Extremely Intense Hurricanes: Revisiting Webster et al. (2005) after 10 Years

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ABSTRACT

Ten years ago, Webster et al. documented a large and significant increase in both the number as well as the percentage of category 4 and 5 hurricanes for all global basins from 1970 to 2004, and this manuscript examines whether those trends have continued when including 10 additional years of data. In contrast to that study, as shown here, the global frequency of category 4 and 5 hurricanes has shown a small, insignificant downward trend while the percentage of category 4 and 5 hurricanes has shown a small, insignificant upward trend between 1990 and 2014. Accumulated cyclone energy globally has experienced a large and significant downward trend during the same period. The primary reason for the increase in category 4 and 5 hurricanes noted in observational datasets from 1970 to 2004 by Webster et al. is concluded to be due to observational improvements at the various global tropical cyclone warning centers, primarily in the first two decades of that study.

1. Introduction

Webster et al. (2005) documented more than a 50% increase in both the frequency as well as the percentage of observed category 4 and 5 hurricanes [tropical cyclones (TCs) with maximum one-minute sustained winds greater than 112 kt] over the period 1970–2004. They found that the largest increase occurred in the northwest Pacific, the Indian Ocean, and the South Pacific, with a smaller increase noted in the northeast Pacific and the North Atlantic. Since that paper was published, several studies have questioned these findings by documenting different results using more than a single historical TC dataset (Wu et al. 2006), examining different subperiods of data (Klotzbach 2006), or investigating the veracity of TC data in the earlier portion of the record (Landsea et al. 2006; Kossin et al. 2013; Kuleshov et al. 2010).

Most numerical model simulations, with the notable exception of Emanuel (2013), indicate that the frequency of global TCs is expected to decrease, not increase, over the course of the twenty-first century (Knutson et al. 2010). While numerical modeling studies indicate an increase in the maximum one-minute sustained wind of TCs by the end of the twenty-first century, these increases are expected to be quite small (~5%) (Knutson et al. 2010, 2013; Camargo 2013). However, Elsner et al. (2008) and Kossin et al. (2013) argue that, while the mean may only change slightly, there may already be increasing signals emerging in the observations for the most intense tropical cyclones. Knutson et al. (2013) indicate the possibility of an increase in the frequency of category 4 and/or category 5 (hereafter, category 4–5) systems of around 40% by 2100, although there are large uncertainties with this assessment. Thus the 57% increase (from 171 in 1975–89 to 269 in 1990–2004; see their Table 1) of category 4–5 hurricanes documented to have already occurred in Webster et al. (2005) from 1970 to 2004 indicates that numerical modeling studies are vastly underestimating a TC's sensitivity to anthropogenic climate change, that there are natural climate modes that impact global TC activity significantly on decadal time scales [such as the Atlantic multidecadal oscillation (Goldenberg et al. 2001), the Pacific decadal oscillation (Mantua et al. 1997) or El Niño–Southern Oscillation (ENSO; Rasmusson and Carpenter 1982)], that the observed increase is mostly artificial and due to observational challenges, or that it is a combination of these three mechanisms.

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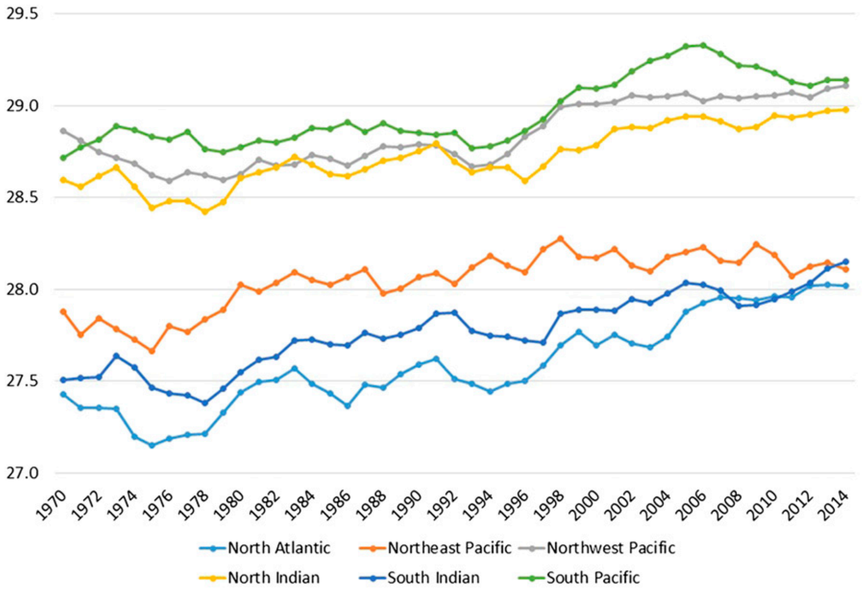

FIG. 1. Five-year running mean of summertime SST values for the various basins where tropical cyclones typically occur. SSTs are plotted for the same regions and months as in Webster et al. (2005) (i.e., North Atlantic: June–October, 5°–25°N, 90°–20°W; northeast Pacific: June–October, 5°–20°N, 120°–90°W; northwest Pacific: May–December, 5°–20°N, 120°–180°E; north Indian: April–May and September–November, 5°–20°N, 55°–90°E; south Indian: November–April, 20°–5°S, 50°–115°E; South Pacific: December–April, 20°–5°S, 155°–180°E).

Over the past decade, global sea surface temperatures (SSTs), as calculated by the NOAA ERSSTv3b dataset (Smith et al. 2008) have continued to increase (Fig. 1). However, a uniform tropical warming impacts TCs in a vastly different manner when compared with relative warming in one tropical ocean basin while keeping SSTs in the remainder of the tropics constant. Vecchi and Soden (2007) showed that using reanalysis data, per 1°C increase in relative SST, an increase in potential intensity of ~8 m s^{-1} is observed, whereas the relationship was actually slightly negative (~-0.5 to -1.0 m s^{-1} °C^{-1}) using tropical mean SST. They found mixed results when using climate model data output from the Intergovernmental Panel on Climate Change Fourth Assessment Report, with a mean positive slope of 0.27 m s^{-1} °C^{-1}. Ramsay and Sobel (2011) found similar results using a single-column model, with an increase of 7–8 m s^{-1} °C^{-1} for a weak temperature gradient mode (representing relative SST) and an increase of ~1 m s^{-1} °C^{-1} for radiative convective equilibrium (representing absolute SST). Emanuel and Sobel (2013) demonstrated that the relationship of TC potential intensity and global CO$_2$ concentrations is also significantly altered by varying surface winds. Large increases, such as those shown in Webster et al. (2005), could potentially manifest under specific forcing conditions, such as a systematic reduction of surface wind speeds in the tropics (e.g., Emanuel and Sobel 2013), but CO$_2$ forcing by itself is expected to cause much smaller changes (e.g., Ramsay and Sobel 2011).

Given the availability of 10 additional years of data since Webster et al. (2005), we feel that it is appropriate to extend their analysis to the present day. Section 2 describes the data and methodology employed for this analysis, while section 3 presents the results. Conclusions are provided in section 4.

2. Data and methodology

TC statistics were calculated from the HURDAT2 database (Landsea and Franklin 2013) for the North Atlantic and northeast Pacific for 1970–2013, while Joint Typhoon Warning Center (JTWC) best-track data (Chu et al. 2002) for 1970–2013 were used for the remaining global basins with the exception of Southern Hemisphere TCs prior to 1985, for which a specialized database from Neumann (1999) was used. This was done due to the fact that JTWC data had some missing intensity information for Southern Hemisphere TCs prior to 1985. A combination of the Neumann and JTWC datasets was also employed in Klotzbach (2006), who found that accumulated cyclone energy (ACE) calculated from the Neumann dataset and ACE calculated from the JWTC dataset over the period 1970–2002 correlated with each other at greater than 0.95. All TC datasets were downloaded from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. 2010). Operational data from the National Hurricane Center (NHC) and the JTWC were utilized for 2014 TC statistics.

TCs were assigned to a specific basin based upon the location where they first became classified as a named storm (one-minute maximum sustained winds ≥ 34 kt). So, if a TC was first named in the northeast Pacific basin and then crossed into the northwest Pacific basin and subsequently intensified into a category 4–5 hurricane there, it would count as a category 4–5 hurricane in the northeast Pacific. A fairly small number of hurricanes cross basin boundaries in any particular year; obviously, global numbers are not impacted regardless of how hurricanes are classified. ACE was calculated based upon which basin the storm was in when the 6-h period was observed. So, a TC that crossed a basin boundary would generate ACE for both basins.

Boundaries between TC basins were classified as in Klotzbach (2006). The International Date Line was used to delimit the boundary between the northeast Pacific and northwest Pacific basins, while 135°E was utilized to delimit the boundary between the south Indian and South Pacific basins.

3. Results

Figure 2 displays the number of category 4–5 hurricanes as well as the percentage of all hurricanes that reached category 4–5 strength in pentads since 1970. These plots are broken down by ocean basin in Table 1. Regions examined are the North Atlantic (NA), northeast Pacific (EP), northwest Pacific (WP), north Indian (NI), south Indian (SI), South Pacific (SP), Northern Hemisphere (NH), Southern Hemisphere (SH), and the globe. As was shown in Webster et al. (2005), there was a significant increase in both the frequency and percentage of category 4–5 hurricanes between the 1970–74 to 1990–94 pentads, but since that point, the number of category 4–5 hurricanes has stabilized, while the percentage of category 4–5 hurricanes has continued to increase, albeit at a much slower rate. This stabilization was noted in Klotzbach (2006) but has since been confirmed with an additional nine years of data. This lack of an increase in category 4–5 hurricane numbers in recent years is more in line with what would be expected from the latest climate model consensus [Knutson et al. 2010; see also Fig. 14.17 in Christensen et al. (2013)].

The linear trend in global category 4–5 hurricanes from 1970 to 1994 was 4.6 storms per decade. To assess the likelihood of this increase occurring due to natural variability during the period when data are likely reliable, we utilize bootstrap resampling of the global category 4–5 hurricane number time series during the period from 1990 to 2014. We assemble 1000 synthetic 25-yr distributions from this time series and find that the 99th percentile of the linear trend from this analysis is 2.8 storms per decade, indicating that the trend found in Webster et al. (2005) is much greater than what would be expected from sampling variability over the more recent period.

Additional evidence for a significant underestimation in hurricane strength during the earlier portion of the record can be gleaned by examining Table 1 in more detail. For example, only 8% of all hurricanes reached category 4–5 status in the Southern Hemisphere from 1970 to 1974, whereas 40% of all hurricanes reached category 4–5 strength over the period from 2010 to 2014. In addition, the percentage of hurricanes reaching category 4–5 strength was 3 times greater in the Northern Hemisphere than it was in the Southern Hemisphere from 1970 to 1974, while in recent years, the percentage of hurricanes reaching category 4–5 strength was similar between both hemispheres. We utilize bootstrap resampling over the 1990–2014 period and assemble 1000 synthetic time series to analyze the likelihood of this occurrence happening by chance. We find that the bottom 1% of Southern Hemisphere 5-yr periods in the synthetic time series had 21% of all hurricanes reach category 4–5 strength, while the top 1% of Northern Hemisphere 5-yr periods in the synthetic time series had 47% of all hurricanes reach category 4–5 strength. Based on variability over the past 25 years, there is less than a 1% chance of a 3:1 difference between the Northern and Southern Hemispheres occurring due to random sampling. In addition, there is no numerical modeling or theoretical basis for such dramatic Southern versus Northern Hemisphere behavior changes in achieving category 4–5 intensity.

Given the data issues briefly discussed earlier in the manuscript, we suggest that most of these changes are due to observational improvements. Several reasons have been given for why this steplike increase in observations should occur and are discussed in detail in Landsea et al. (2006). Outside of the Atlantic basin, routine aircraft reconnaissance today is not conducted. TC intensity estimates are derived almost entirely from satellite data for all basins other than the North Atlantic. Even in the Atlantic, aircraft reconnaissance is only available about 30% of the time, and thus this basin also primarily relies on satellite data. Satellite imagery and data improved dramatically during the 1970s and 1980s in terms of geographic coverage, spatial/temporal resolution, and imagery interpretation tools. The mid to late 1970s heralded the advent of geostationary coverage around much of the world with the launching of *GOES-1*, *Meteosat-1*, and *GMS-1*. However,

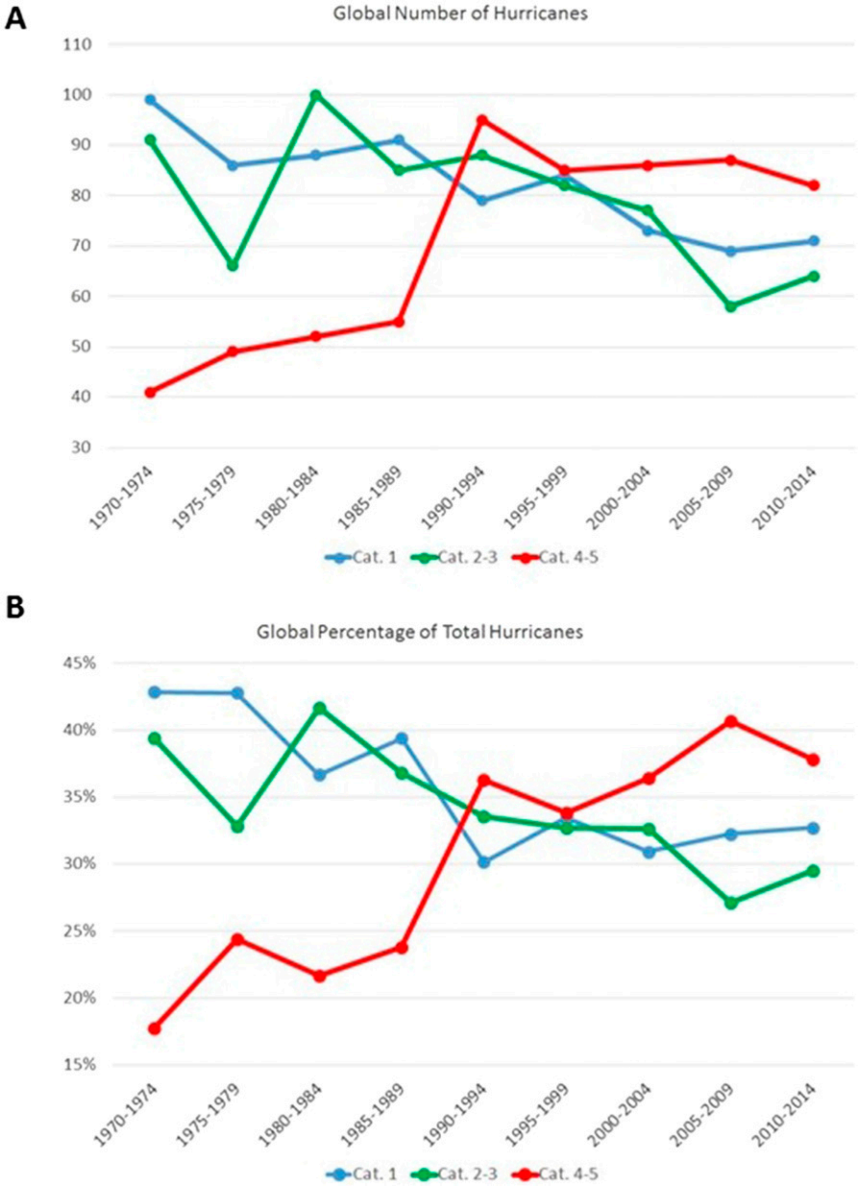

FIG. 2. (a) Pentad total of the number of hurricanes that achieved a maximum intensity of each category grouping as delineated by the Saffir–Simpson scale. (b) As in (a), but for the percentage of total hurricanes achieving each category grouping.

the north (and south) Indian Ocean lacked direct geostationary satellite data until 1989 with the launching of *Meteosat-5* (Knapp and Kossin 2007). Consequently, the archived best-track data from JTWC only report one category 4–5 hurricane from 1970 to 1989 for the north Indian Ocean, whereas during the most recent 20-yr period from 1995 to 2014 a total of 13 category 4–5 hurricanes have been observed. Landsea et al. (2006) identified several missed category 4–5 hurricanes before 1990, which were instead considered to be weaker TCs. After the advent of geostationary satellites, techniques were developed and refined for interpreting the intensity from satellite imagery. In particular, the Dvorak technique—a position and intensity pattern recognition scheme—was first developed in the early 1970s for visible imagery (Dvorak 1975) and later revised to include infrared imagery (Dvorak 1984). The adaptation of this tool globally became standard during the 1980s once the Regional Specialized Meteorological Centers were established for monitoring and forecasting tropical cyclones (Velden et al. 2006). In addition, operational responsibility for the northeast Pacific basin shifted from

TABLE 1. Number and percentage of category 4–5 hurricanes by TC basin by pentad since 1970.

Basin	1970–74	1975–79	1980–84	1985–89	1990–94	1995–99	2000–04	2005–09	2010–14
				No. of category 4 and 5 hurricanes					
NA	2	6	4	6	2	12	11	12	7
EP	6	13	11	12	25	16	9	9	14
WP	27	21	27	26	42	28	41	38	31
NI	0	0	1	0	3	4	0	4	5
SI	5	6	8	6	13	19	20	15	15
SP	1	3	1	5	10	6	5	9	10
NH	35	40	43	44	72	60	61	63	57
SH	6	9	9	11	23	25	25	24	25
Global	41	49	52	55	95	85	86	87	82
				Percentage (%) of all hurricanes reaching category 4–5 strength					
NA	9	21	15	23	9	29	30	32	19
EP	14	31	21	24	40	42	26	24	29
WP	32	31	35	30	41	37	47	51	52
NI	0	0	17	0	50	27	0	67	56
SI	10	17	17	15	32	39	39	38	36
SP	4	15	3	17	37	19	26	45	48
NH	23	27	27	27	37	35	37	41	37
SH	8	16	12	16	34	31	36	40	40
Global	18	24	22	24	36	34	36	41	38

the Weather Service Forecast Office, Redwood City, California, to the National Hurricane Center following the 1987 season, which appears to have caused an artificial jump in 1988 in analyzed intensities between the two agencies (T. Kimberlain 2015, personal communication). Finally, the demise of extensive aircraft reconnaissance missions in the northwest Pacific basin in 1987 likely led to a nonnegligible impact upon analyzed intensities. The efforts within the IBTrACS project (Knapp et al. 2010) have led to global TC datasets, but, while these data are now easily available, there has yet to be an internationally agreed-upon standardized global TC intensity database.

Data over the past 25 years are likely to be more reliable than during the prior two decades. Figure 3 displays category 4–5 hurricane tracks for the periods 1975–84 and 1985–94, respectively, while Fig. 4 displays category 4–5 hurricane tracks for the two most recent 10-yr periods (1995–2004 and 2005–14). There is a large increase in category 4–5 hurricane tracks, especially in the Southern Hemisphere and the north central Pacific between 1975–84 and 1985–94, while category 4–5

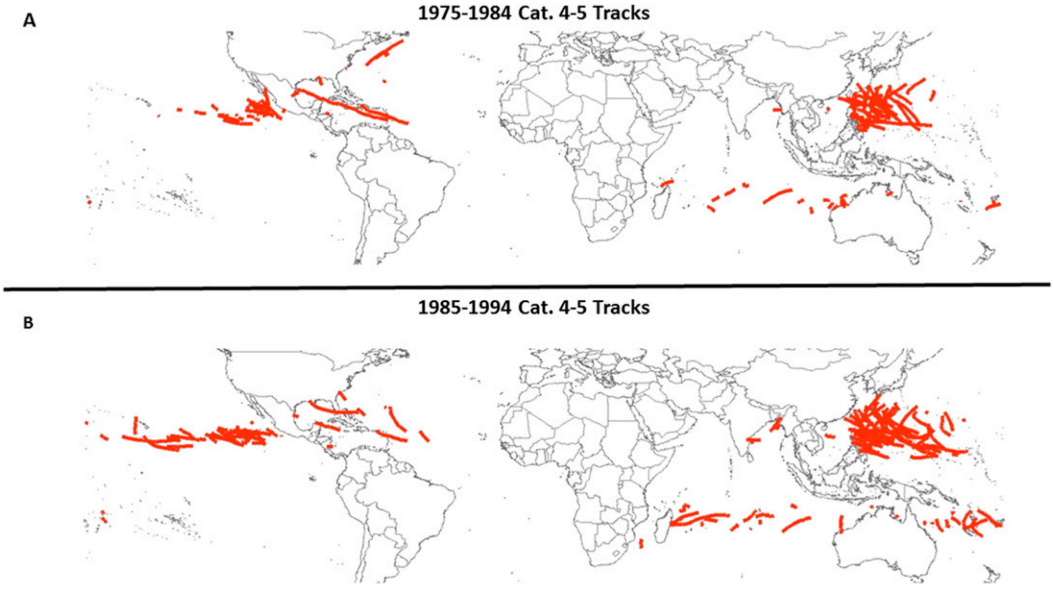

FIG. 3. Tracks of category 4–5 hurricanes for (a) 1975–84 and (b) 1985–94.

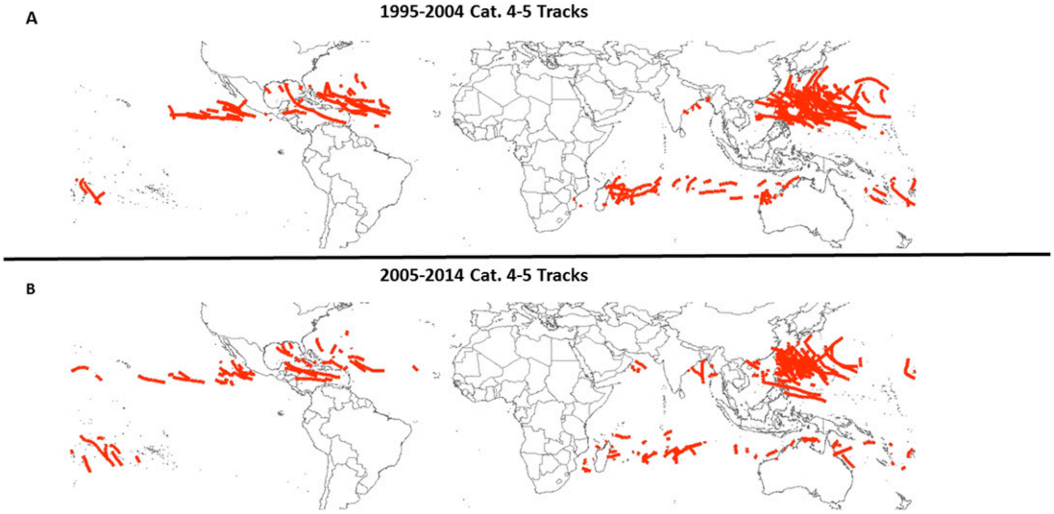

FIG. 4. As in Fig. 3, but for (a) 1995–2004 and (b) 2005–14.

hurricane tracks appear visually similar between the two most recent 10-yr periods, suggesting that the frequency of category 4–5 storms has stabilized.

An additional way of investigating the combined effect of intensity, duration, and frequency of TCs is by examining values of accumulated cyclone energy (Bell et al. 2000) in a manner similar to what was done in Maue (2011). ACE is defined to be the sum of the maximum sustained wind speed at each 6-h interval squared, and consequently, more intense hurricanes are weighed much more strongly than weaker storms. For example, in the North Atlantic, 6% of all tropical cyclones over the period from 1995 to 2014 reached category 4–5 hurricane strength. These category 4–5 hurricanes generated 45% of the basin's ACE during the 20-yr period.

Webster et al. (2005) was published using data through 2004, a time when ACE was at a local maximum (Fig. 5). Maue (2011) noted that global ACE reached lower 24-month running mean values in 2010 than had been observed since the mid-1970s. Given the likely underestimates in TC activity due to poor satellite quality during the 1970s and the 1980s, the period around 2010 has the potential to be the quietest period in the past 40 years if one could properly account for the undersampling of intensity before 1990. Figure 5a displays ACE by year for each of the six global TC basins since 1970. These values are combined into hemispheric sums as well as global sums in Fig. 5b. There has generally been a decreasing trend in ACE since the early 1990s, when a prolonged El Niño enhanced TC levels in the North Pacific (the northwest Pacific and northeast Pacific combined; Maue 2011). North Pacific TC activity accounted for 56% of globally averaged ACE during 1979–2010 (Maue 2011).

Table 2 investigates the linear trends in ACE as well as category 4–5 hurricane numbers and percentages over the periods 1970–2004, 1970–2014, and 1990–2014, respectively. Trends that are statistically significant at the 5% level are highlighted in bold-faced type. We treat each year as an individual degree of freedom, which is reasonable given the lack of autocorrelation between one year's global TC activity and the next. There were statistically significant increases in global ACE, as well as for the Atlantic basin and the Northern Hemisphere over 1970–2004. However, when including data through 2014, the only statistically significant increase in ACE is for the Atlantic. The Atlantic basin is known to have significant multidecadal variability, and 1970 was the beginning of a quiet period for the basin (Goldenberg et al. 2001). In addition, statistically significant decreasing trends in ACE over 1990–2014 are evident for the northeast Pacific, the northwest Pacific, the Northern Hemisphere, the Southern Hemisphere, and the entire globe.

The trend in category 4–5 hurricane numbers is statistically significantly positive for the Atlantic, northwest Pacific, south Indian, and South Pacific Oceans over the period from 1970 to 2004, as well as for both hemispheres and the globe. All trends remain significant when including the past decade; however, the per-decade trends decrease for all basins except for the north Indian Ocean (where the trend becomes significantly positive). However, when examining data just over the period 1990–2014, no statistically significant trends are evident for any basin individually, for either hemisphere or for the globe.

The percentage of category 4–5 hurricanes shows an increasing trend over the period 1970–2014, although at a slower rate than depicted in Webster et al. for 1970–2004. However, for the most reliable period from

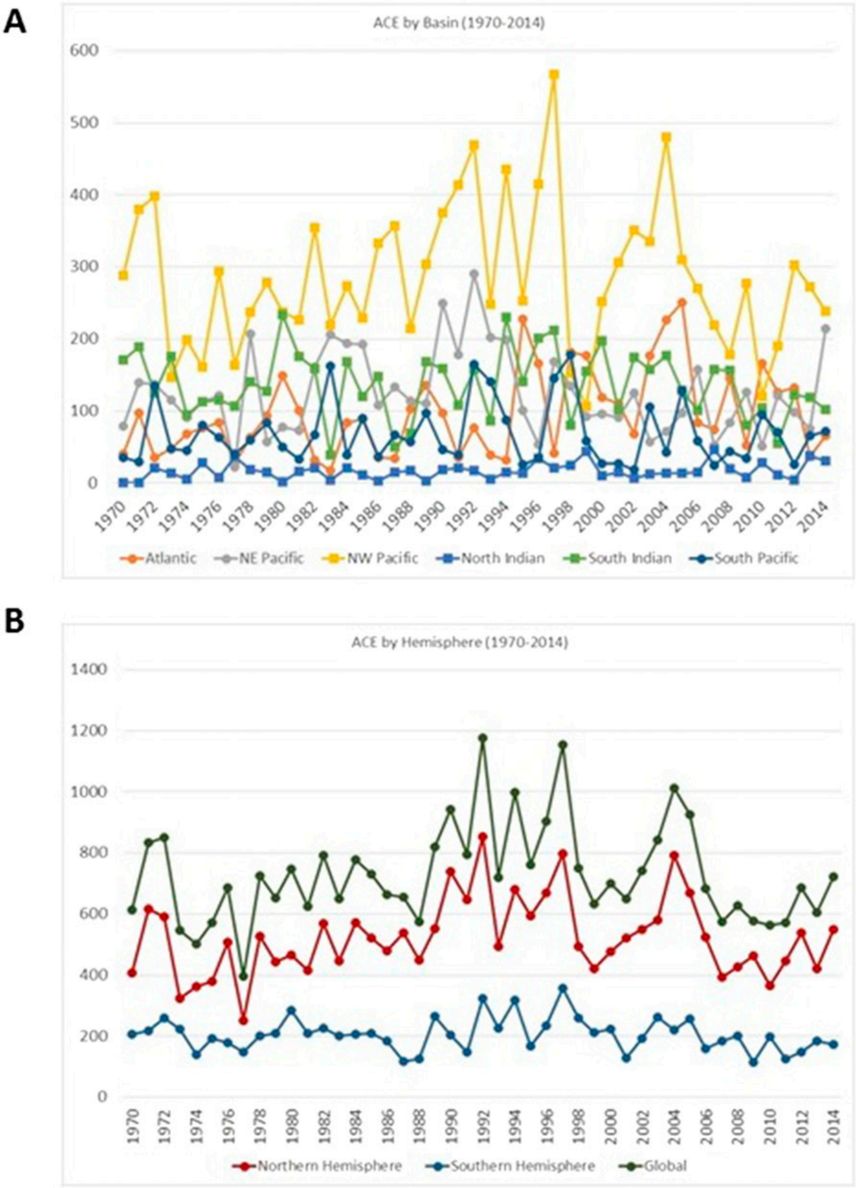

FIG. 5. (a) ACE values (10^4 kt^2) by TC basin from 1970–2014. (b) ACE values summed by hemisphere as well as the global sum.

1990 onward the increasing trends for category 4–5 hurricane percentage are much smaller and insignificant for the Southern Hemisphere, Northern Hemisphere, and globally. The current percentage globally is around 40%, which is consistent with the hypothesis cited by Holland and Bruyère (2014) that the category 4–5 hurricane percentage may saturate at the 40%–50% level.

While the shortness of the reliable observational record belies complete understanding of how modes that oscillate on long-term time scales such as the Pacific decadal oscillation (Mantua et al. 1997) and the Atlantic multidecadal oscillation (Goldenberg et al. 2001) impact global TC frequency and intensity, we note that warm ENSO events are typically associated with more active periods of Northern Hemisphere ACE (Maue 2011) as well as increased frequency of category 4–5 hurricane numbers. Northern Hemisphere ACE and category 4–5 hurricanes accounted for 73% and 72% of the global number, respectively, over the 1990–2014. Utilizing the bimonthly multivariate ENSO index (MEI) to define ENSO (Wolter and Timlin 1998), the four strongest warm ENSO events since 1990 averaged over the May–June and October–November periods occurred from 1990 to

TABLE 2. Per-decade linear trends of ACE (10^4 kt^2) and category 4–5 hurricane numbers and percentages for 1970–2004, 1970–2014, and 1990–2014, respectively. Trends that are significant at the 5% level are highlighted in bold.

Period	NA	EP	WP	NI	SI	SP	NH	SH	Globe
					ACE				
1970–2004	**29**	2	31	1	6	4	**63**	10	**73**
1970–2014	**17**	−4	1	2	−5	0	17	−5	12
1990–2014	8	**−43**	**−72**	2	−24	−15	**−105**	**−40**	**−145**
					Category 4–5 hurricane numbers				
1970–2004	**0.6**	0.5	**1.0**	0.1	**1.0**	**0.4**	**2.2**	**1.4**	**3.6**
1970–2014	**0.4**	0.2	**0.7**	**0.2**	**0.7**	**0.4**	**1.4**	**1.1**	**2.5**
1990–2014	0.3	−1.0	−0.4	0.2	0.0	0.1	−0.9	0.1	−0.7
					Category 4–5 percentages (%)				
1970–2004	5	6	4	7	**10**	6	**5**	**9**	**7**
1970–2014	3	2	**5**	**11**	**7**	**12**	**4**	**8**	**6**
1990–2014	3	−7	7	−2	0	**16**	2	4	2

1997, with four of the five strongest cold ENSO events occurring since 2008. The average of the five warmest ENSO events since 1990 recorded 617 Northern Hemisphere ACE units and 14 category 4–5 hurricanes compared with 411 Northern Hemisphere ACE units and 11 category 4–5 hurricanes in the five coldest ENSO events since 1990. Some of the decrease in global ACE and category 4–5 numbers that has been observed recently is likely due to reduced El Niño frequency and increased La Niña frequency during the more recent period.

4. Conclusions

It was suggested by Klotzbach (2006) and Landsea et al. (2006) that technological improvements during the 1970s and 1980s were primarily responsible for the dramatic increases in the frequency and percentage occurrences of category 4–5 hurricanes worldwide reported in Webster et al. (2005). With 10 additional hurricane seasons now available to analyze, the long-term (1970–2014) trends showed reduced trends in category 4–5 frequency and percentage globally. When restricted to the most recent 25 years (1990–2014) with the most reliable and homogeneous records, the following conclusions are reached from this analysis:

- Small, insignificant decreasing trends are present in category 4–5 hurricane frequency in the Northern Hemisphere and globally, while there is no virtually no trend in Southern Hemisphere frequency.
- Small, insignificant upward trends are present in category 4–5 hurricane percentage in the Northern Hemisphere, the Southern Hemisphere, and globally.
- Large, significant downward trends are present in accumulated cyclone energy in the Northern Hemisphere, the Southern Hemisphere, and globally.

These results provide more evidence that the changes reported by Webster et al. (2005) that occurred in number and percentages of category 4–5 hurricanes globally during the 1970s and 1980s were likely primarily due to improved observational capabilities. These results are more in line with expectations from climate models (Knutson et al. 2010, 2013; Camargo 2013; Christensen et al. 2013; Bender et al. 2010), which suggest that no appreciable change in category 4–5 hurricane numbers or percentages would be detectable at this time due to anthropogenic climate change.

Because of the additional evidence provided here about the artificial impacts of technology on the best-track databases, it is recommended that global studies addressing trends in extreme hurricanes (as well as combined metrics like ACE) begin around 1990. Before this time, the records are currently incomplete and lead to a distorted view of the actual activity that occurred before that time. We would also encourage the further development and extension backward in time of satellite-only homogeneous databases (Kossin et al. 2013) suitable for trend analysis.

Trends in category 4–5 hurricane numbers and percentages and ACE should be revisited whenever historical TC databases are reanalyzed (Hagen et al. 2012) and when another decade or so of additional seasons are recorded. However, given the large natural variability driven by ENSO and other natural phenomena, it is likely to be challenging to confidently ascribe an anthropogenic signal to changes in the most intense tropical cyclones for the next several decades.

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