Ocean Heat

Identification

1. Indicator Description

This indicator describes trends in the amount of heat stored in the world's oceans between 1955 and 2015. The amount of heat in the ocean, or ocean heat content, is an important indicator of climate change because the oceans ultimately absorb a large portion of the extra energy that greenhouse gases trap near the Earth's surface. Ocean heat content also plays an important role in the Earth's climate system because heat from ocean surface waters provides energy for storms and thereby influences weather patterns.

2. Revision History

April 2010:	Indicator published.
December 2012:	Updated indicator with data through 2011.
August 2013:	Updated indicator on EPA's website with data through 2012.
May 2014:	Updated indicator with data through 2013.
June 2015:	Updated indicator on EPA's website with data through 2014.
August 2016:	Updated indicator with data through 2015.

Data Sources

3. Data Sources

This indicator is based on analyses conducted by three different government agencies:

- Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Japan Meteorological Agency's Meteorological Research Institute (MRI/JMA)
- National Oceanic and Atmospheric Administration (NOAA)

MRI/JMA used four different data sets: the World Ocean Database (WOD), the World Ocean Atlas (WOA), the Global Temperature-Salinity Profile Program (GTSPP, which was used to fill gaps in the WOD since 1990), and data from the Japan Maritime Self-Defense Force (JMSDF). CSIRO used two data sets: ocean temperature profiles in the UK Met Office's ENACT/ENSEMBLES version 4 (EN4) database and data collected using 60,000 Argo profiling floats. Additionally, CSIRO included bias-corrected Argo data, as described in Barker et al. (2011), and bias-corrected expendable bathythermograph (XBT) data from Wijffels et al. (2008). NOAA also used data from the WOD and WOA.

4. Data Availability

EPA developed Figure 1 using trend data from three ongoing studies. Data and documentation from these studies can be found at the following links:

- CSIRO: www.cmar.csiro.au/sealevel/thermal_expansion_ocean_heat_timeseries.html. Select "GOHC_recons_version3.1_1950_2012_CLIM_sbca12tmosme_OBS_bcax_0700m.dat" to download data through 2012. See additional documentation in Domingues et al. (2008). Updated data were provided by the author, Catia Domingues.
- MRI/JMA: Data from Ishii and Kimoto (2009) are posted at: www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc_data_en.html. Updated data were provided by the author, Masayoshi Ishii. Data are expected to be updated regularly online in the future. See additional documentation in Ishii and Kimoto (2009).
- NOAA: www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT. Under "Heat Content," select "Basin time series fields." Then, under "Yearly from 1955 to 2015," select the "0 - 700" file under "World." See additional documentation in Levitus et al. (2009).

The underlying data for this indicator come from a variety of sources. Some of these data sets are publicly available, but other data sets consist of samples gathered by the authors of the source papers, and these data might be more difficult to obtain online. WOA and WOD data and descriptions of data are available on NOAA's National Centers for Environmental Information (NCEI) website at: www.nodc.noaa.gov. The EN4 database is available at: www.metoffice.gov.uk/hadobs/en4.

Methodology

5. Data Collection

This indicator reports on the amount of heat stored in the ocean from sea level to a depth of 700 meters, which accounts for approximately 17.5 percent of the total global ocean volume (calculation from Catia Domingues, CSIRO). Each of the three studies used to develop this indicator uses several ocean temperature profile data sets to calculate an ocean heat content trend line.

Several different devices are used to sample temperature profiles in the ocean. Primary methods used to collect data for this indicator include XBT; mechanical bathythermographs (MBT); Argo profiling floats; reversing thermometers; and conductivity, temperature, and depth sensors (CTD). These instruments produce temperature profile measurements of the ocean water column by recording data on temperature and depth. The exact methods used to record temperature and depth vary. For instance, XBTs use a fall rate equation to determine depth, whereas other devices measure depth directly.

Each of the three studies used to develop this indicator relies on different combinations of devices; for example, the CSIRO analysis excludes MBT data. More information on the three main studies and their respective methods can be found at:

- CSIRO: Domingues et al. (2008) and: www.cmar.csiro.au/sealevel/thermal_expansion_ocean_heat_timeseries.html.
- MRI/JMA: Ishii and Kimoto (2009) and: www.data.jma.go.jp/gmd/kaiyou/english/ohc/ohc_data_en.html.
- NOAA: Levitus et al. (2009) and: www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT.

Studies that measure ocean temperature profiles are generally designed using in situ oceanographic observations and analyzed over a defined and spatially uniform grid (Ishii and Kimoto, 2009). For instance, the WOA data set consists of in situ measurements of climatological fields, including temperature, measured in a 1-degree grid. Sampling procedures for WOD and WOA data are provided by NOAA's NCEI at: www.nodc.noaa.gov/OC5/indprod.html. More information on the WOA sample design in particular can be found at: www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html.

At the time of last update, data from all three sources were available through 2015.

6. Indicator Derivation

While details of data analysis are particular to the individual study, in general, temperature profile data were averaged monthly at specific depths within rectangular grid cells. In some cases, interpolation techniques were used to fill gaps where observational spatial coverage was sparse. Additional steps were taken to correct for known biases in XBT data. Finally, temperature observations were used to calculate ocean heat content through various conversions. The model used to convert measurements was consistent across all three studies cited by this indicator.

Barker et al. (2011) describe instrument biases and procedures for correcting for these biases. For more information about interpolation and other analytical steps, see Ishii and Kimoto (2009), Domingues et al. (2008), Levitus et al. (2009), and references therein.

Each study used a different long-term average as a baseline. To allow more consistent comparison, EPA adjusted each curve such that its 1971–2000 average would be set at zero. Choosing a different baseline period would not change the shape of the data over time. Although some of the studies had pre-1955 data, Figure 1 begins at 1955 for consistency. The current CSIRO data series is based on updates to the original data set provided in Domingues et al. (2008) and plotted with a start date of 1960. The updated data set excludes 1955–1959, as the authors (Domingues et al.) have expressed diminished confidence in their data set for this period because there are fewer ocean observations in the early part of the record. The dataset also uses a three-year running mean to smooth the data.

7. Quality Assurance and Quality Control

Data collection and archival steps included QA/QC procedures. For example, QA/QC measures for the WOA are available at: ftp://ftp.nodc.noaa.gov/pub/data.nodc/woa/PUBLICATIONS/qc94tso.pdf. Each of the data collection techniques involves different QA/QC measures. For example, a summary of studies concerning QA/QC of XBT data is available from NCEI at: www.nodc.noaa.gov/OC5/XBT_BIAS/xbt_bibliography.html. The same site also provides additional information about QA/QC of ocean heat data made available by NCEI.

All of the analyses performed for this indicator included additional QA/QC steps at the analytical stage. In each of the three main studies used in this indicator, the authors carefully describe QA/QC methods, or provide the relevant references.

Analysis

8. Comparability Over Time and Space

Analysis of raw data is complicated because data come from a variety of observational methods, and each observational method requires certain corrections to be made. For example, systematic biases in XBT depth measurements have recently been identified. These biases were shown to lead to erroneous estimates of ocean heat content through time. Each of the three main studies used in this indicator corrects for these XBT biases. Correction methods are slightly different among studies and are described in detail in each respective paper. More information on newly identified biases associated with XBT can be found in Barker et al. (2011).

This indicator presents three separate trend lines to compare different estimates of ocean heat content over time. Each estimate is based on analytical methods that have been applied consistently over time and space. General agreement among trend lines, despite some year-to-year variability, indicates a robust trend.

9. Data Limitations

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

1. Data must be carefully reconstructed and filtered for biases because of different data collection techniques and uneven sampling over time and space. Various methods of correcting the data have led to slightly different versions of the ocean heat trend line.

2. In addition to differences among methods, some biases may be inherent in certain methods. The older MBT and XBT technologies have the highest uncertainty associated with measurements.

3. Limitations of data collection over time and especially over space affect the accuracy of observations. In some cases, interpolation procedures were used to complete data sets that were spatially sparse.

10. Sources of Uncertainty

Uncertainty measurements can be made by the organizations responsible for data collection, and they can also be made during subsequent analysis. One example of uncertainty measurements performed by an agency is available for the WOA at: www.nodc.noaa.gov/OC5/indprod.html.

Error estimates associated with each of the curves in Figure 1 are discussed in Domingues et al. (2008), Ishii and Kimoto (2009), and Levitus et al. (2009). All of the data files listed in Section 4 ("Data Availability") include a one-sigma error value for each year.

11. Sources of Variability

Weather patterns, seasonal changes, multiyear climate oscillations, and many other factors could lead to day-to-day and year-to-year variability in ocean temperature measurements at a given location. This

indicator addresses some of these forms of variability by aggregating data over time and space to calculate annual values for global ocean heat content. The overall increase in ocean heat over time (as shown by all three analyses) far exceeds the range of interannual variability in ocean heat estimates.

12. Statistical/Trend Analysis

Domingues et al. (2008), Ishii and Kimoto (2009), and Levitus et al. (2009) have all calculated linear trends and corresponding error values for their respective ocean heat time series. Exact time frames and slopes vary among the three publications, but they all reveal a statistically significant upward trend (i.e., increasing ocean heat over time).

References

Barker, P.M., J.R. Dunn, C.M. Domingues, and S.E. Wijffels. 2011. Pressure sensor drifts in Argo and their impacts. J. Atmos. Oceanic Tech. 28:1036–1049.

Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E. Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090–1093.

Ishii, M., and M. Kimoto. 2009. Reevaluation of historical ocean heat content variations with time-varying XBT and MBT depth bias corrections. J. Oceanogr. 65:287–299.

Levitus, S., J.I. Antonov, T.P. Boyer, R.A. Locarnini, H.E. Garcia, and A.V. Mishonov. 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. Geophys. Res. Lett. 36:L07608.

Wijffels, S.E., J. Willis, C.M. Domingues, P. Barker, N.J. White, A. Gronell, K. Ridgway, and J.A. Church. 2008. Changing expendable bathythermograph fall rates and their impact on estimates of thermosteric sea level rise. *J. Climate* 21:5657–5672.