Tropical Cyclone Activity

Identification

1. Indicator Description

This indicator examines the aggregate activity of hurricanes and other tropical storms in the Atlantic Ocean, Caribbean, and Gulf of Mexico between 1878 and 2022. Climate change is expected to affect tropical cyclone activity through increased sea surface temperatures and other environmental changes that are key influences on cyclone formation and behavior.

Components of this indicator include:

- The number of hurricanes in the North Atlantic each year, along with the number making landfall in the United States (Figure 1).
- Frequency, intensity, and duration of North Atlantic cyclones as measured by the Accumulated Cyclone Energy Index (Figure 2).
- Frequency, intensity, and duration of North Atlantic cyclones as measured by the Power Dissipation Index (Figure 3).

2. Revision History

April 2010:	Indicator published.
December 2012:	Added Figure 1 to show North Atlantic hurricane counts. Updated Figures 2 and 3 with data through 2011.
May 2014:	Updated indicator with data through 2013.
December 2015:	Updated indicator with data through 2014.
August 2016:	Updated indicator with data through 2015.
April 2021:	Updated Figures 1 and 2 with data through 2020; updated figure 3 with data through 2019.
June 2024:	Updated indicator with data through 2022.

Data Sources

3. Data Sources

This indicator is based on data maintained by the National Oceanic and Atmospheric Administration's (NOAA's) National Hurricane Center in a database referred to as HURDAT (HURricane DATa). This indicator presents three separate analyses of HURDAT data: a set of hurricane counts compiled by NOAA, NOAA's Accumulated Cyclone Energy (ACE) Index, and the Power Dissipation Index (PDI) developed by Dr. Kerry Emanuel at the Massachusetts Institute of Technology (MIT).

4. Data Availability

Figure 1. Number of Hurricanes in the North Atlantic, 1878–2022

1878–2017 and 2021–2022 data for Figure 1 were obtained from several data sets published by NOAA:

- Total counts are available from NOAA's Atlantic Oceanographic and Meteorological Laboratory (AOML), Hurricane Research Division, at: www.aoml.noaa.gov/hrd/hurdat/comparison_table.html.
- Landfalling counts are available from: www.aoml.noaa.gov/hrd/hurdat/comparison_table.html, with confirmation from: www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html.
- Adjusted counts for years prior to 1966 are based on a historical reanalysis posted by NOAA at: www.gfdl.noaa.gov/wp-content/uploads/files/user_files/gav/historical_storms/vk_11_hurricane_counts.txt (linked from: www.gfdl.noaa.gov/historical-atlantic-hurricane-and-tropical-storm-records).

Due to a delayed NOAA website update, 2018–2020 data were obtained directly from NOAA staff.

Figure 2. North Atlantic Cyclone Intensity According to the Accumulated Cyclone Energy Index, 1950–2022

An overview of the ACE Index is available at: www.cpc.ncep.noaa.gov/products/outlooks/Background.html. The raw data for this indicator through 2017 and from 2021 to 2022 are published on NOAA's Hurricane Research Division website: www.aoml.noaa.gov/hrd/hurdat/comparison_table.html. Due to a delayed website update, 2018–2020 data were obtained directly from NOAA staff.

Figure 3. North Atlantic Cyclone Intensity According to the Power Dissipation Index, 1949–2022

Emanuel (2005, 2007) gives an overview of the PDI, along with figures and tables. This indicator reports on an updated version of the data set (through 2022) that was provided by Dr. Kerry Emanuel, along with associated sea surface temperature data.

Underlying Data

Wind speed measurements and other HURDAT data are available in various formats on NOAA's AOML website: www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html. Since April 2014, NOAA has revised the format of the HURDAT data output, which is now called HURDAT2. Some documentation is available at: www.aoml.noaa.gov/hrd/hurdat/metadata_master.html, and definitions for the HURDAT2 data format are available at: www.aoml.noaa.gov/hrd/hurdat/newhurdat-format.pdf.

Methodology

5. Data Collection

This indicator is based on measurements of tropical cyclones over time. HURDAT compiles information on all hurricanes and other tropical storms occurring in the North Atlantic Ocean, including parameters such as wind speed, barometric pressure, storm tracks, and dates. Field methods for data collection and analysis are documented in official NOAA publications (Jarvinen et al., 1984). This indicator is based on sustained wind speed, which is defined as the one-minute average wind speed at an altitude of 10 meters.

Data collection methods have evolved over time. When data collection began, ships and land observation stations were used to measure and track storms. Analysts compiled all available wind speed observations and all information about the measurement technique to determine the wind speed for the four daily intervals for which the storm track was recorded.

More recently, organized aircraft reconnaissance, the coastal radar network, and weather satellites with visible and infrared sensors have improved accuracy in determining storm track, maximum wind speeds, and other storm parameters, such as central pressure. Weather satellites were first used in the 1960s to detect the initial position of a storm system; reconnaissance aircraft would then fly to the location to collect precise measurements of the wind field, central pressure, and location of the center. Data collection methods have since improved with more sophisticated satellites.

This indicator covers storms occurring in the Atlantic Ocean north of the equator, including the Caribbean Sea and the Gulf of Mexico. In addition to tropical storms, HURDAT2 includes data from storms classified as extratropical and subtropical, although extratropical storms are not counted in this indicator. Subtropical cyclones exhibit some characteristics of a tropical cyclone but also some characteristics of an extratropical storm. Subtropical cyclones are now named in conjunction with the tropical storm naming scheme, and in practice, many subtropical storms eventually turn into tropical storms. HURDAT2 is updated annually by NOAA and data are available from 1878 through 2022.

Sampling and analysis procedures for the HURDAT data are described by Jarvinen et al. (1984) for collection methods up to 1984. Changes to past collection methods are partially described in the supplementary methods from Emanuel (2005). Other data explanations are available at: www.nhc.noaa.gov/data/#hurdat. The mission catalogue of data sets collected by NOAA aircraft is available at: www.aoml.noaa.gov/hrd/data_sub/hurr.html.

6. Indicator Derivation

Figure 1. Number of Hurricanes in the North Atlantic, 1878–2022

This figure displays three time series: the number of hurricanes per year making landfall in the United States, the total number of hurricanes on record for the North Atlantic, and an adjusted total that attempts to account for changes in observing capabilities. All three counts are limited to cyclones in the North Atlantic (i.e., north of the equator) meeting the definition of a hurricane, which requires sustained wind speeds of at least 74 miles per hour.

Landfalling counts reflect the following considerations:

- If a single hurricane made multiple U.S. landfalls, it is only counted once.
- If the hurricane center did not make a U.S. landfall (or substantially weakened before making landfall), but did produce hurricane-force winds over land, it is counted.
- If the hurricane center made landfall in Mexico, but did produce hurricane-force winds over the United States, it is counted.

- If a storm center made a U.S. landfall, but all hurricane-force winds (if any) remained offshore, it is not counted. This criterion excludes one storm in 1888 and another in 1908.

For all years prior to the onset of complete satellite coverage in 1966, total basin-wide counts have been adjusted upward based on historical records of ship track density. In other words, during years when fewer ships were making observations in a given ocean region, hurricanes in that region were more likely to have been missed, or their intensity underestimated to be below hurricane strength, leading to a larger corresponding adjustment to the count for those years. These adjustment methods are cited in Knutson et al. (2010) and described in more detail by Vecchi and Knutson (2008), Landsea et al. (2010), and Vecchi and Knutson (2011).

The overall adjustment process can be described by the simple formula $x + y = z$, where:

- x = raw total (number of hurricanes) from HURDAT
- y = adjustment factor
- z = adjusted total

NOAA provided adjusted totals (z) in 2012, which EPA converted to adjustment factors (y) by subtracting the corresponding raw totals that were available from HURDAT at the time (x). This step was needed because historical raw totals are subject to change as HURDAT is reanalyzed and improved over time. For example, between summer 2012 and spring 2013, raw hurricane counts changed for 11 years in HURDAT. Most of these cases occurred prior to 1940, and almost all involved an increase or decrease of only one storm in a given year. The adjustment factors (y) do not need to change, as they were calculated by comparing post-1965 storms against ship tracks for pre-1966 years, and neither of these variables is changing as a result of ongoing HURDAT revisions. Thus, where HURDAT reanalysis resulted in a new (x), EPA added the previously determined (y), leading to a new (z). This approach was recommended by the NOAA data providers.

All three curves have been smoothed using a five-year unweighted average, as recommended by the data provider. Data are plotted at the center of each window; for example, the five-year smoothed value for 1949 to 1953 is plotted at year 1951. Because of this smoothing procedure and the absence of endpoint padding, no averages can be plotted for the first two years and last two years of the period of record (1878, 1879, 2021, and 2022).

Figure 2. North Atlantic Tropical Cyclone Activity According to the Accumulated Cyclone Energy Index, 1950–2022

This figure uses NOAA's ACE Index to describe the combined frequency, strength, and duration of tropical storms and hurricanes each season. As described by Bell and Chelliah (2006), "the ACE Index is calculated by summing the squares of the estimated 6-hourly maximum sustained wind speed in knots for all periods while the system is either a tropical storm or hurricane." A system is considered a tropical storm if it has a wind speed of at least 39 miles per hour. The ACE Index is preferred over other similar indices such as the Hurricane Destruction Potential (HDP) and the Net Tropical Cyclone Index (NTC) because it takes tropical storms into account and it does not include multiple sampling of some parameters. The ACE Index also includes subtropical cyclones, which are named using the same scheme as tropical cyclones and may eventually turn into tropical cyclones in some cases. The index does not include information on storm size, which is an important component of a storm's damage potential.

Figure 2 of the indicator shows annual values of the ACE, which are determined by summing the individual ACE Index values of all storms during that year. The index itself is measured in units of wind speed squared, but for this indicator, the index has been converted to a numerical scale where 100 equals the median value over a base period from 1951 to 2020. NOAA chose this long baseline period to ensure full representation of the range of activity that can occur. A value of 150 would therefore represent 150 percent of the median, or 50 percent more than normal. NOAA has also established a set of thresholds to categorize each hurricane season as "above normal," "near normal," or "below normal" based on the distribution of observed values during the base period. The "near normal" range extends from 75.4 to 130 percent of the median, with the "above normal" range above 130 percent of the median and the "below normal" range below 75.4 percent. The thresholds have been set so that each of these three categories captures one-third of the observed values from 1951 to 2020.

ACE Index computation methods and seasonal classifications are described by Bell and Chelliah (2006). This information is also available on the NOAA website at: www.cpc.ncep.noaa.gov/products/outlooks/Background.html. Note that the exact thresholds listed at this link differ from the numbers above because the latter accompany the version of the index that has been normalized to 100 for the 70-year median.

Figure 3. North Atlantic Tropical Cyclone Activity According to the Power Dissipation Index, 1949–2022

For additional perspective, this figure presents the PDI. Like the ACE Index, the PDI is also based on storm frequency, wind speed, and duration, but it uses a different calculation method that places more emphasis on storm intensity by using the cube of the wind speed rather than the wind speed squared (as for the ACE). Emanuel (2005, 2007) provides a complete description of how the PDI is calculated. Emanuel (2007) also explains adjustments that were made to correct for biases in the quality of storm observations and wind speed measurements early in the period of record. The PDI data in Figure 3 of this indicator are in units of 10^{11} m^3/s^2, but the actual figure omits this unit and simply alludes to "index values" in order to make the indicator accessible to the broadest possible audience.

The PDI data shown in Figure 3 have been smoothed using a five-year weighted average applied with weights of 1, 3, 4, 3, and 1. This method applies greater weight to values near the center of each five-year window. Data are plotted at the center of each window; for example, the five-year smoothed value for 1949 to 1953 is plotted at year 1951. The data providers recommend against endpoint padding for these particular variables, based on past experience and their expert judgment, so no averages can be plotted for the first two years and last two years of the period of record (1949, 1950, 2021, and 2022).

The PDI includes all storms that are in the so-called "best track" data set issued by NOAA, which can include subtropical storms. Weak storms contribute very little to power dissipation, however, so subtropical storms typically have little impact on the final metric.

Emanuel (2005, 2007) describes methods for calculating the PDI and deriving the underlying power dissipation formulas. Analysis techniques, data sources, and corrections to raw data used to compute the PDI are described in the supplementary methods for Emanuel (2005), with further corrections addressed in Emanuel (2007).

Sea surface temperature has been plotted for reference, based on methods described in Emanuel (2005, 2007). The curve in Figure 3 represents average sea surface temperature in the area of storm genesis in the North Atlantic: specifically, a box bounded in latitude by 6°N and 18°N, and in longitude by 20°W and 60°W. Values have been smoothed over five-year periods. For the sake of straightforward presentation, the sea surface temperature time series has been scaled to position the curve to show the relationship between sea surface temperature and the PDI.

7. Quality Assurance and Quality Control

Jarvinen et al. (1984) describe quality assurance/quality control procedures for each of the variables in the HURDAT data set. Corrections to early HURDAT data are made on an ongoing basis through the HURDAT re-analysis project to correct for both systematic and random errors identified in the data set. Information on this re-analysis is available at on the NOAA website at: www.aoml.noaa.gov/hrd/data_sub/re_anal.html. Emanuel (2005) provides a supplementary methods document that describes both the evolution of more accurate sample collection technology and further corrections made to the data.

Analysis

8. Comparability Over Time and Space

In the early years of the data set, there is a high likelihood that some tropical storms went undetected, as observations of storms were made only by ships at sea and land-based stations. Storm detection improved over time as ship track density increased, and, beginning in 1944, with the use of organized aircraft reconnaissance (Jarvinen et al., 1984). It was not until the late 1960s, however, when satellite coverage was generally available, that the Atlantic tropical cyclone frequency record could be assumed to be relatively complete. Because of the greater uncertainties inherent in earlier data, Figure 1 adjusts pre-1966 data to account for the density of ship observations, while Figures 2 and 3 exclude data prior to 1950 and 1949, respectively. If the best available science warrants, NOAA occasionally re-analyzes historical HURDAT data (www.aoml.noaa.gov/hrd/data_sub/re_anal.html) to adjust for both random and systematic error present in data from the beginning of the time series. Most of these changes affect data prior to 1950, but NOAA has also revised more recent ACE Index values slightly.

Emanuel (2005) describes the evolution of more accurate sample collection technology and various corrections made to the data. For the PDI, Emanuel (2007) employed an additional bias correction process for the early part of the period of record (the 1950s and 1960s), when aircraft reconnaissance and radar technology were less robust than they are today—possibly resulting in missed storms or underestimated power. These additional corrections were prompted in part by an analysis published by Landsea (1993).

9. Data Limitations

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

1. Methods of detecting hurricanes have improved over time, and raw counts prior to the 1960s may undercount the total number of hurricanes that formed each year. Figure 1, however, presents an adjusted time series to attempt to address this limitation.

2. Wind speeds are measured using several observation methods with varying levels of uncertainty, and these methods have improved over time. The wind speeds recorded in HURDAT should be considered the best estimate of several wind speed observations compiled by analysts.

3. Many different indices have been developed to analyze storm duration, intensity, and threat. Each index has strengths and weaknesses associated with its ability to describe these parameters. The indices used in this indicator (hurricane counts, ACE Index, and PDI) are considered to be among the most reliable.

10. Sources of Uncertainty

Counts of landfalling U.S. hurricanes are considered reliable back to the late 1800s, as population centers and recordkeeping were present all along the Gulf and Atlantic coasts at the time. Total hurricane counts for the North Atlantic became fairly reliable after aircraft reconnaissance began in 1944, and became highly reliable after the onset of satellite tracking around 1966. Prior to the use of these two methods, however, detection of non-landfalling storms depended on observations from ships, which could lead to undercounting due to low density of ship coverage. Figure 1 shows how pre-1966 counts have been adjusted upward based on the density of ship tracks (Vecchi & Knutson, 2011).

The ACE Index and the PDI are calculated directly from wind speed measurements. Thus, the main source of possible uncertainty in the indicator is within the underlying HURDAT data set. Because the determination of storm track and wind speed requires some expert judgment by analysts, some uncertainty is likely. Methodological improvements suggest that recent data may be somewhat more accurate than earlier measurements. Landsea and Franklin (2013) have estimated the average uncertainty for measurements of intensity, central pressure, position, and size of Atlantic hurricanes in recent years. They also compare present-day uncertainty with uncertainty estimates from the 1990s. Uncertainty estimates for older HURDAT data are not readily available.

Because uncertainty varies depending on observation method, and these methods have evolved over time, it is difficult to make a definitive statement about the impact of uncertainty on Figures 2 and 3. Changes in data gathering technologies could substantially influence the overall patterns in Figures 2 and 3, and the effects of these changes on data consistency over the life of the indicator would benefit from additional research.

11. Sources of Variability

Intensity varies by storm and location. The indicator addresses this type of variability by using two indices that aggregate all North Atlantic storms within a given year. Aggregate annual intensity also varies from year to year as a result of normal variation in weather patterns, multi-year climate cycles, and other factors. Annual storm counts can vary from year to year for similar reasons. Figure 2 shows interannual variability. Figures 1 and 3 also show variability over time, but they seek to focus on longer-term variability and trends by presenting a five-year smoothed curve.

Overall, it remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, and so on) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities (Knutson et al., 2010).

12. Statistical/Trend Analysis

This indicator does not report on the slope of the apparent trends in hurricane counts or cyclone intensity, nor does it calculate the statistical significance of these trends. See Vecchi and Knutson (2008, 2011) for examples of such a trend analysis, including statistical significance tests.

References

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