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Recent Rebounding of the Post-Landfall Hurricane Wind Decay Period Over the Continental United States

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Key Points:

- The wind decay period and decay distance are introduced to quantify the longevity of an inland moving tropical cyclone at a certain intensity level
- Prior to 1980, hurricanes making landfall over the continental United States show a downward trend of the wind decay period but rebounds significantly after 1980
- A possible correlation between the hurricane wind decay period and the Atlantic Multidecadal Oscillation is found

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Abstract The hurricane post-landfall wind speed decay is closely linked to the inland damage potential. We introduce the wind decay period as a new metric for assessing the time required for a landfalling hurricane to dissipate to the intensity below tropical storm strength. In the continental United States, the wind decay period was generally decreasing during 1900–1979 but significantly increased during 1980–2019. The 120-year trend pattern of the wind decay period has been found to be correlated with the Atlantic Multidecadal Oscillation. Meanwhile, we show that the storm's distance of movement is not changing simultaneously with the decay period due to the variance of storm translation speed. The spatial variation of the wind decay is also confirmed. While the majority of the historical Gulf landfall hurricanes decayed below tropical storm strength, landfalling hurricanes over Florida in particular, tend to cross the peninsula retaining wind speeds greater than 34-kt.

Plain Language Summary The destructive forces from a hurricane can penetrate far inland. The wind speed decay after hurricanes making landfall is critical for estimating potential inland damages. We introduce the wind decay period as a measurement of the time required for a landfalling hurricane to decay below tropical storm strength. The wind decay period helps quantify the longevity of the storm moving inland at a certain intensity. With the focus on the period 1900–2019, hurricanes making landfall over the continental United States show a decrease of longevity before 1980 but significantly increase thereafter. This trend shows a relationship to the Atlantic Multidecadal Oscillation. Meanwhile, the distance of the storm moving over land is not increasing with longevity, indicating the variance of the storm's speed of movement also plays an important role. Spatial variations exist where landfalling hurricanes over the Atlantic East coast and Florida peninsula are likely to turn back to the ocean without decaying to below the tropical storm strength.

1. Introduction

Landfalling hurricanes (tropical cyclones [TCs] with a maximum sustained wind speed [MSW] over 64-kt) contribute to significant life and economic losses in the United States. Although coastal cities experience major threats of a hurricane particularly due to storm surge, hurricanes moving inland can bring substantial damages from strong wind and torrential rains (Rappaport, 2000). Once hurricanes are over land, they weaken due to the loss of thermal and moisture supply. High wind speeds associated with TCs also exponentially diminish after landfall under the ideal conditions where the land surface is assumed cool and dry (DeMaria et al., 2006; Kaplan & DeMaria, 1995). However, in real-world cases, hurricane wind speed decay does not strictly follow the ideal exponential curve but depends on environmental conditions (Andersen et al., 2013; Kishtawal et al., 2012). Since several studies have demonstrated the power-law relationship between the MSW and hurricane economic losses (e.g., Murnane & Elsner, 2012; Zhai & Jiang, 2014), hurricanes obtaining a weak intensity decay over land could bring more potential damages to the inland region.

The wind decay of hurricanes making landfall over the continental United States was described by an empirical model (Kaplan & DeMaria, 1995). However, the empirical model is dependent on the landfall MSW; comparative analysis of TC inland wind decay could be biased by the occurrence of intense TCs. While the spatial variance is also found in TCs making landfall from different portions of the US coast (Kruk et al., 2010; Malkin, 1959), the temporal variation of the hurricane inland wind decay has not been a focus of studies until a recent study applied the decay timescale and showed that the first-day wind decay rate from a typical landfalling hurricane in the North Atlantic is 40% less now compared to those in the 1960s (Li &

10.1029/2020GL092072

Chakraborty, 2020). Although the first-day slower decay of a landfall hurricane has raised the concerns of greater potential TC inland wind hazards in a changing climate, it may relate to long-term climate modes. In addition, the destructive forces from a hurricane can be sustained days after landfall and penetrate far inland; measuring the temporal variation of the hurricane wind decay without a constant time constrain could provide better insight from the hazard's perspective. Therefore in this study, we introduce the wind decay period as a new metric describing the longevity of an inland moving hurricane during its intensity drop from a Saffir-Simpson Hurricane Wind Scale (SSHWS) Category-1 (≥64-kt) to below the TS intensity (<34-kt). The hurricane records back to 1900 are employed to explore the potential relationship between the hurricane inland wind decay and the long-term climate mode. In considerations of the wind penetration, the TC pathway during the fixed wind speed changes is also obtained by the decay distance.

2. Materials and Methods

2.1. Data

The inland TC data for the continental United States are from the National Hurricane Center's North Atlantic Hurricane Database (HURDAT2; Landsea & Franklin, 2013) as archived in the International Best Track Archive for Climate Stewardship (IBTrACS; https://www.ncdc.noaa.gov/ibtracs/) version 4 (Knapp et al., 2010). The data set reports the TC MSW at each 6-h interval and has the 2019 hurricane season reanalysis completed to date. Due to the lack of satellite imaginary prior to 1966, some open ocean TCs might be missing from the data set (Truchelut & Hart, 2011; Truchelut et al., 2013). However, the landfalling TCs in the continental United States are considered relatively reliable since 1900 (Landsea, 2007; Landsea et al., 1999). This study therefore uses the landfalling TC data since 1900. It should be noted however that even with this relatively reliable period post 1900, data accuracy steadily improved through the years due to increasing the density of weather stations along the coast and the satellite technology. Therefore, the accuracy of the data, along with the analyses outcomes, should be considered in this context of data reliability.

Filtering inland moving hurricanes follows the criteria used by Li and Chakraborty (2020) with some modifications. The MSW of the first inland point should be greater than or equal to SSHWS Category-1 (≥64-kt). Second, for each landfalling hurricane, at least two consecutive TC tracking points inland were required. While the extratropical transition is known to impact TC intensity when moving into high latitudes (Evans & Hart, 2003), this study excludes extratropical cyclones. When treating multi-landfall hurricanes, each landfall counts as a separate event if it meets the above criteria. A total of 108 hurricanes (112 landfall events) were selected based on the filtering procedure described here.

2.2. Wind Decay Period and Decay Distance

Instead of using the wind decay rate, we are interested in the time period for inland moving TCs to undergo a fixed intensity drop. Hence, we introduce the decay period as a metric that counts the time required for a TC to decay from the defined upper MSW to the defined lower MSW. A hurricane's decay period after landfall is then expressed as the time difference ($T_{\text{upper-lower}}$) between its upper and lower defined MSW:

$$T_{\text{upper-lower}} = t_{\text{lower}} - t_{\text{upper}} \tag{1}$$

We note that since the hurricane track is recorded in a 6-h interval, the upper or lower bound MSW may not occur exactly at the interval but in a time between. To address this issue, we use the exponential decay function as it is widely agreed to describe the general TC inland intensity decay (Kaplan & DeMaria, 1995; Vickery, 2005). To find the corresponding time (t') of the desired wind speed ($v_{t'}$), we obtain t' by the two known nearest 6-h observations v_0 and v_t:

$$t' = \left[\ln\left(v_0\right) - \ln\left(v_{t'}\right)\right] t \,/\, \left[\ln\left(v_0\right) - \ln\left(v_t\right)\right] t = 6; t' \in \left(0, t\right) \tag{2}$$

The thresholds of the TC intensity reaching TS and SSHWS Category-1 hurricane strength are 34-kt and 64-kt, respectively. Since the TC data are recorded in a 5-kt increment, we define 35-kt as the lower and 65-kt as the upper bound for the analysis. The T_{65-35} describes the dissipation of a TC from a hurricane intensity

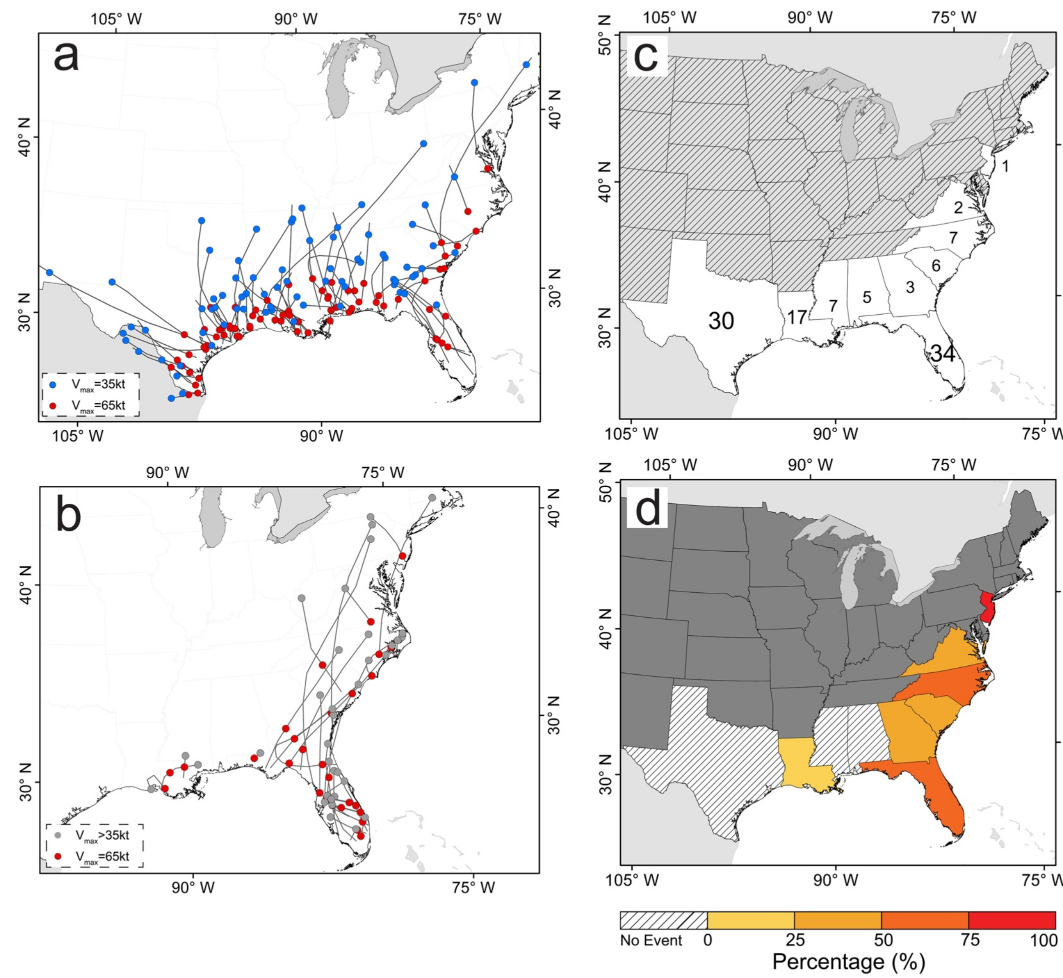

Figure 1. (a): Inland hurricane trajectory with 65-kt and 35-kt as the defined bound of the intensity decay; (b): Inland hurricane trajectory for landfall events not decayed below 35-kt. The Locations with MSW at 65-kt and the last inland locations at TC status are marked with red and gray respectively; (c): Number of landfall events by state; (d): Percentage of landfall events that were not decayed below 35-kt. MSW, maximum sustained wind; TC, tropical cyclones.

to below the TS stage. Inland moving hurricanes with higher T_{65-35} indicate longer durations at tropical TS speed level, thus greater potential damages.

The distance of a TC moving over the continent can be measured by summing the length of the trajectory between each 6-h observation. By acquiring the t' from the above calculation, the distance the storm moved during the inland decay period T_{65-35} can also be obtained. We define it as the decay distance.

It is worth noting that not all landfall events from this study met the requirement to process the calculation above. An inland moving TC could transition to an extratropical system or turn back to the ocean before the intensity drops below 35-kt. For example, 2016 Hurricane Hermine made landfall with the MSW at 70-kt, but it was maintained at 50-kt within 30 h of movement inland before its transition to an extratropical cyclone and movement back to the Atlantic Ocean. There are 35 out of the 112 total landfall events from the data that are exempted from the decay period and decay distance calculation.

3. Results

3.1. Spatial Distribution of Hurricane Landfall Decay

The TC pathway is critical in terms of spatially understanding TC intensity changes over land. Figure 1a and 1b delineate the trajectories of the hurricanes making landfall over the continental United States during the

10.1029/2020GL092072

study period. For each hurricane moving inland undergoing the 65–35 kt decay period, the line segment between the pair of the upper (65-kt) and lower (35-kt) bound of the MSW represents the decay distance (Figure 1a). In comparison, Figure 1b shows hurricane landfall events in which the inland MSW did not drop to below 35-kt. These events are highly clustered over the Florida peninsula and along the Atlantic East coast. Lack of dry air intrusion from a small landmass causes hurricanes following an East-West pathway over Florida to exit the peninsula before dissipating below TS intensity (Zandbergen, 2009). Also, hurricanes moving in a direction parallel to the coastline, especially over the Atlantic East coast, may be sustained with a greater proportion of the hurricane over the ocean while the center is inland (Schwerdt et al., 1979).

The observed spatial pattern is also presented by grouping all landfall events into each coastal state (Figure 1c). Figure 1d shows for each coastal state, the percentage of hurricane landfall events for which the inland TC MSW did not drop below the TS level. Coastal states from the Gulf Coast have either a lower percentage (Louisiana) compared to the Atlantic East coast, or no event (Texas, Mississippi, and Alabama) when considering landfall hurricanes that remain the inland MSW above 35-kt.

In contrast, considering the high frequency of occurrences, hurricanes making landfall over Florida (with 34 landfall events, see Figure 1c) has more than 50% of hurricanes maintain the MSW above 35-kt. Even for the landfall events that eventually dropped below 35-kt (blue dots in Figure 1a), only 1950 Hurricane Easy fell below 35-kt within the state. This highlights the concern of potentially great damage to the peninsula caused by destructive wind forces due to the prevalent weak intensity decay.

3.2. Time Series of Decay Period

To examine the temporal trend of the hurricane inland MSW decay, we begin by calculating the decay period and the decay distance of 65–35-kt from the 77 landfall events as was depicted in Figure 2. By setting three standard deviations (s.d.) from the mean as the threshold for large abnormal values, two outliers are removed from the decay period set (Figure 2a) while three are removed from the decay distance set (Figure 2b). It is noted that outliers from the decay period are not overlapping with those from the decay distance; we remove all five outliers as noted here to maintain the same data size for both data sets.

The decay period from the 72 landfall events is then averaged in the given year to build the time series (Figure 3a). There is no significant linear trend throughout the whole 120-year period. However, fitting with the locally estimated scatterplot smoothing (LOESS) shows a downward trend pattern with a fluctuation during 1900–1979 but a strong positive spike after 1980. To test the significance of the decadal trend, the time series is split into three sections, with each section containing a 40-year period (Figure 3b). The least-square linear regression trend is applied to each section. Both 1900–1939 and 1940–1979 period show significant downward trends at 95% confidence. In comparison, the positive spike of the decay period during 1980–2019 is also statistically significant. This indicates hurricanes making landfall over the continental United States are experiencing an upward trend of the decay period in more recent years. The observed increasing decay period during the last 40 years draws attention to the longevity of the landfalling hurricane as the potential losses from a landfalling hurricane are exponentially related to the MSW (Zhai & Jiang, 2014).

The trend pattern from the time series also draws attention to whether such a pattern is related to climate modes. The Atlantic Multidecadal Oscillation (AMO) describes the long-term changes of the North Atlantic sea surface temperature (SST) anomalies. Since the AMO positive phase has been related to more active Atlantic hurricane seasons (e.g., Klotzbach et al., 2018; Vimont & Kossin, 2007), we employed the monthly AMO index provided by the NOAA Physical Sciences Laboratory (PSL; https://psl.noaa.gov/data/timeseries/AMO/) to examine a possible correlation. We averaged the AMO index from May to November to compile the seasonal mean of the AMO index. As there are gap years from the decay period time series, we applied an 8-year block average to both the decay period time series and the seasonal AMO index to allow paired correlation analysis and remove the noise. While the AMO index already has the long-term trend removed, we also removed the 120-year trend for the decay period.

Figure 3c shows the superposed detrended decay period and the AMO index from 1900 to 2019, with the year on the *x*-axis representing a middle position of the 8-year block (e.g., 1980 represents years from 1977 to 1984). The years 1914 and 1920 were both observed as one of the lowest negative AMO values

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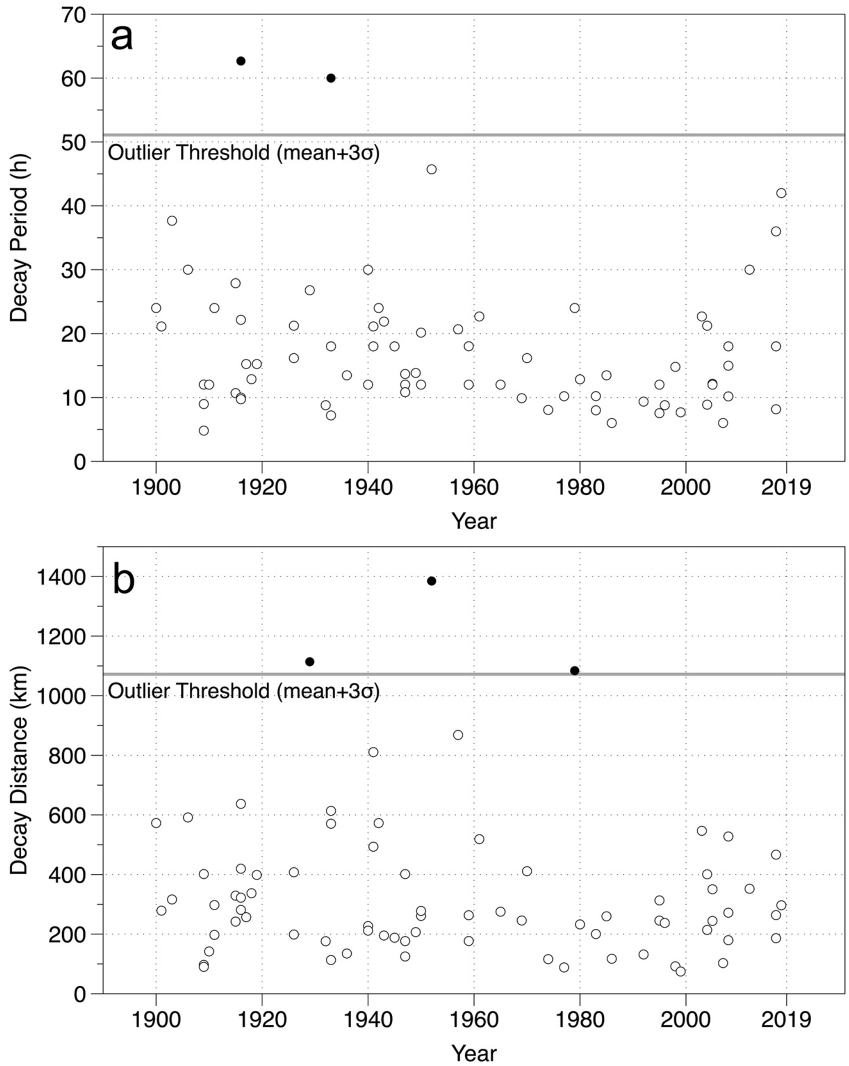

Figure 2. Distributions of (a): decay period and (b): decay distance over 1900–2019. Outliers defined by the 3 s.d. Threshold are highlighted in solid dots. SD, standard deviation.

(Klotzbach & Gray, 2008), while the recent positive phase was argued to have a strong weakening since 2013 (Klotzbach et al., 2015). Such turning points are also shown at the 1916 and 2012 block in the AMO 8-year block average (Figure 3c). Therefore, the correlation analysis considers the years between the 1916 (1913–1920) and 2012 (2009–2016) block-average position to cover a full cycle of the AMO. The strength of the correlation is reported by the Kendall's tau (non-parametric) at 5% significance. The significance of the Kendall rank correlation is more robust than its alternative Spearman rank correlation especially for a small sample size (Croux & Dehon, 2010). The correlation between the decay period and the AMO index shows a positive and significant relationship between the variables (Figure 3d). It's worth noting that the significant correlation only represents one AMO cycle with one positive and negative phase.

In comparison, the strong correlation between the first-day decay timescale and the SST was claimed by Li and Chakraborty (2020). The proposed reason is that hurricanes passing over warmer SSTs store greater storm moisture, and the high storm moisture helps slow down the intensity decay. Since AMO describes the anomaly of the SST decadal variation, our result also supports the positive relationship found between the SST and the rate of the hurricane inland wind decay.

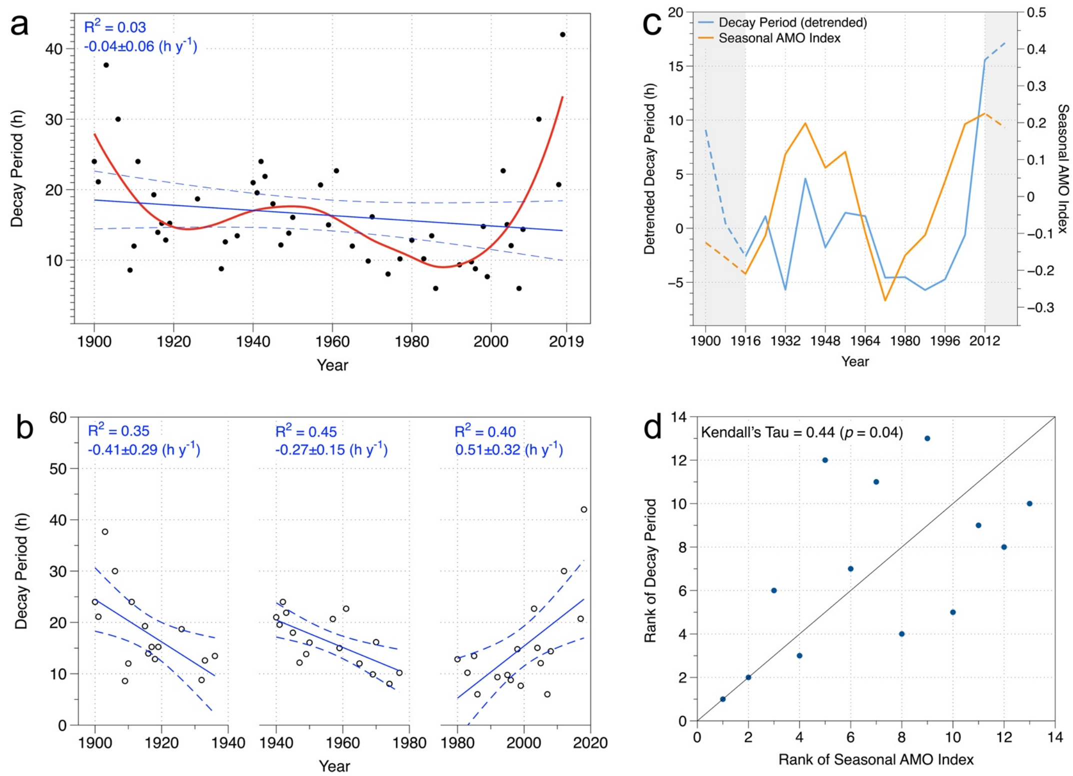

Figure 3. Yearly averaged decay period time series with the linear regression trend reported at the 95% confidence level. The trend is displayed with the blue solid line; Dashed lines represent the 95% confidence interval; (a) the linear regression trend is applied to the entire data set. The solid red line depicts the LOESS; (b) the 120-year time span is divided into three 40-year subsets with the linear regression trend applied. (c): Overlaying the 8-year block average of the detrended decay period with the seasonal AMO index. Solid lines depict the data we used for the correlation analysis; (d): Correlation between the rank of the detrended decay period and the seasonal AMO index. AMO, Atlantic multidecadal oscillation; LOESS, locally estimated scatterplot smoothing.

3.3. Time Series of Decay Distance

Following the same procedures as for the decay period, time series for the decay distance is also constructed. Similar to the decay period time series, the decay distance shows a non-significant downward trend through the entire time span (Figure 4a). The trend from the decay distance shows a similar pattern with the trend found in the decay period through the three sub-series but are not significant at the 5% level (Figure 4b). The detrended decay distance and the AMO index shows moderate correlation but is not significant at the 5% level ($p = 0.13$). While the decay period and the decay distance are considered proportional to each other, the possible causes of the non-significance of the decay distance could be a result of the storm's translation speed.

Considerable attention on the TC translation speed has occurred more recently in the literature as Hurricane Harvey created devastating impacts due to its longevity over Texas (e.g., Moon et al., 2019; Zhang et al., 2020). Although the observed trend on a global scale remained inconclusive (Kim et al., 2020; Kossin, 2018), under anthropogenic climate change, landfalling TCs on the Gulf Coast will likely experience a shift to a faster translation speed in the late 21st century due to northward meridional steering winds over the northern Gulf region (Hassanzadeh et al., 2020). In comparison, it is shown that the frequency of stalling events is increasing near the coast of the United States (Hall & Kossin, 2019). By employing a simple linear regression over the yearly averaged translation speed, no significant trend is found in each 40-year subset (Figure 5a). While this seems to contradict Hall and Kossin (2019), the translation speed here only considers tracks within the 65–35 decay period and therefore could cause the noted difference.

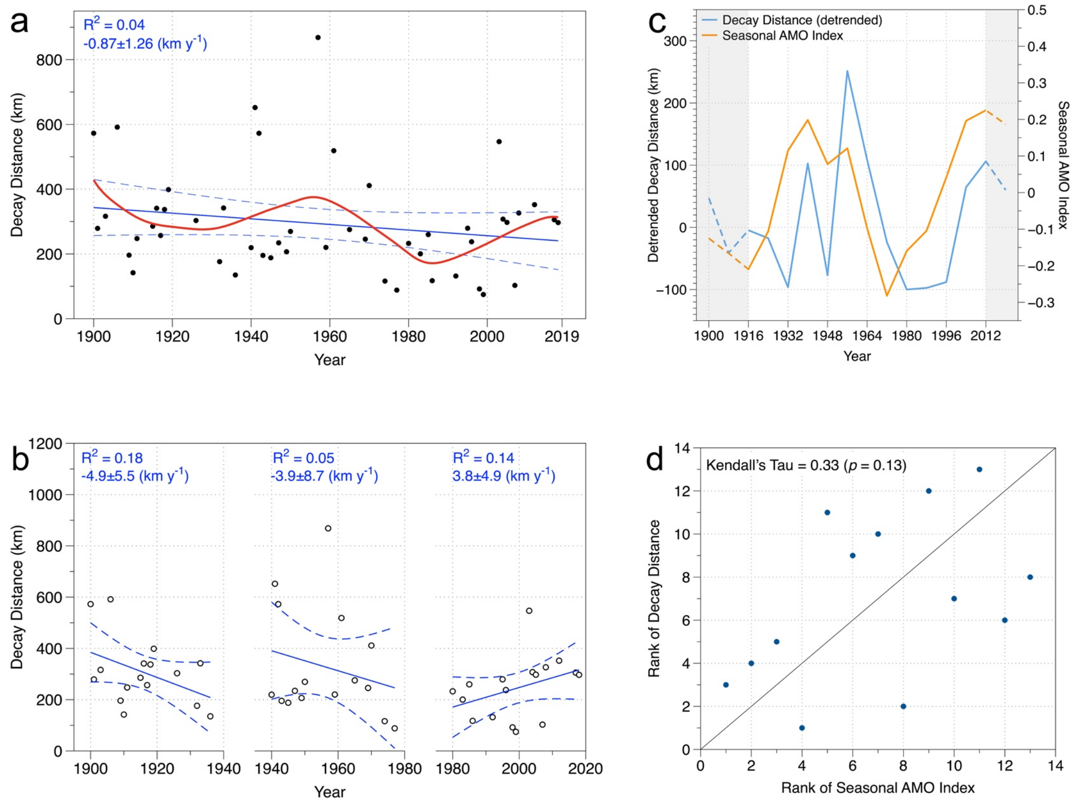

Figure 4. As in Figure 3 but for the decay distance.

By plotting each storm's translation speed presented by the decay distance against the decay period, Figure 5b depicts the variation of decay distance with given decay period. The mean translation speed is indicated by the slope of the diagonal line. The faster (slower) translation speed is determined by how far the landfall event is above (below) from the average. In 1940–1979, two landfall events falling above the +2 s.d. Threshold indicates faster-moving speed than the average translation speed. In the 1980–2019 period, two extreme slow-moving landfall events (Hurricane Harvey and 2018 Hurricane Florence) fell below the −2 s.d. These extreme events along with the variation of the translation speed give a possible explanation of the lack of statistical significance found from the trend of the decay distance, where a hurricane with a long decay period does not necessarily have long decay distance.

4. Conclusions

The focus of this article is on the temporal variation of the inland wind decay of landfalling hurricanes over the continental United States from 1900 to 2019. With the decay period and decay distance introduced as a new toolset, the manuscript examines the long-term changes of a hurricane's inland wind speed decay and provides a discussion of the potential driving forces.

First, from a spatial perspective, we found the Florida peninsula and the Atlantic East coast are highly clustered with landfalling hurricanes that did not drop their MSW below TS strength before transiting to an extratropical cyclone or turning back to the ocean. This confirms the existence of spatial variations of hurricane post-landfall wind decay along the US coast (Kruk et al., 2010). An East-West track trajectory with a lack of dry air intrusion from a small landmass, or the direction of movement parallel to the coast, may be the cause.

Next, we showed that the decay period of landfalling hurricanes over the US coast, in general, has significantly decreased prior to 1980 but significantly rebounds thereafter. Such a trend has shown a moderate correlation with the AMO index and provides support to the recent study showing the warmer SST

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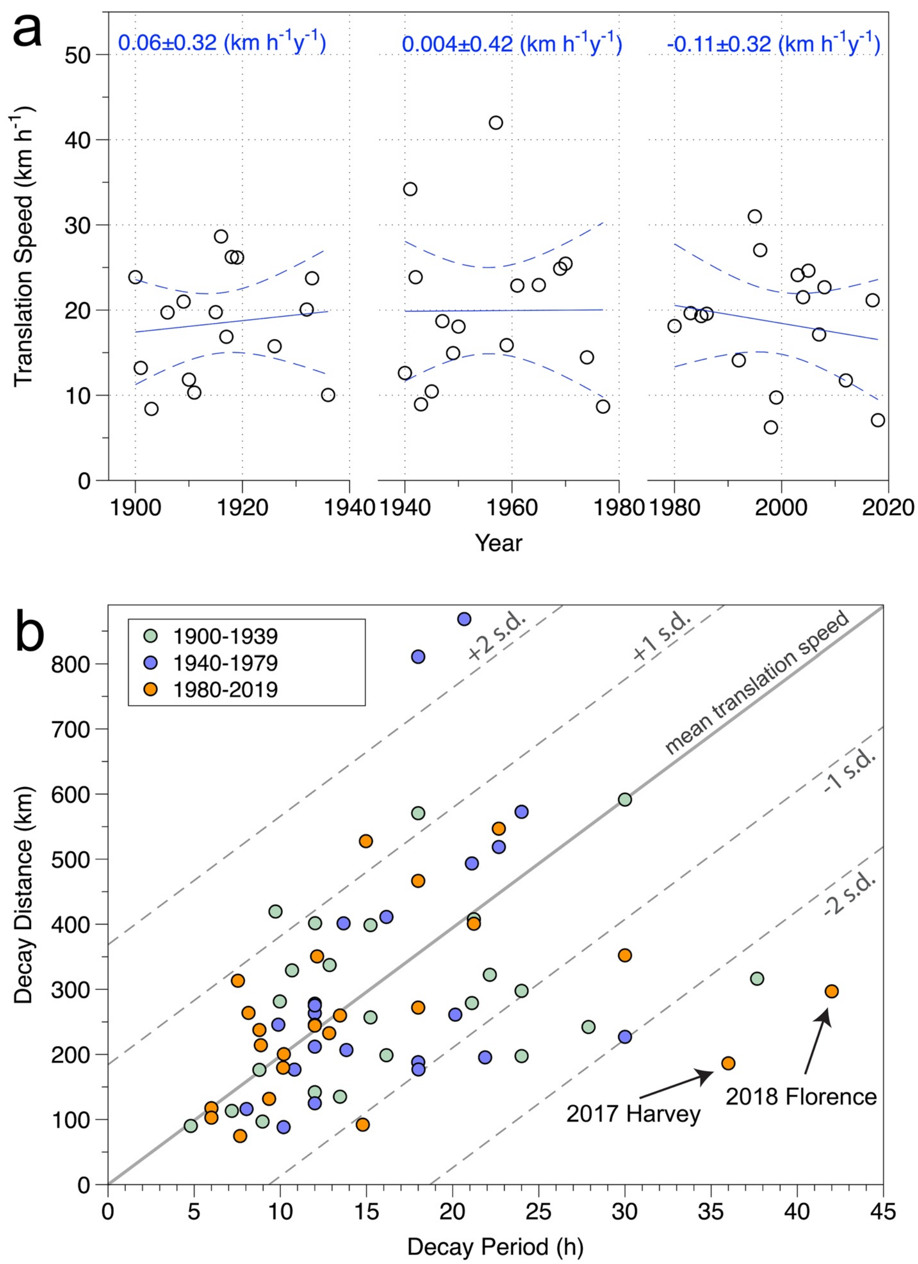

Figure 5. (a) Time series of the yearly averaged translation speed during the period when MSW decreases from 65-kt to 35-kt. The linear regression trend is displayed with the blue solid line; Dashed lines represent the 95% confidence interval. (b) Translation speed of the landfall events displayed by the ratio between the decay distance and the decay period. The solid diagonal line shows the average translation speed. The dash lines represent the spread of each landfall events away from the overall mean translation speed. MSW, maximum sustained wind.

contributions to slower decaying hurricanes (Li & Chakraborty, 2020). However, this relationship only represents one AMO cycle (due to the limitation of the reliable landfalling hurricane data) and future studies are encouraged to include future cycles.

In comparison, the decay distance shows a non-significant change throughout the study period, which is nonconcurrent to the decay period. The large variation of the translation speed represented by the ratio of 65–35 kt decay distance and the decay period provides a possible explanation. The occurrence of extreme slow-moving hurricanes during the 1980–2019 period suggests the important role of the TC translation speed over land in determining the pathway of TC intensity decay. The concept of inland decay in terms of both time and distance brought by this manuscript is critical to inland hazard mitigation and worth expanding to a global scale for future studies.

Data Availability Statement

All original data used in this study are publicly available. The inland TC data were achieved from the International Best Track Archive for Climate Stewardship version 4 (IBTrACS; https://www.ncdc.noaa.gov/ibtracs/). The AMO index data are available from NOAA Physical Sciences Laboratory (PSL; https://psl.noaa.gov/data/timeseries/AMO/).

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