

Observed interannual relationship between ITCZ position and tropical cyclone frequency

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1 **Observed interannual relationship between ITCZ position and tropical**
2 **cyclone frequency**

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ABSTRACT

20 There are no well accepted mechanisms that can explain the annual frequency of tropical
21 cyclones (TCs) both globally and in individual ocean basins. Recent studies using idealized
22 models showed that the climatological frequency of TC genesis (TCG) is proportional to the
23 Coriolis parameter associated with the intertropical convergence zone (ITCZ) position. In this
24 study, we investigate the effect of the ITCZ position on TCG on the interannual time scale
25 using observations over 1979-2020. Our results show that the TCG frequency is significantly
26 correlated with the ITCZ position in the North Atlantic (NA) and Western North Pacific
27 (WNP), with more TCG events in years when the ITCZ is further poleward. The ITCZ-TCG
28 relationship in NA is dominated by TCG events in the tropics (0-20°N), while the
29 relationship in WNP is due to TCs formed in the east sector (140-180°E). We further
30 confirmed that the ENSO has little effect on the ITCZ-TCG relationship despite it can affects
31 the ITCZ position and TCG frequency separately.

32 In NA and WNP, a poleward shift of ITCZ is significantly associated with large-scale
33 environment changes favoring TCG in the Main Development Region (MDR), However, the
34 basin-wide TCG frequency has a weak relationship with the ITCZ in other ocean basins. We
35 showed that a poleward ITCZ in Eastern North Pacific and South Pacific favors TCG on the
36 poleward flank of MDR, whilst it suppresses TCG on the equatorward flank, leading to
37 insignificant change in basin-wide TCG frequency. In the South Indian Ocean, the ITCZ
38 position has weak effect on TCG frequency due to mixed influences of environmental
39 conditions.

40 **1. Introduction**

41 Although many studies have been carried out, there are still no well accepted mechanisms
42 that can explain the annual frequency tropical cyclones (TCs) globally and in individual
43 ocean basins. From year to year, the global TC frequency is about 90 which is relatively
44 stable (Emanuel 1991, 2006), it could be dynamically constrained by the maximum TC
45 disturbances associated with the ITCZ (Intertropical Convergence Zone) breakdown at any
46 instant time under current tropical atmospheric conditions (Wang et al. 2019). The ITCZ can
47 provide sufficient background vorticity and moisture (Kieu and Zhang 2008; Vu et al. 2021)
48 and a disturbance caused by ITCZ breakdown could trigger the TCG (TC genesis) (Ferreira
49 and Schubert 1997; Wang and Magnusdottir 2006; Kieu and Zhang 2008; Yokota et al. 2015;
50 Wang et al. 2019). The basin-wide frequency varies greatly in observations. There are
51 differences in TCG annual frequency and seasonal variations between basins in model
52 simulations (Sobel et al. 2021), and it is difficult for the observed annual TCG frequency to
53 be represented accurately in simulations (Hoogewind et al. 2020). Further studies are needed
54 to understand the role of ITCZ position in determining the annual frequency of TCs globally
55 and in individual basins (Hoogewind et al. 2020; Sobel et al. 2021).

56 Previous studies have focused on the ITCZ-TCG relationship using idealized aquaplanet
57 simulations and the Coriolis effect has been examined (Merlis et al. 2013; Ballinger et al.
58 2015; Merlis and Held 2019; Burnett et al. 2021). Hsieh et al. (2020) showed that there are
59 more TCG events when the ITCZ moves poleward, likely related to both the increase of
60 synoptic precursors and the probability of developing into TC because of the reduced wind
61 shear and increased Coriolis parameter. Merlis et al. (2013) indicated a 40% increase in the
62 TCG frequency per degree poleward shift of the ITCZ location when the radiative forcing is
63 unchanged. Similar idealized simulations were also carried out by Ballinger et al. (2015),
64 who found a climatological increase of TC frequency when the maximum sea surface
65 temperature (SST) shifts poleward, and when the tropical meridional SST gradient increases.
66 Ballinger et al. (2015) showed that both the ITCZ and genesis locations shift poleward when
67 the maximum SST moves poleward. Burnett et al. (2021) also showed an overall increase of
68 the TC frequency in idealized models when the maximum SSTs and ITCZ move poleward,
69 and found that the TCG frequency is proportional to the Coriolis parameter at the ITCZ
70 location, i.e., when the ITCZ shifts poleward, the TCG frequency increases. When applied to
71 observations, this ITCZ-TCG relationship generally captures the seasonal cycle of TC

72 frequency well across most TC basins (Burnett et al. 2021). It was hypothesized that the
73 ITCZ-TCG relationship is due to the higher cyclonic vorticity at the poleward flank of the
74 ITCZ (Ballinger et al. 2015). When the ITCZ moves poleward, the local planetary vorticity
75 felt by precursor disturbances associated with the ITCZ will be enhanced, leading to a higher
76 likelihood of cyclogenesis. The Coriolis parameter f at the ITCZ is considered to be the key
77 factor controlling these precursor disturbances (Burnett et al. 2021). The TCG increases
78 almost linearly with f in the tropical region (Chavas and Reed 2019).

79 These studies concentrated on the correlation between TC frequency and the ITCZ
80 position in idealized model configurations which avoids the complexity caused e.g., by the
81 asymmetry of continents (Merlis et al. 2013; Ballinger et al. 2015; Burnett et al. 2021). On
82 the one hand, both TC formation and the ITCZ have their own unique characteristics over
83 different basins. On the other hand, the TCG development is also restrained by other large-
84 scale environmental conditions, such as the SST, moisture in the middle troposphere, vertical
85 wind shear, and absolute vorticity in the lower troposphere (Palmen 1948; Gray 1968, 1979;
86 Ritchie and Holland 1997; DeMaria et al. 2001; Cheung 2004; Dowdy et al. 2012;
87 Hoogewind et al. 2020). In the real world, these environmental factors could compete with
88 each other, together with the ITCZ effect, modulating the TCG occurrence by affecting the
89 precursors and their survival rate to TCG (Ikehata and Satoh 2021). Further studies are
90 needed to understand what roles are played by these environmental factors in the TCG
91 occurrence when the ITCZ shifts poleward or equatorward. The co-variability of TCG
92 frequency and the ITCZ position on seasonal timescales makes difficult to further interpret
93 the underpinning processes in the ITCZ-TCG relationship. It is not known whether the ITCZ-
94 TCG relationship initially proposed for seasonal timescales will be useful to understand the
95 interannual variability of TCG event.

96 The ENSO (El Niño-Southern Oscillation) can affect both ITCZ and TCG since they
97 significantly influence the large scale atmospheric and oceanic conditions (Ramsay et al.
98 2012; Adam et al. 2016a, 2016b; Zhao and Wang 2019; Feng et al. 2020a, b; Schmitt et al.
99 2020; Kim and Moon 2022). In this study, we will address the following science questions:
100 (1) What is the interannual relationship in observations between the ITCZ location and the
101 TCG frequency globally and in different ocean basins with and without ENSO influences?
102 and (2) What roles are played by environmental conditions in this relationship? The data and
103 methods will be introduced in Section 2. Section 3 will present the observed relationship

104 between TCG frequency and the ITCZ position in each basin and hemisphere, followed by
 105 interpretation of the relationship by employing large-scale environmental factors. Section 4
 106 will present the summary and discussion.

107 **2. Data and methods**

108 *a. Data*

109 The IBTrACS (International Best Track Archive for Climate Stewardship) version 4
 110 dataset (Knapp et al. 2010, 2018) from 1979 to 2020 is used to calculate TCG frequency and
 111 location in the satellite era. IBTrACS data are TC Best Track observations, containing the
 112 maximum sustained wind speed, minimum sea level pressure and location at 6-hourly
 113 intervals. Best Track observations used in this study are from USA agencies, such as the
 114 National Hurricane Center (NHC), Joint Typhoon Warning Center (JTWC) and Central
 115 Pacific Hurricane Center (CPHC). In our study, we only include TCs whose maximum
 116 sustained wind speed $U_{\max} \geq 33$ knots, and the first track point reaching 33 knots is defined as
 117 the TCG location.

118 The monthly ITCZ location and intensity is calculated from the monthly GPCP (Global
 119 Precipitation Climatology Project) version 2.3 data (Adler et al. 2003, 2018), at the spatial
 120 resolution of $2.5^\circ \times 2.5^\circ$. The GPCP data combine data from various sources including satellite
 121 products, gauge measurements and sounding observations.

122 *b. ITCZ position and intensity*

123 To mitigate the effect of the low resolution in precipitation data on the ITCZ
 124 identification, a centroid method is used following Frierson and Hwang (2012), Donohoe et
 125 al. (2013) and Burnett et al. (2021). The ITCZ positions in northern (θ_{NH}) and southern (θ_{SH})
 126 hemispheres can be defined as:

$$127 \quad \theta_{NH} = \frac{\int_0^{20} \varphi \times p \times \cos \varphi d\varphi}{\int_0^{20} p \times \cos \varphi d\varphi} \quad (1)$$

$$128 \quad \theta_{SH} = \frac{\int_{-20}^0 \varphi \times p \times \cos \varphi d\varphi}{\int_{-20}^0 p \times \cos \varphi d\varphi} \quad (2)$$

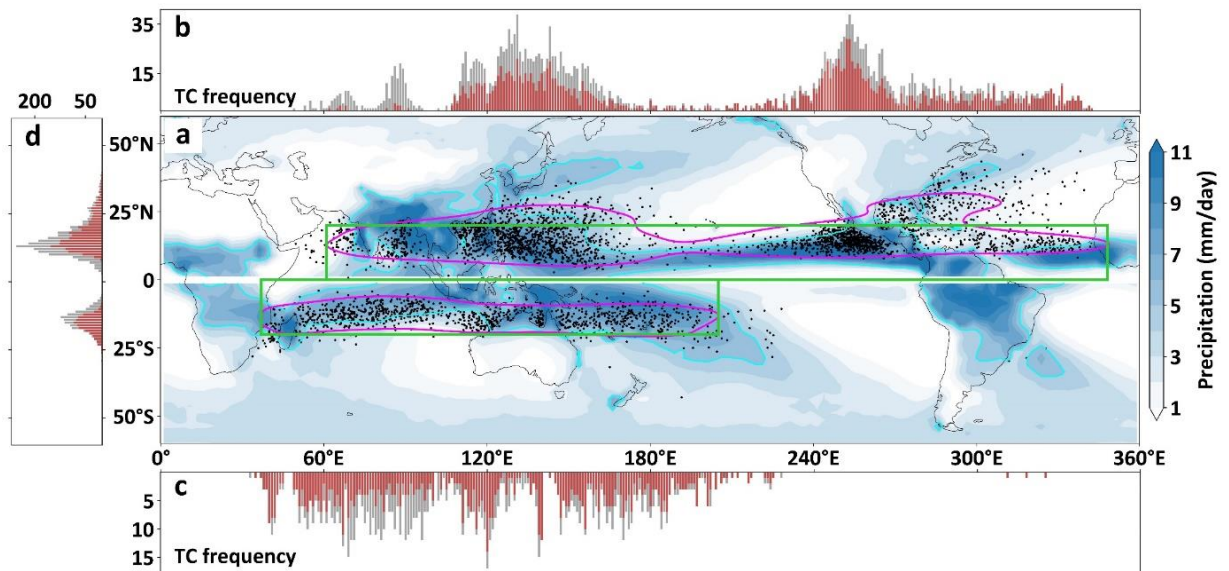
129 where φ is the latitude ($^\circ$) and p the precipitation (mm/day). The integral is from 0° to
 130 $20^\circ N$ for NH basins and from $20^\circ S$ to 0° for SH basins. The corresponding ITCZ intensity is
 131 defined as the mean precipitation of the two latitudes that are closest to the ITCZ position.

132 Both the ITCZ position and intensity are calculated at each longitude first and then averaged
 133 over the longitude range of each basin (see next subsection). Both land and ocean grid points
 134 in the defined area are included in the calculation.

135 Considering the uncertainty of the ITCZ position from different definitions and datasets,
 136 the maximum precipitation method (Liu et al. 2020) is also employed to compare with the
 137 centroid method, and the corresponding ITCZ precipitation is the longitudinal mean at the
 138 ITCZ latitude. Other datasets with different spatial resolutions, including the ERA5
 139 ($0.25^\circ \times 0.25^\circ$), TRMM (Tropical Rainfall Measuring Mission, $0.25^\circ \times 0.25^\circ$, Huffman et al.
 140 2007) and GPCP ($1.0^\circ \times 1.0^\circ$), are also used to check the robustness of our results.

141 *c. TCG and ITCZ regions*

142 As defined in IBTrACS, we have six ocean basins for TCG, which are the North Atlantic
 143 (NA), Western North Pacific (WNP), Eastern North Pacific (ENP) and North Indian Ocean
 144 (NIO) in the Northern Hemisphere (NH), and South Indian Ocean (SIO) and South Pacific
 145 (SP) in the Southern Hemisphere (SH) (Figures 1 and S1-S6). Since there are only three
 146 observed TCs in the South Atlantic over 1979-2020 (Figure 1a), it is excluded from this
 147 study.



148
 149 Figure 1. (a) TCG locations (black dots) and TC season mean precipitation (shaded) in
 150 the NH and SH over 1979-2020. Cyan contours represent the climatological rainfall of 5
 151 mm/day. Magenta contours are areas accounting for at least 80% of the number of TCG using
 152 Kernel Density Estimation. The green boxes represent the area boundaries for ITCZ location
 153 calculation in NH and SH, with the same longitude ranges as the magenta contours. The
 154 green box range is (61° - 348° E, 0° - 20° N) in NH and (37° - 205° E, 0° - 20° S) in SH. The TC
 155 season is JAS in NH and JFM in SH. (b) Red bars represent total TC numbers at 1° longitude

156 interval in NH TC season over 1979-2020, while grey bars represent those in the whole year.
157 (c) As (b), but for SH. (d) As (b) and (c), but for TC numbers at 1° latitude interval. The
158 configurations for basin-wide TCG and ITCZ definitions are provided in Table S1 and
159 Figures S1-S6 in supplementary material. The abbreviated basin names are also listed in
160 Table S1.

161

162 The ITCZ in the main TCG region is used to study the ITCZ-TCG relationship. The main
163 TCG region is estimated for each ocean basin and each hemisphere (Figures 1 and S1-S6)
164 using Kernel Density Estimation (KDE) (Ivezić et al. 2019; Zhao et al. 2015; Zhao et al.
165 2021). The magenta contour (Figures 1 and S1-S6) is calculated from KDE and contains 80%
166 of TCG events over the target basin (Figures 1 and S1-S6). The boundaries of the magenta
167 contour are used to define the longitudinal range (green boxes in Figures 1 and S1-S6) for the
168 calculation of the ITCZ position, except in NA and SP where the green box ends at the west
169 coast of the ocean basin. The latitude ranges for the ITCZ calculation are 0-20°N in NH and
170 0-20°S in SH. The TCG event is counted in each target basin defined by IBTrACS. The
171 boundary ranges for each basin, ITCZ calculations, and abbreviated basin names are shown
172 in Table S1.

173 The TC season is defined to be from July to September (JAS) for basins in the NH and
174 from January to March (JFM) for basins in SH. The whole year is defined to be from January
175 to December in NH and from July to June in SH. The number of TCG in TC seasons is about
176 57.1% of the total occurrence in NH and about 63.4% in SH over 1979-2020 (Figure 1).

177 As expected, there is a clear co-variation between the ITCZ position and TCG frequency
178 on monthly scale in individual ocean basins and hemispheres (Figure S7), except for the NIO
179 where the TCG frequency has two peaks due to the strong vertical wind shear during the
180 monsoon period (Gray 1968; Li et al. 2013; Swapna et al. 2022). The ITCZ location is
181 generally the most poleward in the peak season of TCG (Liu et al. 2020). Unless otherwise
182 stated in this study, the ITCZ position in a basin will be the mean latitude of the ITCZ region
183 in the TC season, and the TCG frequency will be the total number of TCG events in the TC
184 season. The NIO will be excluded in the following analysis because there are too few TCs
185 during the period from July to September.

186 *d. Removal of the linear signal associated with ENSO*

187 Many studies have shown the ENSO influences on the ITCZ position and TC frequency,
188 since it could not only modulate the meridional SST gradient, affect trade winds and lead to

189 the regional ITCZ migration (Bischoff and Schneider 2014; Schneider et al. 2014; Sasaki et
 190 al. 2015; Fu et al. 2017; Zhao et al. 2021), but also modulate the large-scale circulation,
 191 change environmental conditions such as the wind shear, vertical motion and adjust TC
 192 activities. In this study, the ITCZ-TCG relationship is compared before and after removing
 193 the ENSO effect from ITCZ position and TCG frequency.

194 The Oceanic Niño Index (ONI) from NOAA (National Oceanic and Atmospheric
 195 Administration) is an ENSO indicator which is the three-month running mean of SST
 196 anomaly over the Niño 3.4 region (5°N-5°S, 120°-170°W). The El Niño years and La Niña
 197 years are defined such that there is a minimum of 5 consecutive overlapping seasons
 198 including the TC season with $ONI \geq 0.5^\circ\text{C}$ (El Niño year) or $ONI \leq -0.5^\circ\text{C}$ (La Niña year),
 199 which are listed in Tables S2 and S3 for NH and SH, respectively. A linear model $y =$
 200 $m \times ONI + a$ (where m and a are constants) is regressed to estimate the linear effect of ENSO
 201 on the ITCZ position or TCG frequency. The ENSO effect could be excluded by only using
 202 the neutral years, or subtracting the regressed model from the ITCZ and TC frequency
 203 timeseries (Feng et al. 2021). The second method is used in this study.

204 *e. Statistical analysis methods*

205 The Wald test with t-distribution is used for the significance test of the regression slope
 206 and the two-tailed t-test is used for the significance test of the Pearson correlation coefficient
 207 (Wilks 2011) in this study. The time series of the ITCZ position, TCG frequency and TCG
 208 location have been detrended, in order to focus on the interannual variability of their
 209 relationships.

210 *f. Environmental conditions*

211 The environmental variables, such as the SST, relative humidity (RH) at 600 hPa, vertical
 212 wind shear (WS) between 200 and 850 hPa, and the relative vorticity (RV) at 850 hPa, are
 213 important factors affecting the TCG. Their changes and influences on the TCG are
 214 investigated in this study. In order to evaluate the integrated effect of environment factors on
 215 TCG, the GPI (genesis potential index) is also calculated based on Emanuel and Nolan
 216 (2004)

$$217 \quad GPI = |10^5 \eta|^{3/2} \left(\frac{RH}{50}\right)^3 \left(\frac{V_{pot}}{70}\right)^3 (1 + 0.1WS)^{-2} \quad (3)$$

218 where η is the absolute vorticity at 850 hPa (s^{-1}), which is the Coriolis parameter plus the

219 relative vorticity. V_{pot} is the potential intensity (m s^{-1} , Emanuel 1986). All of these variables are
220 downloaded or calculated from the ERA5 monthly reanalysis (Hersbach et al. 2020), with
221 horizontal resolution of $0.25^\circ \times 0.25^\circ$.

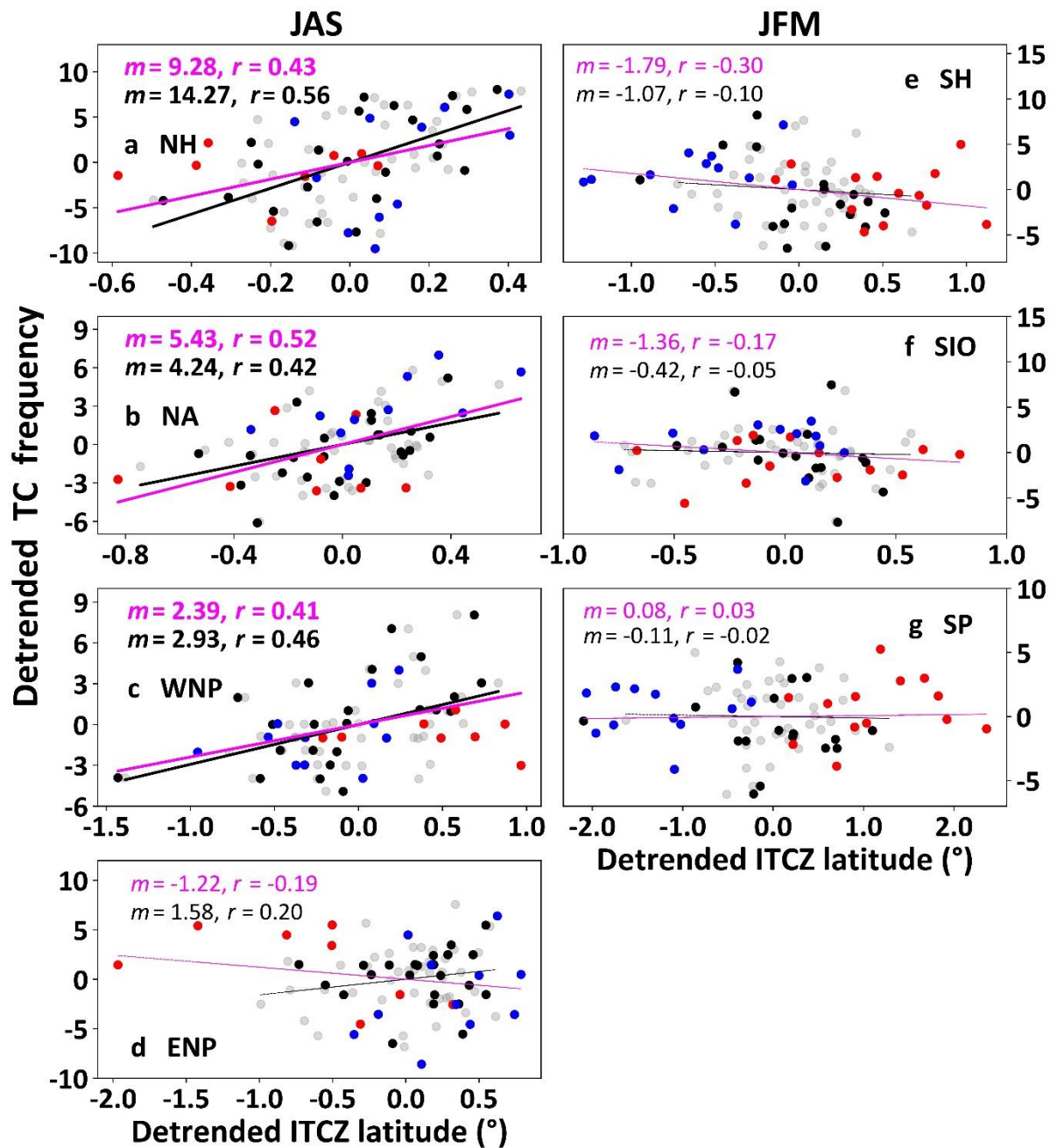
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223 **3. Results**

224 *a. Interannual relationship between ITCZ position and TCG frequency*

225 The relationship between the ITCZ position and TCG frequency over different basins and
226 hemispheres is shown in Figure 2. The regressions and correlations (magenta line and
227 number) are generally positive in the NH basins (left column) and negative in SH (right
228 column), implying the increase of the TCG frequency when the ITCZ shifts poleward.

229 Significant correlations (correlation coefficient r in bold) are only found in NH basins, with r
230 ≥ 0.41 in



231

232 Figure 2. Scatter plot between the detrended values of ITCZ latitude and TC frequency in
 233 TC seasons over 1979-2020 for each basin and hemisphere, including (a) NH, (b) NA,
 234 WNP, (d) ENP, (e) SH, (f) SIO and (g) SP. The magenta line is the linear regression of points
 235 for all years including the La Niña years (blue), El Niño years (red) and neutral years (black).
 236 The black line is the linear regression from all gray points after the ENSO effect has been
 237 removed. The linear regression slope (m) and Pearson correlation coefficient (r) are also
 238 displayed, and they are in bold if they are significant at the 95% significance level.

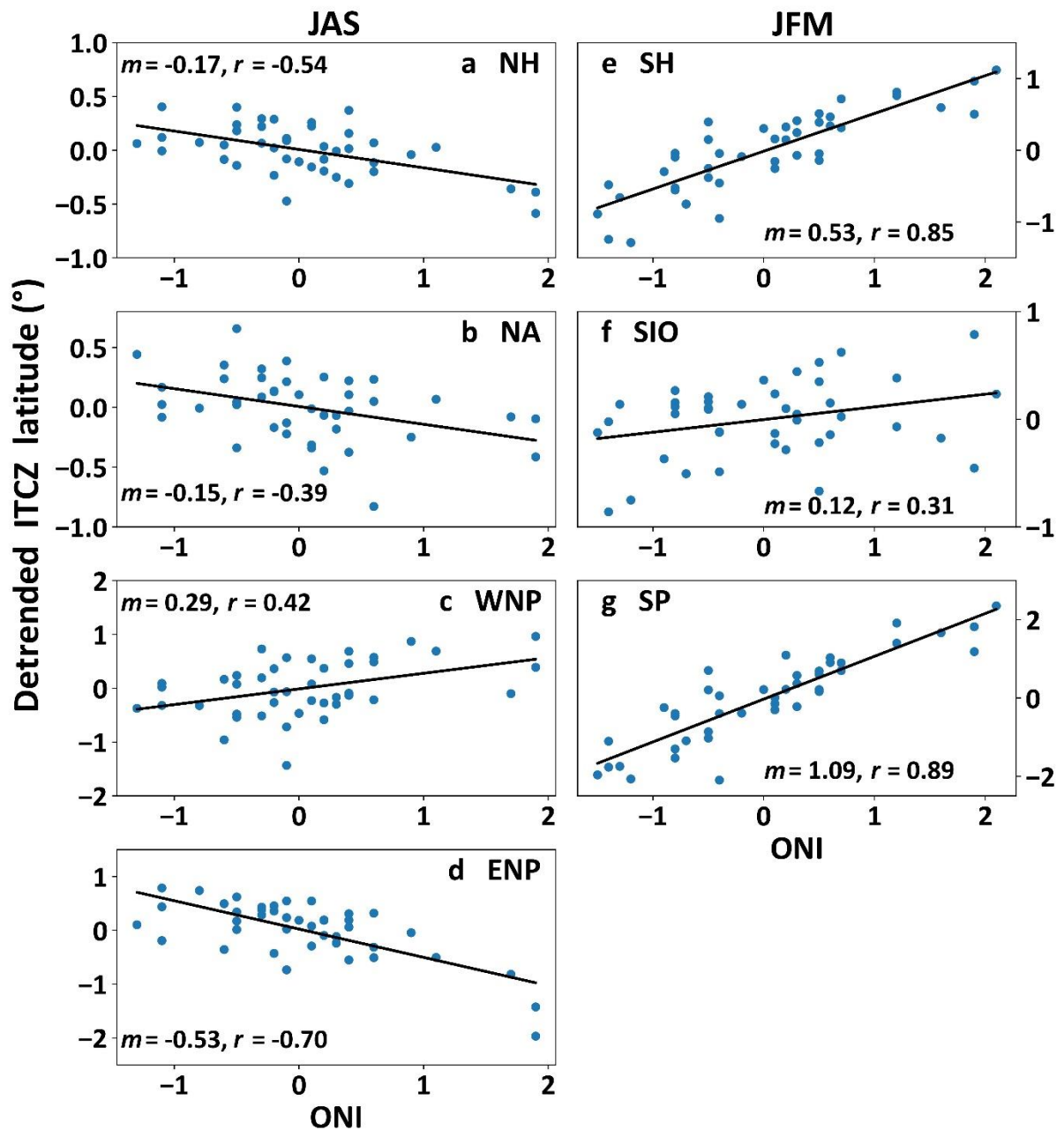
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240 the NA, WNP and in the NH as a whole. As the ITCZ position shifts one degree northward,
 241 the TCG frequency increases by about 5 and 2 in the NA and WNP, respectively. The ITCZ-
 242 TCG correlation is mainly from SIO in SH basins, but it is weak and only significant at the

10

243 90% significance level in the SH. There are no significant correlations between the ITCZ
244 position and TCG frequency in the ENP, SIO and SP.

245 To rule out the ENSO effect on the ITCZ-TCG relationship, the ENSO influence on the
246 ITCZ position has been investigated. Figure 3 shows significant correlations between the
247 ONI and the detrended ITCZ latitude in all basins and hemispheres. The ITCZ is significantly
248 further equatorward for a more positive ONI both globally and in each basin, except in WNP.
249 The negative correlations in the ENP and NA are likely due to the weakening of the
250 meridional SST gradient, the trade winds and the vertical velocity for more positive ONI
251 (Chiang et al. 2002; Alexander et al. 2012; Sasaki et al. 2015; Fu et al. 2017). The correlation
252 between ONI and the detrended TCG frequency is significant in the NA, ENP and SIO
253 (Figure S8). There are fewer TCs in JAS over NA during El Niño (Figure S8b), related to the
254 stronger vertical wind shear (Gray 1984; Latif et al. 2007; Shaman et al. 2009). During El
255 Niño, the fewer TCG in SIO (Figure S8f) may be caused by the suppressed TC activity east
256 of 75°E, which is related to the vorticity, relative humidity and wind shear changes (Ho et al.
257 2006; Kuleshov et al. 2009; Lin et al. 2020). As for ENP, there are more TCG from 140°W to
258 112°W during El Niño (Ralph and Gough, 2009; Jien et al. 2015), which may be caused by
259 the reduced wind shear and stronger vertical motion (Camargo et al. 2007; Fu et al. 2017;
260 Chen et al. 2021). In the WNP, the ONI is not correlated with the basin-scale TCG frequency,
261 which could be caused by the more TCG in the eastern part and less in the western part of the
262 WNP during El Niño years, with the eastward shift of the ITCZ (monsoon trough) (Teng et
263 al. 2014). The correlation between ONI and the detrended TCG latitude is also plotted in
264 Figure S9 for reference.



265

266 Figure 3. The correlation between ONI and the detrended ITCZ position in TC seasons
 267 over 1979-2020 for each basin and hemisphere, including (a) NH, (b) NA, (c) WNP, (d) ENP,
 268 (e) SH, (f) SIO and (g) SP. The ONI index and TC season is from July to September (JAS)
 269 for basins in the NH and from January to March (JFM) for basins in the SH. The linear
 270 regression slopes (m) and Pearson correlation coefficients (r) in bold are significant at 95%
 271 significance level. Please note that the negative latitude anomaly in SH means poleward shift.

272

273 After the ENSO signal is linearly removed from the ITCZ position and TCG frequency,
 274 the correlations and regressions (black lines and numbers in Figure 2) remain significant in
 275 the NA, WNP and NH. Therefore, although the ENSO has strong influences on both ITCZ
 276 position and TC frequency, it has generally little effect on the ITCZ-TCG relationship.

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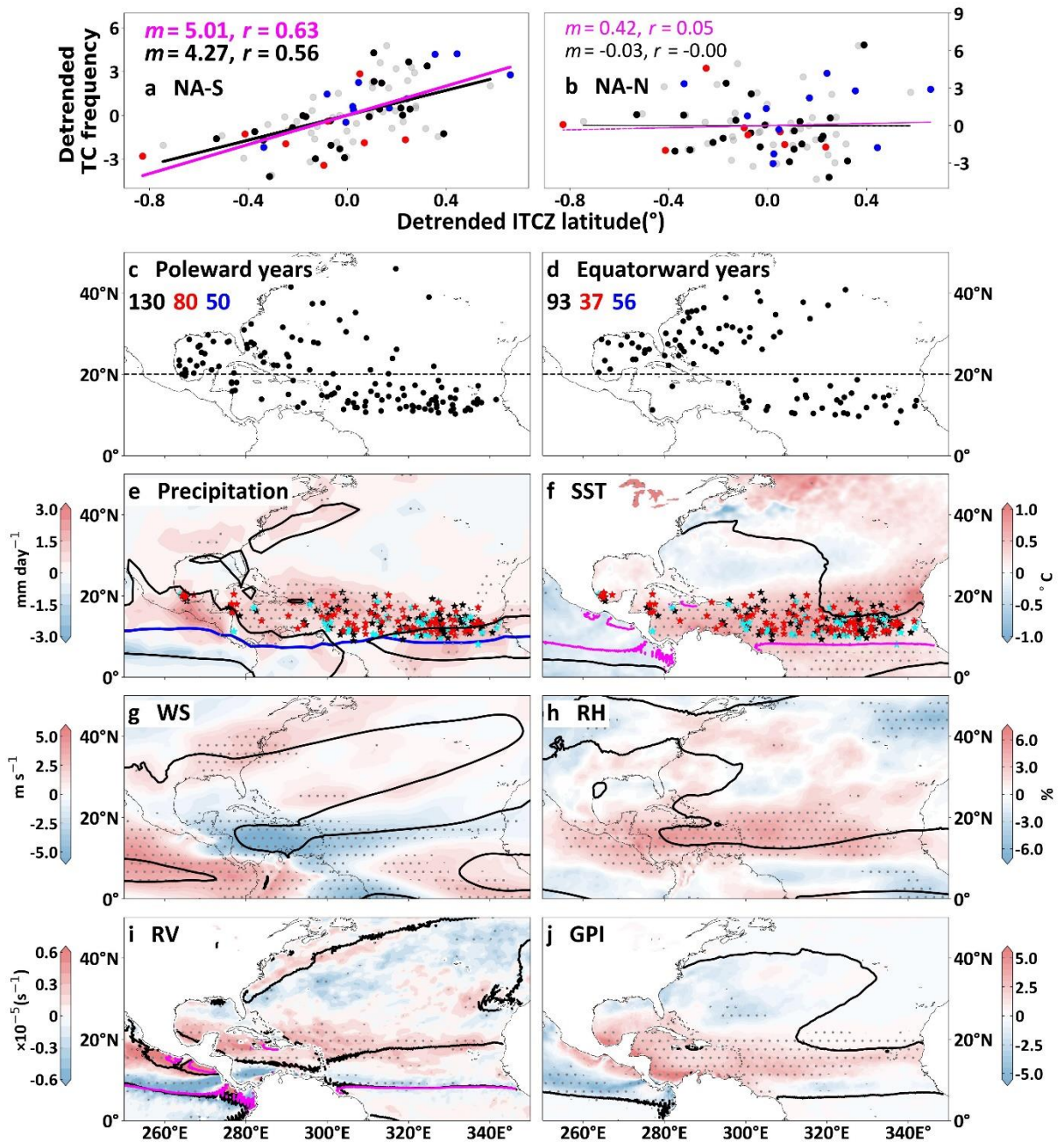
277 To check the sensitivity of the ITCZ-TCG relationship to the ITCZ position from
278 different definitions and datasets with different spatial resolutions, the time series of the
279 detrended ITCZ position using centroid method from GPCP (both $2.5^{\circ} \times 2.5^{\circ}$ and $1.0^{\circ} \times 1.0^{\circ}$),
280 ERA5, and TRMM are plotted in Figure S10. The variability is consistent with significant
281 high correlations. The time series from the maximum precipitation method are plotted in
282 Figure S11 and the variability range is larger compared with that from the centroid method,
283 but results from both methods have significant high correlations. The correlation coefficients
284 between the ITCZ position and TCG frequency, ITCZ intensity and TCG frequency, as well as the
285 ITCZ position and ITCZ intensity over 1979-2020 and 1998-2019 are listed in Tables S5-S8 for
286 references. The correlations vary with datasets, but they are generally consistent, implying
287 the robustness of our results.

288 *b. Large-scale environmental factor influences*

289 In order to further understand the relationship between ITCZ position and TCG
290 frequency, particularly for the interpretation of the weak correlation, large-scale
291 environmental factors affecting TCs are examined. The detrended ITCZ position in NH and
292 detrended absolute ITCZ position in SH over 1979-2020 is sorted in ascending order. The
293 years with the top 12 values are defined as the poleward years, and the bottom 12 years are
294 defined as equatorward years (Table S4). Average differences of the environmental factors
295 between the poleward and equatorward years reveal the changes of these large-scale
296 environmental factors associated with the shift of ITCZ positions.

297 1) NORTH ATLANTIC

298 Unlike in other ocean basins, the latitudinal distribution of TCG has double peaks in the
299 NA (Figure S1c), and the TCG position can reach high latitudes ($>20^{\circ}\text{N}$) that are far away
300 from the ITCZ location. It is found that the ITCZ-TCG relationship is sensitive to the latitude
301 band of TCG. The NA can be split into the north (NA-N, $>20^{\circ}\text{N}$) and south (NA-S, $0-20^{\circ}\text{N}$)
302 bands. The correlation between the ITCZ position and TCG frequency in NA-S can reach
303 0.63 and 0.56 before and after the ENSO effect is removed (Figure 4a), respectively. In
304 contrast, the ITCZ and TCG have no significant correlation in NA-N, even after removing the
305 ENSO effect (Figure 4b). This suggests the dominance of NA-S TCs in the basin-wide
306 correlation between ITCZ and the TCG frequency ($r=0.52$ and 0.42 in Figure 2b).



307

308 Figure 4. (a-b): As in Figure 3, but for scatter plot between detrended ITCZ latitude and
 309 TC frequency in (a) tropical North Atlantic (NA-S), (b) subtropical North Atlantic (NA-N)
 310 during 1979-2020. All variables and numbers are calculated over TC seasons. (c) TCG
 311 positions in NA during ITCZ poleward years. The black, red and blue numbers in the top left
 312 show the numbers of TCG in NA (black), NA-S (0-20 $^{\circ}\text{N}$) (red) and NA-N (>20 $^{\circ}\text{N}$) (blue).
 313 (d) As (c), but for ITCZ equatorward years. (e-j) Differences of composited precipitation,
 314 SST, vertical wind shear between 200 and 850 h Pa (WS), relative humidity at 600 h Pa
 315 (RH), relative vorticity at 850 h Pa (RV) and GPI between the poleward and equatorward
 316 years (poleward minus equatorward). Grey stippling indicates significant differences at the
 317 95% confidence level using two-tailed t-test, and black contours represent the climatology of
 318 5 mm day^{-1} (precipitation), 26.5 $^{\circ}\text{C}$ (SST), 11 m s^{-1} (WS), 50% (RH), 0 s^{-1} (RV) and 1 (GPI),
 319 respectively. RV > 0 means anticlockwise rotation and RV < 0 means clockwise rotation in
 320 NH. In (e-f), the red, black and cyan stars represent locations of the TCG in NA-S during

321 ITCZ poleward years, normal years and equatorward years, respectively. The blue line in (e)
322 represents the climatology of the ITCZ position. The magenta contour in (f) and (i) represents
323 the absolute vorticity climatology of $2 \times 10^{-5} \text{s}^{-1}$.

324

325 The TCG locations for ITCZ poleward and equatorward years in JAS are shown in
326 Figures 4c, d. There are 130 TCG events in the 12 poleward years, with 80 in NA-S and 50 in
327 NA-N. There are 93 TCs in the 12 equatorward years, with 37 in NA-S (less than half that of
328 poleward years) and 56 in NA-N (similar to that in poleward years). In the ITCZ poleward
329 years, the mean ITCZ position is 9.33°N , while the value in the equatorward years is 8.70°N .
330 The above confirms that in the NA the effect of the ITCZ shift on TC formation is restricted
331 to storms generated in 0° - 20°N . The difference of ITCZ positions between poleward and
332 equatorward years is only 0.63° (about 70km), and the TCG frequency difference is 43 in
333 NA-S, which illustrates the strength of the relationship in this region.

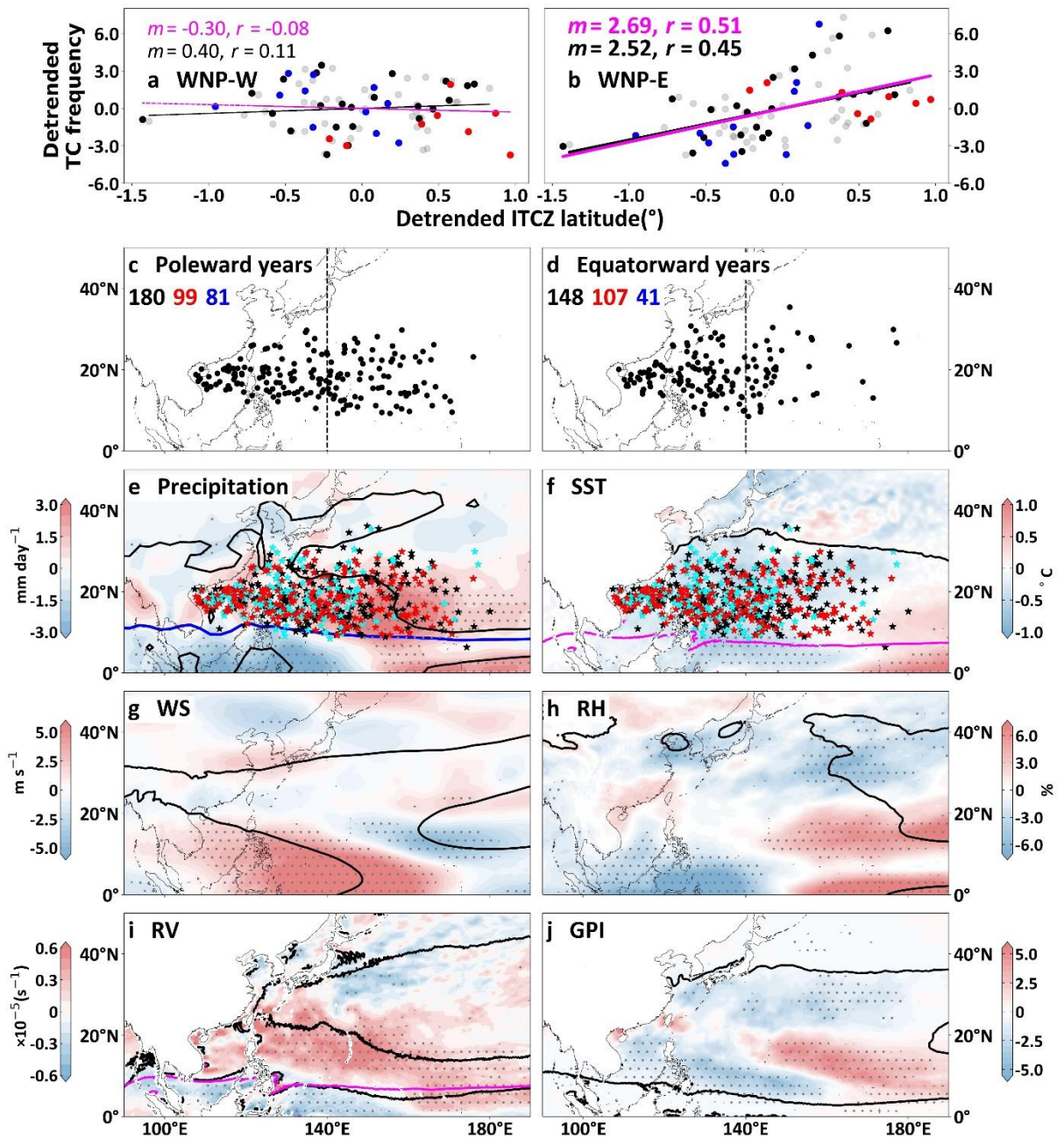
334 The differences (poleward minus equatorward years) in precipitation, SST, vertical wind
335 shear (WS), relative humidity (RH), cyclonic relative vorticity (RV) and the genesis potential
336 index (GPI) are plotted in Figures 4e-j. The TCG locations in the poleward (red star), normal
337 (black star) and equatorward years (cyan star) over the NA-S are also shown in Figures 4e-f.
338 The climatology of the ITCZ position in TC season over 1979-2020 is plotted in Figures 4e-f,
339 showing that TCs all form on the poleward side of this climatological ITCZ. The climatology
340 of other variables is added to Figures 4f-j, such as the contour of 26.5°C for SST, 11 ms^{-1} for
341 vertical wind shear (McGauley and Nolan 2011), 50% for relative humidity (Cheung 2004),
342 and the absolute vorticity threshold (magenta contour in 4f and 4i) of $2.0 \times 10^{-5} \text{ s}^{-1}$ (McGauley
343 and Nolan 2011). In the poleward years, the SST, RH and RV increase over the MDR of the
344 NA-S TCs, and WS decreases. The GPI, which represents the combined effect of the
345 environmental factors (SST, RH, absolute vorticity and WS), has significantly positive
346 anomalies in the MDR in the poleward years as well (Figure 4j). All these environmental
347 factor changes favor TC formation in the tropical NA, and the areas of significant changes in
348 these factors match well with the MDR. These changes are responsible for the close
349 relationship between the ITCZ position and the TCG frequency in the NA-S. The significant
350 warmer SST in NA-S (Figure 4f) caused positive SST anomalies (local minus globally
351 tropical averaged SST) in NA-S and thus reduced the wind shear (Figure 4g, Swanson 2008)
352 and increased the TCG frequency. We also tested the TCG in the area confined by magenta

353 lines in Figures 1 and S1-S6. This area is generally closer to the ITCZ than the overall TCG
354 area. The results are similar to the current one using the basin-wide TCs.

355 Some studies also showed the relationship between the African Easterly Waves (AEWs)
356 and the Atlantic TCG (Simpson et al. 1968, 1969; Frank 1970; Thorncroft and Hodges 2001;
357 McCrary et al. 2014) in tropical Atlantic (NA-S), because AEWs are the primary precursor
358 for Atlantic TCG. Russell et al. (2017) pointed out that the correlation between the seasonal
359 mean eddy kinetic energy (EKE) and TCG is maximized in the lower troposphere below the
360 southern AEW storm track, instead of where the canonical AEW is maximized. However,
361 using the convection-permitting regional model simulations, Danso et al. (2022) found that
362 suppressing AEWs did not substantially change seasonal TC frequency, but did influence TC
363 intensity, genesis time and location. For the NA-N, the TCG mechanism may be different
364 from that in NA-S. In subtropics and relatively high latitude regions, TCs could originate
365 from the baroclinic pathways (McTaggart-Cowan et al. 2013), or TCs which originate from
366 tropical waves could migrate and further develop in this region (Mauk and Hobgood 2012).
367 Latest analyses of aquaplanet simulations suggest that subtropical storms complicate (and
368 possibly weaken) the linear relationship between the ITCZ and TC frequency (Zhang et al.
369 2021). More studies are needed to further understand the combined influences of the ITCZ,
370 AEW and other factors on the TCG.

371 2) WESTERN NORTH PACIFIC

372 In WNP, there are 180 TCG events, with 99 in the west (WNP-W, 100-140°E) and 81 in
373 the east (WNP-E, 140-180°E) in the ITCZ poleward years (Figure 5c). Compared to the
374 equatorward years (Figure 5d), there are 8 fewer TCs in the WNP-W and 40 more in the
375 WNP-E, leading to a net increase of 32 TCs in the whole basin from equatorward years to
376 poleward years. The mean ITCZ position is 10.59°N in the poleward years, contrasting with
377 9.48°N in the equatorward years.



378

379

380 Figure 5. As Figure 4, but for WNP. (a-b): As in Figures 4a-b, but for scatter plot between
 381 detrended ITCZ latitude and TC frequency in (a) WNP-W (100-140°E) and (b) WNP-E (140-
 382 180°E) in TC seasons during 1979-2020. The 140°E longitude line is marked in (c-d) by the
 383 dashed black vertical line. The black, red and blue numbers in (c-d) show the total number of
 384 TCG in WNP (black), WNP-W (red) and WNP-E (blue) in TC season.

385

386 In the ITCZ poleward years, RV significantly increases in the tropical region and overlaps
 387 well with the TC formation area (Figure 5i) in both WNP-E and WNP-W, but the SST and
 388 RH significantly reduce in WNP-W and increase in the WNP-E (Figures 5f and h). In these

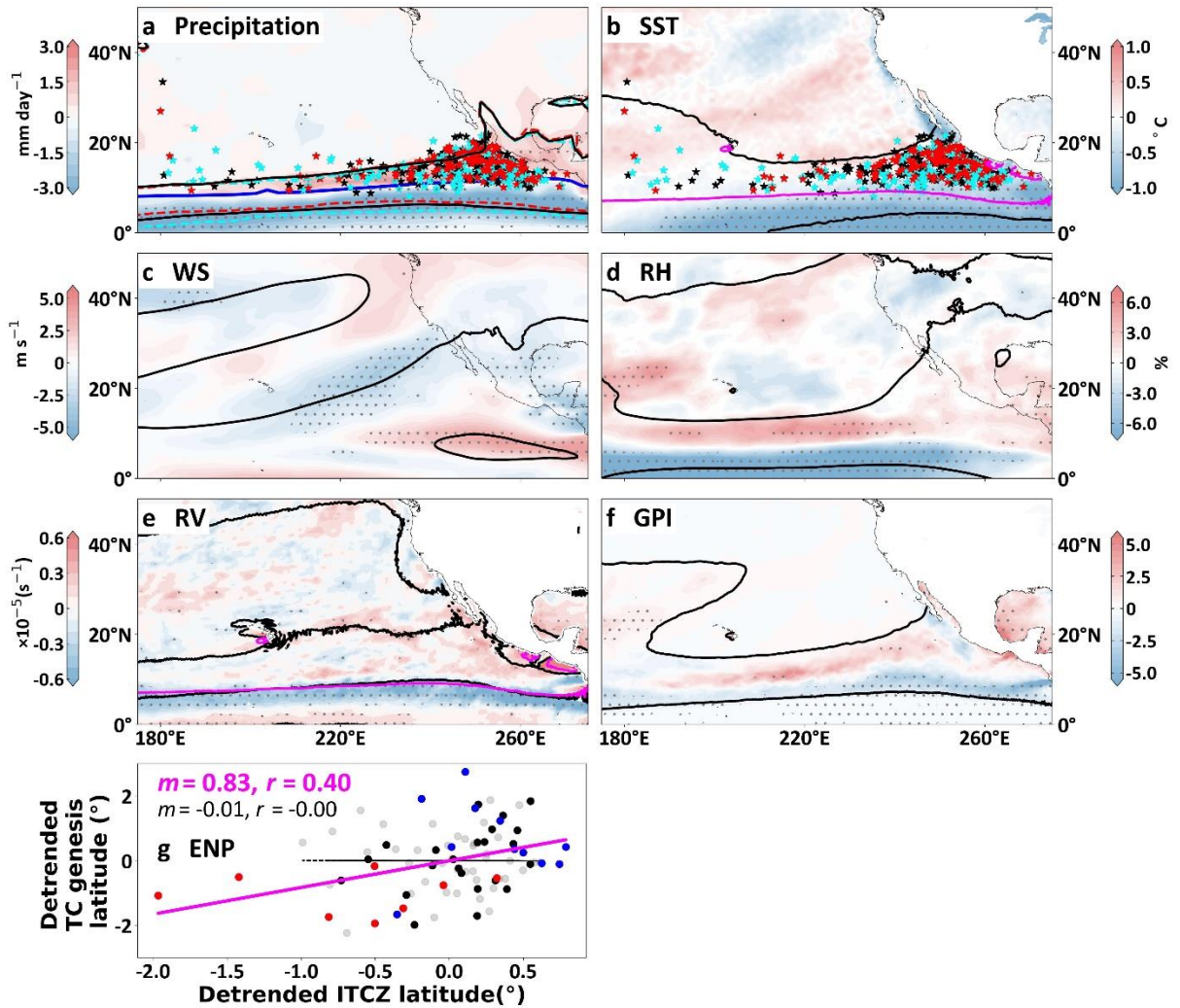
17

389 years, WS significantly increases in the South China Sea and east of the Philippines, where
390 WS is climatologically strong, further inhibiting TC formation (Figure 5g). However, WS
391 significantly reduces in WNP-E (140-180°E, and 10-20°N). GPI further shows a similar
392 pattern with reduction in the west and enhancement in the east. In short, in the ITCZ
393 poleward years, the ITCZ-related environmental changes encourage more TCG events in
394 WNP-E but the effect on the TCG in WNP-W is complicated due to the offsetting changes in
395 environmental conditions. This west-east pattern in the environmental changes corresponds
396 well to the changes in sub-basin TCG frequency. The observed relationship between the
397 ITCZ location and the TCG frequency over the two sub-regions is plotted in Figures 5a-b.
398 Thus, we conclude that the ITCZ-TCG relationship in the WNP is mainly due to the
399 significant environmental changes in the east sector of the basin.

400 The longitudinal separation of the TCG region in WNP was previously noticed by Chen
401 et al. (1998) and it is attributed to the longitudinal shift of the monsoon trough. Similar
402 separation was also investigated by Wang and Chan (2002), they pointed out that the
403 enhanced tropical storm formation in the southeast quadrant (0°–17°N, 140°E–180°) is
404 attributed to the increase of the low-level shear vorticity generated by El Niño–induced
405 equatorial westerlies, while the suppressed tropical storm generation over the northwest
406 quadrant (17°–30°N, 120°–140°E) is ascribed to upper-level convergence induced by the
407 deepening of the east Asian trough and strengthening of the WNP subtropical high, both
408 resulting from the El Niño forcing. Based on the analysis in this study, the factor
409 contributions to the TCG are complicated and beyond the scope of this paper and need more
410 comprehensive investigations.

411 3) EASTERN NORTH PACIFIC

412 Different from NA and WNP, the ITCZ position is weakly correlated with the basin-wide
413 TCG frequency in ENP because of the seesaw changes of large-scale environmental
414 conditions. The decrease of the TCG frequency on the equatorward flank and the increases on
415 the poleward flank cancel each other, leading to small changes in the TCG frequency but
416 large changes in mean TCG latitude. In the ENP, most TCG events concentrate in a small
417 region (10-20°N, 50-90°W, Figures 6a-b), and the ITCZ position is just weakly correlated
418 with the basin-wide TCG frequency (Figure 2d).



419

420 Figure 6. (a-f): As Figures 5e-j, but for Eastern North Pacific. (a) The red and cyan
 421 dashed contours are similar to the black contour (the TC season climatology of 5 mm day⁻¹
 422 precipitation), but for TC seasons in ITCZ poleward and equatorward years, respectively. (g)
 423 As Figure 2d, but for scatter plot of the detrended annual values of ITCZ latitude and TC
 424 genesis latitude in TC seasons during 1979-2020.

425

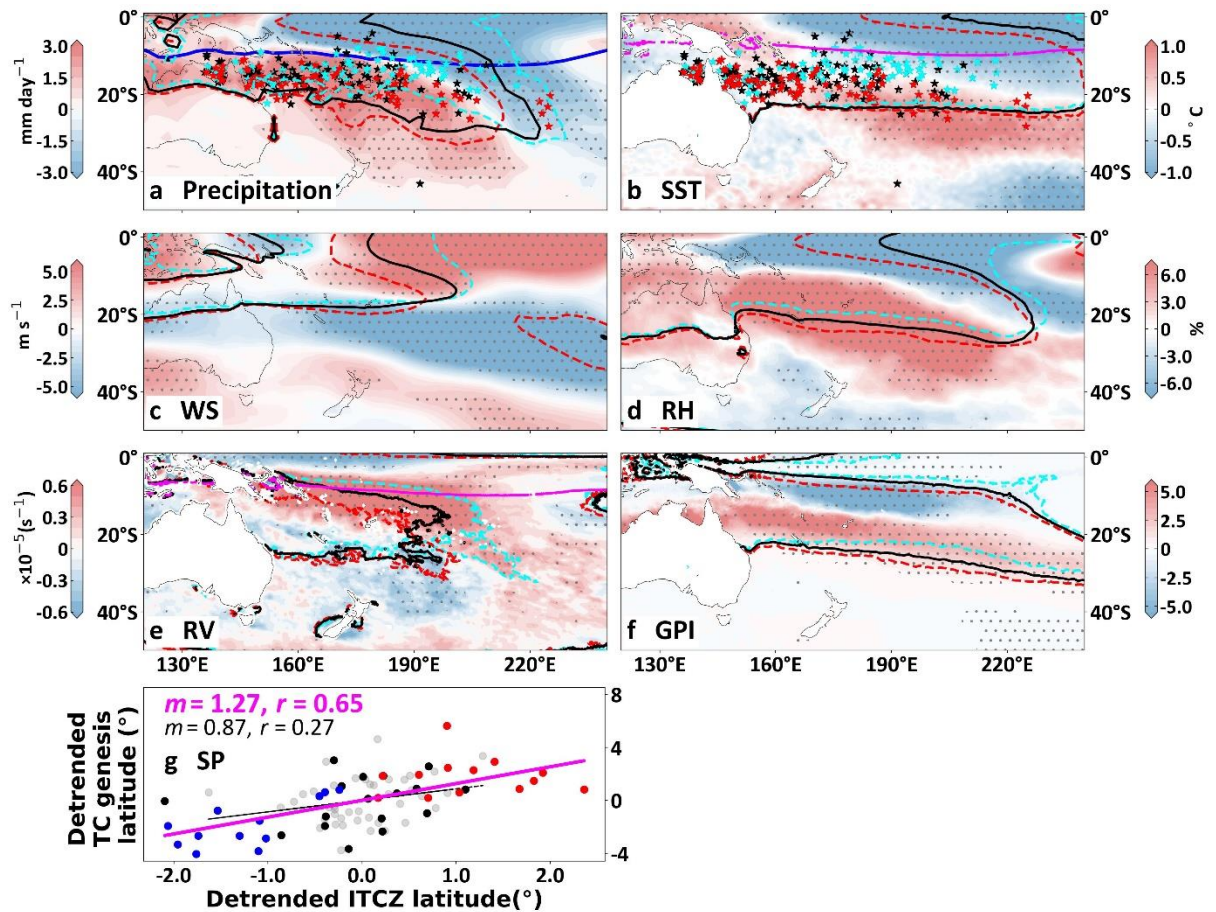
426 In the ITCZ poleward years, the associated large-scale environmental conditions exhibit
 427 an apparent seesaw change, with warmer SST, weaker WS, higher RH in the north flank of
 428 ITCZ, and with colder SST, stronger WS, lower RH and RV in the equatorward flank (Figure
 429 6). The ITCZ shift has a profound effect on the values of environmental conditions especially
 430 in the southern part of MDR, as the ITCZ becomes narrower and its southern boundary shifts
 431 poleward (in Figure 6a, the southern boundary of the 5mm/day precipitation contours shifts
 432 poleward from the cyan one to the black and then the red, which is different from the changes
 433 of the northern boundary). The environmental changes favor TCG occurrence in the north
 434 and suppress TCG occurrence in the south, and the inhibiting effect in the south is stronger

435 than the enhancing effect in the north. The favorable genesis region appears to contract in
436 poleward years with the southern part becoming less favorable, leading to the decrease of 20
437 TCs from equatorward years to poleward years in ENP (from 150 to 130 TCG events).

438 We further find that ENSO plays a critical role in the relationship between ITCZ position
439 and TCG position in this area. The correlation between ITCZ position and TCG position
440 reaches 0.40 in the ENP, while it decreases to about 0 when ENSO signal is removed (Figure
441 6g). Both the ITCZ position and TCG position are equatorward in El Niño years (red dots in
442 Figure 6g) and poleward in La Niña years (blue dots in Figure 6g). Except ENSO, the inter-
443 hemispheric temperature difference could also modulate the ITCZ north-south displacement,
444 which could further affect the TCG location (Zhao et al. 2021). The ENP TC formation could
445 be affected by both the ITCZ breakdown (Ferreira and Schubert 1997; Kieu and Zhang 2008;
446 Yokota et al. 2015) and the teleconnections from the NA (Wang and Lee 2009; Wang et al.
447 2016). To better understand the TCG events in ENP, a further investigation is needed in the
448 future.

449 4) SOUTH PACIFIC

450 In the SP, the relationship between the ITCZ position and the TCG frequency is very
451 weak, regardless of whether the ENSO signal is included (Figure 2g). In the ITCZ poleward
452 and equatorward years, the total TCG number is 82 and 85, respectively. In the ITCZ
453 poleward years, the rain belt and the environmental conditions related to TCG significantly
454 shift southward compared with those in the equatorward years (Figures 7a-f).



455

456

457 Figure 7. As Figure 6, but for SP. (a-f) The red and cyan dashed contours are similar to
 458 the black contour (the TC season climatology), but for TC seasons in ITCZ poleward and
 459 equatorward years, respectively. For basins in SH, the blue shade in (e) represents higher
 460 cyclonic vorticity. (g) As in Figure 2, but for scatter plot between the detrended ITCZ latitude
 461 and TC genesis latitude in TC seasons during 1979-2020. Both the negative ITCZ position
 462 and TCG latitude anomalies mean poleward in SH.

463

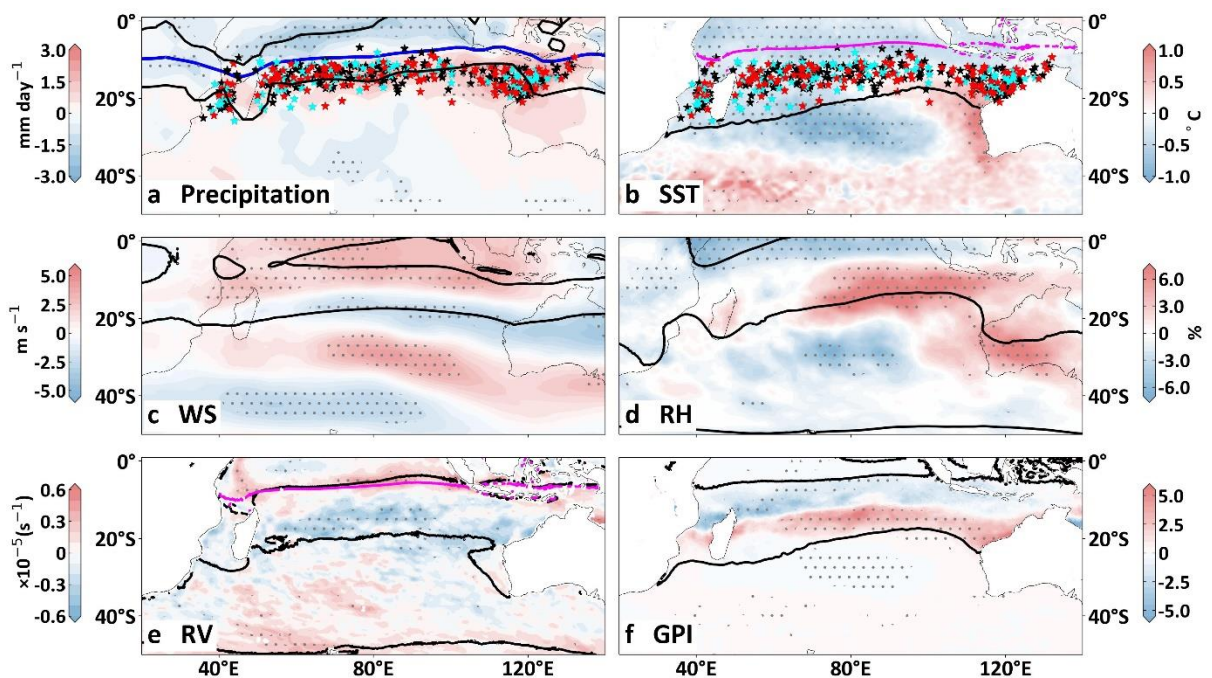
464 From the poleward to equatorward years, the TCG-associated large-scale environment
 465 has significant changes in the tropical region (Figure 7. Note that an increase of cyclonic
 466 relative vorticity in the SH is indicated by the negative value). On the equatorward side (0-
 467 10°S), there are colder SST, stronger WS, lower RH and lower RV values. In contrast, a large
 468 area on the poleward side (10-40°S) sees warmer SST, lower WS, higher RH and higher RV
 469 values. The seesaw-like changes in the meridional direction favor TCG occurrence poleward
 470 of 20°S but do not favor it equatorward of 20°S (Figure 7f). The GPI change due to ITCZ is
 471 constrained to a narrow band (10-30°S). This means that within the climatological position of
 472 TCG (alternatively, the MDR), the ITCZ has an apparent compounding effect on the large-

473 scale environment. This compounding effect can strongly modulate the basin-wide position
 474 of TCG events, while it hardly impacts the basin-wide number of TCG events due to the
 475 canceling effect in the two sub-regions. As in the ENP, the ITCZ position has strong
 476 correlation with the TCG location related partially to the ENSO effect in SP (Figure 7g).

477 5) SOUTH INDIAN OCEAN

478 The ITCZ position is weakly correlated with TC frequency in SIO (Figure 2f). The mean
 479 ITCZ position is 9.76°S in poleward years and 8.96°S in equatorward years. The total TC
 480 number is 115 during poleward years, 20 more than 95 TCs during equatorward years.

481 The changes in environmental factors over the MDR are mixed in SIO. From the ITCZ
 482 poleward years to equatorward years, SST becomes favorable for TCG only in a small area
 483 (80-120°E) (Figure 8b). RH becomes favorable for TCG in the most regions of the MDR,
 484 except in the west of the basin. WS and RV have neither consistent nor significant changes
 485 within the MDR. Consequently, GPI has a weak reduction on the equatorward side of the
 486 MDR and a weak increase on the poleward side. This corresponds to the weak ITCZ-TCG
 487 correlation over the basin.



488
 489 Figure 8. As Figures 7a-f, but for SIO.

490

491 **4. Summary and Discussion**

492 Previous studies have shown that the TCG frequency is associated with the ITCZ
493 migration in idealized models (Merlis et al. 2013; Ballinger et al. 2015; Burnett et al. 2021;
494 Vu et al. 2021). It is hypothesized that as the ITCZ moves poleward, the subsequent increased
495 Coriolis force and the absolute cyclonic vorticity will favor more TCG events (Ballinger et al.
496 2015; Burnett et al. 2021). In this paper, we focus on the interannual ITCZ-TCG relationship
497 using the observational data over the last four decades and investigate how the ITCZ
498 modulates the large-scale environment relevant to TCG. Relationships between the ITCZ
499 position and TCG frequency have been examined on the interannual timescale over different
500 basins and hemispheres. The association of this relationship with ITCZ intensity and TCG
501 location is also briefly discussed.

502 We found that the relationship between the ITCZ position and TCG frequency varies with
503 basins (Figure 2). The ITCZ position is well correlated with the TCG frequency in the NA
504 and WNP. The robust relationship in the NA is from the TCG events in the tropics (0-20N),
505 while the significant relationship in the WNP is due to the TCs formed in the east sector of
506 the basin (140-180°E). A poleward shift of ITCZ in these two basins is associated with
507 significant changes in large-scale environment, which favor TC formation.

508 In contrast with the NA and WNP, weak correlation is found between ITCZ position and
509 TCG frequency in the ENP, SP and SIO. The environment condition changes relevant to
510 ITCZ have seesaw-like features in the meridional direction both in ENP and SP, with the TC
511 activity suppressed on the equatorward side and enhanced on the poleward side (Figures 6
512 and 7), leading to the better ITCZ position-TCG location relationship in the ENP and SP. In
513 SP, during ITCZ poleward years, the rain belt and the environmental conditions related to
514 TCG significantly shift poleward compared with those in the equatorward years (Figure 7). In
515 the SIO, the ITCZ-related changes in environmental factors in the MDR are mixed (Figure 8),
516 corresponding to the weak ITCZ position -TCG frequency relationship (Figure 2f).

517 Although the environmental changes have distinct basin characteristics, there are some
518 similarities across basins between ITCZ poleward and equatorward years. Instead of the
519 Coriolis effect, we focus on the large-scale environment changes modulated by ITCZ
520 movement and its effect on TCG in this study. But the environmental changes related to
521 ITCZ indicate that the Coriolis effect could still play a role. In Figures 4 to 8, the magenta
522 contours in both the relative vorticity (RV) and SST subplots represent the absolute vorticity
523 above the required threshold. Both the climatology regions of the TC formation and cyclonic

524 relative vorticity changes favorable for TC formation are restricted to the poleward side of the
525 magenta contour, and they are all located at the poleward flank of the rain belt (blue line and
526 black contour in precipitation plot). In addition, as the ITCZ moves poleward, the relative
527 vorticity increases at the high latitude side where there is stronger Coriolis effect, which
528 possibly makes the disturbances associated with ITCZ more likely to occur and makes the
529 vortex more likely to strengthen. These are conducive to the increase of TC frequency,
530 although the increase of vorticity and the amplitude of ITCZ migration vary with basins.

531 The weak correlation between the ITCZ position and the TCG frequency in the ENP, SP
532 and SIO does not necessarily mean that the ITCZ has a weak effect on TCs in these basins.
533 The ITCZ could impact TCG frequency by different ways and one is by producing
534 disturbances. Previous satellite observations showed that the ITCZ continuously decomposes
535 and produces mesoscale vortices in the central and eastern Pacific, some of which are likely
536 to form TCs (Ferreira and Schubert 1997; Wang and Magnusdottir 2006; Kieu and Zhang
537 2008). Another way is by providing favorable environment conditions. As shown in Figures
538 6-8, there are compounding effects and mixed changes in the large-scale environment within
539 the MDR during ITCZ poleward years. Whether the disturbances triggered by the ITCZ could
540 eventually develop into TCs may also be restricted by the environmental conditions, thus
541 affecting the correlation between the ITCZ position and the TC frequency.

542 This study focuses on the observed relationship between the ITCZ position and the TC
543 frequency over different basins, and environmental changes have been used to interpret the
544 potential processes behind the relationships. This study will help the understanding of the
545 large-scale circulation influences on the TCG at basin-wide and global scales. There are some
546 works worth further research. The changes in environmental factors and GPI may not fully
547 represent the effects of ITCZ migration on TC frequency because they may miss the transient
548 effect on individual TC precursors. Furthermore, the Coriolis parameter never changes at any
549 fixed location, so the effects of poleward ITCZ position are not all directly captured by maps
550 in Figures 4-8. Recent studies (Vecchi et al. 2019; Hsieh et al. 2020; Ikehata and Satoh 2021;
551 Yamada et al. 2021; Yang et al. 2021) showed that the TCG frequency is constrained by the
552 precursor frequency and the survival rate. The poleward movement of ITCZ could contribute
553 to more TCG by increasing precursors (Hsieh et al. 2020), and the survival rate could be
554 restrained by the large-scale environmental factors (Ikehata and Satoh 2021). The influence

555 of ITCZ position and the large-scale environmental factors on precursor frequency and
556 survival rate need further investigation.

557 The interaction between the ITCZ position and the TC rainfall is another factor
558 influencing the causal relationship between the TCG number and the ITCZ location. We will
559 investigate this in a separate future study, and it would be an interesting study to remove the
560 effect of TC rainfall on the ITCZ position.

561 The SST change could also be responsible for the complexity of the ITCZ-TC
562 relationship. A poleward movement of high SST can possibly cause both the poleward ITCZ
563 movement and higher TC frequency. The ITCZ poleward movement that may be nonlinearly
564 driven by SST could further encourage more TCs, increasing the complexity of the ITCZ-TC
565 relationship. Recent studies discussed the effects of climate warming and SST movement on
566 ITCZ location and TC frequency (Merlis et al. 2013; Ballinger et al. 2015; Viale and Merlis
567 2017; Walsh et al. 2020; Sobel et al. 2021; Zhang et al. 2021). Sensitivity experiments of
568 realistic GCM simulations conditional on ITCZ and SST will help to address this challenge.

569 Although in our study the correlation coefficients between ITCZ position and TCG
570 frequency have little change after removing ENSO signal, the ENSO effect on the
571 relationship between ITCZ position and TC activity could be complex and nonlinear. During
572 the 12 ITCZ poleward years, there are 5, 6 and 10 La Niña years in NA, ENP and SP, and 6
573 El Niño years in WNP, respectively. In SIO, there are 5 El Niño years and 4 La Niña years
574 (Table S4). In ENP and SP, the relationships between ITCZ position and TCG latitude
575 changes become obviously weaker after the ENSO signal is removed (Figures 6g and 7g).
576 Pattern changes in large-scale environment between the poleward years and equatorward
577 years in Figures 4-8 resemble those between ENSO years (Kuleshov et al. 2009; Dowdy et al.
578 2012; Teng et al. 2014; Kim and Moon 2022). These suggest the possible intermediate role of
579 ENSO in regulating the ITCZ-TC relationship, and the ITCZ and ENSO may play a different
580 and nonlinear role in TC activity in different basins.

581 As shown in Tables S5-S8, the intensity and latitude of ITCZ are correlated and the ITCZ
582 intensity can have a strong correlation with TC frequency in some basins, which is consistent
583 with previous studies (Zhang et al. 2013; Sharmila and Walsh 2018). This is related to the
584 changes of vortices that can subsequently intensify into TCs, resulted from the ITCZ
585 breakdown through the combination of the barotropic instability and the westward-
586 propagating AEWs (Bembenek et al. 2021). Contributions to TCG from the barotropic

587 instability and AEW have been investigated by Wang and Magnusdottir (2006), Cao et al
588 (2012) and Wu and Takahashi (2018), and the effect of ITCZ instability and monsoon
589 depression on the WNP TCG has also been studied by Beattie et al. (2016). There are other
590 important mechanisms as well about the TCG (Montgomery et al. 2006; Emanuel 2003;
591 Wing et al. 2016). However, detailed studies of these mechanisms are beyond the scope of
592 this study. Besides the ENSO, other climate modes, such as the North Atlantic Oscillation
593 (NAO), Atlantic Meridional Mode (AMM) and Pacific Meridional Mode (PMM) may also
594 play a similar complex role (Hurrell et al. 2003; Frank and Young 2007; Kossin and Vimont
595 2007; Souza and Cavalcanti 2009; Gao et al. 2018; Murakami et al. 2017; Zhang et al. 2018).
596 The nonlinear processes between ITCZ and TC activity, as well as influences by other
597 climate modes, deserve another study in the future.

598

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609

610 *Data Availability Statement.*

611 The IBTrACS data can be downloaded at <https://www.ncei.noaa.gov/products/international-best-track-archive?name=ib-v4-access>. The GPCP data are available at <https://psl.noaa.gov/data/gridded/data.gpcp.html> from National Oceanic and Atmospheric Administration (NOAA) and <https://www.ncei.noaa.gov/products/climate-data-records/precipitation-gpcp-daily>. The ONI data are from https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. The ERA5 reanalysis data are downloaded at <https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset>.

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