Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878–1965) Using Ship Track Density

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ABSTRACT

This study assesses the impact of imperfect sampling in the presatellite era (between 1878 and 1965) on North Atlantic hurricane activity measures and on the long-term trends in those measures. The results indicate that a substantial upward adjustment of hurricane counts may be needed prior to 1965 to account for likely ''missed'' hurricanes due to sparse density of reporting ship traffic. After adjusting for the estimate of missed hurricanes in the basin, the long-term (1878–2008) trend in hurricane counts changes from significantly positive to no significant change (with a nominally negative trend). The adjusted hurricane count record is more strongly connected to the difference between main development region (MDR) sea surface temperature (SST) and tropical-mean SST than with MDR SST. These results do not support the hypothesis that the warming of the tropical North Atlantic due to anthropogenic greenhouse gas emissions has caused Atlantic hurricane frequency to increase.

1. Introduction

The response of North Atlantic tropical cyclones (TCs, including tropical storms and hurricanes) to changing climate conditions is an area of active scientific inquiry. A variety of methods have been brought to bear on assessing the character of and causes behind past changes in North Atlantic tropical cyclone frequency (see Knutson et al. 2010; Solow and Moore 2002; Mann and Emanuel 2006; Chang and Guo 2007; Landsea 2007; Mann et al. 2007; Holland and Webster 2007; Vecchi and Knutson 2008, hereafter VK08; Landsea et al. 2010; Villarini et al. 2010), as well as in projecting its future evolution (Knutson et al. 2010 and references therein). Essential to this pursuit is a reliable data record of past hurricane activity, along with a quantitative assessment of its uncertainty. Methods have been developed to homogenize the historical record of tropical storms since the late nineteenth century by either assuming the stationarity of statistical relationships between basinwide tropical storm frequency and other measures (e.g., Landsea 2007; Mann et al. 2007), by modeling the impact of changes in the observations (e.g., Chang and Guo 2007; VK08), or a blended approach (e.g., Landsea et al. 2010). Here we present an analysis of 1878–2008 Atlantic hurricane (tropical cyclones whose peak winds exceed 33 m s^{-1}) records from a widely used TC database, along with an estimate of the number of hurricanes that we infer may have been missed in the presatellite era (1878–1965), based on our analysis of storm tracks and reporting ship track coverage.

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2. Data and methods

a. Observational datasets

The historical TC track data we use is the National Hurricane Center (NHC) Atlantic basin hurricane database (HURDAT) ''best track'' dataset; data were downloaded on 30 March 2009. Data are archived every 6 h (at 0000, 0600, 1200, and 1800 UTC) and include reports of storm position and maximum winds from 1851 to 2008 (Jarvinen et al. 1984; Landsea et al. 2004, 2008). We consider storms with either a tropical or subtropical designation and limit our analysis to periods over which storms had reported hurricane strength winds (maximum winds at a height of 10 m > 33 m s^{-1}) while designated as a tropical system.

We use ship observation positions and dates from the International Comprehensive Ocean–Atmosphere Data Set (ICOADS) version 2.3.2a (Worley et al. 2005). To define coastlines we use the Smith and Sandwell 2-min topography dataset (available at http://www.ngdc.noaa.gov/mgg/global/etopo2.html). As in VK08, we assume that all ships and land points to be perfect measurement platforms, and that ships do not alter their course in response to the presence of a hurricane (at least until they reach and measure winds of at least 33 m s^{-1}).

We use two historical SST reconstructions: the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version 1.1 (HadISST1.1) (Rayner et al. 2003) and the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstruction SST version 3 (ERSST3(Smith et al. 2008). Although each product shows a clear tropical warming since the 1880s, there are differences in the spatial structure of these changes (such as long-term trends) in the tropical Atlantic, Pacific, and Indian Oceans (e.g., Vecchi and Soden 2007a). Until the SST discrepancies are resolved, we believe it is prudent to explore multiple datasets.

b. *Hurricane activity measures*

We explore three different, but related, basinwide measures of Atlantic hurricane activity: ''annual hurricane count'' N_{HU} is the number of systems each year that reach 33 m s^{-1} or higher; ''annual hurricane days'' is the sum over all hurricanes present in a year of the total days each system's maximum winds reached at least 33 m s^{-1}; and ''average hurricane duration'' d is the average number of days each hurricane has maximum winds exceeding 33 m s^{-1} D/N_{HU}. In addition to these basinwide measures, we explore the spatial structure of hurricane activity, defined on a 5° × 5° longitude–latitude grid as the total number of days (using 6-h intervals) for which there is a hurricane record inside each grid cell.

c. *Hurricane activity correction scheme*

To estimate the number of hurricanes that are ''missing'' from the presatellite (pre-1966) HURDAT, we adapt the methodology of VK08 to TCs of hurricane intensity (winds $>$ 33 m s^{-1}) from its original application to TCs of tropical storm intensity or greater (winds $>$ 17 m s^{-1}). The VK08 method assesses the probability that a given storm from the satellite era would have gone undetected in a presatellite year based on its proximity to land or to weather-reporting ship traffic. The reader is referred to VK08 for a complete description of the method, along with a discussion of key uncertainties.

The adaptation of the VK08 methodology to storms of hurricane intensity is done by adopting a stochastic model for the storm detection radius (radius of 33 m s^{-1} winds, or R33) for each satellite-era hurricane based on the statistics of Kimball and Mulekar (2004). Since the R33 statistics reported in Kimball and Mulekar (2004) are the maximum radii and not the mean radii, we build the model on 0.85 × R33, as was done for the radius of 17 m s^{-1} winds (R17) in VK08 to account for the differences between the mean and maximum radius. In our scheme, for a hurricane to be ''detectable'' by the presatellite observing system, the best-track position must have passed within 0.85 × R33 of land once, or within 0.85 × R17 of an ICOADS ship report on two 6-h intervals (including once within 0.85 × R33). As in VK08, in the storm detection algorithm we excluded storm 6-h records that were labeled ''extratropical'' and detection had to occur equatorward of 40°. In other words, the hurricane needed to either strike land with hurricane-force winds or have two separate encounters with ship traffic within the radius of tropical storm-force winds, with one of those encounters being within the radius of hurricane-force wind speeds.

As in VK08, we can use our estimate of missed hurricanes to adjust other annually aggregated statistics of hurricane activity. We weigh the value of the statistic to be aggregated (e.g., total storm days, or storm density) by the probability a storm was missed in a particular year (p_m), and the probability-weighted value of the statistic averaged over the satellite-era years is then added to the value computed from the unadjusted data.

3. Results

a. *Basinwide hurricane activity*

The hurricane counts in HURDAT (Fig. 1a) exhibit substantial interannual and interdecadal variability, and show a prominent and statistically significant increase between 1878 and 2008 (Table 1). We use linear least squares trends and medians of pairwise slopes (MPWS; Lanzante 1996) as our measures of centennial-scale changes in Atlantic hurricane activity. On multidecadal time scales, the HURDAT time series exhibits two minima [~(1900s–1940s) and ~(1970s–80s)] and three maxima [~(1880s–1900s), ~(1950s–60s), and mid-1990s–present]. In HURDAT the year with the most hurricanes in the Atlantic is 2005, with 15, and 4 of the top 5 yr occur after 1945.

Our mean estimated number of ''missed'' hurricanes in the Atlantic (dashed line Fig. 1b) has a maximum in the beginning of the record of about three storms per year, decreasing to about half a storm per year before the satellite era. Two local peaks are evident during the two World Wars. At first glance it may seem puzzling that this adjustment to hurricane counts is not noticeably smaller in magnitude than the adjustment to tropical storm counts reported in VK08, since hurricanes are a subset of all tropical storms. However, this adjustment is an estimate of hurricanes for which hurricane strength

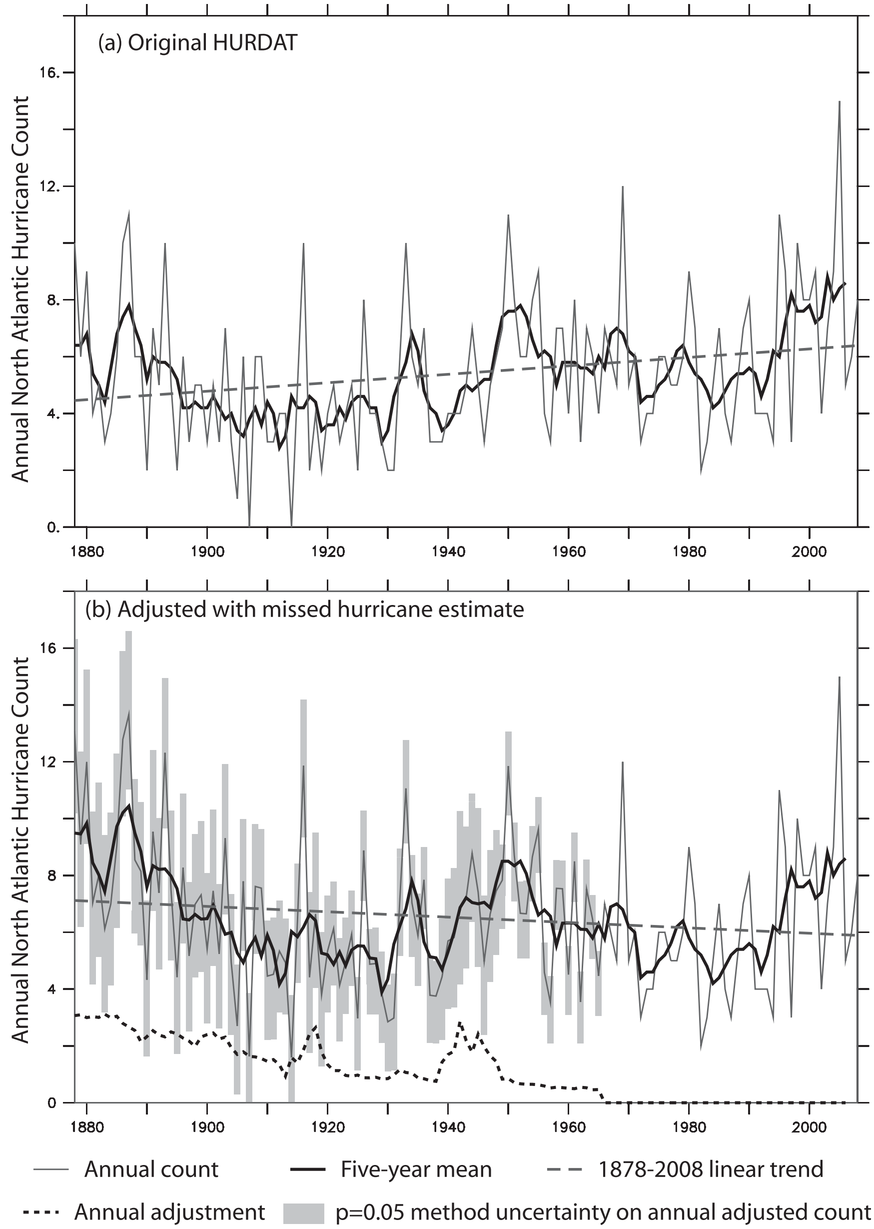

FIG. 1. Time series of Atlantic basin hurricane counts over the period 1878–2008 from (a) the unadjusted HURDAT and (b) after the adjustment for estimated missed hurricanes and the magnitude of the hurricane count adjustment. Plots show the annual (light lines) and 10-yr running mean (dark lines) counts; (b) gray shading indicates the 95% method uncertainty on the adjustment. Dashed lines depict the linear least squares trends computed over the period 1878–2008.

winds would not have been detectable given the historical observing system, while the detection criterion of VK08 was for gale-force winds. That is, comparison of this adjustment and that of VK08 suggests that some of the missed hurricanes may have not been missed altogether, but rather were hurricanes that were misidentified as tropical storms.

The character of the interannual and multidecadal variability is largely unaltered by our hurricane count adjustment (Fig. 1b). However, the mid-twentieth century active period seems to extend from the 1940s to the 1960s in the adjusted data. After the adjustment, we cannot exclude the possibility that the most active decades in historical Atlantic-wide hurricane count occurred in the

TABLE 1. Measures of 1878–2008 secular change in hurricane activity for a series of activity metrics. The first column indicates the metric considered, with its units in parentheses. Secular change is explored for each metric (except landfalling frequency) based on the raw HURDAT data and based on the HURDAT data adjusted based on the possibility of undercount, as indicated in the second column. The third column indicates the long-term (1878–2008) mean of each quantity. The fourth and fifth columns indicate the 1878–2008 linear least squares trend and two-sided p value, respectively. The sixth and seventh columns indicate the 1878–2008 MPWS (Lanzante 1996) and two-sided p value, respectively. Secular change metrics (trend and MPWS) that are statistically significant at the $p = 0.05$ level are in bold.

	Dataset	Mean	Linear trend (century^{-1})	Trend p value	MPWS (century^{-1})	MPWS p value
No. basinwide hurricanes	HURDAT	5.45	**1.42**	**0.021**	**1.37**	**0.0092**
	Adjusted HURDAT	6.54	−1.01	0.18	−0.86	0.19
No. U.S. landfalling hurricanes (#)	HURDAT	1.84	−0.52	0.17	−0.36	0.21
No. U.S. landfalling as fraction of basinwide	HURDAT	0.34	**−0.15**	**0.0033**	**−0.15**	**0.0039**
	Adjusted HURDAT	0.28	−0.024	0.56	−0.0035	0.52
Average hurricane duration (days)	HURDAT	3.98	−0.78	0.063	−0.68	0.076
	Adjusted HURDAT	3.77	−0.34	0.28	−0.26	0.37
Basinwide hurricane days	HURDAT	22.78	1.65	0.54	1.36	0.48
	Adjusted HURDAT	25.82	−5.78	0.14	−4.85	0.19
East Atlantic hurricane days	HURDAT	14.23	**5.37**	**0.0096**	**4.08**	**0.001**
	Adjusted HURDAT	14.92	−0.42	0.72	−0.35	0.84
West Atlantic hurricane days	HURDAT	8.56	−3.73	0.18	−3.15	0.18
	Adjusted HURDAT	10.91	**−5.37**	**0.032**	−4.66	−0.055

late-nineteenth century, not in the late twentieth century. Further, we cannot exclude the possibility (at $p = 0.05$) that as many or more Atlantic hurricanes occurred in 1878, 1880, 1886, or 1887 as in 2005. The long-term change in adjusted hurricane counts is not significantly different from zero at $p = 0.05$ (Table 1); however, the 1878–2008 trend of the adjusted hurricane count time series is significantly different from that from the unadjusted HURDAT series at $p < 0.05$.

U.S. landfalling hurricanes (i.e., tropical cyclones making landfall along the East Coast or the Gulf of Mexico at hurricane intensity) show no significant trend or change in MPWS during the period 1878–2008 (Table 1, third row). This statistical finding is significantly different from the significant increase in Atlantic-wide hurricane counts in the original HURDAT, but it is similar to that of our adjusted hurricane counts. This can also be seen by exploring metrics of long-term change in the fraction of basinwide hurricanes making U.S. landfall, which show a significant decrease in HURDAT but essentially no change in the adjusted data (Table 1). Though U.S. landfalling storms need not be a proxy for basinwide tropical storms or hurricane activity (e.g., Holland 2008), recent decades have been characterized by a relatively stationary fraction of basinwide storms making landfall (e.g., Landsea 2007; Coughlin et al. 2009). Our hurricane count adjustment suggests the fraction of basinwide hurricanes making U.S. landfall may not have exhibited a secular change since 1878.

In the HURDAT record, the average duration of hurricanes has exhibited a decrease since 1878 (Fig. 2a), which is significant using both the MPWS and linear trend statistics at the $p = 0.1$ level but not at $p = 0.05$ (Table 1). In VK08 a similar decrease in tropical storm duration was described (even after the VK08 adjustment was applied), which was shown in Landsea et al. (2010) to have been driven by a strong increase in the number of TCs of short duration (<2 days), which was interpreted as likely arising from changes in observing capabilities. With hurricane duration, applying the missing storm adjustment leads to an average duration time series that has no significant change. Since the hurricane duration decrease after adjustment is not significant, it does not—on its own—argue for a further refinement of the adjustment analogous to that of Landsea et al. (2010). However, this should not be used to conclude that further refinements to our adjustment are not necessary.

Motivated by the results of Landsea et al. (2010), and because hurricanes of extremely short duration (6 h) exist in recent years [e.g., Hurricane Cindy of 2005 (Stewart 2005; Beven et al. 2008) and Hurricane Ernesto of 2006 (Knabb and Mainelli 2006; Franklin and Brown 2008)], we briefly explore the impact of extremely short-duration hurricanes on the record of hurricane counts in the Atlantic. Figure 3 shows the sensitivity of the 1878–2008 trend in Atlantic hurricane counts to setting duration thresholds based on the number of hurricane strength records during the lifetime of the cyclone; it is equivalent to Fig. 6 of Landsea et al. (2010), which focuses on tropical storm records. For unadjusted HURDAT, the amplitude and significance of the trend in hurricane counts is influenced by short-duration hurricanes. Although excluding hurricanes with a single 6-h report of hurricane strength winds does not affect the significance

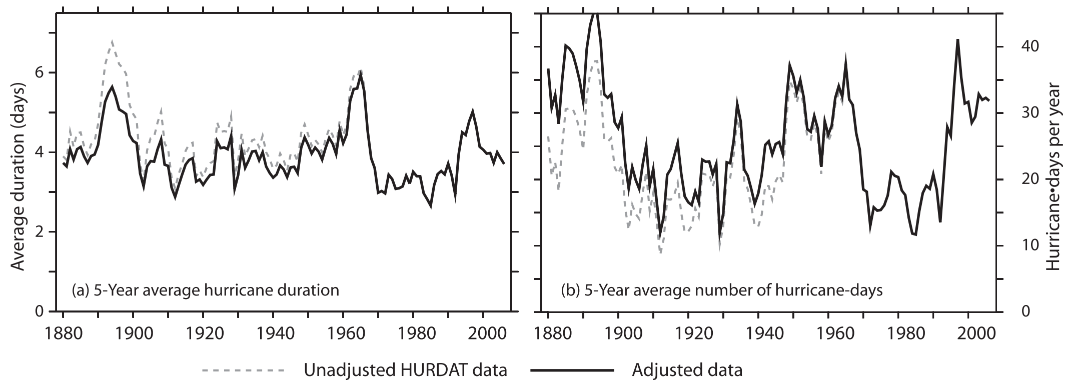

FIG. 2. Time series of 5-yr centered average (a) hurricane duration and (b) basinwide hurricane days per year based on the raw HURDAT data (dashed gray lines) and after adjusting presatellite records based on the estimated missed hurricanes (black lines). Units are (a) days per storm and (b) hurricane days per year.

of the 1878–2008 increase in hurricanes, removing those lasting 12 h or longer leads to the trend no longer being statistically significant at $p = 0.05$ (neither for MPWS or trend calculations), but significant at $p = 0.1$. For the unadjusted HURDAT for the period 1878–2008, neither the trend nor the MPWS of hurricanes lasting longer than 24 h is statistically significant even at $p = 0.1$. For the adjusted time series, there is very little influence of hurricane duration on the trend as a fraction of total hurricanes; the slight decrease in the magnitude of the negative-adjusted trend with increasing duration largely reflects a decrease in the total number of hurricanes with duration. For the unadjusted data, these results are comparable to those of Landsea et al. (2010), where very short-duration tropical storms (storms lasting 2 days or fewer) were the dominant contributor to the significant increase in unadjusted HURDAT; however, and in contrast to Landsea et al. (2010), the inclusion of short-duration hurricanes does not impact the adjusted tropical storm time series.

Basinwide hurricane days (Fig. 2b) show no significant long-term change in the HURDAT (arising from the decrease in mean duration and increase in storm counts) nor in our adjusted dataset. Neither of the measures of 1878–2008 secular change (MPWS and linear least squares trend) indicates a statistically significant change for either the HURDAT or adjusted databases in basinwide hurricane days.

b. *Spatial changes in hurricane activity*

The 1878–2008 secular changes in Atlantic hurricane activity (D) in both the raw (unadjusted) HURDAT and adjusted datasets show spatial heterogeneity (Figs. 4a,b). Both the raw HURDAT and the adjusted hurricane data show a tendency for reduced activity in the western Atlantic Ocean. Meanwhile, hurricane days in HURDAT exhibit a significant increase in the eastern Atlantic, while the adjusted database shows no significant change. On interannual and multidecadal time scales, west Atlantic hurricane activity is little affected by the inclusion of the storm count adjustment (Fig. 4c), while the most active east Atlantic year becomes 1893 (instead of 1995) and the most active decades occur at the end of the nineteenth century (instead of the end of the twentieth century) after the inclusion of our storm count adjustment (Fig. 4d). The long-term decrease in hurricane activity west of 62.5°W is not statistically significant ($p = 0.05$) in the original dataset, but it is marginally significant for the adjusted dataset (Table 1). Meanwhile, the strongly significant increase in east Atlantic activity since 1878 in HURDAT becomes a nonsignificant change after the adjustment.

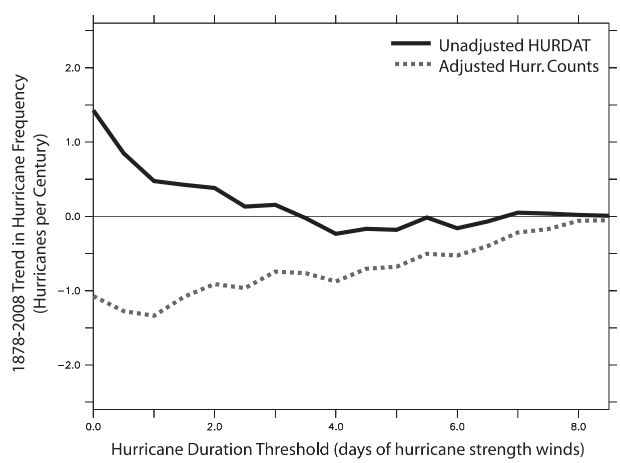

FIG. 3. Trends in North Atlantic basinwide hurricane frequency as a function of threshold duration of hurricane strength winds for raw HURDAT data (black line) and for the adjusted count data (gray dashed line). The threshold represents the number of days a storm had to have recorded winds ≥33 m s^{-1}; the threshold is used for selecting the total number of storms in HURDAT for the entire record as well as the satellite-era storms that were used to compute the adjustment.

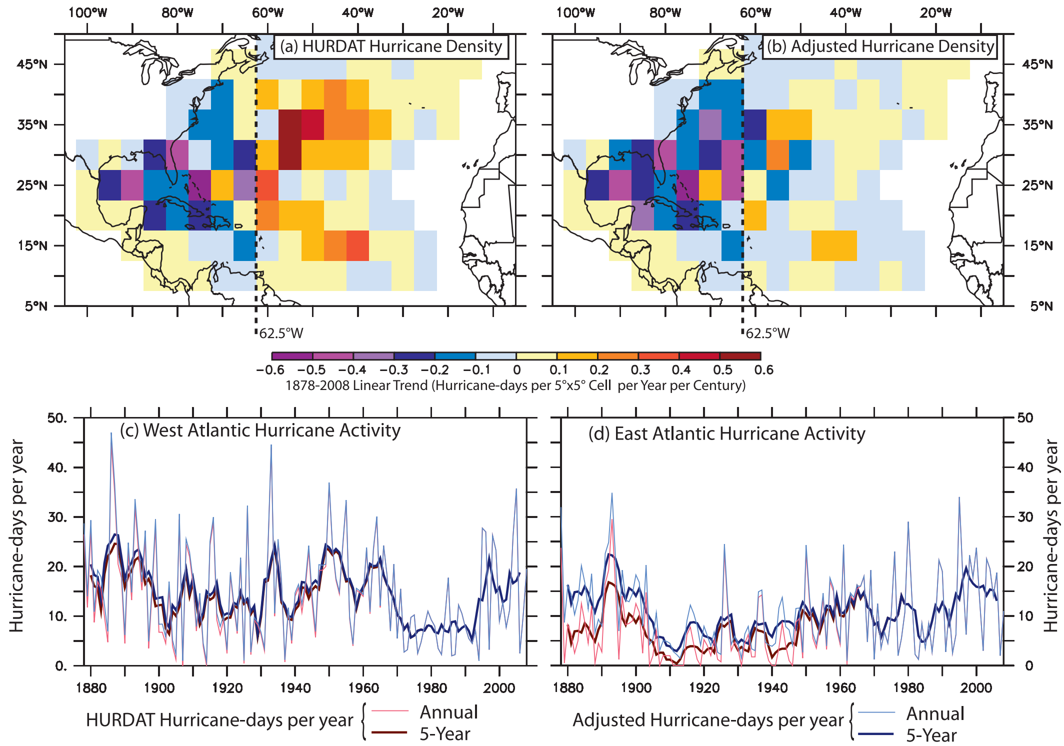

FIG. 4. Maps of linear-least-squares trend in hurricane density (density of positions where HURDAT winds > 33 m s^{-1}) during 1878–2008. (a) Computed from the unadjusted HURDAT; (b) computed after adjusting the presatellite records based on the estimated missed hurricanes. A 5-yr centered mean time series of hurricane days in the (c) Atlantic east of 62.5°W and (d) Atlantic west of 62.5°W; red lines are computed using the raw HURDAT data, and blue lines are computed after adjusting presatellite records based on the estimated missed hurricanes.

The rough pattern of changes in the spatial structure of hurricane activity (and the impact of a storm count adjustment on these changes) resembles that described in VK08 for tropical storms.

c. *Relationships between indices*

In this section, we explore relationships between various measures of Atlantic hurricane activity and between those measures and several SST indices. Figure 5 visually summarizes the relationships between global and tropical Atlantic SSTs and a series of tropical storm and hurricane frequency indices (unadjusted and adjusted basinwide and U.S. landfalling). All time series have been smoothed with a 5-yr running mean and then normalized to have unit standard deviation.

The SST indices we examine include SSTs averaged over the Atlantic main development region (MDR, 10°–20°N, 80°–20°W), which we refer to here as "absolute SST," which has been found to exhibit a correlation with measures of basinwide Atlantic tropical cyclone activity (e.g., Mann and Emanuel 2006; Emanuel 2007; Holland and Webster 2007; Mann et al. 2007; Vecchi et al. 2008). In addition, we explore SSTs in the MDR minus the SSTs averaged over the global tropics (30°S–30°N), which we refer to as "relative SST." Relative SST appears to strongly influence large-scale climate conditions that impact hurricane activity (e.g., Latif et al. 2007; Vecchi and Soden 2007a). It also exhibits a statistical connection to measures of Atlantic basinwide tropical cyclone activity (e.g., Swanson 2008; Vecchi et al. 2008; Villarini et al. 2010). Furthermore, it has been found to describe the response of Atlantic hurricane frequency to anthropogenic warming in high-resolution dynamical model experiments (e.g., Knutson et al. 2008; Zhao et al. 2009, 2010; Vecchi et al. 2011).

The multiyear variability of the various storm frequency measures shown in Fig. 5 is similar, yet the century-scale trends differ. The unadjusted basinwide frequency indices (blue) show significant increases, and a relationship to absolute MDR SST (though the period of enhanced frequency in the late nineteenth century is apparently not accompanied by warm Atlantic SSTs). Meanwhile, the various adjusted storm frequency indices (red) do not show significant increases, and their behavior is more similar to the U.S. landfalling counts (yellow) and to relative SST (bottom time series). While neither the absolute nor the relative SST index shows a strong maximum like that in hurricane counts at the end of the nineteenth

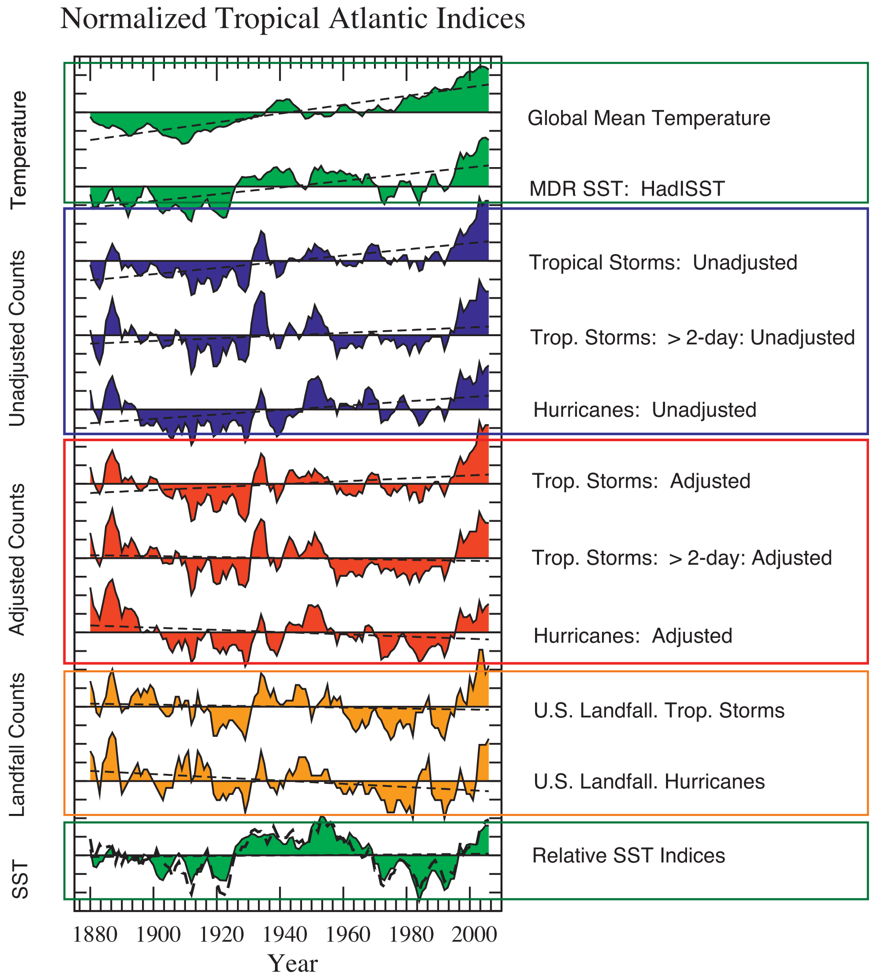

FIG. 5. Indices relevant to Atlantic tropical cyclone activity changes. Filled lines indicate the normalized 5-yr running means, during 1878–2008, with straight dashed lines indicating the linear least squares trends. Green-shaded curves depict global mean temperature [Hadley Centre Climatic Research Unit's land surface air temperature dataset, version 3 (HadCRUT3), August–October. MDR SST anomalies (HadISST; Rayner et al. 2003) and the relative SST (MDR minus tropical mean) from HadISST (Rayner et al. 2003) in solid; ERSSTv3b (Smith et al. 2008) in dashed. Blue-shaded curves represent unadjusted tropical storm and hurricane counts (HURDAT; Jarvinen et al. 1984; Landsea et al. 2008). Red curves include time-dependent adjustments for missing storms based on ship track density (VK08; Landsea et al. 2010) and for the adjusted hurricane count record from this study. Curves labeled >2-day depict storms with duration of at least 2 days (Landsea et al. 2010). Orange curves depict U.S. landfalling tropical storms and hurricanes (no adjustments). Vertical axis ticks represent one standard deviation, with all series normalized to unit standard deviation after a 5-yr running mean was applied. Only the top two temperature series—the unadjusted tropical storms of all duration and the unadjusted hurricane frequency series—have significant linear trends ($p = 0.05$).

century, relative SST anomalies are near 0, while absolute SST anomalies are clearly negative. The discrepancies between the SST indices and the tropical storm–hurricane indices during the 1880s remain unresolved as to whether they reflect problems with SST data, the storm data, or limitations of the statistical approach for this period. Of note, the adjustments to the hurricane counts amount to as much as 50% of the observed unadjusted counts during this period, reflecting the sparseness of ship reports in the ICOADS database over this period. One should explore the influence of applying more rigorous and comprehensive statistical modeling approach (e.g., Villarini et al. 2010) than a simple linear relationship to relative SST.

We can compare the correlations between various sets of 5-yr running mean time series in Figs. 1, 4, and 5. The correlation between U.S. landfalling hurricane frequency and basinwide hurricane frequency is not significant (after adjusting the number of degrees of freedom using the lag-1 autocorrelation of the two time series) for the unadjusted HURDAT data (0.33) but is significant for the adjusted basinwide hurricane data (0.6). The adjusted hurricane counts exhibit a similar correlation with U.S. landfalling hurricanes on interannual and decadal time scales, while the raw hurricane counts exhibit a strong correlation only on interannual time scales (not shown). U.S. landfalling hurricanes are most strongly correlated with overall hurricane activity in the western Atlantic, and they (as might be expected) show little statistical relation to total activity in the eastern part of the basin (Fig. 4).

In computing correlations between hurricane counts and SST indices, we have explored the correlation of 5-yr running SSTs with the logarithm of the 5-yr running hurricane counts (for landfalling storms) and with the 5-yr running mean of the logarithm of the counts (for basinwide activity). U.S. landfalling hurricanes exhibit a stronger correlation with relative SST (0.38 for ERSSTv3b and 0.34 for HadISST1) than with absolute Atlantic MDR SST—with the correlation with absolute SST being essentially 0 (0.01 for ERSSTv3b and 0.05 for HadISSTv1). The raw HURDAT hurricane counts exhibit a stronger significant correlation with absolute SST (0.66 and 0.62 for ERSSTv3b and HadISST1, respectively) than with relative SST (0.46, or still significant, for both SST datasets). Meanwhile, the adjusted hurricane counts exhibit a stronger correlation with relative SST (0.52 and 0.47 for ERSSTv3b and HadISST1, respectively) than with absolute SST (0.31 and 0.28, respectively).

4. Summary and discussion

We have assessed the influence of changes in basinwide hurricane monitoring capability (i.e., weather-reporting ship traffic density) since the late nineteenth century on the long-term changes of several Atlantic hurricane statistics. Although existing records of Atlantic hurricanes show a substantial increase since the late 1800s (Fig. 1a), our analysis suggests that this increase could have been due to increased observational capability. After adjusting for an estimated number of "missed" hurricanes (including hurricanes that likely would have been misclassified as tropical storms), the secular change since the late-nineteenth century in Atlantic hurricane frequency is nominally negative—though not statistically significant (Fig. 1b; Table 1).

Overall, our time-dependent estimate of missed storms results in an adjusted hurricane record that is much more stationary in time, with substantial interannual and decadal variations but little secular trend since the late nineteenth century (Table 1). The significant, or nearly significant, 1878–2008 secular changes in basinwide frequency (increase) average duration (decrease), fraction of storms making landfall (decrease), and storm activity in the eastern tropical Atlantic (increase) seen in the raw database all become nonsignificant after our adjustment. For example, in the raw HURDAT, there is a significant decrease in the fraction of hurricanes making U.S. landfall since the late nineteenth century [as was noted for tropical storms making landfall at all coastal locations, not just the United States by Landsea (2007)]; however, after the hurricane count adjustment, the fraction of hurricanes making U.S. landfall no longer exhibits a significant trend (though substantial interannual and decadal variability remains). Thus, based on known changes in observing capabilities (i.e., onset of satellite coverage in 1966; changes in weather-reporting ship traffic density over time, and so on), we cannot reject the hypothesis that there has been no long-term secular change since 1878 in any of the above-mentioned hurricane activity metrics.

Since the late-nineteenth century, SST datasets show a statistically significant warming of the tropical Atlantic that is very unusual compared to model-generated internal climate variability (Knutson et al. 2006) and has been partially attributed to anthropogenic increases in greenhouse gases (e.g., Santer et al. 2006; Gillett et al. 2008). Although the unadjusted basinwide hurricane count exhibits a strong increasing trend, our analysis indicates that we cannot reject the possibility that the increasing trend was due to changes in our ability to observe and record hurricanes (in fact, the adjusted trend is nominally negative). Thus, because of changes in our observing capability, the hurricane record does not support the notion of a strong sensitivity (positive or negative) of Atlantic hurricane frequency to increasing greenhouse gases, nor does it even unambiguously point to the likely sign of the sensitivity. It is worth noting that dynamical techniques indicate the possibility of either a positive or a negative sensitivity of Atlantic tropical storm or hurricane frequency to increasing greenhouse gases (e.g., Oouchi et al. 2006; Bengtsson et al. 2007; Emanuel et al. 2008; Gualdi et al. 2008; Knutson et al. 2008; Zhao et al. 2009; Bender et al. 2010). However, no existing dynamical studies we are aware of show very large (>200%) positive sensitivity to Intergovernmental Panel on Climate Change (IPCC) twenty-first-century warming scenarios such as A1B (e.g., Vecchi et al. 2008; Knutson et al. 2010).

Both the adjusted and unadjusted basinwide hurricane data indicate the existence of strong interannual and decadal swings. The decadal variations may be a result of internal climate variations (e.g., Goldenberg et al.

2001; Zhang and Delworth 2006, 2009) or of changes in radiative forcing (e.g., Mann and Emanuel 2006), or a combination.

The spatial structure of hurricane activity in the North Atlantic basin has exhibited some secular change in both the HURDAT and adjusted datasets (Fig. 4), with the eastern Atlantic becoming proportionately more active and the western Atlantic less active in terms of hurricane days. In the raw HURDAT, this shift in structure involves a significant increase in eastern Atlantic hurricane days, while in the adjusted data it involves a marginally significant decrease in the western Atlantic. VK08 and Holland (2008) noted a similar pattern in tropical storm activity; VK08 speculated that this change (if not spurious) appeared to be consistent with model projections of the anthropogenic influence on Atlantic tropical storm activity—with overall hurricane activity shifting preferentially toward the eastern part of the basin (Vecchi and Soden 2007b; Knutson et al. 2008; Murakami and Wang 2010). We again raise this possibility and suggest further work should seek to test this hypothesis, though the character and size of possible data problems in the Atlantic hurricane database and uncertainties in future projections of hurricane activity preclude us from drawing firmer conclusions at this stage. Also, the Bender et al. (2010) study does not project such a change pattern for category 4 and 5 hurricanes; we do not explicitly examine these higher-intensity storm categories in the present observational study.

We have explored relationships between various measures of Atlantic hurricane activity and SST indices (Figs. 3, 4; section 3c), examining both absolute SST (in the Atlantic MDR) and a relative SST measure (Atlantic MDR SST relative to the global tropics). For 5-yr running means, the raw HURDAT hurricane counts exhibit a stronger correlation with absolute SST than with relative SST. Meanwhile, the adjusted hurricane counts exhibit a somewhat higher correlation with relative SST than with absolute SST, and also a higher correlation with U.S. landfalling hurricane frequency than does the unadjusted HURDAT data. The relationship between adjusted hurricane counts and relative SST is consistent with the relationship between hurricane frequency and SST in recent dynamical modeling experiments (e.g., Knutson et al. 2008; Zhao et al. 2009, 2010), and with the observed relationship between relative SST and other basinwide Atlantic tropical cyclone activity measures (e.g., Swanson 2008; Vecchi et al. 2008; Villarini et al. 2010). A recent statistical analysis (Villarini et al. 2010) indicates that both local MDR and tropical-mean SSTs act as significant covariates (with similar weights but opposite signs) in modeling the century-scale record of both homogenized basinwide and landfalling Atlantic tropical storm frequency. Our simple correlation analysis showing a relationship of relative SST with both landfalling and adjusted basinwide hurricane frequency suggests that in future work, it may be possible to successfully apply the more rigorous and comprehensive statistical modeling approach of Villarini et al. (2010) to basinwide and landfalling Atlantic hurricane frequency.

Although we have assessed the impact of some of the uncertainties in the long-term Atlantic hurricane database, other issues undoubtedly remain. It seems unlikely that we will ever know with certainty how many Atlantic hurricanes actually occurred in the late nineteenth century and first half of the twentieth century, but our goal in this study has been to better estimate the impact of changing observational networks within a consistent and documented framework. Efforts to refine our hurricane data record using other approaches, such as reanalyzing the historical record with new maritime data (e.g., Landsea et al. 2008), exploring historical documents (Chenoweth and Divine 2008), or using geologic proxy data (Nyberg et al. 2007; Woodruff et al. 2008; Mann et al. 2009), are complementary to our present study and should help refine our understanding of past variations in Atlantic hurricane activity and their sensitivity to environmental changes.

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