Climate Forcing

Identification

1. Indicator Description

The warming influence of greenhouse gases in the atmosphere has increased substantially over the last several decades (USGCRP, 2017). This indicator measures the levels of greenhouse gases (GHGs) in the atmosphere based on their ability to cause changes in the Earth's climate. In particular, this indicator is a measure of what human activity has already done to affect the climate system through greenhouse gas emissions. This indicator is highly relevant to climate change because greenhouse gases from human activities are the primary driver of observed climate change since the mid-20th century (IPCC, 2013). There are no alternative explanations to human activity supported by the evidence that are either credible or that can contribute more than marginally to the observed patterns of global warming, including natural variability observed since the industrial era (USGCRP, 2017). Components of this indicator include:

- Radiative forcing associated with long-lived GHGs as measured by the Annual Greenhouse Gas Index from 1979 to 2019 (Figure 1).
- A reference figure showing estimates of total radiative forcing associated with a variety of human activities since the year 1750 (Figure 2).

2. Revision History

April 2010:	Indicator published.
December 2012:	Updated indicator with data through 2011.
May 2014:	Updated Figure 1 with data through 2013. Added Figure 2 to provide longer-term context and cover other climate forcers.
June 2015:	Updated Figure 1 with data through 2014.
August 2016:	Updated Figure 1 with data through 2015.
April 2021:	Updated Figure 1 with data through 2019.

Data Sources

3. Data Sources

GHG concentrations for Figure 1 are measured by a cooperative global network of monitoring stations overseen by the National Oceanic and Atmospheric Administration's (NOAA's) Earth System Research Laboratory (ESRL). The figure uses measurements of 20 GHGs.

Estimates of total radiative forcing in Figure 2 were provided by the Intergovernmental Panel on Climate Change (IPCC) and published in the IPCC's Fifth Assessment Report (IPCC, 2013).

4. Data Availability

Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2019

Figure 1 is based on NOAA's Annual Greenhouse Gas Index (AGGI). Annual values of the AGGI (total and broken out by gas) are posted online at: www.esrl.noaa.gov/gmd/aggi, along with definitions and descriptions of the data. EPA obtained data from NOAA's public website.

The AGGI is based on data from monitoring stations around the world. Most of these data were collected as part of the NOAA/ESRL cooperative monitoring network. Data files from these cooperative stations are available online at: www.esrl.noaa.gov/gmd/dv/ftpdata.html. Users can obtain station metadata by navigating to: www.esrl.noaa.gov/gmd/dv/site, viewing a list of stations, and then selecting a station of interest.

Methane data prior to 1983 are annual averages from Etheridge et al. (1998). Users can download data from an updated version of this study at: ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/antarctica/law/law_ch4.txt.

Figure 2. Radiative Forcing Caused by Human Activities Since 1750

Figure 2 is adapted from a figure in IPCC's Fifth Assessment Report (IPCC, 2013). The original figure is available at: www.climatechange2013.org/report/reports-graphic. Underlying data came from a broad assessment of the best available scientific literature. Specific sources are cited in IPCC (2013).

Methodology

5. Data Collection

Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2019

The AGGI is based on measurements of the concentrations of various long-lived GHGs in ambient air. These measurements have been collected following consistent high-precision techniques that have been documented in peer-reviewed literature.

The indicator uses measurements of five major GHGs and 15 other GHGs. The five major GHGs for this indicator are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and two chlorofluorocarbons, CFC-11 and CFC-12. According to NOAA, these five GHGs account for approximately 96 percent of the increase in direct radiative forcing by long-lived GHGs since 1750. The other 15 gases are CFC-113, carbon tetrachloride (CCl_4), methyl chloroform (CH_3CCl_3), HCFC-22, HCFC-141b, HCFC-142b, HFC-23, HFC-125, HFC-134a, HFC-143a, HFC-152a, sulfur hexafluoride (SF_6), halon-1211, halon-1301, and halon-2402.

Monitoring stations in NOAA's ESRL network collect air samples at approximately 80 global clean air sites, although not all sites monitor for all the gases of interest. Monitoring sites include fixed stations on land as well as measurements at 5-degree latitude intervals along specific ship routes in the oceans. Monitoring stations collect data at least weekly. These weekly measurements can be averaged to arrive at an accurate representation of annual concentrations.

For a map of monitoring sites in the NOAA/ESRL cooperative network, see: www.esrl.noaa.gov/gmd/aggi. For more information about the global monitoring network and a link to an interactive map, see NOAA's website at: www.esrl.noaa.gov/gmd/dv/site.

Figure 2. Radiative Forcing Caused by Human Activities Since 1750

The broader reference figure presents the best available estimates of radiative forcing from 1750 through 2011, based on the IPCC's complete assessment of the scientific literature. Thus, this part of the indicator reflects a large number of studies and monitoring programs.

6. Indicator Derivation

Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2019

From weekly station measurements, NOAA calculated a global average concentration of each gas using a smoothed north-south latitude profile in sine latitude space, which essentially means that the global average accounts for the portion of the Earth's surface area contained within each latitude band. NOAA averaged these weekly global values over the course of the year to determine an annual average concentration of each gas. Pre-1983 methane measurements came from stations outside the NOAA/ESRL network; these data were adjusted to NOAA's calibration scale before being incorporated into the indicator.

Next, NOAA transformed gas concentrations into an index based on radiative forcing. These calculations account for the fact that different gases have different abilities to alter the Earth's energy balance. NOAA determined the total radiative forcing of the GHGs by applying radiative forcing factors that have been scientifically established for each gas based on its global warming potential and its atmospheric lifetime. These values and equations were published in the Intergovernmental Panel on Climate Change's (IPCC's) Third Assessment Report (IPCC, 2001). In order to keep the index as accurate as possible, NOAA's radiative forcing calculations considered only direct forcing, not additional model-dependent feedbacks, such as those due to water vapor and ozone depletion.

NOAA compared present-day concentrations with those circa 1750 (i.e., before the start of the Industrial Revolution), and this indicator shows only the radiative forcing associated with the *increase* in concentrations since 1750. In this regard, the indicator focuses only on the additional radiative forcing that has resulted from human-influenced emissions of GHGs.

Figure 1 shows radiative forcing from the selected GHGs in units of watts per square meter (W/m^2). This forcing value is calculated at the tropopause, which is the boundary between the troposphere and the stratosphere. Thus, the square meter term refers to the surface area of the sphere that contains the Earth and its lower atmosphere (the troposphere). The watts term refers to the rate of energy transfer.

The data provided to EPA by NOAA also describe radiative forcing in terms of the AGGI. This unitless index is formally defined as the ratio of radiative forcing in a given year compared with a base year of 1990, which was chosen because 1990 is the baseline year for the Kyoto Protocol. Thus, 1990 is set to a total AGGI value of 1. An AGGI scale appears on the right side of Figure 1.

NOAA's monitoring network did not provide sufficient data prior to 1979, and no attempt has been made to project the indicator backward before that start date. No attempt has been made to project trends forward into the future, either.

This indicator can be reconstructed from publicly available information. NOAA's website (www.esrl.noaa.gov/gmd/aggi) provides a complete explanation of how to construct the AGGI from the available concentration data, including references to the equations used to determine each gas's contribution to radiative forcing. See Hofmann et al. (2006a) and Hofmann et al. (2006b) for more information about the AGGI and how it was constructed. See Dlugokencky et al. (2005) for information on steps that were taken to adjust pre-1983 methane data to NOAA's calibration scale.

Figure 2. Radiative Forcing Caused by Human Activities Since 1750

EPA used the data in Figure 2 exactly as they were provided by IPCC. EPA modified the original figure text in a few ways to make it easier for readers to understand, such as by explaining that albedo refers to the reflectivity of a surface.

Indicator Development

Figure 1 was published as part of EPA's 2010 and 2012 climate change indicator reports. EPA added Figure 2 for the 2014 edition to address some of the key limitations of the previous version of the indicator, and to reflect the scientific community's growing awareness of the importance of tropospheric ozone and black carbon as contributors to climate change.

7. Quality Assurance and Quality Control

Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2019

The online documentation for the AGGI does not explicitly discuss quality assurance and quality control (QA/QC) procedures. NOAA's analysis has been peer-reviewed and published in the scientific literature, however (see Hofmann et al., 2006a and 2006b), and users should have confidence in the quality of the data.

Figure 2. Radiative Forcing Caused by Human Activities Since 1750

IPCC (2013) describes the careful review that went into selecting sources for the Fifth Assessment Report. The original peer-reviewed studies cited therein provide more details about specific QA/QC protocols.

Analysis

8. Comparability Over Time and Space

Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2019

With the exception of pre-1983 methane measurements, all data were collected through the NOAA/ESRL global monitoring network with consistent techniques over time and space. Pre-1983 methane measurements came from stations outside the NOAA/ESRL network; these data were adjusted to NOAA's calibration scale before being incorporated into the indicator.

The data for this indicator have been spatially averaged to ensure that the final value for each year accounts for all of the original measurements to the appropriate degree. Results are considered to be globally representative, which is an appropriate assumption because the gases covered by this indicator have long residence times in the atmosphere and are considered to be well-mixed. Although there are minor variations among sampling locations, the overwhelming consistency among sampling locations indicates that extrapolation from these locations to the global atmosphere is reliable.

Figure 2. Radiative Forcing Caused by Human Activities Since 1750

When aggregating data for Figure 2, IPCC selected the best available sources of globally representative information. Total radiative forcing has been aggregated over time from 1750 to 2011.

9. Data Limitations

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

1. The AGGI and its underlying analysis do not provide a complete picture of radiative forcing from the major GHGs because they do not consider indirect forcing due to water vapor, ozone depletion, and other factors. These mechanisms have been excluded because quantifying them would require models that would add substantial uncertainty to the indicator.

2. The AGGI also does not include radiative forcing due to shorter-lived GHGs and other radiatively important atmospheric constituents, such as black carbon, aerosols, and sulfates. Reflective aerosol particles in the atmosphere can reduce climate forcing, for example, while tropospheric ozone can increase it. These spatially heterogeneous, short-lived climate forcing agents have uncertain global magnitudes and thus are excluded from NOAA's index to maintain accuracy. These factors have been addressed at a broader scale in Figure 2 for reference.

10. Sources of Uncertainty

Figure 1. Radiative Forcing Caused by Major Long-Lived Greenhouse Gases, 1979–2019

This indicator is based on direct measurements of atmospheric concentrations of GHGs. These measurements are of a known and high quality, collected by a well-established monitoring network. NOAA's AGGI website does not present explicit uncertainty values for either the AGGI or the underlying data, but exact uncertainty estimates can be obtained by contacting NOAA.

The empirical expressions used for radiative forcing are derived from atmospheric radiative transfer models and generally have an uncertainty of about 10 percent. The uncertainties in the global average concentrations of the long-lived GHGs are much smaller, according to the AGGI website documentation at: www.esrl.noaa.gov/gmd/aggi.

Uncertainty is expected to have little bearing on the conclusions for several reasons. First, the indicator is based entirely on measurements that have low uncertainty. Second, the increase in GHG radiative forcing over recent years is far greater than the estimated uncertainty of underlying measurement methodologies, and it is also greater than the estimated 10 percent uncertainty in the radiative forcing equations. Thus, it is highly unlikely that the trends depicted in this indicator are somehow an artifact of uncertainties in the sampling and analytical methods.

Figure 2. Radiative Forcing Caused by Human Activities Since 1750

The colored bars in Figure 2 show IPCC's best central estimates of radiative forcing associated with various human activities, based on the range of values published in the scientific literature. Figure 2 also shows error bars that reflect the likely range of values for each estimate. The original version of IPCC's figure at: www.climatechange2013.org/report/reports-graphic provides the numbers associated with these ranges, and it also classifies the level of scientific understanding for each category as either high, medium, or low. For example, the scientific community's level of understanding of long-lived GHGs is considered to be high to very high, understanding of aerosols such as black carbon is considered high, understanding of short-lived gases is considered medium, and understanding of cloud adjustment due to aerosols is considered low. Overall, IPCC estimates a net radiative forcing associated with human activities of +2.29 W/m^2 since 1750, with a range of +1.13 to +3.33 W/m^2 (IPCC, 2013).

11. Sources of Variability

Collecting data from different locations could lead to some variability, but this variability is expected to have little bearing on the conclusions. Scientists have found general agreement in trends among multiple data sets collected at different locations using different program designs, providing some assurance that the trends depicted actually represent atmospheric conditions, rather than some artifact of sampling design.

12. Statistical/Trend Analysis

The increase in GHG radiative forcing over recent years is far greater than the estimated uncertainty of underlying measurement methodologies, and it is also greater than the estimated 10 percent uncertainty in the radiative forcing equations. Thus, it is highly likely that the trends depicted in this indicator accurately represent changes in the Earth's atmosphere.

References

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