# Sea Level

## 1 Describe the physical, chemical, or biological measurements upon which this indicator is based. Are these measurements widely accepted as scientifically and technically valid? Explain.

This indicator presents trends in absolute and relative sea level. Absolute sea level (Figure 1)—also called eustatic sea level—represents only the sea height, whereas relative sea level change (Figure 2) is defined as sea height relative to land. Sea level has traditionally been measured using tidal gauges, which are measuring devices located along the shore. These devices measure relative sea level. Satellite measurement of land and sea surface heights (altimetry) began several decades ago; this technology allows for measurement of changes in absolute sea level. Tidal gauge data can be converted to absolute trends (as in Figure 1) through a series of adjustments.

Tidal gauges:

Some locations have had continuous tidal gauge measurements since the 1800s. Tidal gauges 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. Land surfaces move up or down in many locations around the world due to natural geologic processes (uplift and subsidence) and human activities that can cause ground to sink (e.g., from extraction of groundwater or hydrocarbons that supported the surface). Thus, while tidal gauges are reliable measures of the change in sea level relative to the adjoining land surface, tidal gauge data alone are a poor indicator of the absolute change in sea level.

Satellite measurements:

The launch of the National Aeronautics and Space Administration's (NASA's) Ocean TOPography Experiment (TOPEX)/Poseidon mission in 1992, and subsequent analyses, have allowed measurements of changes in absolute sea heights. 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 tide; changes in atmospheric pressure, wind, river discharge, or ocean circulation; changes in water density (e.g., from temperature and salinity); and added or extracted water volume due to the melting of ice or storage of water on land in reservoirs or evaporated with agricultural irrigation.

General discussion:

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 is 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 it 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 caps). Tidal gauges provide more precise local measurements, while satellite data provide more complete spatial coverage. Tidal gauges are used to help calibrate satellite data. For more discussion of the pros and cons of each type of measurement, see Cazenave and Nerem (2004).

## 2 Describe the sampling design and/or monitoring plan used to collect the data over time and space. Is it based on sound scientific principles? Explain.

Figure 1:

Figure 1 shows global trends in absolute sea level based on a combination of (a) satellite data and (b) tidal gauge data that have been adjusted to provide a reconstructed absolute trend.

Satellite data come from the TOPEX/Poseidon and Jason satellite altimeters, operated by NASA. TOPEX/Poseidon began collecting data in late 1992; Jason replaced TOPEX/Poseidon around 2002. Both data sets cover the entire globe between 66 degrees south and 66 degrees north with 10-day resolution.

Tidal gauge data for Figure 1 were collected by numerous networks of tidal gauges around the world. Sampling at tidal gauge stations takes place at sub-daily resolution, and it is representative of changes at each location over time. Data were compiled by the Permanent Service for Mean Sea Level (PSMSL), an online database that provides access to more than a century's worth of monthly tidal gauge data. The number of stations included in the analysis varies from year to year, ranging from 10 stations in 1870 to approximately 300 stations during the 1980s. The methods used to reconstruct a long-term trend (see the response to Question 3) are able to adjust for these changes. Pre-1870 data were not included in the reconstruction because of insufficient tidal gauge coverage.

Figure 2:

Tidal gauge data come from the National Water Level Observation Network (NWLON), operated by the Center for Operational Oceanographic Products and Services (CO-OPS), which is a component of the National Ocean Service (NOS) within the National Oceanic and Atmospheric Administration (NOAA). The NWLON is composed of 175 long-term, continuously operating tidal gauge stations located 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 76 stations along the ocean coasts that had sufficient data over the period from 1958 to 2008.

Extensive discussion of this network and the tidal gauge data analysis can be found in NOAA (2001) and additional sources available from the CO-OPS Web site at: http://tidesandcurrents.noaa.gov. Sampling at tidal gauge stations takes place at sub-daily resolution, and it is representative of changes at each location over time. However, tidal 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. An acceleration of the rate of relative sea level rise at multiple locations would tend to indicate that the overall rate of global sea level rise is also accelerating.

## 3 Describe the conceptual model used to transform these measurements into an indicator. Is this model widely accepted as a scientifically sound representation of the phenomenon it indicates? Explain.

Figure 1:

Figure 1 shows trends in global average absolute sea level over time based on recent satellite measurements and a reconstruction of long-term tidal gauge data.

Satellite measurements were processed by two independent groups, each of which used slightly different methods.

The "University of Colorado" satellite series was processed by a research team based at the University of Colorado at Boulder and several other institutions. Spurious data points were removed, and the remaining data were corrected for instrument drift, using tidal gauge data as a reference. The data were also calibrated to allow for a continuous time series over the time of transition from TOPEX/Poseidon to Jason. 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. To create a single global mean trend line, the data were averaged over the global grid. Data were adjusted using an inverted barometer correction, which corrects for air pressure differences, along with an algorithm to remove seasonal signals. These corrections reflect standard procedures for analyzing sea level data, and are documented in the metadata for the data set. Jason and TOPEX/Poseidon observations are spaced 10 days apart, and the University of Colorado applied a 60-day smoothing procedure to calculate a moving average of seven consecutive data points (which together span a range of 60 days). For consistency with the other annual trends, EPA averaged these 60-day values to derive a single annual value for each year.

The "CSIRO" satellite series was developed by Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). Most standard corrections except the inverse barometer correction were applied, including corrections for instrumental drift and removal of seasonal signals. For more information about methods used to derive this data series, see Church and White (2006).

CSIRO developed the long-term tidal gauge reconstruction, using a series of adjustments to convert relative tidal gauge measurements into an absolute global mean sea level trend. Church and White (2006) describe the methods used, which include data screening, calibration with satellite altimeter data to establish patterns of spatial variability, and removing the influence of glacial isostatic adjustment, which represents the ongoing change in land elevation associated with changes in surface loading.

Long-term trends for the three time series were calculated by ordinary least-squares regression.

Figure 2:

Figure 2 shows relative sea level change for 76 tidal gauges with adequate data for the period from 1958 to 2008. Sites were selected if they had at least 10 months of data in at least 80 percent of the years during the period of interest (41 of 51 years). The process of generating Figure 2 involved only simple mathematics. NOAA used monthly sea level means to calculate annual average sea level for each station. NOAA provided EPA with the annual rate of change for each station, which was determined by linear regression of these annual means. Attempting to determine an average value for this entire data set would not have been appropriate due to the uneven spatial distribution of sample sites.

## 4 What documentation clearly and completely describes the underlying sampling and analytical procedures used?

Figure 1:

Satellite data procedures have been documented by NASA and various research institutes that perform calibrations, analyses, and other manipulations to make the data easier to interpret and use. The NASA Web site at: http://topex-www.jpl.nasa.gov/science/data.html provides links to the various research centers. Documentation for the data manipulations is available from each of the research institutes and must be read carefully before use. A principal site for the TOPEX/Poseidon data sets is: http://podaac.jpl.nasa.gov/DATA_CATALOG/topexPoseidoninfo.html. A main site for the Jason data sets is: http://sealevel.jpl.nasa.gov/science/jason1-quick-look.

Tidal gauge measurements are documented by the PSMSL, which compiled data from various tidal gauge networks around the world. The PSMSL data catalogue provides documentation for these measurements at: www.pol.ac.uk/psmsl/datainfo.

The "University of Colorado" satellite data set and analysis used for this indicator are described in contextual detail in Leuliette et al. (2004) and at: http://sealevel.colorado.edu/documents.html. The "CSIRO" satellite data set and the long-term tidal gauge reconstruction are described in Church and White (2006) and earlier publications cited therein.

Figure 2:

NOAA (2001) describes the tidal gauge 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. The response to Question 3 describes how tidal gauge measurements were used to obtain long-term trend data. Note that the calculation procedure for this indicator differs somewhat from the approach described in NOAA (2001), an earlier version of the analysis in which NOAA calculated trends directly from monthly data, accounting for seasonal signals and the potential for serial correlation.

## 5 To what extent is the complete data set accessible, including metadata, data-dictionaries, and embedded definitions? Are there confidentiality issues that may limit accessibility to the complete data set?

Figure 1:

The "University of Colorado" satellite time series was obtained from the University of Colorado at Boulder, which maintains an online repository of sea level data (University of Colorado at Boulder, 2009). These data are updated periodically; this indicator is based on 2009 release #2 (available at: http://sealevel.colorado.edu).

The "CSIRO" satellite time series and the long-term tidal gauge reconstruction have been published online in graph form at: www.cmar.csiro.au/sealevel. This online graph represents an updated version of the analysis published in Church and White (2006). EPA obtained the data from the authors of Church and White (2006).

Satellite trends are based on measurements from NASA's TOPEX/Poseidon and Jason satellite altimeters. Satellite measurements can be obtained from NASA's online database (NASA, 2008). The reconstructed tidal gauge time series is based on data from the PSMSL database, which can be accessed online at: www.pol.ac.uk/psmsl.

Figure 2:

The relative sea level map is based on individual station measurements that can be accessed through NOAA's "Sea Levels Online" Web site at: http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml. This Web site also presents an interactive map that illustrates sea level trends over different timeframes. NOAA has not yet published the table of 1958-to-2008 trends that it provided to EPA for this indicator; however, a user could reproduce these numbers from the publicly available data cited above. NOAA published an earlier version of this trend analysis in a technical report on sea level variations of the United States from 1854 to 1999 (NOAA, 2001).

## 6 Are the descriptions of the study or survey design clear, complete, and sufficient to enable the study or survey to be reproduced? Explain.

Figure 1:

The analysis of satellite data can and has been reproduced, which has led to improvements and 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

(2006). Methods of developing the long-term tidal gauge reconstruction have also been fully documented (see Church and White, 2006).

Figure 2:

The analysis and interpretation of tidal gauge data can be reproduced from data provided by NOAA, together with the additional calculation steps described in the response to Question 3.

## 7 To what extent are the procedures for quality assurance and quality control of the data documented and accessible?

Figure 1:

Satellite data processing involves extensive quality assurance and quality control (QA/QC) protocols—for example, to identify imagery affected by cloud cover. These processes are covered in the documents and other sources described in the response to Question 4.

Reconstructing a long-term global mean sea level trend from tidal gauge data also required extensive procedures to ensure quality. Church and White (2006) and earlier publications cited therein describe steps that were taken to select the highest-quality sites and correct for various sources of potential error.

Figure 2:

QA/QC procedures for U.S. tidal gauge data are described in various publications available at: www.co-ops.nos.noaa.gov/pub.html#sltrends.

## 8 What statistical methods, if any, have 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)? Are these methods scientifically appropriate?

Figure 1:

Absolute sea level data from satellites have been generalized over space by averaging over the entire global ocean surface. Such averaging is appropriate given the high spatial and temporal resolution of the satellite data.

The tidal gauge reconstruction required the use of a modeling approach to derive a global average from individual station measurements. This approach, published in the peer-reviewed literature (see Church and White, 2006), included calibration with the recent satellite record to account for spatial variability in sea level change over the entire ocean surface. These analytical methods allowed Church and White to incorporate data from a time-varying array of tidal gauges in a consistent way.

The text refers to long-term rates of change, which were calculated using ordinary least-squares regression, a commonly used method of trend analysis. No attempt was made to project data beyond the time periods of measurement.

Figure 2:

No attempt was made to generalize U.S. coastal relative sea level data over space. Results have been generalized over time by calculating long-term rates of change for each station using ordinary least-squares regression. No attempt was made to project data beyond the time periods of measurement.

## 9 What uncertainty measurements or estimates are available for the indicator and/or the underlying data set?

Figure 1:

Leuliette et al. (2004) provide uncertainty data and corresponding discussion 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. The overall trend in the calibrated "University of Colorado" data set has been calculated as 3.2 +/- 0.4 millimeters per year. Error bars for the "CSIRO" satellite data series are approximately +/- 5 millimeters; exact error values can be obtained from the authors of Church and White (2006).

Figure 1 shows bounds of +/- one standard deviation around the long-term tidal gauge reconstruction. For more information about error estimates related to the tidal gauge reconstruction, see Church and White (2006).

Figure 2:

Standard error measurements for each 50-year station-level trend estimate were included in the data set provided to EPA by NOAA. Overall, with 50 years of data, accuracy in determining the mean sea level change can be to the 1-millimeter-per-year level with a 95 percent level of confidence. Standard error measurements for each tidal gauge station are also described in NOAA (2001), 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 50-year period covered by this indicator).

## 10 To what extent do uncertainty and variability impact the conclusions that can be inferred from the data and the utility of the indicator?

The uncertainties in the data do not impact the overall conclusions. Tidal 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 has been some disagreement and debate over the reliability of the tidal 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 tidal 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). This work has in large part closed the gap between "top-down" and "bottom-up" measurements of sea level change, although further improvements are expected as more measurements and longer time series become available. A complete understanding of sources, variability, and trends will continue to evolve.

## 11 Describe any limitations or gaps in the data that may mislead a user about fundamental trends in the indicator over space or over the time period for which data are available.

Limitations to this indicator include the following:

1. Relative sea level trends represent a combination of absolute sea level change and local changes in land elevation. Tidal 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 can be due to multi-year cycles such as El Niño and the Pacific Decadal Oscillation, which affect coastal ocean temperatures, salt content, winds, atmospheric pressure, and currents. Satellite data are not yet available for the multi-decadal time series needed 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 tidal gauge measurements.
3. Satellite data do not provide sufficient 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. 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.

## 12 References

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