Impact of Duration Thresholds on Atlantic Tropical Cyclone Counts*

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ABSTRACT

Records of Atlantic basin tropical cyclones (TCs) since the late nineteenth century indicate a very large upward trend in storm frequency. This increase in documented TCs has been previously interpreted as resulting from anthropogenic climate change. However, improvements in observing and recording practices provide an alternative interpretation for these changes: recent studies suggest that the number of potentially missed TCs is sufficient to explain a large part of the recorded increase in TC counts. This study explores the influence of another factor—TC duration—on observed changes in TC frequency, using a widely used Atlantic hurricane database (HURDAT). It is found that the occurrence of short-lived storms (duration of 2 days or less) in the database has increased dramatically, from less than one per year in the late nineteenth–early twentieth century to about five per year since about 2000, while medium- to long-lived storms have increased little, if at all. Thus, the previously documented increase in total TC frequency since the late nineteenth century in the database is primarily due to an increase in very short-lived TCs.

The authors also undertake a sampling study based upon the distribution of ship observations, which provides quantitative estimates of the frequency of missed TCs, focusing just on the moderate to long-lived systems with durations exceeding 2 days in the raw HURDAT. Upon adding the estimated numbers of missed TCs, the time series of moderate to long-lived Atlantic TCs show substantial multidecadal variability, but neither time series exhibits a significant trend since the late nineteenth century, with a nominal decrease in the adjusted time series.

Thus, to understand the source of the century-scale increase in Atlantic TC counts in HURDAT, one must explain the relatively monotonic increase in very short-duration storms since the late nineteenth century. While it is possible that the recorded increase in short-duration TCs represents a real climate signal, the authors consider that it is more plausible that the increase arises primarily from improvements in the quantity and quality of observations, along with enhanced interpretation techniques. These have allowed National Hurricane Center forecasters to better monitor and detect initial TC formation, and thus incorporate increasing numbers of very short-lived systems into the TC database.

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1. Introduction

Increases in tropical cyclone (TC; here referring only to those with maximum sustained surface winds of at least 18 m s^{-1} including subtropical cyclones)[1] activity due to anthropogenic climate change should be of concern given the massive societal disruptions and potential for large numbers of fatalities that these oceanic phenomena can cause upon landfall in heavily populated coastal communities (IWTC 2007). While possible changes of TC intensity, frequency, duration, track, rainfall, and storm surge must all be considered, in this report our focus is on past records of TC frequency in the Atlantic basin.

From a climate modeling perspective, most studies have focused on future projections of TC activity, limiting their direct utility for comparison with past observed trends. An exception is Bengtsson et al. (2007), who find no significant trend in Atlantic TCs in a twentieth-century radiative forcing hindcast experiment. Concerning future projections, existing climate model and regional downscaling studies yield mixed projections of the influence of a substantial twenty-first-century greenhouse warming on Atlantic basin (including the North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) TC frequency. Some studies suggest modest frequency increases of 15%–35% (Oouchi et al. 2006; Chauvin et al. 2006), some indicate little to no change in numbers (Bengtsson et al. 2007; Emanuel et al. 2008), while others predict even a modest decrease in frequency by 15%–30% (McDonald et al. 2005; Chauvin et al. 2006; Knutson et al. 2008; Gualdi et al. 2008). In some cases (Chauvin et al. 2006; Emanuel et al. 2008) where multiple climate models were examined using a single downscaling model, the sign of the projected change in TC frequency was seen to depend on the particular climate model chosen to provide the large-scale climate change projection. The lack of large modeled increase in TC frequency in the Atlantic in response to CO_2-induced warming may be due to the combination of dynamical changes (e.g., increases in tropospheric vertical wind shear) and changes in the thermodynamic state, which offset the increases in SST (e.g., Vecchi and Soden 2007a,b).

Observational studies similarly report a wide range of conclusions on the long-term frequency changes in Atlantic TCs. Two studies (Mann and Emanuel 2006; Holland and Webster 2007), using unadjusted Atlantic hurricane database (HURDAT) data, concluded that a rather dramatic—at least 100%—increase in TC frequency occurred during the last century (see Fig. 1) that they attributed to SST warming caused by anthropogenic climate change. Both studies made the explicit assumption that the database was complete or nearly so for TC frequency. Documentation accompanying HURDAT (Landsea et al. 2004) had earlier estimated that up to four TCs per year were "missed" near the beginning of the twentieth century because of a lack of observational networks over the open Atlantic Ocean. The number of missed TCs was later estimated by comparing the ratio of landfalling TCs versus the total number of systems in the pregeostationary satellite era (before 1966) versus the current era (Landsea 2007). The ratio showed a large step function drop at 1966, which, it was argued, suggests that about two TCs per year were missed from about 1900 (the first year when nearly all landfalling TCs would likely have been monitored) to 1965, although Holland (2007) questions the hypothesis that the proportion of storms making landfall remains stationary. Mann et al. (2007a) demonstrated that even with the Landsea (2007) adjustment to the TC record there is observed a large and unprecedented increase in TC frequency during the last decade.

Mann et al. (2007b) estimated the frequency of unsampled Atlantic TCs by fitting the TC frequency record against environmental factors thought to be relevant to variability of TC frequency. They related year-to-year seasonal TC numbers to Atlantic sea surface temperatures, the El Niño–Southern Oscillation, and the North Atlantic Oscillation for the period of 1944–2006 and then applied the relationship obtained to the period 1870–1943 in the pre-aircraft reconnaissance era to then estimate how many TCs were missed yearly on average. Their results indicated that an undercount exists of about 1.2 TCs per year (with a likely range of 0.5–2.0) for 1870–1943. However, the study assumed that the physical link between the century-scale trend in Atlantic SSTs and the trend in the Atlantic TC counts can be adequately described by their statistical model. Given that the recent dynamical modeling studies of anthropogenic climate change (described earlier) and other statistical methods (Swanson 2008; Vecchi et al. 2008) suggest only relatively small sensitivity of Atlantic TC frequency to a relatively uniform tropical SST increase, as is projected in typical greenhouse warming scenarios, the authors' underlying assumption may not be physically valid. It should be noted that regional-scale SST changes on the interannual and multidecadal time scale appear quite important for TC frequency variations (e.g., Kossin and Vimont 2007), but there is considerable evidence (e.g., Knutson et al. 2008; Vecchi et al. 2008) that the more

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[1] As discussed in Neumann et al. (1999) and Landsea et al. (2008), while the formal designation of subtropical cyclones began in 1968, such systems were likely included within HURDAT earlier but considered to be tropical cyclones. Without routine satellite imagery to discern the convective structure, differentiating true tropical cyclones from subtropical cyclones is nearly impossible.

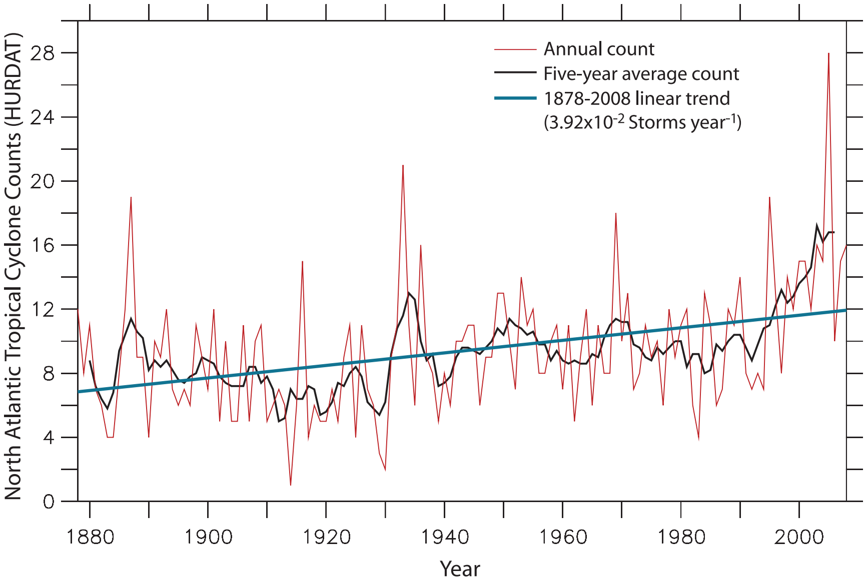

FIG. 1. Frequency of all unadjusted Atlantic tropical cyclones (tropical and subtropical storms) from 1878 to 2008 (red). The black curve is a 5-yr centered mean and the blue line is the 1878–2008 trend.

uniform tropical SST trends, as projected by climate models for increasing greenhouse gases, will affect Atlantic TC frequency quite differently.

An alternative analysis approach has been used (Chang and Guo 2007; Vecchi and Knutson 2008, hereafter VK08) to quantify the time change in the number of ''missing'' Atlantic TCs based upon the density of ship observations during the last century. Both studies suggested that a significant upward trend remains in the counts of TCs when starting from about 1900, although VK08 found that the trend from 1878 onward was not significant. An assumption common to both the Chang and Guo (2007) and VK08 analyses is that any TC observable in the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Worley et al. 2005) ship data would have already been included in HURDAT[2] (Jarvinen et al. 1984). The ICOADS ship database was recently incorporated into the reanalyses that have been completed for 1911–25 (Landsea et al. 2008), and was the primary tool in helping to identify 23 additional TCs for those years; there were also 2 TCs removed from HURDAT because they did not meet today's TC criteria. Unfortunately, ICOADS has not yet been utilized for the reassessment of HURDAT for neither the period of 1851–1910 (Landsea et al. 2004) nor for the years of 1926 onward. Thus, based upon the results obtained thus far with the TC reanalyses incorporating ICOADS, we speculate that about one additional TC per year for the late nineteenth and early twentieth century will eventually need to be added to the numbers of missing TCs estimated earlier (Chang and Guo 2007; VK08).

Landsea (2007) argued that in the last several years, roughly one additional TC per year had been identified and included in HURDAT because of new tools and techniques such as Quick Scatterometer (QuikSCAT) satellite imagery (Atlas et al. 2001), the Advanced Microwave Sounding Unit (Brueske and Velden 2003), and the Cyclone Phase Space analyses (Hart 2003). These methods have allowed for the detection of very short-lived systems that might not have been analyzed as having gale force winds previously as well as more accurate differentiation of cyclones that were better characterized as TCs rather than primarily baroclinic, extratropical cyclones.[3] If one is better able to observe systems over the

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[2] ICOADS contains raw ship-based observations including ship position, wind speed and direction, air and sea temperatures, and sea level pressures. HURDAT, in contrast, is a database of analyzed TC positions and intensities (estimated maximum sustained surface wind speeds and central pressures) every 6 h. The original HURDAT certainly utilized whatever ship observations were available operationally, but ICOADS typically provides significantly more ship data for reassessing existing TCs and for discovering previously undocumented TCs.

[3] It is possible that there have been some cyclones included as tropical/subtropical storms in HURDAT in the past that would not have been included in recent years because of technological advances that, if they had been available in the past, would have indicated that the storms did not have TC intensity and/or structure. However, it is likely that the increase in TC counts due to improved observing capabilities is much larger than the number of nontropical storms misclassified as TCs in the past due to limited observing and analysis capabilities.

tropical and subtropical oceans through enhanced monitoring networks, then these changes could contribute toward more TCs (especially very short-lived ones) being accurately identified and thus included in HURDAT.[4] However, this additional one TC per year during the last several years has not been well quantified nor objectively determined (Landsea 2007).

In 2007, the Atlantic hurricane season was notable for the very large number of very short-lived (and typically weak) TCs that were named and included in HURDAT (Brennan et al. 2009). Out of the total 15, 9 TCs were identified that lasted for 2 days or less at tropical storm–force intensity, compared to an average of about 2 very short-lived TCs per year during the twentieth century. There was also a substantial number—four—of very short-lived, weak TCs in 2008 (Brown et al. 2010). These observations suggest that the number of additional very short-lived TCs introduced in recent years is larger than that estimated earlier in Landsea (2007).

Each of these studies has aimed to improve our understanding of historical Atlantic TC activity by estimating the number of missed TCs, but it is evident that we will never know with certainty how many real storms were not detected, and each of the proposed corrections can be open to criticism. Some of the methods (e.g., Landsea 2007; Mann et al. 2007b) assume a priori that certain characteristics of TCs have remained stationary over the period of analysis, though these assumptions can be open to question. As noted by VK08 (p. 3599), ‘‘while. . .we estimate certain key sources of uncertainty in the historical Atlantic TC database, other possible sources of uncertainty remain. . .. Thus, our current estimates of long-term changes in TC activity should be regarded as tentative, particularly when analyses span periods in which substantial changes in observing practices have occurred, and efforts should continue to update and enhance our historical records of TCs and their uncertainties.’’

Our goal in this paper is to expand our understanding of the character of the historical record of Atlantic TCs, by examining the century-scale trend behavior of TCs of different duration classes. First, an analysis of the time series for very short-lived TCs is conducted to show how this class of storms contributes to the trend in the whole TC database. Then, the methodology of VK08 is employed for the TC database (but with the very short-lived systems removed) to examine how many medium- to long-lived TCs have been unsampled in earlier years and how this impacts trends from the resulting time series. Finally, we offer our interpretation of the results in the summary and discussion section, including a discussion of the impact of duration thresholds on TC counts within a coupled climate modeling framework.

2. Observational results

a. The observational record of very short-lived tropical cyclones

Figure 2 shows the frequency of very short-lived TCs (total duration of 2.0 days or less at tropical storm or hurricane force throughout the TC's lifetime)[5] back to 1878, the first year that the U.S. Army Signal Corps began systematically attempting to trace all West Indian hurricanes (Fernández-Partagás and Diaz 1996). The frequency of these events increased dramatically during the last century. From the late 1870s to about 1940, there was an average of about one very short-lived TC per year. During the 1940s until about 1960, the frequency increased roughly coincident with the advent of aircraft reconnaissance and satellite imagery (see Fig. 6 of Sheets 1990). The frequency remained relatively constant at about three per year from around 1960 to about 2000. Another steplike increase appears to have occurred in the last several years, corresponding to further improvements in TC analysis and monitoring (see discussion section). Spatially, these very short-lived TCs have a similar distribution throughout the Atlantic basin to all of HURDAT (not shown).

The increase in short-duration storm counts in HURDAT, which can be seen clearly in Fig. 2, is statistically significant by a variety of measures. The positive linear least squares trend in short-duration TCs over 1878–2008 (2.79 storms per century) is both large (almost twice as large as the mean over the full period, 1.57) and significantly different from zero at $p < 0.01$, when using a Student's t test and estimating the degrees of freedom from the lag-1 autocorrelation of the detrended time series [see VK08; Santer et al. (2000) for a description of the test]. We also compute an alternative measure of secular change, the median of pairwise slopes (MPWS; Lanzante 1996); this nonparametric test of secular change is robust to outliers and has an influence function that is constant over the entire time series. The 1878–2008 MPWS of short-duration storms is significantly different from zero at $p < 0.01$, using a Spearman's rank test. We use linear

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[4] It is important to note that very short-lived TCs do not significantly contribute toward overall activity in a TC basin using indices such as the ACE index (e.g., Bell et al. 2000) and PDI (e.g., Emanuel 2005; Swanson 2008), which are designed to measure the combined impact of TC frequency, intensity, and duration.

[5] A wide range of duration thresholds for very short-lived TCs was tested and can be found in the online supplement. The conclusions presented here are insensitive to the exact threshold chosen.

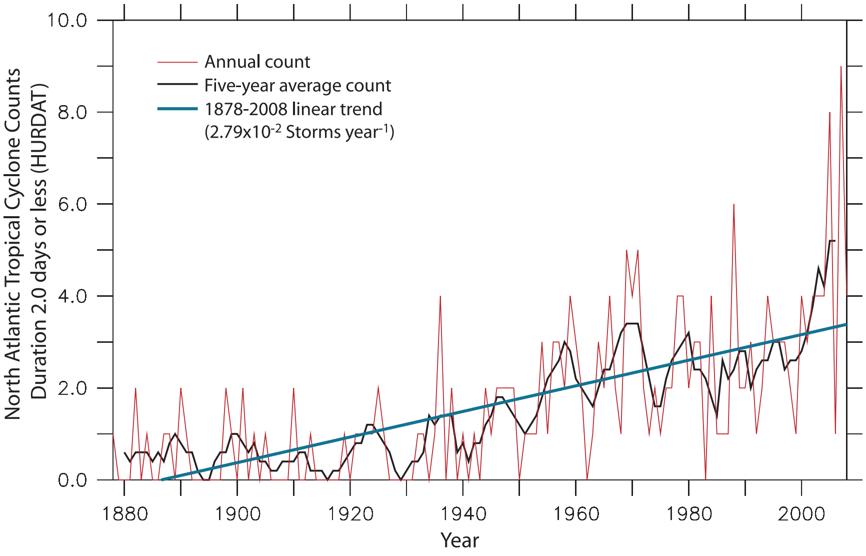

FIG. 2. As in Fig. 1, but for all Atlantic very short-lived tropical cyclones (tropical and subtropical storms) that lasted as gale-force tropical cyclones for ≤2 days.

trends and medians of pairwise slopes in this paper as statistical measures of secular change, not as a ''best fit'' to the observed data. As noted by VK08 (see their Fig. 11), the Geophysical Fluid Dynamics Laboratory Climate Model version 2.0 and 2.1 (GFDL CM2.0 and 2.1) runs suggest that the response of tropical Atlantic SSTs to anthropogenic forcing over the past 140 yr has been a quasi-linear warming, which supports our use of a linear trend test in the present analysis.

The results in Tables 1 and 2 show that the statistical significance of the different measures of secular change in short-storm counts is robust, whether the statistics are computed over the period 1878–2008, 1900–2008, or 1903–94 (the latter using two negative Atlantic multidecadal oscillation periods as endpoints; Zhang and Delworth 2006). The amplitude of the linear trend and MPWS is also relatively unchanged by choosing the three different intervals, indicating that the increase in the counts of short-duration TCs on the century time scale is relatively monotonic. Thus, the long-term increase in short-duration TCs in HURDAT is a robust and significant feature of the database.

b. *The long-term trend of moderate–long-lived tropical cyclone frequency*

Removing very short-lived TCs from the entire database (Fig. 3) reveals a substantially reduced long-term trend during the last century in the remaining medium- to long lived TCs, but interannual and multidecadal variability is relatively unchanged. The medium- to long-lived TC series shows a significant upward trend when starting from 1900, but not from 1878, nor between 1903 and 1994 (see Table 1). The median of pairwise slopes of moderate to long-lived TCs is not statistically significant over 1878–2008 ($p = 0.24$) or over 1903–94 ($p = 0.76$), while it is significant over the period 1900–2008 ($p = 0.02$; Table 2). The statistical significance of the century-scale change in moderate- to long-duration storms appears to depend strongly on choosing a date near 1900 as a starting point and a date near 2005 as an endpoint.

The moderate- to long-duration TC record is still impacted by the complication of how many TCs (of, in this case, greater than 2.0-day lifetime) were not sampled because of sparser shipping traffic over the open Atlantic

TABLE 1. Trend in TC counts per year. Units are expressed in storms yr^{-1} century^{-1}. Significance of trends is indicated as p values in parentheses next to the trend value; values significant at the $p = 0.05$ level are italics. Significance was computed using a Student's t test on the time series of the square root of counts (Vecchi and Knutson 2008).

Type	1878–2008	1900–2008	1903–94
Unadjusted, complete HURDAT	*3.92*	*5.81*	*3.16*
Very short-lived (<2 days) TCs	*2.79* ($<10^{-5}$)	*3.46* ($<10^{-5}$)	*3.12* ($<10^{-5}$)
Moderate to long-lived (>2 days) TCs	1.13 (0.17)	*2.35* (*0.02*)	0.04 (0.73)
Adjusted moderate to long-lived TCs	−0.51 (0.60)	1.20 (0.27)	−1.18 (0.49)

TABLE 2. MPWS of TC counts per year. Units are expressed in storms yr^{-1} $\mathrm{century}^{-1}$. Significance of each MPWS is indicated as two-sided p values in parentheses next to the trend value; values significant at the $p = 0.05$ level are italicized. Significance was computed using a Spearman's rank test (see Lanzante 1996).

Type	1878–2008	1900–2008	1903–94
Unadjusted, complete HURDAT	*3.45*	*5.25*	*2.69*
Very short-lived ($\leq$2 days) TCs	*2.17* ($<10^{-4}$)	*2.86* ($<10^{-4}$)	*2.52* ($<10^{-4}$)
Moderate to long-lived (>2 days) TCs	0.3 (0.10)	*1.78 (0.01)*	0.02 (0.55)
Adjusted moderate to long-lived TCs	−0.45 (0.59)	0.60 (0.21)	−0.55 (0.64)

Ocean in earlier decades of the record (Chang and Guo 2007; VK08). Therefore, we apply the methodology of VK08, which allows for a quantitative estimate of the number of missed TCs that have occurred over the Atlantic, using only the satellite-era storms of duration larger than 2 days to estimate missing storm rates (Fig. 4). Two to three missed moderate to long-lived TCs are estimated for the 1880s, dropping to one to two per year in the 1900s, and down to less than one per year in the 1950s. Of note are the spikes of missed TCs in the 1910s and 1940s, corresponding to reduced ship observations available in ICOADS during World War I and World War II (Worley et al. 2005). Figure 4 also indicates that the estimated number of missed moderate to long-lived TCs is reduced, by a small amount, compared with the total frequency of missed TCs of any duration estimated in VK08. This reduction in missing storms occurs in our new analysis because the very short-lived storms from the satellite era are no longer included in the sample of storm tracks that are tested for "encounters" with the historical ship tracks, so they cannot contribute to the missing storm estimate.

This estimated series of missed medium- to long-lived TCs is added to the HURDAT time series of moderate to long-lived TCs to obtain the adjusted time series (Fig. 5). This series shows no significant (at $p = 0.05$) linear trend nor MPWS when calculated from either 1878 or 1900 onward (see Tables 1 and 2). The notion of no strong upward trend in Atlantic basin tropical storms is consistent also with the slight negative trends in U.S. landfalling tropical storm and hurricane counts since the late 1800s (e.g., VK08). Analyses presented in the online supplement and condensed in Fig. 6 demonstrate that there has been an upward trend in very short-lived TCs during the twentieth century for durations of up to about 3 days with longer-lived TCs showing no significant trend. After inclusion of the estimated number of missed TCs, there remains no significant trend in the medium- to long-lived TCs once the duration threshold for retaining TCs reaches 1 day. Thus the conclusions obtained from our statistical significance tests are quite robust regarding the choice of duration threshold.

3. Summary and discussion

The main findings from this paper include the following:

1) It was shown—for the first time—that there exists a large trend in the reported frequency of very short-lived Atlantic TCs, from less than one per year in the

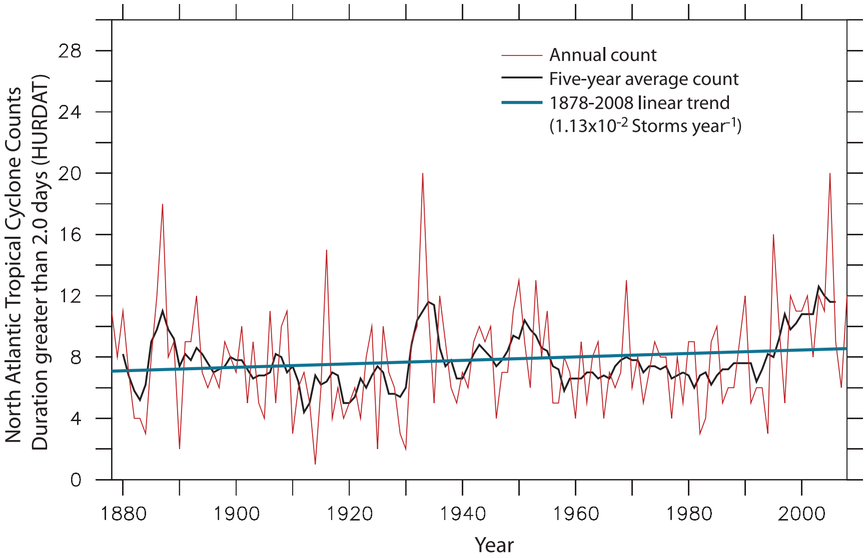

FIG. 3. As in Fig. 1, but for medium- to long-lived Atlantic tropical cyclones.

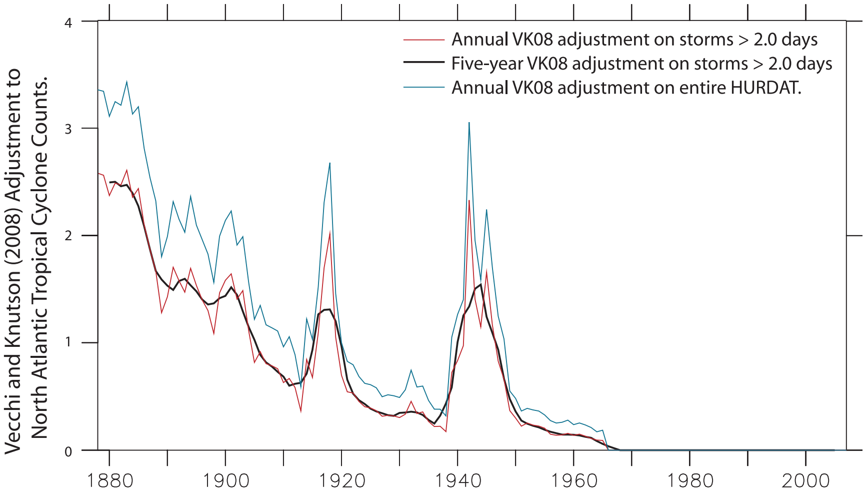

FIG. 4. Estimated frequency (red) of missed tropical cyclones of medium–long duration (>2 days). The black curve is a 5-yr centered mean. The blue curve is the estimated frequency of missed tropical cyclones of any duration. Missed storms were estimated using the methodology of VK08.

late 1800s and early 1900s to about five per year in the first few years of the twenty-first century.

2) Removal of the very short-lived TCs from the full TC frequency record results in a time series of medium- to long-lived TCs that shows a substantially reduced—but still increasing—trend from the late 1800s to the early 2000s. Linear trends from 1878 to 2008 indicate a strongly significant increase from about 7 TCs per year in 1878 to about 12 per year in 2008 for the full TC dataset, but an insignificant increase from 7 to 8 TCs per year for the medium- and long-lived TCs.

3) Application of the VK08 sampling methodology allows us to estimate the number of missed TCs, specifically of medium- and long-lived duration, because of limited reporting ship traffic in the presatellite era. This method suggests that about two TCs of medium to long duration were uncounted in the late 1800s, about one per year the first few decades of the twentieth century (with spikes during World Wars I and II), and less than one per year in the 1950s.

4) Examination of the adjusted time series of medium- to long-lived TCs with our estimated number of missed

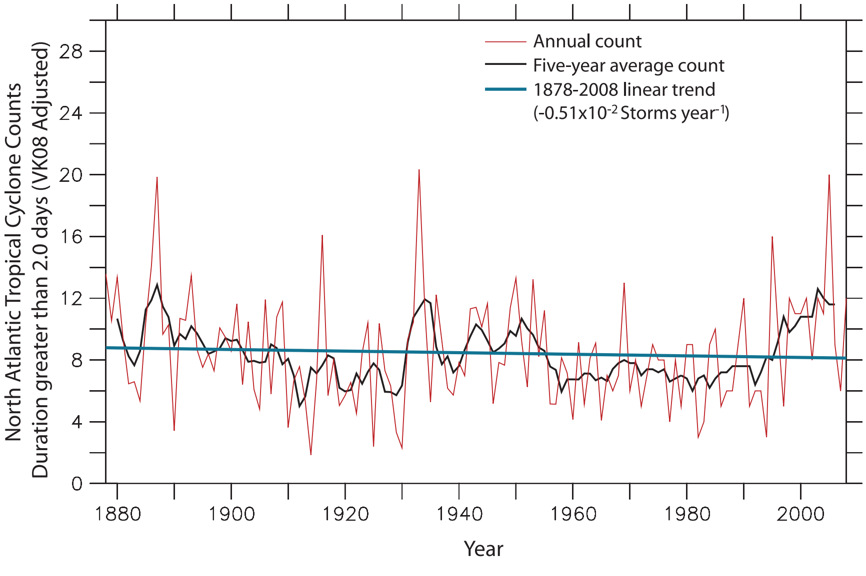

FIG. 5. Adjusted frequency (red) of Atlantic medium- to long-lived tropical cyclones from 1878 to 2008. The black curve is a 5-yr centered mean and the blue line is the 1878–2008 trend.

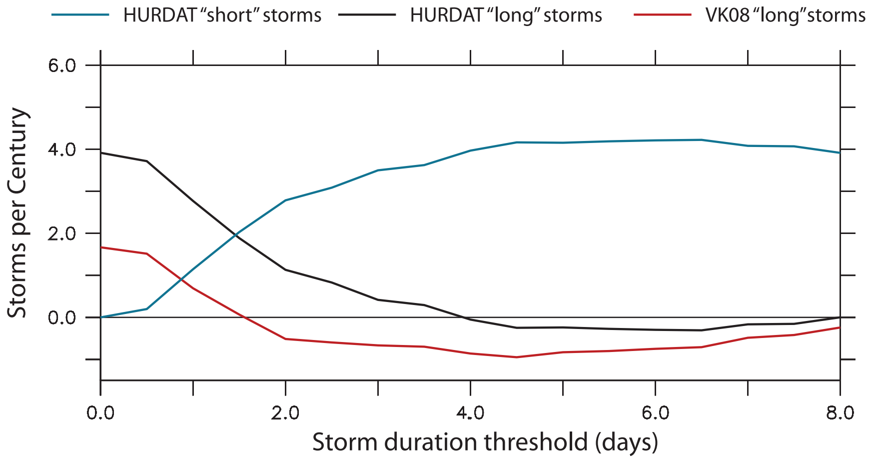

FIG. 6. Comparison of long-term trends as a function of various thresholds of tropical cyclone duration for the period of 1878–2008. Blue indicates trend values for frequency of short-lived tropical cyclones of various durations. Black indicates trend values for frequency of long-lived tropical cyclones. Red indicates trend values for frequency of long-lived tropical cyclones after adjusting for estimated number of missed tropical cyclones using methodology of VK08. For example, at a threshold of 3 days, the trend for the short-lived TCs (≤3 days) is +3.5 storms, the trend for long-lived TCs (>3 days) is +0.5 storms, and the trend for long-lived TCs after adjusting for estimated number of missed TCs is −0.5 storms. Note that at the threshold of 0 days, all TCs are by definition long lived and the short-lived TC trend is 0 (all TCs at that threshold are long lived).

TCs included indicates that no significant trend remains using either an 1878 or a 1900 starting point.

According to our analysis, the increasing trend in total Atlantic TCs since the late nineteenth and early twentieth centuries as documented previously by Mann and Emanuel (2006) and Holland and Webster (2007) can be redescribed as primarily due to a trend in very short-lived TCs, even before the inclusion of likely unsampled TCs (Tables 1, 2). Thus, the dramatic increase in very short-lived TC frequency in the database bears an explanation.

We are unaware of a natural climate variability or anthropogenic climate change signal that should impact only very short-lived TCs, but should one be found, this would be an explanation for the results shown here. An alternative explanation is that the increase in short-duration storms in HURDAT is an artifact of changing observing practices. Given the documented deficiencies in the historical record, it is entirely plausible that some of the increase in very short-lived TCs could have resulted from changes in observational systems and/or analysis techniques.[6] Several recent, very short-lived systems present anecdotal evidence in support of the idea that some TCs now being included into the Atlantic hurricane database may not have been counted previously. Their inclusion is in part due to enhanced technology (such as QuikSCAT) to newly observe tropical storm–force winds as well as new analysis techniques (such as the Cyclone Phase Space diagrams) to better distinguish very short-lived TCs from very short-lived baroclinic systems.

For example, Fig. 7 depicts very short-lived, weak (averaging only 20.6 m s^{-1} maximum intensity) systems in the last two seasons that we believe likely would not have been considered TCs previously (along with the specific new technology that facilitated their naming and inclusion in HURDAT): Andrea (2007; global positioning system dropwindsondes; Hock and Franklin 1999), Chantal (2007; QuikSCAT), Jerry (2007; QuikSCAT, Advanced Microwave Sounding Unit, and the Cyclone Phase Space), Melissa (2007; Advanced Dvorak; Olander and Velden 2007), Arthur (2008; new moored buoy measurements, installed May 2005), and Nana [2008; Advanced Scatterometer (ASCAT); Verhoef and Stoffelen 2009]. It is not disputed that these systems were indeed TCs and deserved to be included in HURDAT. On the contrary, the National Hurricane Center's (NHC's) increased ability to monitor even weak, very short-lived TCs means a better service to mariners in providing warnings of gale-force winds and high seas. The inclusions of systems like these may be partially responsible for the apparent jump in the frequency of short-lived TCs that may

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[6] These issues are also mirrored by those examining trends in tornado frequency (Brooks and Dotzek 2008), who have also seen a large jump primarily in weak tornadoes because of more enhanced observational networks including the Weather Surveillance Radar-1988 Doppler.

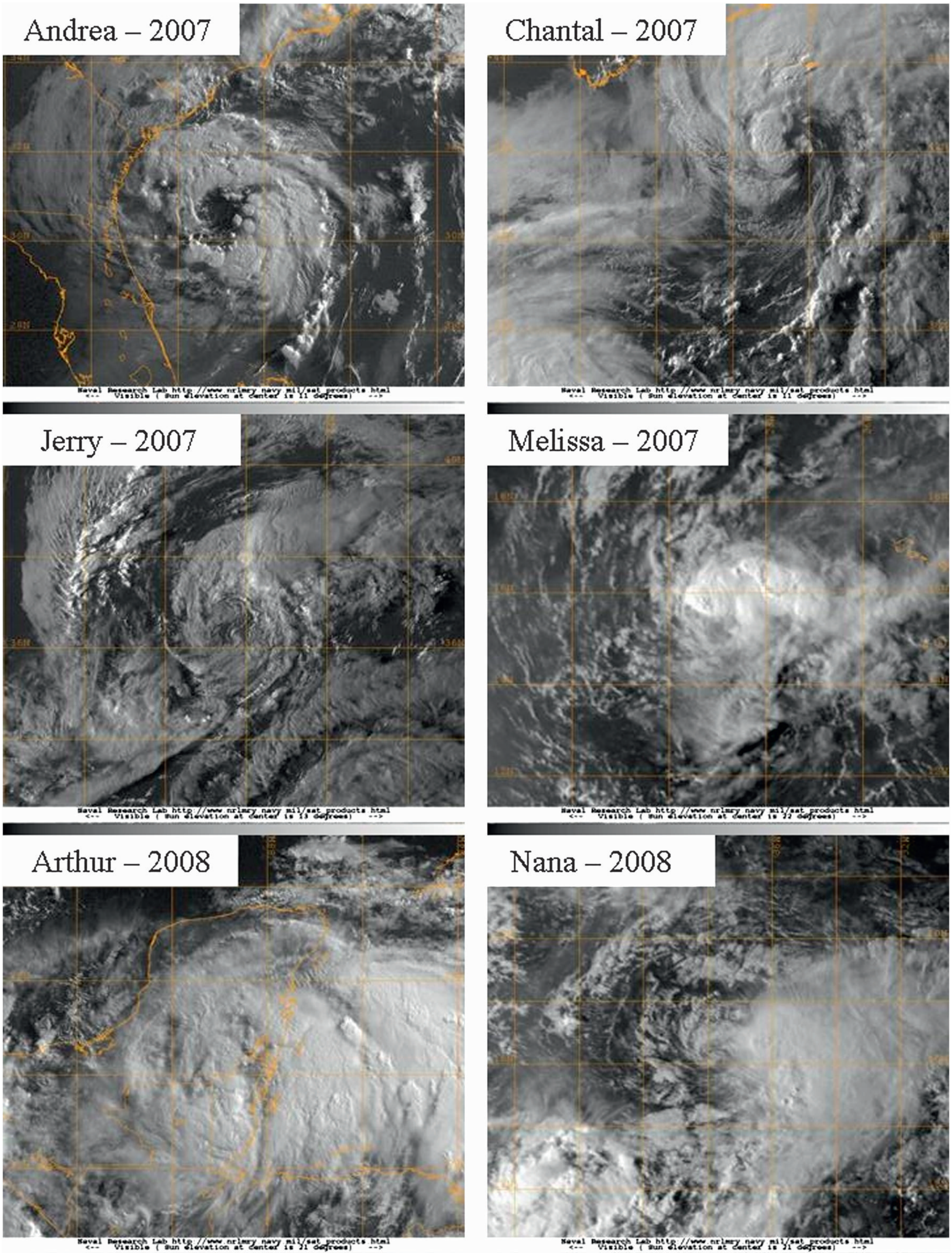

FIG. 7. Six very short-lived, weak (average maximum intensity of 20.6 m s^{-1}) Atlantic basin tropical cyclones during 2007 and 2008 that were named (and included in HURDAT) likely because of newly available technology and analysis techniques. The visible imagery (courtesy of the Naval Research Laboratory) shows each cyclone at the time closest to their maximum intensity as tropical cyclones.

have occurred around 2000 (as shown in section 2a). Given the temporal character of the increases in the number of very short-lived TCs seen in Fig. 2 and their highly suggestive temporal relation with known technological improvements, we argue that the large increases in their frequency are most likely not depicting true climate changes.[7] Examination of the maximum intensities in HURDAT from 1878 to 2008 indicates that the very short-lived systems reached an average of just 25.4 m s^{-1} (tropical storm intensity), while the longer-lived TCs achieved an average of 40.2 m s^{-1} (upper-end category 1 hurricane intensity). This indicates that the increase in short-lived TCs has preferentially been through weaker TCs and that the TC frequency and intensity variability issues are not independent of one another.

Whatever the cause for the sizable increase in very short-lived TC numbers, the trends in very short-lived TCs and moderate- to long-duration TCs are clearly substantially different in HURDAT. A possible contributor to the difference between short- or medium- and long-lived storm trends is that some storms in the early part of the record might have been classified as medium- to long-lived storms even though they were actually short lived. Such misclassification could have occurred because of observational limitations (e.g., intermittent periods during which a storm was not a true tropical storm but was not being adequately observed at the time, or a case where two separate systems might have been mistakenly identified as a single long-lived system in HURDAT). These errors could also partially account for the apparent increased frequency of short-lived TCs in HURDAT in recent years. If so, an adjustment for these errors would decrease the trend in short-lived storms and increase the trend in medium- to long-lived storms, making the trends more similar between duration classes. Using our estimate for possible missing storms, we find no significant century-scale increases in the numbers of medium- to long-lived TCs (as measured either by a linear trend or by a median of pairwise slopes). As discussed by VK08 and in this paper, there are a number of remaining sources of error in our estimate of missing TCs, some of which would increase and some that would decrease long-term trend estimates. In our judgment, it is likely that our storm count adjustment is somewhat conservative overall, in that most of the assumptions utilized—a particularly important one being that all of the TCs to be found in ICOADS are already in HURDAT—would lead to even more missing TCs being estimated in the earlier decades and would act to further reinforce the lack of upward trends. Global warming simulations from high-resolution global climate models and techniques that downscale coarser models to the regional scale are consistent with the findings of no increasing trend in the adjusted TC frequency records.

In addition to the influence on historical estimates of secular TC frequency change, there exists a very large sensitivity in TC frequency from coupled climate models to the duration threshold utilized to count a vortex seen in the simulation as a TC. In a recent study of global climate model simulations of the current climate and an enhanced greenhouse gases climate state (Bengtsson et al. 2007), various minimum thresholds for the parameters of intensity (in their study, this was quantified by lower-tropospheric vorticity), baroclinicity (i.e., lower-minus upper-tropospheric vorticity), and duration of existence were explored to count a vortex as a TC. Bengtsson et al. (2007) found for example in their T213 experiment, that by tightening the criterion of vorticity—in doubling what was required—that the number of vortices counted as TCs was globally reduced from 105 to 62. Thus, in a global climate model, there is a large dependence of the TC counts on the intensity threshold chosen.

The sensitivity of various minimum duration thresholds from their T213 experiments was not elaborated upon in Bengtsson et al. (2007). Further analyses from these runs shows that relaxing the duration threshold from 24 to 12 h leads to a 68% increase in frequency globally for the late twentieth-century climate (102 per year up to 171 per year) and tightening the duration threshold from 24 to 48 h leads to a 39% decrease in frequency (102 down to 62). In contrast, for a given duration threshold the change in frequency between the late twentieth and late twenty-first century (with substantial greenhouse gas warming) displays only a 5%–10% decrease in frequency in the latter time period. These modeling results lead us to speculate that TC counts in the real world are more sensitive to changes in observational monitoring ability for very short-lived TCs than to the influence of global warming. At the very least, comparisons between model and observed TC counts are influenced by the duration threshold chosen for the model TC definition, and efforts should be made to adopt consistent criteria.

In contrast to TC frequency findings reported here, several recent relatively high-resolution modeling studies suggest that the strongest TCs will become more numerous, despite some of them exhibiting reduced overall frequency

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[7] The rather large increase in short-lived TCs in the last decade may be influencing the climatological average number of TCs in the Atlantic basin. Blake et al. (2007) utilized the years from 1966 to the present to best represent the climatology of about 11 TCs per year, as this corresponds with the period of geostationary satellite surveillance. With the jump in the twenty-first century of the frequency of short-lived TCs, a more realistic estimate of the long-term climatology may be closer to 13 TCs per year.

of TCs—owing to increased intensities of the strongest storms (e.g., Knutson and Tuleya 2004; Bengtsson et al. 2007; Emanuel et al. 2008; Knutson et al. 2008). Given that TCs can be considered to be Carnot heat engines to a first approximation (Emanuel 1987), TC intensity theory suggests that increasing sea surface temperatures and boundary layer moisture due to anthropogenic climate change could increase the potential intensity of TCs. Elsner et al. (2008) report that over the period 1981–2006 the intensities of the strongest TCs increased globally, though the signal they identified was most robust in the Atlantic basin, where multidecadal variability in TC activity appears rather large and probably dominates trend calculations performed on relatively short time scales (e.g., since the 1980s). The issue of the temporal behavior of more intense TCs, such as major hurricanes, has not been addressed in this report. Since our ability to observe the maximum intensities of TCs has changed substantially over time, we anticipate severe difficulties in constructing reliable century-long records of these phenomena directly.

With impacts documented here and elsewhere of how limited ship-based observational sampling (and possibly increased technology) dramatically affects TC frequency over time, other aspects of TCs may likewise have observational biases within HURDAT. In particular, frequency of hurricanes and major hurricanes, duration of TCs, length of season, peak intensity, and integrated TC measures [like Accumulated Cyclone Energy (ACE) and Power Dissipation Index (PDI)] should not be used directly from HURDAT for climate variability and change studies without consideration of, or quantitatively accounting for, how observational network alterations are affecting these statistics. In general, the subsampling of TCs back in time will artificially introduce increases in all of these parameters with time. In some cases, progress is being made (e.g., Elsner et al. 2008) at constructing more homogeneous satellite-based records to address these issues, at least for the period since 1981. The currently available twenty-first-century projections of higher-intensity TCs suggest that it would be advisable to increase efforts to reconstruct past time series (historical or prehistoric) of intense TC occurrence both in the Atlantic and the remaining global TC basins and to better monitor cyclone intensity and size in coming years, for example, with a next-generation QuikSCAT satellite, improved sensors on manned reconnaissance, and unmanned aerial systems.

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