Sea Level

Identification

1. Indicator Description

This indicator describes how sea level has changed since 1880. Rising sea levels have a clear relationship to climate change through two main mechanisms: changes in the volume of ice on land (shrinking glaciers and ice sheets) and thermal expansion of the ocean as it absorbs more heat from the atmosphere. Changes in sea level are important because they can affect human activities in coastal areas and alter ecosystems.

Components of this indicator include:

- Average absolute sea level change of the world's oceans since 1880 (Figure 1)
- Trends in relative sea level change along U.S. coasts since 1960 (Figure 2)

2. Revision History

April 2010:	Indicator published.
December 2012:	Updated indicator with data through 2011.
August 2013:	Updated Figure 2 on EPA's website with data through 2012.
May 2014:	Updated Figure 1 with long-term reconstruction data through 2012 and altimeter data through 2013; updated Figure 2 with data through 2013.
June 2015:	Updated Figure 1 on EPA's website with long-term reconstruction data through 2013 and altimeter data through 2014; updated Figure 2 on EPA's website with data through 2014.
August 2016:	Updated Figure 1 altimeter time series and Figure 2 with data through 2015.

Data Sources

3. Data Sources

Figure 1. Global Average Absolute Sea Level Change, 1880–2015

Figure 1 presents a reconstruction of absolute sea level developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). This reconstruction is available through 2013 and is based on two main data sources:

- Satellite data from the TOPography EXperiment (TOPEX)/Poseidon, Jason-1, and Jason-2 satellite altimeters, operated by the National Aeronautics and Space Administration (NASA) and France's Centre National d'Etudes Spatiales (CNES).

- Tide gauge measurements compiled by the Permanent Service for Mean Sea Level (PSMSL), which includes more than a century of daily and monthly tide gauge data.

Figure 1 also presents the National Oceanic and Atmospheric Administration's (NOAA's) analysis of altimeter data from the TOPEX/Poseidon, Jason-1 and -2, GEOSAT Follow-On (GFO), Envisat, and European Remote Sensing (ERS) 2 satellite missions. These data are available through 2015.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2015

Figure 2 presents relative sea level trends calculated by NOAA based on measurements from permanent tide gauge stations. The original data come from the National Water Level Observation Network (NWLON), operated by the Center for Operational Oceanographic Products and Services (CO-OPS) within NOAA's National Ocean Service (NOS).

4. Data Availability

Figure 1. Global Average Absolute Sea Level Change, 1880–2015

The CSIRO long-term tide gauge reconstruction has been published online in graph form at: www.cmar.csiro.au/sealevel, and the data are posted on CSIRO's website at: www.cmar.csiro.au/sealevel/sl_data_cmar.html. CSIRO's website also provides a list of tide gauges that were used to develop the long-term tide gauge reconstruction.

At the time this indicator was published, CSIRO's website presented data through 2013. These results are an update to Church and White (2011), who presented data through 2009.

The satellite time series was obtained from NOAA's Laboratory for Satellite Altimetry, which maintains an online repository of sea level data (NOAA, 2016). The data file for this indicator was downloaded from: http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/slr/slr_sla_gbl_free_all_66.csv. Underlying satellite measurements can be obtained from NASA's online database (NASA, 2016). The reconstructed tide gauge time series is based on data from the PSMSL database, which can be accessed online at: www.psmsl.org/data.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2015

The relative sea level map is based on individual station measurements that can be accessed through NOAA's "Sea Levels Online" website at: http://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 1960–2015 trends that it provided to EPA 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 1960–2015 analysis from the lead author of NOAA (2009), Chris Zervas.

Methodology

5. Data Collection

This indicator presents absolute and relative sea level changes. Absolute sea level change (Figure 1) represents only the sea height, whereas relative sea level change (Figure 2) 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).

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, which means the resulting data reflect both the change in absolute sea surface height and the change in local land levels. Satellite measurement of land and sea surface heights (altimetry) began several decades ago; this technology enables measurement of changes in absolute sea level. Tide gauge data can be converted to absolute change (as in Figure 1) through a series of adjustments as described in Section 6.

The two types of sea level data (relative and absolute) complement each other, and each is useful for different purposes. Relative sea level trends show how sea level change and vertical land movement together are likely to affect coastal lands and infrastructure, while absolute sea level trends provide a more comprehensive picture of the volume of water in the world's oceans, how the volume of water is changing, and how these changes relate to other observed or predicted changes in global systems (e.g., increasing ocean heat content and melting polar ice sheets). Tide gauges provide more precise local measurements, while satellite data provide more complete spatial coverage. Tide gauges are used to help calibrate satellite data. For more discussion of the advantages and limitations of each type of measurement, see Cazenave and Nerem (2004).

Tide Gauge Data

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.

Tide gauge data for Figure 1 were collected by numerous networks of tide gauges around the world. The number of stations included in the analysis varies from year to year, ranging from fewer than 20 locations in the 1880s to more than 200 locations during the 1980s. Pre-1880 data were not included in the reconstruction because of insufficient tide gauge coverage. These measurements are documented by the PSMSL, which compiled data from various networks. The PSMSL data catalogue provides documentation for these measurements at: www.psmsl.org/data.

Tide gauge data for Figure 2 come from NOAA's National Water Level Observation Network (NWLON). NWLON is composed of 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 in Figure 2 shows trends for 67 stations along the ocean coasts that had sufficient data from 1960 to 2015. NOAA (2009) describes these data and how they were collected. Data collection methods are documented in a series of manuals and standards that can be accessed at: www.co-ops.nos.noaa.gov/pub.html#sltrends.

Satellite Data

Satellite altimetry has revealed that the rate of change in absolute sea level differs around the globe (Cazenave and Nerem, 2004). Factors that lead to changes in sea level include astronomical tides; variations in atmospheric pressure, wind, river discharge, ocean circulation, and water density (associated with temperature and salinity); and added or extracted water volume due to the melting of ice or changes in the storage of water on land in reservoirs and aquifers.
Data for this indicator came from the following satellite missions:

- TOPEX/Poseidon began collecting data in late 1992; Jason began to replace TOPEX/Poseidon in 2002. For more information about the TOPEX/Poseidon and Jason missions, see NASA's website at: http://sealevel.jpl.nasa.gov/missions.

- The U.S. Navy launched GFO in 1998, and altimeter data are available from 2000 through 2006. For more information about the GFO missions, see NASA's website at: http://gcmd.nasa.gov/records/GCMD_GEOSAT_FOLLOWON.html.

- The European Space Agency (ESA) launched ERS-2 in 1995, and its sea level data are available from 1995 through 2003. More information about the mission can be found on ESA's website at: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/ers.

- ESA launched Envisat in 2002, and this indicator includes Envisat data from 2002 through 2010. More information about Envisat can be found on ESA's website at: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat.

TOPEX/Poseidon and Jason satellite altimeters each cover the entire globe between 66 degrees south and 66 degrees north with 10-day resolution. Some of the other satellites have different resolutions and orbits. For example, Envisat is a polar-orbiting satellite.

6. Indicator Derivation

Satellite Data for Figure 1. Global Average Absolute Sea Level Change, 1880–2015

NOAA processed all of the satellite measurements so they could be combined into a single time series. In doing so, NOAA limited its analysis to data between 66 degrees south and 66 degrees north, which covers a large majority of the Earth's surface and represents the area with the most complete satellite coverage.

Researchers removed spurious data points. They also estimated and removed inter-satellite biases to allow for a continuous time series during the transition from TOPEX/Poseidon to Jason-1 and -2. A discussion of the methods for calibrating satellite data is available in Leuliette et al. (2004) for TOPEX/Poseidon data, and in Chambers et al. (2003) for Jason data. Also see Nerem et al. (2010).

Data were adjusted using an inverted barometer correction, which corrects for air pressure differences, along with an algorithm to remove average seasonal signals. These corrections reflect standard procedures for analyzing sea level data and are documented in the metadata for the data set. The data were not corrected for glacial isostatic adjustment (GIA)—an additional factor explained in more detail below.

NOAA provided individual measurements, spaced approximately 10 days apart (or more frequent, depending on how many satellite missions were collecting data during the same time frame). EPA generated monthly averages based on all available data points, then combined these monthly averages to determine annual averages. EPA chose to calculate annual averages from monthly averages in order to reduce the potential for biasing the annual average toward a portion of the year in which measurements were spaced more closely together (e.g., due to the launch of an additional satellite mission).

The analysis of satellite data has improved over time, which has led to a high level of confidence in the associated measurements of sea level change. Further discussion can be found in Cazenave and Nerem (2004), Miller and Douglas (2004), and Church and White (2011).

Several other groups have developed their own independent analyses of satellite altimeter data. Although all of these interpretations have appeared in the literature, EPA has chosen to include only one (NOAA) in the interest of keeping this indicator straightforward and accessible to readers. Other organizations that publish altimeter-based data include:

- The University of Colorado at Boulder: http://sealevel.colorado.edu
- AVISO (France): www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global.html
- CSIRO: www.cmar.csiro.au/sealevel

Tide Gauge Reconstruction for Figure 1. Global Average Absolute Sea Level Change, 1880–2015

CSIRO developed the long-term tide gauge reconstruction using a series of adjustments to convert relative tide gauge measurements into an absolute global mean sea level trend. Church and White (2011) describe the methods used, which include data screening; calibration with satellite altimeter data to establish patterns of spatial variability; and a correction for GIA, which represents the ongoing change in the size and shape of the ocean basins associated with changes in surface loading. On average, the world's ocean crust is sinking in response to the transfer of mass from the land to the ocean following the retreat of the continental ice sheets after the Last Glacial Maximum (approximately 20,000 years ago). Worldwide, on average, the ocean crust is sinking at a rate of approximately 0.3 mm per year. By correcting for GIA, the resulting curve actually reflects the extent to which sea level *would* be rising if the ocean basins were not becoming larger (deeper) at the same time. For more information about GIA and the value of correcting for it, see: http://sealevel.colorado.edu/content/what-glacial-isostatic-adjustment-gia-and-why-do-you-correct-it.

Seasonal signals have been removed, but no inverse barometer (air pressure) correction has been applied because a suitable long-term global air pressure data set is not available. Figure 1 shows annual average change in the form of an anomaly. EPA has labeled the graph as "cumulative sea level change" for the sake of clarity.

The tide gauge reconstruction required the use of a modeling approach to derive a global average from individual station measurements. This approach allowed the authors to incorporate data from a time-varying array of tide gauges in a consistent way. The time period for the long-term tide gauge reconstruction starts at 1880, consistent with Church and White (2011). When EPA originally published Figure 1 in 2010, this time series started at 1870. As Church and White have refined their methods over time, however, they have found the number of observations between 1870 and 1880 to be insufficient to reliably support their improved global sea level reconstruction. Thus, Church and White removed pre-1880 data from their analysis, and EPA followed suit.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2015

Figure 2 shows relative sea level change for 67 tide gauges with adequate data for the period from 1960 to 2015. Sites were selected if they began recording data in 1960 or earlier and if data were available through 2015. Sites that experienced significant seismic events within the time-period 1960–2015—such as sites in south-central Alaska between Kodiak Island and Yakutat, which experienced a major earthquake in 1964—were excluded from the analysis because they have exhibited nonlinear behavior. Extensive discussion of this network and the derivation of mean sea level trends from tide gauge data can be found in NOAA (2009) and in additional sources available from the CO-OPS website at: http://tidesandcurrents.noaa.gov. Generating the station values depicted in Figure 2 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 NOAA multiplied the annual rate of change by the length of the analysis period (55 years) to determine total change.

7. Quality Assurance and Quality Control

Satellite data processing involves extensive quality assurance and quality control (QA/QC) protocols—for example, to check for instrumental drift by comparing with tide gauge data (note that no instrumental drift has been detected for many years). The papers cited in Sections 5 and 6 document all such QA/QC procedures.

Church and White (2011) and earlier publications cited therein describe steps that were taken to select the highest-quality sites and correct for various sources of potential error in tide gauge measurements used for the long-term reconstruction in Figure 1. QA/QC procedures for the U.S. tide gauge data in Figure 2 are described in various publications available at: www.co-ops.nos.noaa.gov/pub.html#sltrends.

Analysis

8. Comparability Over Time and Space

Figure 1. Global Average Absolute Sea Level Change, 1880–2015

Satellite data were collected by several different satellite altimeters over different time spans. Steps have been taken to calibrate the results and remove biases over time, and NOAA made sure to restrict its analysis to the portion of the globe between 66 degrees south and 66 degrees north, where coverage is most complete.

The number of tide gauges collecting data has changed over time. The methods used to reconstruct a long-term trend, however, adjust for these changes.

The most notable difference between the two time series displayed in Figure 1 is that the long-term reconstruction includes a GIA correction, while the altimeter series does not. The uncorrected (altimeter) time series gives the truest depiction of how the surface of the ocean is changing in relation to the center of the Earth, while the corrected (long-term) time series technically shows how the volume of water in the ocean is changing. A very small portion of this volume change is not observed as absolute sea level rise (although most is) because of the GIA correction. Some degree of GIA correction is needed for a tide-gauge-based reconstruction in order to adjust for the effects of vertical crust motion.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2015

Only the 67 stations with sufficient data between 1960 and 2015 were used to show sea level trends. However, tide gauge measurements at specific locations are not indicative of broader changes over space, and the 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 like the Mid-Atlantic coast. 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.

9. Data Limitations

Factors that may impact the confidence, application, or conclusions drawn from this indicator are as follows:

1. Relative sea level trends represent a combination of absolute sea level change and local changes in land elevation. Tide gauge measurements such as those presented in Figure 2 generally cannot distinguish between these two influences without an accurate measurement of vertical land motion nearby.

2. Some changes in relative and absolute sea level may be due to multiyear cycles such as El Niño/La Niña and the Pacific Decadal Oscillation, which affect coastal ocean temperatures, salt content, winds, atmospheric pressure, and currents. The satellite data record is of insufficient length to distinguish medium-term variability from long-term change, which is why the satellite record in Figure 1 has been supplemented with a longer-term reconstruction based on tide gauge measurements.

3. Satellite data do not provide sufficient spatial resolution to resolve sea level trends for small water bodies, such as many estuaries, or for localized interests, such as a particular harbor or beach.

4. Most satellite altimeter tracks span the area from 66 degrees north latitude to 66 degrees south, so they cover about 90 percent of the ocean surface, not the entire ocean.

10. Sources of Uncertainty

Figure 1. Global Average Absolute Sea Level Change, 1880–2015

Figure 1 shows bounds of +/- one standard deviation around the long-term tide gauge reconstruction. For more information about error estimates related to the tide gauge reconstruction, see Church and White (2011).

Leuliette et al. (2004) provide a general discussion of uncertainty for satellite altimeter data. The Jason instrument currently provides an estimate of global mean sea level every 10 days, with an uncertainty of 3 to 4 millimeters.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2015

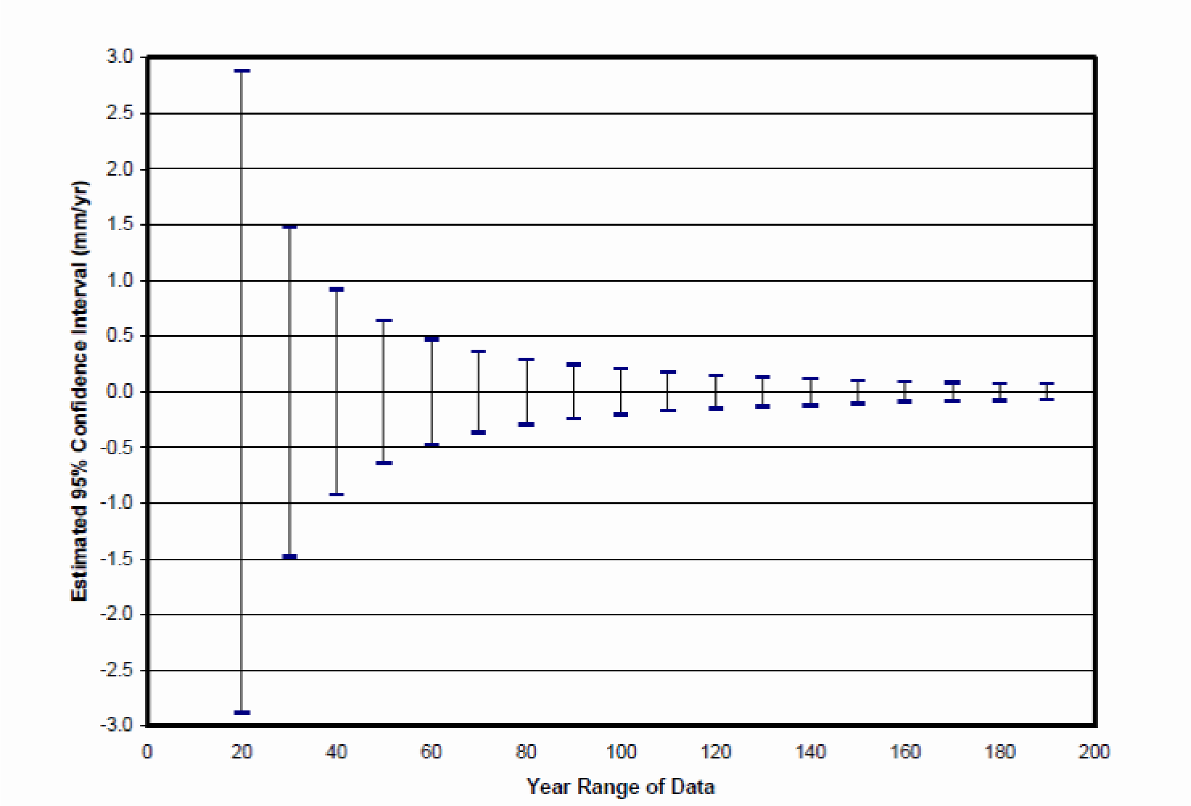
Standard deviations for each station-level trend estimate were included in the data set provided to EPA by NOAA. Overall, with approximately 50 years of data, the 95 percent confidence interval around the long-term rate of change at each station is approximately +/- 0.5 mm per year. Error measurements 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 55-year 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.

General Discussion

Uncertainties in the data do not impact the overall conclusions. Tide gauge data do present challenges, as described by Parker (1992) and various publications available from: www.co-ops.nos.noaa.gov/pub.html#sltrends. Since 2001, there have been some disagreements and debate over the reliability of the tide gauge data and estimates of global sea level rise trends from these data (Cabanes et al., 2001). However, further research on comparisons of satellite data with tide gauge measurements, and on improved estimates of contributions to sea level rise by sources other than thermal expansion—and by Alaskan glaciers in particular—have largely resolved the question (Cazenave and Nerem, 2004; Miller and Douglas, 2004). These studies have in large part closed the gap between different methods of measuring sea level change, although further improvements are expected as more measurements and longer time series become available.

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 (see Figure TD-1). 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.

Figure TD-1. Comparison of 95% Confidence Intervals Versus Series Length for Linear Mean Sea Level Trends



Data source: NOAA, 2009

11. Sources of Variability

Changes in sea level can be influenced by multi-year cycles such as El Niño/La Niña and the Pacific Decadal Oscillation, which affect coastal ocean temperatures, salt content, winds, atmospheric pressure, and currents. The satellite data record is of insufficient length to distinguish medium-term variability from long-term change, which is why the satellite record in Figure 1 has been supplemented with a longer-term reconstruction based on tide gauge measurements.

12. Statistical/Trend Analysis

Figure 1. Global Average Absolute Sea Level Change, 1880–2015

The indicator text refers to long-term rates of change, which were calculated using ordinary least-squares regression, a commonly used method of trend analysis. The long-term tide gauge reconstruction trend reflects an average increase of 0.06 inches per year. The 1993–2013 trend is 0.14 inches per year for the reconstruction, and the 1993–2015 trend for the NOAA altimeter-based time series is 0.11 inches per year. All of these trends are highly significant statistically ($p < 0.001$). Church and White (2011) provide more information about long-term rates of change and their confidence bounds.

Figure 2. Relative Sea Level Change Along U.S. Coasts, 1960–2015

U.S. 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 25 of the stations presented here. For the most comparable 50-year period analyzed by NOAA (2009)—1957 to 2006—all but two of the 25 stations (Astoria, Oregon, and Ketchikan, Alaska) had trends that were significant to a 95-percent level. NOAA's website at: http://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.

No attempt was made to interpolate these data geographically.

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