atmosphere

Article

Extreme Translation Events of Atlantic Tropical Cyclones

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Abstract: Changes in the translational speed of tropical cyclones (e.g., sluggish tropical cyclones) are associated with extreme precipitation and flash flooding. However, it is still unclear regarding the spatial and temporal variability of extreme tropical cyclone translation events in the North Atlantic and underlying large-scale drivers. This work finds that the frequencies of extreme fast- and slow-translation events of Atlantic tropical cyclones exhibited a significant rising trend during 1980–2019. The extreme fast-translation events of Atlantic tropical cyclones are primarily located in the northern part of the North Atlantic, while the extreme slow-translation events are located more equatorward. There is a significant rising trend in the frequency of extreme slow-translation events over ocean with no trend over land. However, there is a significant rising trend in the frequency of extreme fast-translation events over ocean and over land. The extreme slow-translation events are associated with a strong high-pressure system in the continental United States (U.S.). By contrast, the extreme fast-translation events are related to a low-pressure system across most of the continental U.S. that leads to westerly steering flow that enhances tropical cyclone movement. This study suggests that it might be useful to separate tropical cyclone events into fast-moving and slow-moving groups when examining the translational speed of North Atlantic tropical cyclones, instead of examining regional or global mean translational speed.

Keywords: translation events; tropical cyclones; Atlantic; extremes

Citation: Zhang, W. Extreme Translation Events of Atlantic Tropical Cyclones. *Atmosphere* **2021**, *12*, 1032. https://doi.org/10.3390/atmos12081032

Academic Editor: Corene Matyas

Received: 24 June 2021
Accepted: 6 August 2021
Published: 12 August 2021

1. Introduction

Tropical cyclone rainfall is closely related to flash flooding, landslides, and debris flow [1–7]. Recently, the extreme rainfall caused by landfilling hurricanes has wreaked havoc to coastal regions along the U.S. coast [8–15]. For example, hurricane Harvey led to flash flooding in Houston and claimed casualties [8–12]. Hurricane Florence caused extreme water-related hazards in North Carolina [13,16]. The extreme hazards related to hurricanes Harvey and Florence are closely associated with extremely slow translation [13,15,16]. As the translational speed of tropical cyclones is closely associated with rainfall amount and flash flooding [8,9,17–19], it is of central importance to understand the spatial and temporal variability of tropical cyclone translation and underlying synoptic patterns.

Previous studies have advanced the understanding of tropical cyclone translational speed. For example, Kossin reported a 10% decrease in tropical cyclone translation speed during 1949–2016 [17], which has aroused fierce debates on the changes of tropical cyclone translation speed under the present and future climates [20–23]. Overall, it is argued that the slow-moving tropical cyclones may be associated with the weakening of circulation forced by anthropogenic warming [24,25]. Model experiments have indicated that future anthropogenic warming may lead to a robust slowing of tropical cyclone motion, particularly in the midlatitudes [26]. In contrast, a rising trend in translational speed has also been found since 1982 [27]. A recent study also found that there will be increases in the likelihood of faster-moving tropical cyclones that make landfall over Texas in the late 21st century [28]. Using observations and model simulation, the increasing relative frequency of tropical cyclones in higher latitudes has led to an increase in global average tropical cyclone translation speed [21].

Previous works have greatly advanced our understanding of tropical cyclone translational speed in the present and future climates, both globally and regionally. However, there are still research gaps in understanding the extreme translational speed of tropical cyclones in the North Atlantic. For example, it remains elusive regarding the spatial and temporal variability (e.g., frequency) of extreme translation speed events in the North Atlantic and underlying mechanisms. This study will focus on understanding the spatial and temporal variation of extreme translation tropical cyclone events in the North Atlantic. While slow-moving tropical cyclones tend to lead to more water-related damages (e.g., extensive flooding) than fast-moving tropical cyclones, this study analyzes both slow- and fast- tropical cyclones for drawing a broader picture of extreme translation events in the North Atlantic.

This work is organized as follows. Section 2 discusses methods and data, followed by Section 3 presenting the results. Section 4 makes conclusion and discussions.

2. Materials and Methods

Focusing on tropical cyclones in the North Atlantic, this study uses the hurricane database (HURDAT2) available from the National Hurricane Center with variables including longitude, latitude, time, and central pressure (https://www.nhc.noaa.gov/data/#hurdat, accessed on 1 February 2021) [29]. This study focuses on tropical cyclones with an intensity level of tropical storm or above. Daily meteorological variables are taken from the National Centers for Atmospheric Prediction and the National Center for Atmospheric Research (NCEP/NCAR) reanalysis at 2.5-degree spatial resolution [30].

This study uses 500-hPa geopotential height to represent large-scale circulation that modulates tropical cyclone movement. The daily 500-hPa geopotential height anomaly is calculated by subtracting long-term daily mean from daily value at each spatial grid. The translational speed of tropical cyclones is calculated based on great circle distance. Extreme translational speed of tropical cyclones is calculated based on the 5th and 95th percentiles. In other words, extreme slow- and fast-translational events are defined as those being smaller/greater than the 5th/95th percentile of all historical 6-hourly translational speeds. Due to inhomogeneous observations before and after the satellite era, this study focuses on the period 1980–2019. To examine potential impacts of land–sea mark on extreme translational speed, the extreme translational speed events are divided into two groups: over ocean and over land.

3. Results

The extreme slow and fast translation speed events exhibit different spatial patterns (Figure 1). Overall, extreme slow translational speed events are located more equatorward than extreme fast translation events (Figure 1). More specifically, most slow translational events are located adjacent to the coastal regions. For example, there is a hotspot over the southeastern U.S. coast and eastern Mexican coast. In contrast, the extreme fast translational speed is located in the midlatitudes, where the jet streams are located. The extreme fast translational speed may be associated with the impacts of jet streams on tropical cyclone movements after recurvature. To examine whether there is change in hotspots over time, Figure 2 exhibits that the hotpots change during the ten-year periods 1980–1989, 1990–1999, 2000–2009, and 2010–2019, particularly for extreme slow translation events. Meanwhile, the density of fast translation events exhibits an increasing trend for the four periods over the mid-latitude ocean (Figure 2; right columns).

Based on the Poisson regression model, a statistically significant trend (Poisson regression slope; Beta = 0.020; p-value = 0.01) is identified for the frequency of extreme slow-translation events in the North Atlantic during 1980–2019, and this is also true for extreme fast-translation events (Beta = 0.019; p-value = 0.01) (Figure 3). Overall, the trend in the frequency of extremely slow translation events is slightly stronger than that for extreme fast-translation events. Given recent extreme slow-translation cases on land (e.g., Harvey and Florence), it is of interest to examine whether the trend in the frequency of extreme translation events is different over land and over ocean. Figure 4 shows that the frequency of extreme slow (Beta = 0.023; *p*-value = 0.01) and fast (Beta = 0.018; *p*-value = 0.01) translation events over ocean exhibit significant rising trends. However, the trend in the frequency of extreme slow-translation events over land is not statistically significant (Beta = 0.0054; *p*-value = 0.53), while the rising trend in the frequency of extreme fast-translation events over the land is still significant (Figure 5; Beta = 0.034; *p*-value = 0.01), but it is weaker than that over ocean. This suggests that the trend in the frequency of extreme slow-translation events in the North Atlantic is mainly caused by the extreme events over ocean, rather than over land (Figures 4 and 5). The rising trend in the frequency of extreme fast-translation events is statistically significant across ocean and land (Figures 4 and 5).

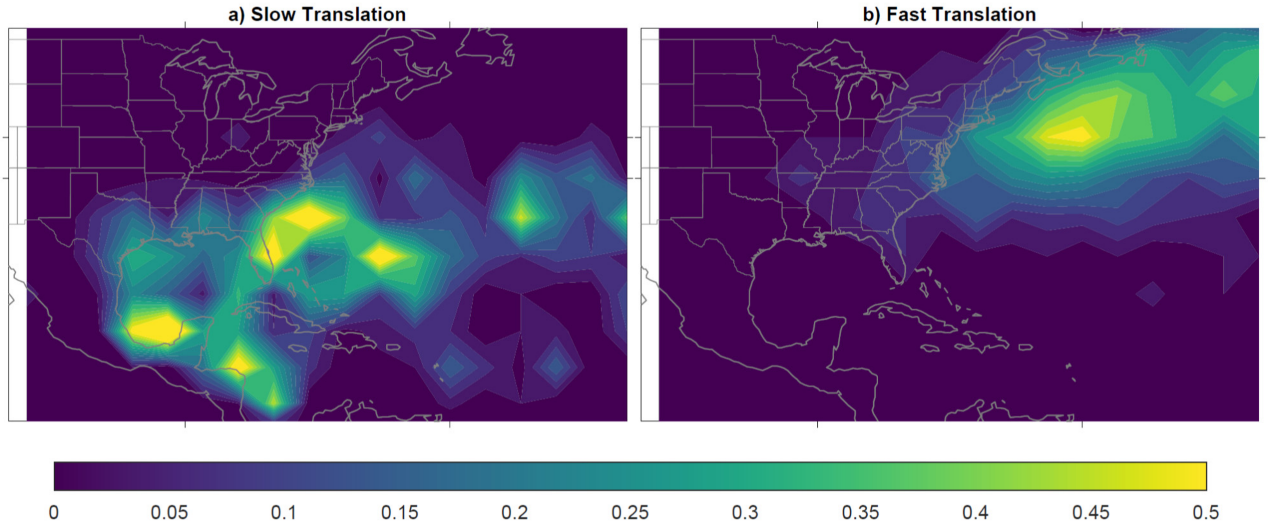

Figure 1. Annual mean density (shading; unit: events) of (**a**) slow and (**b**) fast tropical cyclone extreme translation events in the North Atlantic averaged over 1980–2019. The annual mean density of tropical cyclone extreme translation events is obtained by binning the tropical cyclone extreme translation events into 2 × 2 boxes during 1980–2019 divided by 40 (i.e., the number of years).

To further model the statistical relationship among the variables, a model is built with the number of extreme translation events as a function of year, land/ocean (dummy variable) and fast/slow movement (dummy variable). The land/ocean dummy variable appears to an important variable (*p*-value = 0.00) in examining the number of extreme translation events (Table 1). However, the fast/slow movement does not lead to a significant difference (*p*-value = 0.60) in the number of extreme translation events (Table 1). In addition, the interactions between year and land/ocean and year and fast/slow are not statistically significant (Table 1), suggesting weak interactions.

Table 1. Statistical modeling of the number of extreme translation events as a function of year, land/ocean (dummy variable) and fast/slow movement (dummy variable). The interactions between year and land/ocean, and between year and fast/slow are considered in the statistical model.

	Regression Coefficients	***p*-Value**
Year	0.0207	0.00
Land/Ocean	−1.985	0.00
Fast/Slow	−0.0593	0.60
Interaction: Year and Land/Ocean	−0.00228	0.60
Interaction: Year and Fast/Slow	−0.00112	0.74

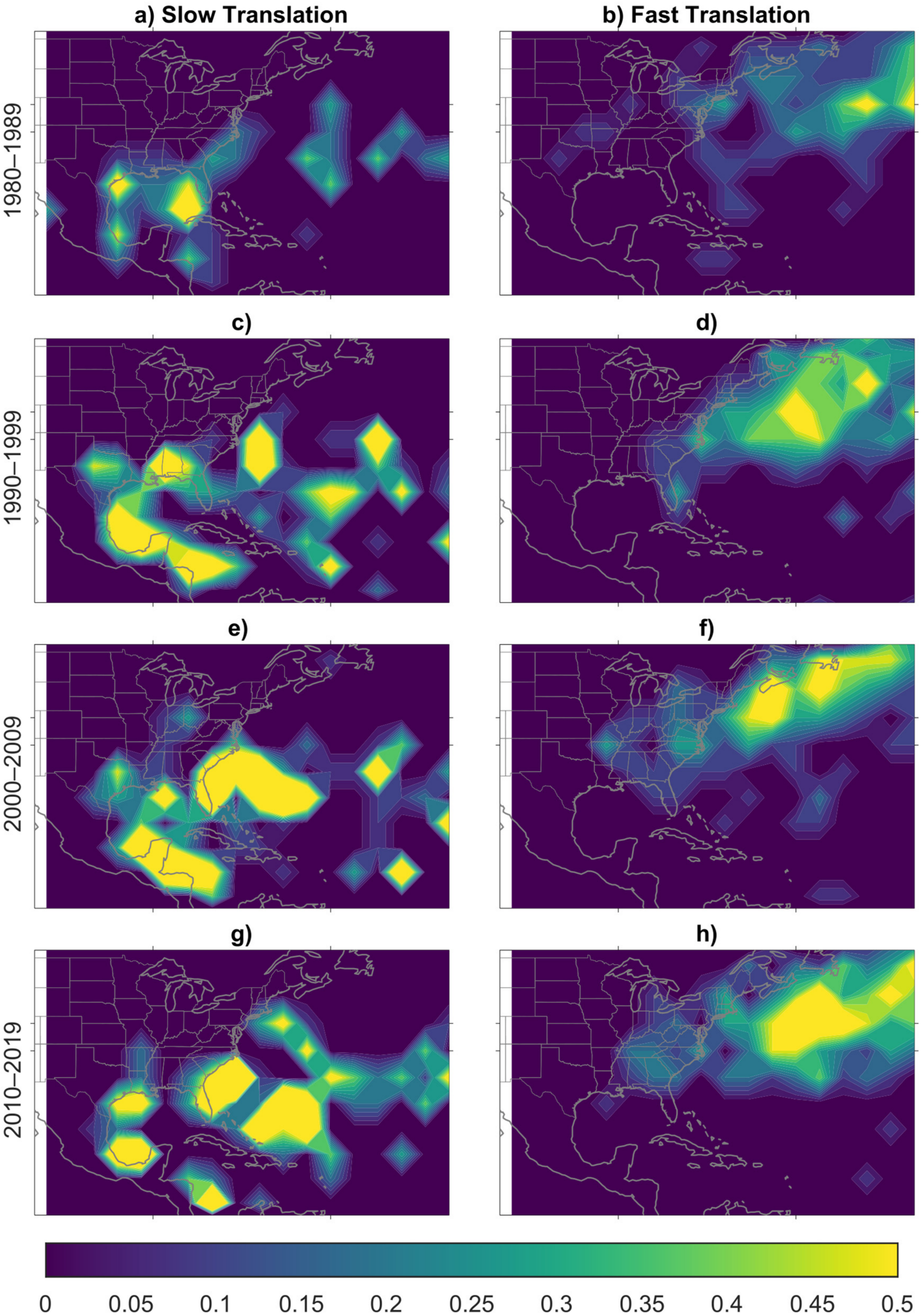

Figure 2. Annual mean density (shading; unit: events) of slow and fast tropical cyclone extreme transla-tion events in the North Atlantic averaged over during (**a**,**b**) 1980–1989, (**c**,**d**) 1990–1999, (**e**,**f**) 2000–2009 and (**g**,**h**) 2010–2019.

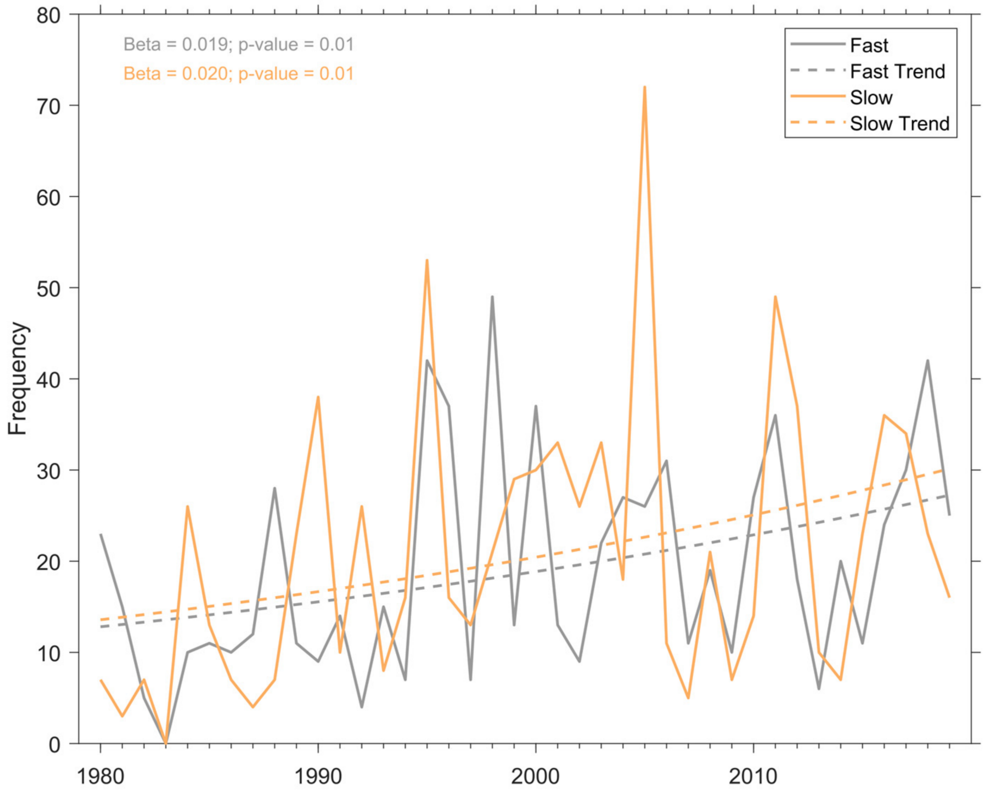

Figure 3. Time series and trend lines of fast (grey) and slow translation (orange) events during 1980–2019.

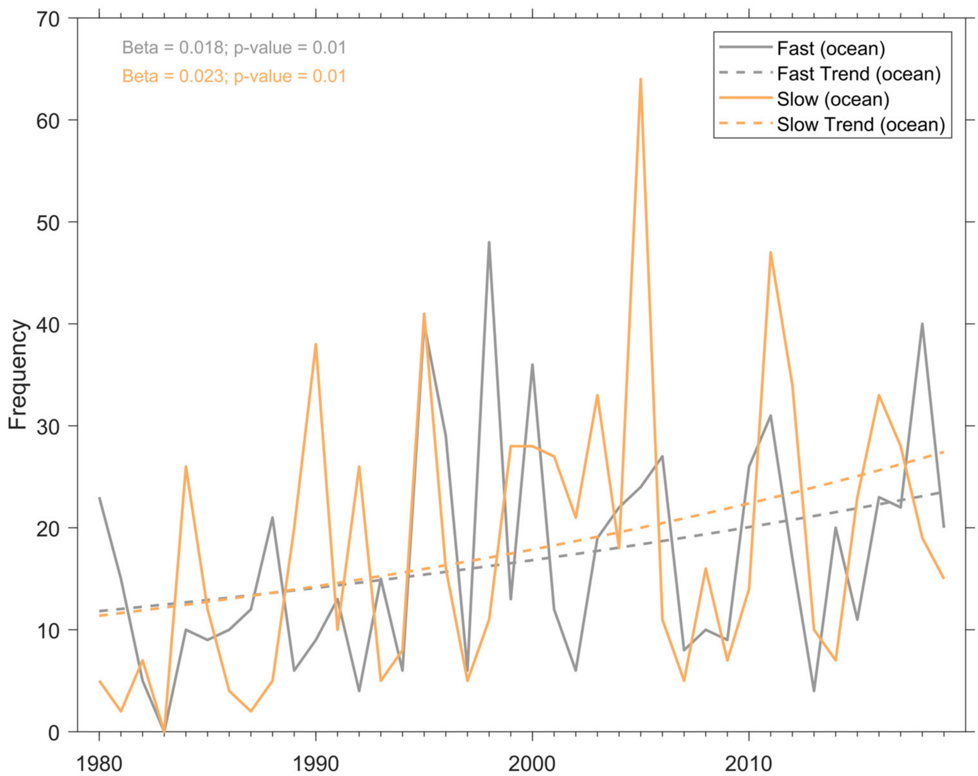

Figure 4. Time series and trend of fast (grey) and slow translation (orange) events over ocean during 1980–2019.

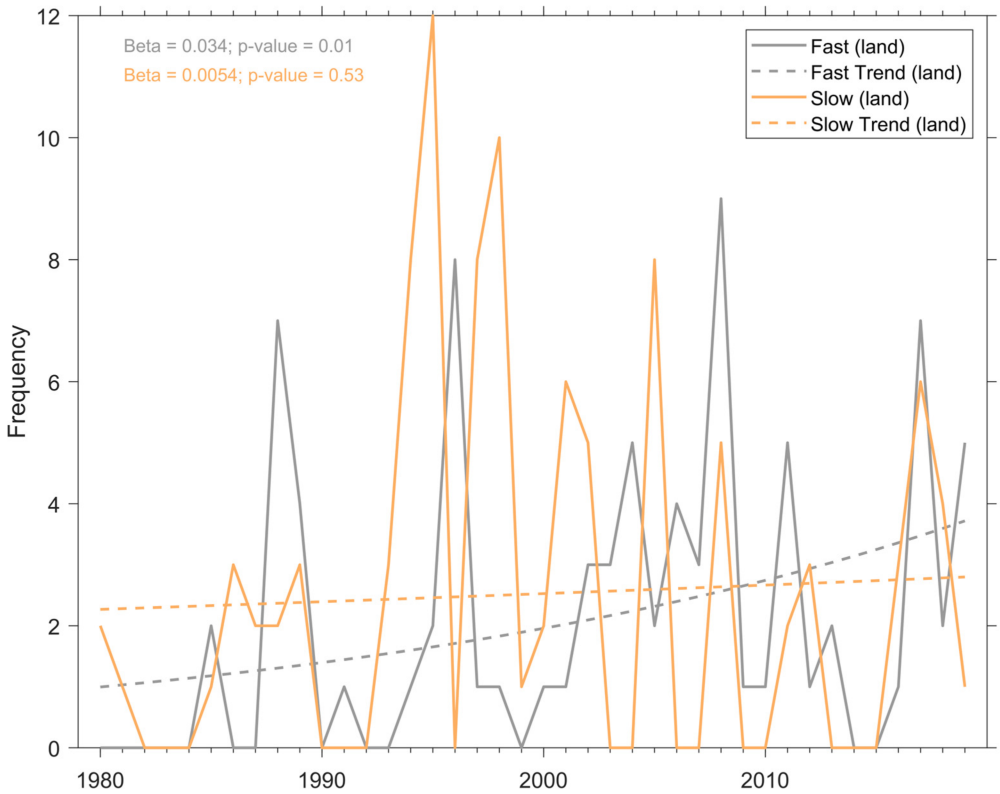

Figure 5. Time series and trend of fast (grey) and slow translation (orange) events over land during 1980–2019.

Associated with 500-hPa wind fields, daily 500-hPa geopotential height anomaly is used to understand underlying mechanisms for extreme slow- and fast-translation events in the North Atlantic. For extreme fast-translation events, a cyclonic pattern sits in the east coast, which leads to westerly steering flow that forces tropical cyclones to move eastward (Figure 6; top panel). Therefore, the cyclonic circulation pattern is consistent with extreme fast translation speed (Figure 6a). In contrast, an anticyclonic pattern is in the eastern and central United States, leading to eastly steering flow that causes tropical cyclones to move westward and preventing tropical cyclones from propagating northward (Figure 6b). Note that the high-pressure system is located poleward of the region where tropical cyclones move in, setting the stage for extreme slow translation speed (Figure 6b). Therefore, the composite daily 500-hPa geopotential height anomaly agrees with extreme slow- and fast-translation speed events.

To further understand the association between the 500-hPa geopotential height and the frequencies of slow- and fast-translation events, the frequency of these events is fitted as a function of 500-hPa geopotential height averaged over the selected domains with strong anomalies using the Poisson regression model (Figure 6). The fitted regression model for fast-moving events is statistically significant (Figure 7; Beta = −0.01; p-value < 0.01), consistent with the composite negative 500-hPa geopotential height anomaly. The fitted regression slope for slow-moving events is also statistically significant with positive regression slope (Figure 7; Beta = 0.02; p-value < 0.01).

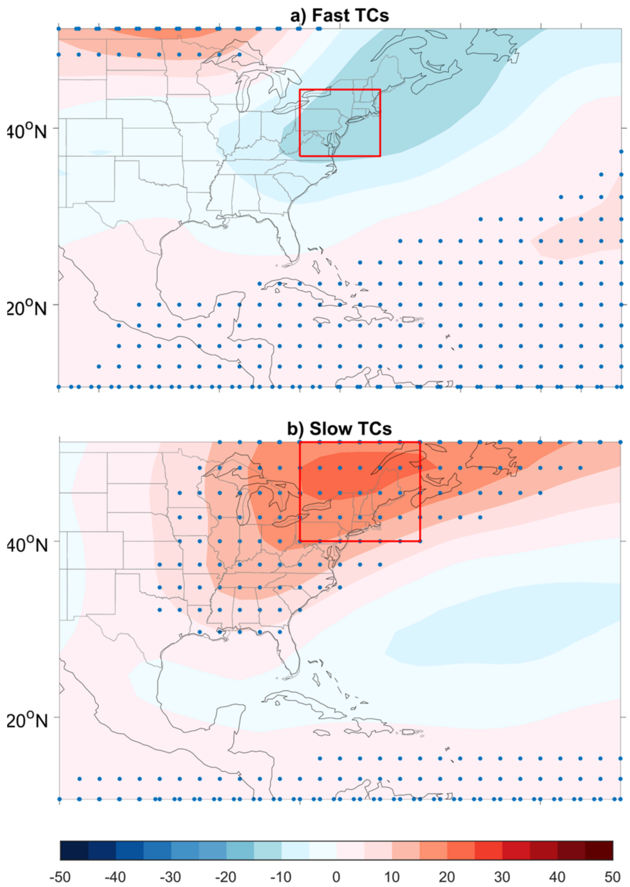

Figure 6. Composites of daily 500-hPa geopotential height anomaly for fast- and slow-moving tropical cyclones. Stippled regions represent those significant at the 0.05 level based on the Student's *t*-test.

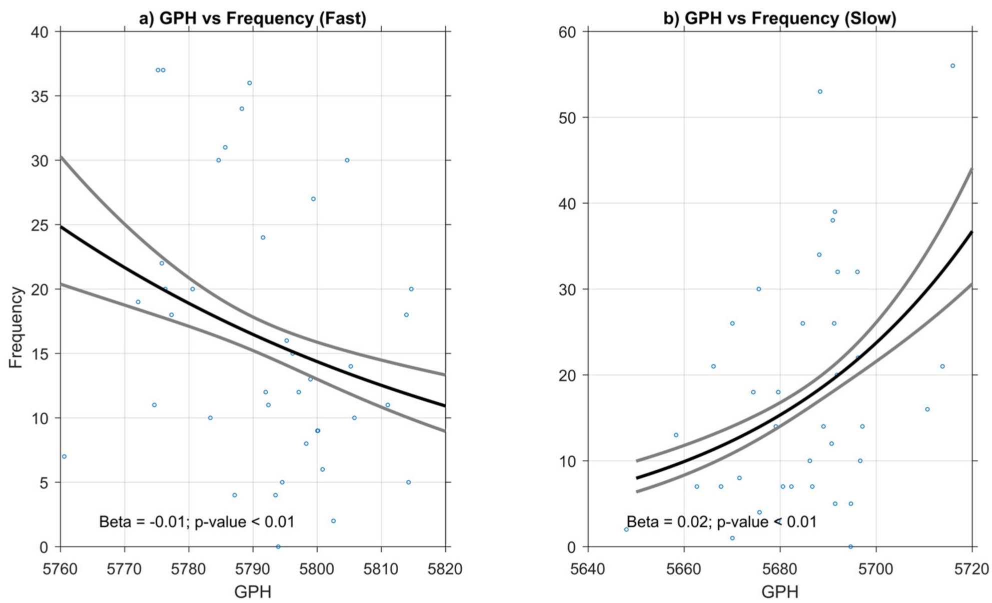

Figure 7. Scatterplot between 500-hPa geopotential height and the frequency of fast- and slow-translation events during June–November (dot). Black curves represent the fitted frequency and grey curves represent the 95th confidence level of the fitted frequency.

Similarly, the Poisson regression model is developed to consider the number of extreme translation events as a dependent variable and geopotential height (GPH) and fast/slow (dummy variable) as independent variables. The model results suggest that fast/slow plays a significant role in modeling the number of extreme translation events (Table 2). The interaction between GPH and fast/slow is negative at 0.00 level of significance (Table 2). The above results further support the significant association between the geopotential height anomaly and the fast- and slow-translation events.

Table 2. Statistical modeling of the number of extreme translation events as a function of geopotential height (GPH) and fast/slow events (dummy variable). This model considers the interactions between GPH and fast/slow.

	Regression Coefficients	*p*-Value
GPH	0.0218	0.00
Fast/Slow	202.98	0.00
Interaction: GPH and Fast/Slow	−0.035459	0.00

The geopotential height anomaly one day before the fast- and slow-moving events (Figure 8) is similar to the composite geopotential height with the fast- and slow-moving events (Figure 6), with the latter being slightly larger than the former, indicating that the 500-hPa geopotential height anomaly over the domains could be a potential predictor for the fast and slow translation events.

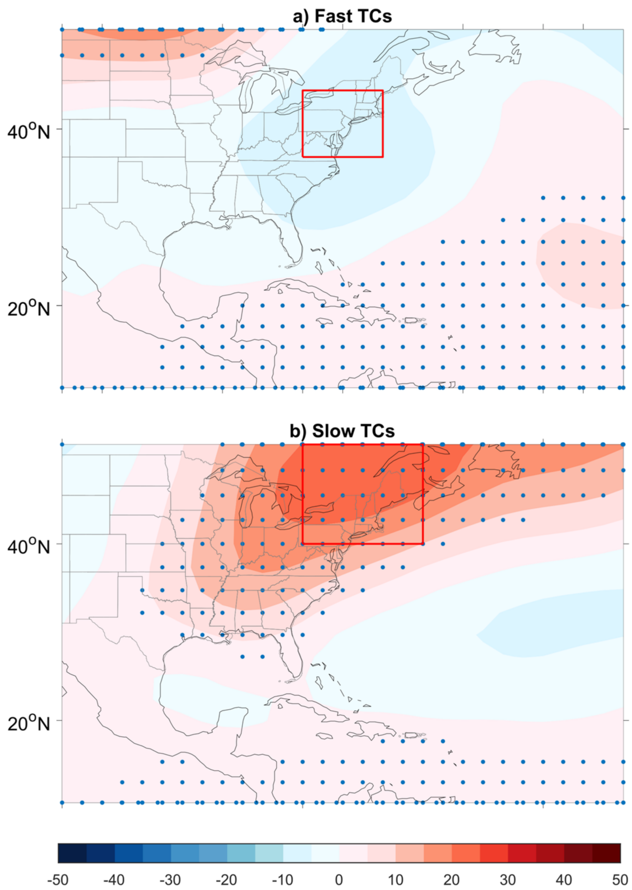

Figure 8. Composites of daily 500-hPa geopotential height anomaly one day before the fast- and slow-moving events. Stippled regions represent those significant at the 0.05 level based on the Student's *t*-test.

4. Discussion and Conclusions

Tropical cyclone translational speed has been a hot topic over the years due to its close linkage with tropical cyclone rainfall, particularly during and after landfall. This work has examined the extreme fast and slow translational speed events of North Atlantic tropical cyclones based on the historical data.

The spatial variability of extreme slow and fast translational speed exhibits different patterns. While the extreme fast translation events are mainly located in the Midlatitude ocean, the extreme slow translation events are located in coastal regions including the southeastern US coast and eastern Mexican coast. The frequency of extreme fast translation events exhibits significant rising trend, over both ocean and land. By contrast, the frequency of extreme slow translation exhibits significant trend only over the ocean and weak or no trend over the land. The 500-hPa geopotential height is consistent with the extreme fast-moving and slow-moving tropical cyclone events, supported by the significant association between the 500-hPa geopotential height anomaly and the frequency of extreme translation events.

This study suggests that fast-moving and slow-moving tropical cyclone events are becoming more frequent at the same time, particularly over the ocean. It may blur the picture of tropical cyclone movement when examining all the slow- and fast-moving samples together with distinct atmospheric drivers. Therefore, it might be useful to separate tropical cyclone events into fast-moving and slow-moving groups, rather than examining all tropical cyclone events together. Moreover, it might also be useful to examine the regional and local variation of translational speed to supplement the analysis of global mean translational speed. The separation of fast- and slow-moving cyclones may also benefit decision- or policymakers because slow-moving cyclones are more catastrophic than fast-moving cyclones that occur mostly in the mid-latitude ocean. The projection of future slow-moving events, their associated precipitation and sea level rise would provide critical information for coastal risk management toward more climate-resilient coast communities.

Funding: This work is partly supported by the startup fund of Utah State University, USDA NIFA Hatch Project (1026229), and the UAES Seed Grant.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Tropical cyclone in the North Atlantic is obtained from National Hurricane Center (https://www.nhc.noaa.gov/data, accessed on 1 February 2021). The geopotential height data is obtained from NCEP/NCAR reanalysis data (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html, accessed on 1 February 2021).

Conflicts of Interest: The authors declare no conflict of interest.

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