Reprint from
ACSM BULLETIN
No. 236, December 2008

Understanding Sea Level Change

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Introduction

Climate change and how it influences sea level is on everybody's mind: Will society be impacted by an increased rate in global sea level rise, and to what degree?

The Intergovernmental Panel on Climate Change (IPCC) reported in their 2007 assessment that the average rise in global sea level during the 20th century was 1.7 mm/yr. Based on satellite altimetry observations since 1993, sea level has been rising at about 3 mm/yr—a rate that is nearly twice the average for the century. It is unclear whether this faster rate is a reflection of decadal variability or whether it is indeed due to an increase in the longer-term trend.

The Nation's nautical charts, shoreline maps, and elevations relative to homes, levees, and other coastal infrastructure depend on the accurate determination of sea level. Rising sea levels can have legal ramifications on national, state, and private boundaries along the coast. These issues are thus highly relevant to coastal surveyors, coastal managers, and everyone working and living along our coasts.

Accurate determination of sea level is also crucial for the establishment of NOAA's nautical chart datum (Mean Lower Low Water), as well as the shoreline (Mean High Water) and National Tide Tables. To ensure that these charts and tide tables are accurate and remain relevant, NOAA's Center for Operational Oceanographic Products and Services and its predecessors have been engaged in determining sea level for the United States since the mid 19th century.

This article discusses how NOAA monitors sea level rise through measurements of Local Mean Sea Level.

Global Sea Level

Change in sea level on a global scale is primarily caused by two effects: the addition of water volume due to the melting of land-based glaciers and ice sheets, and the thermal expansion of the upper layers of the oceans due to a decrease in water density caused by its warming.

The IPCC reported that global sea level has risen over 120 m since the recent ice age. In the current interglacial period, global sea level initially rose and stabilized 3,000 to 2,000 years ago. It was not until the late 19th century that sea levels began to change again significantly (IPCC 2007).

Using tide records from the 20th century, Church and White (2006) estimated that global mean sea level rose at a rate of 1.7 mm/yr.; this finding was included in the IPCC panel report. The determination of global sea level is complicated by regional variations in sea level. As shown in Figure 1, sea level change, determined by TOPEX/Poseidon and Jason altimeter data over a 15-year period (Leuliette et.al. 2004), is highly non-uniform spatially—certain regional rates are several times the global mean (average) rate of sea level rise, whereas sea level is actually falling in other regions.

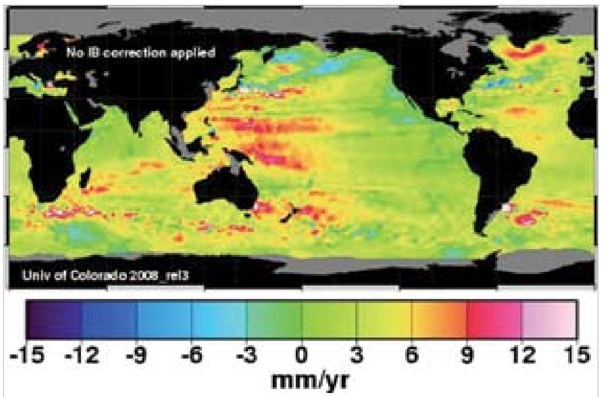

Figure 1. Global distribution of sea level trends, 1993-2007, derived from satellite altimetry [http://sealevel.colorado.edu.]

Over the past decade, the high rate of sea level rise found in the western tropical Pacific was in a region exhibiting large inter-annual variability associated with the global ocean–atmosphere phenomenon known as El Niño Southern Oscillation (ENSO). Since the ocean surface is dynamic (influenced by oceanographic and meteorological processes such as the astronomical tide, ocean circulation, changes in water density, wind, atmospheric pressure, and change in water volume), measuring sea level requires constant attention and long records. When determining the sea level rate of change, it is essential to indicate if it is a global or regional trend. It is equally important to specify the time period of observation, such as a monthly or long-term mean (e.g., a 19-year tidal epoch).

There are two primary methods by which global sea level is measured: satellite altimetry and tide stations. Satellite altimetry provides the potential for observing the variability of global sea level and ocean circulation on space and time scales impossible by any other means. Because of the global coverage provided by international agencies, sea level observations from satellite altimetry have already led to a better understanding of El Niño, the Gulf Stream, and other climatic phenomena.

Tide stations measure sea level relative to specific locations on land. Calculating global sea level from tide stations thus requires removing local land movement, such as land subsidence, glacial rebound, and tectonic movement from the overall signal. Douglas (1991) suggests that in order for a tide gauge record to be used for estimating rates of global sea level rise, the records must cover a period of 50 years or longer; be free of substantial vertical crustal movement (i.e., not located in areas of uplift or subduction/subsidence); be correctable for Global Isostatic Adjustment (GIA) using a recognized GIA model; and have trends insensitive to small changes in record length due to large decadal variations.

NOAA's Center for Operational Oceanographic Products and Services operates and maintains a national network of over 200 long-term tide/water level stations. Since climate change was not a concern during the mid-1800s, the initial stations were installed primarily for supporting navigation and marine boundary determination. These automated sea level measurements were taken using a float inside a protective stilling well. The measurements were quite accurate, as they were compared to measurements on a tide staff surveyed relative to permanent benchmarks on land.

Currently, sea-level measurements are made by an acoustic sensor every six minutes. An important requirement for sea level measurements at tide stations is datum continuity; this requires that sensors and land-based benchmarks are routinely resurveyed. Datum continuity was initially a requirement for maintaining accurate nautical charts. The benefit of doing so is that we can now determine sea level trends on the order of 1 or 2 mm/yr. NOAA conducts differential leveling annually in order to maintain this critical vertical control at its tide stations. The information is available through the National Tidal Benchmark System that provides tidal datums at approximately 1,350 locations nationwide.

Local Mean Sea Level

The U.S. Supreme Court has shaped the legal context of the marine environment by its many decisions on navigable water, marine boundaries and the public trust doctrine. One of the most important decisions related to Local Mean Sea Level (LMSL) was the landmark 1936 case of *Borax, Ltd v. City of Los Angeles*. In this case, the Supreme Court recognized the importance of averaging sea level observations over the 19-year tidal datum epoch established by the Coast and Geodetic Survey, a predecessor of NOAA, when determining the mean high tide line.

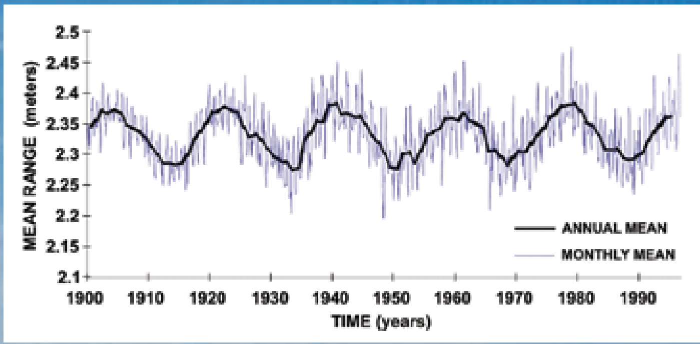

Figure 2. The variation of Mean Range of tide (1900 - 1996) at Seattle, WA, demonstrates the need for averaging the National Tidal Datum Epoch over 19 years.

The importance of a uniform system of tidal datums for all tidal waters in the U.S, its territories, and trusts was recognized and established by the National Tidal Datum Convention of 1980. As a result, NOAA's definitions of tidal datums—Mean High Water (MWH), Mean Lower Low Water (MLLW), and LMSL—were authorized as the official policy of the U.S. Federal Government.

Local mean sea level is a term used to denote the average height of the ocean relative to land. Because the ocean surface is dynamic (being influenced by seasonal-to-decadal oceanographic and meteorological processes), we need to use a long period of observations to determine LMSL. The LMSL for the United States is determined as part of the National Tidal Datum Epoch (NTDE) which is based on 19 years.

Nineteen years is also the length of the Metonic Cycle of recurrence of the lunar phases. This lunar cycle, first determined by Meton of Athens in 432 BC, captures a long-period change in the amplitude of the tide due to the orbital paths of the Earth and Moon relative to the Sun. The Metonic Cycle was selected because it includes daily, monthly, annual, and decadal changes in the amplitude of tides over 19 years.

Figure 2 shows the variation introduced into the amplitude of the annual mean ranges of the tide during the Metonic Cycle. The heavy black curve is the annual mean range, or the difference in height between Mean High Water and Mean Low Water. The time elapsed from peak-to-peak is the Metonic Cycle.

The NTDE includes a 18.61-year cycle for the revolving regression of the Moon's nodes. The NTDE is actually based on 19 complete years so that local seasonal variation in sea level, which can be substantial, would not bias the tidal datum computation. The NTDE was established so that all tidal datums throughout the United States are based on one, recent, specific and common reference period. It is the policy of NOAA to consider a revised NTDE every 20-25 years in order to take into account relative sea level changes caused by global sea level rise as well as the effects of long-term regional oceanographic and meteorological variations and vertical land movement. The LMSL, a tidal datum, is determined for a location using the arithmetic mean of hourly heights observed over a specific NTDE. Previous tidal datum epochs for the United States were determined for the periods 1924-42, 1941-59, and 1960-78. The present NTDE is 1983-2001.

Figure 3. Elevation difference between LMSL (1983-1999 NTDE) and NAVD 88. [Note: The LMSL for Grand Isle, Louisiana is based on the 2001-2006 Modified Tidal Datum Epoch and an updated NAVD 88 epoch 2006.81 specific to the Louisiana region.]

The LMSL varies regionally across the Nation relative to the North American Vertical Datum of 1988 (NAVD88), the vertical component of the National Spatial Reference System maintained by NOAA's National Geodetic Survey (see Figure 3) The difference between LMSL from the Atlantic to the Pacific coast relative to NAVD88 is on the order of 1 meter.

The spatial and temporal variations of LMSL relative to a geodetic datum are important for the accurate depiction of the land–sea interface and emphasize the critical need to reference sea-level measurements to land, as is the use of a 19-year average of sea level data when conducting bathymetric surveys and mapping the shoreline, or when determining elevations above LMSL. This is crucial for safe navigation of coastal waters as well as for determining accurate elevations and vulnerability of coastal infrastructure, such as levees, homes, and roads, to storm surge and sea-level rise.

Seasonal, Inter-annual, and Decadal Sea Level Variations

Although current research on global sea level rise has been focused on determining the water volume added from the melting of glaciers and the extent of the thermal expansion of the oceans due to global warming there is another aspect of climate and sea-level change that needs to be considered. It is the inter-annual-to-decadal sea level signal which can be larger than the actual global sea level trend.

Seasonal variations in sea level at certain locations can be on the order of 40 cm or more. These variations are caused by seasonal changes in temperature, wind, and river runoff. While seasonal variations can be removed from the record using annual means, they have the potential to increase with projections of global warming and possible increases in the frequency and magnitude of coastal storms. Hence, these seasonal variations must also be considered in conjunction with inter-annual sea level variations which are smaller than the seasonal variations but still larger than long-term sea-level trends.

An understanding of the inter-annual-to-decadal variation in sea level requires long records of sea level observations. Coupled ocean–atmosphere interactions can affect regional oceanographic or meteorological phenomena, such that they may have very low frequency components that could then affect sea-level trends.

For example, coasts are subjected to inter-annual-to-decadal changes in wind that impact upwelling, which in turn affects the density of the water column and results in regional thermal expansion or contraction of the water column. Any changes in ocean circulation, especially at the western boundaries of oceans, can also affect sea level through changes in density and through geostrophic adjustments. In the tropical Pacific, one of the most studied inter-annual sea-level variations is that associated with El Niño.

The El Niño of 1982-83 resulted in a temporary sea-level rise of over 30 cm in San Francisco Bay. Douglas (1991) in his analysis of sea-level trends at the NOAA tide station in San Francisco Bay, which has been continuously operating since 1854, found that the 30-year trends varied from -2 to +5 mm/yr over the entire time series. The inter-annual-to-decadal variations clearly produce signals much larger than the 1.7 mm/yr average estimated for the 20th Century sea-level rise signal, which complicates the task of calculating sea-level-rise trends. An appropriate length of record is essential to remove the very low frequency.

The problem of regional effects affecting a calculated sea level trend can be worse if the tide station is located inside an estuary or shallow bay (Parker 1991). The tide which has a nonlinear effect on mean sea level will remain constant as long as the tide regime stays the same. However, in a relatively shallow bay where filling in with sediment and dredging occur, the tidal regime can change and affect mean sea level. Changes in the shoreline from erosion or anthropogenic causes can have similar effects.

Regional Variation in LMSL Trends

Regional LMSL trends for the United States computed from 128 long-term (30+ years) NOAA tide gauges are presented in Figure 4. Individual LMSL trends, seasonal variations, and monthly anomalies

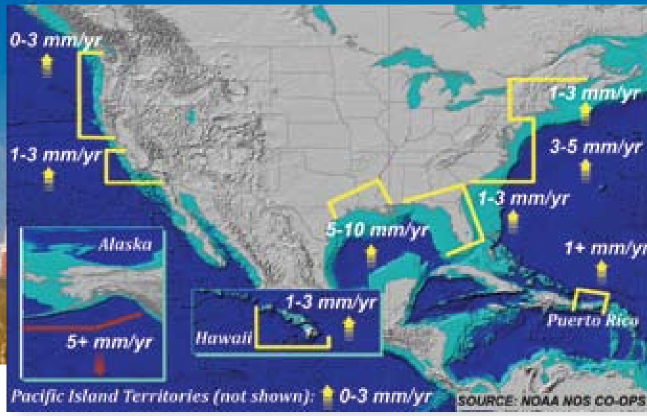

Figure 4. Regional variation of Local Mean Sea Level trends for the United States.

of sea level for each individual station are available from the NOAA website: http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml.

Areas of the U.S. portion of the Gulf of Mexico and portions of Alaska are known to have extreme rates of relative sea-level change due to local and regional vertical land movement. In the northern Gulf of Mexico, the extreme rates are mainly due to subsidence; in Alaska, land uplift caused by post-glacial isostatic rebound and tectonic activity are the main source for LMSL change.

Based on the long-term observations from the NOAA stations, the average sea-level trend across the U.S. coasts is approximately +1.68 mm/yr (Zervas 2001). The anomalous areas show rates from -17.1 mm/yr (1944-2006) at Skagway in southeast Alaska (relative sea-level fall) to + 9.2 mm/yr (1947-2006) for Louisiana's Grand Isle in the Gulf of Mexico. The negative sea level trend at Skagway is a result of land rising due to glacial rebound. The substantial positive seal level trend at Grand Isle is caused by subsidence due to sediment compaction and the extraction of water from the ground. The mid-Atlantic states' higher trending LMSL of 3 to 5 mm/yr is due to regional subsidence of the coastal plain. For example, the trend for LMSL at Annapolis, Maryland, for the period 1928-2006 is 3.4 mm/yr.

Modified Tidal Datum Epoch

Extremely high rates of LMSL change over time can manifest significant offsets in the observed versus predicted tides. When this happens, shipping becomes unsafe, as was the case in the Houston Ship channel in the 1990s; indeed, Houston ship pilots threatened to stop bringing ships into the channel if they are not provided with more reliable tide information. NOAA responded by introducing, in 1997, a Modified Tidal Datum Epoch for the affected regions in the Northern Gulf of Mexico and in parts of Alaska, in order to ensure full support for federal, state, and private-sector coastal zone activities, including hydrographic surveys and coastal mapping, wetland restoration, marine boundary determinations, coastal storm warnings, and emergency management.

The Modified Tidal Datum Epoch (MTDE) is applicable for those anomalous areas where the five-year average of LMSL has changed by 30 mm. The tidal ranges for the Modified Tidal Datum Epoch, such as MLLW and MHW, are computed based on the latest NTDE. However, the updated LMSL takes into account the most recent five years of sea level observations rather than a 19-year epoch value, i.e., the current MTDE for 2002-2006.

Projections for the 21st Century

Projections of sea level rise for the 21st Century is being debated by the climate research community. Some of these projections for the end of the 21st Century are in excess of 2 meters. One scenario reported by the IPCC in their 2007 assessment projects, with an increase of 1.7° C to 4.4° C in global mean surface air temperature, global sea level could rise by 0.21-0.48 m by the end of the 21st century. The recent work by Pfeffer (2008), however, projects that global sea-level rise under accelerated conditions could lead to a total sea level rise of about 0.8 meter by 2100. The possibility of a dramatic rise in sea level in the future will most likely depend on whether the land-based glaciers on Greenland and Antarctica begin melting at an accelerated rate. Thermal expansion of the ocean surface layers alone could probably not account for the larger projections being made. As we monitor sea level rise into the 21st Century, the statement made by Alexander Dallas Bache, the Second Superintendent of the Coast Survey, is as relevant today as when it was made more than 150 years ago, "It seems a very simple task to make correct tidal observations; but, in all my experience, I have found no observations which require such constant care and attention" (1854)..

Bibliography

Church, J.A., and N.J. White. 2006: A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.* **33** (L01602). doi:10.1029/2005GL024826.

Douglas, B. C. Global sea level rise. 1991. *J. Geophys. Res.* 96(C4): 6981-92.

Gill, S., Schultz, J. 2001. Tidal datums and their applications. NOAA Special Publication NOS CO-OPS 1.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007—The physical science basis contribution of Working Group I to the Fourth Assessment Report of the IPCC.

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.

Parker, B. 1991. Sea level as an indicator of climate global change. *Marine Technology Society Journal* 25(4).

Pfeffer W.T., Harper J. T., O'Neel S.O. 2008. Kinematic constraints on glacier contributions to 21st-century sea level rise. Science 321 (Sept 5). (www.sciencemag.org).

Zervas, C. 2001. Sea level variation of the United States, 1854-1999. NOAA Technical Report NOS CO-OPS, July 2001.