Chesapeake Bay Program | Indicator Analysis and Methods Document
Sea Level | Updated July 2018

Indicator Title: Sea Level

Relevant Outcome(s): Climate Monitoring and Assessment

Relevant Goal(s): Climate Resiliency

Location within Framework (i.e., Influencing Factor, Output or Performance): Influencing Factor for other Outcomes. These indicators are "Outputs" themselves, called for in the Climate Monitoring and Assessment Outcome of the 2014 Watershed Agreement.

A. Data Set and Source

(1) Describe the data set. What parameters are measured? What parameters are obtained by calculation? For what purpose(s) are the data used? This indicator presents relative sea level change. Relative sea level change is defined as the change in sea height relative to land. Land surfaces move up or down in many locations around the world due to natural geologic processes (such as uplift and subsidence) and human activities that can cause ground to sink (e.g., from extraction of groundwater or hydrocarbons that supported the surface). Relative sea level trends show how sea level change and vertical land movement together are likely to affect coastal lands and infrastructure.

Sea level has traditionally been measured using tide gauges, which are mechanical measuring devices placed along the shore. These devices measure the change in sea level relative to the land surface.

This indicator has been adapted from a national indicator maintained by the U.S. EPA. For more detailed information about EPA's indicator, see www.epa.gov/climate-indicators/climate-change-indicators-sea-level.

(2) List the source(s) of the data set, the custodian of the source data, and the relevant contact at the Chesapeake Bay Program.
- Source: NOAA's National Water Level Observation Network tide gauge stations
- Custodian: Michael Kolian, Office of Atmospheric Programs, EPA
- Chesapeake Bay Program Contact (name, email address, phone number): Laura Drescher, drescher.laura@epa.gov, 410-267-5713

(3) Please provide a link to the location of the data set. Are metadata, data-dictionaries and embedded definitions included?
The map is based on individual station measurements that can be accessed through NOAA's "Sea Level Trends" website at

https://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml. This website also presents an interactive map that illustrates sea level trends over different timeframes. NOAA has not published the specific table of 1960–2017 trends that it provided to EPA, and subsequently to the Chesapeake Bay Program, for this indicator; however, a user could reproduce these numbers from the publicly available data cited above. NOAA periodically publishes a version of this trend analysis in a technical report on long-term sea level variations of the United States (NOAA, 2009). EPA obtained the updated 1960–2017 analysis from the lead author of NOAA (2009), Chris Zervas. Processed results for the nation are available in spreadsheet and map files on EPA's "Climate Change Indicators in the United States" website at www.epa.gov/climate-indicators/climate-change-indicators-sea-level.

NOAA. 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. www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf.

B. Temporal Considerations

(4) Data collection date(s): Tide gauge sampling takes place at sub-daily resolution (i.e., measured many times throughout the day) at sites around the world. Some locations have had continuous tide gauge measurements since the 1800s. NOAA's source data set comprises 210 long-term, continuously operating tide gauge stations along the United States coast, including the Great Lakes and islands in the Atlantic and Pacific Oceans. The map shown in this indicator displays trends for seven stations within the Chesapeake Bay watershed that had sufficient data from 1960 to 2017.

(5) Planned update frequency (e.g., annual, biannual, etc.):
- Source Data: NOAA tide gauge data updated daily; results compiled annually for the previous full year
- Indicator: To be determined through further discussion with EPA

(6) Date (month and year) next data set is expected to be available for reporting: NOAA data expected in spring 2019; pending arrangement with EPA and NOAA

C. Spatial Considerations

(7) What is the ideal level of spatial aggregation (e.g., watershed-wide, river basin, state, county, hydrologic unit code)? This indicator works best as a disaggregated map that shows trends at each individual tide gauge. The localized nature of tide gauge data does not lend itself to aggregation into larger spatial units.

(8) Is there geographic (GIS) data associated with this data set? If so, indicate its format (e.g., point, line polygon). Yes, point data.

(9) Are there geographic areas that are missing data? If so, list the areas. Yes. There is a gap in coverage between Solomons Island, Maryland, and the Hampton Roads region of Virginia. This means the southern Eastern Shore and portions of Virginia lack a representative tide gauge.

(10) Please submit any appropriate examples of how this information has been mapped or otherwise portrayed geographically in the past. See the map published as part of EPA's national indicator at www.epa.gov/climate-indicators/climate-change-indicators-sea-level.

D. Communicating the Data

(11) What is the goal, target, threshold or expected outcome for this indicator? How was it established? No explicit target. In the Chesapeake Bay region, relative sea level is expected to rise as absolute sea level rises globally due to climate change, compounded by subsidence associated with tectonic processes (on a regional scale throughout the Mid-Atlantic) and groundwater extraction (on a more localized scale). The purpose of this indicator is to monitor the extent to which this climate-related attribute is changing—which, in turn, can inform management decisions designed to increase climate resiliency, especially with regard to shoreline ecosystems and human infrastructure.

(12) What is the current status in relation to the goal, target, threshold or expected outcome? Not applicable.

(13) Has a new goal, target, threshold or expected outcome been established since the last reporting period? Why? Not applicable.

(14) Has the methodology of data collection or analysis changed since the last reporting period? How? Why? No.

(15) What is the long-term data trend (since the start of data collection)? Cumulative increases in relative sea level range since 1960 range from roughly 7 inches at Baltimore, Maryland, and Washington, DC, to more than 10 inches at Sewell's Point in Norfolk, Virginia. The average annual rates of change at these locations range from 3.2 to 4.6 millimeters per year over the period from 1960 to 2017.

(16) What change(s) does the most recent data show compared to the last reporting period? To what do you attribute the change? Is this actual cause or educated speculation? This indicator views data in a long-term context suitable for climatological analysis. Authoritative scientific literature (e.g., assessments by the

Intergovernmental Panel on Climate Change and the U.S. Global Change Research Program) has established that climate change is contributing to global sea level rise, primarily through thermal expansion of water and melting of land-based ice (e.g., glaciers and ice sheets). Global sea level rise contributes to relative sea level rise in many parts of the world, including the Chesapeake Bay region. Numerous studies have also documented subsidence throughout the Mid-Atlantic region, which exacerbates relative sea level rise by causing downward motion of the land surface. For example, see USGS (2013).

USGS. 2013. Land subsidence and relative sea-level rise in the southern Chesapeake Bay region. USGS Circular 1392. http://dx.doi.org/10.3133/cir1392.

(17) What is the key story told by this indicator? Since 1960, relative sea level has risen at all seven tide gauge locations in the Chesapeake region that have collected long-term consistent data.

E. Adaptive Management

(18) What factors influence progress toward the goal, target, threshold or expected outcome? Relative sea level change reflects the influence of global sea level change, which in turn is driven by climate change. Relative sea level change also reflects the influence of local and regional changes in land surface elevation. In the Mid-Atlantic region, the Earth's crust is naturally subsiding as part of a delayed continental-scale tectonic response to the end of the last glacial maximum ("ice age"). Groundwater pumping and other activities can contribute to subsidence on a more localized scale.

(19) What are the current gaps in existing management efforts? Mitigation of climate change requires coordinated global action that is beyond the purview of the Chesapeake Bay Program, but local and regional actions to reduce greenhouse gas emissions can still contribute to these broader solutions. Other opportunities could include groundwater management and actions to help wetland accretion keep pace with sea level rise.

(20) What are the current overlaps in existing management efforts? Wetland protection and restoration efforts not only provide habitat benefits and enhance water quality, but also can help to provide natural buffers against flooding and storm surge associated with sea level rise. Efforts to designate and preserve wetland migration corridors can be part of a strategy to adapt to sea level rise while also preserving the many other benefits that wetlands provide.

(21) According to the management strategy written for the outcome associated with this indicator, how will we (a) assess our performance in making progress toward the goal, target, threshold or expected outcome, and (b) ensure the adaptive management of our work? Not applicable to this outcome.

F. Analysis and Interpretation

Please provide appropriate references and location(s) of documentation if hard to find.

(22) What method is used to transform raw data into the information presented in this indicator? Please cite methods and/or modeling programs. Tide gauge data for the map come from NOAA's National Water Level Observation Network (NWLON). NOAA (2009) describes these data and how they were collected and processed. These methods are documented in a series of manuals and standards that can be accessed at: www.co-ops.nos.noaa.gov/pub.html#sltrends. Generating the station values depicted in the map involved a two-step process. First, NOAA used monthly sea level means to calculate a long-term annual rate of change for each station, which was determined by linear regression. Then, the annual rate of change was multiplied by the length of the analysis period to determine total change.

NOAA. 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. www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf.

(23) Is the method used to transform raw data into the information presented in this indicator accepted as scientifically sound? If not, what are its limitations? Yes. This method has been used in multiple U.S. government publications and has been peer reviewed for inclusion in EPA's climate change indicator suite, which requires each indicator to meet a set of 10 criteria for data quality (see the technical documentation overview at www.epa.gov/climate-indicators/downloads-indicators-technical-documentation).

(24) How well does the indicator represent the environmental condition being assessed? This indicator uses an acknowledged method to analyze trends in sea level. Another option would be to examine absolute global sea level change, which does vary over different parts of the ocean and can be measured using satellite altimetry. In fact, some indicators present trends in both relative and absolute sea level change because of the complementary value that each provides. For a local-scale analysis, though, tide gauges offer more precise measurements than other types of methods for measuring sea level (e.g., satellite data). Also, relative sea level is arguably more relevant to coastal communities than absolute sea level because it reflects the conditions that will actually be observed and experienced along the shore. That said, tide gauge measurements generally do not reveal how much of the observed change can be attributed to global sea level change and how much is a result of vertical land motion. For more discussion of the advantages and limitations of various methods for measuring sea level, see Cazenave and Nerem (2004).

Tide gauge measurements at specific locations are not indicative of broader changes over space, and NOAA's tide gauge network is not designed to achieve uniform spatial coverage. Rather, the gauges tend to be located at major port areas along the coast, and measurements tend to be more clustered in heavily populated areas. Nevertheless, in many areas it is possible to see consistent patterns across numerous gauging locations—for example, rising relative sea level all along the U.S. Atlantic and Gulf Coasts, as EPA's national version of this indicator shows.

Cazenave, A., and R.S. Nerem. 2004. Present-day sea level change: Observations and causes. Rev. Geophys. 42(3):1–20.

(25) Are there established reference points, thresholds, ranges or values for this indicator that unambiguously reflect the desired state of the environment? No.

(26) How far can the data be extrapolated? Have appropriate statistical methods been used to generalize or portray data beyond the time or spatial locations where measurements were made (e.g., statistical survey inference, no generalization is possible)? No attempt has been made to extrapolate data beyond the sampled sites and the timeframe of analysis. No attempt has been made to interpolate results between sampled sites. It is most appropriate to focus this indicator on the specific sites where data have been collected.

G. Quality

Please provide appropriate references and location(s) of documentation if hard to find.

(27) Were the data collected and processed according to a U.S. Environmental Protection Agency-approved Quality Assurance Project Plan? If so, please provide a link to the QAPP and indicate when the plan was last reviewed and approved. **If not, please complete questions 29-31.** No.

(28) *If applicable:* Are the sampling, analytical and data processing procedures accepted as scientifically and technically valid? Yes. All measurements are made according to standard NOAA procedures. Analytical and data processing procedures have been peer reviewed and accepted as valid.

(29) *If applicable:* What documentation describes the sampling and analytical procedures used? See the technical documentation for EPA's "Sea Level" indicator at www.epa.gov/climate-indicators/downloads-indicators-technical-documentation, as well as the NOAA and scientific literature references cited therein.

(30) *If applicable:* To what extent are procedures for quality assurance and quality control of the data documented and accessible? QA/QC procedures for U.S. tide gauge data are described in various publications available at: www.co-ops.nos.noaa.gov/pub.html#sltrends.

(31) Are descriptions of the study design clear, complete and sufficient to enable the study to be reproduced? Yes. The technical documentation for EPA's "Sea Level" indicator at www.epa.gov/climate-indicators/downloads-indicators-technical-documentation, as well as the NOAA references cited therein, provide thorough documentation to allow methods to be reproduced.

(32) Were the sampling, analytical and data processing procedures performed consistently throughout the data record? Yes. Tide gauges have collected data from consistent locations throughout the period of record. Only stations with sufficient data between 1960 and 2017 were used to show sea level trends. All data were processed using the same methods.

(33) If data sets from two or more sources have been merged, are the sampling designs, methods and results comparable? If not, what are the limitations? Not applicable, as all data derive from one source.

(34) Are levels of uncertainty available for the indicator and/or the underlying data set? If so, do the uncertainty and variability impact the conclusions drawn from the data or the utility of the indicator? Standard deviations for each station-level trend estimate were included in the data set provided to EPA by NOAA. Overall, with approximately 50 years of data, the 95 percent confidence interval around the long-term rate of change at each station is approximately +/- 0.5 mm per year (NOAA, 2009). Error measurements for each tide gauge station are also described in NOAA (2009), but many of the estimates in that publication pertain to longer-term time series (i.e., the entire period of record at each station, not the shorter period covered by this indicator). NOAA uses a linear regression with an autoregressive coefficient to obtain accurate error estimates. As described in NOAA (2009), this method is used because of the serial correlation of the residual time series due to inter-annual variability caused by the effects of the El Niño Southern Oscillation (ENSO) and other driving forces on coastal oceanic water temperatures, salinities, winds, air pressures, and currents.

The accuracy of relative sea level trends computed from tide gauge records is highly dependent upon the record length as detailed by NOAA (2009). As discussed in NOAA (2009), each derived linear trend has an associated uncertainty represented by error bars showing the 95% confidence interval. The 95% confidence intervals of the mean sea level trends can be related to the year range of data by an inverse power relationship. It can be seen that to get a linear trend with a confidence interval of 1 mm/yr (+/- 0.5 mm/yr) requires about 50–60 years of data. Thus, NOAA publishes relative trends in mean sea level for only those stations with at least 30 years of data.

NOAA. 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. www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf.

(35) For chemical data reporting: How are data below the MDL reported (i.e., reported as 0, censored, or as < MDL)? If parameter substitutions are made (e.g., using orthophosphate instead of total phosphorus), how are data normalized? How does this impact the indicator? Not applicable, as no chemical data have been collected.

(36) Are there noteworthy limitations or gaps in the data record? No.

H. Additional Information (*Optional)*

(37) Please provide any further information you believe is necessary to aid in communication and prevent any potential misrepresentation of this indicator. Relative sea level results have been generalized over time by calculating long-term rates of change for each station using ordinary least-squares regression. The statistical significance of each trend was not analyzed for this indicator, but NOAA sources have documented the significance of changes in relative sea level. NOAA (2009) Appendix V provides a detailed analysis of long-term trends and their significance over multiple 50-year periods at a subset of sites, including Baltimore, Washington, and Sewell's Point within the Chesapeake watershed. All three of these sites had trends that were significant to a 95-percent level. NOAA's website at: https://tidesandcurrents.noaa.gov/sltrends/sltrends_us.htm provides more detailed statistical information for every station, including linear regression slope and significance over the full period of record available or, in some cases, shorter sub-periods.

NOAA. 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. www.tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf.