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PAPER

The relationship between sea surface temperature anomalies, wind and translation speed and North Atlantic tropical cyclone rainfall over ocean and land

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Abstract

There have been increasing losses from freshwater flooding associated with United States (US) landfalling hurricanes in recent years. This study analyses the relationship between sea surface temperature anomalies (SSTA), wind and translation speed and North Atlantic tropical cyclone precipitation (TCP) for the period 1998-2017. Based on our statistical analysis of observation data, for a 1 °C SST increase in the main development region (MDR), there is a 6% increase (not statistically significant) in the TCP rate (mmhr^{-1}) over the Atlantic, which rises to over 40% over land (US states) and appears linked not only to the Clausius-Clapeyron relationship but also to the increase in tropical cyclone (TC) intensity associated with increasing SSTA. Total annual TCP is significantly correlated with the SST in the MDR. Over the Atlantic there is an increase of 116% and over land there is an increase of 140% in total TCP for a 1 °C rise in SST in the MDR. Again, this is linked to the increase in windspeed and the number of TC tracks which also rises with positive SSTAs in the MDR. Our analysis of landfalling TC tracks for nine US states provides a systematic review and highlights how TCP varies by US state. The highest number of landfalls per year are found in Florida, North Carolina and Texas. The median tropical cyclone translation speed is 20.3kmhr^{-1}, although this falls to 16.5 kmhr^{-1} over land and there is a latitudinal dependence on translation speed. Overall, we find a different TCP response to rising SST over the ocean and land, with the response over land over four times more than the Clausius-Clapeyron rate. The links between SSTA in the MDR and both TCP rate and annual total TCP provide useful insights for seasonal to decadal US flood prediction from TCs.

1. Introduction

Recent record losses from US landfalling hurricanes, including the catastrophic events of 2017 and 2018, highlight the risk they pose. Whilst the risk from wind and storm surge are well-known, it has been the rainfall from Atlantic hurricanes that has caused several freshwater flooding events, notably from hurricanes Ida (2021), Imelda (2019), Florence (2018), Harvey and Irma (2017), Sandy (2012), Irene (2011) and Ike (2008), each of which have caused several billion dollars of damage extending, in some instances, to hundreds of kilometres inland (Czajkowski *et al* 2013, Villarini *et al* 2014).

The US continues to be inadequately prepared for these flood events. For example, Hurricane Harvey's estimated total residential flood losses are $11billion, of which 75% are estimated to be uninsured (Sebastian *et al* 2021). The National Flood Insurance Program (NFIP) provides cost effective flood insurance in the US, as flood insurance is not generally provided for in homeowner insurance. Following the flooding events in 2017, NFIP accrued a debt of US$47bn (Gonzalez 2017) and announced in 2019 that from October 2021 premiums would be based on actual flood risk, whereas historically they have been based on whether a property was inside the 100-year flood plain, an area that would be flooded by a 1 in 100 year flood. This calls for further improvements to our understanding of the changing flood risk from tropical cyclones.

Studies have examined the increasing rainfall associated with tropical cyclones and links to climate change (Emanuel 2017, Risser and Wehner 2017, Trenberth *et al* 2018, Touma *et al* 2019, Reed *et al* 2020, Reed *et al* 2021, Stansfield and Reed 2021). Rainfall rates are expected to increase with increasing temperatures due to the ability of warmer air to carry more atmospheric water vapour. The physical mechanisms for an increase in tropical cyclone precipitation (TCP) rate with rising temperatures are well understood (Allen and Ingram 2002, Hartmann *et al* 2013, Stocker *et al* 2014, Wang *et al* 2015, Knutson *et al* 2020). First, it is predicted that atmospheric water vapor will increase at a rate of 7% per 1 °C of warming (Knutson 2020) in line with the Clausius-Clapeyron relationship and one would therefore expect an approximate 7% increase in lower tropospheric water vapor capacity for a 1 °C rise in temperature (Held and Soden 2006). The Clausius-Clapeyron expression for the saturation vapor pressure e_s, is given by:

$$\frac{\partial ln\ e_s}{\partial T} = \frac{L}{RT^2} \equiv \alpha(T),$$

where L is the latent heat of vaporization and R is the gas constant. At temperatures typical of the lower troposphere, $\alpha \approx 0.07\ \mathrm{C}^{-1}$; the saturation vapor pressure increases by about 7% for each 1 °C increase in temperature. Second, moisture convergence is the main moisture source for TCP and dominates over local evaporation, and moisture convergence scales directly with total moisture content (Wang *et al* 2015, Knutson *et al* 2020). With warming temperatures an increase in moisture convergence and TC rainfall rate is expected, providing other circulation characteristics remain unchanged. An increase in storm wind intensities would add to this moisture convergence (Knutson *et al* 2010).

Several studies have found increases in TCP rate in line with Clausius-Clapeyron (Knutson *et al* 2013, Kim *et al* 2014, Knutson *et al* 2015, Gutmann *et al* 2018). The summary of modelling studies by Knutson *et al* (2020) found an estimated 14% increase in TC precipitation for a 2 °C warming (with a range of 6%–22%) although the studies did not make any distinction between ocean and land.

Other studies, however, have found TCP rate increases in excess of Clausius-Clapeyron (Liu *et al* 2018, Liu *et al* 2019) and associate the super Clausius-Clapeyron with a warming-induced increase in TC intensity. Lonfat *et al* (2004) and Jiang *et al* (2008) also found that higher rainfall rates were associated with more intense tropical cyclones. In studies of Hurricane Harvey in 2017; Trenberth *et al* (2018) link TCP rate to SST and ocean heat content, Van Oldenborgh *et al* (2017) find an increase of 15% (8%–19%) for a 1 °C warming and associate the higher scaling with the higher heat of condensation which provides extra energy to drive the circulation such that the moisture flux is enhanced twice, first by the higher moisture content and also by higher velocities. Wang *et al* (2018) find an increase in TCP rate of 13%–37%, for an 0.7 °C rise in SST in the Gulf of Mexico since 1980.

TCP has also been linked to large scale climatic indices. Villarini *et al* (2014) found that during a negative phase of the North Atlantic Oscillation (NAO) there are more flood peaks along the east coast of the US and in the areas west of the Appalachian Mountains. During this negative NAO phase the Azores high is located further east in the Atlantic, enabling tropical cyclones (TC) to more likely track northwards and make landfall along the east coast of the US. The study also highlights the role of ENSO with more flooding occurring in the central US states during ENSO neutral/La Nina years because more TCs are formed in the basin, in line with findings by Larson *et al* (2005). In terms of trends in the North Atlantic, Groisman *et al* (2004) found that an increase in heavy precipitation has occurred in parts of the US over the last century, and a recent study by Wang and Toumi (2022) showed that the number of TCs making landfall with major intensity has nearly doubled between 1982 and 2020, with a doubling time in the North Atlantic around 31 years which is likely having an impact on the total precipitation from TCs. Knight and Davis (2009) also found that 20%–25% of all extreme rainfall events along the east coast of the US were associated with TCs, whilst Shepherd *et al* (2007) found major hurricanes (Cat 3–5) produced the most extreme rainfall days, but that weaker tropical cyclone systems contribute significantly to the total seasonal rainfall.

For flood risk, the total TCP that a local area receives is key and proportional to the TCP rate (mm hr^{-1}) and inversely proportional to the translation speed of the TC. Kossin (2018) highlighted that there had been an overall 20% reduction in the translation speed of land falling Atlantic TC during the period 1949-2016, but the study by Guo *et al* (2021) emphasises the importance of seasonality where they found increases in translation speed in June and October associated with changes in jet stream position and poleward displacement of storms, contrasting with a slowdown in translation speed in August linked to equatorward storm migration.

In this study we explore the observed relationship between SSTAs in the MDR (10–20°N, 20–80°W), 10 m TC wind (intensity) and translation speed on TCP rates and total annual TCP over the North Atlantic and land (9

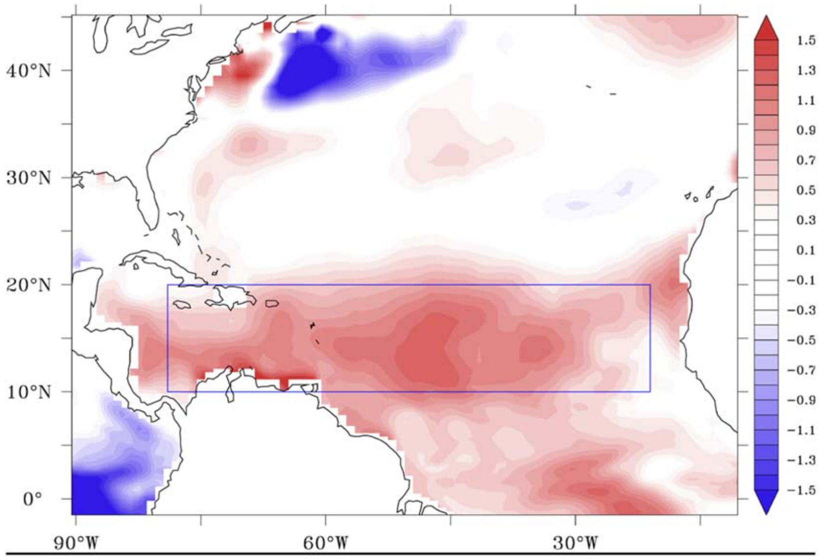

Figure 1. SSTAs (°C) for July to September 2010. The SSTAs are relative to the 1980-2017 period climatology. Blue box indicates the MDR region.

US states). The MDR (blue box figure 1) is the main region for tropical cyclone development in the North Atlantic. Figure 1 highlights the SSTAs in the north Atlantic for the period July-September 2010, the year which had the highest SSTAs in this study. The period studied is 1998-2017 using IBTrACS and the latest TRMM rainfall observations. A unique feature of our study is that we analyse separately the tracks when they are over the ocean and over land to understand the similarities and differences in these relationships.

2. Data and methods

The precipitation data used in this study are taken from Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis TRMM TMPA 3B42 version 6 (hereafter TRMM). TRMM provides 3-hourly/0.25° precipitation estimates for the domain (40°S–40°N), which allows analysis of sub-daily precipitation characteristics.

North Atlantic tropical cyclone data was obtained from the International Best Track Archive for Climate Stewardship (IBTrACS). The database gathers historical records of tropical cyclone characteristics for all hurricane basins (Hodges *et al* (2017), Knapp *et al* (2010)). Data has been used for the period 1998–2017 to coincide with the availability of TRMM data. IBTrACS 6-hourly track information includes latitude, longitude, minimum central pressure and maximum sustained wind (10 m wind speed). In addition, storms continue to be tracked in IBTrACS after they become cold-core, and any precipitation from these extratropical systems is also included in the totals. Tracks are defined in this study as landfalling when the track location, as measured by IBTrACS, is located over land. The TC 10 m wind speed indicates the maximum sustained wind of the TC, in line with the Saffir-Simpson scale (Knapp *et al* 2010).

To assess the tropical cyclone contribution on the precipitation total, this analysis identifies all TRMM precipitation events occurring within a 5-degree radius from the TC centre as rainfall attributable to TCs. This method is in line with the approach adopted by others; Larson *et al* (2005), Lau *et al* (2008), Jiang and Zipser (2010), Schreck *et al* (2011), Prat and Nelson (2013). The 5 degree radius criterion is consistent with the extent of the TC primary wind circulation domain (i.e., 80–400-km radius from TC center) and with the extent of the curved TC cloud shield (i.e., 550–600-km radius) described elsewhere (Englehart and Douglas 2001). An area averaged value is then calculated (mm hr^{-1}). The 6-hourly area averaged precipitation data has been assigned to each 6-hourly IBTrACS point (mm hr^{-1}) and all the results presented here are based on rainfall rates averaged over a 5-degree radius. Only track points with a valid 10 m wind speed have been used. The net 6-hourly translation speed (TS) along the TC track was calculated from the latitude ($\varphi_2 - \varphi_1$) and longitude ($\lambda_2 - \lambda_1$) points of the 6-hourly tracks, using the haversine formula, where R is the radius of the Earth, 6371 km and where dt is 6 h

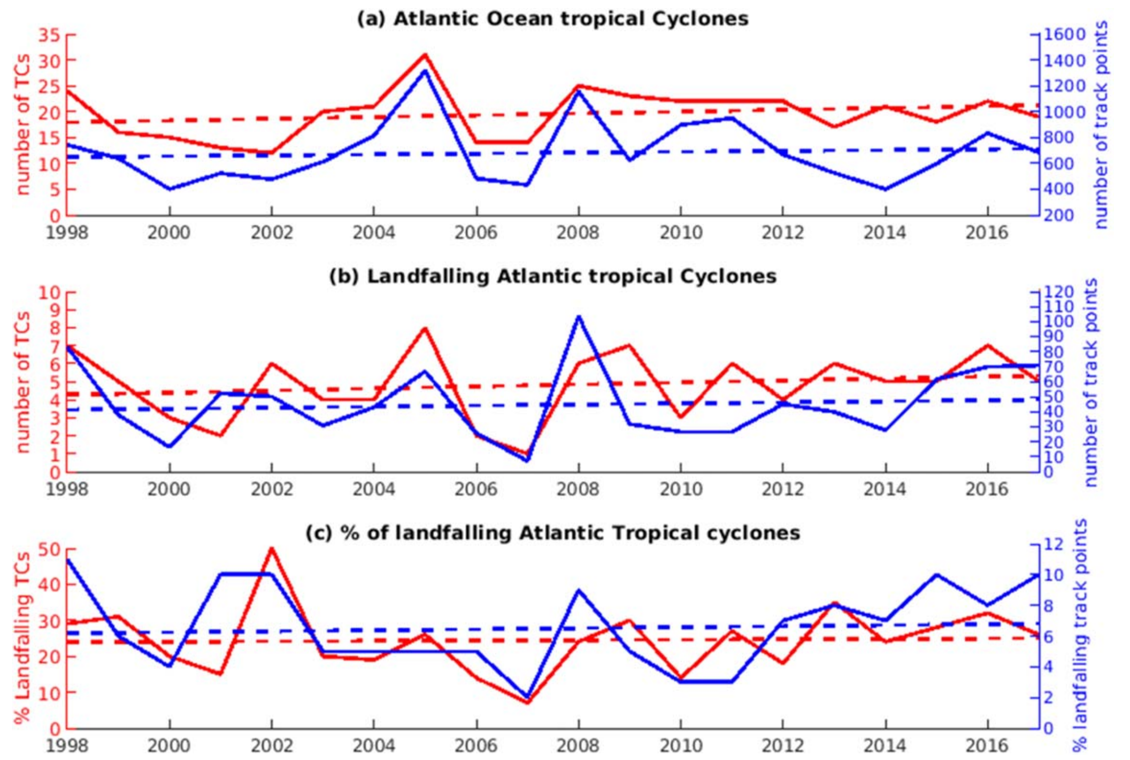

Figure 2. North Atlantic tropical cyclones 1998–2017. (a) Annual number of tropical cyclones (b) US Land-falling tropical cyclones (c) land falling tropical cyclones as a percentage of total tropical cyclones. Red lines relate to total number of tropical cyclones in a year and blue lines relate to total number of 6-hourly tropical cyclone track points in a year. Red and blue dashed line indicates linear best fit line.

$$TS = \frac{D}{dt} = \frac{2R\,\arcsin\left(\sqrt{sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right)}{dt} \tag{1}$$

The rainfall rate (TCP_r, mm hr^{-1}) at a track point i is defined as the rainfall over 6 h within a 5-degree radius of the track point, averaged over the 5-degree radius and 6-hour period and can be written as:

$$TCP_{ri} = \frac{1}{A\Delta t}\int_{t_i}^{t_i+\Delta t} \partial t \oiint_A TCP_r\, \partial A \tag{2}$$

where Δt is 6 h, and A is the area within a 5-degree radius from the track point. The total tropical cyclone precipitation ($TTCP_y$) in a year, averaged over a 5-degree radius, is defined as

$$TTCP_y = \sum_{i=1}^{n_y} TCP_{ri}\Delta t \tag{3}$$

where n_y is the total number of 6 hourly track points in a given year, and $y =$ is the years between 1998-2017.

The dataset was also compared to major climate indices; NAO (August, September, and October average (ASO)) and Nino 3.4 for ASO, as well as vertical wind shear (VWS) and SSTA. SSTA was calculated as the averaged anomaly for July, August and September (JAS)) in the MDR (10–20°N, 20–80°W. The NCEP Global Ocean Data Assimilation System (GODAS) (Behringer *et al* 1998) was used for the ocean temperatures and the SSTAs were based on the reference period 1980 to 2017. The NCEP/NCAR reanalysis (Kalnay *et al* 1996) was employed to calculate the absolute VWS in the MDR as the absolute difference between the 250 mb and 850 mb zonal wind using the reference period 1948 to 2017.

3. Results

3.1. Landfalling tropical cyclones

A total of 392 North Atlantic TC tracks (14260 6-hourly track points) were analysed, of which 997 6-hourly track points (7%) were over land for the period 1998–2017. From a flood risk perspective, landfalling TCs are key. Figure 2(a) highlights the total number of North Atlantic tropical cyclones (red line) and total 6-hourly track

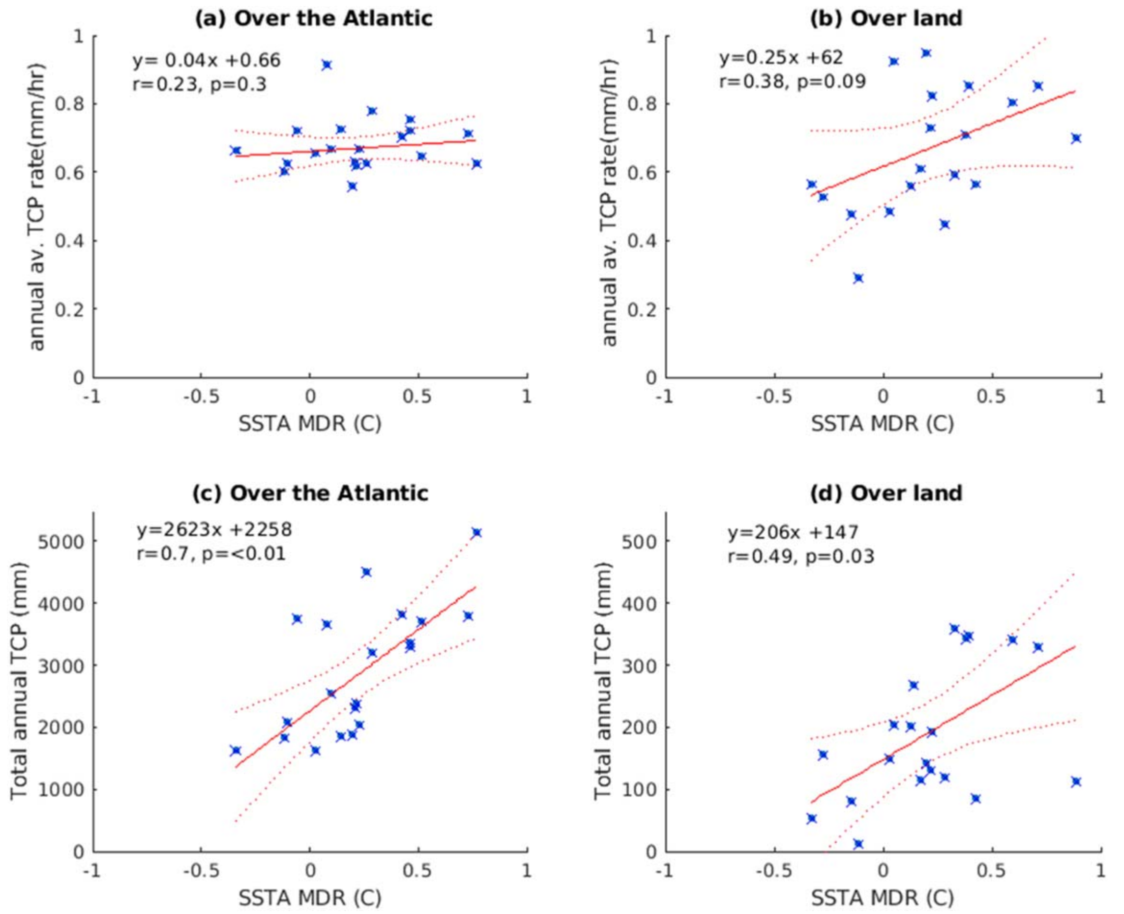

Figure 3. Tropical cyclone rainfall over the Atlantic and over land compared to JAS SSTAs in the MDR 1998–2017 (a), (b) annual average TCP rate (c), (d) Total annual TCP averaged over a 5-degree radius. Red line indicates linear fitted line. Red dash indicates 95% confidence level.

points (blue line). Interannual variability is evident with a maximum of 31 tropical cyclones (and 1297 6-hourly track points) in 2005 and a minimum of 12 TCs in 2002. The mean is 20 TCs per annum with a standard deviation (std) of 4.7. US Landfalling tropical cyclones figure 2(b) shows interannual variability with a range from 1 in 2007 to 8 in 2005 and an annual mean of 4.8 tracks and standard deviation of 1.9. In terms of the total number of 6-hourly track points over land the maximum was in 2008 with 101 (over 2stds from the mean). The number of landfalling track points was also higher in 1998, 2005, 2008 and 2016. The percentage of landfalling tracks, as a proportion of all tracks, also varies annually (figure 2(c)), with a mean of 24.5%, and std of 9.4. The highest landfalling ratio was seen in 2002 at 50% and lowest in 2007 at 7%. There is a correlation between the total number of tropical cyclones and the number of TCs which make US landfall with a correlation of $r = 0.64$ ($p < 0.01$). No significant trends are observed in any parameter.

3.2. Sea surface temperature anomalies and TCP

The annual average TCP rate ($TTCP_y/n_y$)and total annual TCP ($TTCP_y$) were compared to the JAS SSTA in the MDR (figure 3) for the years 1998–2017. The results show the TCP rate (mm hr^{-1}) increases with increasing SSTA.

Over the Atlantic there is a 6% increase (0.04 ± 0.07 mm hr^{-1}) in the TCP rate (figure 3(a)), for a 1 °C increase in SST. Although not statistically significant, the result is consistent with the range expected for Clausius-Clapeyron and in line with other studies (Knutson *et al* 2020). Over land (figure 3(b)), the TCP rate increases by 40% (0.25 ± 0.19 mm hr^{-1}) for a 1 °C rise in SSTA suggesting that other factors in addition to Clausius-Clapeyron are dominant for the increasing rainfall rate of landfalling hurricanes with rising ocean temperatures, which are investigated below. The landfalling TCP rate (mm hr^{-1}) was correlated with SSTA in the MDR ($r = 0.38$, $p = 0.09$), with the low correlation in part attributable to the low number of track points over land in some of those years (Supplementary figure 1a). Similar correlations were also found with VWS during JAS in the MDR ($r = -0.44$, $p = 0.05$) as well as Nino 3.4 for ASO ($r = -0.41$, $p = 0.06$).

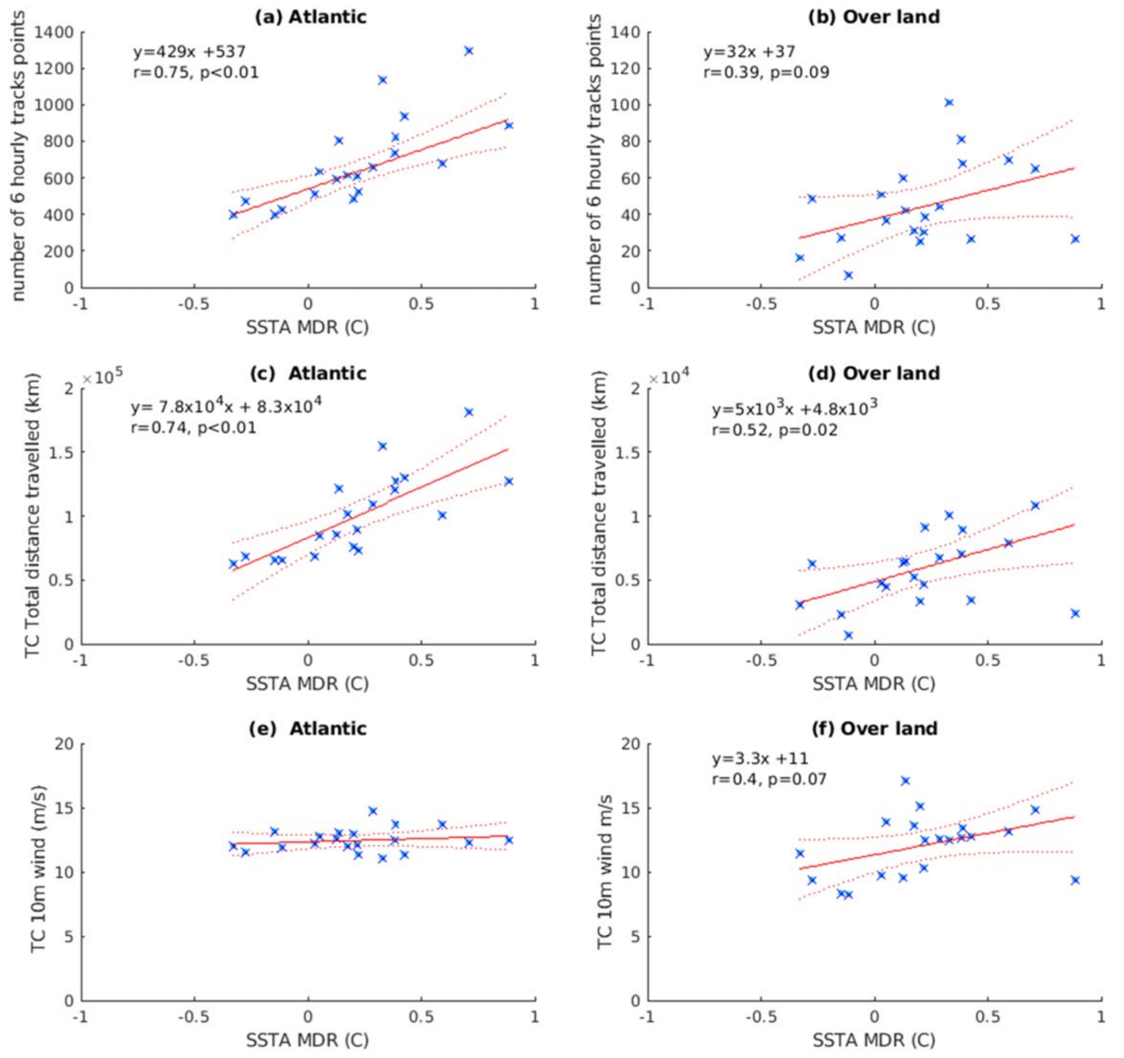

Figure 4. Comparison of JAS SSTAs in the MDR and number of tropical cyclone 6 hourly track points in each year (a), (b), Total distance travelled by all tropical cyclones in each year (c), (d) and annual averaged tropical cyclone intensity (maximum sustained wind speed at 10 m above the surface) (e), (f). Red line indicates linear fitted line. Red dotted lines indicate 95% confidence level.

Total annual TCP (equation 3) was found to be significantly correlated with JAS SSTA in the MDR, over the Atlantic (figure 3(c)) the correlation was $r = 0.7$ ($p < 0.01$) and over land (figure 3(d)) the correlation was $r = 0.49$ ($p = 0.01$). For a 1 °C rise in ocean temperature there is an increase in total TC rainfall of 116% over the Atlantic (2623 ± 663 mm) and 140% over land (206 ± 78 mm) for a 1 °C rise in SSTA. Total rainfall over land was significantly influenced by the number of track points as indicated in Supplementary figure 1b.

To explain the increase in total TCP with rising SSTA in the MDR, SSTA was also compared to the total number of TC 6-hourly track points, 10 m TC wind speed and total TC distance travelled. When SSTAs are higher in the MDR there is also an increase in the number of 6-hourly TC track points (figures 4(a),(b)), with a correlation of $r = 0.75$ ($p < 0.01$) over the Atlantic and $r = 0.39$ ($p = 0.09$) over land. For a 1 °C rise in SSTA there is an increase of 429 ± 128 (80%) 6-hourly track points over the Atlantic and increase of 32 ± 23 (86%) over land, highlighting that an increase in SSTA leads to more TC tracks points over ocean and land which will result in an increase in total TCP. A similar positive correlation is also found between SSTA and TC total distance travelled (figure 4(c),(d)). When JAS SSTA in the MDR is compared to TC 10 m wind speed (figure 4(e),(f)) a positive correlation exists over land $r = 0.4$ ($p = 0.07$). For a 1 °C rise in ocean temperature there is an increase of 3.3 ± 1.76 (30%) in the TC 10 m wind speed over land. The increases in the TCP rate, number of TC tracks, wind speed and distance travelled which coincide with positive SST anomalies are all consistent with a higher total TCP.

Over land the increase in TCP rate far exceeds the increase one would expect from the Clausius-Clapeyron relation. The next section shows how TC intensity is likely to be a key factor contributing to the higher TCP rates over land when the MDR is anomalously warm.

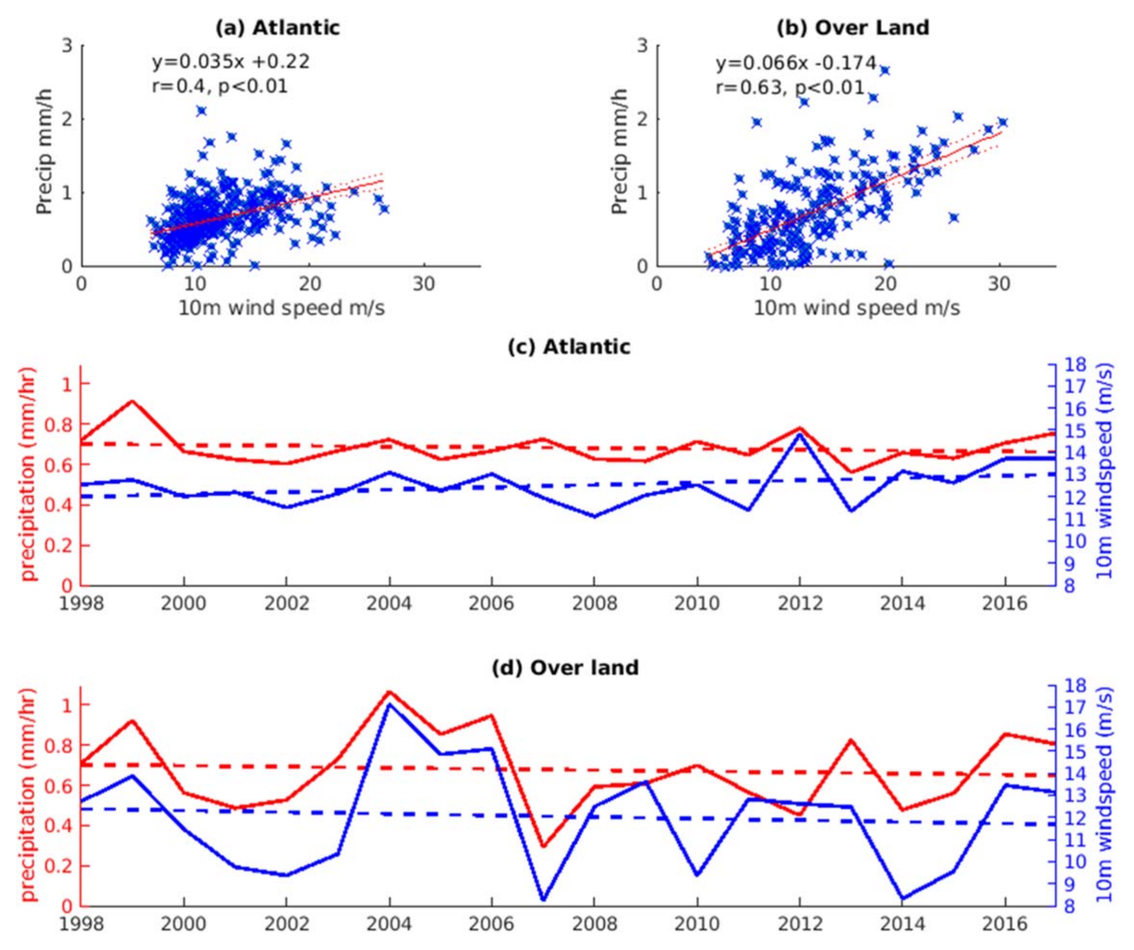

Figure 5. North Atlantic tropical cyclone track precipitation rates and tropical cyclone intensity (maximum sustained wind speed at 10 m above the surface) 1998–2017. (a) Over the Atlantic (b) over land. Blue indicates TC track. Red line indicates linear fitted line. Red dashed line indicates 95% confidence level. Lower: Timeseries North Atlantic tropical cyclone precipitation rate and tropical cyclone intensity (c) over the Atlantic (d) over land. Red and blue dashed line indicates linear best fit line.

3.3. Tropical cyclone precipitation rates and intensity

Positive correlations (figure 5) are found between TC rainfall rates and TC intensity (maximum sustained wind speed at 10 m above the surface), with a correlation over land of $r = 0.63$ ($p < 0.01$), and correlation of $r = 0.4$ ($p < 0.01$) over the Atlantic Ocean, which suggests that TCP rates over land are more strongly influenced by the TC intensity than over the North Atlantic. The results here also show that at windspeed less than 13 ms^{-1} (more than 13 ms^{-1}) the TCP rate is higher over the Atlantic (higher over land).

For example, a wind speed of 25 ms^{-1} is associated with a rainfall rate of 1.5 mmhr^{-1} (averaged over a 5-degree radius) over land, compared to 1.1 mmhr^{-1} over the Atlantic. The TCP rate std is also larger over land at 0.5 mmhr^{-1} compared to 0.28 mmhr^{-1} over the North Atlantic. The timeseries of the average annual TCP rate and average annual TC 10 m wind speed, again highlight the correlation between the two variables (figure 5) ; over the Atlantic $r = 0.6$, $p = 0.05$ (figure 5(c)), over land $r = 0.78$, $p < 0.01$ (figure 5(d)) and highlights the difference in the std. There are no significant trends in the rainfall rates or the 10 m wind speed. An increase in TCP rate with TC wind speed is also found by Lonfat *et al* (2004) and Liu *et al* (2019) and associated with enhanced water vapor convergence, where stronger inrushing winds near the surface increase the evaporation from the ocean surface. So, a rise in SSTA seems to lead to an increasing TCP rate through both a thermodynamic response (Clausius Clapeyron) and dynamic response (increase in wind speed).

Analysing TC landfalling tracks for nine US states (figure 6) reveals that significant positive correlations between 10 m wind speed and rainfall rate exists. The strength of the relationship varies by US state, with the strongest correlation found in Louisiana with $r = 0.78$ ($p < 0.01$). In terms of overall landfalling tracks, the highest number are found in Florida, with 55 over the 20 years (2.75 per annum), with the average track lasting 39 h in the state. Texas had 33 tracks (1.65 per annum) lasting on average 44 h whereas in the other 7 US states the track length was significantly lower at 14 h on average (Supplementary table 1). The mean rainfall rate and std was highest in Florida at 0.83 mmhr^{-1} and 0.61 mmhr^{-1} respectively, where for a 10 m wind speed of 12 ms^{-1} the TCP rate varies from 0.1 and 2.3 mm h^{-1} (averaged over 5 degrees).

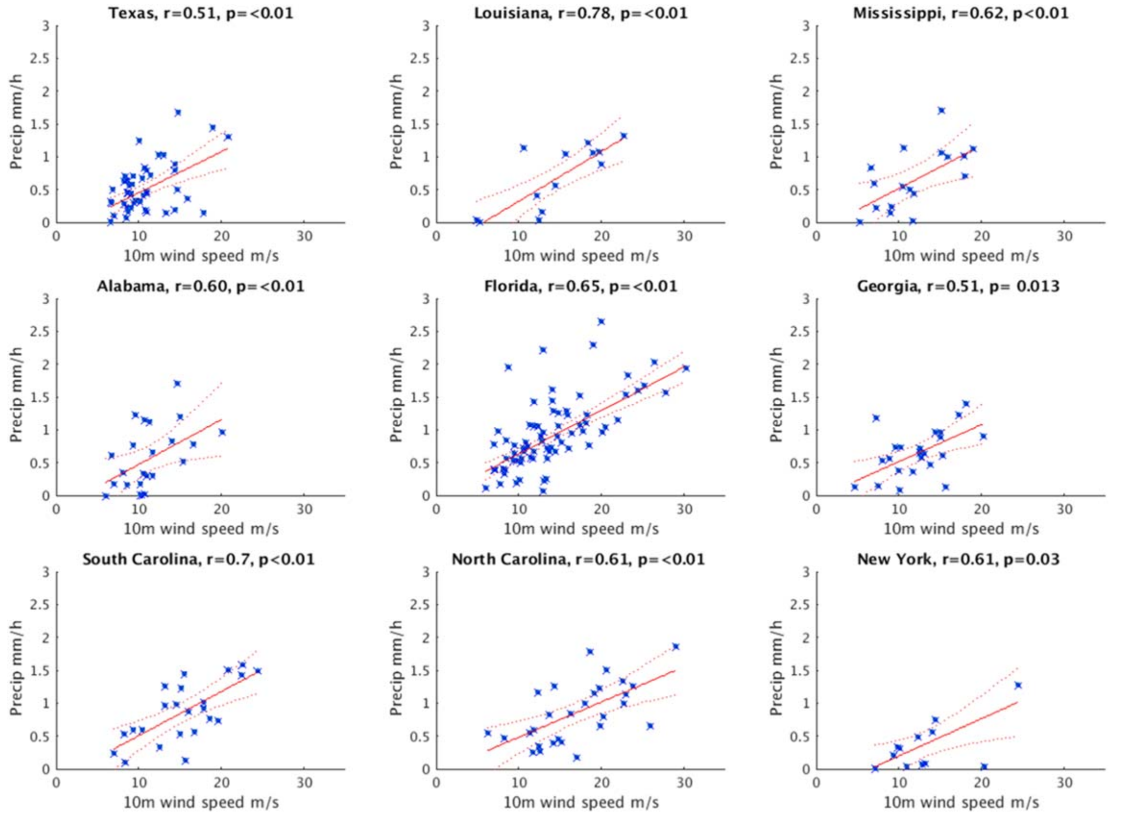

Figure 6. US State tropical cyclone precipitation and tropical cyclone intensity (maximum sustained wind speed at 10 m above the surface) 1998–2017 by individual track. Blue indicates each tropical cyclone track. Red line indicates linear fitted line. Red dotted lines indicate linear trend confidence level.

The histograms of the 10 m wind speed, and TCP rate for all Atlantic track points, landfalling and by US state are illustrated in Supplementary figure 2 and 3 and indicate the higher density of tracks, and of 6-hourly track points, in Florida and Texas, with an average of 2.75 tracks and 1.65 tracks per annum respectively as detailed in Supplementary table 1. The mean track wind speed for all TCs is 12.5 ms^{-1} with a std of 4.9 ms^{-1}. The highest mean 10 m wind speed is seen in North Carolina at 15.8 ms^{-1}. The mean rainfall rate over land and ocean is 0.68 $mmhr^{-1}$ (over a 5-degree radius) with std of 0.52 $mmhr^{-1}$.

3.4. North Atlantic tropical cyclone translation speed

The translation speed (equation (1)) of a tropical cyclone is important as the flood potential is inversely proportional to the translation speed. Here the translation speed is compared between the Atlantic and land (for 9 US states). The median translation speed for all north Atlantic TCs is 20.3 $kmhr^{-1}$, and 16.5 $kmhr^{-1}$ for landfalling TCs (figure 7), indicating how the translation speed slows as part of the transition over land. In terms of variability by state the lowest median translation speeds are found in the more southerly states; Florida at 14.7 $kmhr^{-1}$, Louisiana 15.9 $kmhr^{-1}$, followed by Texas 16.9 $kmhr^{-1}$. Further north the median translation speed is higher; South Carolina 26.8 $kmhr^{-1}$, North Carolina 21.8 $kmhr^{-1}$ and New York 23 $kmhr^{-1}$, which suggests a latitudinal dependence of the TC translation speed.

The translation speed anomaly timeseries is shown in figure 8 and although no trend is evident over the land or ocean there are more years with negative anomalies since 2005 over land. The figure also highlights the difference in translation speed std where over the ocean the std is 1.85 $kmhr^{-1}$ compared to land 6.51 $kmhr^{-1}$. When the 9 US states are considered (figure 8(c)), only Georgia has a significant decreasing trend ($r = -0.44$, $p = 0.09$) between 1998 and 2017. The other states show interannual variability with the lowest std over Florida, more aligned with the variability seen over the ocean.

Looking at TCP rate and total annual TCP and comparing to translation speed (figures 9(a)–(d)) there is no significant correlation between the two variables over the ocean or land and no significant trends. The total annual TCP is closely correlated with total annual distance travelled by tropical cyclones with $r = 0.94$ ($p < 0.01$) over the ocean (figure 9(e)), $r = 0.81$($p < 0.01$) over land (figure 9(f)) and is perhaps to be expected, linked to the high correlation between distance traveled and total TC duration. As such figure 9(e)

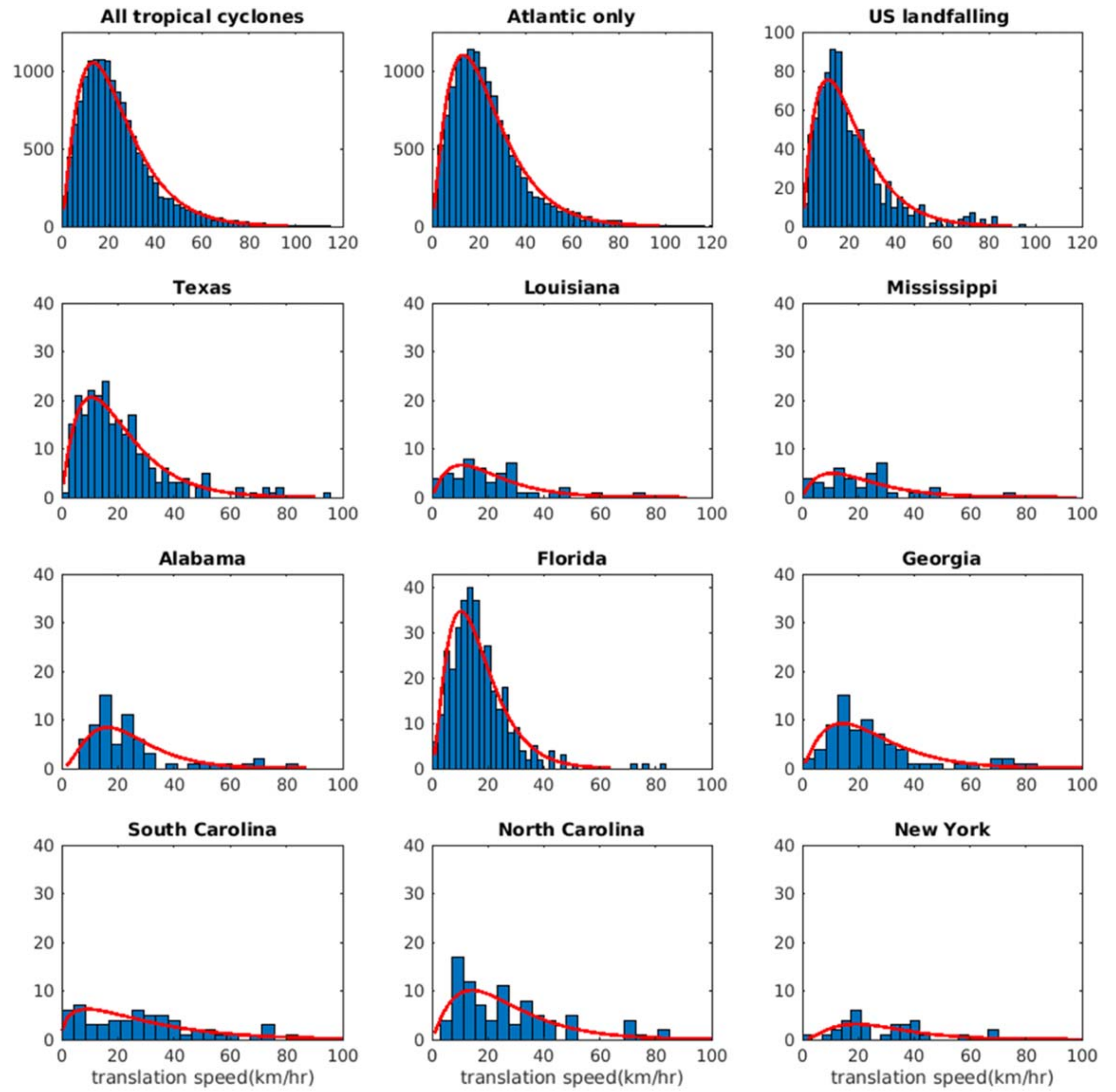

Figure 7. Tropical cyclone translation speed 1998–2017 for the 6-hourly track points for North Atlantic tropical cyclones and for 9 US States.

and (f) indicate the high correlation between number of track points and total TCP, as per the definition of TCP in equation (3). The highest total rainfall and translation distances were seen over the ocean and land in 1998, 2005, 2008, and 2016.

4. Discussion and conclusion

This study looks at the relationship between Atlantic TCP, SSTA in the MDR, 10 m TC wind and translation speed and made comparisons between TC tracks over the ocean and land.

For the period 1998-2017, TCP rate (mm hr^{-1}) is found to increase with rising SSTA over the MDR. Over the Atlantic Ocean there is a 6% increase in the rainfall rate for a 1 °C increase in SST which is broadly in line with the Clausius-Clapeyron relationship, from which we would expect a 7% increase in rainfall for a 1 °C rise in SST (Held and Soden 2006). This result is in line with several studies which predict an increase in TCP in line with Clausius-Clapeyron under global warming and summarised in Knutson *et al* (2020). Over land, however, the TCP rate increases by over 40% for a 1 °C rise in SST over the MDR and appears linked not only to the Clausius-Clapeyron relationship but predominantly to the increase in TC wind speed. The TCP rate (mm hr^{-1}) is significantly correlated with the TC 10 m wind speed with a correlation $r = 0.63$ ($p < 0.01$) over land and correlation 0.4 ($p < 0.01$) over the Atlantic. Over land there is a 30% increase in wind speed for a 1 °C rise in SST. This result is in line with Lonfat *et al* (2004) and Jiang *et al* (2008) who found that higher rainfall rates were associated with more intense tropical cyclones. Global modelling studies, for example by Liu *et al* (2019), also

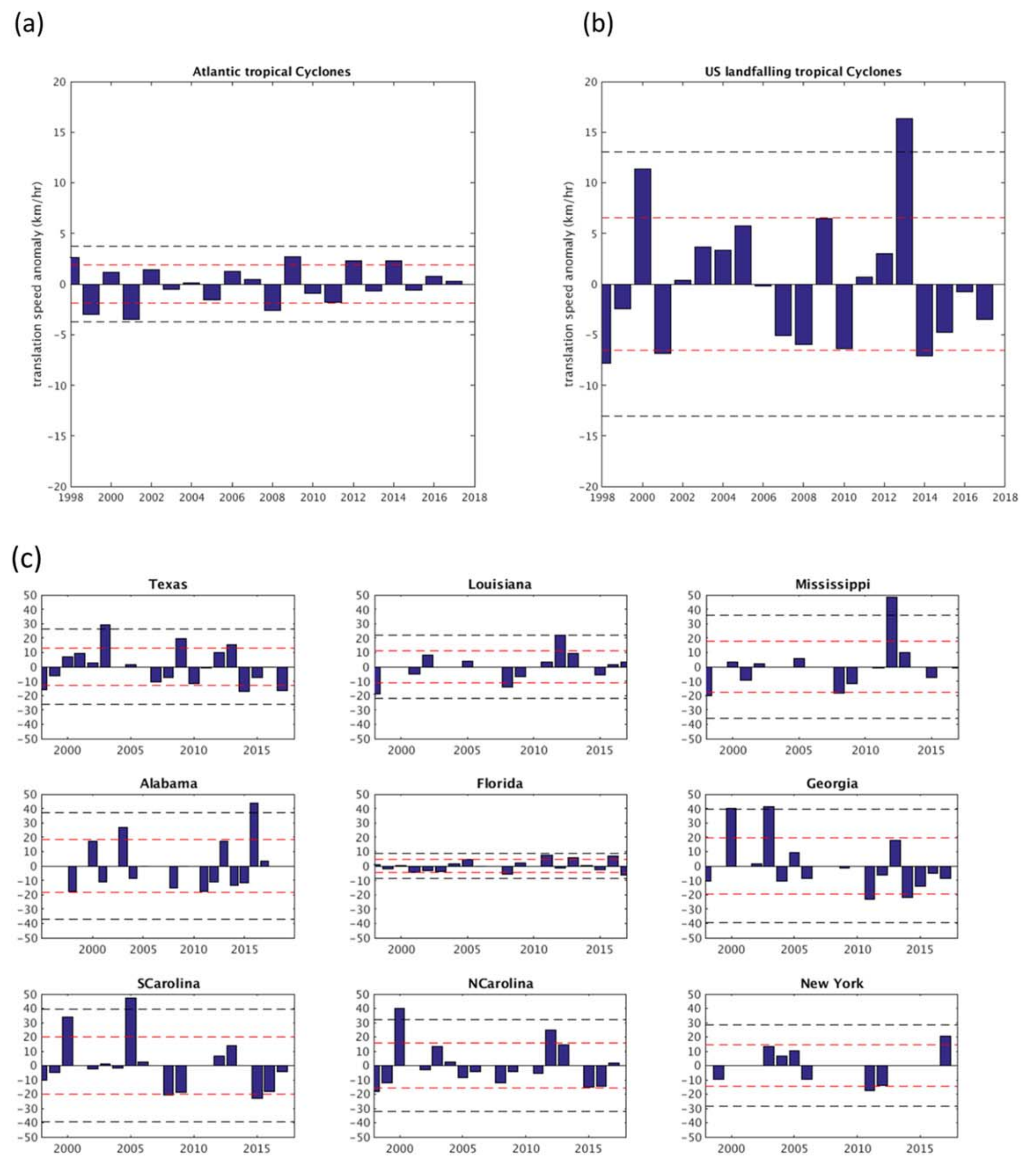

Figure 8. Tropical cyclone translation speed anomaly (kmhr^{-1}) 1998 −2017 (a) Atlantic Ocean tracks (b) US landfalling tracks (c) by US state. Red dashed lines indicate ±1 std, black dashed lines indicate ±2std.

find that the increase in TCP rate is significantly larger than the Clausius-Clapeyron rate, however, when they exclude the impact of wind speed, the rainfall rate increase shows a much better match with the Clausius-Clapeyron rate. The increase in moisture convergence associated with high wind speeds helps explain the higher TCP rates (Knutson *et al* 2010).

More work would be required to establish how TC wind speed and rainfall rates over land are related as orography is likely to contribute as outlined in Chang *et al* (2013). Once a TC makes landfall, it can no longer extract heat via evaporation from the ocean, its energy source, and so starts to decay, which is seen through a decrease in wind strength (Emanuel 2005). To a lesser extent increased friction from the roughness of land's surface also causes the TC to weaken. Windspeeds tend to diminish exponentially losing half their value in around 7 h. Rainfall also diminishes after landfall but less quickly as the storms retain water vapor as they move inland (Emanuel 2005) which helps explain why we see higher rainfall rates over land than the ocean for a given wind speed (figures 5(a), (b)). What we see in this study is that with higher SSTA there is an increase in wind speed of landfalling TCs, and also duration as it takes longer to diminish, which results in a higher rainfall rate and total rainfall.

Overall, what is new here is that using observational data for the 1998-2017 period we find results which support earlier findings based on model-based studies (for example: Knutson *et al* (2020), Liu *et al* (2019)) and

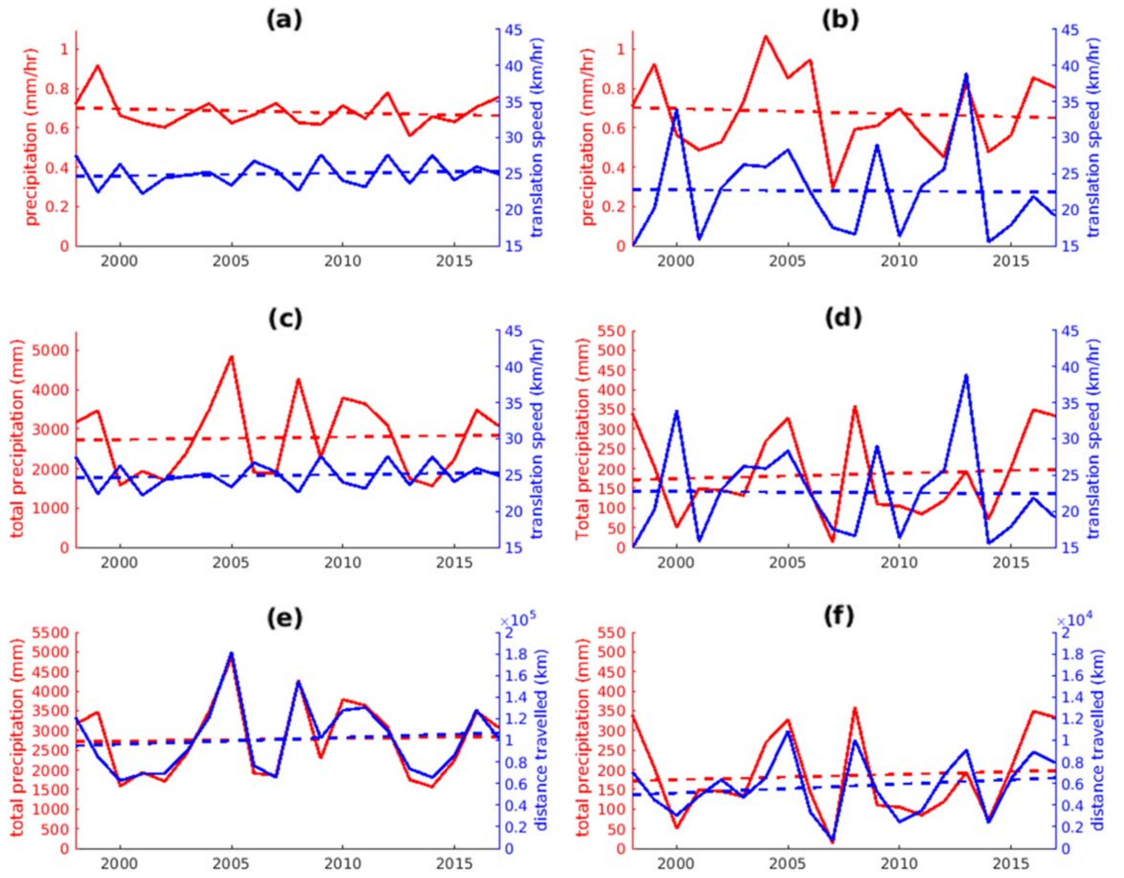

Figure 9. Tropical cyclone precipitation, translation speed and distance travelled timeseries (a)(c)(e) Atlantic Ocean only tropical cyclones (b)(d)(f) US land falling tropical cyclones. Red line indicates precipitation, blue line indicates translation speed/distance travelled. Red and blue dashed lines indicate linear best fit line.

also observed individual extreme events such as Hurricane Harvey (Van Oldenborgh et al (2017), Wang et al (2018)). In addition, a distinction is shown between land and ocean, with TCP rates in excess of Clausius-Clapeyron over land, but in line with Clausius-Clapeyron over the ocean for a 1 °C rise in SST. Many studies do not separate the TCP rate response between ocean and land. As TCs spend most of their time over the ocean, studies which do not separate the land and ocean response may mask the different TCP rate response over the land, which is important for flood risk.

Total annual TCP was also found to be significantly correlated with the SSTA in the MDR with a correlation over the Atlantic of $r = 0.7$ ($p < 0.01$) and over land $r = 0.49$ ($p = 0.03$). Over land (ocean) there is an increase of over 140% (116%) in total rainfall for a 1 °C rise in MDR SST. The increase in TC tracks, wind speed and TC distance travelled with rising MDR SSTA helps explain why the total TCP increase far exceeds the increase expected from the Clausius-Clapeyron relation. We would therefore expect that the increasing major TC landfall counts along the US Atlantic coast, seen between 1982 and 2020 in the study by Wang and Toumi (2022), would be associated with the increase in total rainfall in those years. Overall, the development of positive SSTA in the MDR indicates increased landfalling total TCP and TCP rate are likely and potential increased flood risk.

Overall it is known that favourable (warm) ocean thermal structure in the MDR, together with a low vertical wind shear, are together conducive to intensive and sustained hurricane development (Gray 1968, Gray 1979, Landsea 1993, Frank and Ritchie 2001, Camp et al 2018, Hallam et al 2019). What is highlighted here is that positive SSTA and associated low VWS also lead to an increase in the TC rainfall rate and total TC rainfall over both the ocean and land.

Turning to translation speed, the 10 m wind speed is significantly correlated with translation speed ($r = 0.26$, $p = 0.02$), not shown, on an annual all Atlantic TC track basis, which indicates that more intense TCs are associated with higher translation speeds. In the study by Mei et al (2012), they show how higher translation speeds are linked to more intense storms, whereby a faster translation speed reduces the cooling effect from the upper ocean which can weaken the storm intensity. The translation speed correlations do not hold over land indicating other factors impact on landfalling TC translation speed. The median tropical cyclone translation speed is 20.3 kmhr^{-1}, although this falls to 16.5 kmhr^{-1} over land with the lowest translation speeds found in in the southerly states of Florida and Louisiana. In the more northern states the translation speed is higher which suggests a latitudinal dependence of TC translation speed. The increase in translation speed with latitude aligns with several studies (Kossin *et al* (2014), Camargo (2013), Yamaguchi *et al* (2020) Kim *et al* (2020)) who find translation speed increases with latitude associated with an increase in steering flow from the midlatitude jet above 20°N. Only significant declining trends in translation speed are evident in the US state of Georgia $r = -0.44$ ($p = 0.09$) over the time period. In this study, however, no consistent decline in translation speed has been found over land which is different to the findings by Kossin (2018), but it is perhaps related to the shorter data set used here of only 20 years and the significant interannual variability seen in those years. Other studies are also less conclusive about a declining translation speed in recent decades (Knutson *et al* 2020). There seems to be opposing factors impacting on translation speed in a changing climate which may be why studies show different results. A slowdown in the summertime tropical circulation with a changing climate would reduce translation speed (Kossin 2018, Guo *et al* 2021) as TCs are carried in the environmental wind. At the same time more TC storms at higher latitudes (Kossin *et al* 2014) would increase translation speed due to the increase in steering flow from the mid latitude jet. Guo *et al* (2021) also highlight the importance of seasonality with increases in translation speed observed in June and October in recent decades, and slowdown in August.

This analysis of the 9 US states provides a systematic review and highlights how TC rainfall vary by US states. The US states with the highest number of landfalls per year are Florida (2.75), North Carolina (1.85) and Texas (1.65). The highest rainfall rates are found in Florida at 0.83 mmhr^{-1}, whilst the states with the longest TC durations were Florida and Texas with close to 40 h compared to 14 h in the other states.

Overall, the links between SSTA in the MDR and both TCP rate and annual total TCP (both over the ocean and land) provide useful insights for seasonal to decadal flood prediction from Atlantic tropical cyclones. Importantly, increases in SSTA result in a marked increase in both TCP rate and total TCP over land. The increase in TCP rate over land is far in excess of the expectation from Clausius-Clapeyron and is associated with the increasing wind speed and indicates both a thermodynamic and dynamic response. The increase in total TCP over land reflects the higher wind speed and higher number of TC track points over land, when SSTAs are positive in the MDR. Future research into flood risk from TCs, associated with rising temperatures, will need to consider both the thermodynamic and dynamic responses together with the expected increase in number of track points over land as outlined here.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://climatedataguide.ucar.edu/climate-data/ibtracs-tropical-cyclone-best-track-data.

Declarations

The authors declare no competing interests.

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