Changes of Tropical Cyclone Size in three Oceanic Basins of the Northern Hemisphere since 2001

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Abstract

In this study the latest changes of tropical cyclone size are analyzed based on linear and quadratic curve fittings of the National Hurricane Center (NHC)/Joint Typhoon Warning Center (JTWC) best track data for the radius of maximum wind (RMW), the average radius of 34-kt wind (AR34), and the storm duration index “storm days” (SD) in three oceanic basins of the North Atlantic (NATL), the Western North Pacific (WPAC) and the Eastern North Pacific (EPAC). The computations are done separately for two categories of tropical cyclones: tropical storms (TS), and hurricanes in NATL and EPAC or typhoons in WPAC (HT). The results show that the RMW trends for TS are positive in all basins, and the RMW trends for HT are positive in the NATL basin, but negative in the WPAC and EPAC basins. The AR34 changes are more complex due to the fact that they reflect not only the strength of tropical cyclones, but also the environmental conditions. The trends of two other data sets, with WPAC dataset from the Japan Meteorological Agency (JMA) and the extended best track dataset for NATL and EPAC from NESDIS/RAMMB, are also consistent with the trends derived from the 16-year best track data. The relationships between storm size and sea surface temperature anomaly and the departure from the zonal mean have also been investigated, and some statistically significant correlations are found.

1. Introduction

Tropical cyclones are a major source of natural catastrophic losses worldwide. It is estimated that 10,000 people have died every year since 1980 due to tropical cyclones (Doocy et al. 2013), and thus it is of great importance to study tropical cyclones and to understand their response to changes in environmental conditions such as sea surface temperature (SST). The sensitivity of frequency, intensity, and duration of tropical cyclones to climate change has been extensively investigated with a general conclusion that both global and regional changes in TC behavior should be expected as the climate and SST change (e.g., Emanuel et al 2008, Kossin 2017).

Though numerous studies have examined the complex response of tropical cyclone frequency and intensity to climate change (Emanuel 2005; Webster et al, 2005; Shen 2006; Emanuel et al. 2008; Barbosa 2011; Emanuel and Sobel, 2013; Mei et al. 2015; Kossin, 2017); uniform conclusions have not been reached regarding recent global intensity trends. For example, Webster et al (2005) found that both the number and percentage of global category 4-5 hurricanes increased significantly from 1970 to 2004. Meanwhile, looking at the 1986-2005 period, Klotzbach (2006) found that the trend of global accumulated cyclone energy (ACE) index and global category 4 –5 hurricanes was not significant despite warming SSTs. Likewise, Klotzbach and Landsea (2015) examined the period between 1990 and 2014 and found an insignificant downward trend in global frequency of category 4-5 hurricanes (encompassing an upward trend up to 2004, and then a downward trend thereafter). The same study found the percentage of category 4 and 5 hurricanes showed an insignificant upward trend and significant downward trend in ACE.

Other studies have examined the “storm days” parameter¹, generally finding significant interdecadal variability. Landsea et al (1999) was one of earliest studies to note this, and for the period for 1944-1996 they found a greater degree of statistical significance in storm days than in hurricane frequency. With updated data, Webster et al (2005) found no significant linear trends in storm days from 1970 to 2004, though they did find a significant decadal-scale oscillation. Wang et al (2010) similarly found a large-amplitude fluctuation in storm days from 1965–2008 that was regulated by El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Like previous studies, they did not find a linear trend, suggesting that the rising temperature so far has not yet had an impact on the global total number of storm days.

A number of studies have also uncovered regional relationships between SST and TC trends. For example, Klotzbach (2006) found a statistically significant relationship between SSTs and both ACE and category 4 –5 hurricane frequency in both the North Atlantic (NATL) and the Eastern North Pacific (EPAC). Similarly, Martinez-Sanchez and Cavazos (2014) examined the EPAC main development region (MDR) from 1970-2010 and found a statistically significant SST increase, an insignificant trend in category 4-5 hurricanes, and a significant decrease in the frequency of all hurricanes. The hurricane trend in the EPAC MDR appears to be linked to the PDO, and the frequency category 4-5 hurricanes in that basin is significantly related to both the PDO and ENSO. In a different study, Jin et al. (2014) uncovered an oceanic pathway that brings El Niño's heat into the Northeastern Pacific basin to directly fuel intense hurricanes in that basin two or three seasons after its winter peak. Finally, Mei et al (2015) found that upper

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¹ This parameter counts the number of days in a season that a tropical cyclone exists. If multiple storms coexist, then they both individually contribute to the total.

oceanic temperatures in the central and western Pacific control the rate and duration of typhoon intensification, and recent anomalous warming has led to unprecedentedly high average typhoon intensity during the global warming hiatus period.

In this report we focus on changes in storm size and its relationship with SST, a relatively understudied topic. A major motivation for this work is that storm size can significantly impact damage, particularly that caused by storm surge (e.g., Irish et al. 2008). Another motivation is that storm size impacts predictability; large storms tend to evolve more slowly and are more predictable than small storms (Carrasco et al. 2014). Among the very little work that has related storm size and SST, Lin et. al (2015) suggest that TC size is more strongly related to the departure of local SST from area mean than it is to the SST anomaly from temporal average (SSTA). Therefore, this study examines trends in storm size and relates those trends to both the departure of local SST from the latitudinal mean (SSTD) and SSTA.

Though few have examined the relationship between SST and storm size, a number of previous studies have investigated the climatology of storm size. For example, the radius of the outermost closed isobar (ROCI) was used to examine the climatology and structure of tropical cyclones of different sizes (Merrill, 1984). A climatology with multiple tropical cyclone size parameters for the North Atlantic basin was then established with data from 1988 through 2002 (Kimball and Mulekar, 2004). Recently the Quick Scatterometer (QuikSCAT) surface wind speed estimates and storm-centered infrared data were also used to estimate the climatology of storm size (Chavas and Emanuel, 2010; Knaff et al. 2014; Chan and Chan; 2015). However, observed trends in storm size parameters such as the radius of maximum wind (RMW) and the average

radius of 34-kt wind (AR34) have not been extensively examined due to the limited sampling size and data availability.

The remainder of this study proceeds as follows. The size data and the analytic method for diagnosing the trend and changes of storm size are described in section data and methods. The results are present in section results, and the section summary and discussions summarize the findings and present some discussions.

2. Data and methods

This research makes use of a variety of data sources to give as complete a picture as possible of how hurricane size has evolved over the past 40 years. For years from 2004 onward, the best-track (i.e., b-decks) datasets are used from the National Hurricane Center (NHC) for the NATL and EPAC and from the Joint Typhoon Warning Center (JTWC) for the WPAC. As of the time of this research, post-season quality control (QC) had been applied to the NATL and EPAC data through 2015 and to Western North Pacific (WPAC) data through 2014. Thus, the very latest b-deck data is “real-time” and has not undergone the same rigorous QC as the slightly older data. For years before 2004, the best-track data does not include size information, so we have turned to the extended best track (EBT) dataset², as described in Demuth et al. (2006), for the size data over the NATL and EPAC basins. Finally, the best track cyclone data³ from Japan Meteorological Agency (JMA) RSMC Tokyo - Typhoon Center were also used for comparison (Kishimoto 2008) over the WPAC.

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²http://rammb.cira.colostate.edu/research/tropical_cyclones/tc_extended_best_track_data_set

³<http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.htm>

The EBT dataset uses the NHC best-track postanalysis when possible, but operational size estimates are used for earlier storms. There are some inconsistencies between the EBT dataset and the b-decks for post-2004 storms, so we have chosen to use the b-decks instead of EBT for this time period. The best-track b-deck data contain careful estimates of TC position, intensity and size (Demuth et al 2006; Landsea et al. 2010; Landsea and Franklin 2013). The size parameters include the RMW and the 34-, 50- and 64 kt wind radii (R34, R50, and R64, respectively), but as mentioned above this information has only been included in best-track archives since 2004. The operational size estimates available before 2004 (NATL: 1988-2003; EPAC: 2001-2003) have not undergone the same level of quality control as those in the best-track archives.

For the purpose of this study, we examine trends of RMW and the four-quadrant average of R34 (hereafter AR34) from the extended best track dataset, where one or more of the quadrants with 0 value are not included in the average. The RMW gives a sense of the compactness of the inner core, whereas AR34 demonstrates the breadth of the wind field. The JMA dataset covers the period from 1951 to 2016, but size parameters are not available until 1977. One set of parameters are the longest and shortest radii of 50kt winds or greater (R50_L and R50_S), and another set of parameters are the longest and shortest radii of 30kt winds or greater (R30_L and R30_S). Using this data, we define $50 = \sqrt[2]{R50_L \times R50_S}$, and $30 = \sqrt[2]{R30_L \times R30_S}$ as the area-conserving mean radii for 50kt and 30kt winds.

For all data sources, linear and quadratic curves (McDonald 2014) are fit to the time series with the linear equation

$$Y = a X + b,$$

204 and the quadratic equation

$$205 \quad Y = a X^2 + bX + c.$$

206 Here X is time in yearly index. A P-value test is used to check if the trends of storm size
 207 are statistically significant. Trends are examined separately for hurricanes/typhoons
 208 (HT), tropical storms (TS), and all storms with Vmax > 34 kt (ALL) according to the
 209 storm intensity at each analysis time.

210 To study the relationship between storm size and sea surface temperature, the
 211 Extended Reconstructed SST (ERSST) v3b data (Smith et al. 2008; L'Heureux et al.
 212 2013; Huang et al. 2015) are used to calculate the sea surface temperature anomalies
 213 (SSTA) and the departure of the local sea-surface temperature from the zonal mean
 214 (SSTD). Point values of SSTA (computed from a monthly average with respect to
 215 monthly averages from January 1977 to December 2015), and SSTD are then calculated
 216 according to the best-track position. The collocated SSTA and SSTD yield the annual
 217 time series for each storm category, and correlation is calculated between storm size and
 218 SSTA/SSTD.

219 **3. Results**

220 This section examines the characteristics and trends in storm size, collectively in
 221 the NATL, EPAC, and WPAC, and also individually in each basin. The initial focus is
 222 on 2001-2016, which corresponds to the period when size information is available for all
 223 three basins. Longer-term NATL and WPAC datasets are then interrogated to show
 224 trends in individual basins within a larger context. Emphasis is placed on results that are
 225 statistically significant with 90% confidence based on both linear and quadratic fitting

significance tests, as indicated in Tables 1-7. The changes in size are then related to SST changes (Tables 8-12). As a first step, in order to facilitate comparison of our dataset with those of previous studies, trends in storm days are also examined.

a) Storm days

SD is shown in Fig. 1c as an average over the three basins studied and in Fig. 2 for the individual basins. For the three-basin average, none of the SD trends are statistically significant, which agrees with previous published work. Meanwhile, the per-basin results in Fig. 2 reveal the unique characteristics of each basin. The WPAC has the highest percentage of strong storms, as indicated by the fact that HT storm days are almost equal to those of TS. In addition, the WPAC has the most total storm days for ALL storms. The only basin with statistically significant SD trends is the EPAC, where the positive trend of all three categories is significant. A possible reason for this unique EPAC characteristic will be discussed later.

b) Basic size characteristics and linear trends

In Fig. 1 we first examine extended best-track trends averaged over all three examined basins. The general characteristics of the data, with HT having much larger AR34 and much smaller RMW, are consistent with the knowledge that mature storms are larger but have more compact inner cores (Shen, 2006). With regard to the trends, the general picture painted by Fig. 1 is a tendency for decreasing AR34 driven mostly by hurricanes and typhoons. The AR34 trends for HT and ALL, which are statistically significant, are respectively -15.0 and -7.77 NMi/decade. The significant trends of RMW, on the other hand, are driven by TS. RMW trends in TS and ALL, both of which are significant, are respectively 4.49 and 3.16 NMi/decade.

Figures 3-4 demonstrate a great deal of inter-basin variability in the above results. The RMW, for example, has generally been much larger in the NATL than in the WPAC and EPAC (Fig. 3). Meanwhile, AR34 in the EPAC tends to be smaller than that in the NATL and WPAC (Fig. 4). As for the trends, RMW of TS has increased all three basins, though the trend for HT varies by basin (Fig. 3), and RMW trends are significant only in the NATL and EPAC. In the NATL the inner core size has increased for all three categories, though the increase is not significant for HT. In the EPAC, the RMW trends for HT and TS oppose each other, and only the HT trend is significant. The increasing RMW for WPAC TS is also very close to being significant. Meanwhile, the trends of AR34 are negative for HT in all three basins, but for TS the trends vary by basin. Despite the significant negative HT trend in global AR34, only the HT trend in the EPAC is significant.

c) Quadratic trends

In addition to linear trends, we have examined quadratic trends, which might better highlight decade-scale forcing in the individual basins. The quadratic fitting for all parameters shows a large increase in statistical significance in both East and West Pacific basins, but not in the Atlantic. In fact, in the EPAC, all parameters have a significant quadratic trend. This is likely indicative of the more pronounced decadal forcing (perhaps of SST) in the Pacific basins than in the Atlantic for the period covered.

d) Trends in extended datasets

This subsection examines longer-term NATL (Fig. 5) and WPAC (Fig.6) datasets to show how the above trends fit within a larger context. In the NATL the period examined is from 1988 to 2015, which covers the availability of EBT data. In the

WPAC, a 40-year dataset of R30 and R50 was calculated from data provided by JMA RSMC Tokyo - Typhoon Center.

Since the alternative WPAC dataset is based off of fundamentally different data from an independent source, it is wise to assess how well it corresponds with the EBT and b-deck data during the period of overlap. As such, we have computed the correlation coefficient between R30 from Fig. 6 and AR34 from Fig. 4b for the period of overlap. The correlation for TS, HT, and ALL is respectively 0.56, 0.73, and 0.62. All of these values are statistically significant with at least 95% confidence.

The extended NATL dataset in Fig. 5 exhibits both similarities and differences when compared against more recent data. Both datasets exhibit a significant increase in RMW for TS and ALL, though a significantly negative linear trend in RMW is seen in the extended data set but not the more recent data for HT. However, we consider this trend to be suspicious because it appears to reflect a sudden change centered around the year 2001; before that the RMW was relatively constant near 30 nm, and after that it was relatively constant around 20 nm. Thus, this could reflect a change in measurement method or instrument availability. The linear trends of AR34 and SD for TS are also significant in the extended dataset but not in the recent data. In addition, quadratic fits to the extended NATL dataset exhibit much higher significance than do the quadratic fits to the shorter 2001-2016 data. This suggests that the extended dataset better captures decade-scale forcing in the NATL than does the more recent data.

The major difference between the extended and recent WPAC datasets is that a number of the linear trends are significant in the extended dataset. In particular, HT has exhibited a significant negative linear trend in both AR50 and AR30 since 1977. These

trends are consistent with the negative linear trends of RMW and R34 for WPAC HT since 2002, though the recent trends do not carry statistical significance.

e) Relationship with SSTA and SSTD

This section explores the relationship between storm size and SD with SSTA/SSTD. In general, there are only two or possibly three meaningful, consistent relationships amongst the basins. Some of the correlations that are statistically significant (e.g., Tables 8 & 11) are sufficiently weak that they are not particularly meaningful. In other instances they are sporadic significant correlations for one time series in a basin but not the other (c.f., Tables 9 and 10 with Table 11 for NATL).

In the WPAC, SD is significantly anticorrelated with both SSTA and SSTD in both the JMA and JTWC data sets (Tables 9, 10, and 12). The correlation is significant with all storm categories for JMA and SSTD. However, for JMA with SSTA as well as for JTWC with both SSTA and SSTD, the correlation is significant for only TS and ALL. Despite the statistical significance, the correlation values are generally below 0.3 in the JMA dataset, suggesting at most 10% of the variance in SD can be explained by SST variations. However, in the shorter JTWC dataset the correlations are considerably larger such that up to 35% of the variance in SD can be explained by SST variations.

There is also some suggestion of a negative relationship between storm size and SSTA/SSTD in the WPAC. This significant anticorrelation only shows up in the JMA dataset (Table 12), where it is present for all storm classes with SSTD and for TS and ALL with SSTA. The correlation is strongest for SSTD, where SST variations explain up to 25% of the variance in AR30.

There is also a rather strong relationship between SST and storm behavior in the EPAC. For all three storm categories SD is positively related to SSTA. The correlation magnitudes are the largest for all datasets, suggesting that EPAC SSTA contributes to as much as 50% of SD variability in that basin (Table 9). This is perhaps the most significant finding of this study and warrants some further analysis. Turning back to Fig. 2, recall that there has been a rather large increase in SD over the course of the EPAC dataset (since 2001). Commensurate with this increase, Fig. 7 shows that there has been a substantial increase in SST over most of the EPAC during this same time. This is notably different than in other basins, where SST has regions of both positive and negative trends. Thus, it appears that a positive *local* trend in EPAC SST has been causing an increase in SD in that basin.

4. Discussions

Storm size parameters play a very important role in cyclone forecasts, storm surge studies, and the cyclone climate and its changes (Rotunno and Emanuel, 1987; Irish et al. 2008; Chen et al. 2011; Emanuel 2012; Stern et al. 2015; Xu et al. 2016). We used linear and quadratic curve fittings to investigate the recent trends of cyclone size RMW and AR34 as well as storm duration index and found that (1) RMW for TS increases in all three basins; (2) for stronger HT storms, RMW increases in the NATL basin, but decreases in the WPAC and EPAC basins. (3) AR34 trends for HT storms are negative in all three basins, but positive for TS storms in both NATL and WPAC and negative in EPAC. (4) The storm duration index SD increases over time for all categories of storms

in NATL, but decreases for all categories in EPAC. (5) In WPAC the SD trend for TS is positive while negative for HT storms.

The statistical significances of two storm size parameters RMW and AR34 are quite different, with RMW having more significant trends than AR34. This could suggest AR34 being influenced more by environmental conditions, thus having more complex characteristics. The parameter RWM is more representative of storm size reflecting forcing strength, such as SST, with a better linear trend and decadal scale variability. The quadratic fitting also increases the confidence level of statistical significance, particularly in the WPAC and EPAC basins where the decadal scale variability accounts for a significant part of the size variation.

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List of Figures

FIG. 1. 2001-2016 time series of the radius of maximum wind, the average radius of 34 kt wind, and storm days for 3 basins combined. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines respectively show the best fit linear and quadratic trends. The linear trend values are shown in the top of each panel.

FIG. 2. 2001-2016 time series of storm days for the (a) NATL, (b) WPAC and (c) EPAC individually. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines respectively show the best-fit linear and quadratic trends. The linear trend values are shown in the top of each panel.

FIG 3. 2001-2016 time series of the radius of maximum wind for the (a) NATL, (b) WPAC, and (c) EPAC. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines respectively show the best-fit linear and quadratic trends. The linear trend values are shown in the top of each panel.

FIG 4. 2001-2016 time series of the average radius of 34-kt wind for the (a) NATL, (b) WPAC, and (c) EPAC. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines show the best-fit linear and quadratic trends. The linear trend values are shown in the top of each panel.

FIG. 5. 1988-2015 time series of the radius of maximum wind, the average radius of 34-kt wind, and storm days for the NATL, derived from extended best track data. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines show the best fit linear and quadratic trends. The linear trend values are shown at the top of each panel.

FIG. 6. 1977-2015 time series of the average radius of 50-kt wind, the average radius of 30-kt wind, and storm days for the WPAC, derived from extended best track data. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines show the best-fit linear and quadratic trends. The linear trend values are shown at the top of each panel.

FIG. 7. The difference of 2012-2015 SST 5-year mean and 2001-2005 SST 5 year mean.

TABLE 1. P-values for Linear Fittings of RMW, AR34, and SD time series for TS, HT, and ALL storms for the combined in the NATL, WPAC, and EPAC basins from 2001-2016. Bold red denotes significance levels of at least 90%.

	Combined 3 basins		
	TS	HT	ALL
RMW	0.0085	0.2809	0.0743
AR34	0.9155	0.0043	0.0545
SD	0.2715	0.4332	0.8729

TABLE 2. P-values for Linear Fittings of RMW, AR34, and SD time series for TS, HT, and ALL storms in the NATL, WPAC, and EPAC basins from 2001-2016. Bold red denotes significance levels of at least 90%.

	NATL			WPAC			EPAC		
	TS	HT	ALL	TS	HT	ALL	TS	HT	ALL
RMW	0.0002	0.3186	0.0041	0.1055	0.1539	0.2934	0.6897	0.0341	0.7621
AR34	0.6437	0.3556	0.8532	0.7822	0.4470	0.4355	0.1686	0.0369	0.1426
SD	0.7601	0.2372	0.4677	0.6772	0.1321	0.4323	0.0096	0.0100	0.0046

TABLE 3. P-values for Quadratic Fittings of RMW, AR34, and SD time series for TS, HT, and ALL storms in the NATL, WPAC, and EPAC basins from 2001-2016. Bold red denotes significance levels of at least 90%.

	NATL			WPAC			EPAC		
	TS	HT	ALL	TS	HT	ALL	TS	HT	ALL
RMW	0.0018	0.3186	0.0041	0.0003	0.0930	0.0206	0.0656	0.0003	0.0719
AR34	0.5298	0.2653	0.5015	0.1075	0.0474	0.0157	0.0000	0.0014	0.0007
SD	0.4188	0.1611	0.2767	0.4015	0.0147	0.0938	0.0003	0.0010	0.0001

TABLE 4. P-values for Linear Fittings of RMW, AR34, and SD time series for TS, HT, and ALL storms for the NATL basin from 1988-2016. Bold red denotes significance levels of at least 90%.

	NATL		
	TS	HT	ALL
RMW	0.0002	0.0172	0.0011
AR34	0.0040	0.7103	0.2595
SD	0.0158	0.8774	0.1711

TABLE 5. P-values for Quadratic Fittings of RMW, AR34, and SD time series for TS, HT, and ALL storms for the NATL basin from 1988-2016. Bold red denotes significance levels of at least 90%.

	NATL		
	TS	HT	ALL
RMW	0.0000	0.0115	0.0000
AR34	0.0025	0.5034	0.1581
SD	0.0047	0.0655	0.0271

TABLE 6. P-values for Linear Fittings of AR50, AR30, and SD time series for TS, HT, and ALL storms for the WPAC basin, based on 1977-2016 JMA data. Bold red denotes significance levels of at least 90%.

	WPAC 1977-2016 JMA data		
	TS	HT	ALL
AR50	na	0.0003	na
AR30	0.2359	0.0750	0.8646
SD	0.2295	0.4090	0.8735

TABLE 7. P-values for Quadratic Fittings of AR50, AR30, and SD time series for TS, HT, and ALL storms for the WPAC basin, based on 1977-2016 JMA data. Bold red denotes significance levels of at least 90%.

	WPAC 1977-2016 JMA data		
	TS	HT	ALL
AR50	na	0.0001	na
AR30	0.1288	0.0000	0.0037
SD	0.0958	0.1689	0.2024

TABLE 8. Correlation between SSTA/SSTD and RMW, AR34, and SD time series for TS, HT, and ALL storms in the combined NATL, WPAC, and EPAC basins (2001-2016). Bold red denotes significance levels of at least 90%.

	SSTA			SSTD		
	TS	HT	ALL	TS	HT	ALL
RMW	0.2628	0.1306	0.1445	0.0559	-0.2663	0.0019
AR34	0.1361	-0.0206	0.2535	0.1091	-0.1566	0.0225
SD	0.1949	0.0429	0.0784	0.2469	-0.0482	0.1557

TABLE 9. Correlations between SSTA and RMW, AR34, and SD time series for TS, HT, and ALL storms in the NATL, WPAC, and EPAC basins individually. Bold red denotes significance levels of at least 90%.

	NATL			WPAC			EPAC		
	TS	HT	ALL	TS	HT	ALL	TS	HT	ALL
RMW	0.1238	0.2983	0.1417	0.3363	-0.0833	0.2061	0.3912	0.1292	0.3089
AR34	0.0364	0.0836	-0.0083	-0.2543	-0.2105	-0.2133	0.5059	0.2220	0.3770
SD	-0.0488	-0.6221	-0.3068	-0.4959	-0.2742	-0.4523	0.6714	0.6523	0.7136

TABLE 10. Correlations between SSTD and RMW, AR34, and SD time series (2001-2016) for TS, HT, and ALL storms in the NATL, WPAC, and EPAC basins. Bold red denotes significance levels of at least 90%.

	NATL			WPAC			EPAC		
	TS	HT	ALL	TS	HT	ALL	TS	HT	ALL
RMW	-0.4180	0.4797	-0.2431	0.0593	0.5617	0.3012	-0.4164	-0.0329	-0.1965
AR34	0.1603	0.3483	0.3126	-0.1177	0.1853	-0.0057	-0.5952	-0.0124	-0.3428
SD	-0.3159	-0.3953	-0.2501	-0.6540	-0.2693	-0.5538	-0.4460	-0.0390	-0.4316

TABLE 11. Correlations between SSTA/SSTD and RMW, AR34, and SD in the 1988-2016 NATL time series for TS, HT, and ALL storms. Bold red denotes significance levels of at least 90%.

	SSTA			SSTD		
	TS	HT	ALL	TS	HT	ALL
RMW	0.0559	-0.2663	0.0019	-0.0274	-0.1159	0.2425
AR34	0.1091	-0.1566	0.0225	0.4032	-0.0894	-0.0165
SD	0.5570	0.4195	0.1344	0.2114	0.1829	0.0055

TABLE 12. Correlation between SSTA/SSTD and RMW, AR34, and SD for TS, HT, and ALL storms for the WPAC basin, based on 1977-2016 JMA data. Bold red denotes significance levels of at least 90%.

	SSTA			SSTD		
	TS	HT	ALL	TS	HT	ALL
AR30	-0.2006	-0.1247	-0.2381	-0.3572	-0.1938	-0.4845
SD	-0.1678	-0.1243	-0.2241	-0.1918	-0.3029	-0.3623

FIG. 1. 2001-2016 time series of the radius of maximum wind, the average radius of 34 kt wind, and storm days for 3 basins combined. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines respectively show the best fit linear and quadratic trends. The linear trend values are shown in the top of each panel

FIG. 2. 2001-2016 time series of storm days for the (a) NATL, (b) WPAC and (c) EPAC individually. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines respectively show the best-fit linear and quadratic trends. The linear trend values are shown in the top of each panel.

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580 FIG. 3. 2001-2016 time series of the radius of maximum wind for the (a) NATL, (b)
 581 WPAC, and (c) EPAC. The blue, red, and green solid curves are for TS, HT, and ALL
 582 storms, respectively. Dotted and dashed lines respectively show the best-fit linear and
 583 quadratic trends. The linear trend values are shown in the top of each panel.

FIG. 4. -2016 time series of the average radius of 34-kt wind for the (a) NATL, (b) WPAC, and (c) EPAC. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines show the best-fit linear and quadratic trends. The linear trend values are shown in the top of each panel.

FIG. 5. 1988-2015 time series of the radius of maximum wind, the average radius of 34-kt wind, and storm days for the NATL, derived from extended best track data. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines show the best fit linear and quadratic trends. The linear trend values are shown at the top of each panel.

FIG. 6. 1977-2015 time series of the average radius of 50-kt wind, the average radius of 30-kt wind, and storm days for the WPAC, derived from extended best track data. The blue, red, and green solid curves are for TS, HT, and ALL storms, respectively. Dotted and dashed lines show the best-fit linear and quadratic trends. The linear trend values are shown at the top of each panel.

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615 FIG. 7. The difference of 2012-2015 SST 5-year mean and 2001-2005 SST 5 year mean.

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