Surface Pressure a More Skillful Predictor of Normalized Hurricane Damage than Maximum Sustained Wind

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Abstract

Atlantic hurricane seasons have a long history of causing significant financial impacts, with Harvey, Irma, Maria, Florence, and Michael combining to incur more than 345 billion USD in direct economic damage during 2017-2018. While Michael's damage was primarily wind and storm surge-driven, Florence's and Harvey's damage was predominantly rainfall and inland flood-driven. Several revised scales have been proposed to replace the Saffir-Simpson Hurricane Wind Scale (SSHWS), which currently only categorizes the hurricane wind threat, while not explicitly handling the totality of storm impacts including storm surge and rainfall. However, most of these newly-proposed scales are not easily calculated in real-time, nor can they be reliably calculated historically. In particular, they depend on storm wind radii, which remain very uncertain. Herein, we analyze the relationship between normalized historical damage caused by continental United States (CONUS) landfalling hurricanes from 1900-2018 with both maximum sustained wind speed (V_{max}) and minimum sea level pressure (MSLP). We show that MSLP is a more skillful predictor of normalized damage than V_{max}, with a significantly higher rank correlation between normalized damage and MSLP (r_{rank} = 0.77) than between normalized damage and V_{max} (r_{rank} = 0.66) for all CONUS landfalling hurricanes. MSLP has served as a much better predictor of hurricane damage in recent years than V_{max}, with large hurricanes such as Ike (2008) and Sandy (2012) causing much more damage than anticipated from their SSHWS ranking. MSLP is also a more accurately-measured quantity than is V_{max}, making it an ideal quantity for evaluating a hurricane's potential damage.

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Capsule Summary

Minimum sea level pressure is more easily quantified than maximum sustained wind, and it shows a stronger relationship with hurricane risk for the continental United States .

Keywords

Hurricanes, tropical cyclones, Saffir-Simpson scale, maximum sustained wind, minimum sea level pressure

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1. Introduction

Tropical cyclones (TCs) are the leading driver of natural disaster-caused damage for the United States (Smith and Katz 2013, Klotzbach et al. 2018) as well as many other parts of the globe. More than 345 billion USD in damage to the United States and Caribbean were incurred by the Atlantic hurricanes of 2017 and 2018 (Aon 2019). All references to damage throughout the remainder of the manuscript are provided in USD. Hurricanes Harvey, Irma, Maria, Florence and Michael all caused significant damage to residential and commercial property, infrastructure, and agriculture, but the primary drivers of the damage have varied significantly for each individual storm - from predominantly freshwater-driven impacts for Harvey and Florence to predominantly surge- and wind-driven effects for Irma and Michael. While no singular geophysical quantity can perfectly explain the damage that a storm will cause, here we compare how maximum sustained wind speed (V_{max}) and minimum sea level pressure (MSLP) perform at predicting hurricane-caused damage in the continental United States (CONUS).

The Saffir-Simpson Hurricane Scale was originally designed by Herb Saffir to reflect wind damage caused by hurricanes. The scale was first presented in 1969, and it ranked wind damage associated with hurricanes on a scale from 1 to 5, with 5 being hurricanes with the strongest winds and the highest levels of associated damage (Saffir 1973). Robert Simpson added MSLP and typical storm surge values associated with each hurricane category (Simpson 1974). The Saffir-Simpson Hurricane Scale was used by the National Hurricane Center (NHC) to convey the multiple threats from hurricanes for more than 30 years. However, costly and large-sized hurricanes like Katrina (2005) and Ike (2008) brought more storm surge than would have been expected given their Saffir-Simpson categories at the time of landfall. In response, the NHC

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removed the storm surge and MSLP components from the scale, resulting in the Saffir-Simpson Hurricane Wind Scale (SSHWS) which is currently used operationally by the NHC when providing public warning on hurricanes (Schott et al. 2012).

During the past 15 years, several different scales have been proposed to either augment or replace the Saffir-Simpson Hurricane Scale. These include Kantha et al. (2006), who recommended a scale based on a combination of V_{max}, the radius of maximum wind and the translation speed. Powell and Reinhold (2007) proposed a ranking for wind destruction potential based on the integrated kinetic energy (IKE) of the hurricane. Hebert et al. (2008) developed a Hurricane Severity Index that was based on both the size and the intensity of the wind field. More recently, Pilkington and Mahmoud (2016) used an artificial neural network model to forecast the economic impact from hurricanes using several inputs including population affected, location of landfall, V_{max}, MSLP, precipitation and storm surge. Walker et al. (2018) proposed the Kuykendall scale which related the Advanced Three Dimensional Circulation Model (ADCIRC)-modeled storm surge height and velocity from four hurricanes to several different fiscal loss approaches. While all of these proposed scales are useful for specific applications, several of these scales cannot be calculated in real time, or the inputs of these scales have not been reliably measured in the past. For example, several of them rely on storm wind radii. These are only available for the North Atlantic (hereafter Atlantic) since 1988 as operational values in the extended best track (Demuth et al. 2006) and are only best-tracked in the definitive Atlantic hurricane database (HURDAT2; Landsea and Franklin 2013) since 2004. These records also have large uncertainties: ~20% for 34 kt wind radii for CONUS landfalling hurricanes (Landsea

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and Franklin 2013). Consequently, they cannot be used to evaluate drivers of damage across long periods of record (e.g., >=20 years).

One quantity that is recorded consistently in HURDAT2 for all Atlantic named storms since 1979 and is available for all continental US (CONUS) landfalling hurricanes since 1851 is MSLP. The relationship between MSLP and V_{max} has been discussed in many prior studies (e.g., Dvorak 1975, Atkinson and Holliday 1977, Koba 1990, Knaff and Zehr, 2007). If MSLP were used as the primary intensity metric, it would reduce some of the challenges that arise when analyzing trends in TC intensity on a global or a regional scale (e.g., Knapp et al. 2013, Klotzbach and Landsea 2015).

MSLP is much more easily identified than V_{max}. According to the NHC definition listed in their FAQ page at: https://www.aoml.noaa.gov/hrd/tcfaq/D4.html, V_{max} is defined as:

> “a 1 min averaging time for reporting the sustained (i.e. relatively long-lasting) winds. The maximum sustained wind mentioned in the advisories that NHC issues for tropical storms and hurricanes are the highest 1 min surface winds occurring within the circulation of the system. These "surface" winds are those observed (or, more often, estimated) to occur at the standard meteorological height of 10 m (33 ft) in an unobstructed exposure (i.e., not blocked by buildings or trees).”

Clearly, this quantity is nearly impossible to measure directly, especially over land areas where frictional effects act as a negative influence in often finding a measurement equaling the max overwater TC wind speeds as cited in NHC advisories at landfall. The reference winds are at 10

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m with an open exposure, which happens at sea. However, there are fewer observations at sea. The definition includes a maximum amount anywhere in the circulation system, which is likewise difficult to ascertain even with a dense observational network (Nolan et al, 2014). Conversely, the definition of MSLP is so clear that it does not even warrant a definition in the NHC FAQ.

MSLP occurs at the center of the storm and is part of the large-scale structure of the vortex. It is therefore relatively easy to locate the MSLP (vortex center), and the gradient of pressure naturally flattens near this center. In fact, one of the primary goals of every aircraft reconnaissance mission is to find the storm center. With aircraft reconnaissance, MSLP can be reliably calculated using hydrostatic balance from the flight-level pressure depression, even without using a dropsonde. Landsea and Franklin (2013) also note qualitatively that MSLP is already very accurately measured with aircraft reconnaissance.

Estimating V_{max} from flight-level winds depends on parameterizing the boundary layer turbulence (Franklin et al. 2003). The advent of the Stepped Frequency Microwave Radiometer (SFMR) in recent years has greatly improved our ability to estimate surface winds, but these still remain estimates based on microwave emission from the ocean surface (Uhlhorn and Black 2003). In addition, V_{max} is much more sensitive to small-scale asymmetries like meso-vortices in the eyewall (Hendricks et al. 2014). While eyewall penetrations also aim to measure these maximum winds, the actual maximum wind speeds are much more likely to be missed given the limited number of passes flown by an aircraft through the hurricane.

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When it comes to assessing hurricane intensity at the time of landfall, Nolan et al. (2014) used an observing system simulation experiment and noted that even a perfectly-positioned anemometer in the right-front quadrant of a hurricane underestimated the actual intensity of the hurricane by 10-20%, on average. This study also noted that a barometer that passes through the eye of a hurricane is likely to overestimate MSLP by only 1-3 hPa.

MSLP is much easier to measure at landfall than is V_{max}. Barometers are among the simplest meteorological instruments and will usually operate in a wide range of conditions (Pike and Bargen 1976). Anemometers, on the other hand, are prone to mechanical failure at wind speeds above 50 kt (Howden et al. 2008), precisely when they matter most to estimating V_{max}. Landsea and Franklin (2013) state that the intensity uncertainty of major hurricanes at landfall is about 9.8 kt (for V_{max}) and 3.6 hPa (for MSLP). Converting pressure to wind using the Knaff and Zehr (2007) wind-pressure relationship allows an easier comparison of these uncertainties: the 3.6 hPa MSLP uncertainty is ~4 kt of V_{max} uncertainty for a 935 hPa Category 4 hurricane (using the original Saffir-Simpson scale) increasing to 6 kt of V_{max} uncertainty for a 990 hPa Category 1 hurricane (see Supplemental Material for details on how this calculation is made using Hurricane Michael's landfalling MSLP of 919 hPa as an example).

Chavas et al. (2017) documented that central pressure deficit (the difference between the pressure of the surrounding large-scale environment and the MSLP) and V_{max} are directly physically related through gradient wind balance using a variety of different models. They also

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noted that the central pressure deficit increases not only with V_{max} but also with storm size and background rotation rate. While acknowledging that changes in both the environmental pressure and the Coriolis parameter are not negligible (e.g., Knaff and Zehr 2007), here we focus on MSLP as our primary intensity metric to compare with V_{max}.

Chavas et al. (2017) find that MSLP is effectively an integrated metric of the entire wind field, which makes it more akin to the IKE metric proposed by Powell and Reinhold (2007). However, unlike IKE, only one simple measurement is needed to assess MSLP, while knowledge of the entire wind field is necessary to estimate IKE. The Sea, Lake, and Overland Surges from Hurricanes (SLOSH) parametric wind model, uses the storm track, the radius of maximum winds and the pressure deficit (e.g., the environmental pressure minus the MSLP) as its inputs (Houston et al. 1999). The National Hurricane Center then uses this parametric wind field to force the SLOSH model to forecast storm surge. Likewise, Irish et al. (2008) showed that the effect of storm surge increased with storm size, especially for major hurricanes with mildly sloping coastal shelves - such as areas along the Gulf of Mexico. Larger hurricanes also have larger wind and rainfall footprints (Lonfat et al. 2007). Zhai and Jiang (2014) showed that economic losses from CONUS landfalling hurricanes were better correlated with V_{max} and storm size than either V_{max} or storm size individually.

Consequently, as a single metric, MSLP provides more information about potential hurricane damageability than V_{max}. Bakkensen and Mendelsohn (2016) examined global damage from TCs from 1960-2010 and found that MSLP was a better predictor of damage than V_{max}. Their finding has major practical significance that warrants much greater attention within the

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mainstream atmospheric science and hazard risk communities. Thus, here we examine this result in greater depth.

In this study, we examine a long historical record (1900-2018) of normalized continental United States (CONUS) hurricane damage with the goal to evaluate if V_{max} or MSLP has historically provided a better estimate of the damage that these storms have caused. Section 2 discusses the data sources and briefly outlines the methodology used for the analysis, while section 3 presents the main findings of our study. Section 4 examines the potential implications of these results.

2. Data and Methodology

Normalized CONUS hurricane damage was taken from Weinkle et al. (2018), which provides an update to Pielke et al. (2008). Normalization provides an estimate of how much damage an historical hurricane would hypothetically cause if it were to make landfall today given current levels of exposure and wealth. We use the Pielke-Landsea (PL18) normalization method discussed in Weinkle et al. (2018) which adjusts for population, inflation and wealth per capita. This dataset is available from 1900-2017. Damage estimates for the CONUS landfalling hurricanes of 2018 (Florence and Michael) were taken from the National Hurricane Center Tropical Cyclone Reports for these two storms (Stewart and Berg 2019; Beven et al. 2019). These estimates are similar to those calculated by a private-sector assessment (Aon 2019). The normalized damage dataset initially included seven hurricane events that brushed the North Carolina coastline despite the center of the system not officially making landfall. Given that

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these storms were typically tracking northward or northeastward when they approached the coast, the right front quadrant (which typically generates the strongest winds) did not hit the state, and consequently, damage from these hurricanes was minor. These hurricanes are excluded from this analysis.

Multiple landfalls from the same hurricane were included whenever the normalized hurricane damage dataset (Weinkle et al. 2018) had a separate damage estimate for an additional landfall. There were a total of nine hurricanes where damage from a second landfall was provided. There were also nine hurricanes where separate landfalls were identified by Klotzbach et al. (2018), who used a 100 mile threshold between landfalls to identify multiple distinct landfalls by the same hurricane, but did not include a separate normalized damage estimate. In these cases, we selected the first landfall as its landfalling V_{max} and MSLP, assuming that the two separate landfalls were of approximately equal intensity. In cases where one landfall was clearly the primary driver of the damage (e.g., Charley-2004's landfall in FL versus its landfall in SC), we selected the higher intensity V_{max} landfall. If these nine landfalling hurricanes were removed from the dataset, our results do not change significantly.

While Hurricane Sandy had officially become post-tropical several hours before landfall, we do include it in this analysis given the widespread swath of damage which resulted from the event. While the maximum winds estimated to impact the CONUS from Sandy were 65 kt (e.g., Category 1), its MSLP of 942 hPa at the time of these maximum wind impacts would equate to a Category 4 hurricane using the MSLP values in the original Saffir-Simpson scale (Simpson 1974). We note that these values are slightly different from the 70 kt V_{max} and 945 hPa MSLP

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listed as Sandy's post-tropical landfall intensity in New Jersey in Blake et al. (2012). The 65 kt V_{max} and 942 hPa MSLP intensity for Sandy are what is listed in the AOML dataset discussed in the following paragraph. The final dataset that we employ consists of 165 CONUS hurricane landfall events from 156 hurricanes during the seasons from 1900-2018.

Both V_{max} and MSLP for hurricanes at the time that they made landfall in the CONUS are taken from the Atlantic Oceanographic and Meteorology Laboratory (AOML) website (https://www.aoml.noaa.gov/hrd/hurdat/UShurrs_detailed.html) which is based on HURDAT2 (Landsea and Franklin 2013). The data available at the AOML link above is currently available from 1851-1960 and 1983-2018 and will be available for the entire length of the hurricane database once the Atlantic Hurricane Database Reanalysis Project is complete. For the period from 1961-1982, we used the CONUS hurricane impacts database from AOML: https://www.aoml.noaa.gov/hrd/hurdat/All_U.S._Hurricanes.html. This dataset is very similar to the one just discussed. The only difference is that this dataset only provides the V_{max} and MSLP intensity at the time of a hurricane's strongest landfall, as opposed to the former database which provides intensity information for all hurricane landfalls. The blend of these two AOML landfalling hurricane datasets was also recently employed in Klotzbach et al. (2018). We note that nine hurricanes in our landfalling hurricane dataset had MSLP calculated from a V_{max}/MSLP relationship as opposed to a direct measurement of MSLP. Removing these nine hurricanes from our analysis does not significantly change our results.

There are 32 CONUS hurricane landfalls (29 prior to 1950) where no damage was listed in Weinkle et al. (2018). These storms are not counted in this analysis. Throughout the remainder

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of this manuscript, we use the Weinkle et al. (2018) list of landfalling hurricanes unless otherwise noted.

For measurements of the 50-kt wind radii, we use the extended best track dataset from 1988-2003 (Demuth et al. 2006) and HURDAT2 from 2004-2018. The extended best track provides additional information than what is stored in HURDAT2 including the radius of the outermost closed isobar, the radius of maximum winds, eye diameter, and other size characteristics. The 50-kt wind radii have been best-tracked in HURDAT2 since 2004. Since wind radii at the time of CONUS hurricane landfall are not always provided in HURDAT2 and are unavailable in the extended best track dataset, we use the wind radii at six-hourly resolution (e.g., 0, 6, 12, and 18 UTC), and take the six-hour time-step immediately prior to landfall for the hurricane landfall's 50-kt wind radii. We take the arithmetic average of the four 50-kt wind radii quadrants provided (e.g., NW, NE, SW, SE) as our 50-kt wind radii size metric.

The statistical significance of correlations was assessed using a two-tailed Student's t-test, while the statistical significance of the difference in correlations was computed using the Fisher r-to-z transformation and accounting for the shared correlation between V_{max} and MSLP (Lee and Preacher 2013). We note statistical significance at two different levels in this manuscript: 5% and 1%, respectively.

3. Results

a. Normalized damage relationship with V_{max} and MSLP: 1900-2018

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We begin by examining the relationship between normalized hurricane damage and V_{max} and MSLP for the full period of record: 1900-2018 (Fig. 1a and 1b). The normalized hurricane damage dataset has some very large outliers in damage. For example, the Great Miami Hurricane of 1926 would be hypothetically expected to cause $236 billion if it occurred today. Furthermore, the top ten costliest hurricane landfalls are equal to 52% of the aggregated normalized damage of all 165 hurricane landfalls in our dataset. Due to these large outliers, we use rank correlations as our primary agreement metric, as opposed to the Pearson correlation coefficient. Figure 1a displays the relationship between normalized damage and V_{max}, while Fig. 1b displays the relationship between normalized damage and MSLP. While both quantities correlate significantly with damage at the 1% level, the rank correlation between MSLP and normalized damage (r_{rank} = 0.77) is significantly greater at the 1% level than the rank correlation between V_{max} and normalized damage (r_{rank} = 0.66). MSLP explains ~60% of the variance in normalized damage, without even accounting for the large spatial differences in exposure along the US coastline (Chavas et al. 2012, Weinkle et al. 2018). For these plots, higher ranks indicate greater V_{max} (or lower MSLP) and increased levels of normalized damage. One might argue that the lower correlation for V_{max} is caused by the larger uncertainty of its value (e.g., Landsea and Franklin, 2013). However, that simply suggests that communicating potential damage and humanitarian risk to the public is even more appropriate based on MSLP since it is more accurately measured and more correlated with dangerous direct impact implications (with both damage and with fatalities, as shown later in this manuscript).

While both quantities correlate significantly with normalized damage, we do note that damage is more than a function of the intensity of the TC. Damage is also driven by the size of the exposed

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population that is impacted, with increasing damage typically associated with hurricanes making landfall in major metropolitan areas (Chavas et al. 2012, Weinkle et al. 2018). In addition, TC-generated rainfall can be a large driver of damage for many TCs, with recent examples like Hurricane Harvey (2017) and Hurricane Florence (2018) demonstrating this point. While area-averaged rainfall is positively correlated with TC intensity (Cerveney and Newman 2000) and with TC size (Lonfat et al. 2007), the relationship is relatively weak on an individual TC basis. TC rainfall is also negatively correlated with storm translation speed, with slower TCs typically producing more rainfall (Emanuel 2017, Kossin 2018). Furthermore, higher intensity rainfall events can also enhance greater wind loss potential since a lesser wind can knock down trees when the soil is overly saturated. This was true during recent storms such as Matthew (2016) , Harvey (2017), Florence (2018) and Michael (2018). Consequently, we cannot expect one TC intensity metric to correlate perfectly with damage.

b. *Normalized damage relationship with V_{max} and MSLP: 2007-2018*

We note that in recent years, MSLP has shown much improved skill at predicting normalized damage when compared with V_{max} for landfalling CONUS hurricanes. As shown in Fig. 1c, V_{max} has not worked well as a predictor for landfalling CONUS hurricane damage from 2007-2018 (e.g., rank correlation between V_{max} and normalized damage has decreased to 0.29), while the rank correlation between MSLP and normalized damage has increased to 0.89 for the 15 CONUS landfalling hurricanes from 2007-2018 (Fig. 1d). The correlation difference is significant at the 1% level. This inability of V_{max} to predict hurricane damage is one of the primary reasons why less emphasis has been given to the SSHWS by NHC in recent years.

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Two notable recent failures of V_{max} at predicting normalized damage are Hurricane Ike (2008) and Hurricane Sandy (2012). Both of these storms had much lower MSLP than would be expected for their SSHWS category at the time of landfall. Hurricane Sandy's MSLP of 942 hPa was the lowest for a Category 1 CONUS landfalling hurricane (officially post-tropical, but considered a Category 1 for this analysis) since 1900. Hurricane Ike's MSLP of 950 hPa was tied with Hurricane Edna (1954) for the third lowest for a Category 2 CONUS landfalling hurricane since 1900 – trailing only the Great Atlantic Hurricane of 1944 (940 hPa) and Hurricane Gloria in 1985 (942 hPa).

Given the extremely large size and energy associated with each of these two TCs, both Ike and Sandy generated large and impactful storm surges. While the Bolivar Peninsula was completely inundated by Ike, and consequently exact measurements are not available, ground assessment teams estimated 15-20' of storm surge on the Bolivar Peninsula (Berg 2009). Hurricane Sandy brought more than 14' of storm tide (the combination of storm surge and the astronomical tide) to portions of New York City, with The Battery (where records extend back to 1920) well-surpassing its previous storm tide record (set in December 1992) by more than 4' (Blake et al. 2013). While Sandy's extremely high level of damage was also due to its directly impacting the largest metropolitan area in the United States (i.e.., New York City) and several surrounding states, its large size was the dominant factor in why the system brought such devastating storm surge, as was noted in Blake et al. (2013).

c. Vmax/MSLP relationship with normalized damage: Texas to Florida vs. Georgia to Maine

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In order to investigate the spatial relationship between landfalling V_{max}/MSLP and normalized damage, we divide CONUS hurricane landfalls into those making landfall between Texas and Florida and those making landfall from Georgia to Maine. Kimball and Mulekar (2004), Knaff et al. (2014) and Chavas et al. (2016) have all noted that hurricanes tend to grow as they move poleward (northward), and we hypothesize that this may result in a weakening of the relationship between V_{max} and normalized damage for storms making landfall from Georgia to Maine. The relationship between V_{max} and MSLP with storm size is investigated in more detail in the next section. The correlation is slightly greater between normalized damage and MSLP (r_{rank} = 0.77) than for normalized damage and V_{max} (r_{rank} = 0.74) for hurricanes making landfall from Texas to Florida, but the difference is not significant (Fig. S1). While the correlation between MSLP and normalized damage remains significant and strong for Georgia to Maine landfalls (r_{rank} = 0.81), the correlation is much weaker for Georgia to Maine hurricane landfalls for V_{max} (r_{rank} = 0.42) (Figs. 1e and 1f). The difference in the rank correlations between V_{max} and MSLP with Georgia to Maine normalized hurricane damage is significant at the 1% level. Historically, V_{max} has served as a poor predictor of damage (relative to MSLP) from hurricanes making landfall along the East Coast of the U.S. north of Florida.

d. CONUS landfalling hurricane size relationship with V_{max} and MSLP

We next investigate the relationship between CONUS landfalling hurricane size and V_{max}/MSLP since 1988 (when the extended best track dataset became available). In this analysis, we use 50-kt wind radii as our primary size metric, as this has been shown in prior research to improve the skill in storm surge forecasting (Takagi and Wu 2016). We find that the size of CONUS landfalling hurricanes is significantly correlated at the 1% level with V_{max} (r_{rank} = 0.41), although

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this correlation value implies that only ~17% of the variance in storm size is explained by V_{max}, similar to what was found by Merrill (1984), Chavas and Emanuel (2010) and Chavas et al. (2016). The correlation between MSLP and storm size is much stronger (r_{rank} = 0.60), explaining 36% of the variance in storm size (Fig. 2). The difference in correlations between V_{max} and MSLP with storm size is significant at the 1% level. Since storm surge is related to hurricane size (Jelesnianski et al. 1992, Irish et al. 2008, Takagi and Wu 2016), this helps explain why MSLP is a better overall predictor of damage.

e. MSLP-based definition of major hurricanes - normalized damage implications

We next examine using a MSLP-based definition for major (e.g., Category 3+ on the Saffir-Simpson Wind Scale Scale) hurricanes (Landsea 1993). Since 1979 (when MSLP began being recorded for all Atlantic TCs in HURDAT2), 21% of all named storms in the Atlantic have had a lifetime maximum intensity >= 96 kt (>= 49 ms^{-1}). If we do a similar analysis for MSLP, 22% of all Atlantic named storms have had a lifetime maximum intensity <=960 hPa. We note that in the Saffir-Simpson Hurricane Scale used by the NHC for more than 30 years (Simpson 1974), Category 3 hurricanes were listed as typically having an MSLP between 945-964 hPa. Table 1 displays our proposed MSLP-based addition to the Saffir-Simpson Scale, attempting to fit similar frequency of TC lifetime maximum intensity values to the MSLP criteria (and also setting all MSLP thresholds to values divisible by 5).

There would generally be more confidence in the landfalling Saffir-Simpson category using MSLP than in using V_{max}. This can be shown by doing a simple signal to noise analysis. The

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width of the SSHWS categories varies between 13-24 kt (Table 1). Given the average V_{max} uncertainty of 9.8 kt for CONUS landfalling major hurricanes listed in Landsea and Franklin (2013), that leaves a signal to noise ratio of ~1.3-2.5. The width of the revised MSLP boundaries in Table 1 is 15-20 hPa. Consequently, given the 3.6 hPa uncertainty estimate in MSLP given in Landsea and Franklin (2013), the signal to noise ratio ranges from ~4.2-5.6. We can therefore say with much greater certainty the exact category of a system when using MSLP. We also note that NHC rounds V_{max} values to the nearest 5 kt, while MSLP are rounded to the nearest 1 hPa value, adding additional uncertainty to the V_{max} estimate relative to the MSLP estimate.

In the normalized hurricane dataset since 1900, there have been a total of 67 CONUS major hurricane landfalls. If we use the MSLP-based definition of major hurricane landfalls (<=960 hPa), there would have been a total of 80 CONUS MSLP-based major hurricanes. Using the V_{max}-based definition of major hurricanes, these 67 hurricanes generated 81% of the 1900-2018 normalized hurricane damage. Major hurricanes defined using MSLP yield 92% of the normalized hurricane damage from 1900-2018. Table S1 displays the CONUS hurricane landfalls that would be upgraded and downgraded using the MSLP-based definition of major hurricane. A total of 15 hurricanes would be upgraded using the MSLP threshold. Eight of these major hurricane upgrades have occurred in the past 20 years: Floyd (1999), Isabel (2003), Frances (2004), Gustav (2008), Ike (2008), Irene (2011), Sandy (2012), and Florence (2018). All eight of these hurricanes caused at least $5 billion in normalized damage, with four of these hurricanes generating more than $15 billion in normalized damage: Frances, Ike, Sandy, and Florence. Four hurricanes received a two category upgrade (Gloria (1985), Katrina (2005), Irene (2011), and Florence (2018)), while Hurricane Sandy would have been considered a Category 4

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hurricane had our MSLP-based definition been used (a three category upgrade from its operational classification).

Only two hurricanes would be downgraded using the MSLP-based definition: Storm 5 (1945) and Alicia (1983). We note that Alicia did cause considerable damage in the Houston-Galveston region (National Research Council 1984) despite its small size as it tracked directly through the metropolitan area. Alicia caused ~$2 billion in actual damage (1983), but if it occurred given today's population and exposure growth, the cost would likely be ~$13.6 billion (Weinkle et al. 2018).

The median damage of all CONUS major hurricane landfalls since 1900 is $10.8 billion using the canonical V_{max} definition, while the median damage of CONUS major hurricane landfalls only decreases slightly ($10.4 billion) if the MSLP-based major hurricane threshold is used instead. In the normalized hurricane damage dataset, 6 out of 67 (9%) major hurricanes using the V_{max} definition have made landfall north of Florida along the US East Coast from 1900-2018 (e.g., Georgia to Maine). If the MSLP-based definition were used, the percentage of all CONUS landfalling major hurricanes from Georgia to Maine would increase to 20% (16 out of 80).

If we focus on the past twenty years (1999-2018), there have been 11 major hurricane landfalls using the V_{max} definition, with none making landfall from Georgia to Maine (Fig. 3). If the MSLP definition were used, 19 major hurricane landfalls would have occurred, with five making landfall from Georgia to Maine. All five of the major hurricanes using the MSLP definition

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making landfall from Georgia to Maine caused at least $5 billion in normalized damage, with four of the five causing at least $10 billion in normalized damage.

If the 960 hPa threshold were used to classify hurricanes as major, we also would not have had the frequently-discussed CONUS major hurricane landfall drought that existed from 2006-2016 (Hall and Hereid 2015). Hart et al. (2016) also noted the absence of a major hurricane landfall drought when using a 960 hPa threshold. Figure 4a displays the trend in CONUS major hurricane landfalls (V_{max} >= 96 kt) since 1900 using the Klotzbach et al. (2018) dataset updated with 2018's CONUS hurricane landfalls, while Fig. 4b displays a similar trend in CONUS hurricane landfalls using the 960 hPa threshold. Neither of these trends are statistically significant, as was previously noted for the V_{max} threshold in Klotzbach et al. (2018).

An additional way that the V_{max} vs. MSLP threshold can be examined is by evaluating how often hurricanes with normalized damage exceeding specific thresholds are classified as major hurricanes. Figure 5 displays the results for three different thresholds: $5 billion, $10 billion and $20 billion. Of the 61 hurricanes making landfall that caused >= $5 billion in damage, 69% of all hurricanes are classified as major hurricanes using V_{max}, while 84% are classified as major hurricanes using MSLP. MSLP also correctly identified more hurricanes causing $10 billion and $20 billion in damage. All 25 hurricanes generating >= $20 billion in damage had MSLP <=960 hPa, while 3 hurricanes generating >= $20 billion had V_{max} <96 kt (Ike in 2008, Sandy in 2012 and Florence in 2018). While more hurricanes are classified as major using our MSLP threshold than using the V_{max} threshold, we argue that these additional storms have caused similar levels of damage to the median major hurricane using the V_{max} threshold and warrant being classified as

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major hurricanes given their overall intensity (as measured by MSLP). In addition, 48% (80 out of 165) of CONUS landfalling hurricanes would be classified as major hurricanes using the MSLP threshold, and consequently, we argue that this new classification technique would not simply involve Saffir-Simpson Scale inflation.

f. CONUS landfalling hurricane fatality relationship with V_{max} and MSLP

While there are many different causes for fatalities from hurricanes (Rappaport 2014), ~50% of all fatalities during the period from 1963-2012 were caused by storm surge, while ~25% were caused by freshwater floods and mudslides. This again reinforces the importance of highlighting waterborne physical damage and humanitarian impact risks from TCs. Here we examine direct fatalities from CONUS landfalling hurricanes from 1988-2018, using the fatality numbers that are provided in the National Hurricane Center Tropical Cyclone Reports available online at (http://www.nhc.noaa.gov/data/tcr/) from 1995-2018 and via the storm wallet archive from 1988-1994 (https://www.nhc.noaa.gov/archive/storm_wallets/atlantic/) and correlate them with both V_{max} and MSLP. We only examine direct fatalities during the recent period, where both hurricane forecast track skill and intensity skill has significantly improved relative to earlier in the 20th century (Rappaport et al. 2009). As has been done through the remainder of this analysis, we use rank correlations to eliminate the impacts of large outliers, such as Hurricane Katrina which was responsible for ~75% of all of the direct fatalities from CONUS hurricanes during the 31-year period examined. The correlation between V_{max} and direct fatalities is relatively weak (r_{rank} = 0.33, significant at the 5% level), while the correlation between MSLP and direct fatalities is much stronger (r_{rank} = 0.61, significant at the 1% level) (Fig. 6). The difference between the two correlations is significant at the 1% level. Given the improved

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relationship between MSLP and storm size (as measured by 50-kt wind radii) relative to V_{max}, the improved relationship between MSLP and direct fatalities makes physical sense.

We next examine three groups of fatality rankings during the 31-year period from 1988-2018 and compare it with Saffir-Simpson Scale rankings using V_{max} and our newly-proposed MSLP scale (Table 1). These three groups of fatalities are as follows: 0-5 fatalities (19 hurricane landfalls), 6-14 fatalities (15 hurricane landfalls) and 15 or more fatalities (15 hurricane landfalls). These equate to approximately tercile distributions given that several hurricanes had the same number of fatalities. During the period from 1988-2018, two landfalling TCs classified as hurricanes using V_{max} would not have been classified as hurricanes using MSLP (e.g., MSLP > 990 hPa): Charley's landfall in South Carolina in 2004 and Cindy's landfall in Louisiana in 2005 (plotted as Category 0 in Fig. S2). While the lower tercile (0-5 fatalities) and middle tercile (6-14 fatalities) have similar storm categorizations whether using V_{max} or MSLP (Fig. S2), the upper tercile (>= 15 fatalities) has many more hurricanes classified as major hurricanes using MSLP than using V_{max} (Fig. 7). For example, 8 out of the 15 hurricanes causing >=15 fatalities were classified as Category 1-2 hurricanes using V_{max}, while only two were classified as Category 1-2 hurricanes using MSLP.

We also note that using our MSLP-based classification, Hurricane Katrina was a Category 5 at landfall, joining Michael (2018) and Andrew (1992) as Category 5 hurricanes that have made CONUS landfall since 1988. Michael and Andrew were Category 5 hurricanes using either the V_{max}- or MSLP-based classifications, although both Andrew (Landsea et al. 2004) and Michael (Beven et al. 2019) were not upgraded operationally to Category 5 based on the V_{max} criteria. In

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the case of Andrew, the upgrade to Category 5 for MSLP (from 932 hPa to 922 hPa) did not take place until after the season was over in the post-storm analysis (Rappaport 1993), while the upgrade to Category 5 for V_{max} did not occur until ten years later when a reanalysis was conducted (Landsea et al. 2004). In the next sub-section, we explore the relative uncertainty that exists in assigning hurricane intensity categories by V_{max} and MSLP, using Hurricane Michael's upgrade as an example.

g. Hurricane Michael's upgrade to Category 5 - a case study in V_{max} and MSLP uncertainty

Figs. 8a and 8b display the probability density function (PDF) for V_{max} for both the lifetime maximum intensity of Hurricane Michael (2018) at its operational analysis of 135 kt and the reanalyzed V_{max} of 140 kt (the uncertainty of the latter distribution matches that from Landsea and Franklin (2013) assuming their uncertainties are 95% confidence intervals). The initial operational analysis implied that there remained a 39% chance that Hurricane Michael was a Category 5. Even after the official upgrade to 140 kt, the confidence that Hurricane Michael was a Category 5 given the uncertainty is only 72%. Conversely, the PDF for the landfall pressure of 919 hPa is given in Fig. 8c. The V_{max} uncertainty is slightly less for an MSLP of 919 hPa than for the 935 hPa Category 4 hurricane example given in the introduction based on the Knaff and Zehr (2007) equations (3.7 kt instead of 4 kt). The supplemental information provides additional details on how the calculation of 3.7 kt of V_{max} uncertainty is obtained for a 919 hPa Category 5 hurricane. The probability that Hurricane Michael is a Category 5 using the revised MSLP-based scale is >99.9%. Consequently, Michael would have been classified as a Category 5 hurricane both operationally and in the best track with high confidence using our proposed MSLP-based Saffir-Simpson Scale definition.

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We note that 919 hPa is barely a Category 5 category using the original MSLP (<=920 hPa) on the Saffir-Simpson Scale (Simpson 1974) but is well within the Category 5 using our revised MSLP scale (<=925 hPa). There would obviously be more uncertainty in category if the MSLP were closer to a threshold value. However, given the V_{max} and MSLP uncertainty noted in Landsea and Franklin (2013), and the associated conversion of MSLP uncertainty to V_{max} uncertainty discussed in the introduction using equations from Knaff and Zehr (2007), MSLP should lead to a more confident Saffir-Simpson Scale categorization of real-time CONUS hurricane landfall intensity than using V_{max}.

4. Summary and Implications

Here we have shown that when examining CONUS landfalling hurricanes since 1900, MSLP explains ~60% of the variance in normalized damage, even without accounting for exposure differences (Chavas et al. 2012, Weinkle et al. 2018). This difference in skill has become most notable in recent years, likely due to larger-sized hurricanes such as Ike (2008) and Sandy (2012) which did much more damage than would be typically associated with hurricanes making landfall at Category 2 and Category 1 intensity, respectively. This improvement in skill may also be somewhat due to better independent estimates of V_{max} and MSLP in recent years. We also have shown that V_{max} and MSLP have similar correlations with normalized damage for Texas to Florida hurricanes, while MSLP is a much better predictor of normalized damage than is V_{max} for hurricanes making landfall from Georgia to Maine. MSLP is also considerably easier to measure with aircraft reconnaissance and has less uncertainty with it than does V_{max}.

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We argue that while V_{max} partially describes the overall wind threat, it provides less information on the overall storm risk to life and property than does MSLP. MSLP, on the other hand, is a useful metric in that it is strongly correlated with both V_{max} and storm size, which is directly related to storm surge (Irish et al. 2008) as well as a larger wind and rain footprint (Lonfat et al. 2007). The risk to human life is also more directly correlated to MSLP than to V_{max}, given the better relationship of MSLP with storm size. MSLP was a more skillful predictor of fatalities caused by CONUS landfalling hurricanes from 1988-2018 than was V_{max}.

Consequently, we recommend that more emphasis be placed on MSLP when assessing the potential risks from future landfalling hurricanes. Given that the Saffir-Simpson scale was developed to characterize the risk of hurricanes to the public, we propose classifying hurricanes in the future using MSLP as opposed to V_{max}. While no scale will ever perfectly account for the totality of storm risk to life and property (e.g., inland flooding), any improvements to better explain and warn the potential hurricane impacts to an increasingly vulnerable coastal and inland population is, in our view, a worthwhile endeavor.

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References

Aon, 2019: Weather, Climate and Catastrophe insight: 2018 Annual Report, 86 pp., http://thoughtleadership.aonbenfield.com/Documents/20190122-ab-if-annual-weather-climate-report-2018.pdf

Atkinson, G. D., and C. R. Holliday, 1977: Tropical cyclone minimum sea level pressure/maximum sustained wind relationship for the western North Pacific. *Mon. Wea. Rev.*, **105,** 421–427, https://doi.org/10.1175/1520-0493(1977)105%3C0421:TCMSLP%3E2.0.CO;2

Bakkensen, L. A. and R. O. Mendelsohn, 2016: Risk and adaptation: Evidence from global hurricane damages and fatalities. *J. Assoc. Environ. Resour. Econ.,* **3,** 555–587, https://doi.org/10.1086/685908.

Berg, R., 2009: National Hurricane Center Tropical Cyclone Report: Hurricane Ike, 55 pp., https://www.nhc.noaa.gov/data/tcr/AL092008_Ike.pdf

Beven, J. L. II, R. Berg, and A. Hagen, 2019: National Hurricane Center Tropical Cyclone Report: Hurricane Michael, 86 pp., https://www.nhc.noaa.gov/data/tcr/AL142018_Michael.pdf.

Blake, E. S., T. B. Kimberlain, R. J. Berg, J. P. Cangialosi, and J. L. Beven II, 2013:: National Hurricane Center Tropical Cyclone Report: Hurricane Sandy, 157 pp., https://www.nhc.noaa.gov/data/tcr/AL182012_Sandy.pdf

Cerveney, R. S., and L. E. Newman, 2000: Climatological relationships between tropical cyclones and rainfall. *Mon. Wea. Rev.,* **128,** 3329-3336, https://doi.org/10.1175/1520-0493(2000)128%3C3329:CRBTCA%3E2.0.CO;2.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-19-0062.1.

Chavas, D. R., and K. A. Emanuel, 2010: A QuikSCAT climatology of tropical cyclone size. *Geophys. Res. Lett.*, **37,** L18816, https://doi.org/10.1029/2010GL044558

Chavas, D. R., N. Lin, W. Dong, and Y. Lin, 2016: Observed tropical cyclone size revisited. *J. Clim.*, **29,** 2923-2939, https://doi.org/10.1175/JCLI-D-15-0731.1

Chavas, D. R., K. A. Reed, and J. A. Knaff, 2017: Physical understanding of the tropical cyclone wind-pressure relationship. *Nature Communications*, **8,** 1360, https://doi.org/10.1038/s41467-017-01546-9.

Chavas, D. R., E. Yonekura, C. Karamperidou, N. Cavanaugh, and K. Serafin, 2012: U.S. hurricanes and economic damages: Extreme value perspective. *Natural Hazards Review*, **14,** 237-246, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000102

Demuth, J., M. DeMaria, and J.A. Knaff, 2006: Improvement of advanced microwave sounder unit tropical cyclone intensity and size estimation algorithms. *J. Appl. Meteor.*, **45,** 1573-1581, https://doi.org/10.1175/JAM2429.1

Dvorak, V. F., 1975: Tropical cyclone intensity analysis and forecasting from satellite imagery. *Mon. Wea. Rev.*, **103,** 420–430, https://doi.org/10.1175/1520-0493(1975)103%3C0420:TCIAAF%3E2.0.CO;2.

Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proceedings of the National Academy of Sciences*, **114**, 12681-12684, https://doi.org/10.1073/pnas.1716222114

Franklin, J. L., M. L. Black, and K. Valde, 2003: GPS dropwindsonde wind profiles in hurricanes and their operational implications. *Wea. Forecasting*, **18,** 32-44, https://doi.org/10.1175/1520-0434(2003)018%3C0032:GDWPIH%3E2.0.CO;2

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0062.1.

Hall, T. R., and K. Hereid, 2015: The frequency and duration of US hurricane droughts. *Geophy. Res. Lett.*, **42,** 3482-3485, https://doi.org/10.1002/2015GL063652

Hart, R. E., D. R. Chavas, and M. P. Guishard, 2016: The arbitrary definition of the current Atlantic major hurricane landfall drought. *Bull. Amer. Meteorol. Soc.*, **97,** 713-722, https://doi.org/10.1175/BAMS-D-15-00185.1.

Hebert, C. G., R. A. Weinzapfel, and M. A. Chambers, 2008: The hurricane severity index—A new way of estimating a tropical cyclone's destructive potential. Tropical Meteorology Special Symp./19th Conf. on Probability and Statistics, New Orleans, LA, Amer. Meteor. Soc., JP1.4, https://ams.confex.com/ams/88Annual/techprogram/paper_135054.htm.

Hendricks, E. A., W. H. Schubert, Y. Chen, H. Kuo, and M. S. Peng, 2014: Hurricane eyewall evolution in a forced shallow-water model. *J. Atmos. Sci.*, **71**, 1623–1643, https://doi.org/10.1175/JAS-D-13-0303.1

Holland, G. J., 2008. A revised hurricane pressure-wind model. *Mon. Wea. Rev.* **136**, 3432-3445. https://journals.ametsoc.org/doi/pdf/10.1175/2008MWR2395.1

Howden, S., D. Gilhousen, N. Guinasso, J. Walpert, M. Sturgeon, and L. Bender, 2008: Hurricane Katrina winds measured by a buoy-mounted sonic anemometer. *J. Atmos. Oceanic Technol.*, **25**, 607–616, https://doi.org/10.1175/2007JTECHO518.1

Houston, S. H., W. A. Shaffer, M. D. Powell, and J. Chen, 1999: Comparisons of HRD and SLOSH surface wind fields in hurricanes: Implications for storm surge modeling. *Wea. Forecasting*, **14,** 671-686, https://doi.org/10.1175/1520-0434(1999)014<0671:COHASS>2.0.CO;2

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0062.1.

Irish, J. L., D. T. Resio, and J. J. Ratcliff, 2008: The influence of storm size on hurricane surge. *J. Phys. Oceanogr.*, **38**, 2003–2013, https://doi.org/10.1175/2008JPO3727.1

Kantha, L., 2006: Time to replace the Saffir–Simpson hurricane scale? *Eos, Trans. Amer. Geophys. Union*, **87,** 3–6, https://doi.org/10.1029/2006EO010003.

Kimball, S. K., and M. S. Mulekar, 2004: A 15-year climatology of North Atlantic tropical cyclones. Part I: Size parameters. *J. Climate*, **17,** 3555-3575, https://doi.org/10.1175/1520-0442(2004)017%3C3555:AYCONA%3E2.0.CO;2

Klotzbach, P. J., S. G. Bowen, R. Pielke Jr., and M. M. Bell, 2018: Continental United States landfall frequency and associated damage: Observations and future risks. *Bull. Amer. Meteor. Soc.*, **99,** 1359-1376, https://doi.org/10.1175/BAMS-D-17-0184.1.

Klotzbach, P. J., and C. W. Landsea, 2015: Extremely intense hurricanes: Revisiting Webster et al. (2005) after 10 years, *J. Climate*, **28,** 7621-7629, https://doi.org/10.1175/JCLI-D-15-0188.1.

Knaff, J. A., S.P. Longmore, and D.A. Molenar, 2014: An objective satellite-based tropical cyclone size climatology. J. Climate, **27,** 455-476, https://doi.org/10.1175/JCLI-D-13-00096.1.

Knaff, J. A. and Zehr, R. M. 2007. Reexamination of tropical cyclone wind-pressure relationships. *Wea. Forecasting*, **22**, 71–88, https://journals.ametsoc.org/doi/pdf/10.1175/WAF965.1

Knapp, K. R., J. A. Knaff, C. R. Sampson, G.M. Riggio, and A. D. Schnapp, 2013: A pressure-based analysis of the historical western North Pacific tropical cyclone intensity record. *Mon. Wea. Rev.*, **141,** 2611–2631, https://doi.org/10.1175/MWR-D-12-00323.1.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0062.1.

Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The International Best Track Archive for Climate Stewardship (IBTrACS): Unifying tropical cyclone best track data. *Bulletin of the American Meteorological Society*, **91**, 363-376, https://doi.org/10.1175/2009BAMS2755.1

Koba, H., Hagiwara, T., Osano, S. & Akashi, S., 1990: Relationship between the CI-number and central pressure and maximum wind speed in typhoons (in Japanese). *J. Meteor. Res.*, **42,** 59–67.

Kossin, J. P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature,* **558,** 104-107, https://doi.org/10.1038/s41586-018-0158-3.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.*, **121,** 1703-1713, https://doi.org/10.1175/1520-0493(1993)121%3C1703:ACOIMA%3E2.0.CO;2

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, https://doi.org/10.1175/MWR-D-12-00254.1.

Landsea, C. W., J. L. Franklin, C. J. McAdie, J. L. Beven II, J. M. Gross, B. R. Jarvinen, R. J. Pasch, E. N. Rappaport, J. P. Dunion and P. P. Dodge, 2004: A reanalysis of Hurricane Andrew's intensity. *Bull. Amer. Meteor. Soc.*, **85,** 699-712, https://doi.org/10.1175/BAMS-85-11-1699

Lee, I. A., and K. J. Preacher, 2013. Calculation for the test of the difference between two dependent correlations with one variable in common [Computer software]. Available from http://quantpsy.org.

Lonfat, M., R. Rogers., T. Marchok, and F. D. Marks, 2007: A parametric model for predicting hurricane rainfall. *Mon. Wea. Rev.*, **135,** 3086-3097, https://doi.org/10.1175/MWR3433.1

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-19-0062.1.

Merrill, R. T., 1984: A comparison of large and small tropical cyclones. *Mon. Wea. Rev.,* **112,** 1408-1418, https://doi.org/10.1175/1520-0493(1984)112%3C1408:ACOLAS%3E2.0.CO;2

National Research Council, 1984: Hurricane Alicia, Galveston and Houston, Texas, August 17-18, 1983. National Academies Press, 171 pp, https://doi.org/10.17226/19411

Nolan, D. S., J. A. Zhang, and E. Uhlhorn, 2014: On the limits of estimating the maximum wind speeds in hurricanes. *Mon. Wea. Rev.*, **142,** 2814-2837, https://doi.org/10.1175/MWR-D-13-00337.1.

Pielke Jr., R. A., J. Gratz, C. W. Landsea, D. Collins, M. A. Saunders, and R. Musulin, 2008: Normalized hurricane damages in the United States. *Natural Hazards Review*, **9,** 29-42, https://doi.org/10.1061/(ASCE)1527-6988(2008)9:1(29)

Pike, J. M. and D.W. Bargen, 1976: The NCAR digital barometer. *Bull. Amer. Meteor. Soc.*, **57,** 1106–1112, https://doi.org/10.1175/1520-0477(1976)057<1106:TNDB>2.0.CO;2

Pilkington, S., and H. Mahmoud, 2016: Using artificial neural networks to forecast economic impact of multi-hazard hurricane-based events. *Sustainable Resilient Infrastruct.*, **1,** 63–83, https://doi.org/10.1080/23789689.2016.1179529.

Powell, M. D., and T. A.Reinhold, 2007: Tropical cyclone destructive potential by integrated kinetic energy. *Bull. Amer. Meteor. Soc.*, **88,** 513–526, https://doi.org/10.1175/BAMS-88-4-513.

Rappaport, E. N., 1993: Preliminary Report: Hurricane Andrew, 38 pp., https://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1992/andrew/prenhc/.

Rappaport, E. N., 2014: Fatalities in the United States from Atlantic tropical cyclones: New data and interpretation. *Bull. Amer. Meteor. Soc.*, **95,** 341-346, https://doi.org/10.1175/BAMS-D-12-00074.1.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-19-0062.1.

Rappaport, E. N., and Coauthors, 2009: Advances and challenges at the National Hurricane Center. *Wea. Forecasting*, **24,** 395-419, https://doi.org/10.1175/2008WAF2222128.1.

Saffir, H. S., 1973: Hurricane wind and storm surge. *Mil. Eng.*, **423,** 4-5.

Schott, T., and Coauthors, 2012: The Saffir–Simpson hurricane wind scale. National Hurricane Center, http://www.nhc.noaa.gov/pdf/sshws.pdf.

Simpson, R. H., 1974: The hurricane disaster potential scale. *Weatherwise*, **27,** 169, 186.

Smith, A. B., and R. W. Katz, 2013: US billion-dollar weather and climate disasters: data sources, trends, accuracy and biases. *Nat. Hazards*, **67,** 387-410, https://doi.org/10.1007/s11069-013-0566-5.

Stewart, S. R., and R. Berg, 2019: National Hurricane Center Tropical Cyclone Report: Hurricane Florence, 98 pp., https://www.nhc.noaa.gov/data/tcr/AL062018_Florence.pdf.

Takagi, H., and W. Wu, 2016: Maximum wind radius estimated by the 50 kt wind radius: improvement of storm surge forecasting over the western North Pacific. *Natural Hazards and Earth System Sciences*, **16,** 705-717, https://doi.org/10.5194/nhess-16-705-2016

Uhlhorn, E. W., and P. G. Blake, 2003: Verification of remotely sensed sea surface winds in hurricanes. *J. Atmos. Oceanic Technol.*, **20,** 99-116., https://doi.org/10.1175/1520-0426(2003)020%3C0099:VORSSS%3E2.0.CO;2.

Walker, A. M., D. W. Titley, M. E. Mann, R. G. Najjar, and S. K. Miller, 2018: A fiscally based scale for tropical cyclone storm surge. *Wea. Forecasting*, **33,** 1709-1723, https://doi.org/10.1175/WAF-D-17-0174.1.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0062.1.

Weinkle, J., C. W. Landsea, D. Collins, R. Masulin, R. P. Crompton, P. J. Klotzbach, and R. Pielke Jr., 2018: Normalized hurricane damage in the continental United States: 1900-2017. *Nature Sustainability*, **1,** 803-813, https://doi.org/10.1038/s41893-018-0165-2.

Willoughby, H.E., R. W. R. Darling, and M. E. Rahn, 2006: Parametric representation of the primary hurricane vortex. Part II: A new family of sectionally continuous profiles. *Mon. Wea. Rev.*, **134**, 1102–1120, https://doi.org/10.1175/MWR3106.1..

Zhai, A.R. and Jiang, J.H., 2014. Dependence of US hurricane economic loss on maximum wind speed and storm size. *Environmental Research Letters*, **9,** 064019, https://doi.org/10.1088%2F1748-9326%2F9%2F6%2F064019.

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Sidebar: Relevance to the Insurance Industry

The financial consequences of hurricanes can be substantial for both private citizens, commercial interests, and governments. One of the important players in both the risk mitigation and recovery phases surrounding these events is the insurance industry. Insurers use various methods of data collection, actuarial analysis, and modeling to determine hurricane risk based on current levels of vulnerable exposure, population, and the historical tracks and costs of past events.

Among these methods is catastrophe modeling, which in its simplest form is a simulation of a potential event scenario that includes an insurance portfolio (a combined listing of the location and value of insured assets such as buildings or automobiles) to determine the event's financial implications. Within these wind and/or storm surge-modeled scenarios are mathematical formulations that seek to interpret surface wind and pressure relationships and their overland degradation patterns. To determine actual losses, these models further incorporate MSLP/V_{max} with other hazard parameters -- such as the duration of wind, storm surge, and/or inland flood -- and vulnerability parameters that capture physical assets with considerations such as type of construction, year built, and location. Wind-pressure profile relationship techniques are implemented into both stochastic (hypothetical) and historical event scenarios as one way to calibrate model performance to more accurately match incurred economic and insured losses. Further adjustments to the vulnerability functions/curves within the model are very important in helping to better align loss results. An insured loss is the portion of a resultant economic loss cost that is covered by insurance. It is worth noting that V_{max} and its speed of decay while over land, plus the type of terrain over which a storm crosses, remain very important components in loss modeling. Many studies, such as Willoughby et al. (2006), Knaff and Zehr (2007), Holland

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(2008) and Chavas et al. (2017), have more fully analyzed hurricane wind-pressure relationships that prove critical in model development.

Beyond catastrophe modeling, the insurance industry further uses MSLP as a potential trigger for specifically-placed policies or catastrophe bonds. A catastrophe bond is used by re-insurers or governments to diversify and transfer risk to a variety of bond investors. This provides these groups a means of financial protection in the advent of a major natural catastrophe. For example, if a storm reaches a certain MSLP or V_{max} threshold, this could trigger an insurance payout regardless of how much (or little) incurred damage occurs. These types of contracts are increasingly common for all types of natural and man-made perils. MSLP is not the only parameter utilized as a trigger for weather-based events. Other parameters may include V_{max}, temperature, rainfall, the timing/location of "official agency" declared watches and warnings, and the geographic location of an event. These policies are a unique way to bring insurance availability into non-traditional, disaster-prone markets that are currently underserved or faced with high underinsurance. Many high-stakes financial implications are based on weather-based information, with MSLP being one of many important parameters for the insurance industry.

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Table 1: Saffir-Simpson Hurricane Scale with current V_{max} criteria, proposed MSLP criteria and original MSLP criteria from Simpson (1974). Also provided in parentheses are the percentage of Atlantic storms from 1979-2018 whose lifetime maximum intensity exceeded the weakest intensity criteria for each category threshold.

Category	V_{max} (kt)	Revised MSLP (hPa)	Original MSLP (hPa)
1	64-82 (52%)	976-990 (55%)	>980 (n/a)
2	83-95 (31%)	961-975 (32%)	965-979 (38%)
3	96-112 (21%)	946-960 (20%)	945-964 (24%)
4	113-136 (13%)	926-945 (12%)	920-944 (12%)
5	>=137 (4%)	<=925 (4%)	<=919 (3%)

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FIGURE CAPTIONS

Fig 1. Normalized hurricane damage relationship with V_{max} and MSLP. (a) For CONUS normalized damage vs. V_{max} (1900-2018), (b) for CONUS normalized damage vs. MSLP (1900-2018), (c) for CONUS normalized damage vs. V_{max} (2007-2018), (d) for CONUS normalized damage vs. MSLP (2007-2018), (e) for Georgia to Maine normalized damage vs. V_{max} (1900-2018) and (f) for Georgia to Maine normalized damage vs. MSLP (1900-2018). Individual CONUS hurricane landfalls are labeled on panels (c) and (d).

Fig. 2. 50-knot wind radii at the time of CONUS hurricane landfall versus (a) V_{max} and (b) MSLP for all CONUS landfalling hurricanes from 1988-2018.

Fig. 3. Landfall location of CONUS major hurricane landfalls from 1999-2018 using the (a) V_{max} definition (>=96 kt) and the (b) MSLP definition (<=960 hPa). Larger hurricane symbols represent more normalized hurricane damage.

Fig. 4. CONUS major hurricane landfalls by year since 1900 using the (a) V_{max} definition (>= 96 kt) and the (b) MSLP definition (<=960 hPa).

Fig. 5. Percentage of landfalling hurricanes where the major hurricane threshold was met using the V_{max} and MSLP definitions when normalized damage exceeded \$5 billion, \$10 billion and \$20 billion, respectively.

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Fig. 6. As in Fig. 2 but for CONUS hurricane-caused direct fatalities from 1988-2018.

Fig. 7. Histogram displaying the number of hurricanes receiving each Saffir-Simpson scale classification using V_{max} and MSLP definitions for the upper tercile of fatalities (>= 15) from 1988-2018.

Fig. 8. Probability density functions (PDF) for (a) an operational intensity of 135 kt, (b) a reanalyzed intensity of 140 kt and (c) an MSLP of 919 hPa. For (c), MSLP values were converted to winds using the Knaff and Zehr (2007) wind-pressure relationship. PDF widths are from the Landsea and Franklin (2013) NHC forecaster survey, assuming their uncertainty estimates correspond to 95% confidence intervals. The black vertical lines represent the Category 5 threshold using V_{max} in panels a and b and the Category 5 threshold using MSLP in panel c. The pressure-derived winds using the Knaff and Zehr (2007) equation are labeled below panel c.

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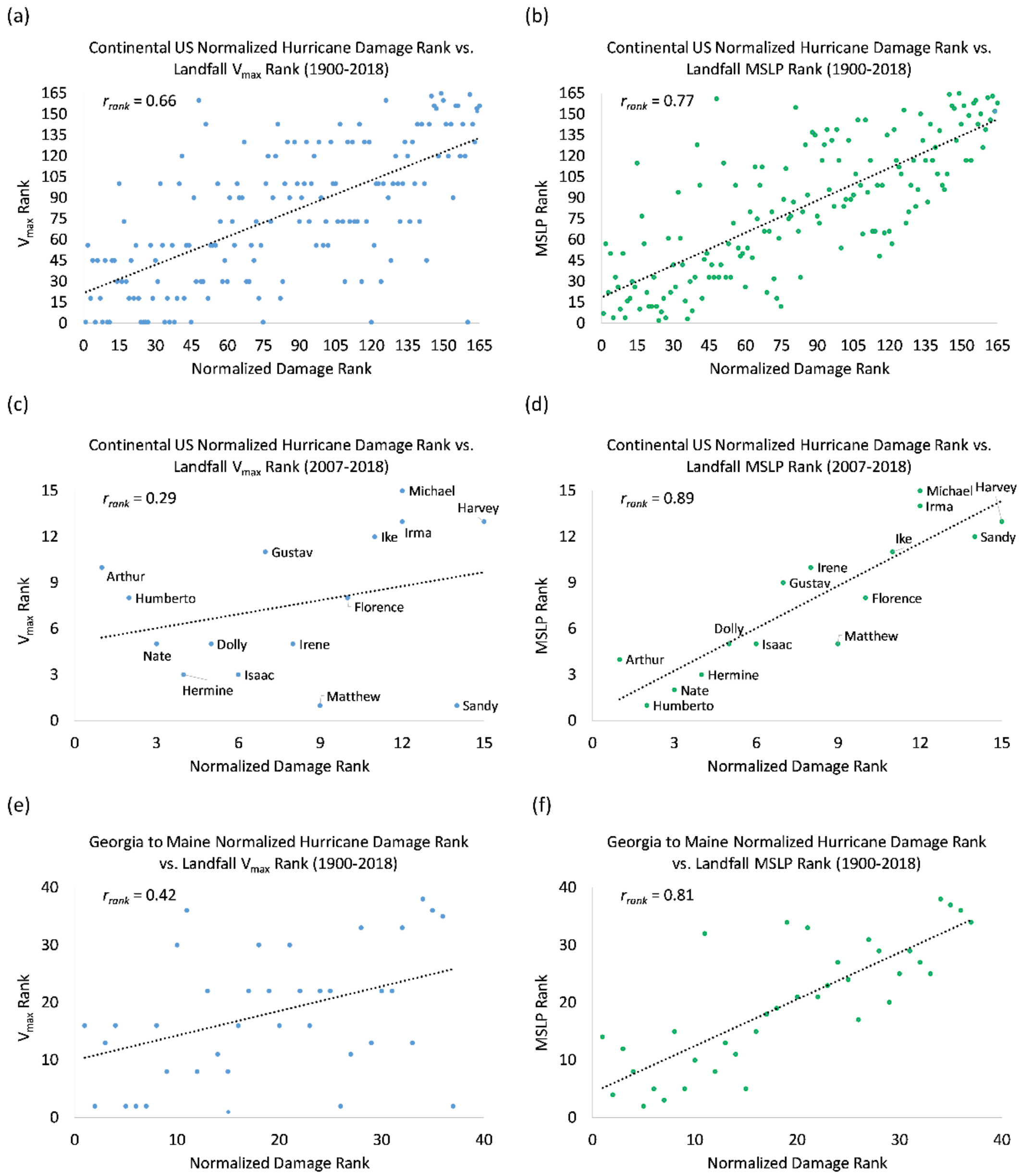

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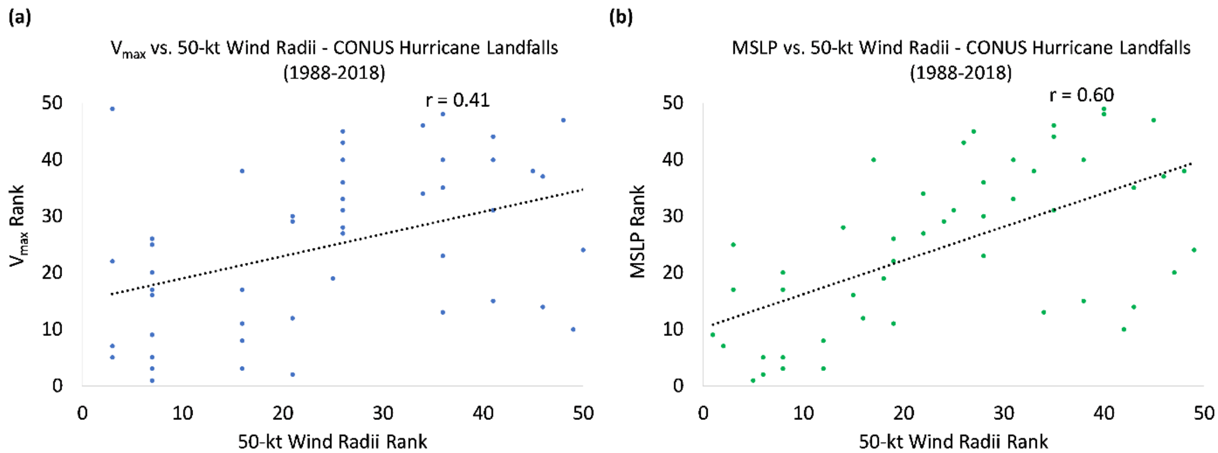

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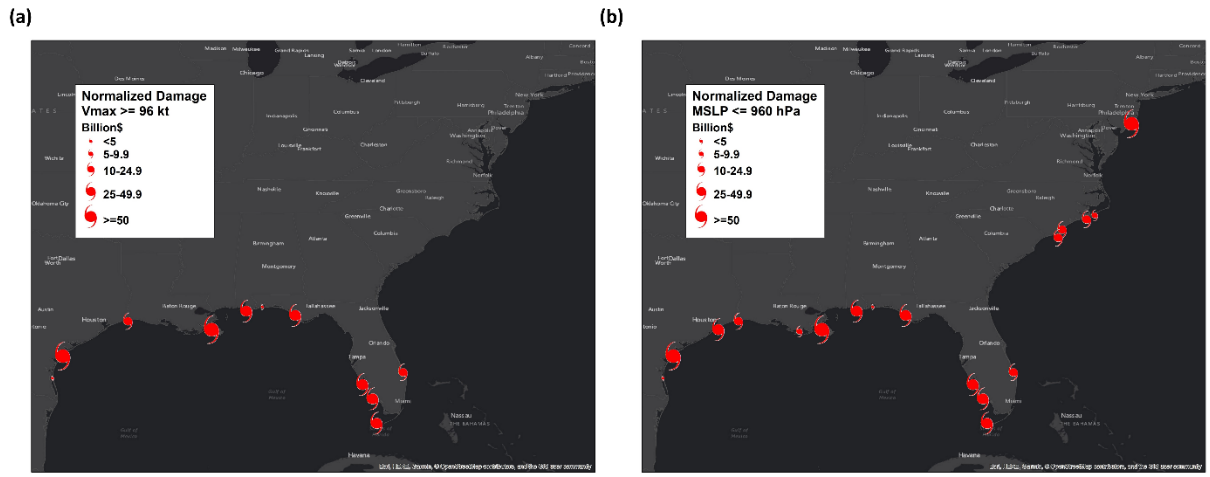

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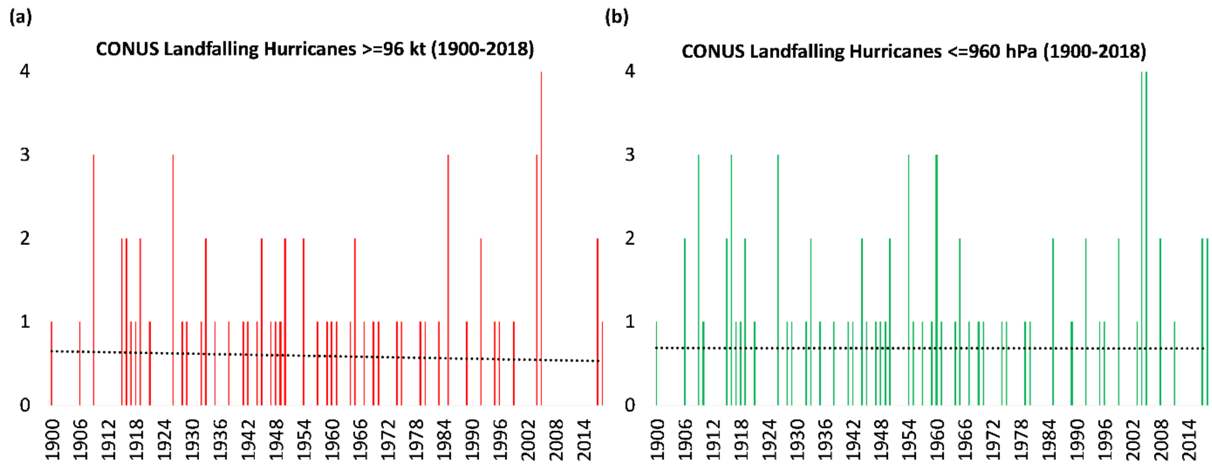

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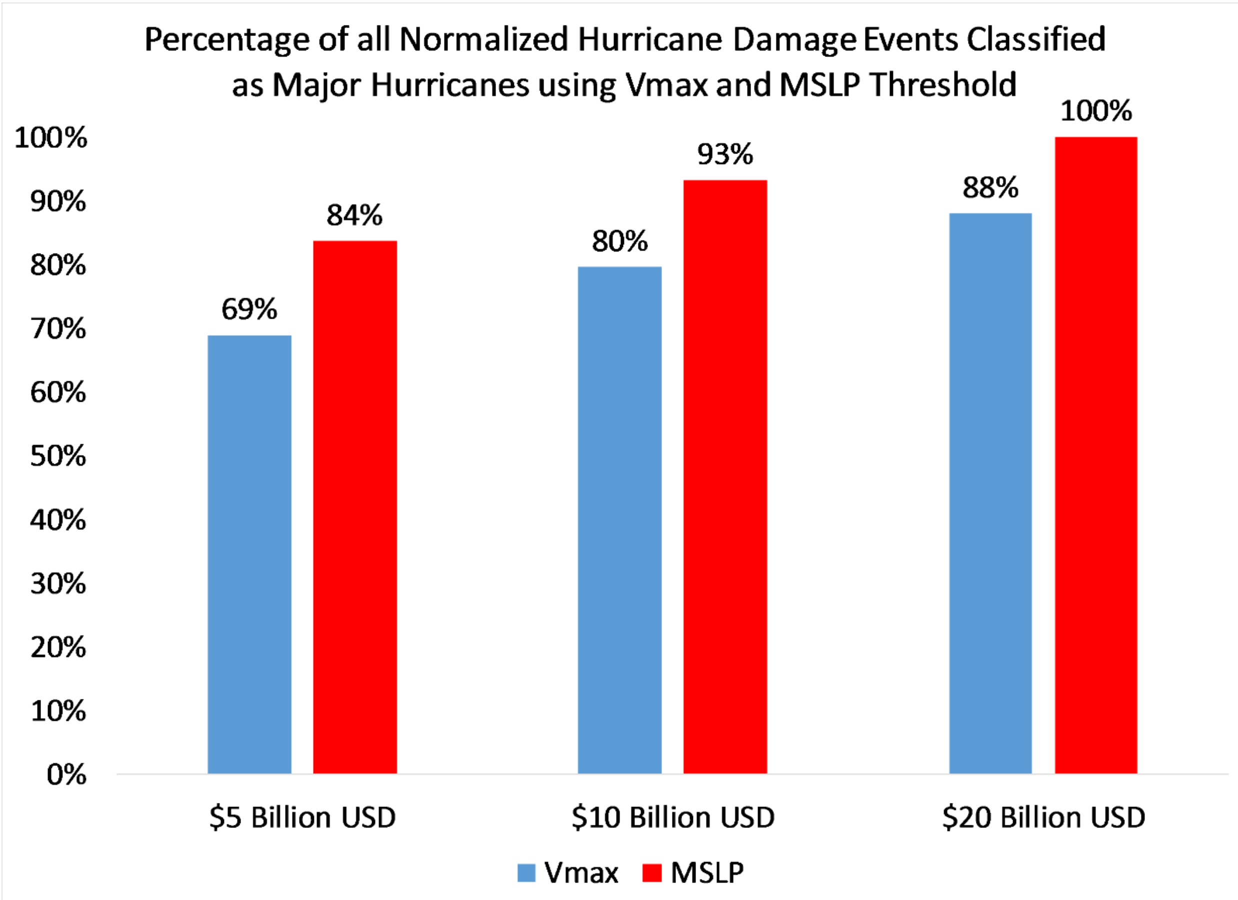

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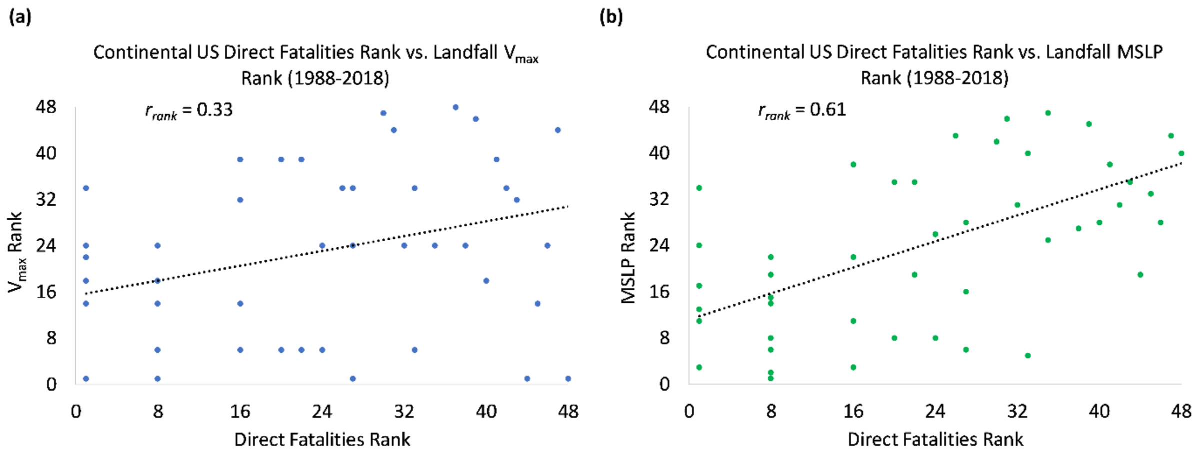

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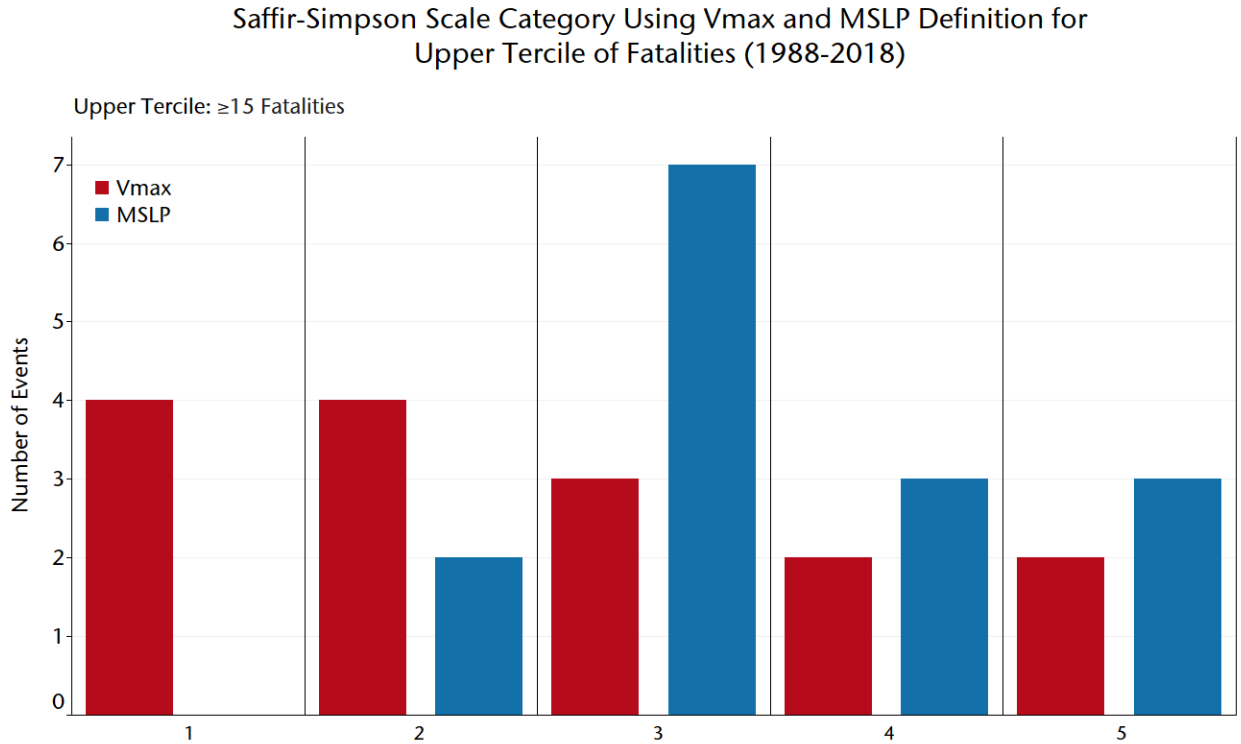

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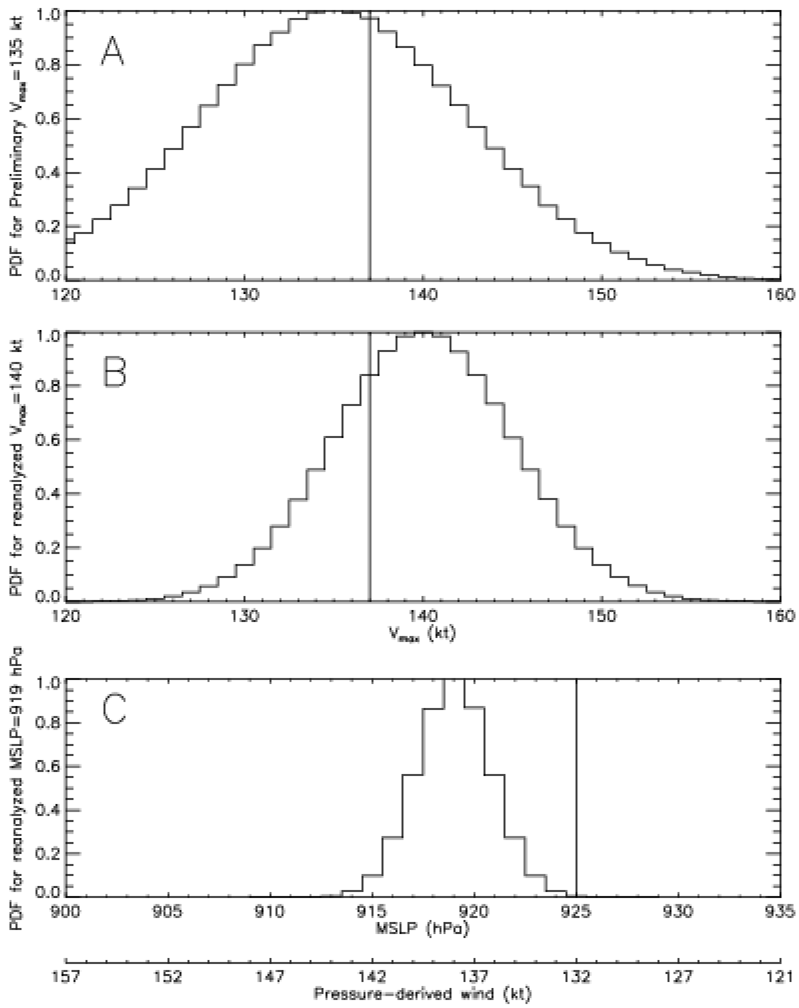

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