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EXPIRES 30 September 2013
SEA-LEVEL CHANGE CONSIDERATIONS FOR CIVIL WORKS PROGRAMS

1. Purpose. This circular provides United States Army Corps of Engineers (USACE) guidance for incorporating the direct and indirect physical effects of projected future sea-level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects. Recent climate research by the Intergovernmental Panel on Climate Change (IPCC) predicts continued or accelerated global warming for the 21st Century and possibly beyond, which will cause a continued or accelerated rise in global mean sea-level. Impacts to coastal and estuarine zones caused by sea-level change must be considered in all phases of Civil Works programs.

2. Applicability. This Circular applies to all USACE elements having Civil Works responsibilities and is applicable to all USACE Civil Works activities. This guidance is effective immediately, and supersedes all previous guidance on this subject. Districts and Divisions shall inform CECW of any problems with implementing this guidance.

3. Distribution Statement. This publication is approved for public release; distribution is unlimited.

4. References. Required and related references are at Appendix A. A glossary is included at the end of this document.

5. Geographic Extent of Applicability.

a. USACE water resources management projects are planned, designed, constructed and operated locally or regionally. For this reason, it is important to distinguish between global mean sea level (GMSL) and local (or "relative") mean sea level (MSL). At any location, changes in local MSL reflect the integrated effects of GMSL change plus changes of regional geologic, oceanographic, or atmospheric origin as described in Appendix B and the Glossary.

b. Potential relative sea-level change must be considered in every USACE coastal activity as far inland as the extent of estimated tidal influence. Fluvial studies (such as flood studies) that include backwater profiling should also include potential relative sea-level change in the starting water surface elevation for such profiles, where appropriate. The base level of potential relative sea-level change is considered the historically recorded changes for the study site. Areas already experiencing relative sea-level change or where changes are predicted should analyze this as part of the study. The project vertical datum must be current or updated to NAVD88 to be held as constant for tide station comparisons and a project datum diagram must be prepared per EM 1110-2-6056.

6. Incorporating Future Sea-Level Change Projections into Planning, Engineering Design, Construction, and Operating and Maintaining Projects.

a. Planning, engineering, designing, operating, and maintaining for sea level change must consider how sensitive and adaptable 1) natural and managed ecosystems and 2) human and engineered systems are to climate change and other related global changes. To this end, consider the following two documents:

(1) The Climate Change Science Program (CCSP) Synthesis and Assessment Product 4.1 (SAP 4.1) *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* details both how sea-level change affects coastal environments and what needs to be addressed to protect the environment and sustain economic growth. SAP 4.1 represents the most current knowledge on regional implications of rising sea levels and possible adaptive responses.

(2) The National Research Council's 1987 report *Responding to Changes in Sea Level: Engineering Implications* recommends a multiple scenario approach to deal with key uncertainties for which no reliable or credible probabilities can be obtained. In the context of USACE project life cycle, multiple scenarios address uncertainty and help us develop better risk-informed alternatives.

b. Planning studies and engineering designs over the project life cycle, for both existing and proposed projects consider alternatives that are formulated and evaluated for the entire range of possible future rates of sea-level change (SLC), represented here by three scenarios of "low," "intermediate," and "high" sea-level change. These alternatives will include structural and nonstructural solutions, or a combination of both. Evaluate alternatives using "low," "intermediate," and "high" rates of future SLC for both "with" and "without" project conditions. Use the historic rate of SLC (as described in Appendix B) as the "low" rate. Base "intermediate" and "high" rates on the following:

(1) Estimate the "intermediate" rate of local mean sea-level change using the modified NRC Curve I and equations 2 and 3 in Appendix B (see Figure B-13) and add those to the local rate of vertical land movement as discussed in Appendix B.

(2) Estimate the "high" rate of local mean sea-level change using the modified NRC Curve III and equations 2 and 3 in Appendix B (see Figure B-13) and add those to the local rate of vertical land movement as discussed in Appendix B. This "high" rate exceeds the upper bounds of IPCC estimates from both 2001 and 2007 to accommodate potential rapid loss of ice from

Antarctica and Greenland, but is within the range of peer-reviewed articles released since that time (see Figure B-10).

c. Determine how sensitive alternative plans and designs are to these rates of future local mean SLC, how this sensitivity affects calculated risk, and what design or operations and maintenance measures should be implemented to minimize adverse consequences while maximizing beneficial effects. Following the approach described in 6b above, alternative plans and designs are formulated and evaluated for three SLC possible futures. Alternatives are then compared to each other and an alternative is selected for recommendation. The approach to formulation, comparison and selection should be tailored to each situation. The performance should be evaluated in terms of human health and safety, economic costs and benefits, environmental impacts, and other social effects. There are multiple ways to proceed at the comparison and selection steps. Possible approaches include:

(1) Working within a single scenario and identifying the preferred alternative under that scenario. That alternative's performance would then be evaluated under the other scenarios to determine its overall potential performance. This approach may be most appropriate when local conditions and plan performance are not highly sensitive to the rate of SLC.

(2) Comparing all alternatives against all scenarios rather than determining a "best" alternative under any specific future scenario. This approach avoids focusing on an alternative that is only best under a specific SLC scenario and prevents rejecting alternatives that are more robust in the sense of performing satisfactorily under all scenarios. This comprehensive approach may be more appropriate when local conditions and plan performance are very sensitive to the rate of SLC.

(3) Reformulating after employing approaches (1) or (2) above to incorporate robust features of evaluated alternatives to improve the overall life-cycle performance.

d. Plan selection should explicitly provide a way forward to address uncertainty, describing a sequence of decisions allowing for adaption based on evidence as the future unfolds. Decision makers should not presume that the future will follow exactly any one of the SLC scenarios. Instead, analyses should determine how the SLC scenarios affect risk levels and plan performance, and identify the design or operations and maintenance measures that could be implemented to minimize adverse consequences while maximizing beneficial effects.

FOR THE COMMANDER:

JEFFERSON M. RYSCAVAGE
Colonel, Corps of Engineers
Executive Director of Civil Works

4 Appendices:
APPENDIX A: References
APPENDIX B: Technical Supporting Material
APPENDIX C: Flowchart to Account for
Changes in Mean Sea Level
Glossary

APPENDIX A

References

A-1. Required References.

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APPENDIX B

Technical Supporting Material

B-1. Background on Sea-Level Change.

a. In the preparation of this document USACE has relied entirely on climate change science performed and published by agencies and entities external to USACE. The conduct of science as to the causes, predicted scenarios, and consequences of climate change is not within the USACE mission. The USACE is a user of the currently accepted community consensus on the state of climate science knowledge and applicable USACE policies will be periodically reviewed and revised as the accepted consensus changes.

b. Global mean sea level (GMSL) over the past several million years has varied principally in response to global climate change (NRC 1987, IPCC 2007a). For example, at the peak of the most recent glacial period about 20,000 years ago, GMSL is inferred to have been on the order of 100-120 meters lower than at present (NRC 1987, IPCC 2007a). As global climate warmed and the glaciers retreated, water stored as continental ice was released, adding to the mass of water in the oceans and causing a corresponding rise in GMSL.

c. Geologic evidence suggests global sea level has fallen and risen with minimums and maximums occurring during cold glacial and inter-glacial warm periods respectively. During the last inter-glacial period, about 125,000 years ago, sea level was 4m to 6m higher than at present. The earth entered the present inter-glacial warm period following the peak of the last Ice Age about 12,000 years ago (CCSP 2009). After a rapid initial rise, GMSL is interpreted as having approximately stabilized within a meter or so of its present value over the last several thousand years (NRC 1987, IPCC 2007a). IPCC (2007a) concludes that global mean sea level rose at an average rate of about 1.7 ± 0.5 mm/year during the twentieth century.

d. Recent climate research has documented global warming during the 20th Century, and has predicted either continued or accelerated global warming for the 21st Century and possibly beyond (IPCC 2007a). One impact of continued or accelerated climate warming is thus continued or accelerated rise of GMSL.

e. Sea-level change can cause a number of impacts in coastal and estuarine zones, including changes in shoreline erosion, inundation or exposure of low-lying coastal areas, changes in storm and flood damages, shifts in extent and distribution of wetlands and other coastal habitats, changes to groundwater levels, and alterations to salinity intrusion into estuaries and groundwater systems (e.g., CCSP 2009).

f. Geologic factors can drive local sea-level change. Vertical land movement can occur due to tectonics (earthquakes, regional subsidence or uplift), compaction of sedimentary strata, crustal rebound in formerly glaciated areas, and withdrawal of subsurface fluids. Networks of long-term Continuously Operating Reference Stations (CORS) are being monitored by NOAA-NGS and when co-located with tide stations will begin to provide direct estimates of local vertical land uplift or subsidence.

g. Atmospheric factors can affect local or regional water levels. Decadal-scale phenomena include El Niño-Southern Oscillation (ENSO) in the Pacific and North Atlantic Oscillation (NAO) in the Atlantic, among others (see IPCC 2007a for a more complete discussion). Climate change may also alter the frequency and severity of tropical storms which could secondarily influence sea level. This is currently the subject of scientific research. Although the coupled effects of decadal and seasonal water level variations and episodic storm events are important to consider throughout the project life cycle, the incorporation of the influence of tropical storm on the application of sea level trends is outside the scope of this document.

B-2. Determination of Historic Trends in Local MSL.

a. *The planning, design, construction, operation, and maintenance of USACE water resource projects in and adjacent to the coastal zone must consider the potential for future accelerated rise in GMSL to affect the local MSL trend.* At the same time, USACE project planners and engineers must be aware of the *historic* trend in local MSL, because it provides a useful minimum baseline for projecting future change in local MSL. Awareness of the historic trend of local MSL also enables an assessment of the impacts that sea-level change may have had on regional coastal resources and problems in the past.

b. Historic trends in local MSL are best determined from tide gauge records. The Center for Operational Oceanographic Products and Services (CO-OPS), of the National Oceanographic and Atmospheric Administration (NOAA), provides historic information and local MSL trends for tidal stations operated by NOAA/NOS in the US (see http://www.co-ops.nos.noaa.gov/index.shtml). Most U.S. tide stations experienced a rise in local MSL during the 20th Century. Note the dominance of green and yellow symbols along much of the Atlantic and Pacific coasts of the continental US (Figure B-1). These stations exhibit local MSL trends between 0 and +0.6 meters per century. The highest rates of local MSL rise in the U.S. have occurred along the Gulf Coast (red symbols), whereas most stations in Alaska exhibit a falling trend of local MSL. Discrete shifts in sea level data or changes in relative sea level trends due to earthquakes are monitored by NOAA at their tide stations, and trends are recomputed from data after a known significant earthquake event (such as the 1964 Alaska earthquake). Trends are not computed from pre- and post event data. Post-event data analyses and surveys from the tide gauges to local bench marks and geodetic bench marks are used to estimate vertical movement. Data from nearby CORS are also now being used to estimate local vertical land motion to help monitor magnitude of the effect of earthquake events on sea level data.

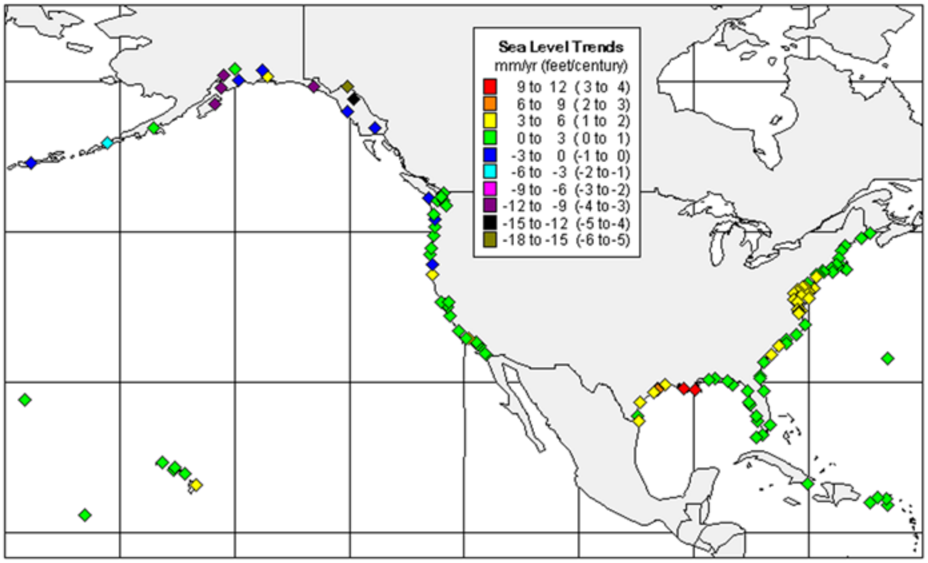

Figure B-1. Mean Sea Level Trends for U.S. Tide Stations (May 2011) (see http://tidesandcurrents.noaa.gov/sltrends/slrmap.html for updated information).

c. It is important to consider the length of tide station record required to obtain a robust estimate of the historic relative mean sea-level change. The length of the record is important because interannual, decadal and multi-decadal variations in sea level are sufficiently large that misleading or erroneous sea level trends can be derived from periods of record that are too short.

d. The Manual on Sea Level Measurement and Interpretation (Intergovernmental Oceanographic Commission 1985) suggests that a tidal record should be of at least of two-tidal epoch duration (about 40 years) before being used to estimate a local MSL trend. Figure B-2 (from Zervas, 2009) shows the relationship between period of record and the standard error of the trend for selected US tide stations. Note the significant decrease in standard error approximately at the 40- or 50-year period of record. Record lengths shorter than 40-years in duration could have significant uncertainty compared to their potential numerical trend values of a few millimeters per year.

e. Figure B-2 qualitatively illustrates the asymptotic nature of increasing record length vs. decreasing standard error of the trend estimate, indicating that standard error of the trend estimate can be can be large for tide stations with shorter records compared to those with longer records. Figure B-3 (from Zervas, 2009) shows the mean-sea level trend 95% confidence interval versus year range of data, with actual data and the least-squares fitted line. The 95% confidence interval from the least-squares fitted line reduces to less than 1 mm/year once at least 40 years of gauge data are available. Figures B-2 and B-3 thus support the suggestion that a tide station should have at least 40 years of data before being used to estimate a local MSL trend, particularly when such a trend will be extrapolated into the future for use as a minimum baseline for projected future change in local MSL. For project planning and design supporting the entire project life cycle, the actual standard error of the estimate should be calculated for each tide gauge data trend analysis, and the estimates in Figures B-2 and B-3 should not be used as the sole supporting data.

f. Using trends in relative mean sea level from records shorter than 40 years is not advisable. In addition to interpretations by the International Oceanographic Commission and NOAA (Figures B-2 and B-3), Pugh (1987) demonstrates that 10-year records at some stations show trends of opposite sign depending upon the interval selected. If estimates based on shorter terms are the only option, then the local trends must be viewed in a regional context, considering trends from simultaneous time periods from nearby stations to ensure regional correlation and to minimize anomalous estimates. The nearby stations should have long enough records (greater than 40 years) to determine reasonable trends, which can then be compared to the shorter, local sea-level records (see paragraph B-2(h)(2)). Experts at NOAA/NOS should be able to assist in cases of short periods of record or where records are otherwise ambiguous.

g. The Permanent Service for Mean Sea Level (PSMSL), which is a component of the UK Natural Environment Research Council's Proudman Oceanographic Laboratory, has been collecting, publishing, analyzing, and interpreting sea-level data from the global network of tide stations since 1933. Global sea level data can be obtained from PSMSL via their web site (http://www.pol.ac.uk/psmsl/). PSMSL should be considered as a source of information for non-U.S. stations not contained in the NOAA report. Please note that the periods of record of PSMSL gauges vary; some gauges have shorter periods of record than are recommended for relative sea-level change trend analysis.

h. The historic rate of relative sea-level change at relevant local tide stations shall be used as the low rate for analysis. The current, historically-based rate of change shall be estimated from local tide station records if oceanographic and geologic conditions at the tide station are determined to be similar to and consistent with those at the project site (Appendix C). For many locations along the U.S. Atlantic and Gulf of Mexico coastlines, there are probably adequate tide station data from perspectives of both spatial density and record duration to permit extrapolating with an adequate degree of confidence. Recognized exceptions are the coastlines between Mobile, Alabama and Grand Isle, Louisiana, and in Pamlico/Albemarle Sounds, North Carolina, which contain no acceptable long-term tide-gauge records. Coastal Louisiana is also subject to extreme rates of subsidence. In the case where there is a tidal station that is close to a project but has a short historic data duration, and another tidal station that is farther away but has a longer historic data duration, a tidal hydrodynamics expert should be consulted as to the appropriate use of the closer tidal station data.

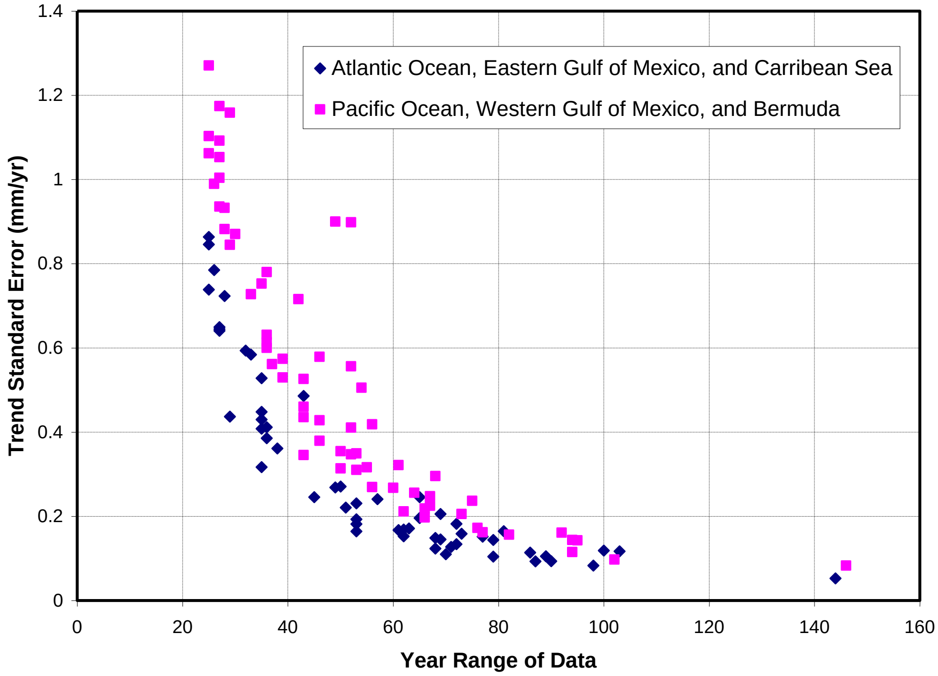

Figure B-2. Standard Error of Linear Trend of Sea-level Change vs. Period of Record, U.S. Tide Stations.

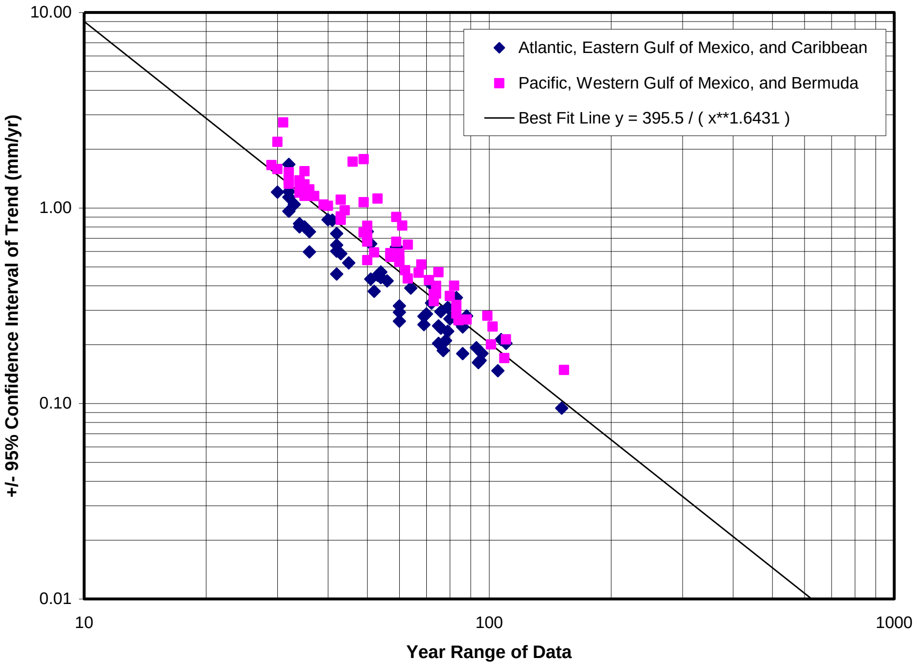

Figure B-3. +/- 95% confidence interval of linear MSL trends (mm/yr) versus year range of data. The least squares fitted line is also shown (Zervas, 2009).

(1) Figures B-4 through B-7show the magnitude and confidence limits (based on standard error of the estimate) of trends for Atlantic coast, Gulf of Mexico, and tropical NOS tide stations (from Zervas, 2009, see updated information online at http://tidesandcurrents.noaa.gov/sltrends/slrmap.html). A pair of stations useful for illustrating the effect of record length on confidence limits is Galveston Pier 21 and Galveston Pleasure Pier (Figure B-7). These stations are located within approximately one mile of each other, with Pleasure Pier on the ocean side and Pier 21 on the navigation waterway side of Galveston Island. The Pier 21 station was established in 1908 and Pleasure Pier station in 1957, thus Pier 21 has approximately 103 years of record and Pleasure Pier approximately 54 years. The confidence limits on Pier 21 are significantly narrower than for Pleasure Pier.

(2) Figures B-8 and B-9 show sea level trends and confidence limits for U.S. Pacific coast stations. Because of the scatter of trends and confidence limits, estimating historical sea-level change for many sites along the U.S. Pacific coast may be problematic. Confidence limits are not as uniform as for the Atlantic and tropical stations. Estimating and extrapolating trends based upon available data will require engineering judgment on a case-by-case basis and, to be robust, should take advantage of interdisciplinary and interagency subject matter expertise. It may be possible, depending upon station location and proximity to nearby stations with longer records, to use the longer record trend as a proxy providing the two records are well correlated for the concurrent period of record.

i. Regional sea-level change rates should be evaluated as well as rates of local sea-level change and global sea-level change. Regional sea-level change rates are expected to be close to global sea-level change rates, but differences may be found in large, semi-enclosed water bodies. Areas which could experience regional rates different than global rates include the northern Gulf of Mexico, the Gulf of Maine, and the Gulf of Alaska.

j. The length of time that the historical record rate of change can be validly projected into the future depends upon at least the following factors:

(1) the confidence of the present trend

(2) local relative rate of change (little or no acceleration)

(3) global rate of change (little or no acceleration)

(4) absence of dramatic geologic or oceanographic events.

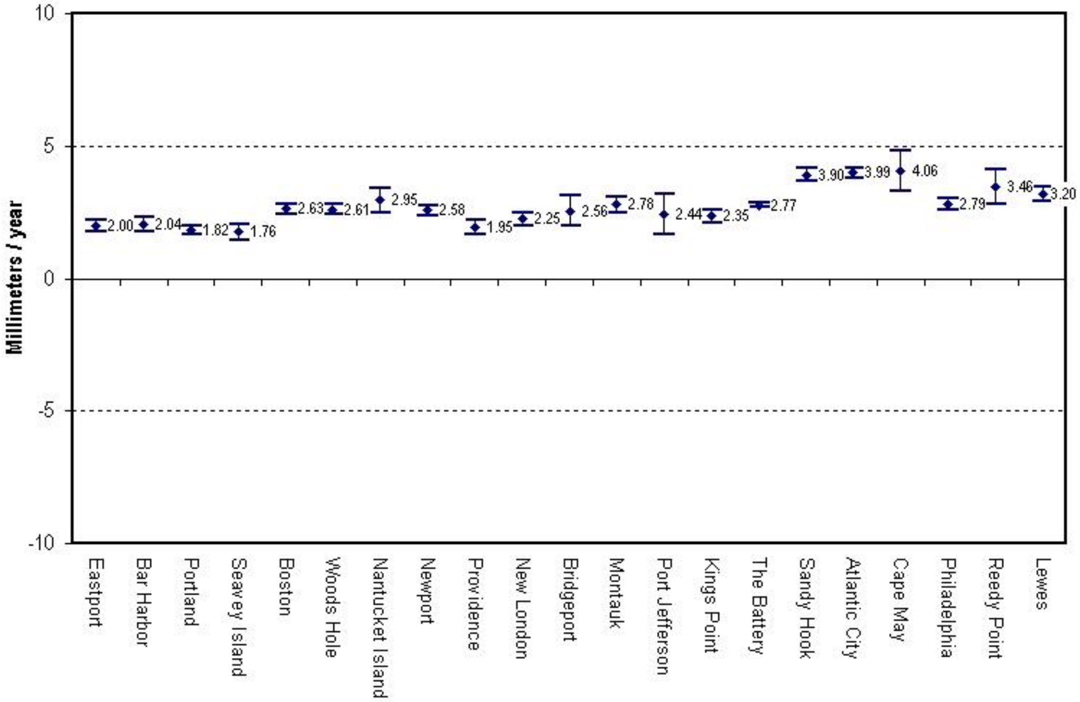

Figure B-4. Magnitude and confidence limits of trends for northern Atlantic coast NOS tide stations. (NOS 2009, http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

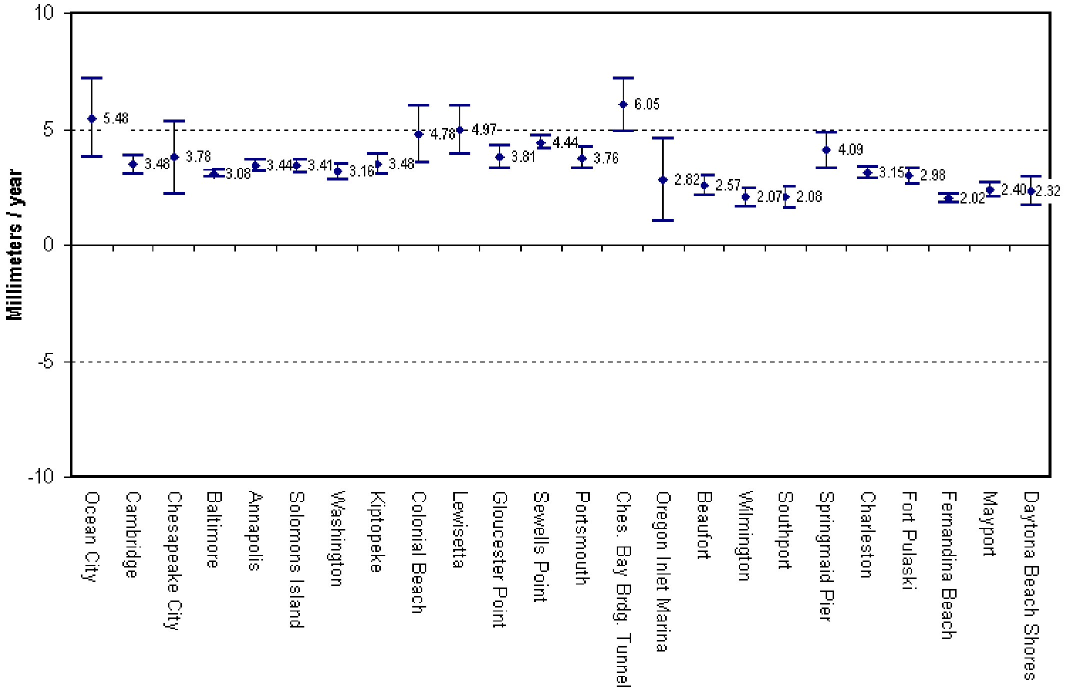

Figure B-5. Magnitude and confidence limits of trends for Southern Atlantic coast NOS tide stations. (NOS 2009, http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

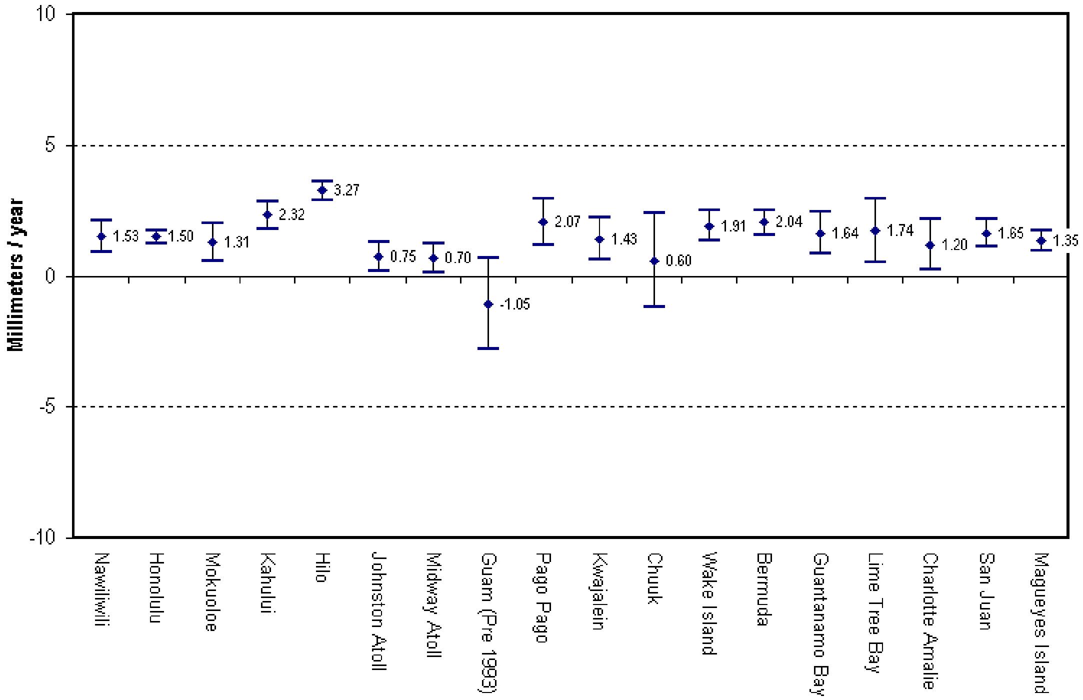

Figure B-6. Magnitude and confidence limits of trends for ocean island NOS tide stations. (NOS 2009, http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

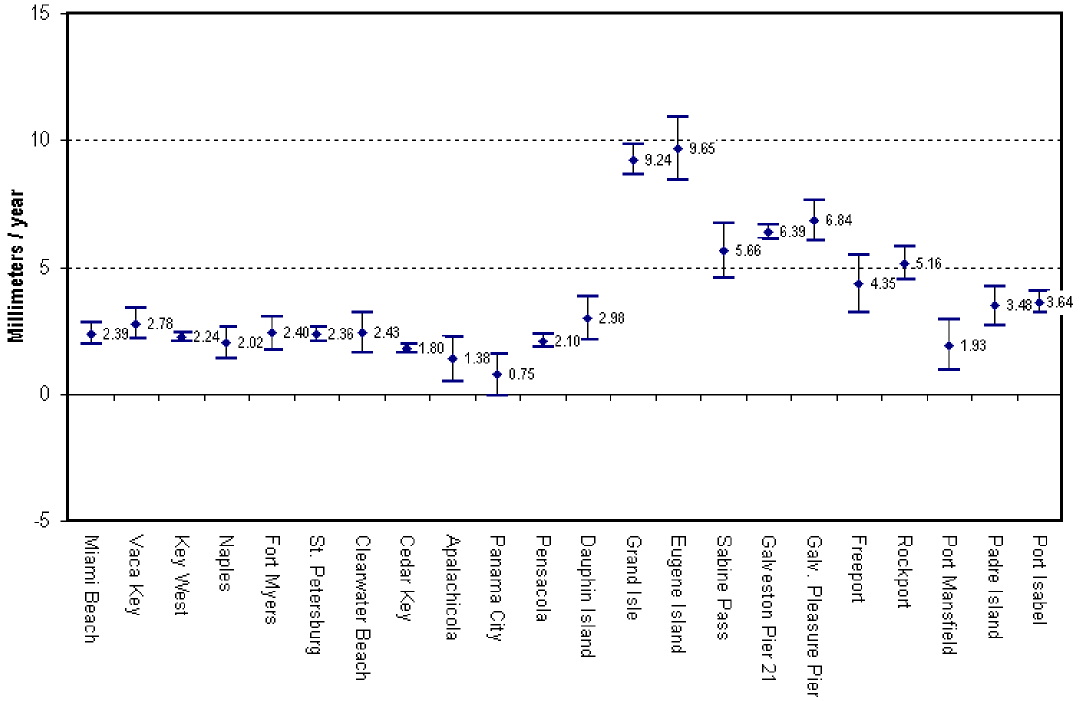

Figure B-7. Magnitude and confidence limits of trends for Florida Keys and Gulf of Mexico coast NOS tide stations. (NOS 2009, http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

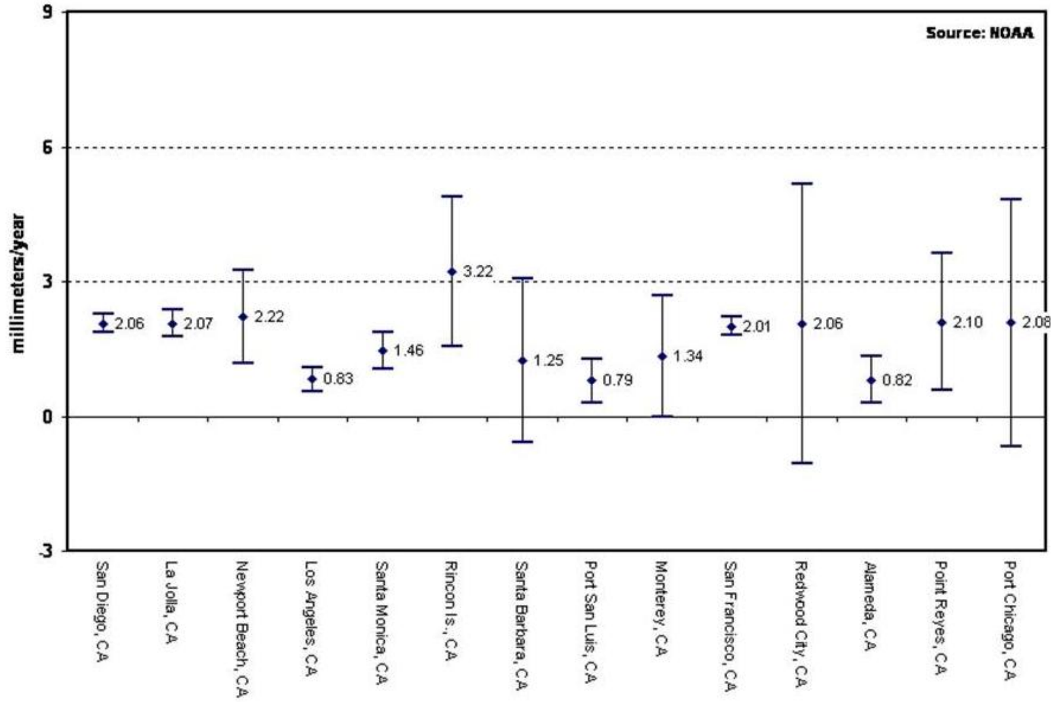

Figure B-8. Magnitude and confidence limits of trends for southern Pacific coast NOS tide stations. (NOS 2009, http://tidesandcurrents.noaa.gov/sltrends/index.shtml).

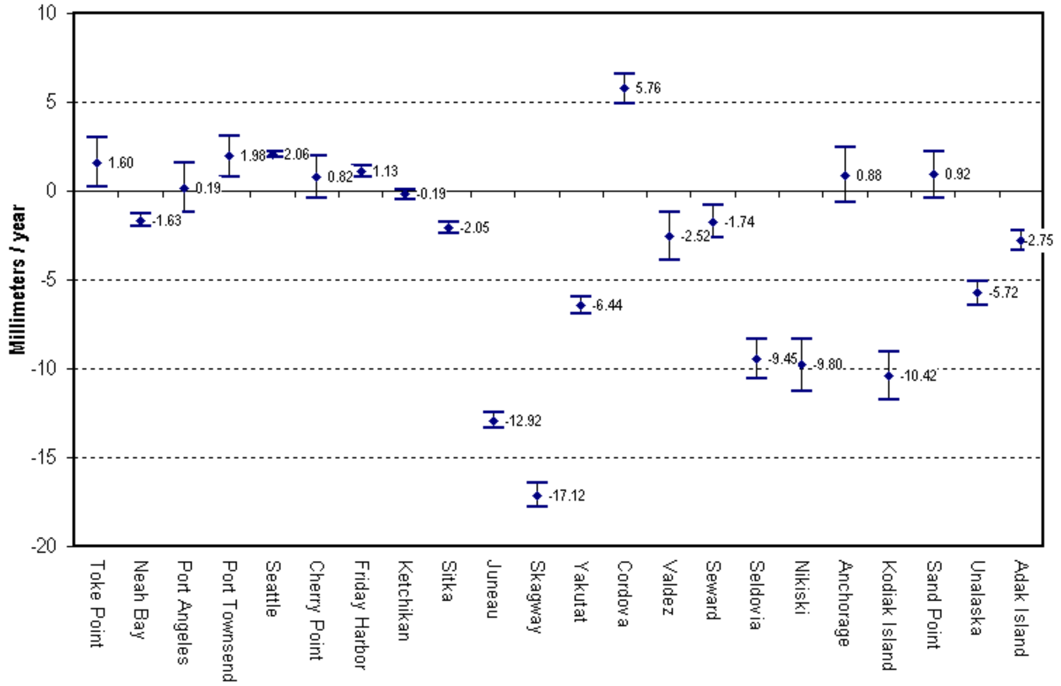

Figure B-9. Magnitude and confidence limits of trends for northern Pacific coast NOS tide stations. (NOS 2009, http://tidesandcurrents.noaa.gov/sltrends/index.shtml)

B-3. Estimating Future Change in Local MSL.

a. In USACE activities, analysts shall consider what effect changing relative sea-level rates could have on design alternatives, economic and environmental evaluation, and risk. The analysis shall include, as a minimum, a low rate which shall be based on an extrapolation of the historical tide gauge rate, and intermediate and high rates, which include future acceleration of GMSL. The analysis may also include additional intermediate rates, if the project team desires. The sensitivity of each design alternative to the various rates of sea-level change shall be considered. Designs should be formulated using currently accepted design criteria. A step-by-step approach is presented in a flow chart in Appendix C.

b. Since the 1987 NRC study on sea-level change was completed, the IPCC has produced four editions of its projections for future climate change and GMSL rise. The NRC study and the IPCC Third and Fourth Assessment Reports, dated 2001 and 2007, are useful in estimating future changes in local MSL (see http://www.ipcc.ch/).

c. The 1987 NRC report reviews data on relative sea-level changes and the resulting effect on engineering structures and coastal wetlands. Despite its age, the information and guidance presented in this study, in terms of considering how different types of projects may be affected by sea-level change, are useful and should be considered by USACE planners and engineers throughout the project life-cycle of studies and projects. An additional factor is that the NRC report includes a range of possible future GMSL rise scenarios that is much greater than those presented in the 2001 and 2007 IPCC reports. The 2007 IPCC report has received some criticism for not fully considering the possibility of rapid ice loss in Antarctica due to massive failures of the West Antarctic Ice Sheet or accelerated ice loss in Greenland due to increased glacial melting. Including the upper scenarios from the NRC report allows planners and engineers to consider the possibility of much greater rates of sea-level change than those presented in the 2007 IPCC report and to thus accommodate some of the criticism directed at the 2007 IPCC report.

d. Subsequent to the IPCC AR4 Report of 2007, there have been several peer-reviewed articles presenting current eustatic sea-level rise estimates ranging from 1.7 ± 0.2 and 1.9 ± 0.4mm/yr (Church and White, 2011) to 3.2 ± 0.4 mm/yr (Merrifield et al., 2009). The latter estimate is based upon tide station and satellite data in the approximate period from 1990 through 2009. The methodology used for developing satellite and tide gauge MSL estimates are not completely independent, since satellite observations rely upon selected tide gauge data to calibrate and de-bias the satellite data (Leuliette et al., 2004). Moreover, for short observation periods (2003 to 2007) there are unexplained long-term systematic errors in at least one of the observing systems (Willis et al., 2008).). Houston and Dean (2011) examined records of 57 tide stations of the PSMSL with record duration lengths of 60 to 156 years and concluded that there was no acceleration of global sea level rise in the 20th century, consistent with Douglas (1992).

Regardless of the observing system used, the premise here is that at least 40 years of data are required to establish a robust sea-level trend.

e. Because the methodology described in this EC uses a scenario-based approach, it may be useful to consider an upper bound on 21st century eustatic sea-level rise. Several peer-reviewed publications have proposed maximum estimates of GMSL rise by year 2100. Although the authors use different physical bases to arrive at the estimates, none of them proposes a 21st century GMSL rise greater than 2 meters. Figure B-10 illustrates the minimum and maximum GMSL change expected by year 2100, along with author or publication. Based upon these bodies of research, it seems reasonable that a credible upper-bound for 21st century GMSL rise would be about 2 meters. This by no means suggests that 21st century GMSL rise cannot exceed 2 meters, but a maximum of 2 meters is reasonable at this time.

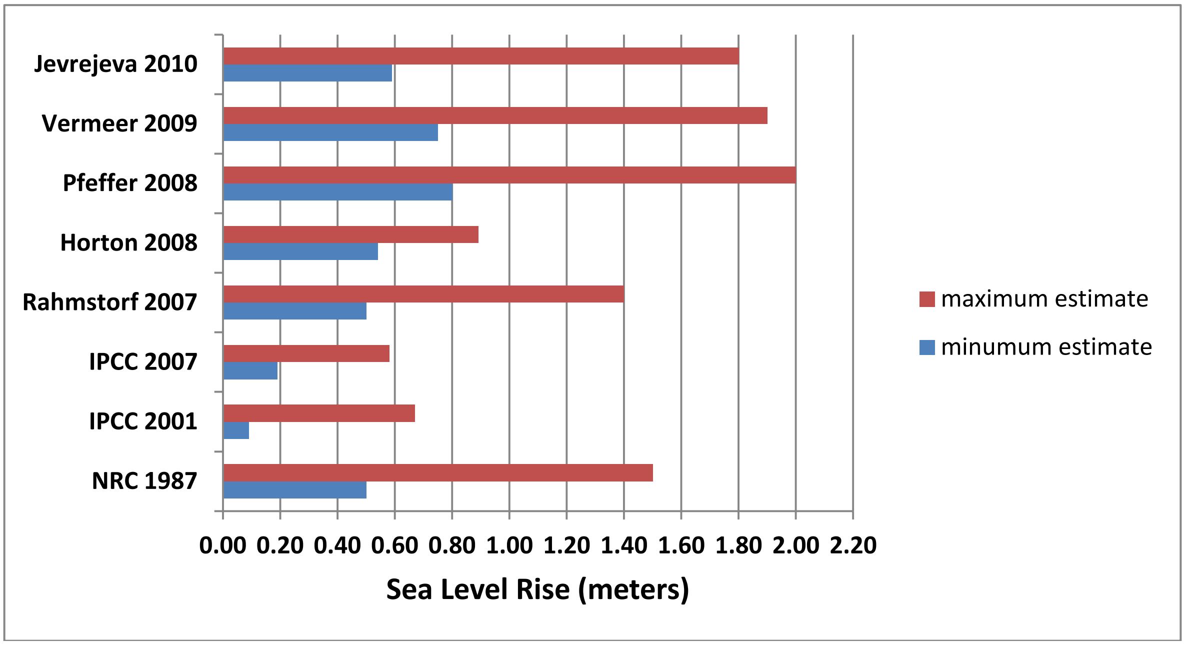

Figure B-10. Comparison of maximum and minimum estimates of global SLR by year 2100.

f. The 1987 NRC report recommended that feasibility studies for coastal projects consider the high probability of accelerating GMSL rise and provided three different scenarios. The 1987 NRC described these three scenarios using the following equation:

$$E(t) = 0.0012t + bt^2 \qquad (1)$$

in which t represents years, starting in 1986, b is a constant, and $E(t)$ is the eustatic sea-level change, in meters, as a function of t. The NRC committee recommended "projections be updated approximately every decade to incorporate additional data." At the time the NRC report was prepared, the estimate of global mean sea-level change was approximately 1.2 mm/year. Using the current estimate of 1.7 mm/year for GMSL change, as presented by the IPCC (IPCC 2007), results in this equation being modified to be:

$$E(t) = 0.0017t + bt^2 \tag{2}$$

(1) The three scenarios proposed by the NRC result in global eustatic sea-level rise values, by the year 2100, of 0.5 meters, 1.0 meters, and 1.5 meters. Adjusting the equation to include the historic GMSL change rate of 1.7 mm/year and the start date of 1992 (which corresponds to the midpoint of the current National Tidal Datum Epoch of 1983-2001), instead of 1986 (the start date for equation 1), results in updated values for the variable b being equal to 2.71E-5 for modified NRC Curve I, 7.00E-5 for modified NRC Curve II, and 1.13E-4 for modified NRC Curve III. The three GMSL rise scenarios updated from NRC (1987) are depicted in Figure B-11.

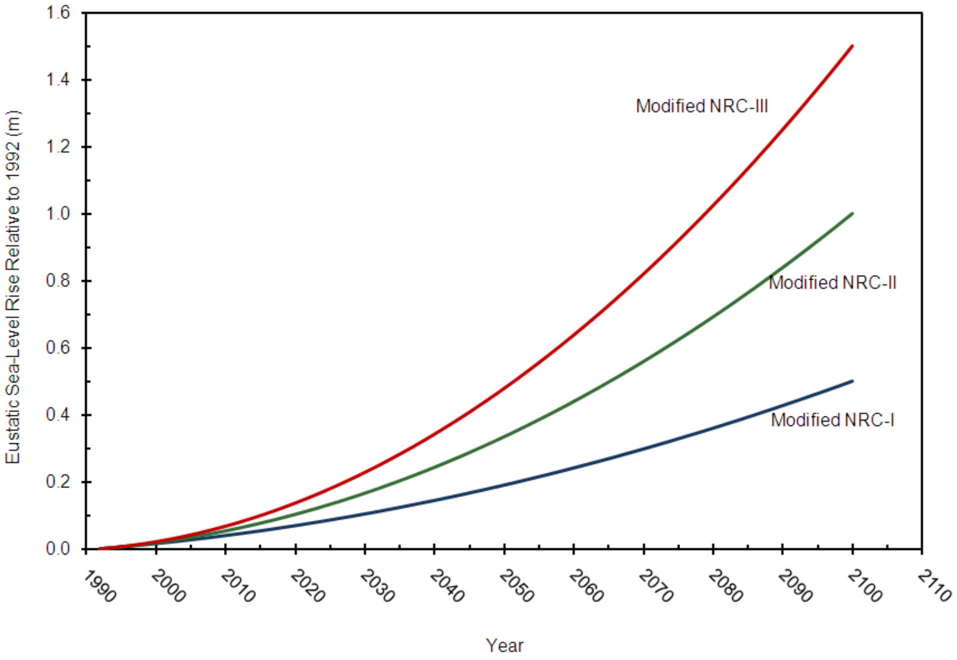

Figure B-11. Scenarios for GMSL Rise (based on updates to NRC 1987 equation).

(2) Manipulating equation (2) to account for the fact that it was developed for eustatic sea-level rise starting in 1992, while projects will actually be constructed at some date after 1992, results in equation (3):

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \tag{3}$$

where t_1 is the time between the project's construction date and 1992 and t_2 is the time between a future date at which one wants an estimate for sea-level change and 1992 (or $t_2 = t_1$ + number of years after construction) (Knuuti, 2002). For example, if a designer wants to know the projected eustatic sea-level rise at the end of a project's period of analysis, and the project is to have a fifty year life and is to be constructed in 2013, $t_1 = 2013 – 1992 = 21$ and $t_2 = 2063 – 1992 = 71$.

g. From the Special Report on Emissions Scenarios (SRES) (IPCC 2000), six emissions scenarios were used to develop six SLR projections. A suite of numerical models that model air-ocean global circulation, with varying degrees of robustness, were used to provide a range of results. For each of these models, IPCC used the six different climate change scenarios for input (see Appendix B-3 for other contributing factors). GMSL rise was calculated for each of the six scenarios by averaging the modeled sea-level values at every model grid cell, for every numerical model.

(1) IPCC used the different emissions scenarios and the range of values obtained from the different numerical models to develop ranges of future GMSL values, and used this as a way to describe the uncertainty associated with projecting future GMSL. These ranges are shown in Table B-1 (for two climate change scenarios, B1 and A1FI, the least and most extreme).

(2) An example of an IPCC intermediate level of model-derived GMSL (scenario A1B) is shown in Figure B-12. Note that the blue shaded area of this figure represents a potential level of uncertainty for the scenario shown, based on the range of model predictions, and does not provide a quantitative estimate. Figure B-13 presents the modified NRC curves of Figure B-10 plus the reported 95% confidence limits of the B1 and A1FI scenarios shown in Table B-1 (IPCC 2007a). It should be noted that the confidence limits shown in these tables only describe the confidence of the range of model results and do not actually represent the confidence of what could physically occur in the future.

Table B-1. Projected GMSL components during the 21st century for the B1 and A1FI scenarios. The table gives the IPCC's reported 5% and 95% confidence limit (m) of the estimated rise in sea level between 1980 to 1999 and 2090 to 2099 based on the SRES models (excerpted from IPCC 2007a, Table 10.7). The confidence limits shown in these tables only describe the confidence of the range of model results and do not actually represent the confidence of what could physically occur in the future.

	B1		A1FI	
	5% CL	95% CL	5% CL	95% CL
GMSL rise, 2090-2099(m)	0.18	0.38	0.26	0.59

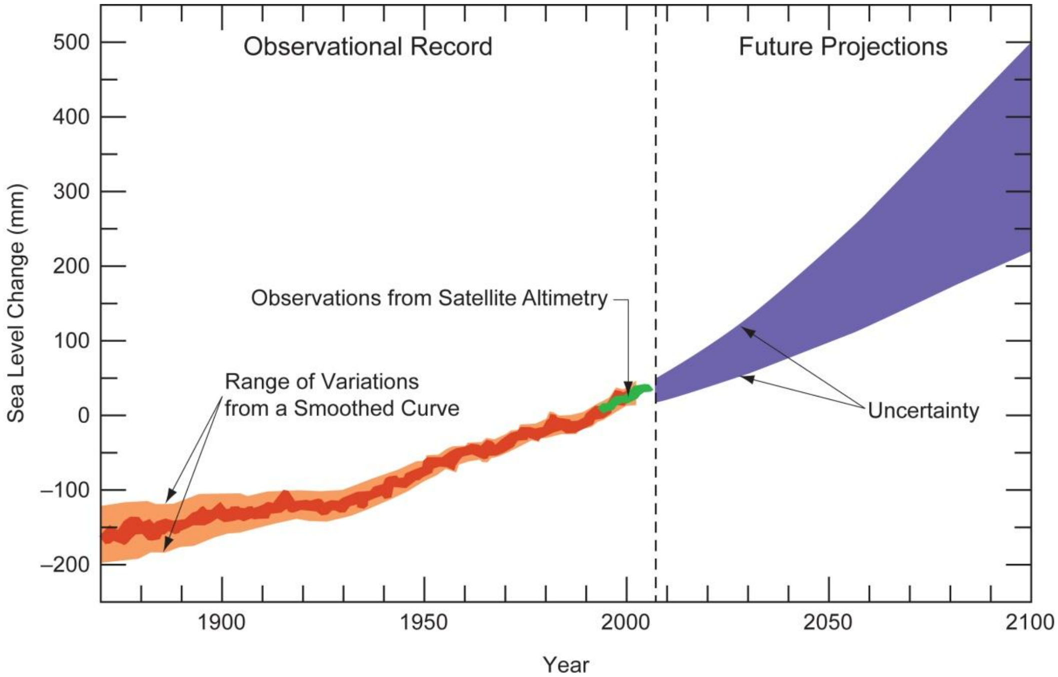

Figure B-12. Illustration of GMSL (deviation from the 1980-1999 mean) as observed since 1870 and projected for the future. The future projections have been calculated independently from the observations (after IPCC 2007a, FAQ 5.1, Figure 1).

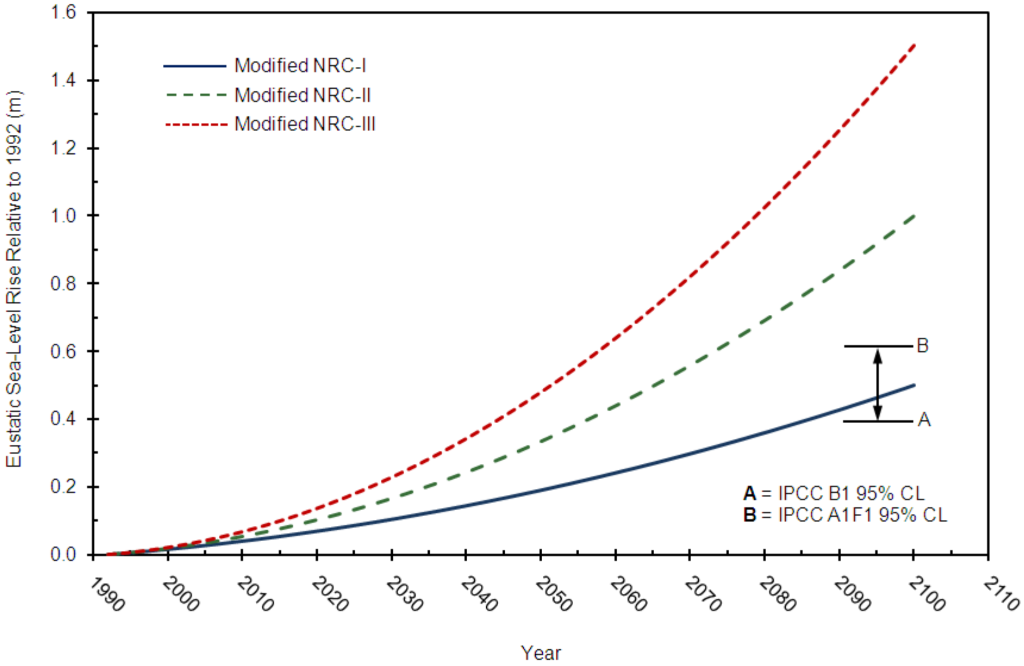

Figure B-13. Modified NRC (1987) GMSL rise scenarios and the IPCC (2007) scenario estimates for use in predicting future sea-level change.

APPENDIX C

Flowchart to Account for Changes in Mean Sea Level

C-1. Premise. Global mean sea level (GMSL) has risen over the past century, and the rate of rise will continue and may accelerate in the future. USACE projects need to be planned, designed, constructed, and operated with the understanding that the rate of rise of GMSL may increase and affect USACE water resource projects in and adjacent to the nation's coastal zone. In other locations, the relative sea-level is dropping, and USACE projects must account for the decrease in water levels and must balance this with the potential for increasing GMSL. The steps below are shown graphically in Figure C-1.

C-2. Flowchart.

Step 1. Is the project in the coastal/tidal/estuarine zone, or does it border those zones such that project features or outputs are now, or may be in the future, subject to influence by continued or accelerated rate of local relative sea-level change? YES-NO?

a. If YES, go to Step 2.
b. If NO, continue with product development process without considering sea-level change.

Step 2. Locate nearest tide station(s) with a current period of record. Is the period of record at least 40 years? YES-NO?

a. If YES, go to Step 4.
b. If NO, go to Step 3.

Step 3. Identify next closest long-term gauge. Assess whether or not the long-term gauge can be used to artificially extend the record of the short-term gauge. YES-NO?

a. If YES, go to Step 4.
b. If NO, Consult with a tidal hydrodynamics expert, such as CO-OPS[1].

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[1] CO-OPS: Center for Operational Oceanographic Products and Services, National Ocean Service, National Oceanographic and Atmospheric Administration, Silver Spring, MD 301-7132981. http://tidesandcurrents.noaa.gov

Step 4. Assess whether identified long-term gauges can be used to adequately represent local sea-level conditions at project site. YES-NO?

a. If YES, go to Step 5.
b. If NO, Consult with a tidal hydrodynamics expert, such as CO-OPS.

Step 5. Assess whether the project site and gauge site have similar physical conditions (coastal/estuarine location, bathymetry, topography, shoreline geometry, and hydrodynamic conditions). YES-NO?

a. If YES, go to Step 6.
b. If NO, Consult with a tidal hydrodynamics expert, such as CO-OPS.

Step 6. Calculate local historic trends for MSL, MHW, and MHHW at long-term gauge. Use CO-OPS values, if available. If not available, use CO-OPS method for sea-level trend analysis.[1] This historic trend is now the low or baseline trend rate for project alternative analysis (see 8(a)). Go to Step 7.

Step 7. Calculate standard error of the linear trend line (use CO-OPS values, if available). Go to Step 8.

Step 8. The next step is to evaluate whether there is a regional mean sea-level trend (see definition) that is different from the eustatic mean sea-level trend of 1.7 mm/year (+/-0.5 mm/year, IPCC 2007a). See Figure C-2 for one example of such a region. Considering regional geology, is it possible to identify a vertically stable geologic platform within the same region as the project site? YES-NO?

a. If YES, go to Step 9.
b. If NO, go to Step 11.

Step 9. Calculate regional MSL trend for the identified vertically stable geologic platform within the region, and go to Step 10.

Step 10. Estimate local rate of vertical land movement by subtracting regional MSL trend from local MSL trend. Go to Step 12.

Step 11. Assume the regional mean sea-level trend is equal to the eustatic mean sea-level trend of 1.7 mm/year (+/-0.5mm/year) and estimate local rate of vertical land movement by subtracting eustatic MSL trend from local MSL trend. Go to Step 12.

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[1] CO-OPS method for sea-level trend analysis is described in NOAA Technical Report NOS CO-OPS 36, "Sea Level Variations of the United States 1854-1999.”.

Step 12. Calculate future values for sea-level change for low (historic or baseline) rate: extrapolate historic linear trend into future at 5-year increments, OR reasonable increments based on both period of analysis and scope of study[1]. Go to Step 13.

Step 13. Calculate future values for sea-level change for intermediate rate (modified NRC Curve I), see 8(a)(1): calculate future sea-level change values at 5-year increments OR reasonable increments based on both period of analysis and scope of study by combining incremental values from equations B-2 and B-3 with values obtained by extrapolating rate of local vertical land movement. Go to Step 14.

Step 14. Calculate future values for sea-level change for high rate (modified NRC Curve III), see 8(a)(2): calculate future sea-level change values at 5-year increments OR reasonable increments based on both period of analysis and scope of study by combining incremental values from equations B-2 and B-3 with values obtained by extrapolating rates of local vertical land movement. Go to Step 15.

Step 15. Assess project performance for each sea-level change scenario developed in Steps 12, 13, and 14. This assessment and Steps 15-18 can occur at any point in the project life-cycle, and thus apply to existing as well as proposed projects. Go to Step 16.

Step 16. Calculate the risk for each project design alternative combined with each sea-level change scenario, as developed in Steps 12, 13, and 14 at 5-year increments OR reasonable increments based on both period of analysis and scope of study. Go to Step 17.

Step 17. Assess risk[2] and reevaluate project design alternatives. Consider at a minimum: planning for adaptive management[1], designing to facilitate future modifications, and designing for a more aggressive future sea-level change scenario. Go to Step 18.

Step 18. Select project designs that best accommodate the range of sea-level change scenarios throughout the project life cycle.

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[1] Use 5-yr increments unless alternate reasonable increments based on both period of analysis and scope of study can be justified. The number of scenarios may be determined through exploratory or iterative analysis.

[2] Policies are under development at the time of this EC.

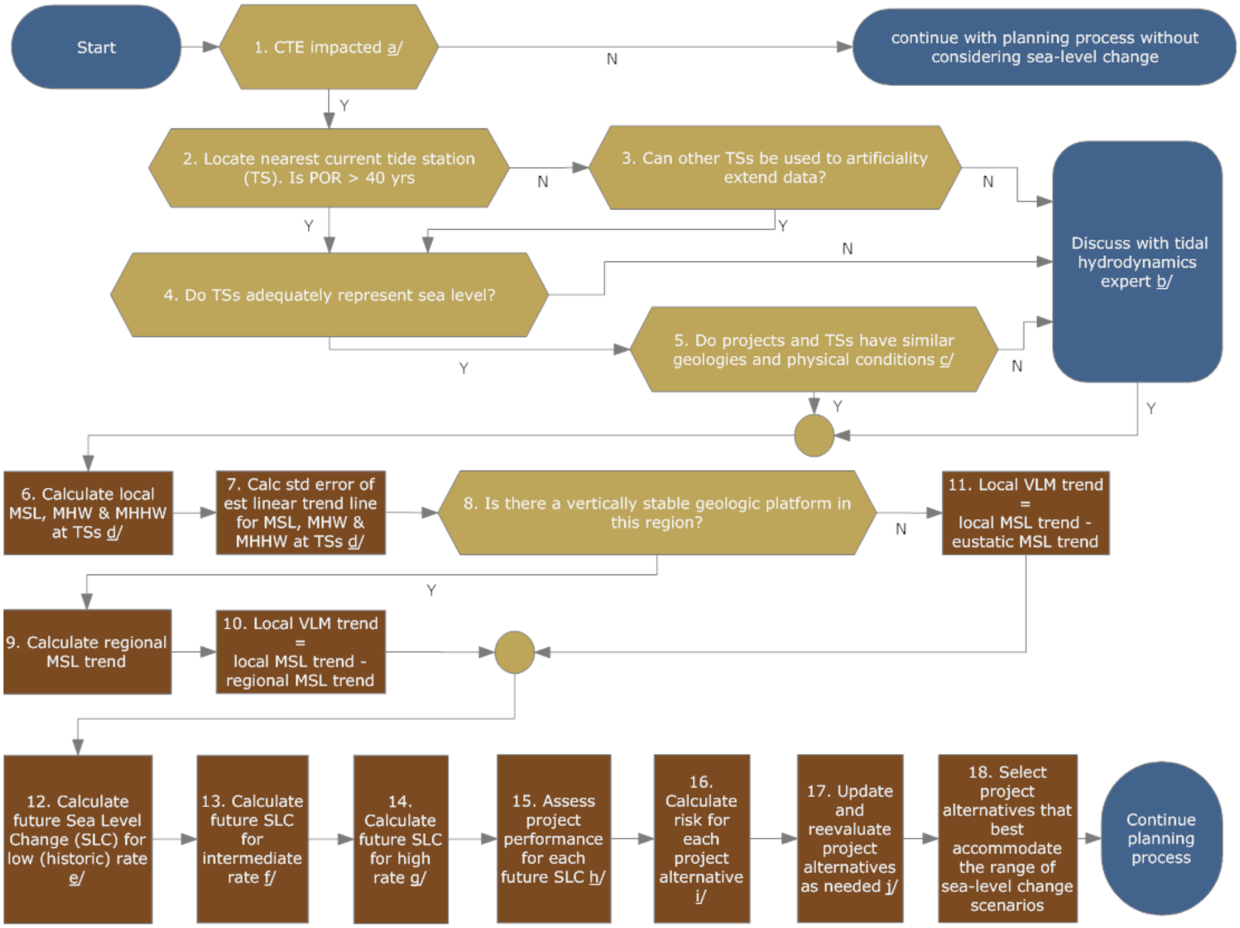

Figure C-1. Graphical illustration of process to account for changes in mean sea level.

a) Is the project in or bordering coastal/tidal/estuarine (CTE) zone such that project features or outputs are now, or may be in the future, subject to influence by continued or accelerated rate of change?
b) Discuss with tidal hydrodynamics expert, such as CO-OPS (NOAA).
c) Similar physical conditions such as coastal/estuarine location, bathymetry, topography, shoreline geometry, and hydrodynamic conditions.
d) Use CO-OPS (NOAA) values, if available.
e) Low rate: extrapolate historic linear trend into future at selected increments.
f) Intermediate rate (IPCC-2007, or modified NRC-Curve-I: calculate future SLC values at selected increments by combining incremental values from equations A-2 and A-3 with value obtained by extrapolating rate of local vertical land movement.
g) High rate (modified NRC-Curve-III): calculate future SLC values at selected increments by combining incremental values from equations A-2 and A-3 with value obtained by extrapolating rate of local vertical land movement.
h) Consider project design function at all phases of the project life cycle: performance, design issues; project stability; and project operation and maintenance.
i) Calculate the risk for each project alternative at selected increments. This assessment and Steps 15-18 can occur at any point in the project life-cycle, and thus apply to existing as well as proposed projects.
j) Consider at a minimum: planning for adaptive management (updating operational strategies based on new information); designing to facilitate future modifications; and adaptive engineering (designing for a more aggressive future SLC scenario

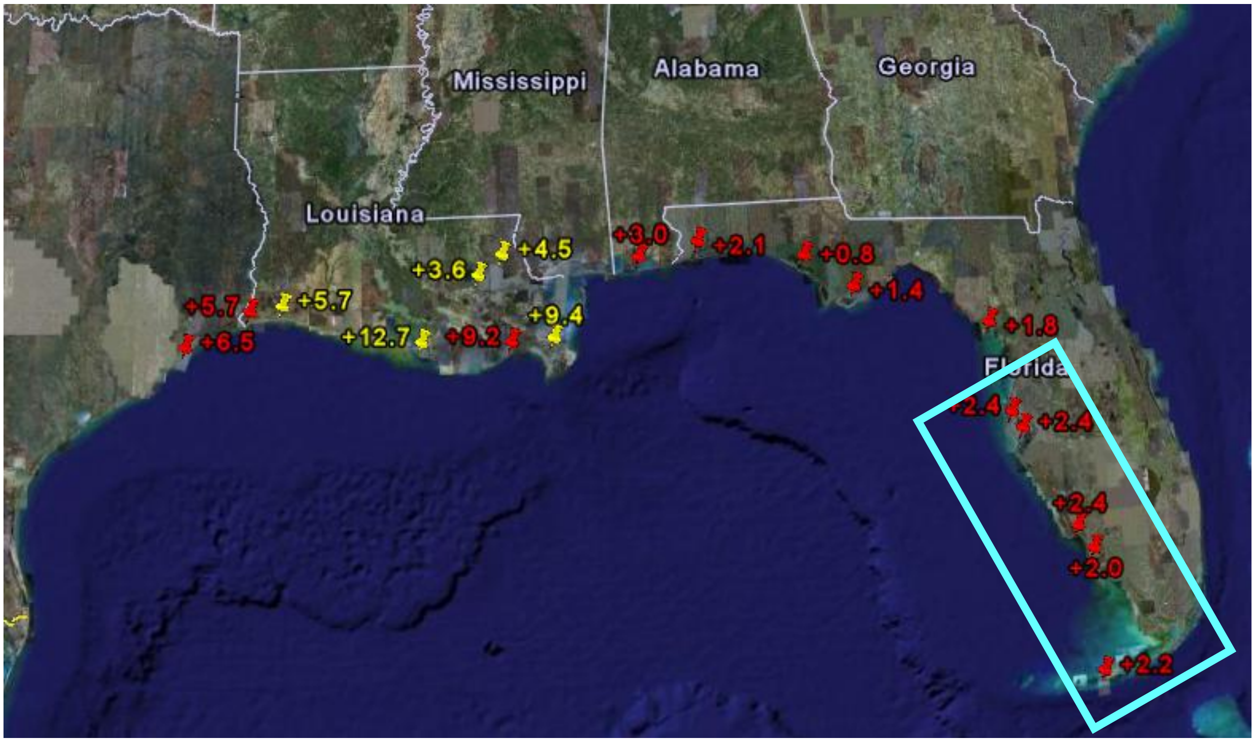

Figure C-2. Example of a region (northern Gulf of Mexico) that may exhibit a regional rate of mean sea-level change that is different than the eustatic rate of mean sea-level rise. Red numbers represent the rate of local mean sea-level change (mm/yr) at NOAA tide stations, yellow numbers represent the same at USACE tide stations. The rectangle represents an area with a geologic platform that is generally thought to be vertically stable (Step 8). While local mean-sea level trends within this rectangle vary, they are consistently higher than the rate of eustatic mean sea-level rise (1.7 mm/year) and are thought to be indicative of the rate of regional sea-level change (Step 9). This higher rate of regional sea-level change could be used, along with rates of local relative sea-level change, to estimate rates of local vertical land movement for studies and projects within the region, such as in Mississippi and Louisiana (Step 10). (From Knuuti, 2006[1]).

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[1] Figure prepared by Kevin Knuuti for oral presentation, 2006.

GLOSSARY

Terms and Abbreviations

Coastal. The term coastal as used in this EC refers to locations with oceanic astronomical tidal influence, as well as connected waterways with base-level controlled by sea-level. In these latter waterways, influence by wind-driven tides may exceed astronomical tidal influence. Coastal areas include marine, estuarine, and riverine waters and affected lands. (The Great Lakes are not considered “coastal” for the purposes of this EC.)

Datum. A horizontal or vertical reference system for making survey measurements and computations. A set parameters and control points used to accurately define the three-dimensional shape of the earth. The datum defines parts of a geographic coordinate system that is the basis for a planar coordinate system. Horizontal datums are typically referred to ellipsoids, the State Plane Coordinate System, or the Universal Transverse Mercator Grid System. Vertical datums are typically referred to the geoid, an Earth model ellipsoid, or a Local Mean Sea Level (LMSL). The current vertical datum used in the United States is the North American Vertical Datum of 1988 (NAVD 88) which replaced the National Geodetic Vertical Datum of 1929 (NGVD 29) (formerly referred to as the Sea Level Datum of 1929). For tidal datums see below.

Eustatic sea-level rise. Eustatic sea-level rise is a change in global average sea level brought about by an increase in the volume of the world ocean [Intergovernmental Panel on Climate Change (IPCC) 2007b].

Global mean sea-level (GMSL) change. Sea level can change globally due to (i) changes in the shape of the ocean basins, (ii) changes in the total mass of water and (iii) changes in water density. Sea-level changes induced by changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric (IPCC 2007b). See Figure B-10.

Local (i.e., “relative”) sea level. Sea level measured by a tide gauge with respect to the land upon which it is situated. See mean sea level (MSL) and sea-level change (SLC). Relative sea-level change occurs where there is a local change in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land-level uplift, relative sea level can fall (IPCC 2007b). Relative sea level change will also affect the impact of any regional sea level change.

Mean sea level (MSL). A tidal datum. The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch (~19 years). Shorter series are specified in the name; e.g., monthly mean sea level and yearly mean sea level (Hicks et al. 2000).

Post-glacial rebound. The vertical movement of the land and sea floor following the reduction of the load of an ice mass, for example, since the last glacial maximum (~21,000 years ago). The rebound is an isostatic land movement (IPCC 2007b).

Regional sea-level change. An increase or decrease in the mean level of the ocean's surface over a specific region. Global sea level has regional variations and regional sea-level change may be equal to, greater than, or less than global sea-level change due primarily to regional differences in ocean heating and cooling or to changes in bathymetry. Regional sea-level change as used here does not include local geologic effects, such as subsidence or tectonic movement.

Risk. Risk is a measure of the probability and severity of undesirable consequences (including, but not limited to, loss of life, threat to public safety, environmental and economic damages).

Sea-level change. A change in the mean level of the ocean.

Tide station. A device at a coastal location (and some deep-sea locations) that continuously measures the level of the sea with respect to the adjacent land. Time averaging of the sea level so recorded gives the observed secular changes of the relative sea level (IPCC 2007b).

Tidal datums. The term tidal datum is used when defined in terms of a certain phase of the tide. Tidal datums are local datums and should not be extended into areas which have differing hydrographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as bench marks.

Uncertainty. Uncertainty is the result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub) population under consideration. There are two types of uncertainty: aleatory and epistemic. Aleatory uncertainty is the uncertainty attributed to inherent variation which is understood as variability over time and/or space. Epistemic uncertainty is the uncertainty attributed to our lack of knowledge about the system (e.g., what value to use for an input to a model or what model to use). Uncertainty can lead to lack of confidence in predictions, inferences, or conclusions.