THE ARBITRARY DEFINITION OF THE CURRENT ATLANTIC MAJOR HURRICANE LANDFALL DROUGHT

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Although nine years have passed since the last U.S. major hurricane landfall, the existence and relative significance of the current drought are largely artifacts of the chosen metric.
A
t the time of this article’s preparation, Saffir–Simpson hurricane wind scale (SSHWS; Simpson 1974) category 4 Hurricane Joaquin was devast-
ating the Bahamas (see title page). It was also threatening landfall in the United States with a projected path by most models—but not all mod-
els—disturbingly similar to Sandy (2012), including the rare turn northwest then west into the coast. This sudden threat was a stark contrast to the lack of U.S. major1 hurricane landfalls [classified as 96 knots (kt; 1 kt = 0.51 m s−1) or greater maximum sustained wind $V_{MAX}$] in recent memory. Indeed, there has been increasing awareness of this major hurricane landfall drought in the United States, as the last major hur-
ricane to landfall in the United States was Wilma on 24 October 2005.

The current gap of 9 yr (potentially extending to 10 with the close of the 2015 season) is the longest since at least 1900, with the next longest gap of only 5 yr (twice: 1901–05 and 1910–14). Recently Hall and Hereid (2015, hereafter HH15) elegantly estimated the wait time between 9-yr droughts as 177 yr using a stochastic–statistical model. While this estimate is striking for its magnitude [in particular because it is similar to the length of Atlantic tropical cyclone (TC) records going back to 1851], those authors also conclude that the current drought is likely “a matter of luck.” Our work complements their results and makes evident that the existence or historical significance of the current period of inactivity varies substantially depending on the choice of metric used. Thus, the definition of drought is largely arbitrary, although the potential impacts of that drought (or lack thereof) are obviously not arbitrary or trivial.

**DEFINITION OF LANDFALL.** The May 2015 version of the revised Atlantic hurricane database (HURDAT2; Landsea and Franklin 2013)—an updated version of Jarvinen et al. (1984)—is used here, starting in 1900. That year has been identified as the start of the reliable record of Atlantic hurricane landfalls (Landsea 2007), prior to which potential significant undetected hurricane activity is likely (Landsea 2007; Truchelut et al. 2013). For the period 1900–55, for Camille (1969), and for 1983 onward, HURDAT2 has an explicit landfall record identified (location, time, and intensity) that was used for this analysis. However, for the period 1956–82, minus Camille (1969), no such HURDAT2 identifier exists, although the ongoing HURDAT reanalysis project aims to fill that gap (Landsea et al. 2004b). Accordingly, for the period 1956–82, excluding Camille (1969), we use the intensity at the last 6-h synoptic time before landfall. We note that while this choice may introduce a slight bias (toward stronger intensity) in the landfalls during that period (Rappaport et al. 2010), alternative choices (temporal interpolation to the landfall point or using the first synoptic time after landfall) would introduce even larger, negative intensity biases (C. Landsea 2015, personal communication). Finally, if a TC made multiple landfalls in the United States [e.g., Andrew (1992) and Katrina (2005)], only the most intense landfall intensity–location combination was used. The locations of the TC landfalls used in this paper are given in Fig. 1, the details of which will be discussed later.

We emphasize that the HURDAT2 is a fluid database undergoing reanalysis and revision. For example, Hurricane Andrew (1992) was upgraded a decade later to SSHWS category 5 landfall (Landsea et al. 2004a), joining Camille (1969) and Labor Day (1935). Moreover, the 1960s have yet to be reanalyzed. Thus, it is possible that further reanalysis may upgrade or downgrade landfall intensities based upon new information and scientific understanding, leading to changes in the various drought measurements presented next. Of course, drought length changes induced solely by HURDAT2 changes would only emphasize further the uncertainties in the historical intensity database and thus the arbitrariness of the definition of landfall drought.

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1 The origins of the word “major” in describing category 3+ hurricanes appear to be later than the establishment of the Saffir–Simpson scale itself (Simpson 1971, 1974), as those publications make no mention of this distinction. However, by 1978 (Hebert and Taylor 1978) the term was in use, although we cannot be certain that the distinction did not appear in an interim work. A much later but comprehensive climatology of major hurricanes in the Atlantic (Landsea 1993) did not discuss the origins of the distinction.
DROUGHT SENSITIVITY TO LANDFALL $V_{\text{MAX}}$ THRESHOLDS. As mentioned, the definition of a major hurricane in the Atlantic basin (SSHWS category 3 or higher) is $V_{\text{MAX}} \geq 96$ kt. Given that operational hurricane intensities are binned every 5 kt, this threshold is more commonly given as $V_{\text{MAX}} \geq 100$ kt. Although the intensities are binned every 5 kt, this bin size does not imply an equivalent level of precision. Indeed, Torn and Snyder (2012) and Landsea and Franklin (2013) found that the typical $V_{\text{MAX}}$ uncertainty is of the order 10 kt, which on average implies that distinctions in $V_{\text{MAX}}$ for a given storm between, for example, 100 and 105 kt may be small compared to the observational uncertainty.$^2$

Given this uncertainty, it is reasonable to examine how the current drought and its historical significance are affected by modifying the landfall intensity threshold by an amount within this uncertainty window. Accordingly, Fig. 2a illustrates the history of landfalls since 1900 as a function of landfall intensity from 95 to 105 kt. For the standard threshold of 100 kt, the widely cited gap of 9 yr is immediately evident, particularly in sharp contrast to the prior 115 yr during which no drought of comparable length exists, consistent with HH15.

However, for a mere 5-kt increase to 105 kt for landfall intensity threshold, though the current gap of 9 yr is immediately evident, particularly in sharp contrast to the prior 115 yr during which no drought of comparable length exists, consistent with HH15.

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$^2$ This is not to say that a 5-kt difference in actual intensity does not have real physical consequences. Indeed, the kinetic energy (power dissipation; Emanuel 2005) difference between 100 and 105 kt is approximately 10% (15%). The argument here is that with a 10-kt mean uncertainty in landfall $V_{\text{MAX}}$, basing droughts solely upon the length of a single intensity threshold is potentially an unstable measure of landfall drought.
drought length remains at 9 yr, a longer 11-yr drought emerges from 1993 to 2003. Most striking about that record drought from 1993 to 2003 is that it may have gone completely undetected until now. This lack of detection is perhaps because three 100-kt landfalls of note occurred in the absence of a single 105-kt landfall, despite the fact that the 100-kt threshold is arbitrary for drought definition and a 5-kt difference is within the observational uncertainty.

Meanwhile, when lowering the landfall threshold from 100 to 95 kt, Hurricane Ike (2008) qualifies, and although the current drought is still the longest of TC landfall based upon $P_{\text{MIN}}$, noting that the bins of $P_{\text{MIN}}$ have been chosen to match the climatological drought length remains at 9 yr, a longer 11-yr drought emerges from 1993 to 2003. Most striking about that record drought from 1993 to 2003 is that it may have gone completely undetected until now. This lack of detection is perhaps because three 100-kt landfalls of note occurred in the absence of a single 105-kt landfall, despite the fact that the 100-kt threshold is arbitrary for drought definition and a 5-kt difference is within the observational uncertainty.

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relationship between $V_{\text{MAX}}$ and $P_{\text{MIN}}$ [consistent with Dvorak (1984) and verified later in Fig. 6; see also www.ssd.noaa.gov/PS/TROP/CI-chart.html]. For example, $V_{\text{MAX}} = 100 \, (105) \text{ kt}$ corresponds to $P_{\text{MIN}}$ of approximately 960 \ (955) hPa in the entire Atlantic HURDAT2 TC existence since 1950. When landfall $P_{\text{MIN}} \leq 960 \text{ hPa}$ is examined, it becomes clear that during the current 9-yr drought there have been four qualifying landfalls [Gustav (2008), Ike (2008), Irene (2011), and post-tropical Sandy (2012)], thus resulting in a trivial 2-yr $P_{\text{MIN}}$ drought. Further, changing $P_{\text{MIN}}$ from 960 to 955 hPa (effectively in the mean from $V_{\text{MAX}} = 100 \text{ to } 105 \text{ kt}$) does not change meaningfully the drought lengths discussed above; the same is true for a 965-hPa threshold. Finally, lowering the threshold further to 950 hPa (the black bars in Fig. 2b) also does not change the drought length.\footnote{This additional threshold ($P_{\text{MIN}} \leq 950 \text{ hPa}$) is also provided as the mean landfall $P_{\text{MIN}}$ is approximately 5 hPa lower than that for the full HURDAT2 database since 1950.}

Although $V_{\text{MAX}}$ and $P_{\text{MIN}}$ differ in what precisely they represent,\footnote{We have not performed any pressure scaling for environment or latitude but recognize that a Northeast U.S. landfalling TC may exist at a similar wind intensity but with deeper pressure (see prior footnote) compared to the surrounding environment than a TC farther south. Accordingly, pressure gradient matters more than $P_{\text{MIN}}$ for determining $V_{\text{MAX}}$. Nonetheless, using $P_{\text{MIN}}$ as a simple comparative metric to $V_{\text{MAX}}$ can be instructive if not more explanatory of resulting damage (Mendelsohn et al. 2012), and thus $P_{\text{MIN}}$ should not be normalized by latitude.} both are valid metrics for the intensity of a TC, particularly given that ultimately the specific interest in landfalling TCs is tied directly to societal impacts. Indeed, $P_{\text{MIN}}$ is as good as if not better than $V_{\text{MAX}}$ as a predictor of historical economic damage (Mendelsohn et al. 2012). One particularly poignant example of this relationship is Sandy (2012), whose relatively modest $V_{\text{MAX}}$ yet record low $P_{\text{MIN}}$ translated to one of the most economically devastating storms in U.S. history, in large part because of the storm surge.

A CLIMATE PERSPECTIVE: GENERALIZATION TO BASIN ACTIVITY AND LAND PROXIMITY. One critical aspect of the ongoing discussion is whether landfall droughts are tied to climate variability, either at the decadetal time scale (e.g., Schlesinger and Ramankutty 1994; Goldenberg et al. 2001; Klotzbach and Gray 2008) or because of anthropogenic influences (Emanuel 2013). Additionally, the clustering of regional landfalls in some years, while suppressed for other sets of years (e.g. Jagger and Elsner 2012), further motivates the question of factors driving landfall and the time scale of such climate factors. However, these questions implicitly assert that the statistics of hurricane landfalls can provide meaningful information about climate-induced variability in the spatial pattern of TC activity. Given that most TCs form over the open Atlantic Ocean and track westward thereafter, the statistics of TC landfall are arguably a convolution of the climatic control of hurricane activity (genesis, track, and intensity) and the orientation and details of the U.S. coastline, topics examined in greater detail by Truchelut (2015). Accordingly, it is relevant to next ask whether the current drought of major hurricane landfall activity in the United States is simply a result of reduced overall Atlantic basin major hurricane activity. In other words, perhaps the drought is not limited to U.S. landfall? Figure 3 addresses this possibility by
analyzing the counts of Atlantic basinwide hurricanes of at least 95-, 100-, or 105-kt intensity, in comparison to the fraction of those hurricanes that made landfall in the United States at those same intensity thresholds. It is clear that during the drought since 2005 (all the dots plotted at a fraction of zero since 2006), there has been no shortage of major or near-major hurricanes in the Atlantic. Thus, the U.S. landfall drought is occurring during a time when overall major hurricane activity is not suppressed. We note that there may be additional suitable measures of landfall drought that may account for variability in overall activity such as the number of consecutive major Atlantic hurricanes that have occurred without impacting the United States at that intensity (P. Klotzbach 2015, personal communication) but are not examined here for brevity.

In light of Fig. 3, we seek to assess the dependence of landfall statistics on the nature of the coastline by exploring these statistics with respect to a simple idealized geographic benchmark in lieu of the complex U.S. coastline. Figure 4 displays historical U.S. landfall probability as a function of TC location. We next count TCs having $V_{\text{MAX}} \geq 100$ kt while simultaneously existing poleward and westward of $20^\circ$N, $70^\circ$W, independent of landfall; this geographic benchmark corresponds to the 50% U.S. TC landfall probability contour in Fig. 4 and is also (perhaps not coincidentally) the approximate latitude of entry into the Gulf of Mexico and longitude of Cape Cod, Massachusetts. As such, this endeavor may be interpreted as evaluating the frequency of major hurricanes “on approach” for U.S. landfall, without concern for whether landfall on an irregular coastline actually occurs. Indeed, HH15 noted that Cuba has taken the brunt of multiple recent major hurricane landfalls. This may imply that hurricanes making landfall in the United States might have done so at higher intensity had this interaction with Cuba not occurred, further providing relevance to the geographic benchmark chosen here.

The results are shown in Fig. 5, which does not indicate a meaningful drought for $V_{\text{MAX}} \geq 100$ kt in the far western Atlantic at any time over the past two decades. Further, this suggests that the current drought may be in part dependent on the orientation of the coastline—or interaction with nearby landmasses (HH15)—highlighting the additional complexity inherent in using TC landfall to attempt to infer climate signals. When Figs. 3, 4, and 5 are compared, they also highlight the need to understand the factors that drive production of Atlantic basin major hurricane activity and major hurricane activity in proximity to the United States, while also suppressing landfall in the United States at that threshold.

**Potential for a Pathological Contribution.** Given the impact that 5-kt shifts in $V_{\text{MAX}}$ near 100 kt have and 5-hPa shifts in $P_{\text{MIN}}$ near 960 hPa do not have on the length of the drought, it is prudent to take a step back and examine the distribution of TC intensity generally. From a theoretical perspective, there is no reason to expect that the frequency of landfall should increase as the landfall intensity increases (once hurricane status is reached, anyway). In other words, more intense hurricanes at landfall are less common than weaker hurricanes, given a long enough record.
Figure 6a demonstrates that while this is indeed true, there are some very interesting departures from that expectation. The red curve in Fig. 6a is the distribution (as a fraction of the peak occurrence) for all landfalls from 1900 to 2014 as defined previously. The intensity at peak landfall frequency is the tropical storm stage, with on average frequency decreasing as one ascends the SSHWS. However, the occurrence of 100 kt at landfall (0.6 of peak) is twice that of 95 kt at landfall (0.3 of the same peak), oddly suggesting that 100 kt at landfall is twice as common as 95 kt at landfall. The $V_{\text{MAX}} = 100$ kt landfall is also 1.5 times more likely than 105 kt, also suggesting a curious propensity for 100-kt TCs at landfall. Note that when the green and black lines (more confident yet smaller subsets) are compared to the prior analysis, the same result occurs, suggesting that when those TCs without an explicit HURDAT2 landfall record are ignored, the relationship does not weaken but instead becomes stronger.

Meanwhile, when this distribution is expanded to include all HURDAT2 times back to 1950 regardless of landfall (gray bars in Fig. 6a), the local maximum at 100 kt decreases markedly, suggesting that this effect at the 100-kt threshold is likely specific to the time of landfall. Of course we note the relatively small sample sizes here: 18 (8) TC landfalls at 100 (95)-kt intensity for the 1900–2014 period. Perhaps with a longer dataset, these differences would decrease and the curves in Fig. 6a would more closely follow the expected Poisson distribution for TC statistics (Elsner and Kara 1999; Elsner 2003; Parisi and Lund 2008). Nonetheless, this result points to the potential existence of bias in landfall intensity at the major hurricane threshold that may arise intentionally for societal awareness and preparedness reasons. However, in principle this effect should be reduced as a result of the postseason best-tracking process when such real-time factors are largely eliminated.

Additionally, in Fig. 6a (gray bars) there exists a striking local maximum at $V_{\text{MAX}} = 65$ kt. This anomalous maximum occurrence at 65 kt was previously noted by Emanuel (2000) and was then speculated to be partially a result of forecaster desire to increase societal awareness implied by the status change to hurricane intensity. If this is in fact the case, it lends support to the explanation for the 100-kt landfall intensity anomaly discussed earlier and potentially further undermines the objectivity and scientific significance of the 100-kt landfall drought (Fig. 6a).

Yet, the existence of local maxima in the $V_{\text{MAX}}$ distribution may also owe to the climatological $V_{\text{MAX}}$ associated with each current intensity (CI) number in the Dvorak technique (Dvorak 1984). Only a fraction of the 5-kt intensity bins shown in Fig. 6a is represented in the CI–$V_{\text{MAX}}$ association, including (when rounded) 55, 65, 75, 90, 100, 115, 125, and 140 kt, thus making those intensities more likely at advisory time in the absence of in situ data. Finally, for completeness, Fig. 6b shows the same analysis in Fig. 6a, except using $P_{\text{MIN}}$ instead of $V_{\text{MAX}}$.

**SUMMARY AND IMPLICATIONS.** We summarize in Fig. 7 most of the various metrics previously discussed. For this figure, the distribution of drought length for each metric is given by the colorized bars. The arrows on the abscissa are where the current drought (ending in 2014) resides based upon (and also colorized by) metric.
The pairs of years labeled above the corresponding bar of the same color are the years of the maximum drought length by metric. Thus, if an arrow of a given color lies left of the labeled year pair of the same color, the current drought is not the longest drought since 1950 by that metric. Across all of the different methodologies shown in Fig. 7, the current drought is unprecedented only in the case of the landfall $V_{\text{MAX}} \geq 100$ kt threshold. We again stress that all of the metrics discussed previously ignore the most important measure of impact—that of human and financial loss (Pielke et al. 2008; Pielke 2012; Chavas et al. 2013). Hurricane Sandy (2012) was barely a hurricane by landfall $V_{\text{MAX}}$. Hurricane Irene (2011) produced historic flooding in parts of New England and yet was a strong tropical storm by landfall $V_{\text{MAX}}$ there because of the greater than normal drought.
reduction of wind to the surface (Avila and Stewart 2013). Nonetheless, Sandy produced $88 billion (U.S. dollars) in losses and the largest loss of life for an East Coast hurricane in over four decades (Blake et al. 2013). Irene produced $8 billion in loss (Avila and Stewart 2013) despite being a storm that would not count toward the major hurricane landfall analysis in terms of landfall $V_{MAX}$. Both of these significant if not extreme losses occurred during the very middle of the current landfall drought as measured by landfall $V_{MAX}$. Thus, we must not lose sight of the fact that our formal definitions of hurricane intensity do not readily scale to loss of life or damage, and in fact there can be considerable outliers.\(^6\)

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\(^6\) As a postscript, we note that after the final preparations for this manuscript, Hurricane Joaquin (2015) 1) easily satisfied the metric shown in Fig. 5 (reaching 931 hPa while existing northwest of 20°N, 70°W), 2) is one of the most intense hurricanes to ever strike the Bahamas, and 3) turned out to sea only 600 km from U.S. landfall. The 100-kt U.S. landfall drought reached 10 yr on 24 October 2015.

REFERENCES


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