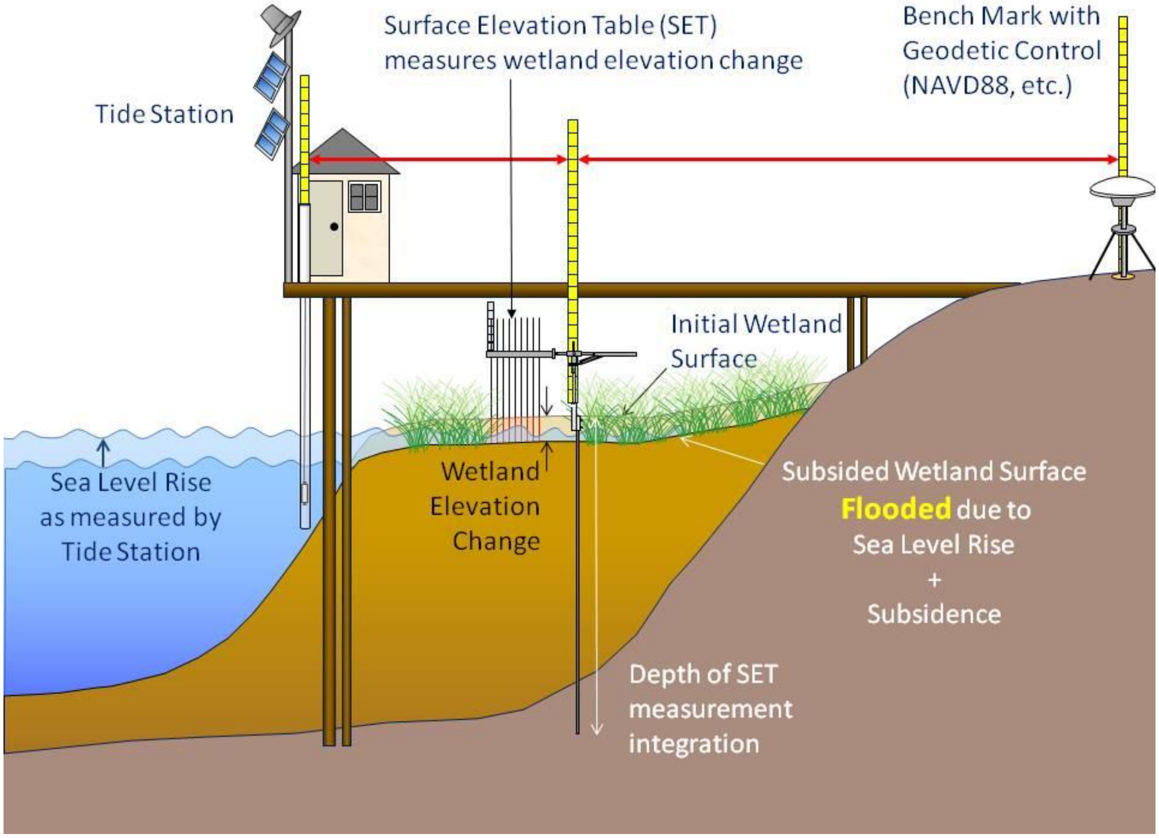


Figure 3.8. This conceptual diagram shows how geodetic connections between local tide stations, SETs, and geodetic control can provide a measurement of wetland elevation dynamics relative to locally-expressed (e.g. "relative") sea level change.

NGS is also assisting in the development of SET technology by defining the sources and magnitude of error associated with the use of SETs as geodetic instruments. Error is present at many levels, and no comprehensive study has addressed the sources of error under field conditions. NGS has developed a new design for the SET to overcome common sources of error. NGS is producing guidelines on the statistical design and analysis of SET data, to assist the community of SET users with a rigorous statistical framework for developing studies and interpreting the data. All of these steps pave new ground for the use of SETs as geodetic tools to bring accurate elevations to coastal intertidal habitats.

Current resources on the Internet relative to SET technology are:

- The US Geological Survey's SET web site: http://www.pwrc.usgs.gov/set/
- The NOAA National Geodetic Survey's guidelines document for obtaining GNSS-derived orthometric heights on SET foundations: http://www.ngs.noaa.gov/PUBS_LIB/ProceduresForConnectingSETBMsToTheNSRS.pdf
- The original SET cooperative data site: http://ecoinformatics.uvm.edu/SET/

3.2 Data Sources

3.2.1 Base Surface Elevation Data: Where to Find Topographic Data, Including Shoreline Data

Public domain elevation data are available in a range of extents, accuracy, and formats. The following list of websites, while not all-inclusive, may be used as a guide for users interested in acquiring elevation data sets for their areas of interest. Those interested in obtaining elevation data are encouraged to also contact their state and local GIS staffs regarding available elevation data.

Digital Coast (NOAA Coastal Services Center)
The NOAA Coastal Services Center's on-line data are provided via Digital Coast. Data are available in several point (.txt, LAS), line (.shp, .dxf), and raster (geotiff, floating point, ASCII grid) formats http://www.csc.noaa.gov/lidar/.

NOAA Coastal Services Center Topographic and Bathymetric Data Inventory
The Topographic and Bathymetric Data Inventory serves as an index to the best-available elevation data sets by regions. Users can use the interactive viewer to locate and learn about available data sets http://www.csc.noaa.gov/topobathy/viewer/index.html.

National Elevation Dataset (NED)
NED data are publicly available from the U.S. Geologic Survey (USGS). The data resolution varies by location; the type of data can be reviewed at http://gisdata.usgs.net/website/usgs_gn_ned_dsi/viewer.htm.

Published accuracy of the NED can be found at: http://ned.usgs.gov/downloads/documents/NED_Accuracy.pdf.

Center for Lidar Information Coordination and Knowledge (CLICK)
The USGS site CLICK provides access to publicly available lidar point file data sets. The goal of CLICK is to facilitate data access, user coordination, and education about lidar remote sensing for scientific needs (http://lidar.cr.usgs.gov).

USGS Topobathy Viewer
The topobathy viewer provides a dynamic on-line map interface that can be used to view U.S. Geological Survey topobathy DEMs (http://edna.usgs.gov/TopoBathy_Viewer/).

National Center for Airborne Laser Mapping (NCALM)
NCALM is the National-Science-Foundation-supported Center for Airborne Laser Mapping. The NCALM@Berkeley website provides public access to high-resolution airborne laser mapping data, documentation, and tools to analyze digital elevation data sets (http://calm.geo.berkeley.edu/ncalm/links.html).

National Geophysical Data Center (NGDC)
NGDC compiles, archives, and distributes bathymetric data from coastal and open ocean areas,

and acts as the long-term archive for NOAA National Ocean Service data collected in support of charting and navigation (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html).

Laboratory for Coastal Research at International Hurricane Research Center
The International Hurricane Research Center's Laboratory for Coastal Research data were produced as part of the Windstorm Simulation Modeling Project in a contract agreement between Florida International University International Hurricane Research Center (IHRC), Palm Beach County, Broward County, Manatee County, and Miami-Dade County (http://www.ihrc.fiu.edu/lcr/data/data.htm).

LiDARDATA.com
Lidardata.com provides an easy way to see where lidar has already been collected and to order off-the-shelf archives of the freshest data (http://www.lidardata.com).

North Carolina Floodplain Mapping Program
This website is a free service provided by the State of North Carolina. The latest information on the Floodplain Mapping Program is provided here (http://www.ncfloodmaps.com).

Atlas: The Louisiana Statewide GIS
The objective of this website is to make data and information related to GIS in Louisiana, GIS data documentation, and data sharing available to the public (http://atlas.lsu.edu).

Puget Sound Lidar Consortium
The Puget Sound LIDAR Consortium (PSLC) is an informal group of local agency staff and Federal research scientists devoted to developing public-domain high-resolution lidar topography and derivative products for the Puget Sound region (http://pugetsoundlidar.ess.washington.edu).

USGS Alaska Topobathy DEM
A seamless topographic–bathymetric surface model has been created for the area around the coastal town of Seward, Alaska. The DEM was developed to study submarine landslides and tsunamis produced by the 1964 earthquake and for generating computer models of tsunami wave propagation and inundation (http://pubs.usgs.gov/ds/374/).

Texas Topobathy DEM
This data set is composed of topobathy DEMs that cover the coastal region and continental shelf of Texas. It was sponsored by Texas Sea Grant and the Texas Parks and Wildlife Department, and work was completed by scientists at Texas A&M University (ftp://ftp2.tnris.state.tx.us/Elevation/BathyTopo/).

Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX)
JALBTCX performs operations, research, and development in airborne lidar bathymetry and complementary technologies to support the coastal mapping and charting requirements of the U.S. Army Corps of Engineers (USACE), the U.S. Naval Meteorology and Oceanography Command, and NOAA. JALBTCX staff includes engineers, scientists, hydrographers, and

technicians from the USACE Mobile District, the Naval Oceanographic Office (NAVOCEANO), the USACE Engineer Research and Development Center (ERDC), and NOAA National Geodetic Survey. JALBTCX research and development supports and leverages work in government, industry, and academics to advance airborne lidar and coastal mapping and charting technology and applications (http://shoals.sam.usace.army.mil/).

Shoreline Data

NOAA's National Shoreline website (http://shoreline.noaa.gov) provides access to the data and many other resources, including applications of shoreline data, definitions of terms, and data resources for Federal shorelines.

As described in section 3.2.1., shoreline datasets representing various data sources and delineation methods are available from myriad other sources, including other Federal and state government agencies, academic or research institutions, and others. These sources are too numerous and diverse to note here; however, for evaluation of the origin and appropriateness of these data, consult the Federal Geographic Data Committee (FGDC) standards for both metadata and content:

> FGDC Shoreline Metadata Profile:
> http://www.csc.noaa.gov/metadata/
>
> FGDC Shoreline Data Content Standard:
> http://www.fgdc.gov/standards/projects/FGDC-standards-projects/shoreline-data-content/index_html

See section 6.4 for information on shoreline-change analyses, including sources for shoreline-change rates across the U.S.

3.2.2 Base Surface Elevation Data: Where to Find Bathymetric Data

NOAA's Office of Coast Survey (OCS) is responsible for charting the coastal waters of the United States and its Territories and has acquired bathymetric data in these areas for nearly 200 years. Its extensive archive of data is maintained by NOAA's National Geophysical Data Center (NGDC) in Boulder, Colorado (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html), which also operates a worldwide digital data bank of oceanic soundings on behalf of the Member Countries of the International Hydrographic Organization (IHO).

NOAA's NGDC bathymetric data holdings include both single beam and multibeam sonar measurements, gridded data from these measurements, and estimated depths derived from satellite altimetry. http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

NGDC also builds and distributes high-resolution, coastal DEMs that integrate ocean bathymetry and land topography to support NOAA's mission to understand and predict changes in Earth's environment, and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs. DEMs can be used for modeling coastal processes (tsunami inundation, storm surge, sea level rise, contaminant dispersal, etc.), ecosystems management and habitat research, coastal and marine spatial planning, and hazard mitigation and community preparedness. (http://www.ngdc.noaa.gov/mgg/coastal/coastal.html)

NOAA's Coastal Services Center (CSC) maintains a topographic and bathymetric data inventory that provides an index to high-accuracy topographic and bathymetric data sets. The Inventory Viewer can be accessed at: http://www.csc.noaa.gov/topobathy/.

3.2.3 Water Surface Elevation: Where to Find Water-Level Data and Sea Level Trends

Tide Stations

Long term, local, relative sea level trends and variations at NOAA stations are published in *NOS CO-OPS Technical Report 53, Sea Level Variations of the United States 1854-2006*, located at: http://www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf.

The CO-OPS website also contains "Sea Levels Online," providing sea level analyses at all the long-term National Water Level Observation Network (NWLON) stations and at a select set of non-U.S. stations, using data obtained from the Permanent Service for Mean Sea Level (PSMSL; www.tidesandcurrents.noaa.gov/sltrends/). PSMSL, the global data bank for sea level data from tide stations, maintains a list of relative sea level trends at hundreds of stations worldwide (www.pol.ac.uk/psmsl/datainfo/rlr.trends).

Satellite Altimetry

Mean sea level trends and variations calculated from satellite altimetry data are documented at the NOAA National Environmental Satellite, Data and Information Service (NESDIS) Laboratory for Satellite Altimetry website: http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/. A series of satellite missions estimate global mean sea level every 10 days. These sea level trends are calculated and compiled using radar measurements, spacecraft orbits and tide station calibrations from 1992 onward and do not include glacial isostatic adjustment (GIA) effects on the geoid.

3.2.4 Reference Elevation: Where to Find Data or Other Resources to Establish or Maintain a Reference Elevation

Existing Reference Elevation Information

Basic elevation data are available on the NGS website for individual bench mark locations: http://www.ngs.noaa.gov/cgi-bin/datasheet.prl

Tools for using and applying geodetic information are found at:
http://www.ngs.noaa.gov/TOOLS/

Data Needed to Account for Vertical Land Motion

The CORS coordinate sheets corresponding to an SLC project site can be downloaded from the NGS web site (http://www.ngs.noaa.gov/CORS/). These sheets provide velocities at CORS sites. For example, the CORS sheet for "GODE" (GODDARD SPACE CTR), contains the following values:

```
NAD_83 VELOCITY
Transformed from ITRF00 velocity in Mar. 2002.
     VX =   0.0016 m/yr      northward =  -0.0007 m/yr
     VY =   0.0017 m/yr      eastward  =   0.0019 m/yr
     VZ =  -0.0019 m/yr      upward    =  -0.0022 m/yr .
```

Alternatively, the Online User Positioning System or OPUS (http://www.ngs.noaa.gov/OPUS/) determines a user's rover positions using static (or rapid-static) observations and CORS data. For purposes of submitting files to OPUS, "static" means more than 4 hours of data; "rapid-static" means 15 minutes to 4 hours of data.

For investigating sea level change, the "upward" one of the three components of velocity, which is associated with the local horizon, is the main point of interest. The *VX*, *VY* and *VZ* values relate to the earth-centered earth-fixed Cartesian reference frame. The component of interest needs to project forward from the date given to the date of interest.

By sampling velocities at discrete CORS in and around an area of interest (assuming their availability) a general idea of regional velocity can be developed. Substantial variation from one site to another within a general area may indicate, and/or be explained by, geologic or man-made forces in the area—tectonic strain, post-glacial rebound, fluid withdrawal, etc.

Stability and vertical motion at specific CORS sites can be estimated by reviewing multi-year plots of daily CORS positions at ftp://www.ngs.noaa.gov/cors/Plots/plots.html.

References Cited

Boak, E.H., and Turner, I.L., 2005. Shoreline Definition and Detection: A Review. *Journal of Coastal Research*, 21(4), 688-703.

Brock, J.C., and Purkis, S.J. 2009. The Emerging Role of Lidar Remote Sensing in Coastal Research and Resource Management. Journal of Coastal Research: Fall 2009, Vol., No. , pp. 1-5.

CCSP, 2009: Coastal Sensitivity to Sea level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [James G. Titus (Coordinating Lead Author), K. Eric Anderson, Donald R. Cahoon, Dean B. Gesch, Stephen K. Gill, Benjamin T. Gutierrez, E. Robert Thieler, and S. Jeffress Williams (Lead Authors)]. U.S. Environmental Protection Agency, Washington D.C., USA, 320 pp.

Crowell, M., Leatherman, S.P., and Buckley, M.E., 1991. Historical Shoreline Change: Error Analysis and Mapping Accuracy. *Journal of Coastal Research*, 7(3), 839-852.

Gesch, D.B., 2009. Analysis of Lidar Elevation Data for Improved Identification and Delineation of Lands Vulnerable to Sea Level Rise. Journal of Coastal Research: Fall 2009, Vol., No. , pp. 49-58.

Graham, D.; Sault, M., and Bailey, J., 2003. National Ocean Service Shoreline—Past, Present, and Future. *Journal of Coastal Research*, Special Issue No. 38, 14-32.

IOC, 2006: Manual on Sea level Measurement and Interpretation, Volume IV: An Update to 2006, JCOMM Technical Report No. 31, WMO/TD. No. 1339, Manuals and Guides 14, Intergovernmental Oceanographic Commission, 80pp.

Leatherman, S.P., 2003. Shoreline Change Mapping and Management Along the U.S. East Coast. *Journal of Coastal Research*, Special Issue No. 38, 5-13.

Maune, D.F., 2007. Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Moore, L.J., 2000. Shoreline Mapping Techniques. *Journal of Coastal Research*, 16(1), 111-124.

Moore, L.J.; Ruggiero, P., and List, J.H., 2006. Comparing Mean High Water and High Water Line Shorelines: Should Proxy-Datum Offsets be Incorporated into Shoreline Change Analysis? *Journal of Coastal Research*, 22(4), 894-905.

Morton, R.A.; Miller, T.L.; and Moore, L.J.; 2004. *National Assessment of Shoreline Change: Part 1: Historical Shoreline Changes and Associated Coastal Land Loss Along the U.S. Gulf of Mexico*. U.S. Geological Survey Open-file Report 2004-1043, 45 p.

Morton, R.A., 1991. Accurate shoreline mapping: past, present, and future. In: Kraus, N.C.; Gingerich, K.J., and Kriebel, D.L. (eds.), *Coastal Sediments '91*, American Society of Civil Engineers, pp. 997-1010.

Morton, R.A. and Speed, M.F., 1998. Evaluation of Shorelines and Legal Boundaries Controlled by Water Levels on Sandy Beaches. *Journal of Coastal Research*, 14(4), 1373-1384.

NOAA, 2001: Tidal Datums and Their Applications, NOAA Special Publication NOS CO-OPS 1, S.K. Gill and J.R. Schultz, eds. NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 111pp.

National Research Council (NRC), 2004. *A Geospatial Framework for the Coastal Zone: National Needs for Coastal Mapping and Charting*, Washington, D.C.: National Academy Press, 149 p.

NRC (National Research Council), 2009, Mapping the zone: Improving flood map accuracy, National Academy Press, Washington, DC., 121 pp.

Pajak, M.J. and Leatherman, S.P., 2002. The High Water Line as Shoreline Indicator. *Journal of Coastal Research*, 18(2), 329-337.

Robertson, Douglas S, 1991: Laboratory for Geosciences, Office of Ocean and Earth Science, National Oceanic and Atmospheric Administration, Rockville, Maryland 20852.

Scavia, D.; Field, J.C.; Boesch, D.F.; Buddemeier, R.W.; Burkett, V.; Cayan, D.R.; Fogarty, M.; Harwell, M.A.; Howarth, R.W.; Mason, C.; Reed, D.J.; Royer, T.C.; Sallenger, A.H.; and Titus, J.G., 2002. Climate Change Impacts on U.S. Coastal and Marine Ecosystems, *Estuaries and Coasts*, 25(2), 149-164.

Scott, G.; Wijekoon, N; and White, S., 2009. Multi-sensor Mapping: Integrating Data Streams for Coastal Science and Management. *Hydro International*, 13(2), 20-23.

Shalowitz, A.L., 1964. *Shore and Sea Boundaries*. VI. U.S. Department of Commerce, Coast and Geodetic Survey, U.S. Government Printing Office, 420p.

Smith, J.T., Jr., 1981. *A History of Flying and Photography in the Photogrammetry Division of the National Ocean Survey*, 1919-79. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, 486p.

Titus, J.G.; and Richman, C., 2001. Maps of lands vulnerable to sea level rise: Modeled elevations along the U.S. Atlantic and Gulf Coasts. *Climate Research,* 18(3), 205-228.

White, S., 2007. Utilization of LIDAR and NOAA's Vertical Datum Transformation Tool (VDatum) for Shoreline Delineation. *Proceedings of the Marine Technology Society / IEEE OCEANS Conference*. Vancouver, B.C.

Zervas, C., 2009: Sea Level Variations of the United States 1854-2006, NOAA Technical Report NOS CO-OPS 053, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 78pp.

Chapter 4.0 New Data Acquisition

4.1 Type of Data Needed

While the type and accuracy of data needed for a specific sea level rise assessment or other geospatial project will be dependent on the application of that product, the four most critical geospatial data elements for any sea level rise assessment are sea level information, topographic data, bathymetric data, and geodetic (or land-based) heights. Chapter 3 discusses the use of existing data, while chapter 4 addresses the collection and/or acquisition of new geospatial data. Once accuracy requirements are determined and existing data availability explored, data collection may be the ideal or only option to meet project needs. As long as all the data sets used in a project can be referenced to a common datum, data are largely modular. For instance, if a new, high-resolution topographic data set exists, but bathymetry data are outdated, new bathymetry can be collected and integrated with the topographic data set using common datum reference. The following sections provide details on collection standards for the four primary data sets.

4.2 How to Acquire the Data to Enable Multiple Uses

Federal agencies are committed to conducting ocean and coastal mapping in a way that permits easy access and use by the greatest range of users. NOAA is adopting these practices, entitled Integrated Ocean and Coastal Mapping (IOCM), throughout its mapping programs with the goal of "map once, use many times."

Key principles of IOCM include acquiring data to commonly agreed-to standards, ensuring the data acquired is documented thoroughly with metadata, and ensuring the data are archived and stored in a way that is accessible to many users. Several state entities (e.g. California, Oregon, and North Carolina) have already coordinated efforts to collect data for both ecosystem and coastal decision making requirements.

NOAA and other Federal and state agencies continue to refine common standards for data accuracy to support multiple uses. The consensus is that all data acquisition should meet or exceed International Hydrographic Organization (IHO) Order 1 standards and be carried out at the maximum resolution obtainable using state-of-the-industry tools. For maximum utility, coverage would ideally include all "lands" from the shore strand line (mean higher high water or MHHW) out to the 3 nautical miles (nm) state water limit. However, obtaining this coverage often requires the application of multiple acquisition sensors, including acoustic (e.g. multibeam echosounder or MBES) and optical (e.g. lidar, hyperspectral, multispectral, and water level measuring systems and systems for other oceanographic parameters affecting acoustic and optical sensor measurements).

The best available positioning instrumentation (e.g. high precision kinematic GPS) should be used when acquiring data, and a common vertical datum needs to be agreed to and used.

Experienced surveyors generally do all bathymetric and topographic surveying on the ellipsoid (e.g. ITRF or WGS84), thereby facilitating more accurate tidal corrections, data fusion and conversion to other datums.

Table 4 lists the agreed-upon IOCM standards proposed by 2006 IOCM workshop participants. These standards would apply in water depths greater than 5 m and extend to the limits of the continental margin. The standards are applicable for surveys conducted with multibeam sonars, interferometric (phase) swath sonars, and, except for coverage and resolution, airborne lidar. Individual programs may specify more stringent standards for their own seafloor mapping projects.

Table 4.1. IOCM standards

Requirement	**Specification**
Horizontal accuracy of a seafloor feature*	5 m + 5% of depth
Depth accuracy at any specified location*	$\pm\sqrt{[a^2+(b*d)^2]}$, where a = 0.5 m, b = 0.013, and d is the depth in meters
Resolution	2 m to 40 m depth; 5% of depth beyond 40 m
Coverage	Full coverage is the standard; but achievement may depend on program constraints or requirements†
Backscatter	Best backscatter mode (typically full-beam time-series) recorded (dependent on sonar)
Ground truth of bottom character backscatter	Optical or grab sample at lateral spacing sufficient to ground truth backscatter segmentation, and not to exceed 2000 m. Unless required by the primary program, bottom sampling is not required in depths exceeding 100 m.
Horizontal Reference	Positions referenced to WGS 84 (NAD83)
Vertical Reference	Depths referenced to mean lower low water datum and/or WGS 84 ellipsoid††
Metadata	FGDC compliant
Archiving	Raw and processed data (with metadata) submitted to NGDC within 1 yr of acquisition
*At the 95% probability level, after application of all systematic corrections including water level	† There may be situations where the requirement for mapping of large areas or the minimal availability of time demands reconnaissance-style mapping that of necessity is not full-bottom coverage
	†† This requires coordination in advance with NOS CO-OPS for the preparation of tidal zoning charts and may require the installation of water level gauges. In areas where water level gauges or shore-based kinematic GPS are not available, this will require the installation of specialized GPS equipment on the survey vessel and subscription to specialized globally-corrected GPS (GcGPS) services.
The availability of seafloor mapping systems to meet the above requirements efficiently in depths less than 5 m is limited. In those depths, mapping by interferometric swath sonar, lidar, single-beam echosounder, side scan sonar, or aerial/satellite imagery should be used to produce the best mapping products practicable.	

One common usage of mapping data, in addition to inundation, is habitat classification. To allow data to be most useful for habitat determination, seafloor mapping information should include seabed geomorphology (relief via *XYZ* digital elevation model—DEM) and texture (substrate type). These two data sets are the minimum needed to support basic habitat classification. In addition, ground truthing (e.g. via video or physical samples) of acoustic and optical remote sensing data used to create the DEM and surface texture data sets is needed to verify the classifications. Where appropriate and possible, subsurface structure (sediment thickness and stratigraphy via subbottom profiles and coring) is highly desirable.

4.3 How to Acquire Specific Data Sets

4.3.1 Long-Term Sea Level and Sea Level Trends

Many agencies other than NOAA/CO-OPS have requirements for long-term water level measurements and have their own observing systems in place to meet project goals and mission requirements. To effectively monitor sea level change (SLC) and accrue the length of data necessary to compute relative sea level trends, a long-term sustainable observing system strategy must be implemented. This involves determining if existing data and observation locations meet requirements, determining the number of and location of new water level measurement stations, determining the cost requirements for long-term installation and annual operation and maintenance, and determining the requirements for data quality control (QC), processing and data base management ,and finally, for data dissemination. The sustainability of the observations are typically a major impediment to long-term sustained operation, so any planning and design of new observation stations or networks must include annual operation and maintenance costs, and long-term administrative and infrastructure costs (such as information technology or IT).

NOAA/CO-OPS has collaborated with other agencies, such as USGS and the U.S. Army Corps of Engineers (USACE), and with state agencies in Florida and Texas, as well as internal organizations, such as the National Estuarine Research Reserve (NERRS) Program, assisting them with long-term monitoring guidance.

For application to climate studies and research, especially in estimating relative mean sea level trends, long-term continuous measurements are required. The networks should have characteristics of a true “end-to-end” system that includes data collection through to data delivery to and application by the user community. To ensure this application, long-term water level networks must be managed in-line with some basic principles of climate monitoring:

- **Management of Network Change**. Water level networks can change with new technology or new scientific information on data gaps or requirements for ancillary measurements and configurations.
- **Parallel Testing.** When new technology systems are implemented into water level networks, they must first be tested in wave tanks and in field tests and then operated simultaneously alongside old technology systems for a duration sufficient to establish transfer functions and instrument bias before removing the older systems.

- **Metadata**. Active metadata systems must be in place and maintained in real time to update sensor configurations, calibration coefficients, and datum offsets. Historical metadata records must be made available and converted from hard copy to electronic format. Access to metadata must be open and public.
- **Data Quality and Continuity**
    - ➢ Water level data must continually undergo automated and manual data quality control as close to real time as possible.
    - ➢ Data must be continuous with only small breaks tolerated, and breaks are filled only under controlled and documented standard operating procedures.
    - ➢ Water level data must have documented reference datum continuity and vertical stability.
    - ➢ Water level station supporting structures should be constructed to ensure vertical stability and minimum damage during large storm events and be high enough to withstand most storm surge elevation.
- **Integrated Environmental Assessment.** Water level data should be examined in context with other ancillary measurements to explain anomalous events and unexpected phenomena. Water level stations should have a geodetic datum connection to geodetic reference systems using either direct leveling to geodetic marks or static GPS surveys.
- **Historical Significance**. Preserve the most important climate sites data by maintaining critical long-term station operation and maintaining data archival systems.
- **Complementary Data.** Water level stations must have backup sensors deployed and alternate data collection and transmission systems in place, and the sensors must be capable of measuring the extreme highs and extreme lows in water level.
- **Continuity of Purpose**. To prevent stations or networks from being dropped due to changing priorities, continuous outreach and training for partners, users, and upper management must be available. The data applications must remain relevant and ongoing. New product development and applied research must be sponsored.

Similar international standards for sea level measurement are detailed by international groups. For instance, the IOC Manual on Sea Level Measurement and Interpretation (IOC, 2006) discusses requirements for long-term sustained measurements of sea level. Specifications used by NOAA for new tide station installation, operation and maintenance are found online at:

- http://tidesandcurrents.noaa.gov/publications/CO-OPS_Specifications_and_Deliverables_for_installation_operation_and_removal_of_water_level_stations_updated_November2008.pdf
- http://tidesandcurrents.noaa.gov/publications/users_guide_for_installation_of_Bench_Mark.pdf

- http://tidesandcurrents.noaa.gov/publications/Users_Guide_for_Electronic_Levels_January_2003.pdf
- http://tidesandcurrents.noaa.gov/publications/CO-OPS_Water_Level_and_Meteorological_Site_Recon_Procedures,_Updated_May_2009.pdf

New installations also need a strong geodetic datum connection, and those specifications are found in:

- http://tidesandcurrents.noaa.gov/publications/Users_Guide_for_GPS_Observations_updated_December_2009.pdf
- http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html

4.3.2 Topographic Data

Several considerations need to be accounted for when acquiring topographic data. When collecting digital elevation data, the following questions should be addressed:

- What is the specific application for which the data will be used? (While applications guide standards, there is a benefit to collecting all data to a minimum set of standards to use data sets for multiple applications.)
- What is the horizontal and vertical accuracy of topographic data needed for the intended application?
- What sensor can best meet this requirement?
- How should the acquisition be tailored to achieve the desired data?
- In which datum does the user need the data, and does the sensor and software provide the correct methodologies for working in that datum?
- Is the user looking for a Digital Terrain Model/bare-earth surface, a Digital Surface Model (DSM) depicting the elevations of the top surfaces of buildings, trees, towers, and other features above the bare-earth surface, or very shallow nearshore submerged topography?

Answers to these questions can lead to designing very different types of acquisition specifications. The following list, although not exhaustive, details requirements and specifications that should be considered before acquiring topographic data:

Specific Project Details:

- Project Area/Extents

•Mission/Data Acquisition Details

- Sensor (Type, Maintenance, Certification)
- Aircraft
- Flight Clearances
- Enabling Technologies (GPS/IMU)
  - GPS/CORS Base Stations
  - GPS Base Line Lengths
  - Aircraft Positioning and Orientation System
  - PDOP/VDOP
- Calibration
  - Factory Calibrations (Radiometric/Geometric)
  - In-situ Calibrations
  - Determination of sensor-to-GPS-antenna offset vector components (“lever arm”)
- Data Post Spacing/Resolution
- Sensor Acquisition Parameters
- Coverage and Overlap
- Flight Direction/Height
- Weather Conditions
- Time of Day
- Tide Coordination

•Production Details

- Data Formats/Data Model Type/Deliverables
- Horizontal/Vertical Datums
- Specific Processing Instructions
- Accuracy Standards, Assessment, and Reporting
- Metadata
- Data Labeling/Shipment/Notifications
- Delivery Schedule/Completion Dates
- Reason for Data Rejections

Additional Information on topographic data acquisition can be found at:

NOAA’s Coastal Mapping Program Scope of Work (SOW) for Lidar:

- http://www.ngs.noaa.gov/RSD/SOW_LIDAR.shtml

NOAA’s Data Acquisition Contracting Vehicle

- Through established contracting vehicles with geospatial industry leaders, state and local agencies can work with NOAA’s Coastal Service Center (CSC) staff to contract for coastal data collection and other geographic information system services. Fund transfers are coordinated through an established memorandum of understanding process. The Center does not charge overhead; therefore, 100% of state and local dollars applied to the contracts go to the service requested. For more information, e-mail the Center at *csc.info@noaa.gov*.

U.S. Geological Survey National Geospatial Program Lidar Guidelines and Base Specification:

- http://lidar.cr.usgs.gov/USGS-NGP%20Lidar%20Guidelines%20and%20Base%20Specification%20v13%28ILMF%29.pdf

Chapter 13, DEM User Requirements: assist with the decision making process for developing standard requirements and also provides an example SOW:

- Maune, D.F., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

4.3.3 Bathymetric Data

Before acquiring new bathymetric data, it is important to consider many of the same questions as those asked for topographic data acquisition; “What is the exact application you will be utilizing the data for?” (like topographic data, while applications guide standards, there is a benefit to collecting all bathymetric data to a minimum set of standards in alignment with the principles of the Integrated Ocean and Coastal Mapping initiative, in order to utilize data sets for multiple applications), “What is the needed horizontal and vertical accuracy of bathymetric data for the intended application?”, “What sensors can best meet this requirement?”, and “How does the acquisition need to be tailored to achieve the desired data?”

The accuracy of bathymetric data is dependent on a number of factors: the sonar system and positioning system being used, calibrations of these systems, corrections for errors resulting from environmental conditions (tides, sound speed variability in water, vessel motion), and the processing and quality control of the acquired data sets. While accurate depths may be obtained from single beam sonar, multibeam sonar provides much greater detailed bathymetry of the sea floor. The Global Positioning System (GPS) is currently the predominant means of positioning vessels, but care must be taken to obtain the high accuracy position required for quality bathymetric data. Both systems must be tested and calibrated to ensure that all systematic errors have been minimized.

The description of the methods and procedures for acquiring high accuracy bathymetric data can be found in the *NOS Hydrographic Surveys Specifications and Deliverables* document ,which is located at http://www.nauticalcharts.noaa.gov/hsd/specs/SPECS_2010.pdf and the *NOAA OCS Field Procedures Manual*, (http://www.nauticalcharts.noaa.gov/hsd/docs/Field_Procedures_Manual_April_2010.pdf). Additional information can be found in *the U.S. Army Corps of Engineers Hydrographic Surveying Manual* (http://140.194.76.129/publications/eng-manuals/em1110-2-1003/toc.htm).

4.3.4 Orthometric Heights

Orthometric heights can be determined using either or both of two different methods: differential leveling and satellite observations. Each method is a substantial topic in its own right. The choice of one over the other depends on particular circumstances. A compare-and-contrast overview follows.

Differential leveling is most suited to relatively small areas, such as connecting a tide gauge to nearby bench marks. Satellite observations (referred hereafter as GNSS or Global Navigation Satellite System) are most suited to connecting two or more sites distant from each other, such as two tide stations. Leveling is labor intensive and hands-on, whereas GNSS is largely set-it-up-and-guard-it. Leveling is typically more precise than GNSS over short distances up to several kilometers, but the distance-dependent precision of the two methods tend to equalize in the range of 50 km to 100 km; beyond 100 km the uncertainty of leveling begins to exceed that of GNSS, although not alarmingly so.

The heights directly determined by GNSS are referenced to the ellipsoid, a geometric reference, rather than the physical one determined by leveling with reference to a gravitational surface (see chapter 2). For GNSS-derived ellipsoid heights to be converted to orthometric heights, a quantity known as the geoid height must be added to the ellipsoid height. The result is an orthometric height known within the combined uncertainty of the ellipsoid height and the geoid model.

Each method is useful in its own way for monitoring long-term trends. At a tide station, the gauge itself is established, as well as several nearby permanent marks. These marks should be in different settings (if possible) and of different character to aid stability. Then, leveling from the gauge (if possible) to each nearby mark in succession is performed, first in one direction (gauge to A to B to C etc), then in the opposite direction (C-B-A-gauge) for a comparison. The result of this work is a set of height differences between marks, with the starting elevation referred to the gauge. (Standards for the forward-backward comparison of the two directions of leveling are found in several publications (http://www.ngs.noaa.gov/PUBS_LIB/Geodeticleveling_nos_3.pdf pg. 3-7 and http://www.ngs.noaa.gov/FGCS/tech_pub/Fgcsvert.v41.specs.pdf , pg. 6). The type of leveling known as second-order class I, for example, has an accuracy expectation of 1.0 mm per square root of the number of kilometers of leveling performed. Thus, two level runs, forward and backward, between two marks 2.0 km apart would be expected to agree within 1.4 mm. This sort of uncertainty propagates with distance when moving along a line of leveling to connect two sites.) Technicians can then return annually, repeating the process of leveling from gauge to mark to mark, looking for the original height differences to be repeated within the accuracy specification. If differences exceed this specification, personnel should first confirm that they are not a result of an observational blunder; if differences are legitimate, they indicate relative vertical movement that needs to be investigated.

A similar monitoring process can be used with GNSS, where vectors can be determined between marks at one site and marks at a distant site at one point in time, then re-determined in subsequent occupations. Repeatability of the vector components at an expected accuracy level indicates stability (no relative vertical movement).

A campaign-style GNSS project can be carried out repetitively at several sites to monitor heights simultaneously. At secure sites, GNSS receivers can be left to collect data for several days at a time, or even continuously. Specifications for this type of multi-station survey for accurate height determination are given in http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html.

Leveling is generally carried out with a digital barcode level rather than with the human eye, where a technician looks through a level at a rod. If a connection to the nationwide datum, North American Datum of 1988 (NAVD 88), is desired, observation begins at a published bench mark, (see following paragraph). The most reliable method is to level between two published marks and confirm the difference of elevation within acceptable standards before continuing to new work.

Heights (elevations) referenced to the national vertical datum, currently NAVD 88, are available on data sheets from the National Geodetic Survey (NGS) at http://www.ngs.noaa.gov/cgi-bin/datasheet.prl. From the introductory page, the user can navigate to subsequent pages. These give options of retrieving data sheets for bench marks in a given area and of a desired accuracy and stability. The top of each file of retrieved data sheets contains a link to further information, http://www.ngs.noaa.gov/cgi-bin/ds_lookup.prl?Item=DSDATA.TXT.

Tying two tide gauges to NAVD 88 enables a comparison of heights between the two stations, similar to the result obtained when using GNSS to occupy the two sites. The NAVD 88 comparison is subject to the propagated leveling errors between the two sites, as well as any movement of the marks being compared either between epochs or since the bench marks were originally installed. A GNSS tie is usually more current and therefore less affected by passage of time. However, the historic reference to older leveling can be very useful to get at least an order-of-magnitude estimate of any movement at one or both sites.

For specific instructions to accomplish a leveling or GNSS project, manuals and textbooks in surveying literature, as well as training, are available from various government agencies and private firms.

References Cited

2005 California Strategic Mapping Workshop: http://euclase.csumb.edu/DATA_DOWNLOAD/StrategicMapgWrkshp05/MappingWorkshop12_12-13/Final_Report/CA%20Habitat%20Mapping%20Rpt.pdf

2006 NOAA Integrated Ocean and Coastal Mapping Seafloor Mapping Standards Workshop, April 18 –19, 2006, NOAA/UNH Joint Hydrographic Center; Durham, New Hampshire Federal Geodetic Control Committee, September 1984; Standards and Specifications for Geodetic Control Networks, Section 3.5, pages 3-6 through 3-8. http://www.ngs.noaa.gov/FGCS/tech_pub/Fgcsvert.v41.specs.pdf

Hicks, S.D.; Morris, P.C.; Lippincott, H.A.; and O'Hargan, M.C., October 1987: User's Guide for the Installation of Bench Mark and Leveling Requirements for Water Level Stations, 73pp. http://tidesandcurrents.noaa.gov/publications/users_guide_for_installation_of_Bench_Mark.pdf

Maune, D.F., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

NOAA, August 1981: Geodetic Leveling – NOAA Manual NOS NGS 3, NOAA National Ocean Service National Geodetic Survey, 3-7. http://www.ngs.noaa.gov/PUBS_LIB/Geodeticleveling_nos_3.pdf

NOAA, January 2003: User's Guide for Electronic Levels, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 27pp. http://tidesandcurrents.noaa.gov/publications/Users_Guide_for_Electronic_Levels_January_2003.pdf

NOAA, November 2008: CO-OPS Specifications and Deliverables for Installation, Operation, and Removal of Water Level Stations, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 26pp. http://tidesandcurrents.noaa.gov/publications/CO-OPS_Specifications_and_Deliverables_for_installation_operation_and_removal_of_water_level_stations_updated_November2008.pdf

NOAA, December 2009, Draft: Light Detection and Ranging (LIDAR) Requirements – Scope of Work for Shoreline Mapping Under the NOAA Coastal Mapping Program, NOAA National Ocean Service National Geodetic Survey Remote Sensing Division, 30pp. http://www.ngs.noaa.gov/RSD/LIDAR_SOW_NGSDec2009.pdf

NOAA, December 2009: User's Guide for GPS Observation at Tide and Water level Station Bench Marks, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 25pp. http://tidesandcurrents.noaa.gov/publications/Users_Guide_for_GPS_Observations_updated_December_2009.pdf

NOAA, April 2010: NOS Hydrographic Surveys Specifications and Deliverables, NOAA National Ocean Service Office of Coast Survey Hydrographic Surveys Division, 149pp. http://www.nauticalcharts.noaa.gov/hsd/specs/SPECS_2010.pdf

NOAA, April 2010: Field Procedures Manual, NOAA National Ocean Service Office of Coast Survey Hydrographic Surveys Division, 325pp. http://www.nauticalcharts.noaa.gov/hsd/docs/Field_Procedures_Manual_April_2010.pdf

Servary, B.L. Jr., May 2009: CO-OPS Water Level and Meteorological Site Reconnaissance Procedures, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 6pp. http://tidesandcurrents.noaa.gov/publications/CO-OPS_Water_Level_and_Meteorological_Site_Recon_Procedures,_Updated_May_2009.pdf

U.S. Army Corps of Engineers, Jan 2002 updated April 2004: EM 1110-2-1003 Engineering and Design– Hydrographic Surveying, http://140.194.76.129/publications/eng-manuals/em1110-2-1003/toc.htm

U.S. Geological Survey, February 2010: USGS National Geospatial Program Lidar Guidelines and Base Specification, Version 13 – ILMF 2010; 18pp. http://lidar.cr.usgs.gov/USGS-NGP%20Lidar%20Guidelines%20and%20Base%20Specification%20v13%28ILMF%29.pdf

Zilkoski, D.B.; D’Onofrio, J.D.; Frakes, S.J., November 1997: Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2cm and 5 cm), Version 4.3, NOAA Technical memorandum NOS NGS-58. http://www.ngs.noaa.gov/PUBS_LIB/NGS-58.html

Chapter 5.0 Data Integration and Interpolation

Chapter 5 provides a fundamental understanding of the potential error sources in the various input elevation layers and discusses how these errors can be treated when interpolating or integrating various data sets for a decision-support tool. The vertical accuracy is the main point being addressed, although horizontal accuracy is also important.

5.1 Error Quantification

This section addresses information on error sources of the fundamental data sets needed for data integration and interpolation, which are necessary for application of impacts of sea level rise assessments. Summaries of various sources of error are provided for control point sources and datum transformation, as well as geospatial *x-y* fields. Whether tidal control points or geodetic control points, strategic use of their number and location is required to obtain accurate geospatial interpolation for use in mapping.

5.1.1 Sea Level

Local Mean Sea Level and Other Tidal Datums

As discussed in chapter 2, tidal datum elevations are computed from time series of observed tides at specific tide station locations. By legal definition used by NOAA, tidal datum elevations are computed relative to specific 19-year periods called National Tidal Datum Epochs (NTDEs). The current official NTDE is the 1983-2001 period (except in areas with special 5-year datums as discussed in chapter 2). Local mean sea level (LMSL) is also computed as a tidal datum relative to the NTDE based on the observed hourly heights.

NOAA manages a nation-wide network of long-term continuously operating water level stations called the National Water Level Observation Network (NWLON). The NWLON is the fundamental observing system necessary to compute and maintain a tidal datum reference framework for the U.S. For many NWLON stations, tidal datum elevations were computed directly by performing the averaging over the 1983-2001 NTDE. For practical application, the error in datum elevation for these “first-reduction” averages is zero by definition. However, tidal datum elevations have been determined from hundreds of short-term tide stations along the coast that were established for periods much less than 19-years—typically only for 3-months to a year, depending on the project or application. The NOAA accepted procedure is to compute equivalent NTDE tidal datums at these short-term stations by comparing simultaneous observations with an appropriate NWLON control (or reference) station. This method of simultaneous comparison for tidal datum determination is detailed in NOS CO-OPS 2 (2003).

This comparison process for determining equivalent 19-year NTDE datums results in an error in the tidal datum elevations because they were not based on full NTDE. NOAA estimates errors in tidal datums at short-term subordinate stations using the set of Bodnar equations (1981) and the procedures outlined in the *NWLON Gaps Analysis* (Gill and Fisher 2008). Datum errors are generally higher in areas that contain NWLON gaps. These errors are a function of the distance between the short-term and the control station, of the difference in time of high and low waters between the short-term station and the control, and of the ratio of the mean ranges of the tide between the short-term and control stations. Thus, the errors are spatially variable depending on the number and density of good NWLON stations and the complexity of the tidal hydrodynamics. Table 5.1 provides the equations used to estimate errors in tidal datums at the one-standard deviation level based in geographic distance and tidal differences between the control land subordinate stations. The equations for MLW datum are shown but are the same as those used for MLLW. Generically and in practice, this set of equations is used to express the estimated error for all datums at a particular tide station and represents an upper bound, as errors for the low water datums are slightly higher than for the high water datums.

Table 5.1. The regression equations and parameters for estimating uncertainties in tidal datums for mean low water (Bodnar, 1981)

$$\mathrm{S1M} = 0.0068\ \mathrm{ADLWI} + 0.0053\ \mathrm{SRGDIST} + 0.0302\ \mathrm{MNR} + 0.029$$
$$\mathrm{S3M} = 0.0043\ \mathrm{ADLWI} + 0.0036\ \mathrm{SRGDIST} + 0.0255\ \mathrm{MNR} + 0.029$$
$$\mathrm{S6M} = 0.0019\ \mathrm{ADLWI} + 0.0023\ \mathrm{SRGDIST} + 0.0207\ \mathrm{MNR} + 0.030$$
$$\mathrm{S12M} = 0.0045\ \mathrm{SRSMN} + 0.128\ \mathrm{MNR} + 0.025$$

Where:

S	is the standard deviation (in feet),
M	is the number of months of subordinate station observation,
ADLWI	is the absolute time difference of the low water intervals between control and subordinate stations (in hours),
SRGDIST	is the square root of the geographic distance between control and subordinate stations (in nautical miles),
MNR	is a mean range ratio that is defined as the absolute value of the difference in mean range between control and subordinate stations divided by the mean range of tide at the control station (using range values in feet), and
SRSMN	is the square root of the sum of the mean ranges at the control and subordinate stations (in feet).

Geospatially, the tidal datum errors can be visualized by plotting historical tide station locations and their error estimates using the previous equations. Figure 5.1 illustrates this distribution compiled for a VDatum model assessment for Tampa Bay, FL. These errors are used as part of the VDatum error budget analysis described in section 5.1.5 of this report.

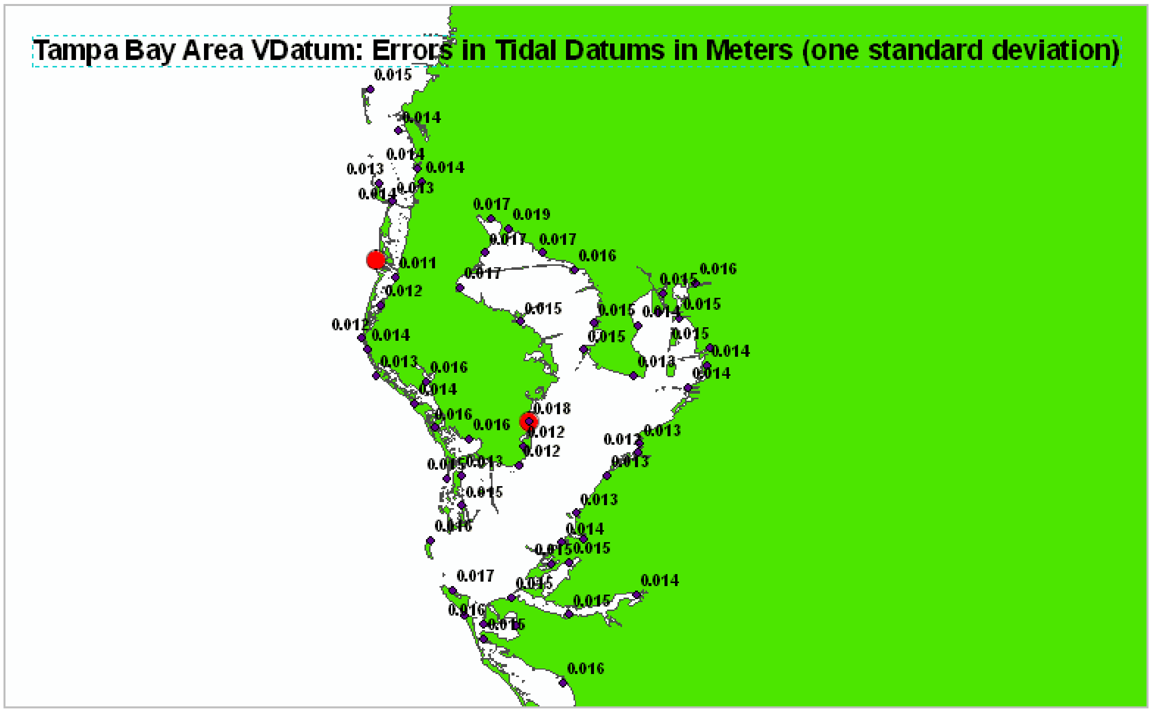


Figure 5.1. Estimated errors in tidal datums (including MSL) for tide stations in the Tampa Bay Region.

Sea Level Trends

As discussed in chapter 2, relative sea level trends can be computed from observed monthly mean sea level observations at tide stations. Assuming that the trends are linear over the period of the observations, a least squares linear fit can be used to determine the trends and estimate the standard error of the trends. Zervas (2009) discusses how standard errors can be computed while determining linear least squares fits. Accounting for the average seasonal cycle by using an autoregressive formula and a time series over 30 years minimizes the standard error, and uncertainty is the trend estimate.

As mentioned in previous sections, the standard errors can be transformed into 95% confidence intervals that, for application to relative sea level trends, are highly dependent upon record length (figure 5.2).

Sea level trends should always be provided as the computed trend, along with information on the uncertainty of the trend, and are usually expressed as 95% confidence intervals.

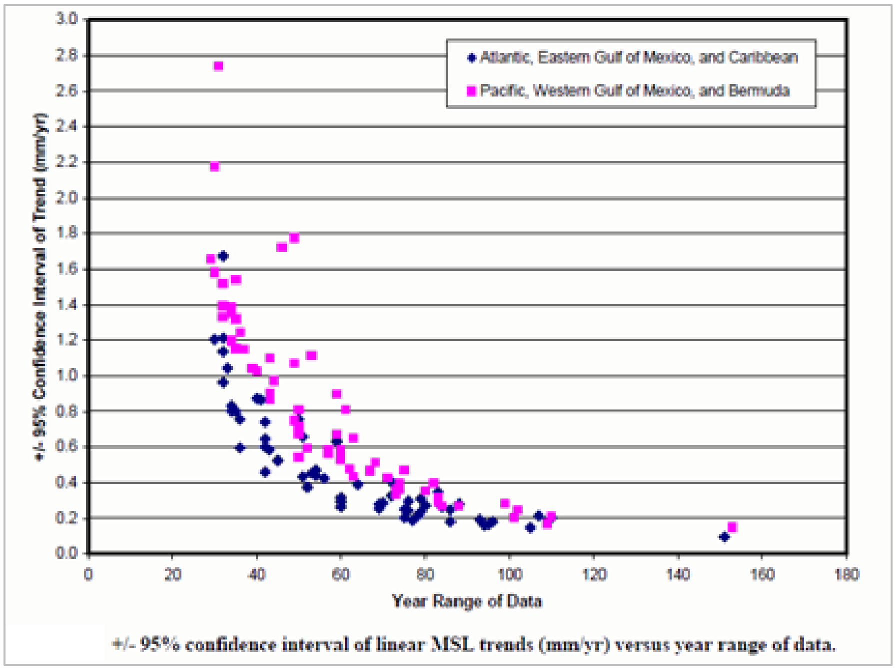


Figure 5.2. Confidence intervals and record length dependencies for relative sea level trend (Zervas 2009).

Relative sea level trends can be highly variable within geospatial regions of significant vertical land motion, especially in area of localized subsidence due to fluid withdrawal (fossil fuels or water), isostatic rebound (recent retreat of glaciers), or post earthquake response. Depending upon a particular area of interest or project, the sea level trends from several locations in the region should be assessed for regional consistency and to understand any particular anomalous trend.

5.1.2 Elevation

Geodetic Leveling

The National Geodetic Survey (NGS) publishes and maintains guidelines for performing accurate surveys to establish ellipsoidal and geodetic elevations on the land. Errors in elevation are often associated with the methodology and equipment used to perform a survey.

The *NGS Manual on Geodetic Leveling* (NGS, 1981)[2] provides information on elevation error sources using classic geodetic leveling techniques between bench marks. Updated information on survey elevation errors in the context of NAVD 88 is found in Zilkoski (1992)[3].

Geodetic leveling determines the height differences between adjoining points. It can be extended over large distances and/or densified in a local area. Hundreds of thousands of kilometers of

---

[2] See: various sections and sections 3.1.2 and 3.1.3 in http://www.ngs.noaa.gov/PUBS_LIB/Geodeticleveling_nos_3.pdf

[3] See http://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm

leveling have been observed and adjusted throughout the United States to compute Helmert orthometric heights for thousands of bench marks. All bench marks have some uncertainty associated with their published height. While the uncertainty in geodetic leveling is directly proportional to the square root of the distance leveled, the actual uncertainty in published North American Vertical Datum of 1988 (NAVD 88) bench mark heights is much more complicated. A recent study (Wang 2009) shows that the error built up in NAVD 88 has a dependence on topography and may indicate second-order corrections that were not accounted for in the original adjustment of the leveling data, which led to the original datum realization.

Leveling between bench marks "near" each other, such as at one particular tide station, can be expected to agree under 1 cm (often much more precisely than that). If no vertical land motion is present, repeated leveling surveys that re-visit these marks will maintain this integrity, predicated on lack of disturbance at each mark and presuming proper field procedures are followed. For example, using geodetic leveling standards, two points 40 km apart with second-order/class one heights have an uncertainty between them of [1.0 mm × (SqRt(40)) = 6.3 mm]. Numerous factors combine to make it likely that two points may not agree that well today, years after the most recent leveling. For example, one or both points could have been disturbed since their last leveling.

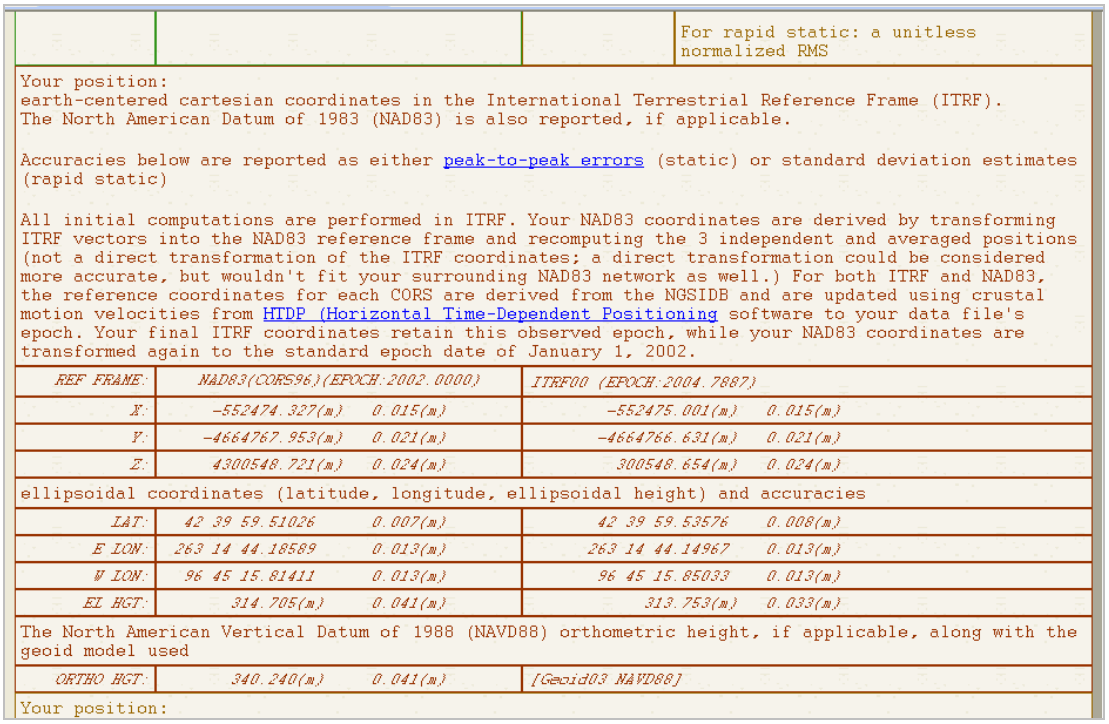
GPS Surveying

With the completion of the general adjustment of the NAVD 88 (Zilkoski et al. 1992), computation of an accurate national high-resolution geoid model (currently GEOID 09, and publication of NGS' *Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm) NGS-58* (Zilkoski et al. 1997), NGS has demonstrated that GPS-derived orthometric heights can provide a viable alternative to classical geodetic leveling techniques for many applications.

NGS-58 issued guidelines for performing GPS surveys intended to achieve ellipsoid height *network* accuracies of 5 cm and ellipsoid height *local* accuracies of 2 cm or 5 cm (Zilkoski et al. 1997). The official definitions of "local" and "network" accuracy are those adopted by the Federal Geodetic Control Subcommittee (FGCS 1998) of the Federal Geographic Data Committee. NGS-59 (Zilkoski et al. 2008) developed guidelines for performing GPS surveys intended to achieve orthometric height *network* accuracies of 5 cm and orthometric height *local* accuracies of 2 cm or 5 cm. The guidelines were developed in partnership with Federal, state, and local government agencies, academia, and independent surveyors.

NGS-59 also addresses errors from the NGS Online Positioning User Service (OPUS) in the context of the need to have higher accuracies: "Readers may rightly ask why campaign-style guidelines are needed in an era when NGS' OPUS yields "peak-to-peak" consistency in ellipsoid heights at the 2-3 cm level, with as little as 15 minutes of GPS data (roughly equal to a network accuracy of 4-6 cm), and the latest hybrid geoid models of NGS have "local accuracies" as small as 1 cm over 10 km in some states. The answer is that using tools such as OPUS and hybrid geoids to achieve NAVD 88 Helmert orthometric heights achieve 5-cm network accuracies only *rarely* and 2-5 cm local accuracies *occasionally* (due to the combined errors of both the GPS and geoid). In contrast, the campaign-style guidelines contained in this document are intended to achieve those accuracies *almost always*. When tools such as OPUS and hybrid geoid models can single-handedly achieve a similar success rate, these guidelines should certainly be modified to reflect those results" (Zilkoski et al. 2008).

OPUS can be found at http://www.ngs.noaa.gov/OPUS/about.html.



```
                                              For rapid static: a unitless
                                              normalized RMS
Your position:
earth-centered cartesian coordinates in the International Terrestrial Reference Frame (ITRF).
The North American Datum of 1983 (NAD83) is also reported, if applicable.

Accuracies below are reported as either peak-to-peak errors (static) or standard deviation estimates
(rapid static)

All initial computations are performed in ITRF. Your NAD83 coordinates are derived by transforming
ITRF vectors into the NAD83 reference frame and recomputing the 3 independent and averaged positions
(not a direct transformation of the ITRF coordinates; a direct transformation could be considered
more accurate, but wouldn't fit your surrounding NAD83 network as well.) For both ITRF and NAD83,
the reference coordinates for each CORS are derived from the NGSIDB and are updated using crustal
motion velocities from HTDP (Horizontal Time-Dependent Positioning software to your data file's
epoch. Your final ITRF coordinates retain this observed epoch, while your NAD83 coordinates are
transformed again to the standard epoch date of January 1, 2002.
  REF FRAME:   NAD83(CORS96)(EPOCH:2002.0000)   ITRF00 (EPOCH:2004.7887)
          X:    -552474.327(m)   0.015(m)          -552475.001(m)   0.015(m)
          Y:   -4664767.953(m)   0.021(m)         -4664766.631(m)   0.021(m)
          Z:    4300548.721(m)   0.024(m)           300548.654(m)   0.024(m)
ellipsoidal coordinates (latitude, longitude, ellipsoidal height) and accuracies
        LAT:   42 39 59.51026    0.007(m)          42 39 59.53576   0.008(m)
      E LON:  263 14 44.18589    0.013(m)         263 14 44.14967   0.013(m)
      W LON:   96 45 15.81411    0.013(m)          96 45 15.85033   0.013(m)
     EL HGT:         314.705(m)  0.041(m)                313.753(m) 0.033(m)
The North American Vertical Datum of 1988 (NAVD88) orthometric height, if applicable, along with the
geoid model used
  ORTHO HGT:         340.240(m)  0.041(m)      [Geoid03 NAVD88]
Your position:
```

Figure 5.3. Sample output from OPUS, showing the *x-y-z* positional values and their associated errors.

5.1.3 Topographic Mapping

When quantifying error in topographic map data, it is important to know whether you are using data where an accuracy assessment has already been performed. If the data error has been quantified, the first place to look is in the metadata record. Within Federal Geographic Data Committee (FGDC)-compliant metadata, a section titled "Data Quality" provides a general quality assessment of the data set. This section may provide horizontal and vertical positioning accuracies, attribute accuracy, lineage, processing steps, and contact information. If an accuracy assessment has not been performed for the dataset, the data must be evaluated for acceptability.

A quantitative approach is the most common method for assessing/validating the horizontal and vertical accuracies of a topographic data set. This process initially begins with the collection of independent, higher accuracy ground control data or check points to be used for assessing the topographic data set of interest. Generally, the accuracy of the check points should be an order of magnitude better than the data being evaluated. The check points are then used for computing errors and performing accuracy test. There are a myriad of ways to assess and specify accuracies. The following documents provide different guidelines and specifications for performing quantitative accuracy assessments on topographic data.

National Map Accuracy Standards (NMAS):
Bureau of the Budget, 1947. *National Map Accuracy Standards (NMAS)*, Office of Management and Budget, Washington, DC.

National Standard for Spatial Data Accuracy (NSSDA)
FGDC 1998. Geospatial positioning accuracy standards, Part 3: National standard for spatial data accuracy (NSSDA), Federal Geographic Data Committee (FGDC), URL: http://www.fgdc.gov/standards/standards_publications/.

Federal Emergency Management Agency (FEMA) Guidelines and Specifications:
FEMA 2003. Appendix A, Guidance for aerial mapping and surveying, in *Guidelines and Specifications for Flood Hazard Mapping Partners*, Federal Emergency Management Agency (FEMA), April 2003, URL: http://www.fema.gov/plan/prevent/fhm/gs_main.shtm.

National Digital Elevation Program (NDEP) Guidelines:
NDEP 2004. Guidelines for digital elevation data, Version 1.0, National Digital Elevation Program (NDEP), May 10, 2004, URL: http://www.ndep.gov.

American Society for Photogrammetry and Remote Sensing (ASPRS) Guidelines for Lidar:
ASPRS 2004. ASPRS guidelines, vertical accuracy reporting for lidar data, American Society for Photogrammetry and Remote Sensing (ASPRS), May 24, 2004, URL: http://www.asprs.org/society/committees/standards/standards_comm.html.

Chapter 3, Accuracy Standards and Chapter 12 DEM Quality Assessment:
Maune, D.F., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Although a topographic data set may pass a quantitative accuracy assessment, anomalies can still be present and can be identified through a qualitative assessment. Technologies used today for acquiring topographic data produce enormously dense data sets. The quantitative assessment usually samples only a small portion of the data set. Visualizing the dataset can provide a method for finding anomalies such as voids or a data holiday, biases between flight line swaths or tile seam lines, striping or banding, data density issues, and outliers. Viewing the topographic data set in a three-dimensional (3-D) perspective or creating by-products, such as slope or shaded relief surfaces, can facilitate the detection of problematic issues. Therefore, a blend of quantitative and qualitative methods should be employed to assess the validity, completeness, and cleanliness of the dataset to be exploited.

USGS National Elevation Dataset (NED)

The accuracy of the USGS National Elevation Dataset (NED) (Maune 2007) varies spatially because of the variable quality of the source DEMs. As such, the NED inherits the accuracy of the source DEMs. In an effort to provide more information to users on the vertical accuracy of the NED, the data set has been tested by comparing it to an independent reference source of high accuracy. The reference data are the geodetic control points that NGS uses for hybrid geoid modeling (known as "GPS on bench marks", or GPSBMs (Wang et al. 2010). The overall absolute vertical accuracy, expressed as the root mean square error (RMSE), is 2.44 meters (m). As better sources of data are incorporated, the accuracy improves.

For some applications of elevation data, the relative, or point-to-point, vertical accuracy is more important than the absolute vertical accuracy. Whereas absolute accuracy accounts for the combined effects of systematic and random errors, relative accuracy is a measure of only random errors. Averaged over all 9,187 point pairs, the relative vertical accuracy is 1.64 meters for points separated by less than 50 km.

One caveat to note about the accuracy assessment presented here is that, even though the reference control point data set is large, the number of quadrangle-based USGS DEMs on which the points are located is relatively small. Thus, if users have a need for very specific accuracy NED information for a local area, a separate assessment should be done with suitable reference data only for that area.

5.1.4 Bathymetry

NOS Bathymetry Terminology

Sounding: A measurement from the sea surface to the seafloor, regardless of method—acoustic or otherwise; e.g., echosounder, lidar, lead line, diver's least depth gauge, etc. A "sounding" may be corrected for factors (e.g., for echosounder soundings: sound speed, vessel draft, and water levels for normalizing to a common datum), but remains the product of a single measurement sample.

Depth: A fully-processed seabed elevation value relative to an established vertical datum, calculated from each sounding or otherwise formulated into a gridded dataset or a navigation product surface. A hydrographic survey "depth" may be computed based on statistical analyses and uncertainty estimates from a sample set of "soundings". Rounding of depth values may be unbiased (round half up) or biased (e.g., shoal-biased rounding).

Bathymetry Attributed Grid (BAG): A gridded bathymetry product that includes co-registered data uncertainty measures and built-in FGDC-compliant metadata documentation.

Charted Depth: A depth destined for portrayal on a nautical chart. Navigation product surface "charted depths" typically have some amount of shoal-biasing applied (e.g., NOAA cartographic rounding) in the interest of safety-of-navigation.

Error and Uncertainty

“Errors” in the three-dimensional (3D) values of bathymetry are typically partitioned into components of the one-dimensional (1D) uncertainty in depth value and the two-dimensional (2D) uncertainty in depth horizontal position. A given component of bathymetric uncertainty may be reported about the reference value (the depth- or position-value estimate) in terms of a scalar residual at a specified confidence interval. Whether such a uncertainty value is a veracious gauge of (true) error is dependent upon the inclusion of all systematic biases, in addition to all the random errors involved with the bathymetric measurement system (accuracy versus precision). Scalar confidence interval estimates assume a certain statistical error distribution. Root mean square (RMS) error or standard deviation simplifies the otherwise bivariate distribution of the (2D) horizontal position statistic, and scaling of the RMS for some stated confidence level percentage entails an assumption about the (fixed) correlation between horizontal components. For example, two-times distance RMS (2*d*RMS; here, *d* means "distance”, to emphasize the scalar or 1D nature of the statistic) may be a pessimistic estimate of the 95% confidence interval.

When the bathymetry is packaged in terms of a surface model, the 1D uncertainty in depth value may be the single relevant statistical assessment of bathymetric error. That is, a surface model of bathymetry may be constructed using a set of a priori locations that do not involve any measurement process; rather, sounding measurements and uncertainty are statistically assimilated to most-probable depth estimates at desired “perfect” horizontal grid locations. The Combined Uncertainty and Bathymetric Estimator (CUBE) method used by NOAA is an example of how such a bathymetric surface model may be assimilated (Calder and Wells 2007). NOS-finalized CUBE surfaces are packaged into the BAGs and archived at NGDC. BAG uncertainties may be propagated through the additional data integration and interpolation steps involved in the sea level change synthesis.

Uncertainty Standards

NOS specifications for bathymetric uncertainty are based partly on the International Hydrographic Organization (IHO) Standards for Hydrographic Surveys as outlined in *Special Publication 44 (S-44)*, 5th Edition (IHO, 1998). IHO S-44 specifications are suggested minimum standards that member states may choose to follow. The IHO minimum standards for uncertainty are used in the *NOS Hydrographic Survey Specifications and Deliverables* (NOS 2009) as a convenient point of reference. NOS standards for uncertainty in hydrographic surveys apply to general water depths and least depths over wrecks and obstructions. By extension, they also apply to the elevations of rocks or other features that uncover at low water and to the measurement of overhead clearances. Additionally, the NOS standards apply regardless of the method of determination; whether by single-beam echosounder, multi-beam echosounder, lidar, lead line, diver investigation, or other method.

The NOS standard for the maximum allowable Total Horizontal Uncertainty (THU) in position of *soundings* shall not exceed a radial measure of 5 meters + 5% of the depth, at the 95% confidence level.

The NOS standard for the maximum allowable Total Vertical Uncertainty (TVU) for depth values included in processed bathymetric data at the 95% confidence level, after application of "correctors" for all system-specific random and systematic errors is according to the formula:

$$\pm\sqrt{a^2 + (b \star d)^2}$$

Where:

a	represents that portion of the uncertainty that does not vary with depth
b	is a coefficient which represents that portion of the uncertainty that varies with depth
(b × d)	represents that portion of the uncertain that does vary with depth *d* is the depth

The variables *a* and *b* shall be defined as follows:
In depths less than 100 meters, *a* = 0.5 meters and *b* = 0.013 (IHO Order 1)
In depths greater than 100 meters, *a* = 1.0 meters and *b* = 0.023 (IHO Order 2)

5.1.5 Composite Error Budget Considerations

Each of the errors for the data layers previously discussed (water level data, tidal datums and sea level trends; topographic data and bathymetric data) must be considered when applying them to a sea level risk assessment, map, or data integration process. Sea level trends are determined at the millimeter per year level and their impacts are determined in terms of centimeters by 2100, or in some cases1 meter and above, depending upon climate scenario. Tidal datums errors are described in terms of a few centimeters. The topographic and bathymetric data sets have errors of several centimeters. Users of these data must consider an overall target error budget, depending upon the application and desired outcome, and be careful in their conclusions not to overstate or imply accuracy that cannot be supported by the accuracies of the fundamental layers described above. A baseline DEM built on the fundamental data sets cannot have accuracies implied at the few centimeter or millimeter level. Considering the accuracy of the source data and the limitations of graphical representation, realistic impacts of sea level rise generally cannot be depicted on bathymetric and topographic elevation layers for incremental changes in sea level of a few millimeters but must be visualized using increments of several centimeters. The following sections in this chapter describe integrating data sources in the context of error and uncertainty.

5.2 Integration of Multiple Data Sources to Better Address Sea Level Issues

5.2.1 CORS and Tide Stations

The Continuously Operating Reference Station (CORS) network is an international network of GNSS stations established for long-term operation (section 3.2.1) and serves as one of the fundamental observing systems of the National Geodetic Survey (NGS). CORS data can be used to compute continuous precise time series of land movement, both horizontally and vertically, at the location of the instrument. The ability to provide millimeter per year resolution in vertical land movement is most useful to the sea level community. When co-located with a long-term tide station, the two “signals” for the land and the ocean can be combined for a better understanding of impacts of both local and global sea level variations. Snay (2007) estimates that the standard error for a GPS-derived vertical velocity is reduced from over 3 mm/yr with a two-year observation period to just above 0.5 mm/yr with a 12-year period. The NGS CORS network has been established only over the last two decades as the technology matured, so data sets of several decades have not yet been accrued. Zervas (2009) estimates that the standard error for a linear relative mean sea level trend from tide gauge data is reduced from approximately 3.0 mm/yr for a 20-year record to less than 0.5 mm/yr for a 60-year record length.

The benefit of a CORS is that very accurate rates of local land motion that have previously only been estimated from local leveling or the inferred geologic models and indirect measurements can now be obtained. Subtracting out the land movement provides a method for converting the relative sea level change into a point estimate of the regional signal of global sea level change. No matter the source of the motion (local fluid withdrawal, continental glacial isostatic adjustment (GIA), earthquakes and related relaxation, etc), a CORS will detect the composite motion and allow it to be removed from the relative sea level change record that the tide gauge provides.

Once subtracted from the relative sea level trends from a co-located or nearby tide gauge record, the composite analysis with similar analysis of other tide gauges can also provide an estimate of absolute global sea level change. Snay (2007) estimates a 1.80 ±0.18mm/yr rate of change using tide gauge data from a 1900–1999 period from 50 stations in North America and the Pacific Islands and assuming constant vertical velocities found from the nearby CORS data.

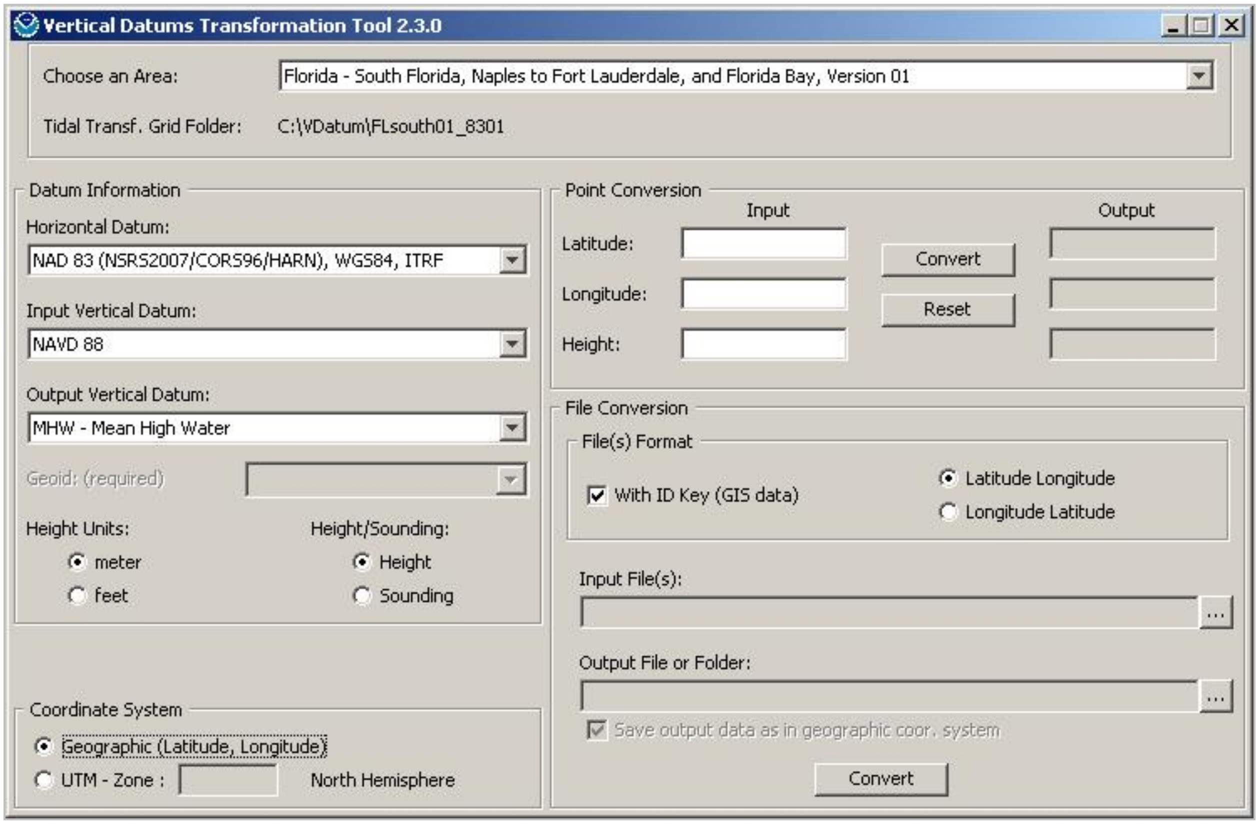
5.2.2 VDatum and How It Can Be Used

VDatum is a free software tool that is being developed jointly by NOAA’s National Geodetic Survey (NGS) (http://www.ngs.noaa.gov), Office of Coast Survey (OCS) (http://nauticalcharts.noaa.gov), and Center for Operational Oceanographic Products and Services (CO-OPS) (http://www.tidesandcurrents.noaa.gov). VDatum (figure 5.4) is designed to transform geospatial data between a variety of vertical (and horizontal) datums. This allows users to convert their data from different vertical references into a common system, which enables the fusion of disparate geospatial data, particularly in coastal regions.

VDatum currently supports vertical datum transformations that can be placed into three categories:

- **Ellipsoidal:** realized through GNSS systems.
- **Orthometric:** defined relative to a geopotential surface and realized through geodetic leveling from bench marks with published heights.
- **Tidal:** based on a tidally-derived surface in the vicinity of a tide gauge.

The software is currently available for certain areas of the U.S. (figure 5.5) and supports many diverse applications. The VDatum tool allows for transformation of a single height/depth or file/files of points from one vertical datum to another. Uncertainties associated with VDatum are currently being made available to inform users when transforming heights/soundings among the various supported vertical datums.



Vertical Datums Transformation Tool 2.3.0

Choose an Area: Florida - South Florida, Naples to Fort Lauderdale, and Florida Bay, Version 01

Tidal Transf. Grid Folder: C:\VDatum\FLsouth01_8301

Horizontal Datum: NAD 83 (NSRS2007/CORS96/HARN), WGS84, ITRF

Input Vertical Datum: NAVD 88

Output Vertical Datum: MHW - Mean High Water

Height Units: ● meter ○ feet

Height/Sounding: ● Height ○ Sounding

Coordinate System: ● Geographic (Latitude, Longitude) ○ UTM - Zone : North Hemisphere

☑ With ID Key (GIS data)

● Latitude Longitude ○ Longitude Latitude

☑ Save output data as in geographic coor. system

Figure 5.4. The VDatum software interface for converting between vertical datums.

VDatum enables:

- The extraction of consistent, non-interpreted tidal datum based shoreline from lidar.
- Vertically referencing hydrographic surveys collected relative to the ellipsoid, eliminating time-consuming water level corrections.
- Enabling the fusion of diverse geospatial datasets on one common vertical datum.

Additional information, the software, user’s guides, education material, and references to reports and papers can be found:

- On the Web:
  http://vdatum.noaa.gov
- By email:
  vdatum.info@noaa.gov

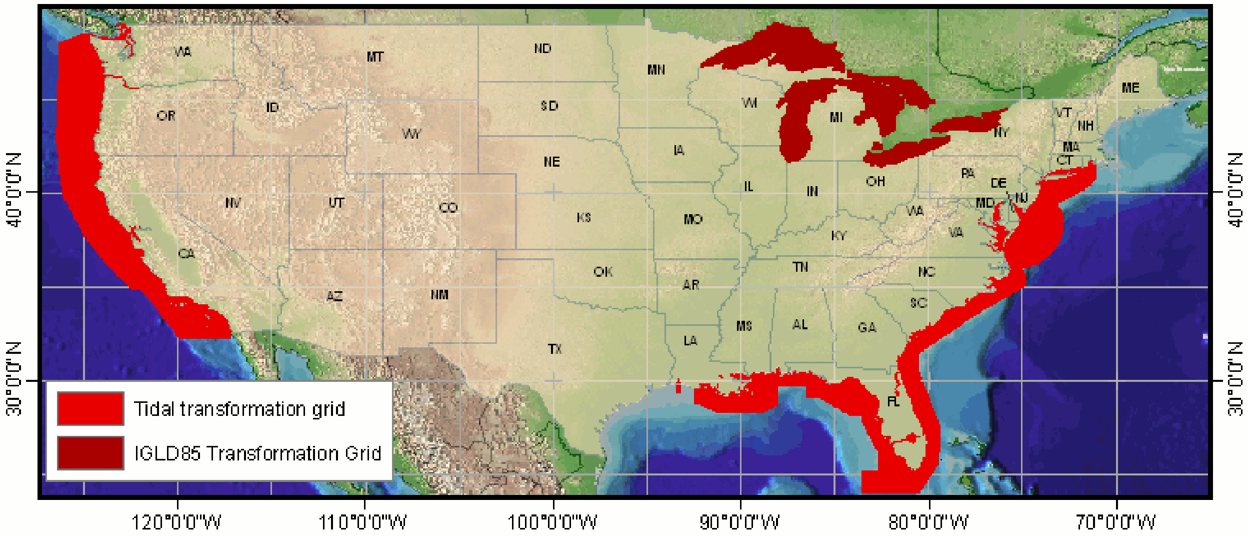


Figure 5.5. Current VDatum coverage as of July 16, 2010

Limitations

Estimation of Vertical Uncertainties in VDatum

Users of VDatum should be aware of the potential uncertainties, or errors, in computed heights when applying the software to convert values between vertical datums. Random errors in VDatum may arise from inaccuracies in either the gridded fields employed in the datum transformations, such as GEOID 09 or the mean sea level (MSL)-to-mean higher high water (MHHW) transformation, or in the source observational data used to create VDatum, such as the elevation of the tidal datums or the height of the North American Vertical Datum of 1988 (NAVD 88). Users should also be aware of the existence of measurement errors in their own vertical elevation data, i.e., uncertainties related to bathymetric measurement, GPS measurement, leveling, etc.

There are, however, inconsistencies in the datum field input resolutions. Additionally, some areas present higher unresolved hydrodynamic and datum relationship complexities that would require additional gauging to achieve some required minimum "full model" accuracy. Tide data/datum and geodetic relationship requirements were not targeted at a prescribed accuracy prior to the development of the initial models and therefore inconsistencies exist in the resolution of these data. Future operational plans will address data needed to develop models to meet some minimum accuracy across the gridded models. Also, subsequent quality assessments are limited to validating transformations at tide gauge sites only, whereas assessing the value of VDatum should occur along shore and offshore where tide gauges are not generally available. Formal VDatum model evaluation procedures are being developed to ensure user knowledge of the variable uncertainties and observational plans include use of GPS buoy technology to enhance offshore measurements for model calibration and evaluation. For the evaluation of VDatum, the standard deviation (SD) is the primary statistical variable used to quantify the random uncertainty in both the vertical datums (i.e., the source data) and the transformations between them. Standard deviation is a measure of the average size of the errors in a data set (when errors are normally distributed) and is denoted by the Greek letter sigma (σ). Uncertainties for the source data and transformations in the Chesapeake Bay VDatum region are shown in figure 5.6 as an example.

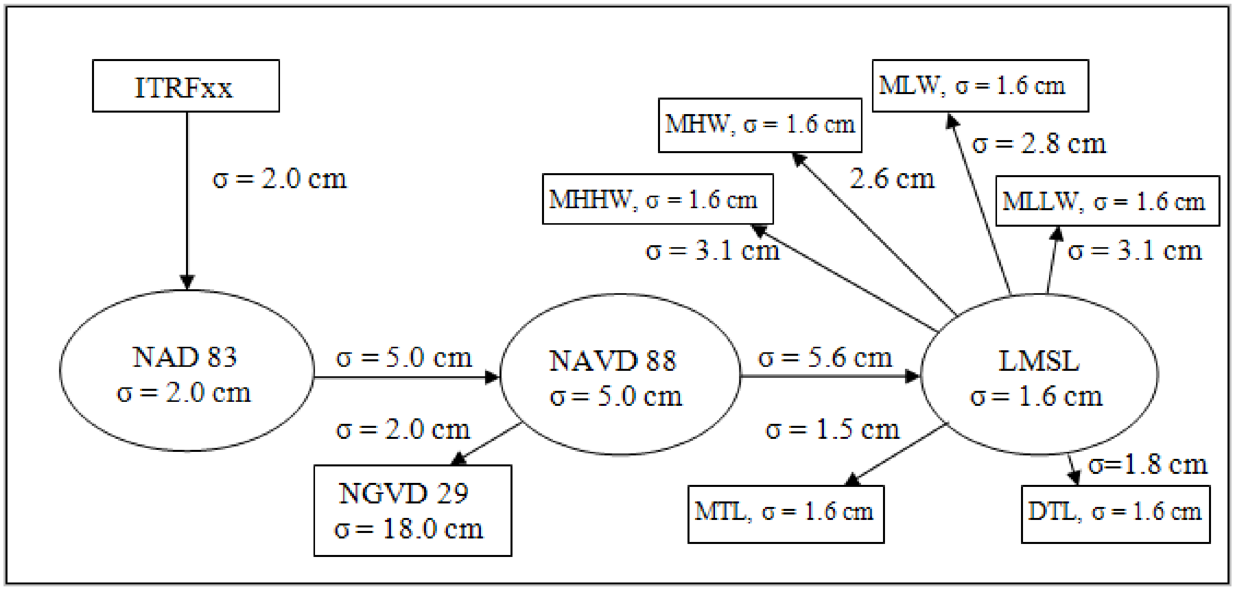


Figure 5.6. Schematic shows how VDatum handles the transformation (arrows) of a value from an ITRFxx ellipsoid to several vertical datums (boxes) through the core datums (ovals) for the Chesapeake Bay VDatum region. Estimated errors in the transformations are shown as standard deviation values (σ) and are placed next to the arrow relating to each transformation. The estimated uncertainties for each individual vertical datum, shown as the σ values inside the ovals/boxes are also included.

Total random uncertainty for a sequence of conversions such as those used in VDatum is obtained by taking the square root of the sum of the squares of the individual uncertainties. Total uncertainty also includes systematic errors such as those due to land subsidence or sea level rise. (The present study currently does not include these systematic errors.). A preliminary assessment of VDatum uncertainty using the Chesapeake Bay region as an example (figure 5.6), reveals that the uncertainty due to only the transformations from the International Terrestrial Reference Frame of year *XX* (ITRF*xx*) through the North American Datum of 1983 (NAD83), NAVD 88, and local mean sea level (LMSL) to a tidal datum (i.e., MHHW) can be as large as 8.36 cm (the maximum in Chesapeake Bay occurs when the tidal conversion is to either MHHW or MLLW). An explanation of how this number was computed appears in the “Accuracy of Transformations” section of the uncertainty documentation available on the VDatum website (http://vdatum.noaa.gov/docs/est_uncertainties.html). In addition, the uncertainty due to only the source data is 5.84 cm. An explanation of how this number was computed appears in the “Accuracy of the Source Data” section of the Web documentation.

The maximum cumulative uncertainty (MCU) is the value of cumulative uncertainty for the transformation from ITRF*xx* to the tidal datum whose transformation has the greatest uncertainty. For the Chesapeake Bay region, that tidal datum transformation is to MHHW or

MLLW. The maximum cumulative uncertainty therefore represents uncertainty, expressed as the standard deviation of the error. If the errors are normally distributed, then 68% of the errors will be smaller than the MCU when using VDatum, and 95% of the errors will be smaller than 1.96 times the MCU. The MCU values for most VDatum regions have been computed and are shown in the website text. NOAA is actively engaged in updating this methodology, adding new regions of coverage and improving the VDatum files for the various existing regions.

Further in-depth information about the uncertainties associated with VDatum can be found at: http://vdatum.noaa.gov/docs/est_uncertainties.html

Limited Coverage for Tidal Datum Transformations:

Another limitation of the VDatum software is the limited areal coverage where tidal datum transformations are permitted inland from the land/water interface. Transformations between ellipsoid heights in different geometric reference systems are available worldwide. Transformations between NAD83 ellipsoid heights and NAVD 88 Helmert orthometric heights are currently available in regions where NGS has developed an appropriate hybrid geoid model. Tidal transformations are only available for select regions (figure 5.5) of the U.S. where tidal datum fields have been created. Figure 5.7 demonstrates where the VDatum software will allow/restrict the transformation to a tidal datum in the La Jolla, CA vicinity. Areas of the image that are shaded green are where height/sounding data can be transformed to a tidal datum. Transforming elevation data in a red shaded area of the image returns a value of −999999, informing the user that a tidal transformation is invalid (not allowed). Tidal datum transformations are usually allowed approximately 100 meters landward from the land/water interface. Research is currently being performed to extend the validity of tidal datum transformations further inland. More detail can be found in section 5.2.2 (*Extrapolating Beyond the Grid)*.

Figure 5.7. Illustrated are the areal extents of where VDatum allows/restricts tidal datum transformations.

Further VDatum limitations being addressed by the NOAA VDatum team:

- Transition of VDatum into operational hydrographic surveying and GIS software packages. The VDatum team is working toward coordination with software manufacturers on VDatum coverage, dynamic-link libraries, file formats, etc.
- Development of improved uncertainty estimates, including the possibility of spatially-varying uncertainties.
- More automatic and real-time updating of VDatum transformation fields to account for new data (tidal, ellipsoidal, orthometric), updates to data (epoch adjustments, data corrections), and updates to models (tidal and geoid).
- Transformations between tidal datums and ellipsoidally-referenced datums currently require intermediate transformations through the geoid. The VDatum team is evaluating the possibility of having direct transformation fields between the tidal datums and ellipsoidally-referenced datums through the use of GPS data on tide gauges.
- VDatum is evaluating the possibility of incorporating offshore data and models that could help improve the offshore accuracy of the sea surface topography.

Extrapolating Beyond the Grid

Tidal datum transformations in VDatum extend only slightly beyond the mean high water (MHW) shoreline, but many applications seek to reference to tidal datums further inland. One example is the application of VDatum to lidar data to compute a shoreline referenced to a tidal datum. Lidar data collected during low tides can be processed in VDatum and referenced to MHW. The resulting contours of the MHW-referenced data at a value of zero will then represent the MHW shoreline. If the tidal datum transformations do not extend far enough inland to make this transformation, though, users must make decisions about how to manually readjust the datum transformations to enable the shoreline computation to be made.

Another example of a need to extend tidal datum transformations further inland can occur with sea level change studies that are making static assumptions to look at which areas of a digital elevation model (DEM) would be influenced if sea level were adjusted by a fixed amount. If the DEM heights are referenced to a tidal datum, then transformations are necessary in inland areas affected by sea level rise scenarios.

Variations in the nearshore tidal datums influence the method of approximating their inland extension, no matter whether the extension is for shoreline determination studies or static sea level change scenarios. Tidal datums along a coastline can vary locally for many reasons, some of which include bathymetry, tidal flats, river interactions, presence of barrier islands, geographic/volumetric changes in the shoreline and associated embayments, and the presence of shoreline engineering structures. If none of these factors affects a given area (e.g. straight coastline, absence of other factors mentioned above), extrapolation of the tidal datums can usually be made by assuming a constant datum difference to be extended inland. For example, Figure 5.8 shows how a constant offset between NAVD 88 and local mean sea level could be extended inland.

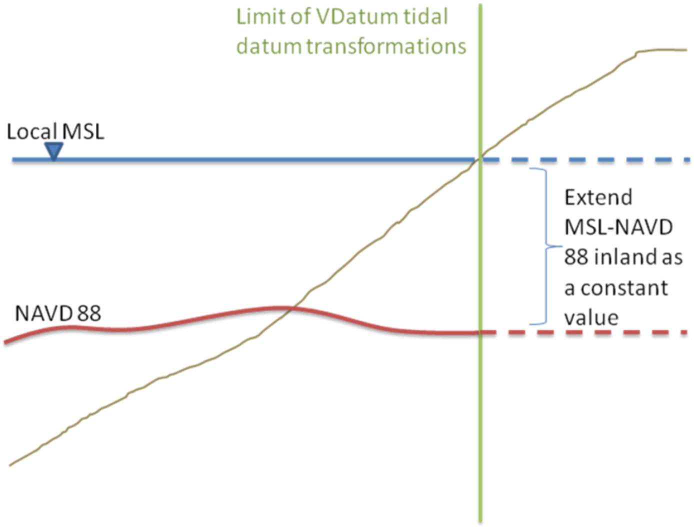


Figure 5.8. Assuming a constant vertical datum transformation offset to be extended inland.

However, after evaluation of the extension of tidal datum fields inland, most scenarios encounter some level of complexity due to the factors affecting local tidal datum variations. Therefore, some assumptions need to be made, while also acknowledging the uncertainty that can arise due to the associated factors. For example, figure 5.9 illustrates several inland locations for which decisions would be made on how to extrapolate tidal datums inland. The star symbols in these figures indicate the inland locations in question, with sections of Chesapeake Bay on the left and of North Carolina on the right. Questions that might arise in such an extrapolation include:

> Should the user extrapolate from the nearest water point, from the nearest river location, or from the nearest bay/ocean value?
>
> Because there is more uncertainty in tidal datums in rivers, marsh areas, and tidal flats, should the user extrapolate from a VDatum location in one of these regions?
>
> If the location is on a barrier island, should the user extrapolate from the ocean or inland waterway side?
>
> Does the user want the extrapolation routine to blend the tidal datums between the river and bay sides, and if so, is that physically realistic?

The common element in all of these questions is related to the fact that tidal datums have no physical meaning inland (until or unless that inland location becomes inundated), but the applications need to make some assumption about how to vertically reference them based on the issue being resolved, such as preparing for potential inundation. The user must be aware of local tidal datum variations due to a variety of factors, and any extrapolation/interpolation routine used to extend them inland should evaluate those factors as part of the decision process.

No matter what decision is made on how to extrapolate the tidal datums in such situations, it is suggested that statistics be computed on the variability of the datum transformations in the user's area of interest. This information can then be used to document the uncertainty introduced by assuming a certain interpolation scheme or even by using a constant offset value. In some cases, the variability in transformation values between different regimes (river, bay, ocean, marsh, tidal flats, etc.) may be small enough in relation to the coastal issue being addressed.

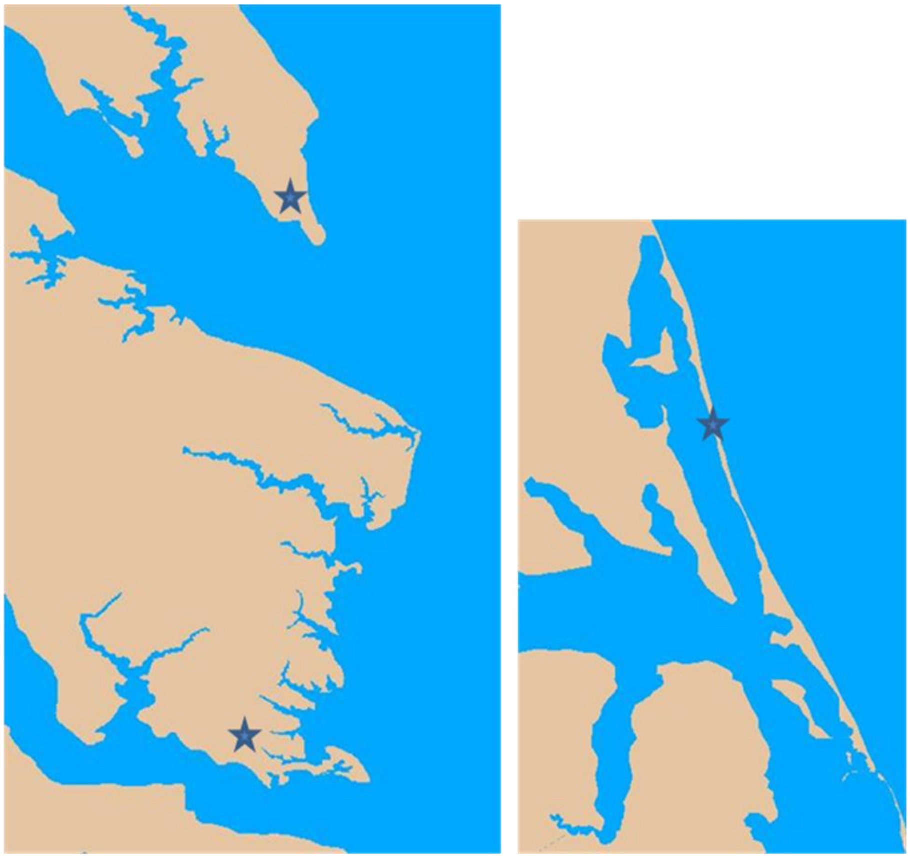


Figure 5.9. Locations (shown in stars) for which extrapolating tidal datums inland is more complex due to proximity to waters of different tidal regimes. The left figure shows a portion of Chesapeake Bay, and the right figure shows some of the barrier islands off North Carolina.

In extending tidal datums inland for sea level change (SLC) studies, the assumptions of how that change will occur need to be considered. For example, if sea level rises by a constant amount in a region, the tides will also change due to new areas now being flooded or dried. The local tide patterns used to construct VDatum may no longer be completely applicable if significant changes occur as a result of a sea level change scenario. For example, a barrier island may be so low that in some sea level rise scenarios some parts of the island would be breached. This changes the flow of water significantly, allowing the tides to more easily propagate into the inland waterway. Marshes and tidal flats can likewise be flooded and/or dried in sea level change scenarios, thus changing the local tidal datum patterns accordingly. Aside from the static effects of these SLC scenarios, dynamic influences related to morphological changes to the marshes and shoreline environments would also be present. Sediment erosion and marsh accretion would change in ways that could only be evaluated through detailed studies that link processes across a variety of scales together in a physically realistic manner.

Quantifying how all of these static and dynamic effects could change tidal datums extended inland is a difficult task. In many cases, it may be more appropriate to make an assumption of a constant datum transformation offset to be used for the area of interest, while acknowledging these effects in the documentation of the uncertainty. A constant offset, (e.g. between NAVD 88 and local mean sea level) could be determined by examining an offshore average difference between these two datums, far enough away from local factors affecting the nearshore tidal datum patterns. This offset could then be applied to transform topographic land heights from NAVD 88 to local mean sea level.

What to Do When VDatum is Not Available

The report *Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration; Part II of a Roadmap to a Seamless Topobathy Surface*, included in the references, outlines different methods for applying vertical datum transformations to data. While the report describes VDatum and recommends it for areas where available, it also provides analysis of the benefits and limitations of other methods that may be used when VDatum is not available. These options include interpolation algorithms and the harmonic constant datum method. This report is available on the Web at the following address: http://www.csc.noaa.gov/topobathy/topographic-and-bathymetric-data-considerations.pdf

If cost effective for the desired application and accuracies, it may be advisable to obtain new data to interpolate between existing locations. This may require installing a tide station and determining new/or updated tidal datums on bench marks, as well as using GPS surveying methods to establish a geodetic datum connection (see chapter 3). For topographic elevation requiring better accuracy than VDatum and lidar, it may be advisable to conduct a localized survey using Kinematic GPS surveying procedures, along with the point measurements established by a tide station and static GPS survey.

As a note, almost all valid applications requiring the use of datums and transformations of datums have some prescribed accuracy for respective applications. Users should perform an error assessment of the desired product or outcome to see if VDatum may be of limited use as a tool.

5.3 How to Build Integrated Data Products Such as a Digital Elevation Model (DEM)

5.3.1 Methodology

Several different methods exist for building Digital Elevation Models (DEM), and there is no one perfect process for deriving the optimal elevation surface. The DEM can be only a topographic data model or a blended topo/bathy surface. A topo/bathy DEM can be thought of as a surface where land elevation is combined with the sea surface floor elevation information.

The first step in building a DEM is to obtain the elevation data that is correct for the specific application. The horizontal and vertical accuracy of the data should be appropriate for the application. Another consideration is obtaining data with the needed density, for DEM creation that is suitable for the application. Note that the post spacing of elevation information obtained can be quite different between topographic and bathymetric surveys. A greater the density of data will allow for a higher resolution DEM to be created, which can enhance the ability to accurately realize sea level change results.

Attaining the necessary coverage or areal extent of elevation data is important, especially when creating topo/bathy DEMs. However, obtaining shallow water submerged topography has been a challenge in the past. Large gaps can be present from the land water interface where the topographic surveys end, seaward to where it is safe to perform the bathymetric or hydrographic surveys. Bathymetric lidar is one tool/technology that can be used to assist with acquiring this often neglected swath of elevation data when environmental conditions are feasible. Such systems as the former NASA, and current USGS Experimental Advanced Airborne Research Lidar (EAARL) fills the niche of collecting highly accurate shallow water topography, aided by the laser's short pulse width and narrow beam divergence. Additionally, obtaining data processed to the appropriate level should also be considered. For a particular sea level change scenario, the user could ask, "What is the appropriate model for this scenario? Is it a bare earth model, (elevations of the ground free from vegetation, buildings, and other anthropogenic structures) or a Digital Surface Model (DSM), (depicting the elevations of the top surfaces of buildings, trees, towers, and other features above the bare-earth surface)?"

Once the user has the data that fits the specific application, having the data in a point format assists with easing datum transformations, blending, and gridding. The next step is to transform all of the data into a common horizontal and vertical datum. For the vertical component, the topography is usually in an ellipsoid or orthometric datum, while the bathymetry is more likely referenced to a tidal surface. Converting the diverse datasets to a common reference system helps minimize the discontinuities or stair-step effect between the data sources. After the data are commonly referenced, the next step is gridding the data for a combined surface. Considerations should include what data model to use, the appropriate resolution, and what construction method or interpolation technique to employ. Again, there are several different pathways for gridding the elevation information, and the method of choice should be based on the exact application for which the data are being used.

5.3.2 Considerations When Generating DEMs

Often, elevation data are only available as point data, and the user needs to create a raster data set for use in modeling and visualization. Software and methods for performing this step are varied and can range from easy and free to complicated and expensive. Tools to handle software and create elevation surfaces range from freeware to costly commercial packages. When selecting a software package, cost is an important factor. Increased cost often results in increased functionality and analysis power, but a trade-off may be complexity of use. Inexpensive or free software may have fewer sophisticated analysis capabilities but may provide the needed tools in a simple interface.

Many statistical approaches exist to generate a DEM (surface) from point data; they include nearest neighbor, kriging, binning (min, max, average, most common), inverse distance weighted, and gridding a TIN (triangulated irregular network) surface. Several papers and textbooks discuss these approaches in detail; one suggested resource is *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition (Maune 2007). The most common are the gridded TIN and inverse distance weighted approaches. Use of the other techniques is valid but may require additional information for a specific use.

The cell size selected should be chosen to accurately represent the elevation data while considering the cost and time needed to build and run through inundation models. DEMs are commonly in raster format, largely because of its efficiency, but they can have other structures or forms as well.

The structure of the DEM grid (structured or unstructured) should also be considered. A structured grid has a uniform grid cell shape—a rectangle—with elevation values at each of the cell's four nodes or at the center of the cell. An unstructured grid (such as a TIN) has grid cells with a triangular shape so that elevation values are at each of the three nodes. Cell size can be highly variable in an unstructured grid and therefore show more detail in areas of a DEM where elevation change may be variable, such as at the shoreline, and less detail in areas of uniform elevation.

When creating elevation surfaces, special care must be taken to use the proper horizontal and vertical datums. Neglecting this step introduces avoidable error into the final elevation surface. For example, individual terrain (topography and bathymetry) data sets for topobathy surfaces may be referenced to different vertical datums, including orthometric, tidal, and ellipsoidal datums. Each of these datums is best suited for particular applications, such as water flow, navigation, and satellite positioning, respectively. A thorough discussion on resolving datum issues can be found in the NOAA Coastal Services Center's publication, *Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration* (www.csc.noaa.gov/topobathy/topographic-and-bathymetric-data-considerations.pdf).

5.3.3 Review of the DEM Surface

Quantitative Accuracy

The accuracy values are calculated by comparing surveyed ground control points (GCP) to the elevation surface. A TIN surface generated from the lidar elevation data is compared to the GCP data. A TIN surface is used because there is very little chance that the GCPs will exactly coincide with the lidar elevation data points, and a TIN is a straightforward method for interpolating a value from the nearest points.

In most cases, 20 GCPs are collected per land cover or classification category, and five different land covers or terrain types are chosen. Use of the data for specific applications may depend on the accuracy of the data for specific land covers. For example, shoreline delineation requires only a high level of accuracy in the bare-earth category, whereas flood mapping requires that both bare earth and forested areas have accuracies suitable for creating a specific contour interval. If a data set has a high bare-earth accuracy but was poorly classified for vegetation, then it may not be usable for flood mapping; however, the data set will still work well for shoreline delineation.

For lidar data sets, The American Society for Photogrammetry and Remote Sensing (ASPRS) has published guidelines for analyzing and reporting on lidar's vertical accuracy. The report can be downloaded from: www.asprs.org/society/committees/lidar/Downloads/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf.

Qualitative Accuracy

Unlike the clearly-defined statistical accuracy requirements, the qualitative aspect of the data is more subjective. While it does not commonly receive the same amount of attention on the front end, attention to the qualitative side is a critical check for the successful use of the data. In essence, the accuracy assessment tests only 200 to 300 points in a data set of a billion points, so the qualitative review can be seen as a test of the other billion or so points. There are, however, no specified qualitative accuracy procedures, so familiarity with lidar data in general and the location and intended use in particular are necessary. This "fuzzy" analysis is generally best performed by a third party, the purchaser, or a user group. Some of the most common qualitative "errors" are flight line mismatches, high frequency noise (also called "corn rows"), formatting, misclassification, and data holidays or voids. While many of these problems can be fixed, corn rows are more difficult to remedy. Ultimately, there are no "perfect" data sets, but there is generally a level at which the data lose some of their usability, and that threshold should be considered when specifying the data.

Sources of Integrated Products

NOAA National Geophysical Data Center (NGDC)

NGDC builds and distributes high-resolution, coastal digital elevation models (DEMs) that integrate ocean bathymetry and land topography to support NOAA's mission.

Coastal Relief & Tsunami Inundation
http://www.ngdc.noaa.gov/mgg/coastal/coastal.html

Coastlines & Coastline Extractor
http://www.ngdc.noaa.gov/mgg/shorelines/shorelines.html

Digital Elevation Model (DEM) Discovery Portal
http://www.ngdc.noaa.gov/mgg/dem/demportal.html

Global Relief (ETOPO1, ETOPO2, ETOPO5)
http://www.ngdc.noaa.gov/mgg/global/global.html
SRTM DEMs (tied to EGM96)

NOAA Coastal Services Center (CSC)
Integrated bathymetric- and topographic-elevation lidar data are available from CSC as part of the NOAA Digital Coast Project (Digital Coast Elevation http://www.csc.noaa.gov/digitalcoast/data/index.html#elevation).

References Cited

Bodnar, A.N. 1981: Estimating accuracies of tidal datums from short term observations, Draft Report, Tides and Water levels Division, NOAA National Ocean Survey, 44pp.

Calder, B.R. and Wells, D.E., 2007: CUBE User's Manual, version 1.13, *University of New Hampshire (UNH)*, Center for Coastal and Ocean Mapping (CCOM)/Joint Hydrographic Center (JHC), Durham, NH. URL: http://www.ccom-jhc.unh.edu/publications/Calder_07_CUBE_User_Manual.pdf.

FGDC, 1984: Standards and Specifications for Geodetic Control Networks, Federal Geodetic Control Committee, Rockville, MD, September 1984. http://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.htm.

Gill, S.K. and K.M. Fisher, 2008: A network gaps analysis for the national Water Level Observation Network, NOAA Technical memorandum NOS CO-OPS 0048. 50pp. http://tidesandcurrents.noaa.gov/publications/Technical_Memorandum_NOS_COOPS_0048.pdf.

IHO, 1998: International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, Special Publication No. 44, 4th Edition.

Maune, D.F., 2007: *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

NGS, 1981: Geodetic Leveling, NOAA Manual NOS NGS 3, NOAA, NOS, National Geodetic Survey, August 1981, reprinted June 2110. Available on-line at: http://www.ngs.noaa.gov/PUBS_LIB/Geodeticleveling_nos_3.pdf

NOAA, 2003: Computational Techniques for Tidal Datums Handbook, NOAA Special Publication NOS CO-OPS 2, NOAA National Ocean Service, Center for Operational Oceanographic Products and Services, 90pp http://tidesandcurrents.noaa.gov/publications/Computational_Techniques_for_Tidal_Datums_handbook.pdf.

NOAA, 2001: Tidal Datums and Their Applications, NOAA Special Publication NOS CO-OPS 1, S.K. Gill and J.R. Schultz, eds. NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 111pp http://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf

NOS, 2009: NOS Hydrographic Specifications and Deliverables. http://www.nauticalcharts.noaa.gov/hsd/specs/SPECS_2010.pdf

Zervas, C., 2009: Sea Level Variations of the United States 1854-2006, NOAA Technical Report NOS CO-OPS 053, NOAA National Ocean Service Center for Operational Oceanographic Products and Services, 78pp. http://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

Zilkoski, et al. 2008: Guidelines for Establishing GPS-Derived Orthometric Heights, NOAA Technical Memorandum NOS NGS 59, National Geodetic Survey, Silver Spring, MD. 15pp.

Zilkoski et al. 1997: Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm) Version 4.3, NOAA Technical Memorandum NOS NGS-58, National Geodetic Survey, Silver Spring, MD.

Chapter 6.0 Applications

The preceding chapters outlined the characteristics of the myriad datasets typically used in sea level change (SLC) mapping and assessment projects, including information on how to obtain existing or collect new data. This chapter provides select examples of these data in action—how these datasets and other resources can be harnessed to examine particular issues or challenges that scientists, engineers, and decisions makers face when identifying and dealing with changing sea levels.

6.1 Common Applications for Sea Level Change Data

As briefly noted in chapter 2, there are a wide range of potential applications for SLC mapping and assessments, from detailed evaluation of SLC impacts on critical infrastructure or sensitive ecological resources to regional or state-level climate adaptation or hazard mitigation planning efforts. For example, the U.S. Climate Change Science Program (CCSP 2009), particularly Gill et al. (2009), examined the impacts of SLC along the Mid-Atlantic coast; figures 6.1 and 6.2 show application of data to evaluate the sensitivity of the region's coastal environments and resources to various scenarios of SLC.

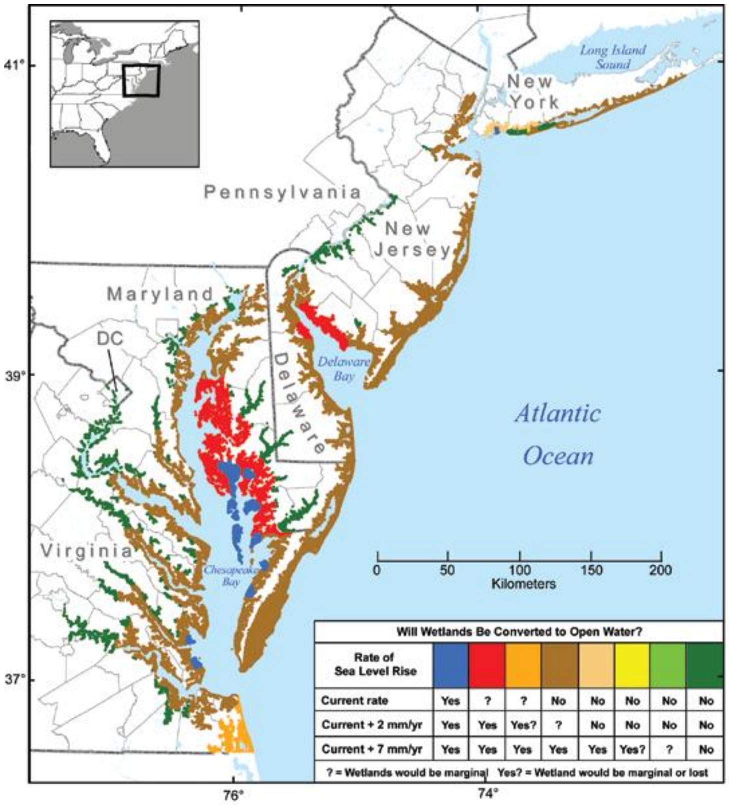


Figure 6.1. Estimating wetland impacts, specifically, which areas will become marginal or lost (i.e., converted to open water) under three SLC scenarios (CCSP 2009).

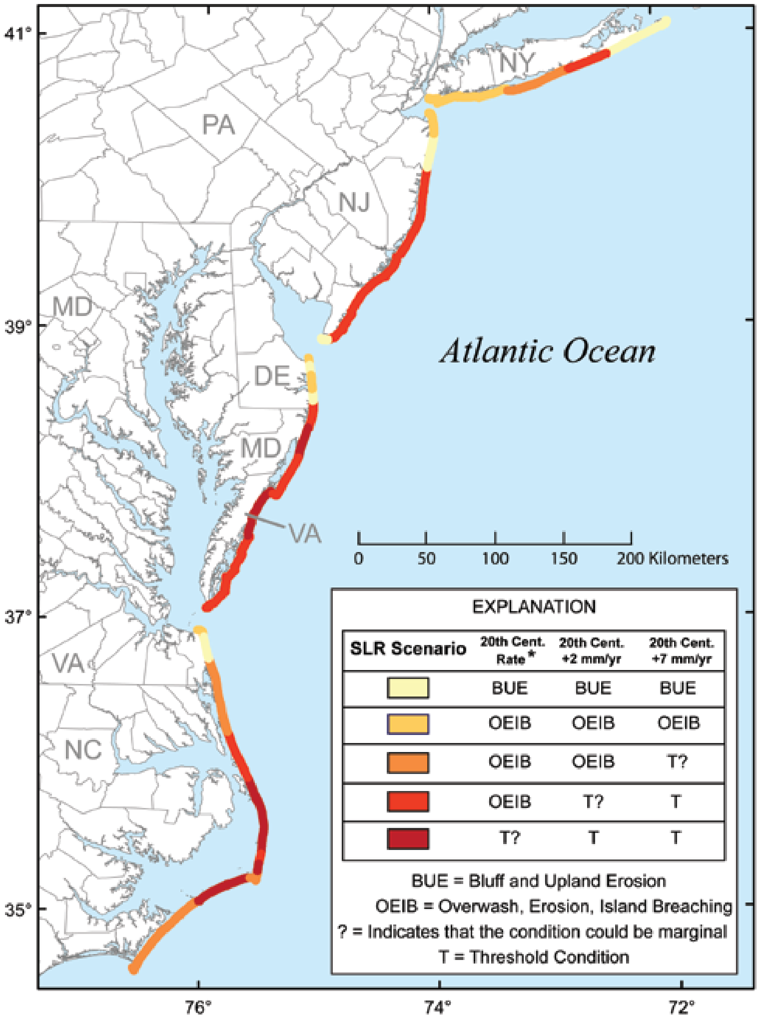
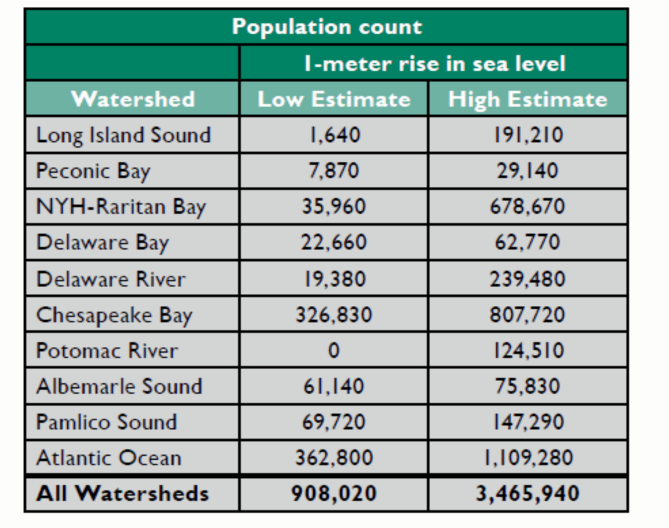


Figure 6.2. Map shows potential geomorphologic responses to SLC for four coastal compartments along the Mid-Atlantic region (NY, NJ, Delmarva Peninsula, VA/NC coast) (CCSP 2009). Potential responses shown in the inset table based on work by Gutierrez et al. (2007).

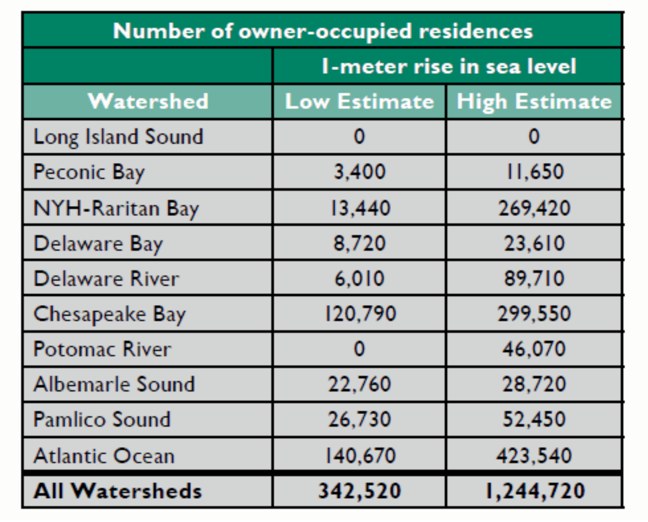
CCSP (2009) also applied SLC information to improve understanding of the socioeconomic consequences of SLC. A geographic information system (GIS) analysis in the study evaluated the intersection of inundation caused by SLC of 1 m against U.S. Census population data and a land-use layer. Tables 6.1 and 6.2 show a subset of the results, specifically estimates of how many people and residential housing units are likely to be affected by 1 m of SLC. Note that the results are expressed in high and low estimates because of the uncertainty in the base elevation layer and in the data interpolations made in the GIS analysis. One meter of SLC is the minimum increment in the analysis due to the inherent uncertainties in the various data layers, especially the base elevation layer.

Table 6.1. Potential population to be affected by SLC in the Mid-Atlantic region (CCSP 2009).



Population count		
	1-meter rise in sea level	
Watershed	Low Estimate	High Estimate
Long Island Sound	1,640	191,210
Peconic Bay	7,870	29,140
NYH-Raritan Bay	35,960	678,670
Delaware Bay	22,660	62,770
Delaware River	19,380	239,480
Chesapeake Bay	326,830	807,720
Potomac River	0	124,510
Albemarle Sound	61,140	75,830
Pamlico Sound	69,720	147,290
Atlantic Ocean	362,800	1,109,280
All Watersheds	**908,020**	**3,465,940**

Table 6.2. Potential number of residences in the Mid-Atlantic region at risk with 1 meter of SLC (CCSP 2009).



Number of owner-occupied residences		
	1-meter rise in sea level	
Watershed	Low Estimate	High Estimate
Long Island Sound	0	0
Peconic Bay	3,400	11,650
NYH-Raritan Bay	13,440	269,420
Delaware Bay	8,720	23,610
Delaware River	6,010	89,710
Chesapeake Bay	120,790	299,550
Potomac River	0	46,070
Albemarle Sound	22,760	28,720
Pamlico Sound	26,730	52,450
Atlantic Ocean	140,670	423,540
All Watersheds	**342,520**	**1,244,720**

SLC data are increasingly being used in the development of land-use plans. The Maryland Department of Natural Resources (MD DNR) and the U.S. Geological Survey (USGS) completed the development of the Worcester County (MD) Sea Level Rise Inundation Model in November 2006 (Johnson et al. 2006). Using lidar data recently collected for the county, a Digital Elevation Model (DEM) was produced as the base elevation layer upon which results from various SLC scenarios model for three periods (2025, 2050, and 2100) were overlain. The three scenarios were: 1) the historic rate of regional SLC estimated from tide station records (3.1 mm/year), 2) the average accelerated rate of SLC projected by the IPCC (2001), and 3) the worst-case scenario using the maximum projection of accelerated SLC by the IPCC (2001) (85 cm to 90 cm by 2100). The scenarios were applied to present-day elevations of mean sea level (MSL), mean high water (MHW), and spring tides derived at local tide stations. Figure 6.3

shows a typical result for 2100 using the worst-case (accelerated) SLC scenario from the IPCC (2001).

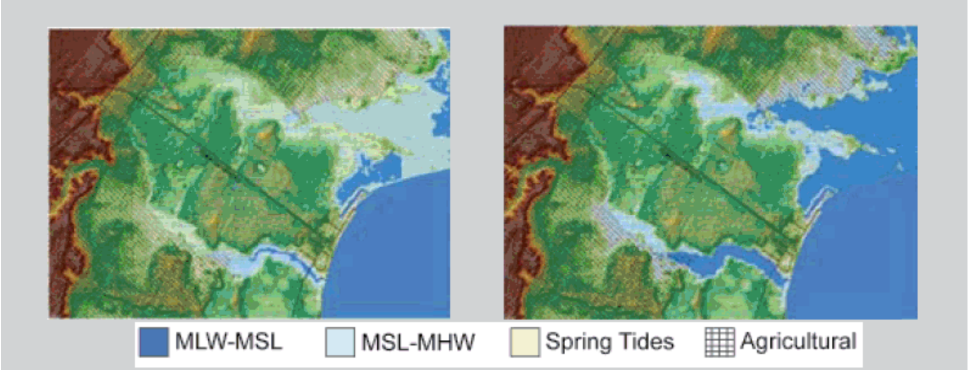


Figure 6.3. Johnson et al. (2006, as cited in CSP, 2009) examined SLC inundation potential for agricultural land in Worcester County, Maryland. On the left, blue areas show present-day inundation. On the right, inundation expected in 2100 using IPCC's (2001) accelerated rate of SLC is shown.

Incorporation of sea level change data is also becoming more prevalent in coastal engineering design and construction. The U.S. Army Corps of Engineers (USACE 2009) recently published a new guidance document concerning use of SLC in project planning and design. This report assesses the risks associated with specified project designs based on regional mean sea level trends. It provides a step-by-step process (figure 6.4) to determine an extrapolated base-line rate, an intermediate rate, and a high rate of future SLC in five-year increments.

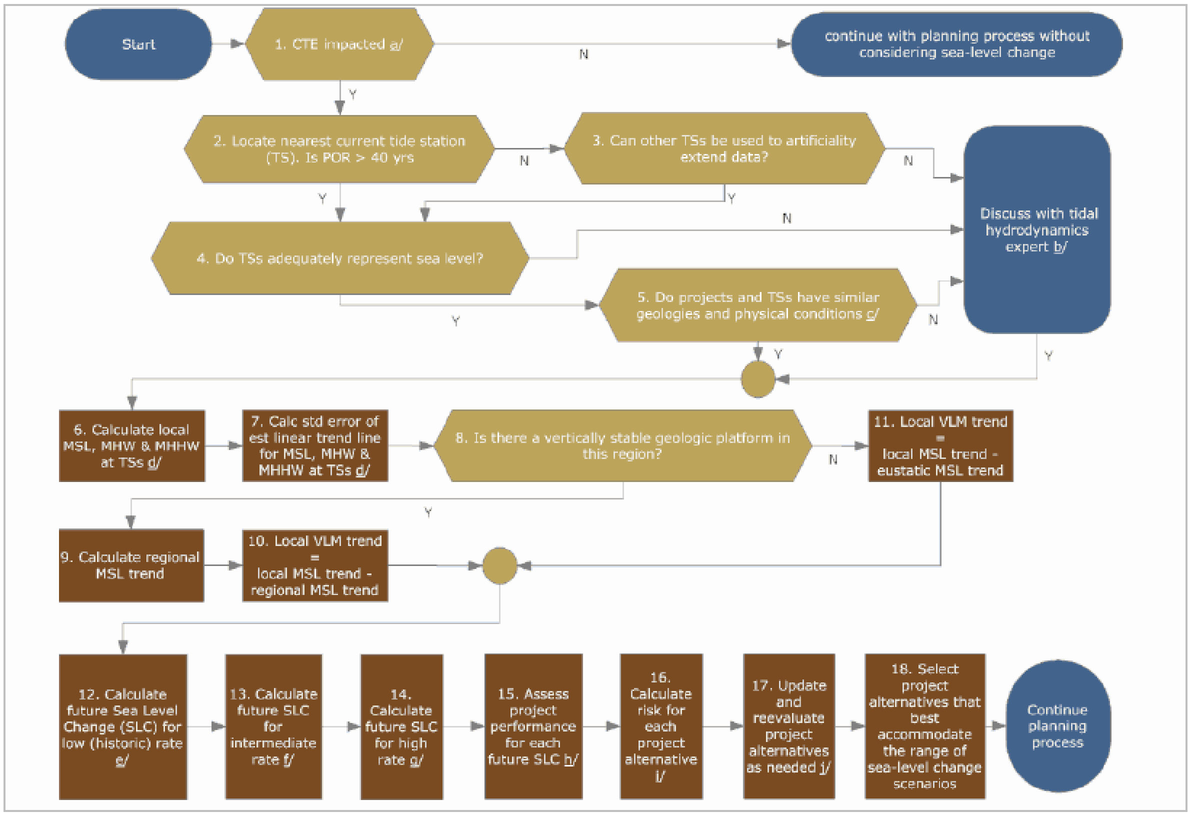


Figure 6.4. USACE (2009) decision-making process to account for SLC in project planning and design.

6.2 Digital Elevation Model in Mapping and Assessing the Impacts of Sea Level Change

SLC mapping can be viewed as a four-step process. The following outlined consist of a framework to create inundation maps, with each step explained in detail in the NOAA Coastal Services Center's Coastal Inundation Mapping Guidebook (http://www.csc.noaa.gov/digitalcoast/inundation/_pdf/guidebook.pdf). The guidebook discusses the mapping process and some of the limitations, such as how the resolution of the data will drive the scale of the planning, and explains why the accuracy of the data needs to be known and communicated to the users.

1) **Obtain and Prepare Elevation Data**: (http://www.csc.noaa.gov/digitalcoast/inundation/map/obtain.html)
   Elevation data (including nearshore bathymetry) serve as the base data layer for mapping coastal inundation. Before using elevation data for inundation mapping, it is important to understand requirements and specifications of the data, how to assess data quality, and where to obtain accurate data for a community. Chapters 2 through 4 of this document provide supplemental information on these points.

2) **Prepare Water Levels:**
   (http://www.csc.noaa.gov/digitalcoast/inundation/map/prepare.html**)**
   To map inundation, a water surface must be generated. That surface can be based on

model output or a change in water height using a single value. Both approaches require different inputs and technical skill, and each has advantages. Information in chapters 3 and 4 of this document provide additional information on identifying and obtaining appropriate water-level data.

3) **Map Inundation:** (http://www.csc.noaa.gov/digitalcoast/inundation/map/map.html) Using a digital elevation model (DEM) and water-level information, GIS processes can create layers that represent inundation extent and depth.

4) **Visualize Inundation**: (http://www.csc.noaa.gov/digitalcoast/inundation/map/visualize.html) Visualizing the inundation results is important for assessing exposure and impacts and serves as a powerful tool for education and awareness. Visualizations may range from simple maps to interactive Web viewers. See section 6.7 for further information on this topic.

Both the number and complexity of SLC mapping projects grow daily, providing a rich resource of experience for those newly engaged in similar efforts. The feature boxes in figures 6.1 and 6.2 show two such examples. Additional coastal inundation case studies are available on NOAA’s Digital Coast website (http://www.csc.noaa.gov/digitalcoast), under the “In Action” area.

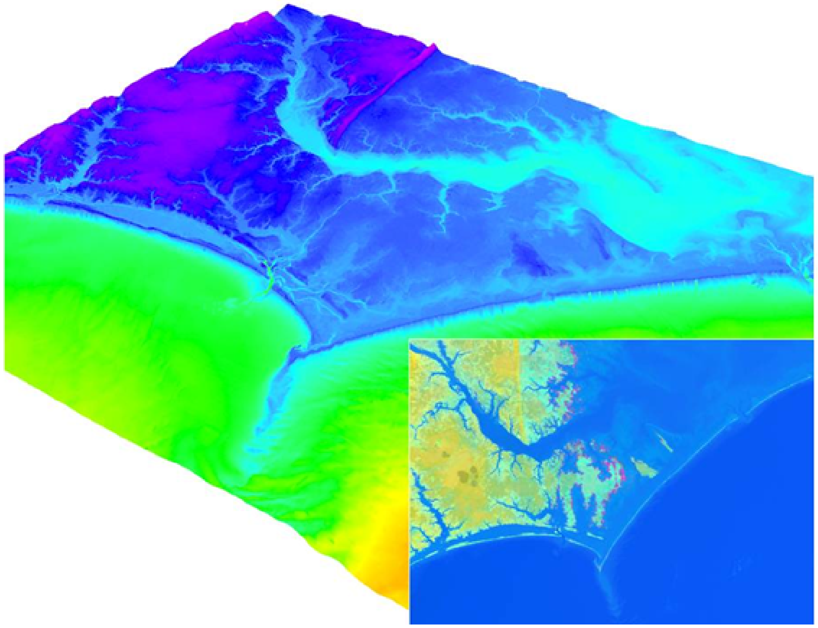
For additional information on building Digital Elevation Models see:
http://www.csc.noaa.gov/topobathy/topographic-and-bathymetric-data-considerations.pdf

Project 1: Ecological Effects of Sea level Rise in North Carolina

Rising sea level has worldwide consequences because of its potential to alter ecosystems and habitability of coastal regions. The vulnerability of coastal areas varies with shoreline physical attributes and the amount of development. Low-lying areas in the Mid-Atlantic, Southeast, and Gulf Coast are especially at risk.

To examine the complex relationships between SLC and coastal ecosystems, the Ecological Effects of Sea Level Rise (EESLC) program was initiated in North Carolina. The program brings together University researchers and NOAA scientists to help coastal managers and planners better prepare for changes in coastal ecosystems due to land subsidence and SLC. Specialists in biology, geomorphology, and coastal modeling joined forces to integrate storm surge models with ecological models for more precise predictions of how future sea level will affect coastal wetlands, submerged aquatic vegetation, sub-tidal habitat, and oyster reefs. For more information on the study, see: http://www.cop.noaa.gov/stressors/climatechange/current/sea_level_rise.aspx http://www.cop.noaa.gov/stressors/climatechange/current/SLC/default.aspx

A major component of this study was the development of a topographic/bathymetric DEM for a portion of eastern North Carolina. The adjacent image shows a portion of this DEM, with the extent of 1 m of SLC above the Mean High Water (MHW) datum shown in the inset. VDatum was used to adjust the source bathymetric and topographic data, which were collected with different survey techniques, to a common vertical datum. This step ensured that there was no artificial jump in the DEM at the topo/bathy interface, an area of vital importance to many species and habitats that are highly sensitive to small changes in water level.



Project 2: Shallow Flooding in Downtown Charleston, SC
Shallow coastal flooding occurs when seawater inundates low-lying areas. Higher than average high tides, sometimes worsened by heavy rainfall and onshore winds, can cause damage to buildings and homes and temporarily restrict traffic.

DEMs developed from high-resolution lidar elevation data allow managers to map predicted inundation with enough accuracy to estimate impacts from relatively small changes in sea level. For example, in Charleston, South Carolina, low-lying portions of the downtown can be flooded by tides that reach a threshold of 2.1 meters (7 feet). (For comparison, Charleston’s highest high tides are typically less than 1.8 meters [6 feet] above the mean lower low water datum.)

This map, based on a highly accurate lidar-derived DEM, shows areas susceptible to tidal flooding (dark blue areas). An additional sea level rise of 0.5 meters (1.6 feet), which may occur over the next 100 years according to IPCC, would make the extent of flooding much greater (light blue areas).Rising sea levels will also increase the expected frequency of flooding. For example, with a 0.5 meter sea level rise, the areas currently susceptible to a 2.1 meter tide twice per year would be susceptible to flooding on 289 days—and twice on 66 of those days.

6.3 Amount of Sea Level Change to Use in Specific Projects

When choosing which SLC level or range to depict on a map, the user has many options. Published SLC projections are available through a variety of sources, including the IPCC (see http://www.ipcc.ch/ or http://www.ipcc.ch/publications_and_data/publications_and_data.htm). In some cases, states or local governments have chosen SLC increments as planning targets, such as 1 m by 2100. The increment chosen should be relevant to the timescale of decisions being made based on the project results. For example, different values of anticipated SLC would be needed to evaluate placement of new housing developments over the next 20 years versus what would guide similar decisions for water and sewer infrastructure expected to function for 50-75 years. The ability of evacuation routes to serve their purpose over decades must consider both SLC as well as vertical land motion throughout the route corridor.

The following references are select examples of either recent scientific projections of SLC (1-5) or specific studies or assessments where the sponsoring organization selected SLC increments suitable for their project goals (6-7).

1. Intergovernmental Panel on Climate Change. 2000. Special Report on Emissions Scenarios. Cambridge University Press, U.K.

2. Meehl, G. A., T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.- C. Zhao. 2007. “Global Climate Projections.” In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). Cambridge, United Kingdom and New York, New York, USA: Cambridge University Press.

3. Rahmstorf, S., A. Cazenave, J. A. Church, J. E. Hansen, R. F. Keeling, D. E. Parker, and R. C.J. Somerville. 2007. “Recent Climate Observations Compared to Projections.” Science. Volume 316. Number 5825. Page 709.

4. Rahmstorf, S. 2007. “A Semi-Empirical Approach to Projecting Future Sea level Rise.” Science. Volume 315. Number 5810. Page 368.

5. Vermeer and Rahmstorf, 2009. “Global Sea level Linked to Global Temperature.” Proceedings of the National Academy of Sciences, Volume 106, Number 51, Page 21527-21532.

6. Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick. 2009. Climate Change Scenarios and Sea Level Rise Estimates for California 2008 Climate Change Scenarios Assessment. California Climate Change Center. In preparation.

7. Cayan, D., P. Bromirski, K. Hayhoe, M. Tyree, M. Dettinger, and R. Flick. 2006. Projecting Future Sea Level. California Climate Change Center. California Energy Commission, Public Interest Energy Research Program. CEC-500-2005-202-SF.

Regardless of source, the selected SLC increment should be carefully chosen and supported by the vertical accuracy of the elevation data. The root mean square error (RMSE) of the elevation data is a useful guide, generally equal to 1 standard deviation or a confidence interval of approximately 66%. For example, when mapping a 10-cm inundation event using elevation data that have an RMSE of 10 cm, the mapped area of inundation is, on the whole, approximately 66% correct, where some areas shown to be inundated in the analysis should not have been and vice versa. Mapping inundation levels below the RMSE of the data returns lower confidence, and borders on a 50-50 chance that it is correct. Mapping an inundation level of twice the RMSE increases the confidence of accuracy at any one location to approximately 90-95%, depending on the surrounding topography.

The following example illustrates how RMSE should determine the SLC increments used. In 2007, the State of Florida collected lidar for the entire state to the Category 5 Hurricane Storm Surge Line. These data were reported to have a vertical accuracy of 9.3 cm RMSE, which corresponds to a linear error of 18.2 cm at 95% confidence (9.3cm × 1.96). A rule of thumb to get the minimum useful SLC increment for inundation mapping is to multiply the elevation error value (at a 95% confidence level) by 2. Thus, in this example, 18.2 cm is multiplied by 2, which results in 36.4 cm or 1.2 ft. Therefore, the smallest SLC increment to consider for useful planning purposes should be 1.2 ft (which can be rounded off to the nearest foot). In the absence of reliable error estimates, 1ft is a reasonable SLC increment to apply in mapping projects that use most current lidar data collection specifications.

6.4 What Vertical Reference Datum to Use

When developing analyses using elevation, bathymetry, or datum elevations, it is extremely important to know the vertical reference datum being used for your source documents or data source, as well as to obtain metadata documenting information on the reference datum.

When blending elevation data and datum elevation information for a map depiction or GIS layer display, the various layers must be displayed appropriately relative to a common reference datum so that any subsequent analyses are not subject to datum shifts along the land-water interface that will bias the final analysis. This usually involves a datum transformation of one or more layers.

The specific vertical reference datum used also depends upon the application and analyses to be performed, as well as the accuracy desired. For inundation studies for which estimates are required to determine the amount of land affected by sea level inundation, the elevation of a tidal datum (such as MHW, or MHHW in areas with diurnal tides) is often used as the base elevation. This is because the high water datum represents the elevation of the normal daily excursion of the tide where the land area is normally inundated. Taking this normal extent of inundation into account is important when trying to delineate land areas inundated by abnormal events such as storm surge, tsunami run-up, or SLC.

In the past, many users have assumed that the base vertical reference datum for topographic information was mean sea level. Some of this confusion comes from colloquialism and some from actual naming issues. Specifically, the datum originally used for the USGS Quadrangle was the National Geodetic Vertical Datum of 1929 (NGVD29), but that datum was originally called the “Sea Level Datum of 1929.” The USGS topographic quadrangle maps now have heights in the North American Vertical Datum of 1988 (NAVD 88). That datum should be used when performing analyses involving only land elevation data. Any older source topographic information should be transformed to NAVD 88 using a datum transformation tool such as VDatum.

Recent bathymetric data from NOAA represent depths and soundings relative to the NOAA Chart Datum of MLLW. Older bathymetric data prior to 1980 are relative to MLW on the East Coast and need to be transformed to MLLW. Older bathymetric data are also relative to tidal datums from previous NTDE time periods and should be updated to the latest NTDE prior to use; however, this difference (0.10 ft) between adjoining NTDEs is typically small with respect to the accuracy and resolution of the soundings.

The accuracy of the elevation data and the accuracy of the desired product are also important, and the incremental elevations being used for the product come into play as discussed elsewhere in this document. For instance, between LMSL and NAVD 88, for some areas of the country where that general difference may only be a few centimeters, a source transformation may not be necessary if the source elevation data only have accuracies to several centimeters.

6.5 Measure and Quantify Shoreline Change

Shoreline change is the analysis of shoreline variability and shoreline erosion-accretion trends through time. Many factors influence the evolution of the shoreline in response to SLC, including geologic framework, physical processes, sediment supply, and human activity. Not only do these factors influence the response of coastal landforms to changes in sea level, but they also contribute to the local and regional variations of sea level rise impacts that are often hard to quantify using prediction methods. For more on the physical processes that influence shoreline change and response to SLC, see both chapter 3 in CCSP (2009) and the papers in a special issue of the *Journal of Coastal Research* edited by Byrnes et al. (2003).

Changes in shoreline position through processes of accretion and erosion can be analyzed in a GIS by measuring differences in past and present shoreline locations that were derived from a variety of potential sources (e.g., National Ocean Service raster shoreline manuscripts (T-sheets), aerial photography, and high-resolution, lidar-based elevation data sets). As discussed in chapter 3, NOAA maintains a National Shoreline, which was originally intended to support NOAA nautical chart production but has also been used for shoreline-change analysis, boundary determination, and cartographic representation. However, determination of sea level change using shoreline data is only valid if the data sets being compared were acquired to the same accuracy and are on the same datum.

Other Federal agencies have developed datasets and other resources that support assessment of shoreline change along the U.S. coast. For example, the Coastal and Marine Geology Program of the USGS conducts analyses of historical shoreline changes along open-ocean sandy shores of the conterminous U.S. and parts of Alaska and Hawaii. A primary goal of this USGS work is to develop standardized methods for mapping and analyzing shoreline movement so that internally consistent updates can periodically be made to record shoreline erosion and accretion. Results from these shoreline change studies are available at http://coastal.er.usgs.gov/shoreline-change/. Additionally, Thieler et al. (2005) developed a suite of tools for both extracting shoreline positions and quantifying shoreline change; an updated version of this toolkit is available at: http://woodshole.er.usgs.gov/project-pages/DSAS/version4/index.html

States have also undertaken efforts to map shorelines and understand shoreline-change trends in their jurisdictions, often in partnership with Federal agencies. The Coastal Management Program, which is authorized by the Coastal Zone Management Act of 1972 and is administered by the NOAA Office of Ocean and Coastal Resource Management (OCRM), is a partnership among OCRM and 34 coastal and Great Lakes states, territories, and commonwealths. Each participating coastal program monitors shoreline change in its locality and, in some cases, uses historical erosion rates to establish building setbacks. These setbacks are typically used to permit new construction (residential and commercial) and hard shoreline-stabilization efforts, and to promote a policy of retreating from historically erosive coasts.

To aid coastal programs, OCRM created the Shoreline Management Technical Assistance Toolbox as an online guide for state coastal managers. It provides centralized access to information, resources, and tools to address shoreline erosion and management, focusing on alternatives to traditional shoreline hardening. The website is organized into four main sections: Planning, Policy, and Regulatory Tools; Economics of Shoreline Management; Soft/Alternative Stabilization Methods; and Resources (http://coastalmanagement.noaa.gov/shoreline.html).

While state coastal programs may share common goals related to identifying and managing eroding coastlines, the quantity and quality of source data available and the methods used to determine shoreline-change rates are highly variable across the U.S. (Honeycutt et al. 1999; Byrnes et al. 2003). This heterogeneity in erosion analyses complicates efforts to compare results from one region to another, which makes products like the USGS's regional shoreline-change assessments (referenced earlier) such valuable resources for those needing to understand the range of potential shoreline-change impacts triggered by SLC.

6.6 Applications of Ecosystem/Marsh Change Models

While the scientific community agrees that sea level is rising and coastal marshes are changing as a result, it is a challenge to predict the result, since natural systems are inherently unpredictable. Empirical models can serve as a guide to help us understand when and where impacts have the potential to occur and as a gauge as to how severe they may be.

Existing models, such as the Sea Level Rise Affecting Marsh Model (SLAMM) (http://warrenpinnacle.com/prof/SLAMM/) attempt to serve as such a guide to understanding. For example, the U.S. Fish and Wildlife Service uses SLAMM for wildlife refuge management (http://www.fws.gov/slamm/). SLAMM simulates the dominant processes involved in wetland conversions and shoreline modifications resulting from long-term sea level rise. Map distributions of wetlands are predicted under conditions of accelerated sea level rise, and results are summarized in tabular and graphical form. SLAMM is free, user-friendly software that is capable of being run by operators with basic GIS experience. SLAMM models potential impacts and the resulting changes in marsh-type distribution that could result due to user-identified level of predicted sea level rise. SLAMM attempts to account for six primary processes: inundation, erosion, overwash, saturation, accretion, and salinity.

Because SLAMM handles these processes simply, and users of SLAMM often will have little or no information to input for some of these variables, default values or incorrect values are used, resulting in inaccurate or incorrect model output. For instance, the spatial processing for saturation can result in linear "streaks" of wetland migration onto uplands, often into unrealistic elevations, and in unnatural ways.

Other GIS-based methods that use a similar elevations-based rule set for marsh change prediction are being developed but ignore erosion, overwash, saturation, and the more complex salinity models (see draft at: *http://www.csc.noaa.gov/beta/slr/assets/pdfs/Marsh_Migration_Methods.pdf*). These methods rely instead on predicted SLC and estimated accretion only. Salinity and saturation are handled as a function of elevation and tide ranges. Accretion is also handled in a simple way. Results are easier to understand and more consistent through time and in many different geographies, and there is less room for user-introduced error in this approach.

Regardless of which modeling method is used for predicting marsh impacts from SLC, these model outputs have the potential to be used by coastal managers who do not fully understand the limitations and uncertainty of predictive models (i.e. there is always a high level of uncertainty in such models because natural systems are inherently unpredictable). Unfortunately, the general public often does not understand this uncertainty either, especially when only maps and charts of model outputs are shown. To ensure that the end user is properly informed, certain precautions must be taken when interpreting the results.

6.7 Interaction of Sea Level Rise, Episodic Flooding, and Extreme Events

One of the most significant consequences of sea level rise is the impact of increased water level on the height and extent of inundation during extreme events (e.g., hurricanes; nor'easters and other extratropical storms; tsunamis). Projected water levels and impacts associated with SLC and extreme events are generally considered independently. For example, the data and technical analyses used to produce the most commonly available, storm-related inundation maps (e.g., FEMA's probabilistic Flood Insurance Rate Maps, NOAA's SLOSH inundation maps, USACE's hurricane evacuation maps) consider only present-day water-level conditions or past conditions (e.g., historical tide gauge records, storm high water marks). SLC analyses and maps typically only consider changes relative to some fair-weather condition (e.g., projected change relative to MHW or other tidal datum).

Increasingly, coastal officials and decision-makers, including emergency and floodplain managers, recognize the need for inundation products that integrate across all physical inundation processes. As described below, a range of techniques for assessing inundation from both SLC and extreme events are available, each with benefits and shortcomings depending on the intended use of the results. The science behind these techniques is rapidly evolving, so "best practices" cannot be presented at this time. The approaches outlined in the remainder of this section, therefore, reflect the current state-of-practice.

6.7.1 Statistical Approaches to Integrate SLC and Extreme Events

NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) provides mean sea level (MSL) trend information at tide stations based on monthly data (http://www.tidesandcurrents.noaa.gov/sltrends). These trends can be applied to published bench mark elevations for specified tide stations to infer future water level datum elevations and can be used as the basis for other statistical and probability analyses for risk assessment of extreme events.

CO-OPS is also currently developing a Web-based tool to display exceedance probability statistics for each tide station with sufficient historical data. This product will become available in 2011 at http://tidesandcurrents.noaa.gov. CO-OPS uses the generalized extreme value (GEV) theory to determine the statistical probability that water levels will exceed a specific elevation every 1 year, every 2 years, every 10 years, and every 100 years. GEV theory describes the expected statistical distribution of the extreme values of a sequential process or set of observations. GEV analyses are done on monthly highest and lowest water level data at NOAA tide stations to determine exceedance probability statistics at the 99%, 50%, 10%, and 1% elevations. The highest monthly water levels are referenced to mean higher high water (MHHW) and the lowest monthly water levels are referenced to MLLW. Current MSL trends are subtracted from the monthly series. The resulting series consists of levels of the extreme events beyond the normal diurnal tide range, as if they had all occurred in the same year. This normalizes the sea level data to account for long-term sea level change.

CO-OPS has also developed a frequency-and-duration-of-inundation tool, which analyzes past elevations of high tides and produces statistical profiles of the distribution of elevations and their associated duration of inundation above a user-defined elevation surface, such as MHW, NAVD 88 or a local marsh surface elevation. These profiles can also be adjusted for various sea level change scenarios to estimated changes in future distributions. This tool is scheduled to become available on the CO-OPS website in 2011.

All of these statistical tools attempt to blend analyses of the historical observation record with future projections of sea level rise. Observation statistics are often used as baseline “present condition” information. The value of statistics is also highly dependent upon the length of the observed series. For instance, computation of relative sea level trends requires record lengths longer than 30 years to obtain reasonable standard errors. Frequency and duration of inundation events are seasonally-dependent, and record lengths of less than one year need to be adjusted by comparison with nearby stations with longer record lengths.

6.7.2 Other Approaches to Integrate SLC and Extreme Events

Beyond these statistical tools, other methods have been developed to permit joint consideration of SLC with storm-related water levels. One of the earliest approaches developed is the adding a single value for SLC onto existing storm model output, and remapping the combined inundation extent. For example, see the work by The Nature Conservancy (in partnership with NOAA and others) that examines the impact of SLC on inundation hazards along Long Island, NY (http://www.csc.noaa.gov/digitalcoast/inundation/longisland.html). This approach is very effective at providing a coarse-scale assessment of combined flooding risk, which is useful for vulnerability assessments, strategic resource planning, and similar applications. That said, the simplifications inherent to this approach (i.e., considering SLC and storm water levels independently and combining later) does not capture the complex geomorphic (landform) changes along the coast that are expected to occur in response to the many physical (water- and sediment-transport) processes operating over a variety of spatial and temporal scales.

More recently, storm-surge modelers and researchers have examined the utility of running a given storm-surge model (including the underlying topo/bathy grid) with both present-day and future sea levels. For example, NOAA's study on the ecological impacts of SLC in North Carolina (http://www.cop.noaa.gov/stressors/climatechange/current/SLC/default.aspx) includes SLOSH storm surge modeling that incorporates projected SLC. While this approach does bring SLC-induced higher water levels into the surge model, the results still fail to reflect the complex geomorphic changes that are expected over the long-term in response to SLC and other processes operating over shorter timescales. In the end, this shortcoming may not be important in light of the intended application of the study results, but efforts to apply the specific results or the approach in other settings or toward solution of other problems may not be appropriate.

Another emerging approach is to consider geomorphic change related to SLC within the storm surge model, specifically via changes to the model's topo/bathy grid. Such an approach is being applied in a SLC Risk Management Study sponsored by the Federal Emergency Management Agency and the State of North Carolina (http://www.ncsealevelrise.com/). In this study, a team of coastal engineers and geologists are attempting to identify changes in barrier island and mainland shoreline morphology, including number and size of tidal inlets along the Outer Banks, which can be incorporated into the grid for the ADvanced CIRCulation (ADCIRC) storm surge model. Again, even with the addition of geomorphic changes to the model, this approach still has shortcomings with respect to considering the full suite of water- and sediment-transport processes that operate over temporal and spatial scales beyond the storms and SLC that are being considered explicitly. That said, this project and others like it represent a significant step forward in the evolution of techniques to integrate inundation due to SLC and extreme events.

6.7.3 Resources for Extreme Event Information

CO-OPS has published a series of data and technical reports of the station records during some of these events. Data reports, such as Hurricanes Katrina and Ike, provide the maximum observed water level and meteorological parameters recorded at each station, along with a brief storm synopsis. Technical reports supply a more detailed analysis of storm-induced water levels, tides, currents and meteorological conditions, in addition to historical storm comparisons. For example, the Hurricane Isabel report includes corrections for sea level rise on maximum observed water level recorded at select stations. Various CO-OPS reports are available at http://tidesandcurrents.noaa.gov/publications/.

In addition, CO-OPS provides the time, date, and value of the highest (and lowest) water levels recorded over a station's history, on the datums webpage of each station. For example, the highest recorded water level at the Grand Isle station was due to Hurricane Katrina (http://www.tidesandcurrents.noaa.gov/data_menu.shtml?stn=8761724%20Grand%20Isle,%20LA&type=Datums). These records are becoming increasingly more important, as CO-OPS stations that once would have been damaged or have malfunctioned at the peak of the storm are now routinely capturing the complete oceanographic and meteorological records during a storm. All CO-OPS stations can be found at www.tidesandcurrents.noaa.gov.

Tropical storm surge forecasts and recorded water level observations for historical storms have been compiled (where available) within the National Weather Service (NWS) Sea Lake and Overland Surges from Hurricanes (SLOSH) model. SLOSH is a computerized model run by the National Hurricane Center (NHC) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes. More information on SLOSH can be found at http://slosh.nws.noaa.gov/sloshPub/.

The NHC's Tropical Cyclone Reports contain comprehensive information on each tropical cyclone, including synoptic history, meteorological statistics, casualties and damages, and the post-analysis best track (six-hourly positions and intensities). The NHC reports are located in its webpage archives found at http://www.nhc.noaa.gov/pastall.shtml. Finally, post-storm surveys are often carried out by FEMA, NHC, and other government agencies after an unusually damaging event in order to collect and measure the high water marks on the inside and outside of structures to characterize the spatial variability of the peak water levels.

6.8 Considerations for Sea Level Change Visualization

A wide array of techniques and tools are available to take the results from an SLC project and present (or visualize) them. Visualizations include maps, computer animations, or other products that graphically depict the technical results, whether they are anticipated inundation areas, inundation depths, expected impacts on the built or natural environment, or other information. This following section provides information about developing the most common type of visualizations (principally maps), as well as guidance for interpreting the source data and understanding the uncertainty inherent to the mapping process.

6.8.1 How to Create SLC Visualizations

With prepared digital elevation model (DEM) and water-level information, geographic information system (GIS) processes can be used to create mapping layers that represent inundation extent and depth. This includes:

Single Value Surfaces (simple, "flood the bathtub" approach)

1. Use GIS tools to create inundation depth rasters.
2. Use GIS tools to convert depth rasters to polygons representing inundation extent only.

Modeled Surfaces

1. Use GIS tools to extract points from gridded model output.
2. Use GIS tools to create a water surface by interpolating points.
3. Use GIS tools to subtract the DEM from the water surface to create the inundation depth raster.

4. Use GIS tools to convert depth rasters to polygons representing inundation extent only.

The NOAA Coastal Services Center's Coastal Inundation Mapping Guidebook (http://www.csc.noaa.gov/digitalcoast/inundation/_pdf/guidebook.pdf) , gives specific examples of how to perform both of these analyses.

6.8.2 How to Interpret SLC Visualizations

When interpreting and using SLC impact maps, it is important to consider various aspects or caveats about the data in order to understand what has or has not been considered in their creation. The following issues and solutions represent a sample of those that should be considered when evaluating this and other SLC impact data.

- **Hydrology.** SLC impact maps may not completely capture the area's hydrology, such as canals, ditches, storm water infrastructure, hardened shoreline, and/or dikes. Data may not take into account the amount of freshwater inputs, or how such upstream flows might be affected in the future, such as impacts to these water resources from change precipitation or human uses. All impacts may be based on elevation values and relative location within the tidal range of the area. This is true even if these areas are not directly connected to any other wetland or water feature.
- **Erosion and Storms.** SLC maps may not consider several natural processes, such as erosion and the impacts of coastal storm. These factors can have significant impact on location of shoreline and sediment dynamics. Local knowledge should be used to evaluate these data in light of these other potential impacts.
- **Accretion.** Accretion can be accounted for, but such accretion does vary by region and is specific to local geography. Such variation is based on a number of factors, including plant health, location in tide range/frequency of flooding, distance and source of input sediments, etc. Users are responsible for selecting the appropriate values for these factors, given their individual interests and application.
- **Error.** There is uncertainty (or potential error) in the elevation data, as well as the tidal correction and mapping process. The presentation of these predictions can include some representation of that uncertainty, by showing transition areas as a graduated color transition (instead of a hard line location). This transition zone can be based on the approximate RMSE associated with the data and mapping process.
- **Uncertainty.** Uncertainty associated with the exact amount of sea level rise or the timing associated with each scenario may not be considered. It may be up to the users to select the scenario with which they feel most comfortable and evaluate how they will treat the predicted impacts and timing associated with each scenario. When looking at marsh impacts, it is important to not focus on the exact timing or location of class transitions, but rather to use the timeframe and areas highlighted as a guide to when and where such impacts have the potential to occur, and a gauge as to how severe they may be.
- **Wetland Data.** Wetland data portrayed as the initial condition in many maps can be derived from several sources. One such source is from NOAA's Coastal Change Analysis Program (C-CAP). C-CAP produces a nationally standardized database of land

cover and land change information for the coastal regions of the U.S. Data used in this analysis reflect conditions as they existed when mapped in 2005 to 2006 timeframe. More information on C-CAP land cover data can be found at http://www.csc.noaa.gov/digitalcoast/data/ccapregional/. Different wetland source data can cause different results.

6.8.3 Quantify and Show Error in SLC Visualizations

Mapping inundation using elevations as the sole variable places a high dependency on the accuracy of the elevation data. This type of mapping has only two variables, the water height and the ground elevation. More complex hydraulic and geomorphic models are also used to depict inundation and contain additional variables. These models have their own error budgets, which can be complex depending on model assumptions. This section focuses mainly on a simple elevations analysis and how its associated errors affect the resulting inundation maps

A simple, elevation-based analysis uses a defined water elevation overlaid on the topography (elevation). The water surface grid elevations, the first source of uncertainty, has variable error depending on the vertical datum used, area extents, and, most importantly, location. The simplest datum to use is the North American Vertical Datum of 1988 (NAVD 88), although this choice can be an issue when dealing with coastal inundation that is inherently tied to local tidal variability. Use of tidal datums will help adjust elevations to a uniform tidal stage (e.g., MHHW) across an area, but they create some uncertainty because tidal elevations are not constant, and there are only a limited number of gauge stations from which to interpolate. For example, MHHW at Station *X* is 3 ft NAVD 88, while 15 miles away at Station *Y*, it is 3.5 ft NAVD 88. Between these two stations, there can be additional differences, which depend on geometry and location. VDatum is one tool that helps provide the tidal values for an area and is available in many locations (http://vdatum.noaa.gov/). VDatum converts elevation values between NAVD 88 and tidal values but has a level of error on the order of 5 cm to 20 cm, depending on location in the U.S. (http://vdatum.noaa.gov/docs/est_uncertainties.html).

The second, and potentially higher and spatially variable, source of uncertainty with a modified single value surface model is the elevation data. Digital Elevation Models (DEMs), derived from lidar data, are used in most inundation mapping applications. Lidar is among the most accurate of the elevation remote sensing techniques, but the data from lidar can have limitations in certain land covers. In addition, not all lidar data are collected to the same accuracy standards; the vertical accuracy of the lidar can vary from 5 cm (RMSE) to more than 30 cm (RMSE), even within any one collection area. To quantify this variability, accuracy assessments are often performed with lidar collections. The results of the accuracy assessments help to document the errors and the statistical properties of the errors. The process of determining these values and the tests that are run are not covered in this text, but additional information on accuracy assessments can be found at http://www.csc.noaa.gov/digitalcoast/data/coastallidar/What_is_Lidar.pdf. For inundation mapping, the most important result of the accuracy assessments is the vertical root mean square error (RMSE) that depicts the accuracy of the data.

The varying level of elevation surface water level accuracy affects the accuracy of inundation mapping. There are several techniques used to depict this uncertainty. A technique used by the USGS details the linear error of the 'inundation extent' (i.e., the line depicting the extent of inundation) based on the 95% confidence level of the elevation data (Gesch 2009). In its simplest form, the 95% accuracy value is added to the mapped inundation extent to depict additional areas above the mapped area that may be flooded (figure 2.15). This technique is used to represent data above the mapped area of inundation, although it could also be used to show areas below the mapped area. This technique does not include water surface uncertainties.

Gesch (2009) (CCSP 2009) illustrates how to map this uncertainty and shows a comparison of the uncertainty in the 1 arc-second NED elevation data and the 1/9 arc-second NED elevation data (based on lidar) in eastern North Carolina.

New Techniques

The techniques used to generate 'areas of high uncertainty' in the NOAA Coastal Services Center's Sea Level Rise and Coastal Flooding Impacts viewer (see draft at: http://www.csc.noaa.gov/beta/slr/assets/pdfs/Elevation_Mapping_Confidence_Methods.pdf) are similar in principle to that used by the USGS. The major differences are in the use of an 80% confidence level instead of a 95% confidence level, use of a cumulative percentage, and mapping this interval both above and below the inundation extent. Water level surface inaccuracies are also included; for many parts of the U.S. where VDatum coverage exists, the standard deviation of the water level error has been documented (http://vdatum.noaa.gov/about/availability.html). In areas without VDatum, the errors may be greater and may have to be estimated. For more information on mapping uncertainty refer to this document (pending posting on the NOAA Digital Coast website (http://www.csc.noaa.gov/digitalcoast/).

References Cited:

Byrnes, M., Crowell, M., and Fowler, C., (eds), 2003. Shoreline Mapping and Change Analysis: Technical Considerations and Management Implications. *Journal of Coastal Research, Special Issue no. 38.*

Maune, D.F., 2007. *Digital Elevation Model Technologies and Applications: The DEM Users Manual*, 2nd Edition. American Society for Photogrammetry and Remote Sensing. Bethesda, MD.

Gesch, D.B., B.T. Gutierrez, and S.K. Gill, 2009. Coastal elevations. In: *Coastal Sensitivity to Sea level Rise: A Focus on the Mid-Atlantic Region.* A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Environmental Protection Agency, Washington DC, pp. 25-42.

Gill, S.K., Wright, R., Titus, J.G., Kafalenos, R., and Wright, K., 2009. Population, land use, and Infrastructure. In: *Coastal Sensitivity to Sea level Rise: A Focus on the Mid-Atlantic Region.* A report by the U.S. Climate Change Science Program and the Subcommittee on

Global Change Research, U.S. Environmental Protection Agency, Washington DC, pp105-116.

Gutierrez, B.T., Williams, S.J., and Thieler, E.R., 2007. *Potential for Shoreline Changes Die to Sea level Rise along the U.S. Mid-Atlantic Region.* Open file report 2007-1278. U.S. Geological Survey, Reston, VA, 26 pp.

Honeycutt, M.G., Crowell, M., and Hatheway, D., 1999. Coastal erosion hazards study: Phase one mapping: *Journal of Coastal Research*, Special Issue no. 28, p. 10-20.

Intergovernmental Panel on Climate Change (IPCC), 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linder, P.J., Dai, X., Maskell, K., Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, UK, and New York, 881 pp.

Johnson, Z. *et al*, 2006: Worcester County Sea Level Rise Inundation Model, Technical Report, Maryland Department of Natural Resources, DNR Publication No. 14-982006-166, 15pp

Thieler, E.R., E.A. Himmelstoss, J.L. Zichichi, and T.L. Miller. 2005. *Digital Shoreline Analysis System (DSAS) Version 3.0: An ArcGIS Extension for Calculating Shoreline Change.* Open-File Report 2005-1304. U.S. Geological Survey. Accessed April 4, 2008, at http://pubs.usgs.gov/of/2005/1304/.

U.S. Army Corps of Engineers (USACE), 2009. Water Resource Policies and Authorities, Incorporating Sea level Change Considerations in Civil Works Programs, EC 1165-2-211, Expires July 2011, CECW-CE Circular No. 1165-2-211, Department of the Army, U.S. Army Corps of Engineers, Washington, DC.

Chapter 7.0 Case Studies

7.1 California IOCM

The California Seafloor Mapping Program (CSMP) is a cooperative program to create a comprehensive coastal/marine geologic and habitat base map series for all of California's state waters. The Ocean Protection Council authorized funds to establish the CSMP in 2007 (OPC 2007) and assembled a team of experts from state and Federal agencies, academia, and private industry to develop the best approach to mapping and classifying estuarine and marine geologic habitats, while also updating all nautical charts. Initiated in 2008, the CSMP is collecting bathymetry (underwater topography) and backscatter data (providing insight into the geologic makeup of the seafloor) that will be turned into habitat and geologic base maps for all of California's state waters mean high water (MHW) line out to three nautical miles). Although the CSMP was originally developed to support the design and monitoring of marine reserves through the Marine Life Protection Act (CDFG 2007), accurate statewide mapping of the seafloor will also:

- Improve climate change and ocean circulation models
- Help evaluate the potential for ocean energy
- Improve our understanding of ecosystem dynamics
- Identify submerged faults and improve our understanding of tsunami potential
- Enable more effective regulation of offshore development.
- Improve maritime safety
- Improve our understanding of sediment transport and sand delivery

CSMP focus is to fund ship-based collection of high-resolution sonar data, which is the undersea equivalent of satellite remote sensing data in terrestrial mapping. The CSMP plan is based largely on earlier findings and recommendations of a State-wide Marine Mapping Planning Workshop (Kvitek et al. 2006: http://seafloor.csumb.edu/StrategicMappingWorkshop.htm) attended by coastal and marine managers and scientists. That workshop established geographic priorities for a coastal mapping project and identified the need for coverage of "lands" from the strand line (MHHW) out to the 3 nm (5.6 km) State water limit. A subsequent USGS-hosted Coastal Map Development Workshop held in May 2007 helped define the CSMP comprehensive mapping approach.

The CSMP is a cooperative partnership between state, Federal agencies, universities, and industry including:

- California Coastal Conservancy (http://scc.ca.gov/internal-search/)
- California Ocean Protection Council (http://opc.ca.gov)
- California Department of Fish and Game (http://dfg.ca.gov)
- California Geological Survey (http://www.conservation.ca.gov/CGS)
- California State University, Monterey Bay - Seafloor Mapping Lab (http://seafloor.csumb.edu)

- Moss Landing Marine Laboratories - Center for Habitat Studies (http://habitat.mimi.calstate.edu)
- Fugro Pelagos Inc. (http://www.fugro.com)
- Pacific Gas and Electric (http://www.pge.com)
- US Army Corps of Engineers (http://www.usace.army.mil)
- Office of Coast Survey, NOAA (http://nauticalcharts.noaa.gov)
- National Geophysical Data Center, NOAA (http://www.ngdc.noaa.gov)
- National Marine Fisheries Service, NOAA (http://www.nmfs.noaa.gov)
- National Marine Sanctuaries, NOAA (http://sanctuaries.noaa.gov)
- Coastal Services Center, NOAA (http://www.csc.noaa.gov)
- Minerals Management Service (http://www.mms.gov)
- Western Coastal and Marine Geology Team, U.S. Geological Survey (http://walrus.wr.usgs.gov)

Data collected during this project reveal the sea floor offshore of the California coast in unprecedented detail and provide an ecosystem context for the effective management of this precious marine resource. The partnership with NOAA Office of Coast Survey will also result in updated digital nautical charts for all state waters. This website monitors the progress of the project and provides a background to the different data collection operations and mapping products.

7.2 North Carolina Sea Level Project

A model to examine the impacts of long term sea level rise (SLR) has been implemented in the coastal North Carolina ecosystem http://www.nauticalcharts.noaa.gov/csdl/sealevelrise.html. This area, as a fragile system of barrier islands that protect an extensive but sensitive estuarine system, is particularly vulnerable to sea level change (SLC). The primary impact of SLC is on the hydrodynamic response of the system: circulation, tidal amplitude, and inundation patterns due to tides, winds, and storms that can all change in response to rising sea level. Rates of SLC in the region are nearly 3 mm/year and are increasing; furthermore, inundation is tied to inlet conveyance, which can be modified by SLC. A two-dimensional hydrodynamic model is being used to simulate tidal response, regional synoptic wind events, and hurricane storm surge propagation to study changes due to SLC. Accurate simulation of inundation patterns is accomplished by high localized resolution in the coastal zone, continuous bathy/topo data, and an accurate wetting/drying algorithm. The model will be validated against observational data before modification of initial and boundary water levels to represent eustatic SLC. Shoreline migration can be dynamically computed from the model simulation output as a function of SLC. Finally, the hydrodynamic model will be coupled to submodels that characterize the ecological impact of SLC. This work comprises the *Ecological Effects of Sea Level Rise* project being led by NOS' National Centers for Coastal Ocean Science (http://www.cop.noaa.gov/stressors/climatechange/current/slr/default.aspx).

Model Development

The Coast Survey Development Lab (www.nauticalcharts.noaa.gov/csdl/welcome.htm) has implemented a hydrodynamic model of the Pamlico/Albemarle Sound of North Carolina. The two-dimensional version of the ADCIRC finite element model is used. A triangular grid was created to cover the entire domain and a water level time series was produced at each node in the grid. The semidiurnal tidal high water and low water marks were extracted from the modeled time series and used to calculate tidal datums (e.g., MHW, MLLW). The calculated tidal datums were compared to NOS water level station data at locations throughout the domain. The model results were adjusted to match the station data at those locations by spatially interpolating the error, so the corrected model results match the published NOS datum information in the region. The final tidal datum results were used to populate regularly-spaced grids that were created as a component to the VDatum software (http://vdatum.noaa.gov). The VDatum tool allows the transformation (http://www.nauticalcharts.noaa.gov/csdl/learn_datum.html) between ellipsoidal, orthometric, and tidal datums. After the VDatum tool was created, it was used to transform the bathymetry data in the region to the North American Vertical Datum of 1988 (NAVD 88). The adjusted bathymetry was combined with topographic LIght Detection and Ranging (LIDAR) data (also referenced to NAVD 88) to create a seamless elevation field. A 6-meter (m) horizontal resolution continuous bathymetric/topographic (bathy/topo) Digital Elevation Model (DEM) was constructed for accurate modeling of inundation (figure 7.1). The final DEM covers a subset of the VDatum region with the focus at Beaufort, NC.

A Coastal Flooding Model (CFM) has been developed for the region by combining the tidal finite element hydrodynamic model with the continuous bathymetric and topographic elevation dataset. The CFM domain extends from 90 km offshore of the Outer Banks to the 15 m topographic contour and from northern Currituck Sound south to the New River. The CFM provides high resolution of coastal features down to 50 m. The CFM is relative to the NAVD 88 vertical datum and is populated with DEM elevations where available and other topographic and bathymetric data relative to NAVD 88 elsewhere to create a continuous bathy/topo elevation field.

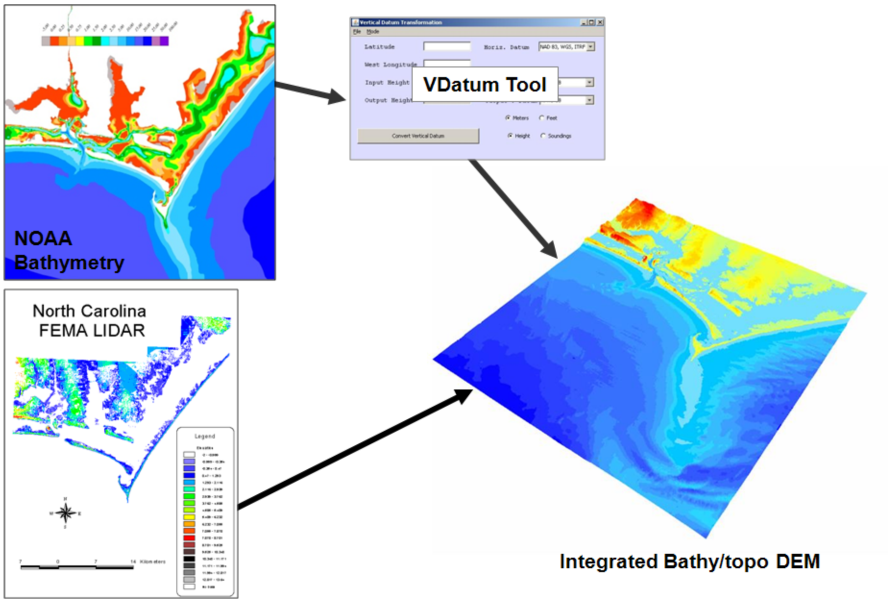


Figure 7.1. Construction of the continuous bathy/topo DEM

Model Application

The CFM will model different scenarios of sea level rise, as well as inundation from high intensity storms that sweep through the region. First, changes in tidal harmonic constants can be calculated to simulate the effect of SLC. Second, changes in tidal datum shorelines can be calculated throughout the study area as demonstrated for the local test region. For example, the Figure 7.2 shows a nautical chart of the Morehead City and Beaufort, NC area. The dark black line shows the charted MHW shoreline. The red line shows the modeled present day MHW shoreline. The green line shows the modeled MHW shoreline with a 30 cm rise in sea level. Third, the impact of synoptic wind events can be examined by forcing the CFM with wind fields and validating with water level records. This is an important process in the North Carolina sounds, since much of the system is non-tidal, and the primary inundation events are wind-driven, such as northeasters. The range and extent of inundation will be affected by SLC, which can be shown by model output. Fourth, the CFM can be used to study hurricane storm surge flooding of the NC system and the significance of changes in flooding with SLC. Fifth, the model output will provide input to other models being developed for the project.

The CFM was developed to support the ecological effects of SLC study (http://www.coop.noaa.gov/stressors/climatechange/current/slr/welcome.html). Using the CFM to study changes in inundation with SLC is not complete without considering ecological processes, which include: erosion and deposition; marsh evolution; productivity of oyster reef, submerged aquatic vegetation, and benthic habitats; and anthropomorphic change. Therefore, the CFM is used to drive a suite of ecological submodels of these processes. These submodels and the CFM can provide iterative updates to each other to generate an overall prediction of the ecological effects of SLC. The impacts of anthropomorphic changes, such as shoreline hardening in response to SLC, are included in these ecological submodels and can provide coastal managers with key modeling and mapping tools to assess the risk of SLC to the NC coastal environment.

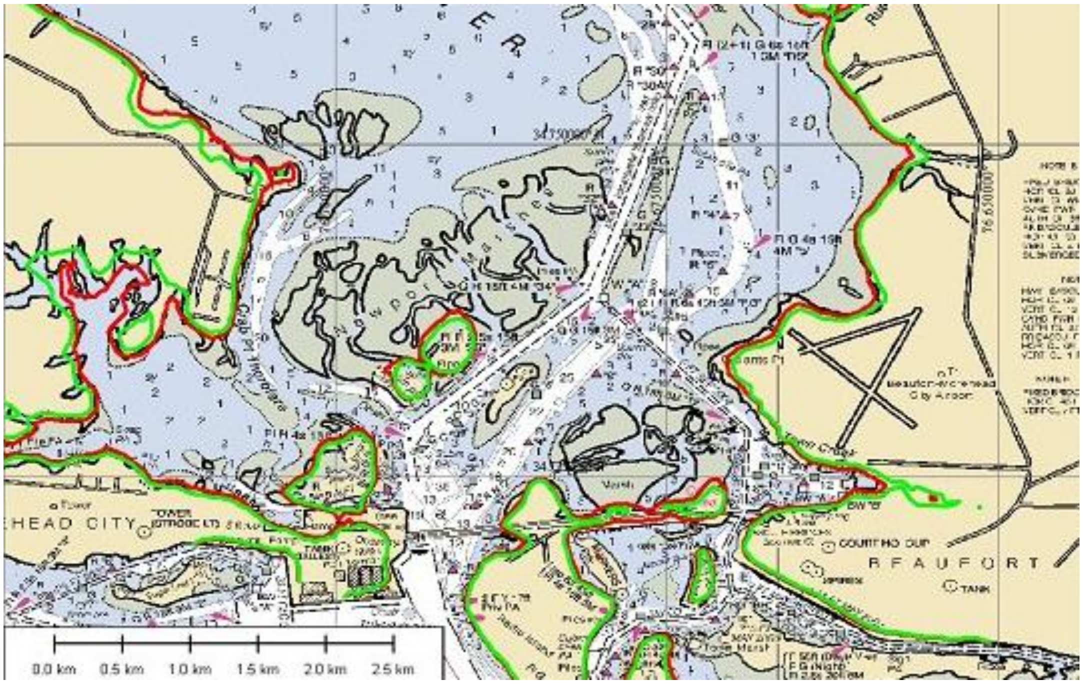


Figure 7.2. Predicted shoreline change due to sea level rise by use of the Coastal Flooding Model

7.3 East Coast Anomaly

Sea level variability occurs on many different time and space scales as highlighted in chapter 2. Anomalies, both high and low in nature, occur as significant deviations from a defined climatology. Short-period anomalies that garner most attention are events in which water levels are significantly different than those predicted by local tidal dynamics. Along the U.S. East Coast, these events are usually noticed as surges from regional wind storms such as East Coast winter storms (nor’easters) or as more localized impacts from tropical storm strikes. They can affect a coastal region over a period ranging from hours to several days. Post-storm surveys are often carried out by FEMA and other government agencies after an unusually damaging event to collect and measure the high water marks on the inside and outside of structures in order to characterize the spatial variability of the peak water levels. This procedure is especially important when NOAA tide stations become damaged or malfunction at the peak of the storm and do not capture the complete record of water levels. CO-OPS and its predecessors have published a series of relevant reports containing station records for particularly large events, which can be found at http://tidesandcurrents.noaa.gov/publications/NOAA_NOS_Storm_Reports.pdf.

Longer-period sea level anomalies, such as those normal along the U.S. Pacific Coast from El Niño Southern Oscillation (ENSO) forcing, appear as regional deviations from the long-term mean seasonal and annual cycles. Long-period anomalies are less noticed, but when positive, can effectively raise the level on which the spring-neap tidal cycle and incident storm surges occur, increasing the potential for coastal flooding. An example of an important seasonal-scale sea level anomaly occurred during June and July 2009 when NOAA tide stations recorded sustained higher than normal levels along the U.S. East Coast. A detailed report can be found at http://tidesandcurrents.noaa.gov/publications/EastCoastSeaLevelAnomaly_2009.pdf. The event unfolded when near-peak levels in the latter half of June coincided with a *perigean-spring* tide, which added to the observed sea level anomaly, produced minor coastal flooding, and caught the attention of many coastal communities because of the absence of coastal storms that normally cause such anomalies. In terms of monthly mean sea levels, the event was not particularly abnormal, as many locations have higher levels in the late-summer. The sea levels were anomalous because of their unexpected geographic scope and timing, unaccounted for within the normal seasonal cycles of the winds and atmospheric pressure, ocean currents, and heating/cooling of coastal waters. The two probable mechanisms responsible for the anomaly was sustained northeasterly wind forcing north of Cape Hatteras, and a reduced transport of the Gulf Stream system south of Cape Hatteras that reduced the eastward-rising cross-current slope, effectively raising coastal sea level. The June-July 2009 sea level anomaly is unique in that the winds were not at a multi-year high or transport at its low. But the coupled effect of the two forces created high sustained sea levels between North Carolina and New Jersey in the region of greatest overlap of the two forces.

7.4 Southeast Florida Sea Level Rise Mapping Consensus-Building Workshop

Southeast Florida Inundation Mapping Criteria Workshop - April 20–21, 2010

Southeast Florida is highly vulnerable to sea level rise (SLR) due to its peninsular nature and low topography. Mapping different sea level rise inundation scenarios helps to identify areas at potential risk and aids in planning for a climate-resilient community. At the October 23, 2009 Southeast Florida Regional Climate Leadership Summit, the local diversity in the data sources, methods, and criteria used to generate the currently available sea level change (SLC) inundation scenarios was highlighted as a concern and barrier to achieving regionally consistent vulnerability analyses. The National Oceanographic and Atmospheric Administration (NOAA) Coastal Services Center (CSC) worked closely with Broward County and the South Florida Water Management District (SFWMD) to coordinate a two-day technical workshop in April 2010. The purpose of the workshop was to develop a unified set of methodologies and criteria for creating sea level inundation maps in the Southeast Florida region.

Workshop participants were Geographic Information System (GIS) practitioners representing Monroe, Miami-Dade, Broward, and Palm Beach, as well as the SFWMD, local universities and Federal agencies. Using information gained by surveying the participants in advance of the workshop, NOAA and its partners brought significant resources that helped in understanding inundation mapping methodologies currently in use, defining the local challenges, and working toward creating a consensus set of methods and criteria. Through a facilitated process, the group agreed to:

- Use Florida Division of Emergency Management (FDEM) Light Detection And Ranging (lidar) elevation data where it is available

- Recognize that the United States Geological Survey (USGS) SGS High Accuracy Elevation Dataset (HAED) is the best available dataset for its extent and scale in areas not covered by FDEM
- Use regionally-consistent digital elevation models (DEMs) provided by SFWMD
- Use 10-foot cell size DEMs at the county level for inundation/vulnerability analysis
- Use larger cell-size DEMs as appropriate at regional level
- Use Mean Higher High Water (MHHW) tidal datum relative to NAVD 88 as the starting elevation for inundation scenarios
- Use the VDatum MHHW tidal grid surface in NAVD 88 to be provided by NOAA to ensure smooth transitions across county boundaries
- Map SLR inundation on 1-ft increments
- Map scenarios not to exceed a maximum of 6 ft of SLC
- Calculate uncertainty (75/25) using NOAA's recommended methodology
- Show inundation polygons as areas at or below MHHW for the given scenario, including unconnected low-lying areas and without differentiation from hydrologically-connected areas
- Use a minimum mapping unit of ½ acre
- Explore disclaimer language for maps

Commitments following the workshop included:

Participants:

- ➢ Abide by the agreed upon methodologies for the generation of sea level rise inundation modeling
- ➢ Attend future workshops to further refine vulnerability analysis methods for Southeast Florida

USGS Representative:

- ➢ Report back to the group the status of HAED elevation information (See chapter 5)

SFWMD:

- ➢ Prepare and share DEMs using FDEM lidar for each of the four county areas, including any future updates
- ➢ Assist with planning and hosting the next inundation mapping workshop

NOAA:

- ➢ Supply methodology details to calculate uncertainty
- ➢ Generate the VDatum MHHW tidal surface for all coastal counties within SFWMD boundary
- ➢ Act as a resource in the future as the counties begin to develop local inundation maps

The workshop participants agreed to reconvene in 3-4 months to further discuss pending items and to outline the specific parameters to include in a regionally consistent vulnerability analysis. The project FTP site provides post workshop deliverables including additional contact information related to HAED elevation coverage, tidal datum reference material, sample disclaimer language, information regarding the VDATUM tidal surface, and notes on uncertainty.

A NOAA Digital Coast In Action article briefly explaining this workshop and the process that was used to come to a consensus regarding mapping methods can be found at: http://www.csc.noaa.gov/digitalcoast/action/slr-seflorida.html.

Chapter 8.0 Additional Resources

8.1 Organizations/Programs

NOAA Coastal Services Center:
http://www.csc.noaa.gov/

NOAA Office of Coast Survey:
http://www.nauticalcharts.noaa.gov/

NOAA Center for Operational Oceanographic Products and Services:
http://www.tidesandcurrents.noaa.gov/

National Geodetic Survey:
http://www.ngs.noaa.gov

USGS National Assessment of Coastal Change Hazards Program:
http://coastal.er.usgs.gov/national-assessment/

USGS Center for Lidar Information Coordination and Knowledge (CLICK):
http://lidar.cr.usgs.gov/

National Geophysical Data Center (NGDC):
http://www.ngdc.noaa.gov/

National Digital Elevation Program (NDEP):
http://www.ndep.gov/

Joint Airborne Lidar Bathymetry Technical Center of Expertise:
http://shoals.sam.usace.army.mil/

NOAA CSC Training:
http://www.csc.noaa.gov/bins/training.html

8.2 Publications

FEMA Guidelines and Specifications for Flood Hazard Mapping Partners:
http://www.fema.gov/plan/prevent/fhm/dl_cgs.shtm#volume1
Appendix D (Coastal Mapping):
Appendix A: Guidance for Aerial Mapping and Surveying

FEMA FAQ's for Digital Flood Data:
http://www.fema.gov/plan/prevent/fhm/fq_main.shtm

Seaside, Oregon Tsunami Pilot Study:
http://pubs.usgs.gov/ds/2006/236/index.shtml

FEMA Coastal Construction Manual:
http://www.fema.gov/rebuild/mat/fema55.shtm

National Standard for Spatial Data Accuracy (NSSDA):
http://www.fgdc.gov/standards/standards_publications/

International Hydrographic Association Standards for Hydrographic Surveys:
http://www.iho.shom.fr/

NDEP Guidelines for Digital Elevation Data:
http://www.ndep.gov/

NOAA Coastal Services Center. "IfSAR Data: Notes and Considerations".
Contact: Kirk Waters

NOAA, Office of Ocean and Coastal Resource Management, 2010. Adapting to Climate Change: A Planning Guide for State Coastal Managers.
http://coastalmanagement.noaa.gov/climate/docs/adaptationguide.pdf

NOAA Coastal Services Center, 2007. "Topographic and Bathymetric Data Considerations: Datums, Datum Conversion Techniques, and Data Integration.". Part II of A Roadmap to aSeamless Topobathy Surface. Technical Report No. NOAA/CSC/20718-PUB.
Contact: Kirk Waters

NOAA, 2007. "FAQ / State of the Science: Inundation". Forthcoming.

Additional References:

Airborne Laser Hydrography, 1985: Gary Guenther, U.S. Department of Commerce, NOAA, National Ocean Service, Charting and Geodetic Services, 1985, 385pp.

Coastal Mapping Handbook, 1978: Melvin Y. Ellis, Editor. U.S Department of the Interior Geological Survey and U.S Department of Commerce National Ocean Survey Office of Coastal Zone Management, U.S Government Printing Office, 1978, 199pp.

Decomposition of Sea Level Variations, 1990. W.D. Sherer. An Approach, National Ocean Service, Oceanography Workshop, unpublished manuscript, 1990.

NOAA Hydrographic Manual, Fourth Edition, 1976 by Melvin J. Umbach, U.S. Department of Commerce, NOAA, National Ocean Survey, July 4, 1976, 400pp.

Manual of Photogrammetry, Fifth Edition, 2004, Editor J. Chris McGlone, American Society of Photogrammetry and Remote Sensing, 1151pp.

Manual of Photogrammetry, Fourth Edition, 1980, Editor Morris M. Thompson, American Society of Photogrammetry and Remote Sensing 1168pp.

Understanding Sea-level Rise and Variability, Edited by J.A. Church, P.L. Woodworth, T. Aarup, and W.S. Wilson, Wiley-Blackwell, 2010, 428pp.

Sea Surface Topography from Space, Proceedings, 1972, Editor John R. Apel, NOAA Technical Report ERL 228-AOML 7

Shore and Sea Boundaries, Volume One, 1962.
http://www.nauticalcharts.noaa.gov/hsd/shalowitz.html

Shore and Sea Boundaries, Volume Two, 1964.
http://www.nauticalcharts.noaa.gov/hsd/shalowitz.html

Shore and Sea Boundaries, Volume Three, 2000.
http://www.nauticalcharts.noaa.gov/hsd/shalowitz.html

The American Practical Navigator, 1995. Originally by Nathaniel Bowditch, LL.D. Defense Mapping Agency Hydrographic/Topographic Center. Ch. 2. pp.63-163.

8.3 Data/Models

NOAA National Weather Service Probabilistic Hurricane Storm Surge Mapping:
www.weather.gov/mdl/psurge/

FEMA Coastal Recovery Maps:
http://www.fema.gov/hazard/flood/recoverydata/index.shtm

Sea, Lake and Overland Surges from Hurricanes (SLOSH) Model:
http://www.nhc.noaa.gov/HAW2/english/surge/slosh.shtml
Contact: Arthur Taylor*

Advanced Circulation (ADCIRC) Model: ADCIRC Development Group:
http://www.nd.edu/~adcirc/index.htm

Method of Splitting Tsunami (MOST) Model:
http://nctr.pmel.noaa.gov/model.html

USGS National Elevation Dataset:
http://ned.usgs.gov/

Global Land 1 Kilometer Base Elevation (GLOBE) Dataset:
www.ngdc.noaa.gov/mgg/topo/globe.html

National Ocean Service (NOS) Hydrographic Database:
www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

NGDC Topo/Bathy Grids:
http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html

Extratropical Storm Surge Forecasts:
http://www.nws.noaa.gov/mdl/etsurge/

USGS National Water Information System (NWIS):
http://waterdata.usgs.gov/nwis

NWS Flood Severity Inundation Mapping:
http://www.weather.gov/ahps/inundation.php

8.4 Software/Tools

HURREVAV Storm Surge Module:
www.hurrevac.com

Digital Coast Data Access Viewer (DAV):
http://csc-s-maps-q.csc.noaa.gov/dataviewer/viewer.html?keyword=lidar

North American Datum Conversion (NADCON) Tool:
http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html

Vertical Conversion (VERTCON) Tool:
http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

VERTCON PC Version:
http://www.ngs.noaa.gov/PC_PROD/VERTCON/

Vertical Datum Transformation (VDATUM) Tool:
http://vdatum.noaa.gov

Corpscon Conversion Tool:
http://crunch.tec.army.mil/software/corpscon/corpscon.html

Java Runtime Environment (requirement for VDATUM):
http://java.sun.com/

NOAA CSC Risk and Vulnerability assessment Tool (RVAT):
http://www.csc.noaa.gov/rvat/

NOAA CSC Community Vulnerability Assessment Tool (CVAT):
http://www.csc.noaa.gov/products/nchaz/startup.htm

Chapter 9.0 Acronyms and Abbreviations

A

ADCIRC	Advanced Circulation (model)
AHPS	Advanced Hydrologic Prediction Service
ASFPM	Association of State Floodplain Managers
ABFE	Advisory Base Flood Elevation

B

BAG	Bathymetry Attributed Grid
BFE	Base Flood Elevation

C

CBN	Cooperative Base Network
C-CAP	Coastal Change Analysis Program
CCSP	Climate Change Science Program
CFM	Coastal Flooding Model
CHARTS	Compact Hydrographic Airborne Rapid Total Survey
CLICK	Center for Lidar Information Coordination and Knowledge
cm	centimeter
CO-OPS	Center for Operational Oceanographic Products and Services
CORS	Continuously Operating Reference Stations
CSMP	California Seafloor Mapping Program
CUBE	Combined Uncertainty and Bathymetric Estimator

D

DEM	Digital Elevation Model

E

ENSO	El Niño Southern Oscillation

F

FBN	Federal Base Network
FDEM	Florida Division of Emergency Management
FEMA	Federal Emergency Management Agency
FGDC	Federal Geographic Data Committee
FIS	Flood Insurance Study
FIRM	Flood Insurance Rate Map

G

GCP	Ground Control Point
GEV	Generalized Extreme Value
GFS	Global Forecast System
GIA	Glacial Isostatic Adjustment
GIS	Geographic Information System
GPS	Global Positioning System
GLOBE	Global Land One-Kilometer Base Elevation (dataset)
GNSS	Global Navigation Satellite System

GOES	Geostationary Operational Environmental Satellite

H

HAED	High Accuracy Elevation Dataset
HES	Hurricane Evacuation Study
HURREVAC	Hurricane Evacuation (computer program)
HWL	High Water Line

I

IDW	Inverse Distance Weighting
IERS	International Earth Rotation and Reference Frame Service
IfSAR	Interferometric Synthetic Aperture Radar
IHO	International Hydrographic Organization
IOC	Intergovernmental Oceanographic Commission
IOCM	Integrated Ocean and Coastal Mapping
IPCC	Intergovernmental Panel on Climate Change
ITRF	International Terrestrial Reference Frame

J

JALBTCX	Joint Airborne Lidar Bathymetry Technical Center of Expertise

K

L

LDART	Lidar Data Retrieval Tool
Lidar	Light Detection and Ranging

M

m	meter
MBES	Multibeam Echosounder
MCU	Maximum Cumulative Uncertainty
MDL	Meteorological Development Lab
MEOW	Maximum Envelope of Water
MHW	Mean High Water
MHHW	Mean Higher High Water
MLW	Mean Low Water
MLLW	Mean Lower Low Water
mm	millimeter
MOM	Maximum of MEOW
MSL	Mean Sea Level

N

NADCON	North American Datum Conversion
NCEP	National Centers for Environmental Prediction
NTDE	National Tidal Datum Epoch
NED	National Elevation Dataset (USGS dataset)
NERRS	National Estuarine Research Reserve
NESDIS	National Environmental Satellite Data and Information Service
NFIP	National Flood Insurance Program

NGDC	National Geophysical Data Center
NGS	National Geodetic Survey
NHC	National Hurricane Center
nm	nautical mile
NMAS	National Map Accuracy Standards
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRC	National Research Council
NWS	National Weather Service
NSRS	National Spatial Reference System
NSSDA	National Standard for Spatial Data Accuracy
NWIS	National Water Information System
NWLON	National Water Level Observation Network
NWLP	National Water Level Program

O

OPUS	Online User Positioning System
ORRI	Orthorectified Radar Image

P

PDOP	Position Dilution of Precision
PMEL	Pacific Marine Environmental Laboratory
PSMSL	Permanent Service for Mean Sea Level

Q

QC	Quality Control

R

RMS	Root Mean Square
RMSD	Root Mean Square Difference
RMSE	Root Mean Square Error
RVA	Risk and Vulnerability Assessment

S

SD	Standard Deviation
SET	Surface Elevation Tables
SIFT	Site-Specific Inundation Forecasting of Tsunamis
SFHA	Special Flood Hazard Area
SLAMM	Sea Level Rise Affecting Marsh Model
SLC	Sea Level Change
SLOSH	Sea, Lake, and Overland Surges from Hurricanes (model)
SONAR	Sound Navigation and Ranging
SOW	Scope of Work

T

TIN	triangulated irregular network
THU	Total Horizontal Uncertainty
TVU	Total Vertical Uncertainty

U

UDN	User Densification Network
URL	Universal Resource Locator
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

V

VDOP	Vertical Dilution of Position
VLBI	Very Long Baseline Interferometry