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Is the recorded increase in short-duration North Atlantic tropical storms spurious?

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[1] The number of North Atlantic tropical storms lasting 2 days or less exhibits a large increase starting from the middle of the 20th century, driving the increase in recorded number of tropical storms over the past century. Here we present a set of quantitative analyses to assess whether this behavior is more likely associated with climate variability/change or with changes in observing systems. By using statistical methods combined with the current understanding of the physical processes, we are unable to find support for the hypothesis that the century-scale record of short-lived tropical cyclones in the Atlantic contains a detectable real climate signal. Therefore, we interpret the long-term secular increase in short-duration North Atlantic tropical storms as likely to be substantially inflated by observing system changes over time. These results strongly suggest that studies examining the frequency of North Atlantic tropical storms over the historical era (between the 19th century and present) should focus on storms of duration greater than about 2 days.

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1. Introduction

[2] The HURDAT data set [*Jarvinen et al.*, 1984; *McAdie et al.*, 2009] forms the backbone for studies examining observed changes in North Atlantic tropical storm frequencies. However, due to inhomogeneities in the observing systems [e.g., *Landsea et al.*, 2004; *Chang and Guo*, 2007; *Mann et al.*, 2007; *Chenoweth and Divine*, 2008; *Vecchi and Knutson*, 2008], questions remain about the reliability of tropical storm counts prior to the middle of the 20th century. Quantitative assessments of the reliability of trends in the number of tropical storms recorded in the HURDAT data set are of paramount importance in developing a better understanding of the character and possible causes of changes in tropical storm frequency since the mid-19th century. They are also important in developing understanding of the possible changes in such metrics over the coming decades.

[3] Using the HURDAT data set in its original (unadjusted) form, *Mann and Emanuel* [2006] and *Holland and Webster* [2007] found large increasing trends over the past century in North Atlantic tropical storm activity. Both of these studies interpreted this increase in tropical storm frequencies as largely due to human-induced climate change. *Mann and Emanuel* [2006] considered the record of tropical storm frequencies to be reasonably reliable back to the late 1800s. *Holland and Webster* [2007] commented that the number of missed storms was most likely 1–3 per year prior to 1900 and less than 2 per year in the early 20th century, but did not include such adjustments in their analysis. Subsequent studies have used several quantitative methods to estimate varying degrees of undercounts in the HURDAT database in the pre-1944 era [e.g., *Chang and Guo*, 2007; *Mann et al.*, 2007; *Landsea*, 2007; *Landsea et al.*, 2008, 2010; *Chenoweth and Divine*, 2008; *Vecchi and Knutson*, 2008, 2011]. Moreover, recent studies looking at projections of tropical storm frequency in a warmer climate do not point to an increase in tropical storm activity consistent with extrapolation of the raw HURDAT trend [e.g., *Oouchi et al.*, 2006; *Bengtsson et al.*, 2007; *Vecchi et al.*, 2008; *Gualdi et al.*, 2008; *Zhao et al.*, 2009; *Sugi et al.*, 2009; *Bender et al.*, 2010; *Knutson et al.*, 2010; *Villarini et al.*, 2011].

[4] Recently, *Landsea et al.* [2010] showed that the increasing trend in North Atlantic tropical storm frequency over the past 140 years was largely due to the increasing trend in short-lived storms (storms lasting 2 days or less; we will refer to them as "shorties") after the 1940s (Figure 1, top). They did not detect a significant increasing trend in medium- to long-lived storms (storms lasting more than 2 days). They wrote that "while it is possible that the recorded increase in short-duration TCs [tropical cyclones] represents a real climate signal, we consider it is more plausible that the increase arises primarily from improvements in the quantity and quality of the observations, along with enhanced interpretation techniques." *Landsea et al.* [2010] did not provide a quantitative analysis of the relationship between shorties and climate-related variables to support this statement. The goal of the present study is to quantitatively assess this hypothesis, by further examining and comparing the statistical relationships between sea surface temperatures (SSTs) and both short-lived and medium- to long-lived tropical

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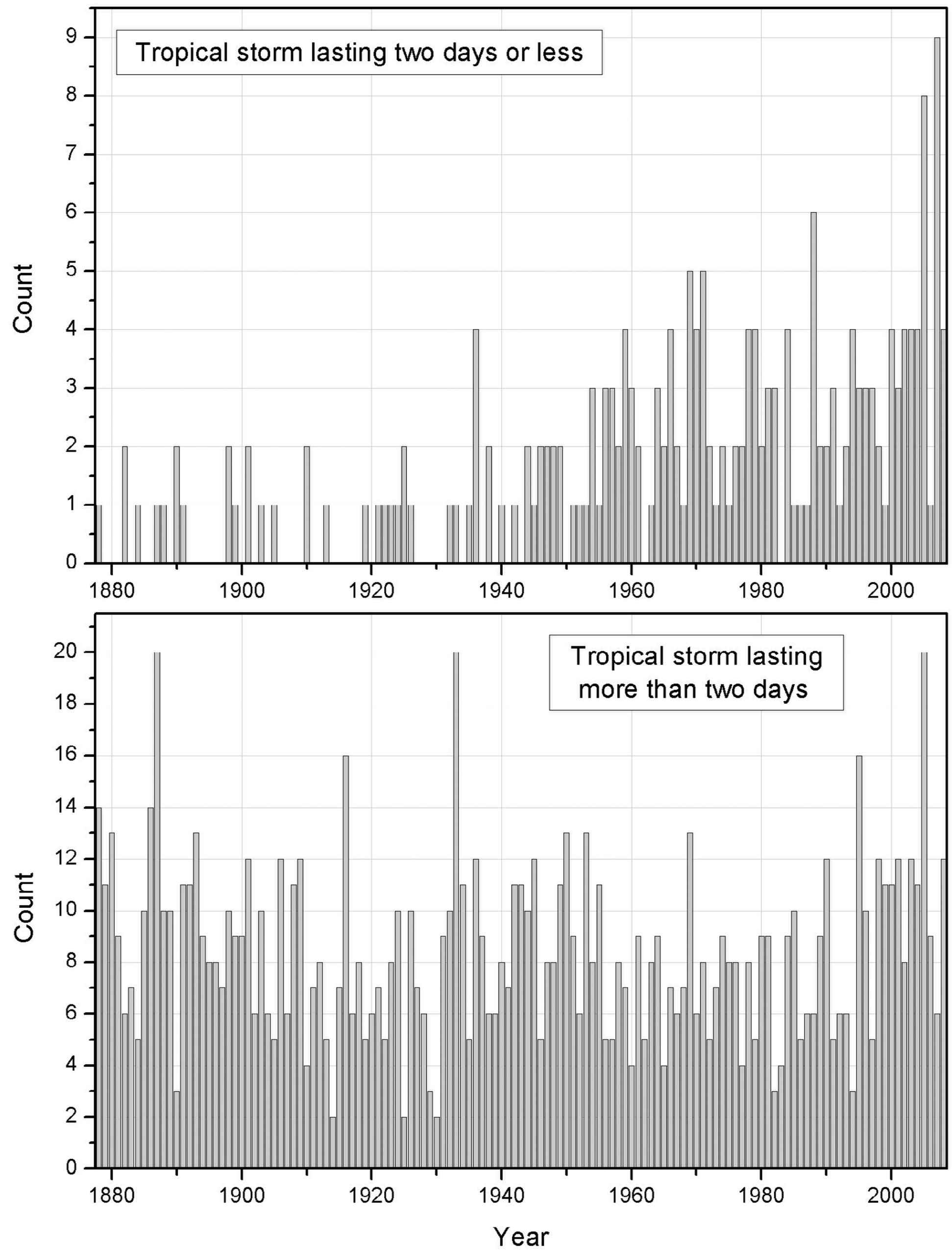

Figure 1. Time series of the number of North Atlantic tropical storms lasting (top) 2 days or less (shorties) and (bottom) more than 2 days (corrected according to *Landsea et al.* [2010]).

storm frequency. These results are important in order to assess the likelihood of a real secular trend in the frequency of North Atlantic tropical storms over the past century.

2. Poisson Regression

[5] Given that we are examining counts of tropical storms (defined as tropical cyclones with maximum sustained winds exceeding 17 m s^{-1} and including subtropical storms), a Poisson regression model represents a natural statistical framework with which to model the tropical storm frequency [e.g., *Elsner and Jagger*, 2006; *Mestre and Hallegatte*, 2009; *Villarini et al.*, 2010]. Poisson regression is a form of Generalized Additive Model [e.g., *Hastie and Tibshirani*, 1990]. We provide only a brief description of the Poisson regression model since we follow the same notation and approach as *Villarini et al.* [2010]. The interested reader is referred to that study. Let N_i be the number of shorties in the ith year. We can model N_i by a conditional Poisson distribution:

$$P(N_i = k|\Lambda_i) = \frac{e^{-\Lambda_i}\Lambda_i^k}{k!} \quad [k = 0, 1, 2, \ldots] \tag{1}$$

where the rate of occurrence Λ_i is a nonnegative random variable. The rate of occurrence can be modeled as a linear or nonlinear function h of n covariates $x_{1i}, x_{2i}, \ldots, x_{ni}$:

$$\Lambda_i = \exp[\beta_0 + \beta_1 h_1(x_{1i}) + \beta_2 h_2(x_{2i}) + \ldots + \beta_n h_n(x_{ni})] \quad (2)$$

where β_j ($j = 1, \ldots, n$) is the coefficient for the jth covariate. If $\log(\Lambda_i)$ depends linearly on the predictors, we have a Generalized Linear Model [e.g., *McCullagh and Nelder*, 1989; *Dobson*, 2001], while it reduces to a homogeneous Poisson process when $\Lambda_i = \exp[\beta_0]$.

[6] Following *Villarini et al.* [2010], we consider tropical Atlantic and tropical mean SSTs, North Atlantic Oscillation (NAO), and Southern Oscillation Index (SOI) as possible covariates for the model due to their relation with North Atlantic tropical storm genesis and development. The NAO is defined as in the work of *Jones et al.* [1997] (averaged over two periods: May–June and August–October), SOI as in the work of *Trenberth* [1984] (averaged over the period August–October), while for the SSTs we use both the UK Met Offices HadISSTv1 [*Rayner et al.*, 2003] and NOAAs Extended Reconstructed SST (ERSSTv3b) [*Smith et al.*, 2008] data sets (averaged over the period June–November).

[7] The tropical Atlantic SST anomalies (SST_{Atl}) are computed for a box 10°N–25°N and 80°W–20°W, while the tropical mean ST (SST_{Trop}) over the global tropics (30°S–30°N). Rather than assuming that Λ_i is a linear function of the covariates via a logarithmic link function, we include both linear and smooth dependencies using cubic splines. To avoid model overfitting, both in terms of covariates and their functional relation to the rate of occurrence parameter, we use a stepwise method penalizing with respect to both the Akaike Information Criterion (AIC) [*Akaike*, 1974] and the Schwarz Bayesian Criterion (SBC) [*Schwarz*, 1978]. A discussion of the impact of correlation among predictors is presented in Appendix A. As in the work of *Villarini et al.* [2010], quality of the fit is assessed by comparing the first four statistical moments of (normalized randomized quantile) residuals [*Dunn and Smyth*, 1996] against a standard normal distribution, together with their Filliben correlation coefficient [*Filliben*, 1975], and by visual investigation of the residuals' plots (e.g., qq plot, worm plot) [*van Buuren and Fredriks*, 2001; *Stasinopoulos and Rigby*, 2007]. All the calculations are performed in R [*R Development Core Team*, 2008] using the freely available gamlss package (available at http://gamlss.org/).

3. Results

[8] The time series of the shorties for the period 1878–2008 (Figure 1, top) shows a very low number of shorties before 1940s and a rapid increase afterward (the mean count between 1878 and 1943 is 0.58, while it is 2.58 between 1944 and 2008). The rough coincidence of this increase with the end of World War II and the beginning of the aircraft reconnaissance period, together with the lack of a significant trend in medium to long-lived storms (Figure 1, bottom; corrected according to *Landsea et al.* [2010]) raise the possibility that some of the increase may be spurious. Meanwhile, evidence supporting the interpretation the historical record of shorties as a real climate signal would include systematic and physically sensible connections to climate indicators.

[9] By fitting a Poisson regression model with a rate of occurrence Λ_i that is a function of climate-related covariates, we can evaluate whether the frequency of shorties in the HURDAT database could be explained in terms of climate indexes. When fitting the Poisson regression model and using a stepwise approach for covariate selection, we find that only SOI and SST_{Trop} are retained as significant covariates (Figure 2). When using the ERSSTv3b time series, independently of the penalty criteria, we find a linear dependence of $\log(\Lambda_i)$ on these two covariates (Figure 2, top). We obtain the same results when using the HadISST data (Figure 2, bottom), with the only difference being that $\log(\Lambda_i)$ is related to SST_{Trop} by means of a cubic spline when penalizing with respect to AIC. Using SBC as penalty criterion, the rate of occurrence depends linearly (via a logarithmic link function) on both SOI and SST_{Trop}, independently of the SST data set. Results concerning the quality of the fit do not suggest any problem with the selected model. This result is rather surprising: even though recent studies point to the importance of the tropical Atlantic SST relative to the tropical mean SST [e.g., *Tang and Neelin*, 2004; *Latif et al.*, 2007; *Vecchi and Soden*, 2007; *Swanson*, 2008; *Vecchi et al.*, 2008, 2011; *Knutson et al.*, 2008; *Wu et al.*, 2010; *Zhao et al.*, 2010; *Villarini et al.*, 2010], our expectation was that tropical Atlantic SST should have been retained by the model as a positive covariate [e.g., *Emanuel*, 2005; *Mann and Emanuel*, 2006; *Sabbatelli and Mann*, 2007; *Vecchi and Soden*, 2007; *Swanson*, 2008; *Knutson et al.*, 2008; *Zhao et al.*, 2009; *Wu et al.*, 2010; *Villarini et al.*, 2010; *Vecchi et al.*, 2011], if the variability and the trend in the shorties were a true climate signal. The fact that tropical Atlantic SST is not considered as a significant covariate in the model selection suggests that the increase in shorties may be at least partly spurious.

[10] We have also fitted a model with only tropical Atlantic and tropical mean SSTs as covariates (in agreement with the model of *Villarini et al.* [2010]). In this case, the estimated coefficient for tropical Atlantic SST was very close to zero, indicating that the rate of occurrence does not depend on SST_{Atl}. We have also performed other experiments, in which we fitted different Poisson regression models for different starting periods (all ending in 2008) using the same five predictors (Figure 3). More specifically, we have fitted 120 models, one from every year from 1878 to 1997. We performed model selection with respect to AIC. Up until the 1940s, both SOI and SST_{Trop} were retained as significant predictors. Starting from the 1950s, both of the NAO covariates were selected as the only significant predictors. During the 1960s, SST_{Atl} was generally selected, while in the late 1970s and early 1980s SOI was the only covariate. Finally, from 1988 to 1997, no covariate was retained by the model as significant predictor. Based on these results, it appears that the shorties record even in the most recent periods may contain serious inhomogeneities, possibly due to the inclusion of more midlatitude systems by the National Hurricane Center from 1970 [*Holland and Webster*, 2007; *Landsea et al.*, 2010]. These results are very different from what we obtain by focusing on the time series of North Atlantic tropical storms lasting more than 2 days (Figure 4), for which tropical Atlantic SST is always

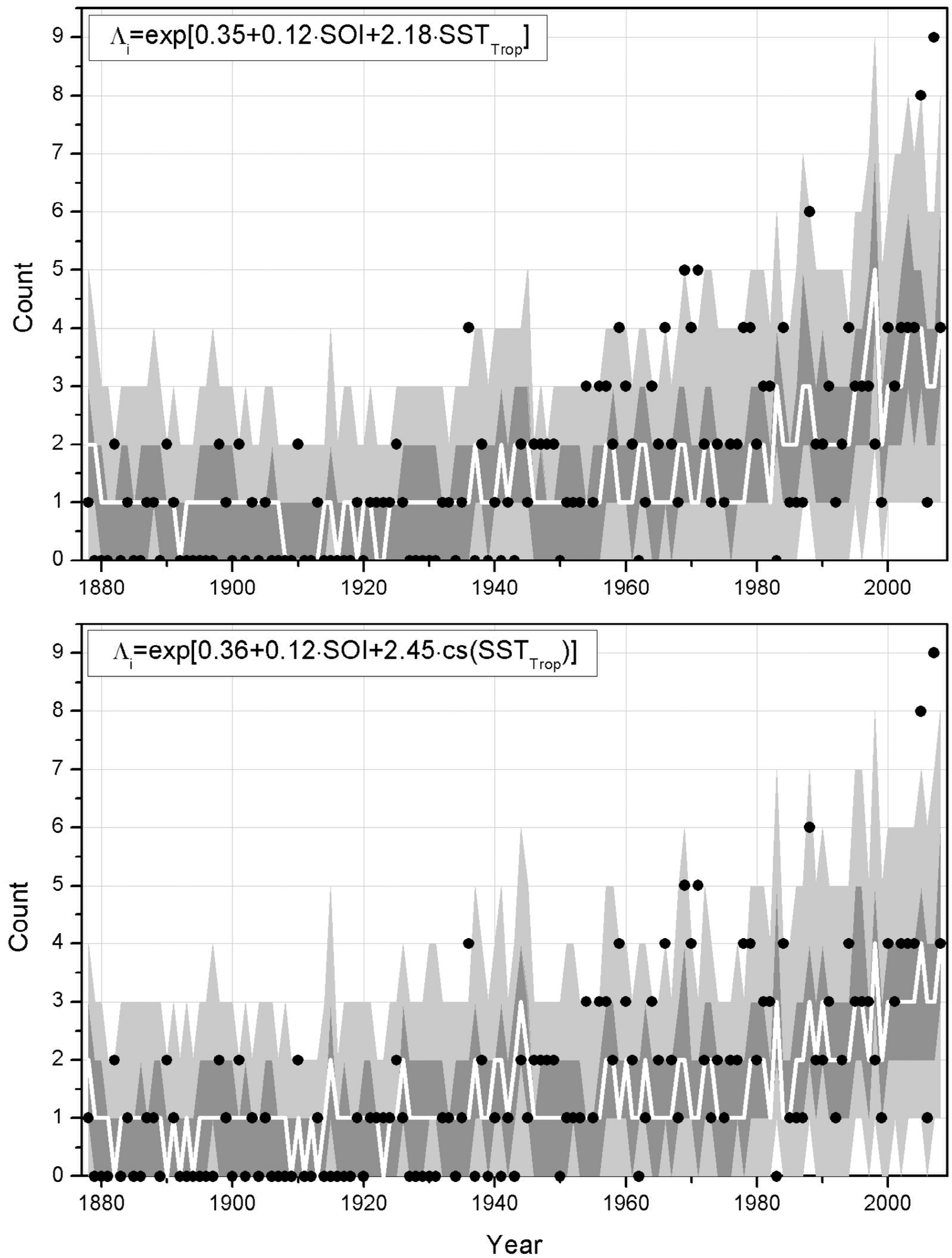

Figure 2. Modeling of the shorties with a Poisson regression model, with a parameter that is a function of SOI and tropical mean SST. (top) The results based on the ERSSTv3b data; (bottom) the results based on the HadISST data. Model selection is performed with respect to AIC (similar results in terms of selected covariates were obtained using SBC). The dots are observations; the white line represents the 50th percentile, the dark gray area represents the region between the 25th and 75th percentiles, and the light gray area represents the region between the 5th and 95th percentiles. "Cs" stands for cubic spline.

retained by the model as a significant covariate, independently of the starting year.

[11] Apart from the Poisson regression model, we have performed other analyses to examine the relationship of the record of shorties to climate conditions. Using both the ERSSTv3b (Figure 5, left) and HadISST (Figure 5, right) data sets, we have looked at 1880–2008 trends in 5 year mean SST and shorties for the period 1880–2005. In Figure 5 (top) we show the correlation between SST (averaged over the period June–November) and the linear trend regression. There is a coherent increase in SST (significant at the 5% level) consistent with other studies [*Intergovernmental Panel on Climate Change*, 2007], more pronounced when using the ERSSTv3b data set. These increases tend to be the largest in the Arabian Sea and the South Atlantic Ocean (not shown). In Figure 5 (middle) we show the correlation coefficient between 5 year averaged SST and the 5 year shorties. These maps tend to be very similar to the ones in Figure 5 (top),

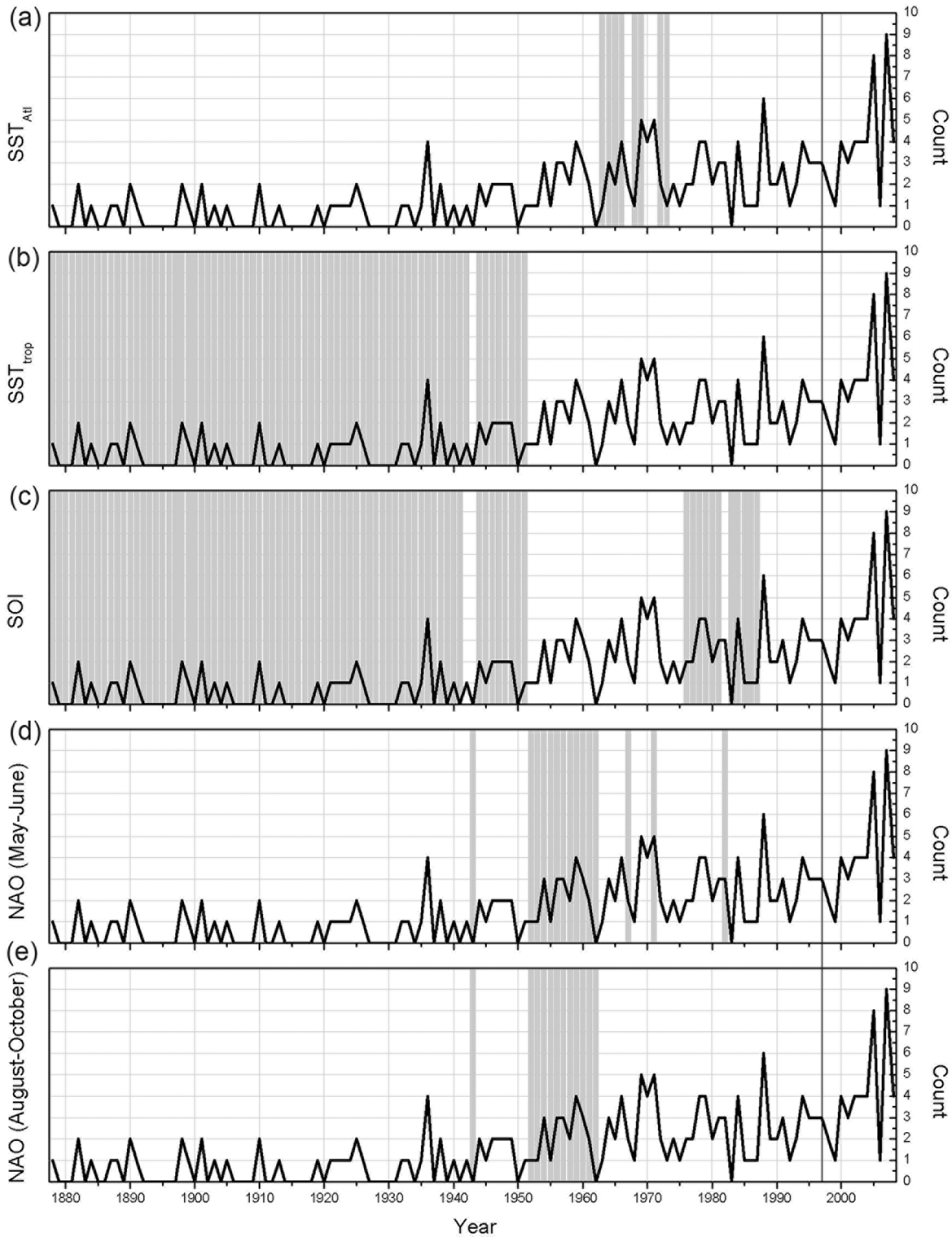

Figure 3. Results from the fitting of a Poisson regression model to different starting years (one model for every year from 1878 up until 1997, for a total of 120 models). The values on the *x* axis indicate the beginning of the fitting period (for instance, 1930 refers to the model fitted between 1930 and 2008). Five difference covariates are considered: (a) tropical Atlantic sea surface temperature (SST), (b) tropical mean SST, (c) Southern Oscillation Index, (d) North Atlantic Oscillation (NAO) averaged over May–June, and (e) NAO averaged over August–October. Model selection was performed with respect to AIC and the SST time series are obtained from the HadISSTv1 data. The black lines refer to the shorties time series. The gray bars indicate whether a particular covariate was retained by the model. The black vertical line marks the last year of the fitting (1997).

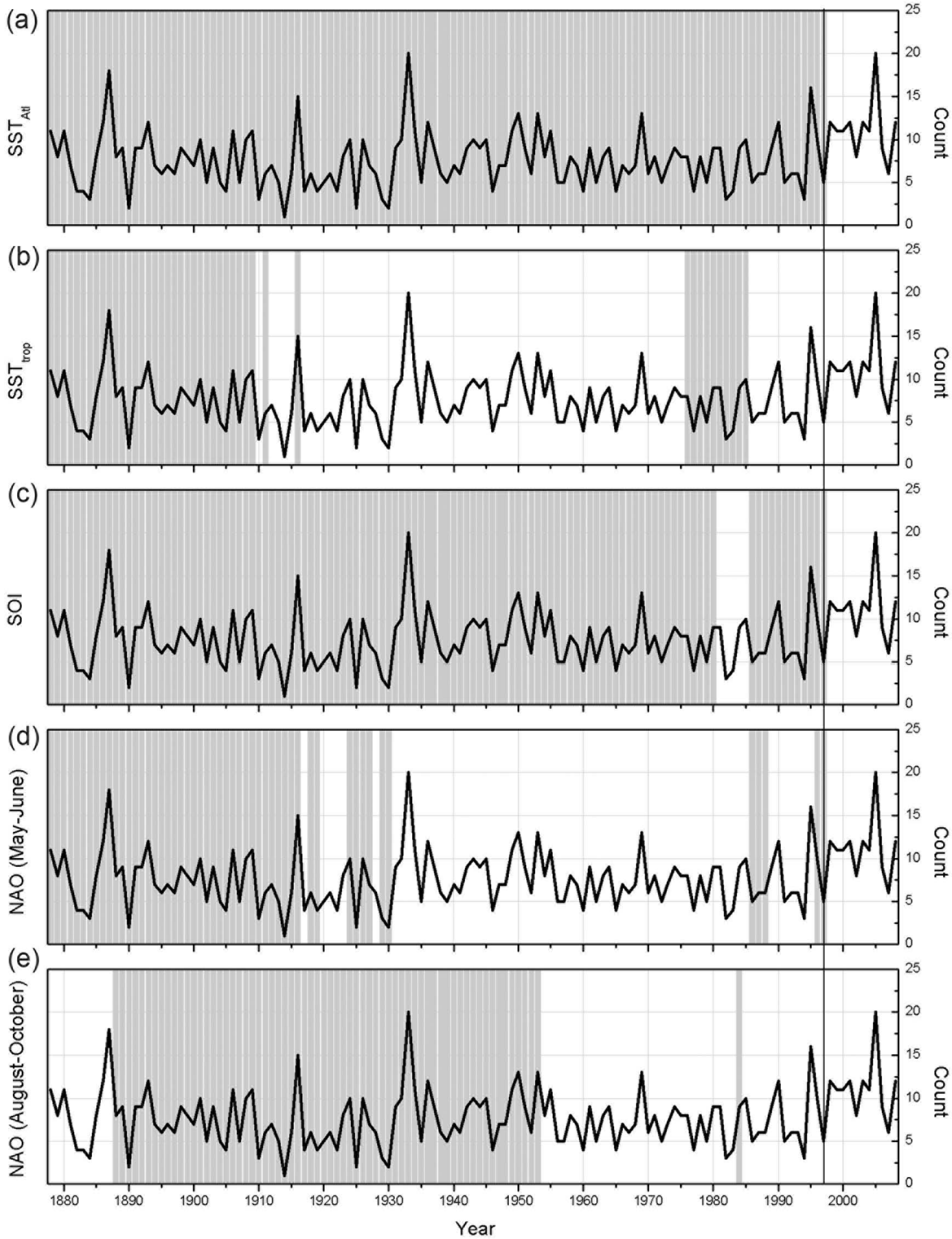

Figure 4. Same as Figure 3 but for the number of North Atlantic tropical storms lasting more than 2 days.

with higher correlation values between SST and shorties in the Arabian Sea and the South Atlantic Ocean. These results indicate that the frequency of shorties is most strongly correlated with the South Atlantic Ocean and the Arabian Sea, rather than with the tropical North Atlantic Ocean. Due to the presence of trends in both of the data sets, the value of the correlation coefficient is inflated by the presence of these trends, so it is of interest to examine the correlations in the data apart from the trend (to take into account the presence of significant autocorrelation in these time series, we compute the effective sample size as in the work of *Bretherton et al.* [1999]; see also *Butler et al.* [2007]). In Figure 5

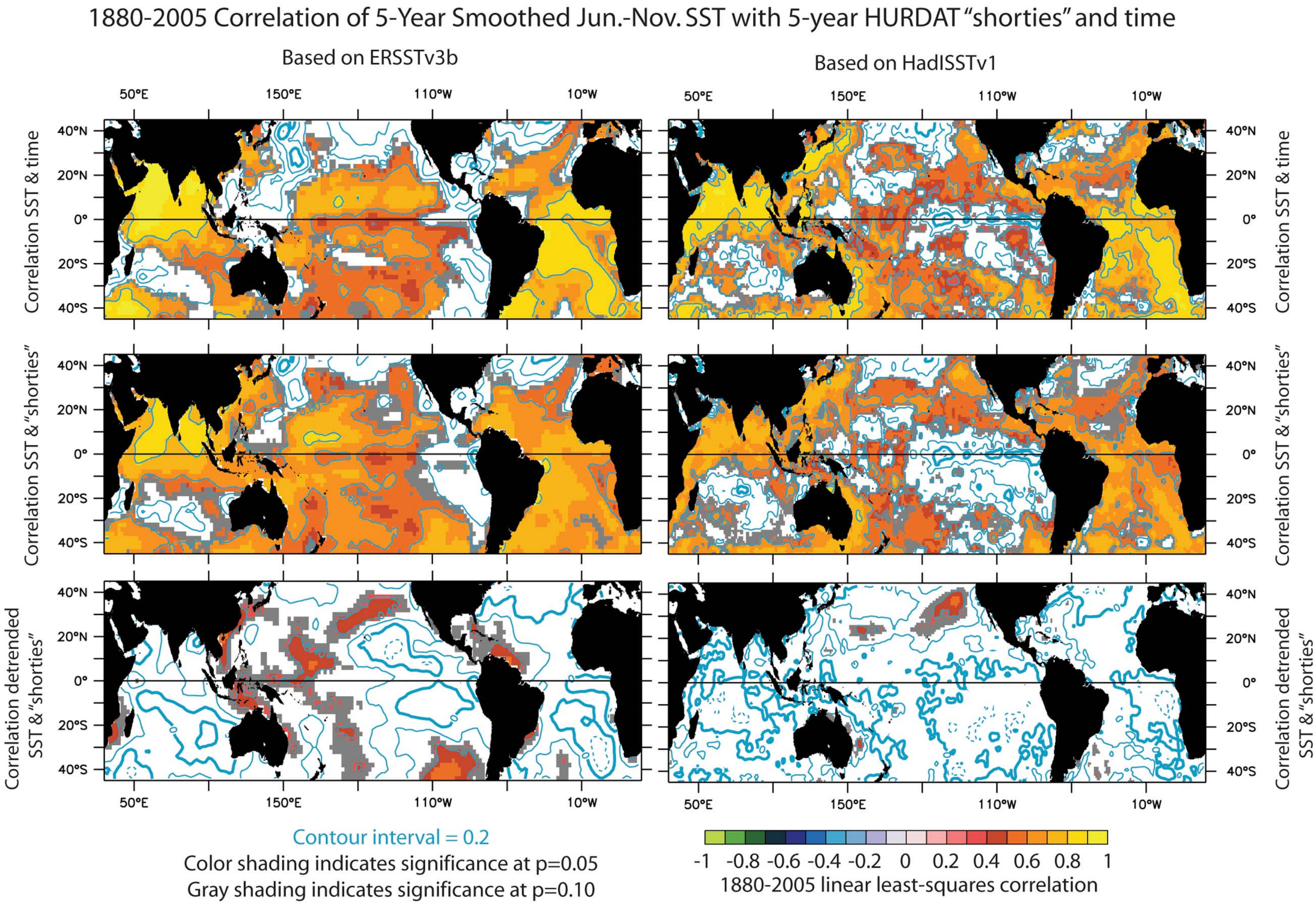

Figure 5. Maps with (top) the temporal correlation (i.e., correlation associated with the linear trend regression) of the 5 year mean SST and with the correlation between 5 year SST and 5 year shorties (middle) before and (bottom) after removing the trend in each series. These results are based on the (left) ERSSTv3b SST data and (right) HadISSTv1 data, averaged over the period June–November.

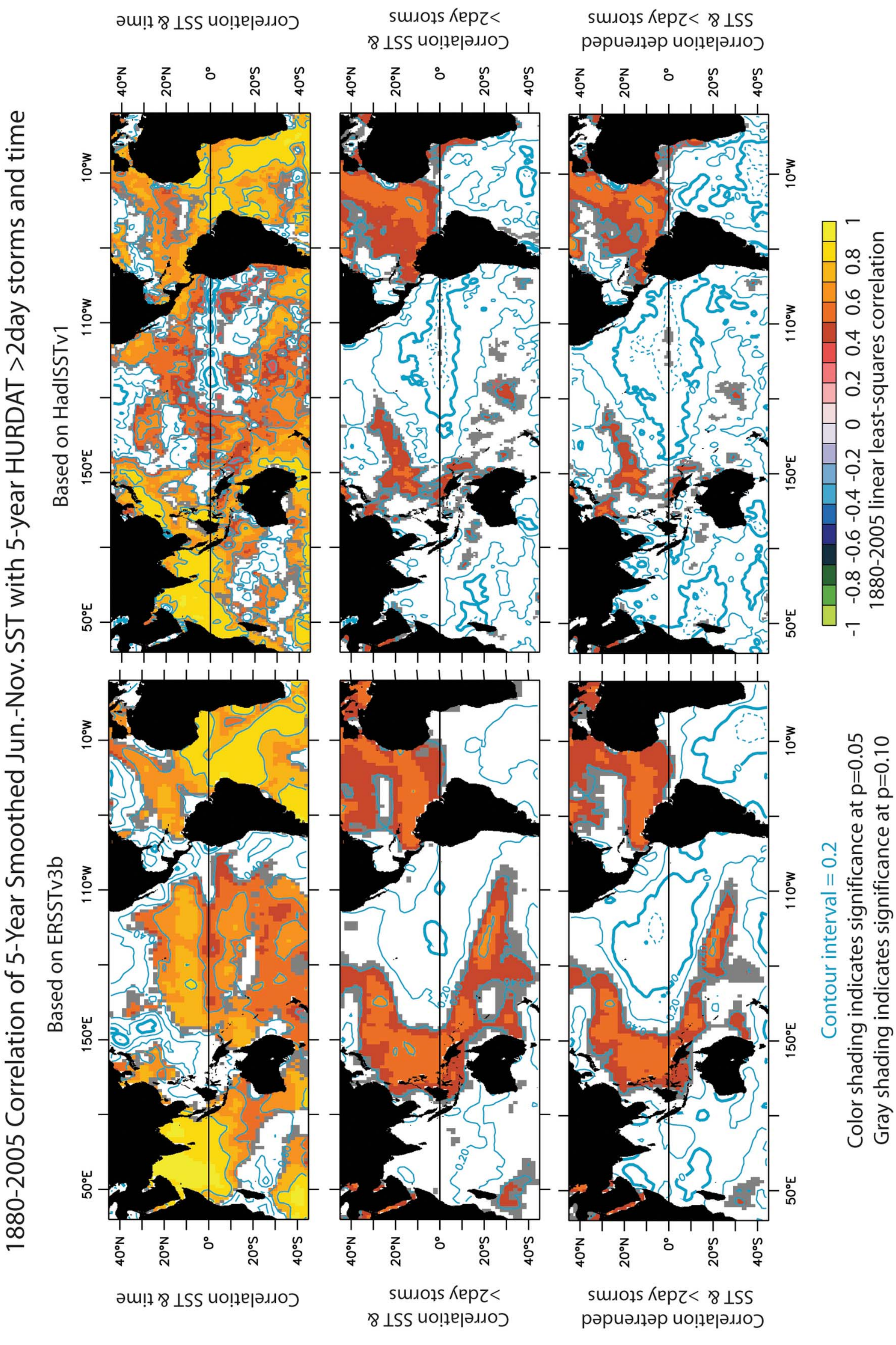

Figure 6. Same as Figure 5 but for the number of North Atlantic tropical storms lasting more than 2 days.

(bottom) we show the correlation coefficient between detrended SST and detrended shorties. These results indicate that there is no remaining statistically significant correlation between SST and shorties for most of the oceans. The strongest correlation for both of the SST data sets is with respect to a region of the northern subtropical Pacific Ocean (Figure 5, bottom). On the other hand, these analyses do not reveal a correlation between tropical North Atlantic SST and shorties statistically significant at the 10% level. Thus, the relationships between low-frequency changes in SST and the record of shorties are principally nonlocal, dominated by the presence of trends in both series, and have a spatial structure that does not indicate an obvious physical connection.

[12] The picture changes if we focus on the tropical storms lasting more than 2 days (Figure 6). This record is correlated with the SST time series (for both HadISSTv1 and ERSSTv3b), in particular with tropical Atlantic and West Pacific SSTs. We obtained very similar results even when computing the correlation between detrended SST and detrended time series of tropical storms lasting more than 2 days because of the lack of significant trends in the latter time series. These findings point to the significant relation between tropical Atlantic SST and tropical storms lasting more than 2 days, as we would expect from our current understanding of the physical processes at play. Therefore, these results support the notion that the long-term trend in the shorties contains a very substantial nonphysical or spurious component.

4. Conclusions

[13] In this study we have focused on North Atlantic tropical storms lasting 2 days or less (shorties) over the period 1878–2008, and examined whether their long-term evolution (including an increase over the 20th century) is more likely associated with a climate signal or with changes in the observational system.

[14] We have used a combination of statistical methods and physical reasoning to further support the idea that the observed increasing trend in the shorties from the 1940s is likely associated in large part with changes in the observational system. Based on a Poisson regression model over 1878–2008, only SOI and tropical mean SST are significant covariates in describing the frequency of shorties. Further, the statistical model is sensitive to the period over which it is trained, and tropical Atlantic SST is never retained. Based on our current understanding of the physical processes governing genesis and development of tropical storms in the North Atlantic basin, tropical Atlantic SST should have been an important covariate in describing the frequency of the shorties, but it is not identified as such in our analysis. In agreement with the results from the statistical model, maps of the correlation coefficient between SST and the shorties time series show that North Atlantic SST is not strongly related to the temporal variability of the shorties.

[15] Based on all of these analyses, we are unable to find evidence against the interpretation of the long-term change of the shorties as having a very substantial non climate-related component due to data quality issues. We note that our analysis does not rule out that shorties may have exhibited climatically driven variation and change, including a possible nominally positive trend over portions of the 20th century [e.g., *Emanuel*, 2010] or regions of the Atlantic [e.g., *Kossin et al.*, 2010]. However, based on our results, it appears that the long-term record of the basin-wide shorties is sufficiently contaminated by spurious components to mask any climatically induced variation within the raw data. Moreover, based on these results and those of *Vecchi and Knutson* [2008] it is unlikely that a homogeneous record of Atlantic tropical storm counts would contain a statistically significant positive trend since the late 1800s. Our results provide a context for interpreting studies exploring trend behavior in the North Atlantic tropical storm activity starting prior to the 1940s. In particular, the conclusions of certain studies reporting large secular increases in North Atlantic tropical storm activity in which shorties are included [e.g., *Holland and Webster*, 2007; *Mann et al.*, 2007] could be affected by what we interpret as likely spurious nonphysical trends unless an alternative physical explanation can be uncovered for the pronounced increase in shorties starting from the middle of the 20th century. Further, statistical models of tropical storm activity built using century-scale records that include shorties [e.g., *Mann et al.*, 2007; *Sabbatelli and Mann*, 2007; *Mann et al.*, 2009] likely include an element reflecting the spurious shorties in the record.

Appendix A: Analysis of Collinearity Influence

[16] We have used five possible predictors to relate the count of shorties to climate indices, and found that only SOI and tropical mean SST were retained as significant predictors, independently of the SST input data and penalty criterion. One possible objection to the validity of our results is that these covariates are not independent but correlated (collinearity), and that these findings are due to statistical artifacts. Despite the fact that collinearity is not a desirable property in statistical modeling, it is an issue that we often have to deal with when modeling geophysical processes.

[17] In this study, the strongest correlation is between tropical Atlantic and tropical mean SSTs, with a correlation coefficient of 0.73 for HadISSTv1 and 0.78 for ERSSTv3b. Even though these values may appear to be large, they are not as large as correlations among variables encountered in similar studies from other disciplines, such as social sciences [e.g., *Burnham and Anderson*, 2004; *Stasinopoulos and Rigby*, 2007]. As a rule of thumb, *Burnham and Anderson* [2002] suggest not to drop a predictor unless the correlation coefficient is extremely high (near collinearity problem), indicating |0.95| as a cutoff value for dropping a covariate. To assess the impact of collinearity on the outcome of our study, we use the variance inflation factor (VIF), a diagnostic tool commonly used to evaluate the impact of collinearity, which quantifies how much of the sampling variance of an estimated regression coefficient is "inflated" because of collinearity. We compute the VIF using the vif function in the Design package (available at http://CRAN.R-project.org/package=Design) in R [*R Development Core Team*, 2008], in which the method described by *Davis et al.* [1986] is implemented (see also *Wax* [1992]). A VIF value of 1 indicates that the covariates are uncorrelated, while larger values point to correlation among predictors. To decide whether collinearity is unacceptably high, different rules of thumb have been suggested, with a value of 10 generally used as cutoff

[e.g., *O'Brien*, 2007]. *Davis et al.* [1986] wrote that a value of 10.5 was indicative of a "modest amount of dependency among the variables." We therefore consider collinearity to be a substantial problem if VIF is larger than 10. Let us start by considering the model with all five predictors. When using the HadISSTv1 data, the largest VIF value is 2.87 for tropical mean SST. This value increases to 3.33 when using the ERSSTv3b data, following from the larger degree of correlation between the two SST predictors when using these input data. On the other hand, if we focus on the models described in Figure 2, we obtain VIF values slightly larger than 1. Because VIF is much smaller than 10, the correlation among predictors cannot be claimed to justify the fact that tropical mean SST and SOI are the only significant covariates in our analysis of the shorties, and we can rule out statistical artifacts arising from collinearity as a possible explanation for the spuriousness of the shorties.

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