An energetic perspective on United States tropical cyclone landfall droughts

Ryan E. Truchelut[1] and Erica M. Staehling[1]

[1] Research and Development Division, WeatherTiger, LLC, Tallahassee, FL 32302, USA.

Corresponding author: Ryan E. Truchelut (ryan@weathertiger.com)

Key Points:

- The major hurricane landfall drought from October 2005 to August 2017 recently ended with the landfalls of Hurricanes Harvey and Irma. (136)
- Tabulating Accumulated Cyclone Energy over the U.S. landmass quantifies the aggregate annual severity of tropical cyclone impacts. (132)
- A continuous landfall activity dataset shows net U.S. landfall energy during the drought was lower than average, but had recent precedent. (140)

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2017GL076071

Abstract

The extremely active 2017 Atlantic hurricane season concluded an extended period of quiescent continental United States tropical cyclone landfall activity that began in 2006, commonly referred to as the landfall drought. We introduce an extended climatology of U.S. tropical cyclone activity based on Accumulated Cyclone Energy (ACE), and use this dataset to investigate variability and trends in landfall activity. The drought years between 2006 and 2016 recorded an average value of total annual ACE over the U.S. that was less than 60% of the 1900-2017 average. Scaling this landfall activity metric by basin-wide activity reveals a statistically significant downward trend since 1950, with the percentage of total Atlantic ACE expended over the continental U.S. at a series minimum during the recent drought period.

1 Introduction

Tropical cyclones (TCs) are the foremost natural hazard to the continental United States (U.S.). Over the past three decades, TC impacts in the U.S. have tallied economic damages exceeding $500 billion (Aon Benfield, 2014), in addition to intangible impacts to coastal citizens and communities. However, the previous eleven hurricane seasons (2006-2016) leading up to a hyperactive 2017 have been notably inactive in terms of TC landfalls in the continental U.S., even as these years tallied near-normal overall TC activity and destructive impacts in other portions of the Atlantic Basin (Hall & Hereid, 2015). Remarkably, the landfall of Hurricane Harvey near Rockport, Texas on 26 August 2017 ended a span of nearly twelve years between U.S. landfalls of Category 3 or higher hurricanes on the Saffir-Simpson hurricane wind scale (SSHWS; Simpson, 1974), the longest such interval since the 19th Century. Hurricane Irma's landfall just over two weeks later was only the second hurricane landfall in Florida since 2005.

The emergence of the U.S. landfall drought was noted by researchers as it unfolded, with two primary studies quantifying its rarity. Using a statistical-stochastic model based on observed U.S. landfall data over the period 1950 to 2012, Hall and Hereid (2015) estimate that an eleven-season U.S. major hurricane drought (e.g., from 2006 to 2016) has a return period on the order of 300 years, arguing that although unusual, the drought was likely a matter of random variability. Hart et al. (2016) interrogated the dependence of the U.S. landfall drought on the arbitrary choice of 96 kt or greater as the threshold defining a "major hurricane," and found that the length of landfall drought is highly sensitive to selection criteria. Those authors showed the drought would be much less unusual in the historical record if the wind threshold changed by as little as five knots, or if the intensity metric was based on a minimum central pressure criterion.

These studies provide context on the historical rarity of the recent landfall drought, and are distinguished in the TC literature in that they focus directly on landfalling hurricanes rather than overall activity. This is notable, as most studies of the causes and nature of interannual variability in Atlantic TCs have focused on explaining variance in terms of overall activity, even though the relationship between overall activity and U.S. landfall count is surprisingly weak (Staehling & Truchelut, 2016). However, there are inherent limitations to relying on counting discrete events. Saunders and Lea (2005) argue for the utility of an Accumulated Cyclone Energy index (ACE) to address these limitations, which we adopt here.

In the wake of the definitive end to the recent hurricane landfall drought, in section 2, we reaffirm the findings of prior discrete studies of the drought from before its conclusion. In section 3, we describe our methods for building a temporally and spatially rich U.S. landfall ACE index, which we then use in section 4 to provide insight into temporal and spatial trends of U.S. landfall activity. Finally, we conclude in section 5 with implications for future studies of landfall variability and risk assessment.

2 Quantification of Landfall Drought Lengths using Discrete Methods

Twin continental U.S. landfalls of 115 kt hurricanes in 2017 ended the hurricane landfall drought that has been the subject of media attention and scientific study (Hall & Hereid, 2015; Hart et al., 2016), so we calculated updated drought lengths and frequencies to include Hurricanes Harvey and Irma using HURDAT2 (Landsea & Franklin, 2013) and preliminary best track data. In terms of discrete landfall events, we found that the rarity of the just-concluded drought is markedly sensitive to arbitrary threshold selection, as suggested by Hart et al. (2016).

Figure 1 is a plot of the number of calendar days between historical U.S. landfalls of various intensities at increments of 5 kt, between 85 kt (SSHWS minimal category 2) and 120 knots (SSHWS category 4). Landfall is here defined as the center of a TC passing directly over the continental U.S. coastline. Only the recent U.S. landfall droughts of hurricanes with 90, 95, and 100 kt or greater wind speeds are the longest in the historical records since 1900. The recent drought length appears uniquely impressive for the 100 kt threshold (Figure 1d), which corresponds to the minimum intensity of a category 3 (major) hurricane in the SSHWS. The time elapsed between the U.S. landfalls of Hurricanes Wilma and Harvey, 4,324 days, is almost double the length of the next-longest gap in major hurricane landfalls.

However, the gaps for other intensities are far less remarkable. For 85 kt or higher landfalls, Harvey ended an interval of 1,148 days beginning with Hurricane Arthur on 4 July 2014 which was only the seventh-longest on record. Figures 1e, 1f, and 1g show the recent gaps for 105, 110, and 115 kt U.S. landfalls were each the second-longest on record, and considerably shorter for category 4 or greater hurricanes than a September 1900 to August 1915 gap. For 120 kt or greater hurricane landfalls, the gap since Hurricane Charley in August 2004 continues at the time of this writing, but is not of an unusual length. Interestingly, the 16-day gap between the U.S. landfalls of Harvey and Irma is the shortest on record since 1900 for 115 kt or greater hurricanes.

3 Continuous Landfall Activity Dataset Construction

We drew from existing datasets and methodologies to create a continuous dataset of landfall activity over the continental U.S. for analysis of variability and trends. Below we describe the choices and limitations of the datasets we used to determine the position and intensity at landfall for storms from 1900 through 2017, and our methodology for calculating ACE and landfall ACE.

The study of TC variability is fraught with limitations, since return periods for extreme events are not trivial in comparison to the length of the reliable historical record, and even the most reliable contemporary datasets are under continual revision. To determine historical storm positions and intensities for 1900-2016, we used the most recent iteration available at the time of writing (11 April 2017) of the National Hurricane Center's HURDAT2 dataset (Jarvinen et al., 1984; Landsea & Franklin, 2013). While the dataset likely misses some pre-satellite era open ocean TCs (Vecchi & Knutson, 2011; Truchelut et al., 2013), the dataset is considered complete for landfalling TCs beginning in 1900 for the continental U.S. (Landsea et al., 1999). Although weaker open ocean TCs may be absent from the historical record prior to 1966, reconnaissance aircraft coverage in the 1950s aided in capturing stronger open-ocean TCs (Landsea, 2007). Since we utilize metrics weighted by intensity rather than simple event counts, when we consider activity in the entire Atlantic Basin, we begin with the 1950 hurricane season. The extratropical cyclone stage is discarded for the purpose of this analysis.

HURDAT2 reports six-hourly position and intensity data, with additional data entries at estimated times of landfall for storms occurring prior to 1961, which have been subjected to thorough revision, and after 1982. To handle the relative dearth of reliable landfall data entries between 1961 and 1982, we consulted the Atlantic Oceanographic and Meteorological Laboratory (2017) hurricane landfall list to identify systems that officially made landfall. We then used existing track maps to qualitatively estimate a landfall position and intensity data point to the nearest hour, which we manually added to the extant six-hourly data from HURDAT2. This data was then linearly interpolated to hourly temporal resolution. As HURDAT2 final best tracks are not yet available for the 2017 hurricane season, all six-hourly position and intensity data for 2017 TCs were obtained from the National Hurricane Center's preliminary best track files, as accessed on 15 November 2017. These data are provisional and subject to post-season revision.

We used our hourly interpolated dataset to calculate ACE (Waple et al., 2001), defined as

$$ACE_h = v^2/60000, \quad [1]$$

where v is the maximum sustained wind in knots, and the normalization factor in the denominator is chosen such that a 100 kt hurricane yields around 1 ACE unit each six hours, while a minimal 35 kt tropical storm produces around an eighth of an ACE unit in that time. In aggregate, Atlantic TCs produce approximately 100 ACE units annually.

Since ACE does not incorporate any information regarding the size of the system, it is an imperfect metric for capturing the actual kinetic energy of a TC windfield. Unfortunately, historical detailed wind radii data are only available in HURDAT2 beginning in 2004, and the most comprehensive study of track-integrated kinetic energy (Misra et al., 2011) begins with the 1990 hurricane season. Either starting point provides too short of a period of study to properly contextualize the recent drought. While limited by the availability of historical observations, ACE is a more meaningful way to capture the cumulative societal impact of TCs than simple counting, as it avoids the influence of arbitrary thresholds, more heavily weights storms that remain destructive for long periods of time after moving inland, and captures near-miss TCs that still had significant impacts on U.S. despite the center of circulation not directly crossing the coastline.

To yield an annual timeseries of "landfall ACE," we applied a spatial land mask to this hourly ACE metric, to isolate all TC positions over or within 0.5° of the continental U.S. We selected the half-degree buffer to correspond to the typical radius of maximum winds of a mature TC and to account for possible small observation errors, particularly early in the record (Torn & Snyder, 2012). To determine Integrated Storm Activity Annually over the Continental U.S. (ISAAC) from 1900 through 2017, we summed this landfall ACE spatially over the entire continental U.S. and temporally over each hour of each hurricane season. We used the same methodology to calculate integrated annual landfall ACE for five additional geographic subsets of the continental U.S.

4 Results and Discussion

Using our dataset of landfall ACE, we examined temporal and spatial patterns in storm activity over the continental U.S., the percent of total ACE occurring over the entire U.S., and the percent of total ACE occurring in five U.S. sub-regions.

Figure 2 shows landfall ACE metrics, summed spatially for the entire U.S. to produce a timeseries of ISAAC in Figure 2a and summed temporally over 1900-2017 to produce a spatial map in Figure 2b. Along with ISAAC, Figure 2a also includes a 10-year centered average. In this period, ISAAC averaged 4.9 ACE units, ranging from less than 0.1 unit in 1922 to nearly 17.9 units in 1935, with a median value of 4.0 ACE units. The 2017 hurricane season recorded a provisional ISAAC value of just over 10 ACE units, or around the 90th percentile for 1900-2017. The spatial map of ACE over land totaled between 1900 and 2017 at right shows that the highest values are found near Cape Florida in the southern Florida peninsula, where approximately 16 ACE units have occurred within 0.5° of several 0.125° resolution gridpoints. While the highest ACE values are found along the Gulf and Southeast U.S. coasts, non-zero ACE extends well inland, particularly into the southern U.S.

Framing historical activity in terms of ISAAC shows net TC activity over the continental U.S. has recently been at a relative low in historical terms. The mean ISAAC is around 2.75 units for 2006-2015, which jumps to 3.8 ACE units over 2008-2017. Despite the presence of a top 10 ISAAC season in 2008, ISAAC over 2006-2015 was below 60% of the long-term mean, or just around 35% of the series maximum value of nearly 8 units, on average, recorded over 1941-1950.

Other relatively recent periods did record similarly low, or lower, values of decadal mean ISAAC. The minimum 10-year average of the series is 2.33 units for 1972-1981, and most recently fell below 2.75 prior to the recent drought from 1986-1995. Overall, seven decadal averages of ISAAC over roughly the last century were below the 2006-2015 relative minimum. These were all within the last four decades, which means it is unlikely other such droughts were artifacts of an observational bias towards missed or unrepresentatively weak landfalls early in the record. In this measure of energetic terms, Figure 2a shows the recent landfall drought is unusual, but not climatologically unprecedented even in recent TC history.

This energetic perspective on U.S. landfalls incorporates richer climatological information than counting TC landfalls above an arbitrary intensity threshold, and also enables us to easily consider aggregate landfall activity relative to observed variance in basin-wide activity. Calculating proportional ISAAC as a percentage of the total ACE partially controls for known sources of interdecadal variability in Atlantic TC activity. For instance, the relatively inactive cool phase of the Atlantic Multi-Decadal Oscillation observed between 1970 and 1994 (Kerr, 2000) corresponds to a period of notably lower ISAAC in Figure 2a. Since 1970-1994 was a period of low activity in the Atlantic, it makes sense that there might be proportionally less activity over land. In contrast, there is a much less noticeable signature over the same timeframe in Figure 3a, which shows ISAAC normalized by basin-wide ACE.

Figure 3a plots the percentage of each Atlantic hurricane season's observed basin-wide ACE that occurred over or within a 0.5° buffer of the continental U.S. for 1950-2017. Figure 3b plots annual ISAAC versus annual total ACE, expressed as percentages of their respective period means, with the distance above (below) the identity line denoting the overperformance (underperformance) of U.S. TC activity within an individual hurricane season. The Spearman's rank correlation coefficient between ISAAC and total ACE is $r = 0.56$, meaning about 30% of variance in U.S. TC activity is explained by basin-wide activity. This estimate is in-line with Staehling & Truchelut (2016).

ISAAC accounts for 4.3% of annual total Atlantic ACE since 1950, with a seasonal median value of 3.4%. The maximum value of 18.5% occurred in 1985, in which there were six U.S. hurricane landfalls despite near-normal basin-wide total ACE. Minimum values of lower than 0.5% occurred in several years in the timeseries. In 2017, around 4.5% of total Atlantic TC activity occurred over the continental U.S., almost exactly in-line with the long-term mean percentage.

Figure 3a shows that the 2006-2015 average is the lowest on record, with just under 3% of the total ACE in the period occurring over the continental U.S. This absolute minimum in ISAAC relative to basin-wide ACE was driven by several busy hurricane seasons with little U.S. landfall activity, including 2010. Figure 3b shows that while overall ACE was 160% of normal in 2010, ISAAC was less than 20% of normal, which is the single greatest seasonal landfall underperformance since the beginning of the timeseries in 1950. While 2010 was exceptionally quiet given the overall level of observed TC activity, with the exception of the

2008 hurricane season, all eleven years between 2006 and 2016 underperformed in mean-normalized ISAAC relative to basin-wide ACE. There are only three other values of normalized ISAAC that are less than 3%, all centered on the early 2010s, during the recent landfall drought.

A portion of this underperformance may be endemic to active hurricane seasons generally, as past studies have put forth evidence of an inherent trade-off between environmental conditions favorable for TC development and those likely to direct TC activity towards the continental U.S. (Staehling & Truchelut, 2016; Kossin, 2017). Figure 3b offers observational support for this idea, as of the 29 hurricane seasons since 1950 for which overall ACE fell above the 1950-2017 mean, only 9, or just 31% overperformed in terms of ISAAC. This is in contrast with below-average ACE seasons, in which more than 50% of years overperformed in terms of mean-normalized ISAAC. Years like 1950, 2005, and 2017, in which TC activity is both well above average Atlantic-wide and over the continental U.S., are rare and exceptional.

Interestingly, while there is no trend in the decadal mean ISAAC timeseries, there is a downtrend in ISAAC as a percentage of total ACE that is statistically significant at a 99% confidence level by Spearman's rank correlation (*r* = -0.53). This apparent trend should be interpreted with caution, as it is based on only 68 years of data, and the climate modes that influence the interdecadal variability of Atlantic TC activity oscillate on the order of 50-70 years. Additionally, basin-wide ACE values in the dataset prior to the mid-1970s are likely lower than reality due to changes in observational technology and analysis techniques (Hagen & Landsea, 2012), which is likely to contribute to the downward trend of proportional ISAAC in Figure 3a. Overall, while the recent drought has precedent in terms of the level of TC activity over the U.S., the proportion of ACE occurring over the U.S. relative to basin-wide totals from 2006-2016 was unprecedentedly low.

Finally, examining regional trends, Figure 4 shows the percentage of annual Atlantic ACE occurring over five regions of the continental U.S.: the western Gulf, eastern Gulf, eastern Florida and the Florida Keys, Southeast U.S., and mid-Atlantic and Northeast U.S. These zones, respectively, comprise 34%, 24%, 18%, 17%, and 6% of total ISAAC. Overall, there is a statistically significant downward trend in the decadal mean for three out of these five regions since 1950, with only the eastern Gulf (*r* = 0.03) and eastern Florida (*r* = -0.20) showing no statistically significant trend in the percentage of basin-wide ACE. The Spearman's rank correlation coefficients are -0.41, -0.43, and -0.38 for the western Gulf, Southeast, and mid-Atlantic and Northeast, respectively, all statistically significant at a 99% confidence threshold. While these trends over U.S. sub-regions are inherently noisy, the signal of decreasing proportions of landfall ACE is consistent, and the recent landfall drought period is at or near series lows in most areas.

5 Conclusion and Implications

When counting time elapsed between discrete landfall events, we found that the rarity of the just-concluded hurricane landfall drought is sensitive to arbitrary threshold selection, with the 100 kt wind speed threshold (i.e., major hurricane) drought length being remarkable, in that it is the longest on record since the 19^{th} century, and anomalously pronounced compared to other wind speed threshold drought lengths. To avoid the influence of arbitrary thresholds, we developed a dataset of climatological Accumulated Cyclone Energy (ACE) over the U.S. continent. This landfall ACE includes all TC activity over or near land, but major hurricanes contribute strongly to the total. We found that this landfall ACE was unusually, but not unprecedentedly, low during the major hurricane drought from 2006 to 2016. However, normalizing landfall ACE by basin-wide Atlantic ACE, the recent landfall drought did have an unprecedentedly low average since the beginning of reliable TC records in 1950. Our findings shed light on a variety of conceptual interpretations advanced while the drought was still ongoing (Hall & Hereid, 2015; Klotzbach, 2015; Hart et al., 2016; Kossin, 2017).

In particular, these results support the central premise first advanced by Staehling and Truchelut (2016) and later expanded upon by Kossin (2017), that there is an inherent tension between conditions most likely to direct hurricanes toward the U.S. and the environmental conditions most favorable for TC development. Kossin (2017) identifies an increased tendency for enhanced vertical wind shear near the continental U.S. in the warm state of the Atlantic Meridional Mode as a potential contributor to diminished landfall efficiency in active seasons, and Klotzbach (2015) noted a propensity for anomalous deep-layer troughing over the eastern U.S. in the drought years. We conclude that a combination of stochastic variability (Hall & Hereid, 2015), luck (Hart et al., 2016), and the inherent physical tradeoff between ACE over the U.S. and basin-wide activity (Staehling & Truchelut, 2016; Kossin, 2017) is the most likely explanation for the recent observed drought.

Ultimately, the 2017 hurricane season is a stark reminder that understanding interannual variability in TC hazard risk is of utmost importance to scientists, policymakers, emergency managers, insurers, and coastal citizens. The use of energetic metrics is a step toward better acuity in diagnostic and predictive modeling of this risk variance; for instance, in years during which three hurricanes made U.S. landfall, the number of ACE units over the continental U.S. ranged from fewer than 4 to more than 14. As a means of more fully incorporating the reliable climatological record into this and future studies, landfall ACE is promising for properly contextualizing the rarity of events like the recent landfall drought.

Acknowledgments and Data

HURDAT2 data is publicly available from NOAA's National Hurricane Center at http://www.nhc.noaa.gov/data/#hurdat. The preliminary Best Track files used for provisional 2017 TC track and intensity data can be found at ftp://ftp.nhc.noaa.gov/atcf/btk/. We thank C. Landsea and one anonymous reviewer for their thoughtful and constructive reviews of this manuscript.

References

Aon Benfield Impact Forecasting Group (2014), Annual Global Climate and Catastrophe Report: Impact Forecasting—2013, Aon Benfield, London, U.K.

Atlantic Oceanographic and Meteorological Laboratory (2017), Continental United States Hurricane Impacts/Landfalls (1851-2016), Hurricane Research Division, AOML, Miami, Florida, http://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html.

Hagen, A. B., and C. W. Landsea (2012), On the classification of extreme Atlantic hurricanes utilizing mid-Twentieth Century monitoring capabilities. J. Clim., 25, 4461-4475.

Hall, T., and K. Hereid, (2015), The frequency and duration of U.S. hurricane droughts. Geophys. Res. Lett., 42, 3482–3485.

Hart, R. E., D. R. Chavas, and M. P. Guishard (2016), The arbitrary definition of the current Atlantic major hurricane landfall drought. Bull. Amer. Met. Soc., 97, 713-722.

Jarvinen, B. R., J. Neumann, and M. A. Davis (1984), A tropical cyclone data tape for the North Atlantic basin, 1886–1983, contents, limitations, and uses, NOAA Tech. Memo. NWS NHC 22.

Kerr, R. A. (2000), A North Atlantic climate pacemaker for the centuries, Science 288, 1984-1985.

Klotzbach, P., W. Gray, and C. Fogarty (2015), Active Atlantic hurricane era at its end? Nature 438 Geoscience, 8 (10), 737–738.

Kossin, J.P. (2017), Hurricane intensification along United States coast suppressed during active hurricane periods, Nature, 541, 390-393.

Landsea, C. W. (2007), Counting Atlantic tropical cyclones back to 1900. Eos, Trans. Amer. Geophys. Union, 88, 197–202.

Landsea, C. W., R. A. Pielke, A. M. Mestas-Nuñez, and J. A. Knaff (1999), Atlantic basin hurricanes: indices of climatic changes, Clim. Change, 42, 89-129.

Landsea, C. W., and J. L. Franklin (2013), Atlantic hurricane database uncertainty and presentation of a new database format. Mon. Wea. Rev., 141, 3576–3592.

Misra, V., S. DiNapoli, and M. Powell (2013), The track integrated kinetic energy of Atlantic tropical cyclones. Mon. Wea. Rev., 141, 2383–2389, doi:10.1175/MWR-D-12-00349.1.

Saunders, M. A. and A. S. Lea (2005), Seasonal prediction of hurricane activity reaching the coast of the United States, Nature, 434, 1005-1008.

Simpson, R. H. (1974), The hurricane disaster–potential scale. Weatherwise, 27, 169–186, doi:10.1080/00431672.1974.9931702.

Staehling, E. M., and R. E. Truchelut (2016), Diagnosing United States hurricane landfall risk: An alternative to count-based methodologies, Geophys. Res. Lett., 43, doi:10.1002/2016GL070117.

Torn, R. D., and C. Snyder (2012), Uncertainty of tropical cyclone best-track information. Wea. Forecasting, 27, 715–729, doi:10.1175/WAF-D-11-00085.1.

Truchelut, R. E., R. E. Hart, and B. Luthman (2013), Global Identification of Previously Undetected Pre-Satellite-Era Tropical Cyclone Candidates in NOAA/CIRES Twentieth-Century Reanalysis Data, J. of Appl. Meteorol. Climatol., 52(10), 2243-2259.

Vecchi, G. A. and T. R. Knutson (2011), Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878-1965) using ship track density, J. Clim. 24, 1736-1746.

Waple, A. M. (2001) and Co-authors (2001), Climate assessment for 2001, Bull. Amer. Met. Soc., 83, S1-62.

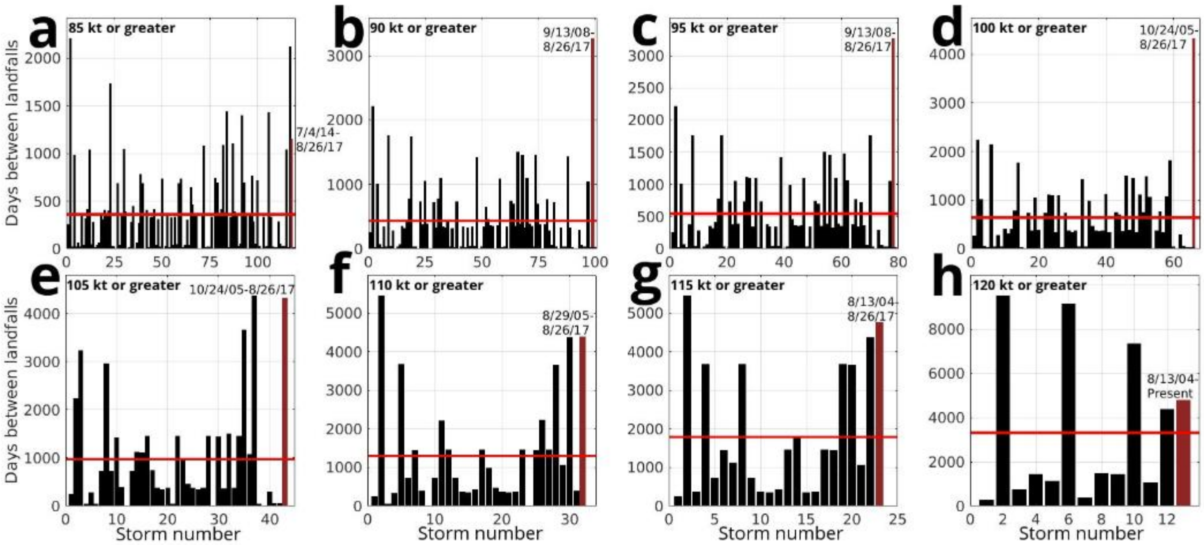

Figure 1. Time series of calendar days between continental U.S. hurricane landfall events of **(a)** 85 kt or greater, **(b)** 90 kt or greater **(c)** 95 kt or greater, **(d)** 100 kt or greater, **(e)** 105 kt or greater, **(f)** 110 kt or greater, **(g)** 115 kt or greater, and **(h)** 120 kt or greater between 1 January 1900 and 15 November 2017. The red line designates the mean return period for each intensity. The dates of the gap terminating with the landfall of Hurricane Harvey on 26 August 2017, or ongoing, are labeled on each panel, with the matching bar in dark red. Note that spaces with no visible bar represent short lengths of time, such as the 16-day interval between the U.S. landfalls of Hurricanes Harvey and Irma, each provisionally estimated to be 115 kt intensity hurricanes at landfall.

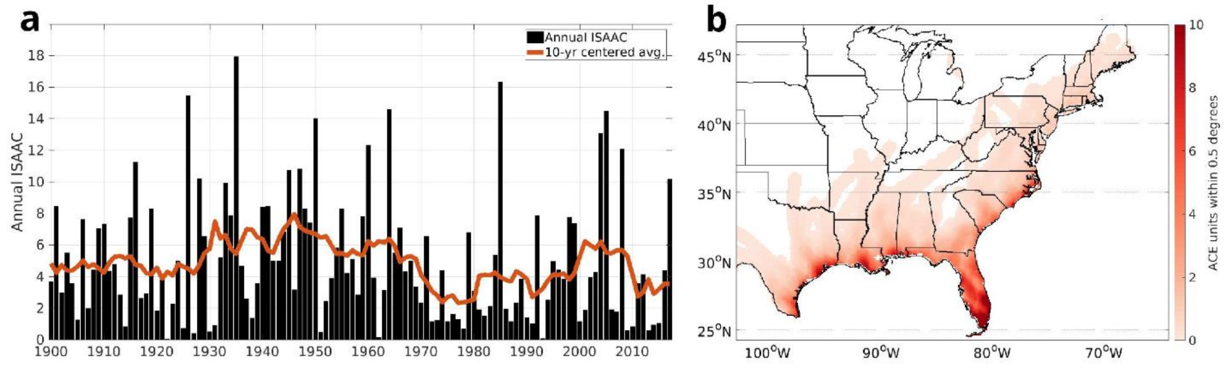

Figure 2. (a) Timeseries of ISAAC for 1900-2017, with a ten-year centered average value (red**). (b)** Spatial distribution of ACE over the U.S. for 1900-2017, summing all hourly intensities of TCs occurring within 0.5° of each grid point.

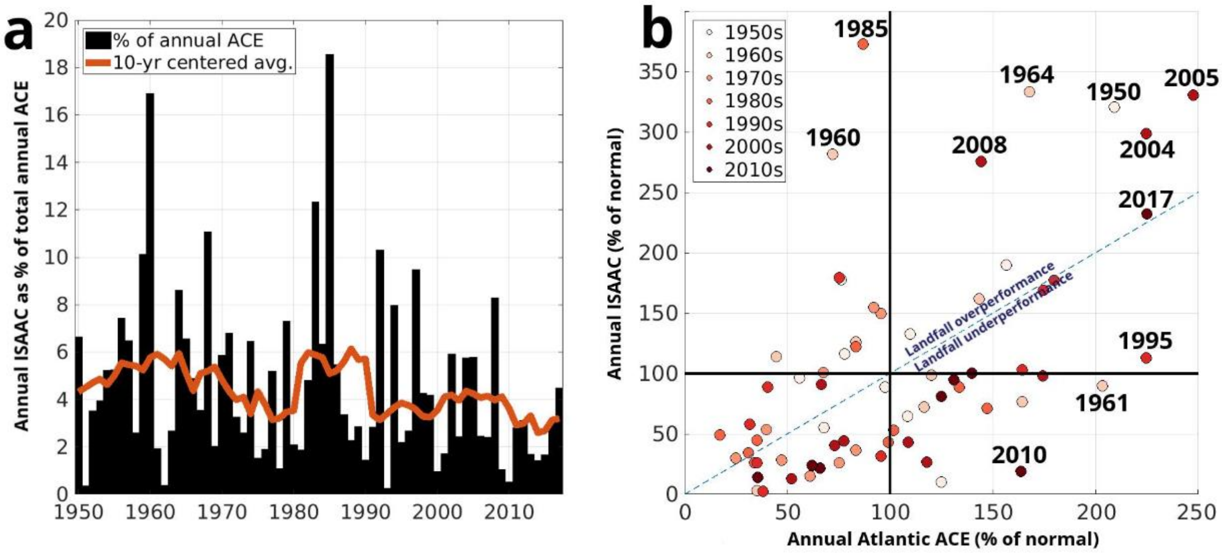

Figure 3. (a) Timeseries of proportional ISAAC over 1950-2017, expressed as a percentage of the annual cumulative ACE occurring in the Atlantic Basin, with a ten-year centered average (red). **(b)** ISAAC expressed as a percentage of the 1950-2017 mean ISAAC on the ordinate against total Atlantic ACE expressed as a percentage of the 1950-2017 mean Atlantic ACE on the abscissa for individual hurricane seasons over 1950-2017. Some notable seasons are individually labeled.

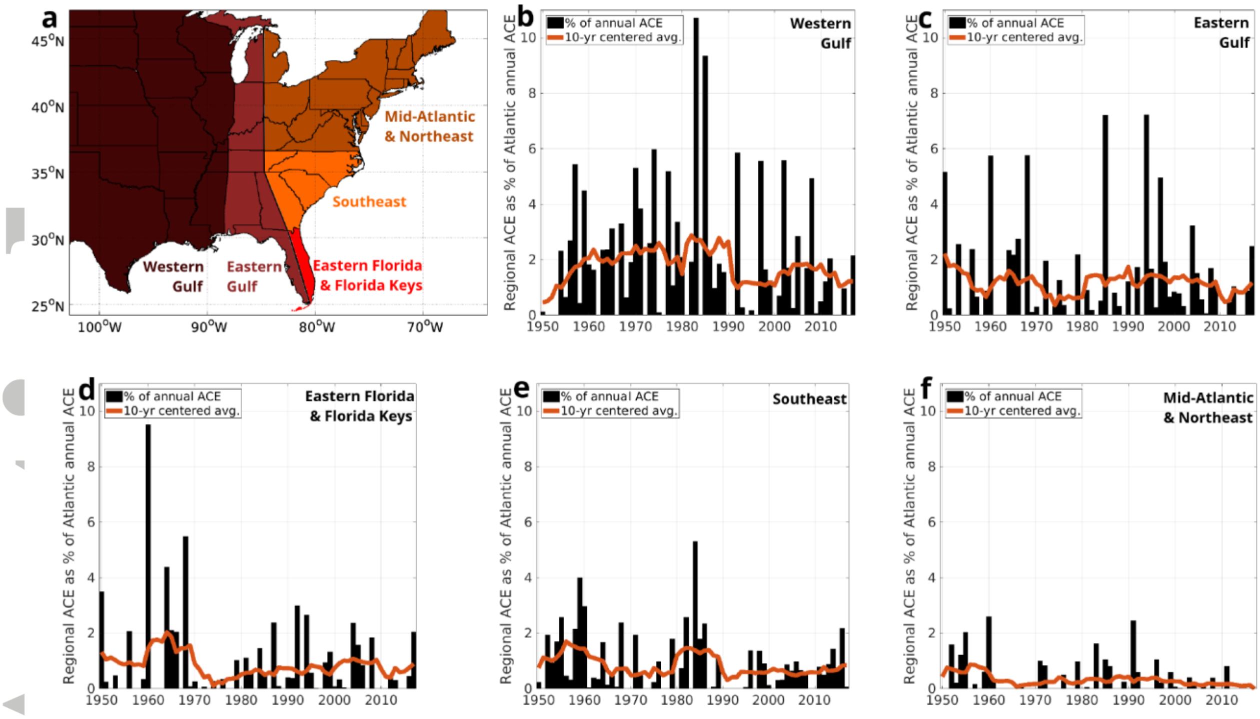

Figure 4. (a) Map of regional sub-divisions of U.S. used to bin ACE activity. **(b-e)** Timeseries of U.S. regional ACE over 1950-2017, expressed as a percentage of the annual cumulative ACE occurring in the Atlantic Basin, with a ten-year centered average (red), for the western Gulf, eastern Gulf, eastern Florida and the Florida Keys, Southeast U.S., and mid-Atlantic and Northeast U.S., respectively. All five regions are plotted on the same scale for ease of comparison.