Indicator: Sea Level (353)

The status of the coastline is an important aspect of the ecological and economic balance of the U.S. One element of that balance is the level of the sea relative to the land. Coastal areas in the U.S. host a rich set of natural and economic resources and include some of the most developed and rapidly growing population centers in the nation. More than 100 million people globally live within 1 meter of the mean sea level and more than 40% of the U.S. population lives in watersheds along U.S. ocean coasts. Changing sea levels have the potential to impact U.S. coasts in numerous ways, such as inundating low lying wetlands and dry lands, eroding beaches, increasing coastal flooding, and increasing the salinity of estuaries and aquifers, all with human and ecological consequences.

A number of factors affect sea level including but not limited to changes in sea temperature, salinity, and total water volume and mass (e.g. from melting glaciers or changes in the amount of water stored on land). Sea-surface height moves up with warming sea temperatures and down with cooling. In addition, because saltwater takes up more volume than an equivalent mass of freshwater, the freshening of the oceans from melting ice and snow results in small reductions in sea level and volume. Changes in the total volume and mass of ocean water also result from the melting (or accumulation) of Antarctic and Greenland ice sheets, melting of non-polar glaciers, and changes in the amount of water stored in lakes, rivers and groundwater. Observed sea level changes reflect seasonality as well as longer-term variability, such as “El Nino,” and potentially climate change. As such, global average sea level is one indicator of the physical and climatic stability of our environment.

This indicator presents trends in relative sea level along the US coast based on tidal gauge data, and absolute sea level trends derived from satellite data. Relative sea level rise is defined as global (eustatic) sea level rise plus land subsidence (or minus land uplift), whereas absolute sea level represents only the change in sea height. Tidal gauge station measurements and analysis are from the National Water Level Observation Network (NWLON), operated by the Center for Operational Oceanographic Products and Services (CO-OPS), a component of the National Ocean Service (NOS). The NWLON is composed of approximately 175 long-term, continuously operating stations located along the United States coast, including the Great Lakes and islands in the Atlantic and Pacific Oceans (Smith, 1980; Gill and Schultz, 2001). Tidal gauges have been used to monitor sea levels, including tides, for many decades, with the New York and San Francisco stations dating back to 1856 and 1854, respectively (CO-OPS 2001). Satellite data are from NASA’s Ocean TOPography EXperiment (TOPEX/Poseidon spacecraft) which uses radar to map the precise features of the oceans’ surface, and the “Jason” satellite which monitors ocean circulation. The two satellites operate in tandem, using radar altimetry to collect sea surface height data from all the world's oceans. These satellite measurements have been available since 1993 and provide a reference by which changes in regional ocean height can be determined regardless of changes in land height.

What the Data Show

The tidal gauge measurements at stations along the US coasts (Figure 353.1) show that, in many locations, relative sea levels (combined land and sea movement) have been rising, typically at rates of 1.5-3 millimeters (mm) per year (6-12 inches per century). Sea level is rising more rapidly (3-4 mm/yr) along the mid-Atlantic coast from North Carolina to New Jersey. At some locations, rates are much higher, such as at several stations in Louisiana on the Gulf of Mexico, with rates of 5-10 mm per year. At the same time, other locations, such as along the southern coast of Alaska, show rates of relative sea level *drop* of over 16 mm per year. Average relative sea level rise was not calculated because the tidal gauge stations are not spatially representative and therefore such a measure is not meaningful.

Measurement of absolute sea heights is the principal way to understand the relative importance of the location of land (e.g. uplift and subsidence) versus sea level changes. Satellite measurements available since 1993 from NASA's TOPEX/Poseidon and Jason missions allow reliable estimates of global mean change in sea level – independent of land movements - over the past 12 years (Figure 353.2). The amount and direction of change vary greatly but tend to show the greatest increase along the Atlantic coast and the central Pacific, and the greatest decrease along the Pacific coast of the U.S.

The long-term, land-based tidal gauges over the past century indicate a global mean sea level rise of about 1.5-2.0 millimeters per year (mm/yr). In the last 12 years, global mean sea level appears to have risen by more than half to about 3 mm/yr (.12 inches per year). Satellite measurements similarly suggest that GSLR has been about 2.9 mm $yr^{-1} \pm 0.4$ mm/yr^{-1} over the past 12 years (Figure 353.3) (Leuliette et al. 2004).

In sum, this indicator shows that relative sea levels have been rising along much of the U.S.' coasts, although in some locations, relative sea levels are falling. The relative change is caused by rising and falling of land due to geologic and human factors, as well as by global sea level rise which is not evenly distributed around the globe. The relative contributions of these factors depend on the specific location and cannot be generalized for relative sea level change. However, both tidal gauge data and satellite data indicate that global mean sea level has been rising and appear to have accelerated in the past couple of decades.

Indicator Limitations

- An estimated 50 to 60 years of data are required for obtaining linear mean sea level trends having a 1 mm/yr precision with a 95% statistical confidence interval.
- Tidal gauge measurements do not represent more generalized (i.e. average) relative sea level change along US coasts (or globally).
- Tidal gauge measurements do not indicate whether changes in relative sea level are due to changing water level or land level.
- Satellite data are not available for a long enough time series to be able to separate out medium-term variability from long-term change.
- Satellite data are not horizontally precise enough to resolve SLR for small water bodies, such as many estuaries, or for localized interests (such as a particular harbor or beach).

Data Sources

The data sources for this indicator include: the National Water Level Observation Network's tidal gauge monitoring network (http://140.90.121.76/sltrends/sltrends.shtml), and satellite measurements from NASA's Ocean TOPography EXperiment and Jason satellite (http://topex-www.jpl.nasa.gov/science/data.html).

References

Antonov, J.I., S. Levitus, and T.P. Boyer (2002) Steric sea level variations during 1957 – 1994: Importance of salinity, Journal of Geophysical Research, 107(C12), 8013, doi: 10.1029/2001JC000964

Arendt, Anthony A, Keith A. Echelmeyer, William D. Harrison, Craig S. Lingle, Virginia B. Valentine 2002. “Rapid Wastage of Alaska Glaciers and Their Contribution to Rising Sea Level” Science Vol. 297:382-386 19 July 2002

Cabanes, Cecile, Cazenave, A. and LeProvost, C. (2001) “Sea Level Rise During Past 40 Years Determined from Satellite and In Situ Observations” Science 295, 840-842, 2001

Cazenave, A., and R. S. Nerem (2004), “Present-day sea level change: Observations and causes” *Rev. Geophys.*, *42*, RG3001, doi:10.1029/2003RG000139.

Chambers, D.P., J. C. Ries, and T. J. Urban (2003) “Calibration and Verification of Jason-1 Using Global Along-Track Residuals with TOPEX” Marine Geodesy, Special Issue on Jason-1 Calibration/Validation, Part 1, 2003

Dyurgerov, Mark Glacier Mass Balance and Regime: Data of Measurements and Analysis Editors: Mark Meier (INSTAAR), Richard Armstrong (NSIDC), Institute of Arctic and Alpine Research, University of Colorado, Occasional Paper 55, 2002 ISSN 0069-6145 at http://instaar.colorado.edu/other/download/OP55_glaciers.pdf

Dyurgerov, Mark B. and Mark F. Meier (2005) GLACIERS AND THE CHANGING EARTH SYSTEM: A 2004 SNAPSHOT Institute of Arctic and Alpine Research, University of Colorado, Occasional Paper No. 58 available at: http://instaar.colorado.edu/other/download/OP58_dyurgerov_meier.pdf

Gornitz, V. (2001) Impoundment, groundwater mining and other hydrologic transformations in the land judrological cycles on global sea level rise, in Sea Level Rise, History and Consequences, edited by B.C. Douglas, M. S. Kearney, and S. P. Leatherman, pp. 97 – 119, Academic, San Diego CA

Intergovernmental Panel on Climate Change (2001a) Working Group I Technical Summary: Chapter 11: Changes in Sea Level at http://www.grida.no/climate/ipcc_tar/wg1/410.htm#box111

Intergovernmental Panel on Climate Change (2001b) Working Group II Technical Summary: Chapter 6.4 Coastal Systems at http://www.grida.no/climate/ipcc_tar/wg2/292.htm#641

Leuliette, E. W, R. S. Nerem, and G. T. Mitchum (2004) Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Marine Geodesy*, **27**(1-2), 79-94. Up-to-date measurements are available on the internet at: : Leuliette et al. at http://sealevel.colorado.edu/results.html

Meier, Mark F. and Mark B. Dyurgerov**, “**SEA LEVEL CHANGES: How Alaska Affects the World” *Science*, Vol 297, Issue 5580, 350-351 , 19 July 2002

Miller, Laury and Bruce C. Douglas (2004) “Mass and volume contributions to twentieth-century global sea level rise” NATURE Vol. 428:406-409 25 March 2004

Mitchum, G.T., Comparison of TOPEX sea surface heights and tide gauge sea levels, J. Geophys. Res., 99 (C12), 24,541-24,554, 1994.

NASA “Ocean Surface Topography from Space” at http://topex-www.jpl.nasa.gov/science/data.html

NOAA, *Population Trends Along the Coastal United States: 1980-2008*, available at http://www.oceanservice.noaa.gov/programs/mb/supp_cstl_population.html

NOAA CO-OPS, Sea Level Variations of the United States 1854 – 1999, NOAA Technical Report NOS CO-OPS 36, July 2001 available at: http://www.co-ops.nos.noaa.gov/pub.html#sltrends

Vaughan, David G. "How Does the Antarctic Ice Sheet Affect Sea Level Rise?" SCIENCE VOL 308 24 JUNE 2005

Graphics

Figure 353.1
Mean Relative Sea Level Trends along US Coasts from 1950 to 1999
from Tidal Gauge Measurements

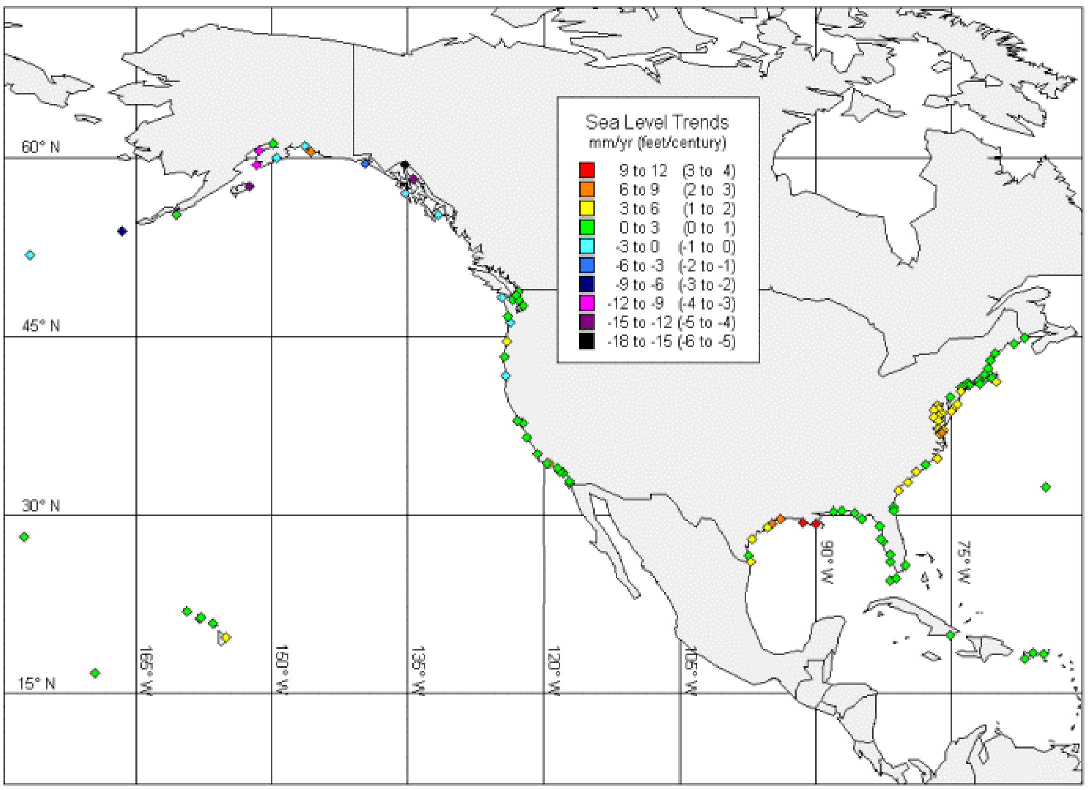


Figure 353.2
Change in Absolute Sea Level Along US Coasts from 1993 – 2005
From Satellite Measurements

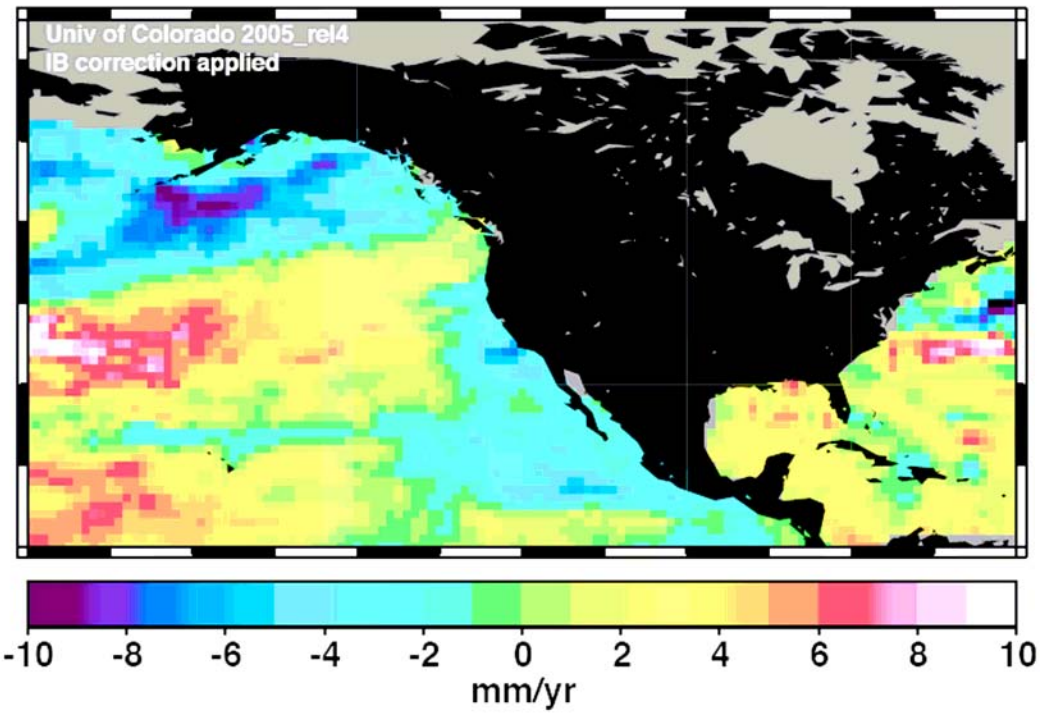
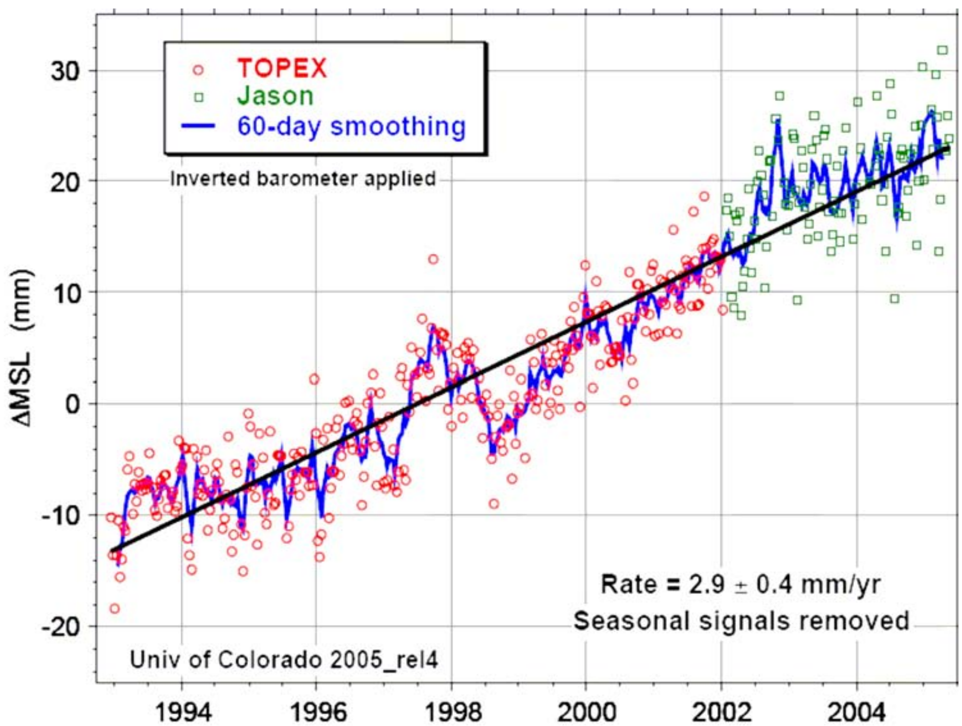


Figure 353.3
GLOBAL MEAN SEA LEVEL RISE FROM SATELLITE DATA
1993-2005



R.O.E. Indicator QA/QC

Data Set Name: SEA LEVEL
Indicator Number: 353 (139048)
Data Set Source:
Data Collection Date:
Data Collection Frequency:
Data Set Description: Sea Level
Primary ROE Question: What are the trends in the critical physical and chemical attributes of the Nation's ecological systems?

Question/Response

T1Q1 Are the physical, chemical, or biological measurements upon which this indicator is based widely accepted as scientifically and technically valid?

Yes, the tidal gauge measurements are fairly accurate, and some, such as the San Francisco station, have been operating for more than a century. As a total measure of the relative change of sea levels to the land surface, the tidal gauges are very reliable. With 50 years of data, precision in determining the mean sea level change can be to the 1 mm/year level with a 95% level of confidence. However, the measurements include both the change in the absolute sea surface height, as well as changes in land levels. Land surfaces move up or down in many locations around the world, both due to natural geologic processes, such as those playing out in this post-glacial period, as well as human activities that in some cases, cause ground to sink (e.g. from the weight of human structures, or extraction of groundwater or oil that supported the surface). Thus, the tidal gauges are reliable as measures of the relative change in levels of sea to adjoining land surface. However, it is not possible to understand what is causing sea level changes and relative contributions with tidal gauge data alone. Satellite measurements of land and sea surface heights (altimetry) began several decades ago. But the launch of the TOPEX/Poseidon mission in 1992, and subsequent analyses, have allowed very precise and reliable measurements of changes in absolute sea heights from 1993 to the present (as in Figure 344-1). Moreover, the satellite altimetry has revealed that global sea levels are not evenly distributed around the globe, but can increase several times more than the mean in some locations (Cazenave and Narem 2004). Factors that lead to change in sea levels include: the astronomical tide, changes in atmospheric pressure, wind, river discharge, 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.

T1Q2 Is the sampling design and/or monitoring plan used to collect the data over time and space based on sound scientific principles?

Over time: yes; Over space: not for the tidal gauge data, which are neither comprehensive nor spatially representative, but yes for satellite data, which are globally comprehensive. The National Water Level Observation Network (NWLON) is operated by the Center for

Operational Oceanographic Products and Services (CO-OPS), a component of the National Ocean Service (NOS). The NWLON is composed of approximately 175 long term, continuously-operating stations located along the United States coast, including the Great Lakes and islands in the Atlantic and Pacific Oceans. Extensive discussion of this network, and of the tidal gauge data analysis can be found in NOAA CO-OPS 2001 in the list of references, and at http://140.90.121.76/publications/techrpt36doc.pdf. Additional sources are available from the CO-OPS web site at: The sampling at tidal gauge stations is representative of changes at each location, but not of broad changes over larger spaces and time. The challenge of using tidal gauge measurements for drawing conclusions about changes in global means has lead to controversy since about 2001, as attention to the lack of representative stations has lead to questioning and reanalysis of the global means. Fortunately, a long enough time series of global satellite altimetry data has become available for providing very accurate and reliable measurements that are representative globally and since 1993. This is not a long enough time period for assessing multi-decadal trends and their causes, making it necessary to continue the tidal gauge measurements for decades more and for calibration and comparison with the satellite data. The two data sets together provide good representativeness, although all uncertainties will not be eliminated regarding the various contributions to changes in particular locations for many years. Longer discussion and history of the debate can be found in Cazenave and Nerem (2004). A summary of the methods for calibrating satellite data is found at: http://www.csr.utexas.edu/gmsl/calibration.html . A more extensive discussion is available in Leuliette, Nerem and Mitchum (2004) for TOPEX/Poseidon data and in Chambers et al. (2003) for Jason data.

T1Q3 Is the conceptual model used to transform these measurements into an indicator widely accepted as a scientifically sound representation of the phenomenon it indicates?

Yes. The challenges of using tidal gauge data, as presented in this indicator, is well described in “Sea Level As an Indicator of Climate and Global Change “ by Bruce B. Parker, available at: http://140.90.121.76/sltrends/mtsparker.html. Further discussion is available at: http://www.co-ops.nos.noaa.gov/pub.html - sltrends. Moreover, the availability for over a decade of precise and reliable satellite measurements complements and enriches the tidal gauge measurement data set. In tandem, the tidal gauge and satellite measurements provide both long-term and spatially sound measures of sea level rise. 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 it (Cabanes et al. 2001). However, further research both with comparisons of satellite data with tidal gauge measurements, and improved estimates of contributions to sea level rise by sources other than thermal expansion – and by Alaska glaciers in particular, have largely resolved the question (Cazenave 2004; Miller et al. 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.

T2Q1 To what extent is the indicator sampling design and monitoring plan appropriate for answering the relevant question in the ROE?

The tidal gauge data are fairly well distributed along US coastlines, covering all 50 States and some Territories (e.g. Puerto Rico). The show clear regional similarities and differences, and provide a useful picture of overall trends and distinctions in relative sea levels. Sea level change is an important indicator of physical changes affecting ecosystem condition of many habitats and population centers in the US, and is also an important indicator itself of impacts of changes in ocean temperatures (which may be partially attributable to climate change). The tidal gauge data are critical, because of their available for over a century in some locations, to understanding long-term variability and change. They are supported by satellite data that are more precise and help to sort out among the potential contributions to changes in relative sea level. The satellite data coming from TOPEX/Poseidon are measurements of global mean sea level variations at 10 day intervals with a precision of 4 mm, more than sufficient to detect the very low frequency (VLF) changes associated with climate change given a sufficiently long time series and accurate monitoring of the instrument calibration. More importantly, TOPEX/Poseidon makes it possible to geographically map the spatial variations of VLF sea level (Nerem et al., 1999; Cabanes et al., 2001), though a better characterization and understanding of these patterns is still sought. It is difficult to detect the geographic "fingerprint" of long-term climate change signals using altimeter data from a single satellite mission such as TOPEX/Poseidon, because the mission length will probably be insufficient to easily differentiate these signals from inter-annual and decadal variations. Therefore, a multi-decadal time series of sea level derived from several altimeter missions will likely be required. As the TOPEX/Poseidon mission generates a longer time series, much better separation of the interannual, decadal, and secular sea level signals will be possible. (from: http://sealevel.jpl.nasa.gov/science/invest-nerem.html)

T2Q2 To what extent does the sampling design represent sensitive populations or ecosystems?

The tidal gauge data are not representative of sensitive populations or ecosystems, but because of their locations tend to represent important human utilities for understanding tidal and coastal changes. However, in tandem with the more recent satellite measurements of TOPEX/Poseidon and Jason, comprehensive measurement of sea level height of all US coastlines are available, and in the future, geodetic and other methods for precisely determining land changes will provide comprehensive information. In combination with the multi-decadal time series of tidal gauge measurements, a robust picture of changes in relative sea levels, its causes and implications will be available.

T2Q3 Are there established reference points, thresholds or ranges of values for this indicator that unambiguously reflect the state of the environment?

There are no unambiguous reference points, thresholds or ranges of value for this indicator, although anomalies are often measured against a recent multi-decadal period designated as a “normal.” However, these “normal” values change as trends evolve, as well as from place to place. In addition, the implications of the indicator may also be determined by the rate of change, which is sensitive to the time period chosen to determine the average or “normal.” Tide gauge data are an important resource, not only for instrument calibration, but also for tying different altimeter missions together, and understanding the sea level variations observed in the relatively short altimetry record in the context of the tide gauge observations of sea level rise over the last century [Mitchum, 1997].

T3Q1 What documentation clearly and completely describes the underlying sampling and analytical procedures used?

The tidal gauge data and their manipulation and analysis to provide the station data for this indicator are available in NOAA CO-OPS (2001), available on the worldwide web at http://www.co-ops.nos.noaa.gov/pub.html - sltrends. The satellite data are available from NASA and from various research institutes that perform calibrations, analyses and other manipulations to make them easier to interpret or use. The NASA website at http://topex-www.jpl.nasa.gov/science/data.html provides links to the various research centers. The 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 at http://podaac.jpl.nasa.gov/cgi-bin/dcatalog/fam_summary.pl?ost+topex and for Jason at http://sealevel.jpl.nasa.gov/science/jason1-quick-look/ . The data set and analysis used specifically for the figure presented with this indicator as contextual detail is described in Leuliette et al. (2004) and at http://sealevel.colorado.edu/documents.html.

T3Q2 Is the complete data set accessible, including metadata, data-dictionaries and embedded definitions or are there confidentiality issues that may limit accessibility to the complete data set?

Yes, the tidal gauge data are available online at: http://www.co-ops.nos.noaa.gov/sltrends/sltrends.shtml The satellite data are available online at: http://sealevel.colorado.edu/results.html

T3Q3 Are the descriptions of the study or survey design clear, complete and sufficient to enable the study or survey to be reproduced?

The tidal gauge data themselves cannot be reproduced, but the analysis and interpretation of them can be from data provided by NOAA. The analysis of satellite data can, and have, been reproduced, which has led to improvements and high level of confidence in the associated measurements of sea level rise. Discussion of this is found in Cazenave (2004) and Miller et al. (2004).]

T3Q4 To what extent are the procedures for quality assurance and quality control of the data documented and accessible?

The tidal gauge data and their manipulation and analysis to provide the station data for this indicator are available in NOAA CO-OPS (2001), available on the worldwide web at http://www.co-ops.nos.noaa.gov/pub.html - sltrends . Various publications available through that website describe the QA/QC procedures for tidal gauge data. The satellite data are available from NASA and from various research institutes that perform calibrations, analyses and other manipulations to make them easier to interpret or use. The NASA website at http://topex-www.jpl.nasa.gov/science/data.html provides links to the various research centers. The 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 at http://podaac.jpl.nasa.gov/cgi-bin/dcatalog/fam_summary.pl?ost+topexand for Jason at http://sealevel.jpl.nasa.gov/science/jason1-quick-look/. The data set and analysis used specifically for the figure presented with this indicator as contextual detail is described in Leuliette et al. (2004) and at http://sealevel.colorado.edu/documents.html.

T4Q1 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)?

Yes, although some of the data interpretations are not without controversy. However, the reproduction and recalculation of analyses, sometimes using alternative methods, has led to increased confidence in the research results.

T4Q2 Are uncertainty measurements or estimates available for the indicator and/or the underlying data set?

Yes. For tidal gauge data, these are available in NOAA CO-OPS (2001) among other sources. For satellite data, uncertainty is provided and discussed in Leuliette et al. (2004).

T4Q3 Do the uncertainty and variability impact the conclusions that can be inferred from the data and the utility of the indicator?

No. The complementarity of the tidal gauge data and the satellite data provide a reliable indicator of sea level rise generally, although with considerable spatial variation. The data sets are providing a much improved picture and understanding of the degree and causes of the variability, which will continue to improve over coming decades. The conclusions that may be drawn regarding sea level rise are robust. However, while confidence has decreased and grown again in assessment of the contributions to sea level rise, complete understanding of sources, variability and trends will continue to evolve for at least several years. A good discussion of these is provided by Cazenave and Nerem (2004).

T4Q4 Are there limitations, or gaps in the data that may mislead a user about fundamental trends in the indicator over space or time period for which data are available?

No biases have been identified for the tidal gauge data in representing relative sea level change at individual sites. However, an estimated 50 to 60 years of data are required for obtaining linear mean sea level trends having a 1 mm/yr precision with a 95% statistical confidence interval. Also, the variability of change among stations and the lack of comprehensive or representative tidal gauges mean that are not distributed well to represent more generalized (i.e. average) relative sea level change along US coasts (or globally) and have limitations in sorting out sea level rise from rising or falling land.

Understanding the causes of relative sea level change is important for addressing adverse consequences of relative sea level change. Considerable controversy arose, for example, in 2001, when Cabanes (2001) published an analysis contending that averaging tidal gauge data provided estimates of global mean sea level rise that were double the “true” increase (Cabanes, 2001). Complementary satellite data are instrumental in providing precise and reliable measures of sea level height, and in the near future, of land level changes. However, they are not available for a long enough time series to be able to separate out medium-term variability from long-term change. As a set, the complementary tidal gauge and satellite measures are strong and reliable.