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An increase in global trends of tropical cyclone translation speed since 1982 and its physical causes

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Abstract

In this study, the causes of the increase in global mean tropical cyclone translation speed (TCTS) in the post-satellite era were investigated. Analysis reveals that the global-mean TCTS increased by 0.31 km h^{-1} per decade over the last 36 years, but the steering flow controlling the local TCTS decreased by -0.24 km h^{-1} per decade in the major tropical cyclone (TC) passage regions. These values correspond to a change of 5.9% and -5.6% during the analysis period for the mean TCTS and steering flow, respectively. The inconsistency between these two related variables (TCTS and steering flows) is caused by relative TC frequency changes according to basin and latitude. The TCTS is closely related to the latitude of the TC position, which shows a significant difference in mean TCTS between basins. That is, the increased global-mean TCTS is mainly attributed to the following: (1) an increase (4.5% per decade) in the relative proportion of the North Atlantic TCs in terms of global TC's position points (this region has the fastest mean TCTS among all basins); and (2) the poleward shift of TC activities. These two effects account for 76.8% and 25.8% of the observed global-mean TCTS trend, respectively, and thus overwhelm those of the slowing steering flow related to the weakening of large-scale tropical circulation, which leads to a global mean increase in TCTS. Given that TC activity in the North Atlantic is closely related to the Atlantic Multi-decadal Oscillation and a poleward shift of TC exposure is likely induced by global warming, the recent increase in the global-mean TCTS is a joint outcome of both natural variations and anthropogenic effects.

1. Introduction

Tropical cyclones (TCs) affect human societies in many ways. The vertical mixing and upwelling by TCs deliver nutrients to the near surface from the deeper ocean, which can increase the fish catch. However, destructive winds, torrential rainfall, and storm surges due to TCs also cause enormous damage. The intensity of damage and the upper-ocean mixing caused by TCs are closely related to the duration of TC impacts, which is largely determined by the TC translation speed (TCTS). For slower moving TCs, increased duration affects the surrounding environment for longer periods. For example, the slow movement of Typhoon Morakot in 2009 resulted in one of the highest recorded rainfall amounts in southern Taiwan (Chien and Kuo 2011, Lin *et al* 2011, Wu

2013). The four-day accumulated rainfall produced by this storm in August 2009 reached about 3000 mm and killed more than 600 people. In heavily populated coastal areas, the slow movement of TCs can result in critical damage due to prolonged exposure to strong winds, heavy rain, and storm surges (Emanuel 2017, van Oldenborgh *et al* 2017).

The slow down of TCTS also increases the amount of momentum transfer from the TC to the ocean. This leads to deeper vertical mixing and enhanced sea surface cooling, which reduces the heat flux from the ocean to the TC, thereby inhibiting TC reinforcement (Liu *et al* 2007, Lin *et al* 2009, Mei *et al* 2012, Hormann *et al* 2014).

Due to the important role of TCTS in TC impact and intensity, there is growing interest in knowing how the TCTS may have changed under global

warming conditions. Kossin (2018; hereafter, K18) showed that tropical circulation weakened by global warming causes TCs to slow down globally by about 10% during 1949–2016, which would increase local rainfall totals in their path. Moon *et al* (2019), however, pointed out that prior to satellite observations, there were limitations in detecting TCs that are weak or located in distant oceans, which result in non-homogenous TC data. They concluded that the decreasing trend in global TCTS seen in K18 is not an actual signal but, rather, is related to undetected and omitted low-latitude TCs with relatively slow TCTS in the pre-satellite era. Lanzante (2019) also suggested that the long-term changes in K18 appear to be due primarily to a few abrupt, step-like changes, both natural and artificial, in the early part of the record and not driven primarily by anthropogenic effects. Chan (2019) reported that the slow down of the global mean TCTS is not evident in the reliable satellite era starting from 1970 and the slow down of TCTS in K18 was exaggerated due to the difference in observations before and after the satellite era. Based on historical and future model simulations, Yamaguchi *et al* (2020) showed that a slow down trend in K18 is not found for the period 1951–2011 and the annual-mean TCTS could increase in a future warmer climate. These studies consistently point out that the slow down of the global mean TCTS referred to in K18 was due to changes in observational practices before and after the satellite eras.

What is the actual trend of global TCTS in the post-satellite era (1982–2017) when TC data is believed to be most reliable? figure 1 shows the time series of mean TCTS for the global, Northern and Southern Hemispheres, which all showed an increase of 0.31, 0.23, and 0.21 km h⁻¹ decade⁻¹, respectively. These values correspond to an increase of 5.9%, 3.0%, and 4.8%, respectively, over 36 years for the mean TCTS. The global trend is statistically significant based on the nonparametric Mann-Kendall test. These results are in contrast to K18's alleged decrease in the TCTS, despite the fact that the post-satellite era is the most pronounced warming phase in the last half-century.

The next question is what is the cause of this increase? In order to answer this, we investigate the trends of the steering flow (STF), which is known to be most relevant to TC movement. We also perform a quantitative analysis to identify other possible contributing factors to the global TCTS trend.

2. Data and method

The TCTS and the positions of TCs were obtained from International Best Track Archive for Climate Stewardship (IBTrACS) version 4 during 1982–2017 and analyses were performed at 6-hour intervals for TCs that had a wind speed at or above 34 kt. The short-lived TCs (less than two days duration at 34

kt) were excluded from the analysis to remove the heterogeneity of data caused by improvements in the observational capabilities during the analysis period (Landsea *et al* 2010, Villarini *et al* 2011). Considering the difference in the definition of maximum sustained wind speed of TCs between institutions, this study only uses data from the National Hurricane Center (NHC) and Joint Typhoon Warning Center (JTWC), which use a 1-min sustained wind. The Atlantic Multidecadal Oscillation (AMO) and Ocean Niño Index (ONI) are obtained from the Physical Sciences Division (PSD) of the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESL). The STF was calculated from monthly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis 1 data. The STF is derived from the vertically integrated pressure-weighted tropospheric layer-mean flows from 850 hPa to 200 hPa (Chu *et al* 2012) and averaged over the TC peak seasons of each basin (August–October in the North Atlantic; July–October in the western North Pacific and the Eastern Pacific; May–June and October–December in the North Indian; December–April in the South Indian and the South Pacific). In this study, the track density-weighted steering flow, not a simple mean of the latitude-longitude region, is used to consider the density of TC activity in the analysis of STF.

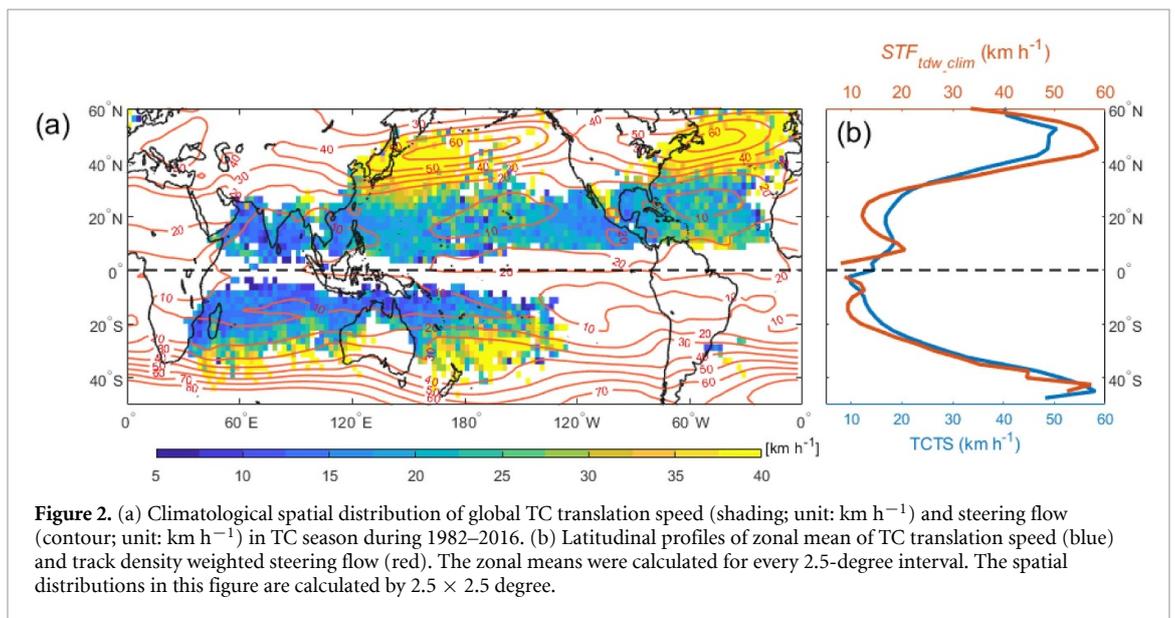
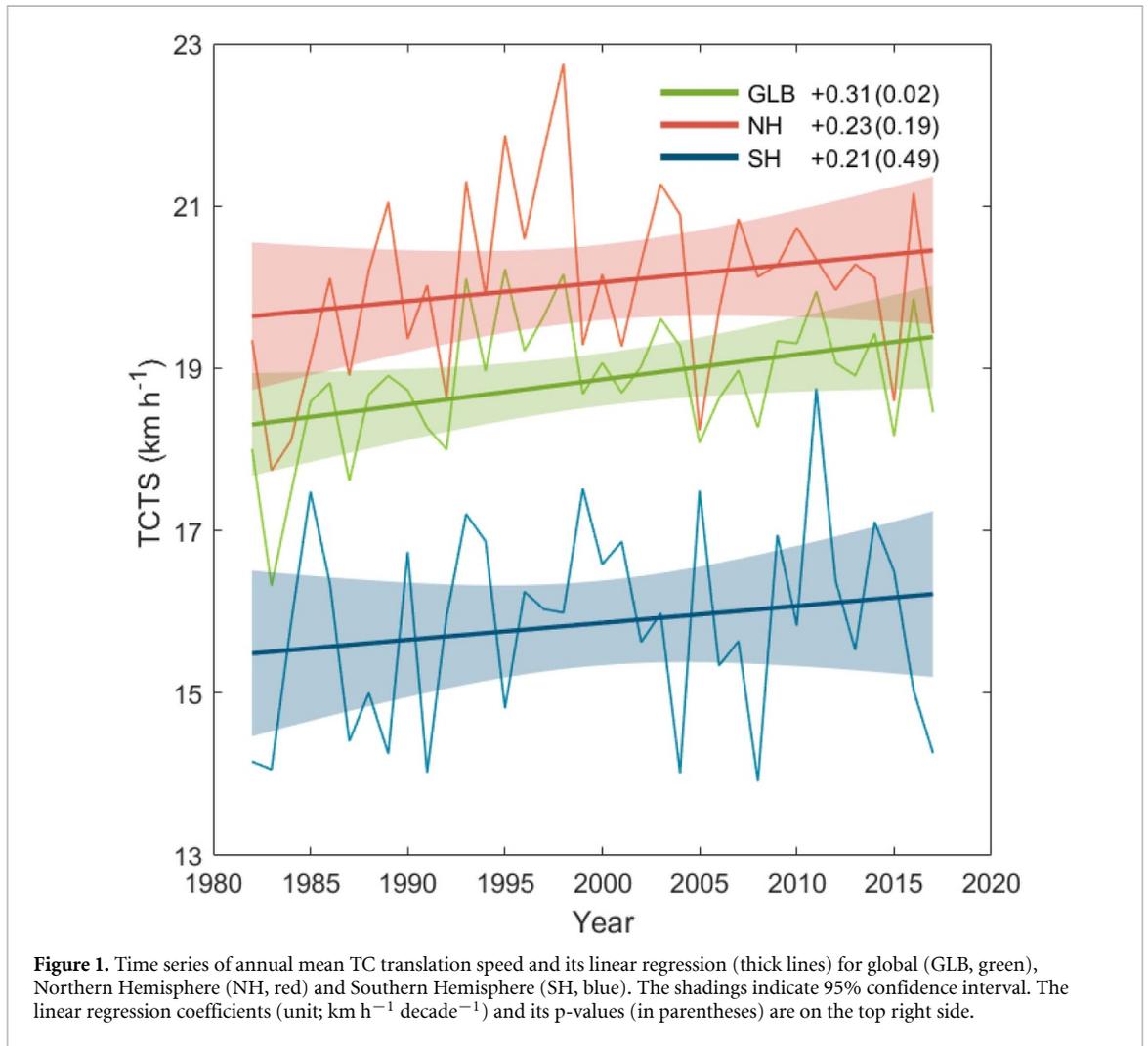
3. Results

3.1. The relationship between the TCTS and STF

Tropical cyclone movement is mainly governed by basic current or STF and small modulation of STF by β -effects (Holland 1983). Therefore, a change in STF can have a major influence on TCTS. It is known that the higher the latitude, the faster the STF, and the greater the TCTS (Moon *et al* 2019). The climatological distributions of STF (contours) and TCTS (shading) also show a general increase with latitude (figure 2(a)). To investigate the relationship between STF and mean TCTS, the track density-weighted steering flow (STF_{tdw_clim}) for each latitude was calculated using the following equation.

$$STF_{tdw_clim}(lat) = \sum_{lon=1}^{360} STF_{clim}(lon, lat) \times \frac{\rho_{clim}(lon, lat)}{\sum_{lon=1}^{360} \rho_{clim}(lon, lat)} \quad (1)$$

Where $STF_{clim}(lon, lat)$ and $\rho_{clim}(lon, lat)$ represent the climatological mean of the STF and the TC track density at a specific latitude and longitude, respectively. In the tropics (<20°), the mean STF_{tdw_clim} is 10–20 km h⁻¹, increases rapidly with latitudes from 20° where influence from the mid-latitude jet begins, and reaches up to 58 km h⁻¹ at 45°N and 48 km h⁻¹



at 40°S (see red line in figure 2(b)). The variations of zonally averaged TCTS are very similar to those of $\text{STF}_{\text{tdw_clim}}$ (see blue line in figure 2(b)), where their correlation is as high as 0.96. The regional difference between the zonally averaged TCTS and the

$\text{STF}_{\text{tdw_clim}}$ in figure 2(b) is related to the use of a constant vertical level (i.e. 850 hPa to 200 hPa) in the current STF calculation, although the vertical level associated with a TC’s movement can vary with TC intensity. Because the mean intensity of TC varies with latit-

ude and basin, the vertical level of STF, which affects TC movement, may vary slightly depending on latitude and basin.

Next, we investigate whether the recent global TCTS increase is related to STF. For this purpose, the track density-weighted STF was calculated (STF_{tdw}), as shown below.

$$STF_{tdw}(t) = \sum_{lon=1}^{360} \sum_{lat=-45}^{60} STF(lon, lat, t) \times \rho_{clim}(lon, lat) \quad (2)$$

$STF(lon, lat, t)$ is the TC season-mean STF at a given latitude, longitude, and year (t). The linear trends of the STF_{tdw} time series were -0.24 , -0.18 , and $-0.38 \text{ km h}^{-1} \text{ decade}^{-1}$ in the global, Northern (NH) and Southern Hemispheres (SH), respectively. These values correspond to a change of 5.6%, 3.8% and 11.5%, respectively, over 36 years for the mean STF. Note that all three series exhibit a downward trend. Here, the trends for the global and the SH are statistically significant at 95% confidence (figure 3). Chu *et al* (2012) also reported the slow down of the STF slow over the western North Pacific (WNP). These trends of STF are the opposite of the global mean TCTS that we found. This suggests that there are factors other than STF that lead to an increase in the TCTS.

3.2. Changes in relative proportion of each basin in the number of global TC position points (RPN)

To examine the contribution of each basin in global mean TCTS, we analyzed the trend of TCTS in each basin. Among six basins, the South Pacific (SP), South Indian Ocean (SI), and WNP have an increasing trend, but the increase is not statistically significant (figure 4(a) and table 1). The other three basins—North Atlantic (NA), Eastern Pacific (EP), and North Indian (NI)—show decreasing trends in TCTS, but are statistically insignificant. Separate analysis for the tropics and extratropics also do not reveal significant trends for all regions. These results suggest that the observed speed up of the global mean TCTS is likely not caused by local TCTS changes.

Unlike the local TCTS, the ratio of the annual number of TC position points for each basin to the total number of global TC position points (RPN), which is the relative proportion of each basin in the number of global TC position points, shows a significant trend in the NA. The RPN of NA increases significantly by 4.5% over 10 years, which corresponds to 16.2% during the analysis period of 36 years (figure 4(b), table 1).

Because of the latitudinal dependency of STF, the mean TCTS varies by basin (see table 1). For example, in the WNP and NA, where TCs move to higher latitudes, the TCTS is fast ($20\text{--}24 \text{ km h}^{-1}$). In the SI and NI, where most TCs stay in the tropics, the TCTS is slow ($14\text{--}15 \text{ km h}^{-1}$). This suggests that the global TCTS increase is influenced not only by faster TCTS

in the entire or specific basins, but also by an increase in RPN for basins or specific regions where the mean TCTS is relatively fast. Considering the mean TCTS in the NA is fast (24.2 km h^{-1}) and mean TCTS in the tropics of the WNP and the SP is slow (17.3 km h^{-1} and 14.6 km h^{-1} , respectively), the changes in RPN in these regions seem to contribute to increased global mean TCTS. In the next section, we examine the contributions of the local TCTS and RPN change to global TCTS through a quantitative analysis.

3.3. Quantitative analysis on the contributions to the global TCTS trend

In order to quantify the contributions of the local TCTS and RPN change to global TCTS increase, the global mean TCTS ($TCTS_{global}(t)$) for each year is divided into four components (equation (5)) and their contributions to global TCTS trend are estimated (table 1). The annual global mean TCTS is determined by the sum of multiplying the basin mean TCTS by the RPN for each basin (equation (3)). Furthermore, these two quantities (i.e. TCTS and RPN) can be decomposed by their means and deviations from their mean via equations (4) and (5) as described below.

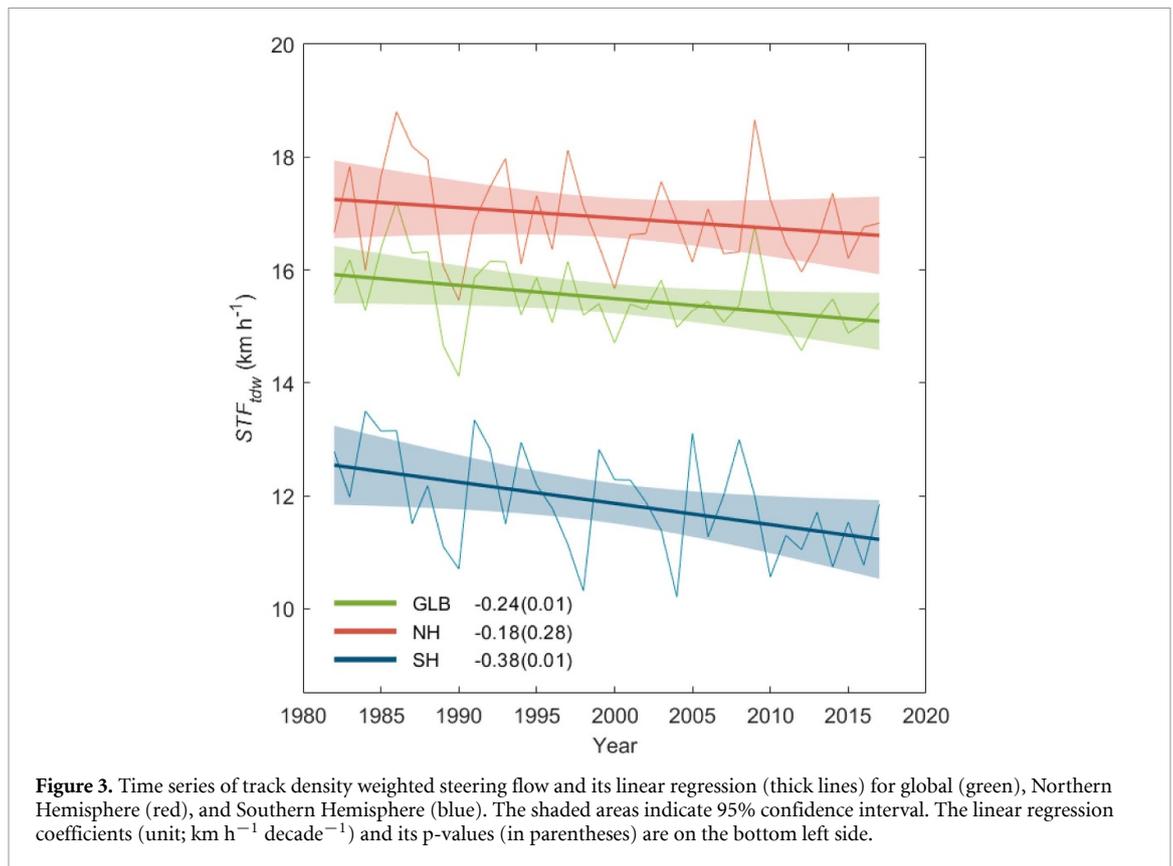
$$TCTS_{global}(t) = \sum_{b=basin}^6 (RPN(b, t) \times TCTS(b, t)) \quad (3)$$

$$= \sum_{b=basin}^6 ((\overline{RPN}_{Clim}(b) + RPN'(b, t)) \times (\overline{TCTS}_{Clim}(b) + TCTS'(b, t))) \quad (4)$$

$$= \sum_{b=basin}^6 (\overline{RPN}_{Clim}(b) \times \overline{TCTS}_{Clim}(b)) + \sum_{b=basin}^6 (\overline{RPN}_{Clim}(b) \times TCTS'(b, t)) + \sum_{b=basin}^6 (\overline{TCTS}_{Clim}(b) \times RPN'(b, t)) + \sum_{b=basin}^6 (RPN'(b, t) \times TCTS'(b, t)) \quad (5)$$

Where $RPN(b, t)$ and $TCTS(b, t)$ are values at a specific basin (b) and year (t). $\overline{RPN}(b)$ and $\overline{TCTS}(b)$ are the climatological mean values at a specific basin. $RPN'(b, t)$ and $TCTS'(b, t)$ denote the deviations of $RPN(b, t)$ and $TCTS(b, t)$ from the climatological mean values, respectively.

The first term on the right side of equation (5) represents the product of the climatological mean RPN and TCTS in a basin. The second term refers to the contribution of local TCTS change because the annual-mean RPN at each basin is fixed to the climatological values and only TCTS changes annually. The third term represents the influence of RPN change because the annual-mean TCTS at each basin is set to the climatological values and only the RPN varies annually. Lastly the fourth term is the product of



residual terms. Apart from the six basins, the contributions of local TCTS and RPN in the tropics ($<20^\circ$) and extratropics ($\geq 20^\circ$) are estimated separately in the same manner.

Based on the quantitative analysis, the most prominent results among the six basins are found in the NA, where climatological TCTS is the fastest. In the NA, RPN increased significantly by 4.5% per decade (table 1). This contributes to the global TCTS increase by $0.24 \text{ km h}^{-1} \text{decade}^{-1}$, which accounts for 76.8% of the global TCTS increase ($0.31 \text{ km h}^{-1} \text{decade}^{-1}$). In particular, the RPN increase in the extratropical NA (2.9% per decade) contributed to a large increase in global TCTS by as much as $0.19 \text{ km h}^{-1} \text{decade}^{-1}$.

Why is the increase in RPN in the NA region so prominent during this period? The major climate modes such as the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Mode (AMO) are likely the driving force because they are highly associated with the genesis of NA hurricanes and their duration. The tropical convection shift during El Niño leads to enhanced upper-level divergence over the Caribbean Sea and tropical Atlantic, resulting in enhanced vertical wind shear, and therefore reducing the frequency and duration of hurricanes. The positive anomalies of SST in tropical NA during the positive phase of the AMO lead to the weakening of the vertical wind shear and consequently increases the frequency of hurricanes (Gray 1984, Landsea *et al*

1999, Bell *et al* 2000, Goldenberg *et al* 2001, Trenberth and Shea 2006, Klotzbach and Gray 2008).

In this study, partial correction coefficients were calculated to investigate the relationship between the two climate modes and the RPN of NA (and global mean TCTS). For the NA, the partial correlation coefficient between RPN and AMO (ENSO), after controlling for ENSO (AMO), is 0.75 (-0.64), which is statistically significant, with AMO having a higher correlation than ENSO (figure 5(a)). Multiple regression analysis using these two climate modes explains about 72% of the RPN variability of NA. The partial correlation coefficient between global mean TCTS and AMO (ENSO), after controlling for ENSO (AMO), is 0.34 (-0.12), and only the AMO correlation is significant (figure 5(b)). Because ENSO has a positive correlation ($r = 0.71$) with the RPN of WNP, where TCTS is the second fastest among the entire basins, the global mean TCTS reduction by the RPN of NA during El Niño can be offset by an increase in the RPN of WNP. For example, in 1993 and 1997 when the global TCTS was faster than 19.5 km h^{-1} (yellow cross marks in figure 5(b)), the RPN of the NA was less than 10%. The TC activity observed over the WNP was very high. Specifically, the RPNs of WNP in these two years are 39.5% and 39.3%, respectively, which is about 6% higher than the climatology mean. The AMO is known to have undergone several decades of cycles and may be more influential on the long-term trend of TCTS than ENSO,

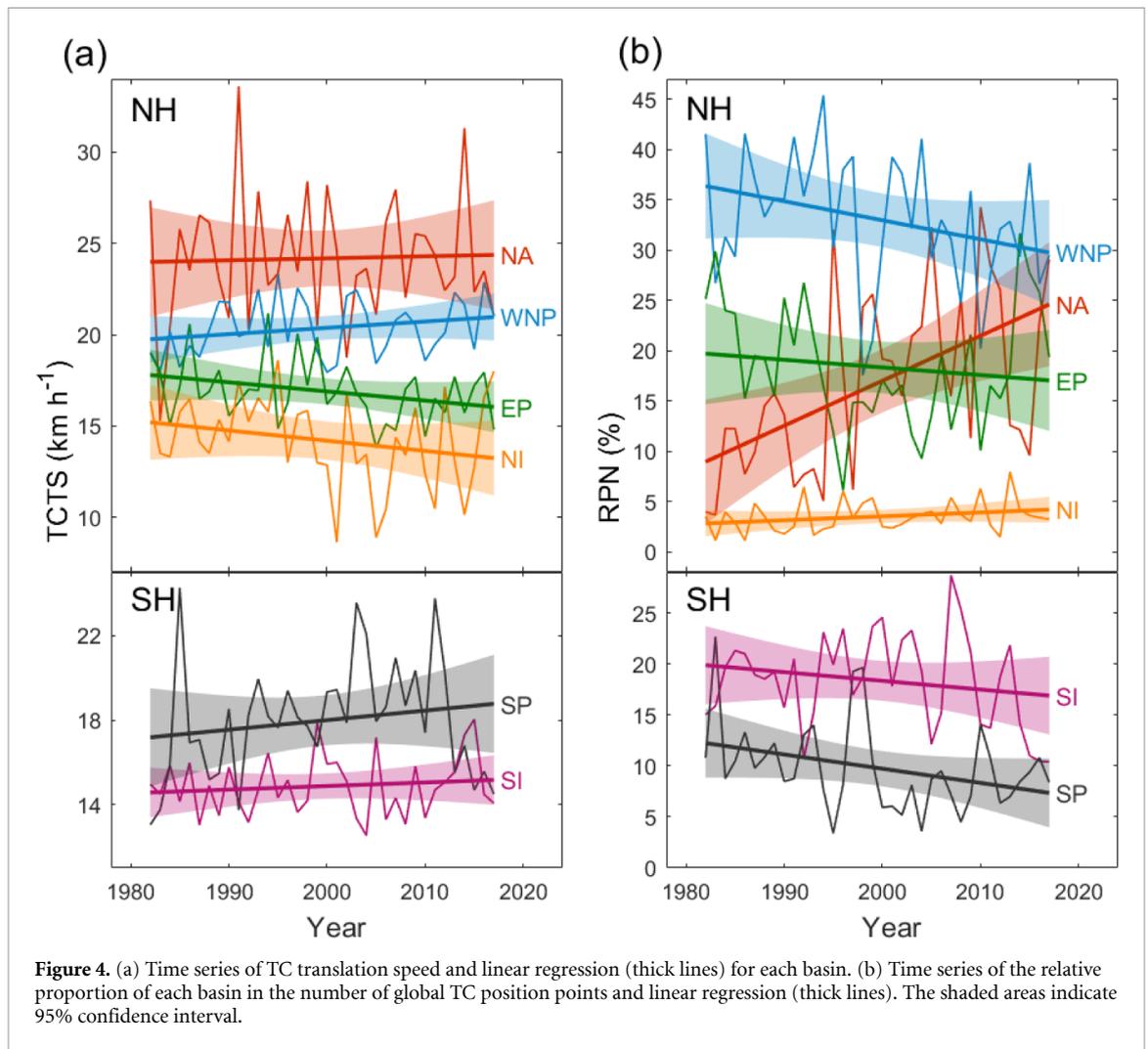


Figure 4. (a) Time series of TC translation speed and linear regression (thick lines) for each basin. (b) Time series of the relative proportion of each basin in the number of global TC position points and linear regression (thick lines). The shaded areas indicate 95% confidence interval.

which are manifested by relatively short cycles (e.g. interannual). The AMO was in a positive phase for 6 out of 7 years when the global mean TCTS was faster than 19.5 km h^{-1} (figure 5(b); orange circles). The increase in global TCTS is due to the increase in TC frequency and duration in the NA, which correspond to a steadily increasing AMO index from the cold peak phase in the mid-1970s to the warm phase in the late 2010s (figure 5(c)).

In the analysis for the tropics and extratropics, we found a significant poleward shift in RPN of 3.5% per decade. This shift contributes to global TCTS increases by 0.09 and $0.15 \text{ h}^{-1} \text{ decade}^{-1}$ for the tropics and extratropics, respectively (table 1, bottom).

Kossin *et al* (2014) showed that the lifetime maximum intensity (LMI) position of global TC migrated poleward over the past few decades. They suggest that the cause of this migration is a shift in the environment favorable for TC development (weak vertical wind shear and high potential intensity) from the tropics to extratropics due to global warming. Daloz and Camargo (2017) found that the poleward migration of TC LMI latitude was mainly due to the poleward shift of the TC genesis location, especially in

the Pacific basin. Their results suggest that the tropics in the Pacific have recently become unfavorable for TC genesis and development.

Consistent with previous studies, we found that RPN of tropics in the Pacific decreased by about 15.2% (p -value < 0.01) over the last 36 years, of which WNP and SP accounted for 78.3% of the total decrease. The decreases in RPN for the tropics in the Pacific correspond to an increase in RPN for the extratropics in the NA, which is related to AMO because there is no significant increase in the RPN of extratropics other than in the NA. Therefore, the contribution of the poleward shift of the RPN presented in this study can be an overlapped result of both global warming and AMO. Thus, in order to identify only the influence of the poleward shift of TC activities due to global warming, it is necessary to exclude the increase of RPN in NA from the results. The contribution of the decrease in RPN for the tropics in WNP and SP, which showed significant RPN reduction in the tropical Pacific, to the global mean TCTS trend were 0.03 and $0.05 \text{ km h}^{-1} \text{ decade}^{-1}$, respectively, with the sum of these two accounting for about 25.8% of the total increase.

Table 1. Climatological mean values, linear trends, and contributions to global TCTS trend, by region, of local TCTS and the relative proportion of each basin in the total number of global TC position points (e.g. RPN) over 1982–2017. ‘Extra’ denotes extratropics (poleward of 20°) and ‘tropics’ denotes tropics (equatorward of 20°). Bold-faced font and bold-faced font with asterisk represent trends that are significant at the 95% and 99% confidence level, respectively, based on the Mann-Kendall test. NA, North Atlantic; WNP, western North Pacific; EP, Eastern Pacific; NI, North Indian; SI, South Indian; SP, South Pacific; NH, Northern Hemisphere; SH, Southern Hemisphere; GLB, global.

Basin	Climatological mean			Linear trends			Contribution to global TCTS trend		
	TCTS (km h ⁻¹)	RPN (%)	TCTS (km h ⁻¹ per decade)	RPN (% per decade)	RPN change (km h ⁻¹ per decade)	Local TCTS change (km h ⁻¹ per decade)	Residual (km h ⁻¹ per decade)	Residual (km h ⁻¹ per decade)	
NA	All	24.2 ± 3.5	16.8 ± 8.7	0.11	4.5*	0.24*	0.02	-0.05	
	Extra	25.5 ± 4.6	11.9 ± 6.1	-0.03	2.9*	0.19*	-0.00	-0.03	
	tropics	22.5 ± 4.7	4.9 ± 3.4	-0.68	1.5*	0.06*	-0.03	0.02	
WNP	All	20.4 ± 1.5	33.1 ± 6.5	0.35	-1.9	-0.03	0.11	-0.00	
	Extra	23.7 ± 3.3	15.7 ± 3.2	0.20	0.2	0.01	0.03	-0.00	
	tropics	17.3 ± 1.5	17.4 ± 5.0	0.16	-2.1*	0.03*	0.03	-0.02	
EP	All	16.9 ± 1.7	18.4 ± 6.0	-0.50	-0.8	0.01	-0.09	0.01	
	All	14.2 ± 2.5	3.5 ± 1.6	-0.56	0.4	-0.02	-0.02	-0.00	
	All	14.9 ± 1.4	18.4 ± 4.6	0.17	-0.9	0.03	0.03	-0.01	
	Extra	19.1 ± 2.9	4.4 ± 1.5	0.21	0.3	0.00	0.01	0.00	
	tropics	13.5 ± 1.6	14.0 ± 3.8	-0.14	-1.1	0.06	-0.02	-0.00	
SP	All	18.0 ± 2.8	9.8 ± 4.3	0.45	-1.4	0.01	0.04	0.02	
	Extra	26.5 ± 6.5	3.1 ± 1.5	0.15	-0.2	-0.02	0.00	0.02	
	tropics	14.6 ± 2.4	6.7 ± 3.5	0.24	-1.2	0.05	0.02	0.01	
NH	All	20.0 ± 1.1	71.8 ± 5.1	0.23	2.2*	0.03*	0.17	-0.01	
	Extra	23.6 ± 2.2	31.4 ± 6.0	0.29	3.4*	0.16*	0.09	-0.05	
	tropics	17.3 ± 0.7	40.4 ± 5.3	-0.08	-1.2	0.02	-0.03	-0.01	
SH	All	15.9 ± 1.2	28.2 ± 5.1	0.21	-2.2*	0.07*	0.06	0.00	
	Extra	21.6 ± 2.7	7.5 ± 1.9	0.21	0.1	0.00	0.02	0.00	
	tropics	13.8 ± 1.5	20.7 ± 4.4	-0.06	-2.3*	0.11*	-0.01	0.01	
GLB	All	18.8 ± 0.8	-	0.31	-	-	-	-	
	extra	23.1 ± 1.9	38.9 ± 6.0	0.29	3.5*	0.15*	0.11	-0.04	
	tropics	16.1 ± 0.7	61.1 ± 6.0	0.00	-3.5*	0.09*	0.00	-0.00	

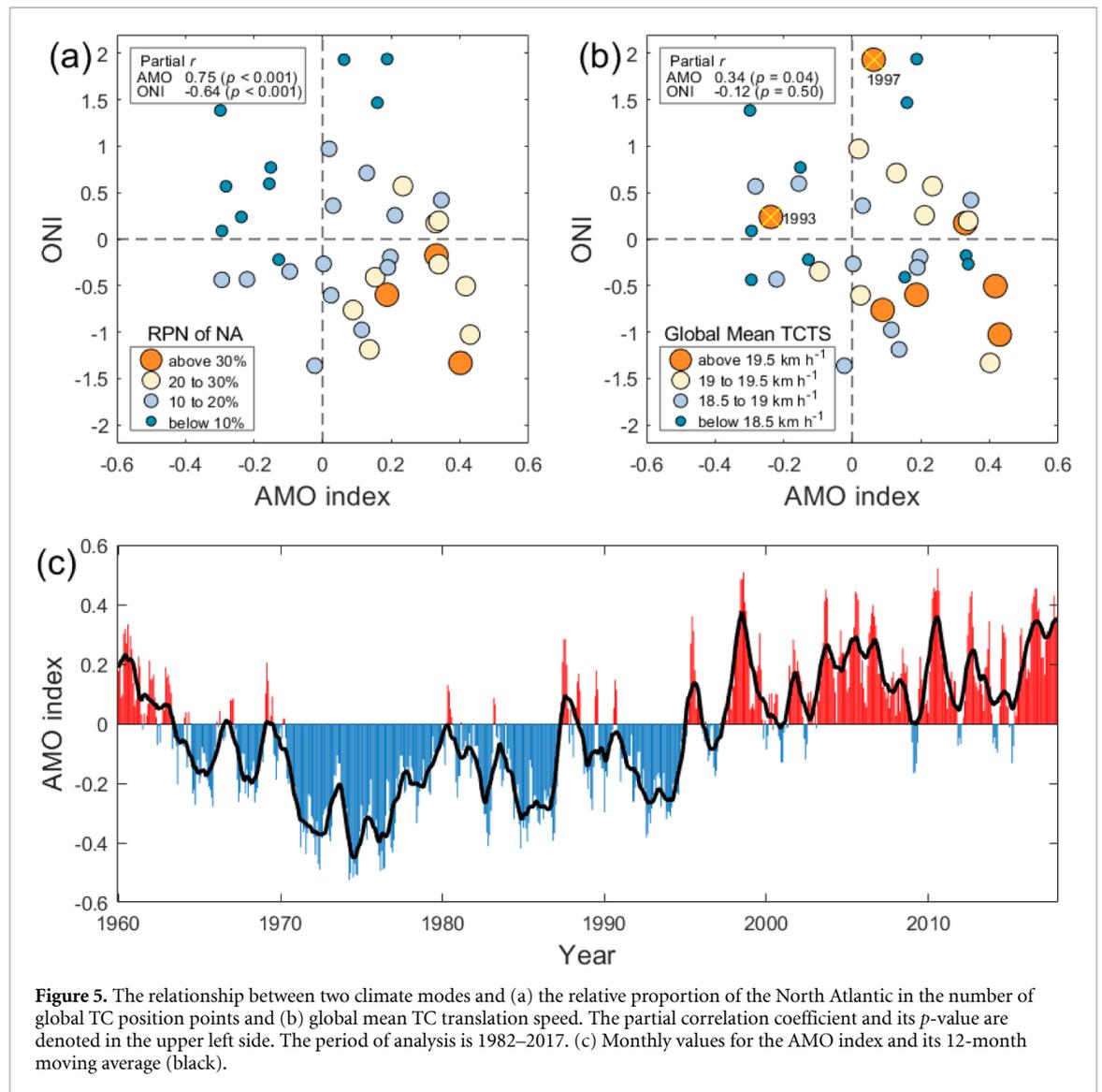


Figure 5. The relationship between two climate modes and (a) the relative proportion of the North Atlantic in the number of global TC position points and (b) global mean TC translation speed. The partial correlation coefficient and its p -value are denoted in the upper left side. The period of analysis is 1982–2017. (c) Monthly values for the AMO index and its 12-month moving average (black).

Overall, the contributions of local TCTS change are small for all basins as well as in the sub-regional analysis for tropics and extratropics (table 1, the second column from the last). The largest positive contribution ($0.11 \text{ km h}^{-1} \text{ decade}^{-1}$) is found in the WNP, although its linear trend ($0.35 \text{ km h}^{-1} \text{ decade}^{-1}$) is statistically insignificant. Note that the contribution of the local TCTS in the WNP is greatly reduced after sub-regional analysis (e.g. $0.03 \text{ km h}^{-1} \text{ decade}^{-1}$ in the tropics, $0.03 \text{ km h}^{-1} \text{ decade}^{-1}$ in the extratropics, and combined contribution is $0.06 \text{ km h}^{-1} \text{ decade}^{-1}$). In the meantime, the contribution of RPN change in the WNP increased by $0.07 \text{ km h}^{-1} \text{ decade}^{-1}$ after sub-regional analysis from $-0.03 \text{ km h}^{-1} \text{ decade}^{-1}$ to $0.04 \text{ km h}^{-1} \text{ decade}^{-1}$ (which is the sum of the contributions in the tropics and extratropics, 0.03 and $0.01 \text{ km h}^{-1} \text{ decade}^{-1}$, respectively). This suggests that the contribution of local TCTS change in the WNP to the increase in global mean TCTS in the inter-basin analysis was exaggerated by the poleward shift of RPN in the intra-basin scale.

4. Summary and discussion

Tropical cyclones are one of the deadliest weather hazards on Earth, causing tremendous damage through destructive winds, heavy rainfalls, and storm surges. Slower moving TCs amplify these impacts because of their longer duration. Understanding how the TCTS changes in a warming climate is an important research topic. In this study, we investigated the trend of TCTS during the post-satellite period (1982–2017) using the most reliable TC data to examine what controls the recent TCTS change. Analysis reveals that the global mean TCTS increased 0.31 km h^{-1} per decade over the last 36 years but STE, which is known to govern TC movement, decreased significantly by -0.24 km h^{-1} per decade in the TC active region. These values correspond to a change of 5.9% and -5.6% during the analysis period for the mean TCTS and steering flow, respectively. Individually, only the SH and WNP showed a TCTS increase among six basins but it is statistically insignificant. However, the relative proportion of the number of TC

position points (RPN) for the NA increased considerably by $\sim 16.2\%$ over 36 years. The RPN for the NA extratropics, where the mean TCTS is the fastest in the world, increased by about 10.4% in the same period.

Quantitative analysis on the contributions to the global TCTS trend shows an increase in the RPN of NA along with a poleward migration of TCs from tropics to extratropics are the main contributors to the increase in the global mean TCTS. These two effects account for 76.8% and 25.8% of the observed global mean TCTS trend, respectively. The increase in RPN of NA was highly related to the phase change in AMO and the poleward shift of RPN was linked to a decrease in TC activity in the tropical Pacific due to global warming.

As noted in the literature, the weakening of large-scale circulation due to global warming (Held and Soden 2006, Vecchi *et al* 2006, Vecchi and Soden 2007, Coumou *et al* 2015, He and Soden 2015, Mann *et al* 2017, He *et al* 2017, Grise and Polvani 2017) may eventually reduce STF, leading to a decrease in TCTS. However, global warming also leads to a poleward migration of TC track density so TCs move into a region of faster speed. Yamaguchi *et al* (2020) also predicted that the mean TCTS at higher latitudes becomes slower in a warmer climate, but the relative frequency of TCs at higher latitudes increases, which will lead to a global mean increase in TCTS. Because of these two conflicting effects, as climate changes, it is difficult to predict the global mean TCTS changes in a warmer climate.

The increase in global mean TCTS is not directly caused by an increase in the global TCTS but by spatial changes in TC activity, such as increasing the number of samples in a particular basin and poleward shift of the TC active region. Therefore, even if the global mean TCTS increases, it is difficult to conclude that the TCTS has actually increased. The local TCTS change, the second term on the right-hand-side in equation (5), is appropriate for assessing the potential impact of TC with respect to TC residence time at a given location. However, contrary to expectations that the reduction in STF will lead to a slower TCTS, our study shows insignificant trends in inter-basin scale for the analysis period (table 1, the second column from the last). The results of the analysis may still include the effect of the track density shift in the intra-basin scale. This shift may compound the contribution of pure TCTS changes to the global mean TCTS increase, as described in section 3.3. Therefore, it is expected that the quantitative analysis with a spatial-scale division small enough to remove the influence of the track shift in the intra-basin scale can reveal the tendency of pure TCTS change.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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