Clim Dyn (2011) 36:2279–2293
DOI 10.1007/s00382-010-0908-x

# Atlantic tropical cyclones in the twentieth century: natural variability and secular change in cyclone count

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Received: 28 October 2009 / Accepted: 10 September 2010 / Published online: 7 October 2010


**Abstract** The twentieth century record of the annual count of Atlantic tropical cyclones (TCs) is analyzed to develop consistent estimates of its natural variability and secular change components. The analysis scheme permits development of multidecadal trends from natural variability alone, reducing aliasing of the variability and change components. The scheme is rooted in recurrent variability modes of the influential SST field and cognizant of Pacific-Atlantic links. The origin of increased cyclone counts in the early 1930s, suppressed counts in 1950–1960s, and the recent increase (since 1990s) is investigated using the count data set developed by Landsea et al. (J Clim 23: 2508–2519, 2010). We show that annual TC counts can be more closely reconstructed from Pacific and Atlantic SSTs than SST of the main development region (MDR) of Atlantic TCs; the former accounting for ~60% of the decadal count variance as opposed to ~30% for MDR SST. Atlantic Multidecadal Oscillation (AMO) dominates the reconstruction, accounting for ~55% of the *natural* decadal count variance, followed by the ENSO Non-Canonical and Pan-Pacific decadal variability contributions. We argue for an expansive view of the domain of influential SSTs—extending much beyond the MDR. The additional accounting of count variance by SSTs outside the MDR suggests a role for remotely-forced influences over the tropical Atlantic: the Pan-Pacific decadal mode is linked with decreased westerly wind shear (200–850 hPa) in its warm phase, much as the AMO impact itself. Non-canonical ENSO variability, in contrast, exerts little influence on decadal timescales. Interestingly, the secular but non-uniform warming of the oceans is linked with increased westerly shear, leading to off-setting dynamical and thermodynamical impacts on TC activity! The early-1930s increase in smoothed counts can be partially (~50%) reconstructed from SST natural variability. The 1950–1960s decrease, in contrast, could not be reconstructed at all, leading, deductively, to the hypothesis that it results from increased aerosols in this period. The early-1990s increase is shown to arise both from the abatement of count suppression maintained by SST natural variability and the increasing SST secular trend contribution; the abatement is related to the AMO phase-change in early-1990s. Were it not for this suppression, TC counts would have risen since the early 1970s itself, tracking the secular change contribution. The analysis suggests that when SST natural variability begins to significantly augment counts in the post-1990 period—some evidence for which is present in the preceding decade—Atlantic TC counts could increase rapidly on decadal timescales unless offset by SST-unrelated effects which apparently account for a non-trivial amount (~40%) of the decadal count variance.

**Keywords** Tropical cyclone counts · Sea surface temperature · Natural variability · Secular change

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## 1 Introduction

The recent increase in Atlantic hurricane activity has generated intense scientific debate as to its origin.

Following a relatively quiescent phase in the 1970/1980s, the number of Atlantic tropical cyclones (TCs) has steeply increased in the recent 1–2 decades (e.g., Mann and Emanuel 2006). Annual TC numbers averaged ~7 during 1986–1995 and ~11 during 1996–2005, i.e., a 50% increase in one decade. The intensity of TCs measured by the number and/or proportion of the most intense ones has also increased during recent decades (Goldenberg et al. 2001; Webster et al. 2005; Kossin et al. 2007; Elsner et al. 2008). An increase in hurricane destructiveness has also been noted (Emanuel 2005).

The cause of the recent increase in Atlantic TC activity is intensely debated in context of climate change. Some studies (e.g., Goldenberg et al. 2001; Zhang and Delworth 2006) suggest that increased TC activity is related to the natural variability of Atlantic sea surface temperatures (SSTs), especially the Atlantic Multidecadal Oscillation (AMO; Enfield et al. 2001; Delworth and Mann 2000; Guan and Nigam 2009), while others attribute the increase in activity to anthropogenic climate change (Webster et al. 2005; Trenberth and Shea 2006; Mann and Emanuel 2006; Holland and Webster 2007). It has also been argued that annual TC counts do not presently exhibit any low-frequency variability beyond the range expected from a random Poisson process (Elsner 2008). The attribution of heightened TC activity to natural variations and/or secular change of climate thus remains challenging, especially in view of the short length of the observational record and its uneven quality (Landsea 2007; Mann et al. 2007; Chang and Guo 2007; Vecchi and Knutson 2008; Landsea et al. 2010), and the modest simulation skill of current climate models; leaving much to debate.

The TC activity in the Atlantic is closely related to SST variations in the main development region (MDR; Mann and Emanuel 2006 6°–18°N, 20°–60°W; marked in Figs. 1 and 3) where ocean waters above 26.5 C are generally required for TC formation (Gray 1979). More than half of the decadal time-scale variance in the annual Atlantic TC count can be explained by SST variations in the main development region (MDR; Mann and Emanuel 2006). The nonlocal SSTs, i.e., the ones outside MDR are also influential as indicated by analyses that show the MDR SST variations relative to the global tropical average to be more pertinent (Emanuel 2005; Swanson 2008; Vecchi et al. 2008; Vecchi and Soden 2007), and studies that document the impact of Pacific SST on tropospheric circulation (vertical shear and stability) over the tropical-subtropical Atlantic (e.g., Elsner et al. 2001; Aiyyer and Thorncroft 2006; Camargo et al. 2007). Swanson specifically cautions against a singular focus on MDR SSTs by showing improved accounting of the TC power dissipation index using the 'relative' MDR SST variations; correlation increased from 0.55 to 0.73 in the 1950–2006 period. Vimont and Kossin (2007) show MDR SST variations to be correlated to the larger-scale Atlantic Meridional Mode.

The following features of the current analyses of Atlantic TC count variability motivate the present study:

- Natural variability is generally estimated, statistically, as a residual from detrending the observational record. The residual approach can be problematic as there is no assurance that natural variability is not aliased into the detrending index/marker or the linear trend. If such aliasing did occur, it would preclude the possibility of obtaining decadal-to-multidecadal trends from natural variability alone. For robust attribution, especially to secular change, the analysis scheme must allow for this possibility; flexibility not found in current analyses.
- The focus is almost exclusively on the recent increase in TC activity whereas causes of a similar (percentage wise) increase in the 1930s when the annual TC count increased from ~7 in the 1910/1920s to ~10 in the 1930s (cf. Fig. 2a) has generally not been addressed. Although TC counts in this period are somewhat uncertain, the jump is too large to be ignored (Goldenberg et al. 2001).
- Inter-basin interaction is ignored when investigating the origin of the recent warming of SSTs in the main hurricane development region (in the northern tropical Atlantic)[1]—this despite evidence for the Pacific's influence on the Atlantic at both interannual (e.g., Lanzante 1996; Enfield and Mayer 1997; Ruiz-Barradas et al. 2000; Kossin et al. 2010) and decadal time scales (Latif 2001; Guan and Nigam 2008, 2009).

Interestingly, the authors recently concluded an analysis of natural variability and secular trend in the Pacific and Atlantic SSTs (Guan and Nigam 2008, 2009)—one where both components are simultaneously characterized, i.e., contextually, as opposed to residual estimation of the former. By focusing on spatial and temporal recurrence but without imposition of any periodicity constraints, their analysis discriminates between biennial, ENSO, and decadal variabilities in the Pacific, leading to refined evolutionary descriptions and, equally importantly, separation of natural variability and the secular trend; all without any advance filtering (and potential aliasing) of the seasonally

[1] 'Mann and Emanuel's (2006) diagnosis, for instance, seeks evidence for AMO's role in the spectrum of the residual obtained after fitting SST variation in the main hurricane development region with a large-scale warming index (the global SST trend) and an anthropogenic aerosol index (a hemispheric cooling mechanism), but not one representing the influence of Pacific decadal variability.

resolved SST record.[2] The implicit accommodation of natural variability leads to a nonstationary SST secular trend, one that includes mid-century cooling. The physicality of the decadal variability modes—of key interest here—was evaluated using analog counts and fish recruitment records (Guan and Nigam 2008, hereafter GN2008).

The Atlantic SSTs were subjected to a similar spatiotemporal analysis but after removal of the Pacific basin's influence; footprints of the seven Pacific variability modes (including SST-trend) on Atlantic SST were linearly removed. The leading mode—a multidecadal oscillation focused in the extratropical basin with a period of ~70 years, and referred as the AMO-*Atl*—differs from this mode's conventional description (e.g., Enfield et al. 2001; Enfield and Cid-Serrano 2010) in the near-quiescence of the tropical-subtropical basin (which includes the MDR). The different signal strengths in this region in current and previous analyses indicate, implicitly, the significant influence of the Pacific basin on this region. The related principal components and modal structures are shown in Guan and Nigam (2009, hereafter GN2009) where robustness of the analysis, including the impact of pre-filtering the Pacific influence, is also assessed.[3]

The Pacific basin influences Atlantic TC activity through its impact on Atlantic SSTs as well as the overlying atmospheric circulation. The impact on SST during ENSO episodes is well documented in the aforementioned studies. For instance, ENSO accounts for ~20% of the record-high warming of the tropical North Atlantic in 2005 in the multivariate regression analysis of Trenberth and Shea (2006), surpassing the AMO contribution. The Pacific's influence on the Atlantic atmosphere is also pronounced during ENSO when it impacts the 200–850-hPa zonal-wind shear (e.g., Aiyyer and Thorncroft 2006) and tropospheric temperatures (Tang and Neelin 2004) over the tropical Atlantic, and consequently TC activity in the basin. The Pacific's influence on decadal time scales is of more interest in context of the low-frequency fluctuations and trends in Atlantic TC activity, but such influences have not been extensively studied. Latif (2001) made a case for inter-basin links using a low-pass filtered ENSO index. More recently, the authors have presented observational evidence for a significant link between Pacific decadal SST variability and the Atlantic SSTs via the Pan-Pacific mode (see Fig. 11 in GN2008).

The present study seeks to clarify the relationship of Atlantic TC activity (annual count) with global SST variations in the twentieth century using improved characterization of natural variability in the Pacific and Atlantic basins, and a simultaneously obtained, and thus, more consistent estimate of the nonstationary SST secular trend. The goal of the study is to obtain a refined estimate of the secular change in Atlantic TC activity as well as resolve its natural variability into components linked with the well-known modes of SST variability in both basins. The present study thus moves away from the traditional focus on MDR SST which, interestingly, is also a reconstruction target but after the Atlantic TC count.

Data and analysis method are briefly described in Sect. 2. The annual Atlantic TC count is analyzed in Sect. 3 where it is decomposed into secular trend and natural variability components, and further into contributions of the leading decadal-multidecadal modes of the two basins. The decomposition offers insight into the origin of increased TC activity in the 1930s and in the recent decade, and can facilitate the development of decadal projections of TC activity. Characteristic fall-season SST patterns that influence Atlantic TC count on decadal time scales are described in Sect. 4 which concludes with analysis of the MDR SST record, a common regional marker/predictor of TC activity. The impact of SST secular trend and select modes of decadal SST variability on zonal-wind shear (an influential environmental variable) over the tropical Atlantic is discussed in Sect. 5. Summary and concluding remarks follow in Sect. 6.

## 2 Data sets and analysis method

### 2.1 TC count data

The North Atlantic TC count data set developed by Landsea et al. (2010, hereafter LVBK2010) is analyzed in this study. It is based on the National Hurricane Center's best track data set (HURDAT; Jarvinen et al. 1984) which is the longest available and relatively reliable measure of Atlantic TCs, dating back to late 1800s. The earlier part of this record has however been questioned, particularly with

[2] Canonical ENSO variability is captured as two modes, the growth (ENSO−) and decay (ENSO+) modes. Departure from canonical development, especially in the 1976/1977-onward period, is identified as a distinct mode, referred as ENSO Non-Canonical (ENSO-NC), hereafter. Pacific decadal variability is resolved into two modes, Pan-Pacific and North Pacific. The former exhibits connections to the tropical-subtropical Atlantic resembling the AMO. The latter, capturing the 1976/1977 climate shift, is close to Pacific Decadal Oscillation in structure, but with interesting links to the North Atlantic as well as the western tropical Pacific and Indian Ocean SSTs. The nonstationary secular trend consists of wide-spread but non-uniform warming of all basins along with a sliver of cooling in the central equatorial Pacific. See Guan and Nigam (2008) for additional details.

[3] The second and third mode capture the growth and decay of interannual variations in the eastern tropical Atlantic, the Atlantic Niño, while the fourth describes lower-frequency variability whose mature phase resembles the SST footprint of the North Atlantic Oscillation. The fourth mode is referred as the low-frequency NAO (LF-NAO).

respect to the upward trend in annual TC count. Veechi and Knutson (2008) used statistical methods to account for the potentially missing TCs in the pre-satellite period of the record. Meanwhile, LVBK2010 showed the increasing TC count to result, in part, from the growing number of short-lived storms (duration $\leq 2$ days) in the recent period; arguably, from improvements in observational platforms and techniques. Based on these adjustments, a new TC count data set was developed—the LVBK2010 record. It factors for TC-subsampling in the earlier period and seeks to track the count of moderate-to-long lived TCs. The 1900–2008 record of LVBK counts is analyzed here.

Some of the problems associated with TC count records are common to all observational data sets spanning historical and modern periods, with attendant gradients in observational density and techniques; SST included. Observational records are thus repeatedly reprocessed and refined—atmospheric reanalysis being a case in point—but also continually analyzed to advance understanding of climate variability and change. The present analysis of the LVBK counts is in this spirit; it will be likely repeated when this count record is further refined in the future.

### 2.2 SST data

The SST data come from the U.K. Met Office's (UKMO) Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) 1.1 (Rayner et al. 2003), which is globally available on a $1^\circ \times 1^\circ$ grid for the 1870-onward period. The uneven quality and coverage of SST observations in the first half of the twentieth century is also a potential concern for the undertaken analysis. The HadISST gridded record for this period is generated using large-scale field covariance (reduced space optimal interpolation, to be precise)—a technique that can handle under-sampling (Rayner et al. 2003). Our focus on recurrent, basin-scale SST variability patterns that are extracted from analysis of the spatiotemporal field covariance reduces the influence of regional data voids even further. Regardless, uncertainty estimates for the earlier period SSTs are reasonably modest (Kaplan et al. 1998) and not too consequential for the analysis of SST–TC count links (Mann et al. 2007). The full twentieth century SST record analyzed here is moreover widely used in the analysis and modeling of climate variability and change; e.g., the Climate of the twentieth century project (Scaife et al. 2009).

### 2.3 SST analysis

In two recent papers (GN2008; GN2009), the authors characterized the twentieth century SST variability in the Pacific and Atlantic basins from spatiotemporal analysis of the seasonal anomalies, using the extended EOF technique (Weare and Nasstrom 1982). A total of 11 principal components (PCs) constitute the analysis backbone. Of these, 7 (including the nonstationary SST Trend mode) are from the Pacific analysis while the remaining 4 come from the analysis of residual (i.e., Pacific basin uninfluenced) SST variability in the Atlantic basin. The authors' original Pacific basin analysis for the 1900–2002 period (GN2008) was updated using data up to 2007, as reported in GN2009.[4] The principal components are defined over a somewhat shorter period than the data itself in extended-EOF analysis as spatiotemporal sampling precludes PC definition at a few points at both ends of the record, with the number of undefined points depending on the width of the temporal sampling window. Seasonally resolved Pacific and Atlantic PCs are available from fall 1901 to winter 2005/2006. The intra-basin PCs are temporally orthogonal (assured by the analysis method) while the inter-basin ones are nearly so (ensured by filtering of Pacific's influence from Atlantic SSTs prior to latter's analysis); the largest inter-basin PC correlation is 0.11.

### 2.4 Reconstruction of TC Counts and MDR SSTs

The present analysis is for the fall season (September–November), and not the preferred peak hurricane season (August-October; e.g., Mann and Emanuel 2006), as the underlying SST analysis was based on the conventionally defined seasonal anomalies. Simple linear regressions of the fall season SST PCs (unsmoothed) on the annual Atlantic TC count and concurrent SST anomalies in the full record (1901–2005) constitute the building blocks in reconstruction of the TC count and MDR SST variations, respectively. The reconstruction proceeds, simply, from the multiplication of each SST PC (fall value) with its above-obtained 'fixed' regression pattern (number, in case of TC count), followed by the summing of the 11 (or any subset thereof) elemental contributions.

### 2.5 Inter-basin SST links

Inter-basin links on decadal time scales are of key interest in context of the low-frequency fluctuations and trends in Atlantic TC activity. The Pan-Pacific mode of decadal variability, having a horse-shoe structure (with SST anomalies extending eastward from the Bering Sea and

[4] A few Atlantic grid points were inadvertently included in the Pacific SST analysis, following a rectangular definition of the Pacific basin in GN2008 (and GN2009). These were masked out and the Pacific and Atlantic analysis repeated, with minor effects;old and new PCs are correlated in the 0.95–1.0 range. The updated PCs are available online at http://dsrs.atmos.umd.edu/DATA/NIGAM/Diab.Heating/SST-PCs/.

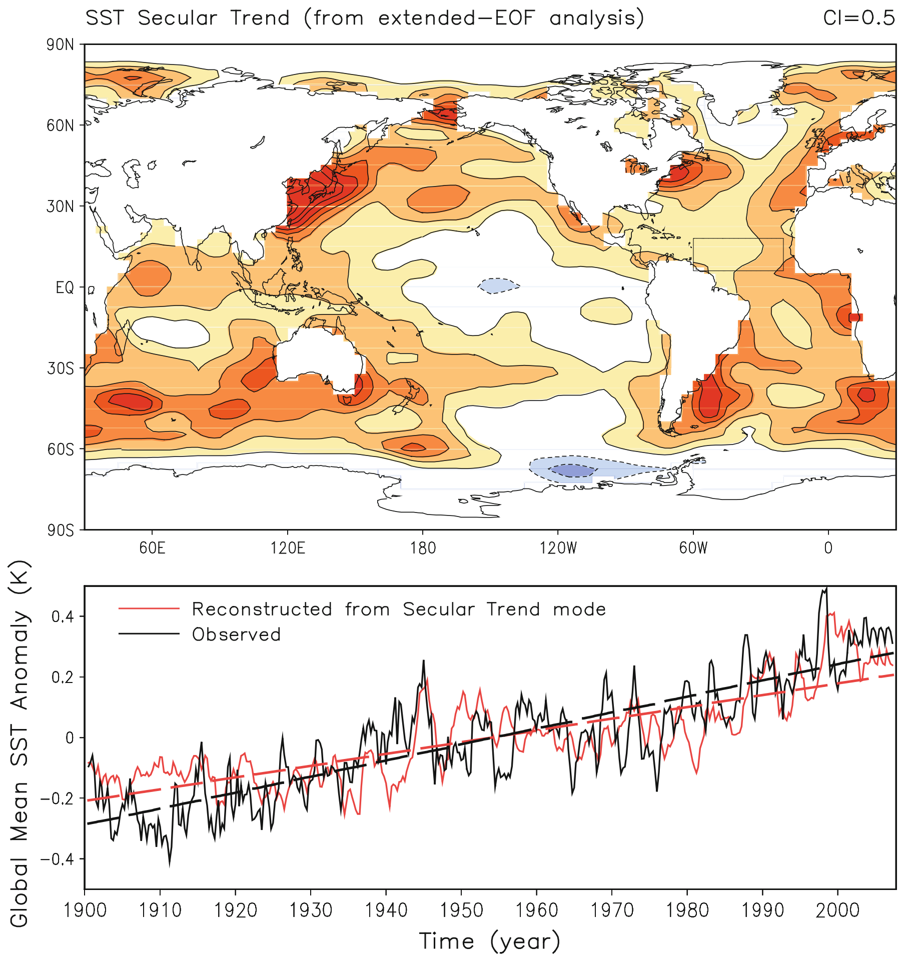



**Fig. 1** Secular trend in twentieth-century (1900–2007) SSTs based on extended-EOF analysis of Pacific basin SSTs, and consistent with natural variability in the same period. The global mean SST anomaly in observations is plotted in black in the lower panel, while the one based on SST reconstruction with the SST trend mode is in red; the latter is shown in lieu of the trend mode PC to facilitate comparison. *Dashed lines* mark the *least-squares fitted lines* to the curves. Red (*black*) line has a slope of 0.39 K/century (0.53 K/century), i.e., the global-mean linear trend is about 25% weaker when decadal-multidecadal SST variability is factored in. SST regressions on the trend mode based global-mean SST anomaly (*red curve*) are shown across the globe in the upper panel after one application of '*smth9*' in GrADS. Solid (*dashed*) contours denote positive (*negative*) values and the zero-contour is suppressed; contour interval is 0.5. The Main Development Region of Atlantic tropical cyclones (MDR, 6–18N, 20–60W) is marked

then downward until Baja California, before sweeping back southwestward towards the tropical Pacific) northward of a quiescent central/eastern equatorial Pacific, was shown linked with Atlantic SSTs, especially in the western tropical/subtropical basin (which includes the MDR); 0.4–0.5 correlation with the Caribbean SSTs (cf. Fig. 11 in GN2008). The similarity between the Pan-Pacific mode's footprint on Atlantic SSTs and the conventional AMO's tropical-subtropical structure is noteworthy, and reflected in the seasonal correlation (0.42) of the related indices; correlation is 0.48 when the Pan-Pacific principal component leads the conventional AMO index by five seasons.[5]

## 2.6 Non-stationary SST secular trend

In view of the emphasis placed on characterization of secular change, the non-stationary SST Trend mode extracted in GN2008 is shown in Fig. 1 (upper panel). The absence of notable trends in the central-eastern tropical Pacific temperatures is noteworthy. It is also instructive to compare the global mean SST anomaly based on the trend mode (red curve in lower panel) with one based on raw data (black curve); the latter has been used to mark long-term trend (e.g., Trenberth and Shea 2006). Both indices show a broad upward trend but with notable differences in some decades that can be attributed to aliased natural variability, especially Pacific decadal variability:[6] The

[5] Interestingly, this influence on Atlantic SSTs is recovered as an independent mode when Atlantic SST variability is analyzed without pre-filtering the Pacific's influence (see sensitivity test T7 in GN2009) .

[6] Aliasing of the AMO is not as evident in the raw global index because of AMO's high latitude focus (i.e., smaller areal footprint).

negative-to-positive phase build-up of the Pan-Pacific mode during 1900–1940, and the phase-swing of the North Pacific mode in the 1940s and early 1980s (see Fig. 2 in GN2008 for both) are clearly aliased into the linear trend of the raw data, for example. Departures from natural variability are thus more modest at the beginning of the record in the trend mode based index. Least-squares fit of the two SST indices leads to significantly different linear trends: 0.53 K/century for the one based on raw anomalies and 0.39 K/century for the trend mode one. The SST-warming trend is thus about 25% smaller when decadal-multidecadal SST variability is factored in!

## 3 Atlantic TC count: secular trend and natural variability

The annual Atlantic TC count in the LVBK record is shown in Fig. 2a (TC-Tot Observed, solid black), after 10 applications of the 1-2-1 smoother. Raw counts are also

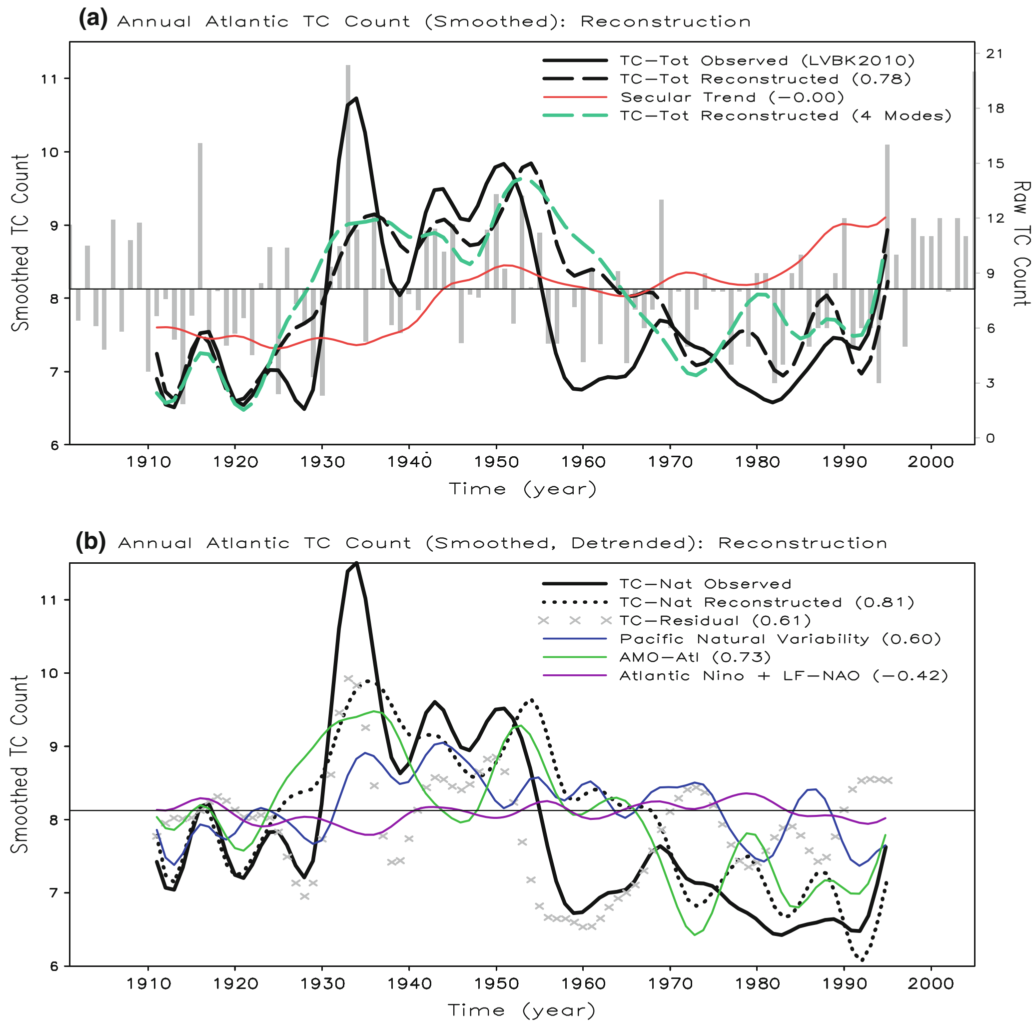



**Fig. 2** Reconstruction of the annual Atlantic TC count (Landsea et al. 2010, referred as LVBK2010) from Pacific and Atlantic SST variability: **a** Observed (*solid black*) and reconstructed (*dashed black*) *total* counts are shown after smoothing, using the left scale. Partial reconstruction from the SST secular trend (*solid red*), and from four decadal time-scale SST principal components (SST Trend, AMO-*Atl*, ENSO Non-Canonical, and Pan-Pacific decadal; *dashed green*) is also shown; the *dashed black* and *green curve* are correlated at 0.93. Lightly *shaded vertical bars* in the background depict the *raw* (i.e., unsmoothed) TC counts using the right scale, with the horizontal line marking the long-term count-average (8.2) in both; **b** Observed (*solid black*) and reconstructed (*dotted black*) *natural* count variations. Subtraction of the SST secular trend related counts (*red curve* in the above panel) from TC-Tot Observed yields the former, while the latter is based on SST natural variability in the Pacific and Atlantic basins. The SST-unrelated count variability (TC-Residual, 'x' marked) is obtained by subtracting the *dotted black curve* from the solid one in this panel. Contribution of Pacific SST natural variability (*blue*), AMO-*Atl* (*green*), and the Atlantic Niño plus Low-Frequency NAO (*purple*) to TC-Nat Reconstructed are also shown. Time series in both panels are smoothed by ten applications of the 1-2-1 smoother, which leads to record truncation at both ends. Correlations of the smoothed reconstructed and observed records are indicated next to line labels in each panel

plotted, as departure from the full-record average ($\sim$8), using lightly shaded vertical bars and the right scale. An abrupt increase in count is seen in the 1990s. Before that, counts are relatively stable but suppressed over a $\sim$30-year period beginning in the mid-1950s, albeit with decadal modulation. A strong abrupt increase occurred also in the early 1930s. Both this and the recent count increase will need attribution using a common framework to advance understanding of count variability.

The annual TC count is reconstructed from SST variability in the Pacific and Atlantic basins using fall season regressions of the secular trend and natural variability modes, as discussed in Sect. 2.4. The full reconstruction (dashed black) accounts for as much as 60% of the decadal variance in view of the 0.78 correlation between the reconstructed and observed TC-Tot. Increased counts during 1930–1950s and the decline since then are broadly captured in the reconstruction; suppressed counts in the 1950–1960s are however a notable exception. The SST Trend mode (red) contributes negligibly to this reconstruction given its near-zero correlation (−0.002); all curves are smoothed as TC-Tot Observed, the target. The steep increase in TC count in the 1930s is partially reconstructed. Smoothing related record truncation,[7] unfortunately, precludes assessment of the reconstruction of the 1990s count increase.

The natural variability in TC count (TC-Nat) is the focus of Fig. 2b, which shows both the observed (solid black) and reconstructed (dotted black) counts sans the SST Trend mode contribution. Their 0.81 correlation indicates that $\sim$65% of the natural decadal variance in TC count is related to the basin-scale natural variability of SST, in particular, the 6 Pacific and 4 Atlantic modes of recurrent variability mentioned above. The Pacific contribution to count variance ($\sim$35%) is not too far behind the AMO-*Atl* one ($\sim$53%).[8] The SST-unrelated variability in TC count (TC-Residual, marked by 'x's), obtained from subtraction of the dotted and solid black curves, must arise from other factors, including SST-unrelated meteorological phenomena (e.g., quasi-biennial oscillation in the lower stratosphere) and, potentially, aerosol's influence on clouds/convection.

[7] Ten applications of 1-2-1 smoothing on yearly TC counts shrink the observational (1900–2008) and reconstructed (1901–2005) records by 10 years at both ends, with the termination points being 1998 and 1995, respectively.

[8] Basin contribution in accounting of decadal count variance cannot always be obtained as sum of the squared correlation of the smoothed basin PCs and the count index since smoothed PCs need not be orthonormal like their unsmoothed counterparts.

The natural variability modes generally do not exhibit long-term trends but they can, individually and collectively, generate decadal-multidecadal trends. It is noteworthy that natural variations in TC count, observed as well as reconstructed, exhibit decadal-multidecadal variations, including trends—for example, the declining trend during 1950–1990s and an upward one during 1920–1930s. Such multidecadal trends can be aliased into the secular change component should the latter not be extracted simultaneously; a motivating concern mentioned in the introduction.

The components in reconstruction of TC-Nat are also shown in Fig. 2b, using color. The AMO-*Atl* contribution to TC activity (green) shows both its long time scales and considerable influence, including suppression of TC count in the late-1960s onward period and its enhancement in the 1930s. The other Atlantic modes, Niño and the low-frequency NAO, contribute quite weakly (purple curve), in comparison. Pacific natural variability (blue) is more influential, contributing to increased counts during 1935–1945 and diminished activity around 1980 and 1990. Further decomposition (not shown) indicates the Pan-Pacific decadal mode and the ENSO Non-Canonical mode of variability to be largely responsible for the Pacific contribution. The latter represents the departure from ENSO's canonical development in the post climate-shift period (1976/1977-onward); see Fig. 5 and related discussion in GN2008.

The reconstruction of annual TC counts is formally based on individual regressions of all 11 SST PCs (7 Pacific plus 4 Atlantic, all unsmoothed) but is, in fact, shaped by the contributions of only a select few, as seen from Table 1. Correlations of the fall season SST PCs and annual TC counts (LVBK), both unsmoothed, are noted in this table. Their significance was assessed through Monte Carlo re-sampling of the TC count record; 10,000 synthetic versions were generated and correlated with the SST PCs, yielding the $p$ values noted in column 3 of the table. The analysis indicates that annual Atlantic TC counts are significantly impacted by only a few modes: SST-Trend, canonical and non-canonical ENSO variability, Pacific biennial variability, and AMO-*Atl* variability; the Pan-Pacific decadal variability mode is also influential, but not as much as the ones above. If one focuses on decadal modulation of TC counts, the list is even shorter: SST-Trend, AMO-*Atl*, ENSO Non-Canonical, and perhaps, the Pan-Pacific mode, i.e., just 4 of the 11 modes. A partial reconstruction of TC counts based on these 4 modes (dashed green line in Fig. 2a) closely tracks the full reconstruction at decadal time scales (correlation 0.93), supporting our assertion of the importance of a select few modes of SST variability for annual TC counts in the Atlantic.

**Table 1** Correlation of the fall season SST principal components and annual TC counts from the LVBK record (Landsea et al. 2010); both unsmoothed. The SST analysis is briefly discussed in Sect. 2.3 and 2.5, 2.6, and in Footnotes 2–4, and extensively in Guan and Nigam (2008, 2009). Statistical significance was assessed from Monte Carlo re-sampling of the TC count record: 10,000 synthetic versions were generated and correlated with the SST PCs, yielding the p values. The latter were computed by counting the number of synthetic records whose correlation with the SST PC equaled or exceeded that of the observed one in magnitude (i.e., a two-tailed test). Correlations, displayed in bold face, are deemed statistically significant; they include one (+0.12) that is viewed as only marginally so. Only 4 of these 7 PCs vary on longer-than-interannual timescales, and thus relevant for decadal modulation of TC counts; their names are highlighted in bold. Yes: √; No: X; Perhaps: √ ?

| SST principal component | Correlation with annual TC counts | *p* values | Significance |
|---|---|---|---|
| ENSO decay (ENSO+) | **−0.25** | 0.011 | √ |
| ENSO growth (ENSO−) | **−0.39** | 0.000 | √ |
| **SST trend mode** | **+0.21** | 0.031 | √ |
| **Pan-Pacific decadal variability** | **+0.12** | 0.203 | √ ? |
| **ENSO non-canonical** | **−0.19** | 0.048 | √ |
| North Pacific decadal variability | −0.09 | 0.359 | X |
| Biennial variability | **−0.17** | 0.081 | √ |
| **AMO-*Atl*** | **+0.31** | 0.002 | √ |
| Atlantic nino+ | +0.01 | 0.899 | X |
| Atlantic nino− | −0.08 | 0.422 | X |
| Low frequency NAO (LF-NAO) | −0.04 | 0.653 | X |

### 3.1 The 1930s count increase

The SST-based reconstruction can partially account for the steep count-increase in the early 1930s and precipitous decline in the late 1930s (a signal in the natural variability realm given its short duration?). About one-half of the signal can be linked to SST natural variability which can, evidently, generate the rapid build-up but not the steep decline in counts in the latter part of that decade; the former from in-phase contributions of the Pan-Pacific and AMO-*Atl* modes. Interestingly, Veechi and Knutson (2008) have argued that some of the steep decline in counts is an artifact of undercounting during/preceding World War II.

### 3.2 The 1950–1960s count decrease

The large variance in observed and reconstructed counts during the 1950–1960s—largest in the century-long record (see TC-Residual in Fig. 2b)—remain puzzling, not because fields other than SST cannot be influential, but because it is difficult to conceive of factors that can be so singularly influential; in just one sub-period of the twentieth century? The 1950s and 1960s are, of course, well known as the period when "average global temperatures leveled off, as increases in aerosols from fossil fuels and other sources cooled the planet." (IPCC 2007, WG1).[9] The cooling is manifest in SST—see the SST secular trend in Fig. 2a—but aerosol's influence on TC counts need not be transmitted only through its SST impact; aerosol induced changes in cloud condensation nuclei distribution can directly impact the strength of deep convection (Cotton et al. 2007).

### 3.3 The early 1990s count increase

The TC count increased from the early 1990s, in part, from the abatement of count suppression maintained by SST natural variability in the preceding decades (Fig. 2b, black curves). Were it not for this suppression, TC counts would have risen steeply since the 1970s itself, tracking the secular trend contribution (Fig. 2a, red). The abatement of count suppression in early-1990s is captured in the reconstruction and results mostly from SST natural variability (Fig. 2b). Both basins contribute to the abatement but the AMO-*Atl* contribution dominates, tracking the combined basin impact (TC-Nat Reconstructed).

### 3.4 Count increase during 1996–2005

Smoothing related truncation of TC counts (cf. footnote 7) precludes analysis of increased TC activity during 1996–2005, a recent period of considerable interest. A perspective on the relative influence of SST natural variability and secular trend on this period's TC counts can nonetheless be obtained by focusing on the *average value* of the unsmoothed reconstruction components in this 10-year period (Table 2); all values are relative to the 1901–2005 long-term mean (∼8). The analysis indicates that high TC activity during 1996–2005 (a 3.1 count increase over the

[9] "The eruption of Mt. Agung in 1963 also put large quantities of reflective dust into the upper atmosphere." (IPCC 2007).

**Table 2** Mean annual TC count during 1996–2005 relative to the 1901–2005 long term mean (∼8), based on the time series in Fig. 2. Reconstructed counts are shown in brackets for TC-Tot and TC-Nat

| TC-Tot Obs. (Recon.) | Secular trend | TC-Nat Obs. (Recon.) | Pac. Nat. Var. | AMO-*Atl* | Atl. Niño + LF-NAO |
|---|---|---|---|---|---|
| 3.1 (2.1) | 1.5 | 1.6 (0.6) | −0.4 | 0.9 | 0.1 |

mean) is as much linked with the SST secular trend (1.5 counts, or ∼50% of the observed increase) as with SST natural variability and other effects (which together contribute 1.6 counts, or the remaining 50% increase). As SST-based reconstruction accounts for only 2.1 of the observed 3.1 count increase in this period, the SST secular trend contribution (1.5) dominates the SST natural variability one (0.6). Interestingly, AMO-*Atl* contributes to a 0.9 increase but this is offset by Pacific SST effects, a −0.4 count contribution.

## 4 Characteristic SST anomalies and the MDR SST record

### 4.1 Characteristic SST anomalies

Basin-scale natural variability of SST in the Pacific and Atlantic oceans accounts for almost 65% of the natural decadal variance in Atlantic TC count in view of the 0.81 correlation in Fig. 2b. As modes of decadal SST variability are already described in GN2008 and GN2009, the focus here is on the fall season SST patterns linked with natural decadal variability in TC count; the count, rather than SST, is the starting point in the analysis described here.

The SST correlations of TC-Nat (Fig. 2b, solid black) indicate the Atlantic to be quite influential (Fig. 3a). The tropical basin, including MDR (marked), and the middle-high latitude basin exhibit correlations exceeding 0.4, which are strongly reminiscent of the AMO-*Atl* mature-phase structure (cf. Fig. 5b in GN2009). SST correlations of the three constituents of 'TC-Nat Reconstructed'—Pacific natural variability, AMO-*Atl*, and the Atlantic Niño plus LF-NAO related TC indices (all in color in Fig. 2b)—are shown in Fig. 3b–d.

The Pacific correlations (Fig. 3b) principally reflect the influence of the ENSO Non-Canonical and Pan-Pacific decadal variability, given the footprint of these modes (cf. Figs. 5, 11, respectively in GN2008). The 'Pan-Pacific' name, unfortunately, does not convey this mode's substantial links to the Atlantic basin, including the MDR; the Atlantic links are as strong as the Pacific ones, and evident both here and in GN2008 (Fig. 11).

Correlations of the AMO-*Atl* which contributes most significantly to TC-Nat variations (cf. Fig. 2b) are shown in Fig. 3c; correlations are largest in the extratropical North

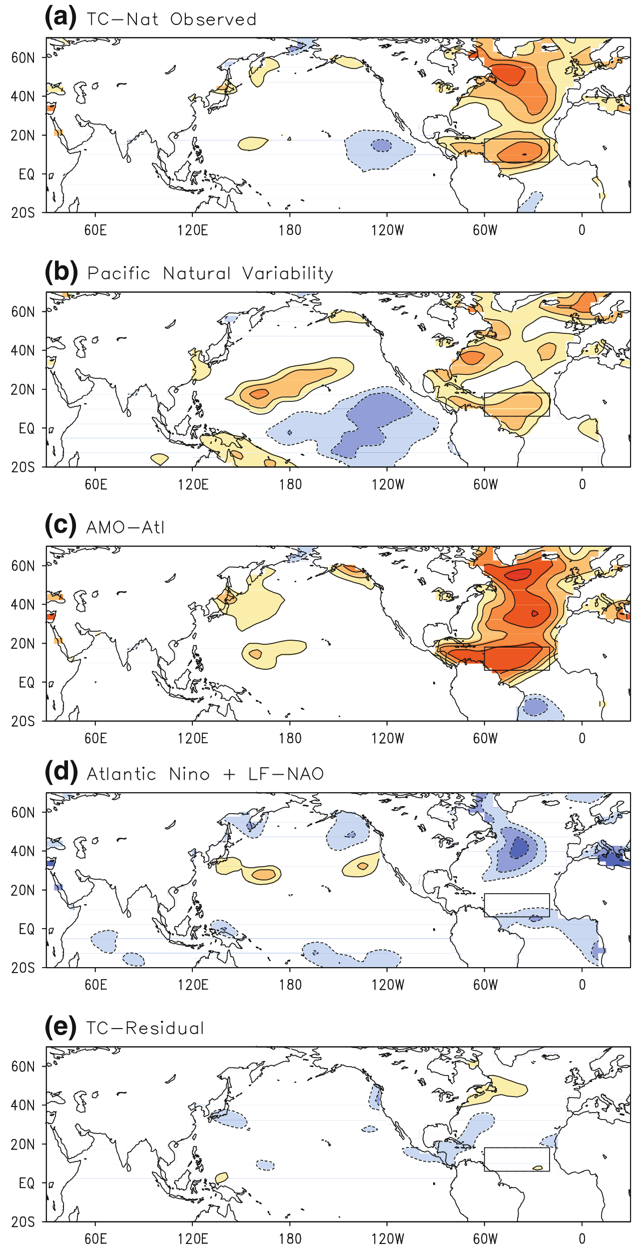



**Fig. 3** Fall season SST correlations of the annual TC count record linked with (**a**) Natural variability (TC-Nat Observed, *solid black*), (**b**) Pacific SST natural variability (*blue*), (**c**) AMO-*Atl* (*green*), (**d**) Atlantic Niño plus LF-NAO (*purple*), and (**e**) factors *unrelated* to SST variability in the Pacific and Atlantic basins (TC-Residual, 'x' marked). The bracket identifiers above refer to curves in Fig. 2b. The MDR region is marked. Solid (*dashed*) contours denote positive (negative) values and the zero-contour is suppressed. Contour interval is 0.1 and the contouring threshold 0.2. 'S*mth9*' is applied once in each map

Atlantic and the MDR. The similarity in Atlantic basin structure in Fig. 3a, c is another indication of the dominance of the AMO-*Atl* contribution in natural variability of TC count. As noted before, the AMO-*Atl* structure is obtained after factoring inter-basin links and the secular trend (GN2009), and is quite different from AMO's conventional structure: the former has a high-latitude focus with a secondary feature in the Tropics, vice versa for the latter. SST correlations of the Atlantic Niño and LF-NAO based TC index (purple curve in Fig. 2b) are weaker but not insignificant in the tropical Atlantic (Fig. 3d).

Finally, it is of some interest to examine the SST correlations of TC-Residual ('x'-marked curve in Fig. 2b), the variability in TC counts unaccounted for by the seven Pacific and four Atlantic modes of SST variability. The correlations are insignificant (Fig. 3e), indicating that the eleven basin-scale SST modes considered above are sufficient in representing the pertinent SST variability. TC count variations represented by TC-Residual are thus unrelated to any underlying SST variability.

### 4.2 Main development region SSTs

An analysis of TC counts would be incomplete without a corresponding analysis of SST variations in the main development region (MDR) of cyclones in the tropical Atlantic basin. The fall season MDR SST anomaly and annual TC count records are shown in Fig. 4a after smoothing (as in Fig. 2). Both the LVBK and HURDAT counts are plotted, for reference; the smoothed records are correlated at 0.57. The fall MDR SSTs and annual LVBK counts broadly track each other in the post-war period, when LVBK counts are smaller than HURDAT ones by 2–3. Over the full period, LVBK and MDR records are correlated at 0.57, i.e., not as strongly as the HURDAT and MDR records [0.75; as also in Mann and Emanuel (2006, Fig. 2)].

The above analysis is interesting as it suggests that MDR SSTs ('local' in context of TCs) do not account for as much decadal variance in annual LVBK counts as the Pacific and Atlantic basin SSTs (i.e., local plus remote); 32 versus 60%, respectively. This finding is not specific to LVBK counts except for the larger spread; corresponding values for HURDAT counts are 56 versus 70%. The influence of remote SSTs (e.g., Pacific ones) on TC counts is, evidently, not just from their impact on MDR SSTs.

The link between *natural* variations of TC count (TC-Nat) and MDR SST is examined in Fig. 4b. The trend in MDR SST was first removed using the SST Trend mode, just as with TC counts earlier. The resulting 0.67 correlation with TC-Nat Observed (LVBK) suggests that $\sim$45% of the natural decadal variance in counts is related to MDR SST variations, considerably less than the amount related to SST variability in the larger Pacific and Atlantic basins ($\sim$66%, cf. Fig. 2b). The additional variance explained by the non-local SSTs is thus similar for both total and natural count variability: 25 and 22%, respectively.

The MDR SST record is reconstructed in Fig. 4b from the same ten modes of SST natural variability (6 Pacific and 4 Atlantic) that were used in reconstruction of TC counts in Fig. 2b. The reconstruction is impressive (red curves correlated at 0.93) but not surprising in view of the SST-based building blocks. The rapid warming of MDR SSTs during the 1920s and early 1930s is apparently of natural origin (AMO-*Atl* related; see the green curve in Fig. 4b) whereas the recent one is a result of both the SST secular trend and natural variability (abatement of AMO-*Atl* related SST-cooling, especially in the 1990s, cf. Fig. 4b).

The contribution of Pacific SST variability (blue) and the AMO-*Atl* mode (green) in MDR SST reconstruction is also shown in Fig. 4b; both are quite influential given the 0.77 (0.64) correlation between the solid red and green (blue) curves. The AMO-*Atl*-related MDR SST is as strongly linked to TC count (0.73 correlation) as the AMO-*Atl* principal component itself (cf. Fig. 2b); as expected. The Pacific-related MDR SST, generated from the contribution of six Pacific modes through their inter-basin links, however exhibits a relation with TC count (0.10 correlation) that is much weaker than the one obtained directly from the six Pacific modes (0.60 correlation, cf. Fig. 2b). The direct impact of the Pacific on Atlantic TC activity must thus result from more than its impact on MDR SSTs: modulation of atmospheric circulation and static stability over the tropical Atlantic can be another pathway for the Pacific's impact on TC counts.

## 5 Decadal SST variability and zonal-wind shear over the tropical Atlantic

Vertical shear of the zonal wind over the tropical Atlantic basin is widely viewed as an influential environmental variable for cyclone development, impacting TC counts (Gray 1968; Goldenberg and Shapiro 1996; Aiyyer and Thorncroft 2006). The influence is well documented in case of ENSO (e.g., Aiyyer and Thorncroft 2006; Camargo et al. 2007) and is such that increased westerly shear, as during the ENSO warm phase (El Nino), is linked with diminished TC activity. ENSO's impact on the 200–850 hPa difference in zonal wind during fall is shown in the bottom panel of Fig. 5 for La Nina conditions. The interest here is on influence of the SST secular trend and select decadal variability modes on zonal wind shear over the tropical Atlantic, with the ENSO impact serving as reference,

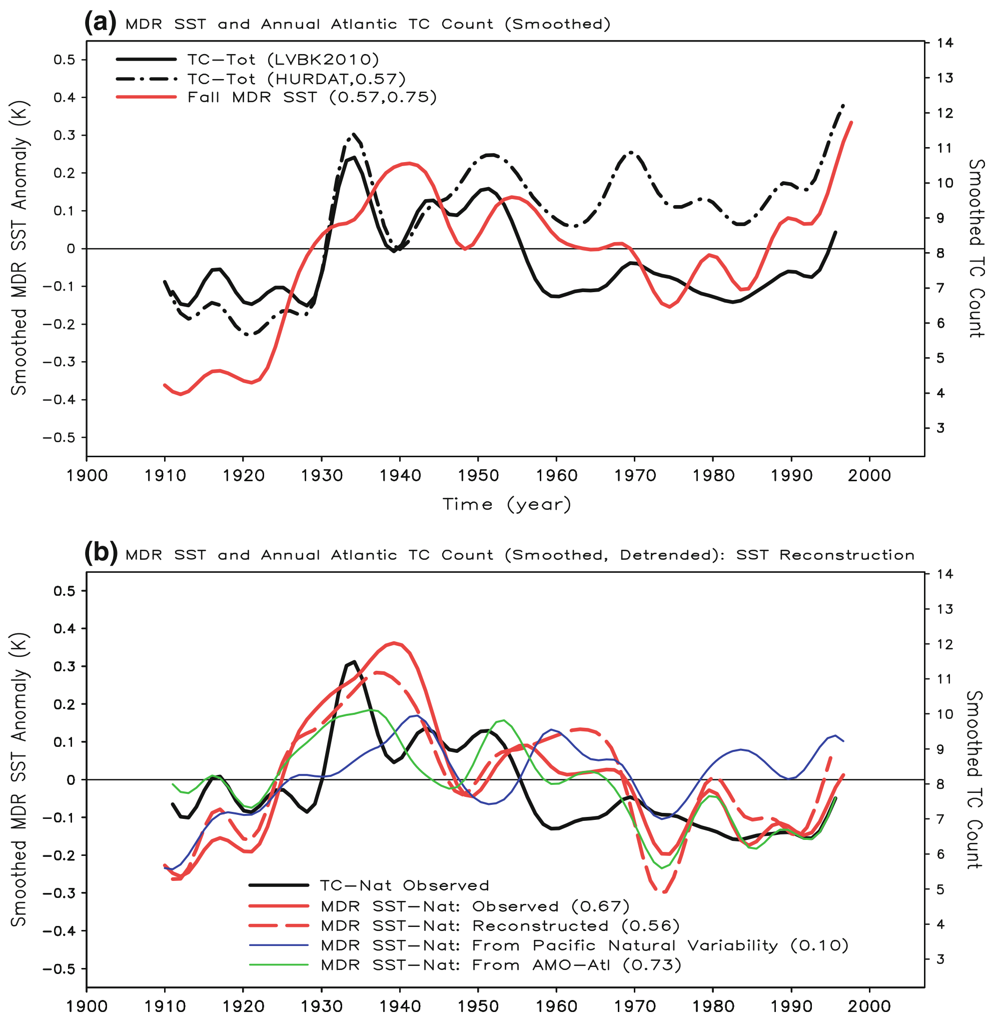
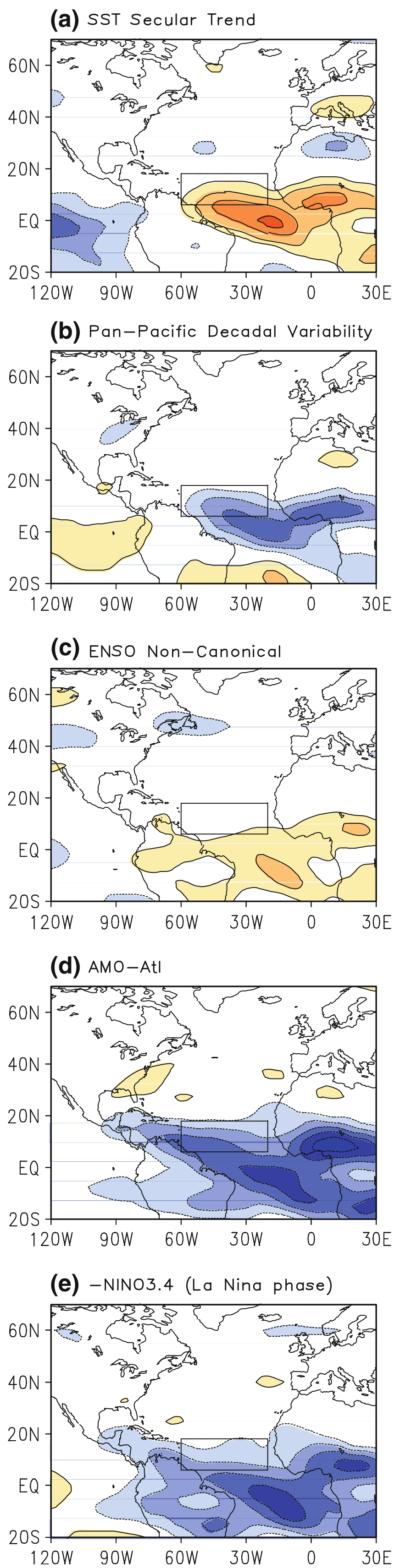



**Fig. 4** **a** Fall season SST in the Main Development Region (MDR) of the Atlantic TCs and their annual count. Both the LVBK2010 (*solid black*) and HURDAT (*dot-dash*) counts are shown after smoothing (as in Fig. 2); the LVBK record is identical to TC-Tot Observed in Fig. 2a. The smoothed records are modestly correlated with each other (0.57) and with MDR SST (0.57 and 0.75, respectively). **b** Observed (*solid red*) and reconstructed (*dashed red*) natural variability of MDR SST. The former is obtained by detrending the observed record with the non-stationary SST secular trend while the latter is generated using Pacific and Atlantic SST natural variability; solid and dashed red curves are correlated at 0.93. Contribution of the Pacific basin (*blue*) and AMO-*Atl* multidecadal variability (*green*) in the reconstruction is shown. Natural variability in observed TC counts (TC-Nat Observed, *solid black* in Fig. 2b) is also shown for reference. Smoothed counts are plotted in both panels using the right scale. Time series in both panels are smoothed by ten applications of the 1-2-1 smoother, as before. Smoothed records are correlated with TC-Nat Observed in the lower panel, with correlations stated next to the line labels

especially for what would be considered a significant wind-shear signal in context of TC modulation.

This wind-shear analysis is motivated by the finding that Pacific SST variability is influential on Atlantic TC counts (0.6 correlation, cf. Fig. 2b) but not through the correlated MDR SST variations (0.10 correlation, cf. Fig. 4b), suggesting that Pacific's influence is transmitted mainly via the atmosphere. Wind-shear regressions, computed from NCEP reanalyses, are displayed in Fig. 5; the fall-season SST PCs were smoothed just as TC counts in Fig. 2, prior to computation. Some aliasing of the secular trend and decadal variability signals is unavoidable given this smoothing but even more the shorter period of the regression analysis vis-à-vis SST analysis. The latter yields orthonormal modes but over the century-long analysis period (1901–2005); not the NCEP reanalysis sub-period.

Wind shear associated with the SST secular trend in shown in the top panel. Interestingly, the widespread but non-uniform warming of all basins (Fig. 1) is associated with enhanced westerly shear over the tropical Atlantic, including MDR, which should suppress TC activity, if the ENSO impact is any guidance. It is noteworthy that the thermodynamic (SST-warming) and dynamic (increased westerly shear with height) impacts are offsetting! Clearly,




◀ **Fig. 5** Fall-season zonal-wind shear (200−850 hPa) regressions on SST principal components of (**a**) SST Secular Trend, (**b**) Pan-Pacific decadal variability, (**c**) ENSO Non-Canonical mode, (**d**) AMO-*Atl*, and (**e**) −NINO3.4 (i.e., for the La Nina phase). Wind data is from the NCEP Reanalysis, and regressions for 1949-1995, the common period of smoothed PCs and NCEP data. Fall-season SST PCs were smoothed by ten applications of the 1-2-1 smoother (as TC counts in Fig. 2) and then re-normalized over the 1949–1995 sub-period before regression analysis. Contour interval and shading threshold is 1 m/s. Displayed fields are smoothed by one application of '*smth9*'

mechanisms generating increased westerly shear need to be investigated and the potential aliasing of decadal signals ruled out before this offset is interpreted further.

The warm phase of Pan-Pacific decadal variability which is associated with a warmer tropical-subtropical north Atlantic as well, leads to decreased westerly shear. The signal is similar to the AMO-*Atl* (warm-phase) impact (panel *d*), at least over the northern tropical Atlantic. In both cases, TC count would be enhanced, following the ENSO paradigm. ENSO Non-Canonical variability, referred in the literature also as El Nino Modoki (Ashok et al. 2007), on the other hand, is linked with a modest increase in westerly shear southward of the MDR.

## 6 Summary and concluding remarks

The twentieth century record of the annual count of Atlantic tropical cyclones is analyzed to develop consistent estimates of its natural variability and secular change components. The analysis scheme, in particular, permits development of decadal-to-multidecadal trends from natural variability alone, reducing aliasing of the variability and change components into one another. The analysis scheme is rooted in the modes of recurrent variability of the influential SST field and cognizant of inter-basin links, especially Pacific-Atlantic. The origin of increased Atlantic TC counts in the early 1930s, suppressed counts in the 1950–1960s, and the recent increase (since 1990s) is investigated to develop confidence in attribution.

Refined estimates of natural variability and secular change in TC counts are developed using SST because Atlantic TC activity has been closely linked to SST variability in the northern tropical basin (MDR; e.g., Mann and Emanuel 2006). The present analysis however begins with a more expansive view of the influential SST region in order to potentially tap all SST-related impacts on TC activity, including those transmitted from afar through the atmosphere. The ready availability of improved characterizations of natural SST variability in the Pacific and Atlantic basins, and a simultaneously obtained (and thus, more consistent) estimate of the nonstationary SST secular trend (Guan and Nigam 2008, 2009) facilitated development of a refined estimate of the secular change in Atlantic TC activity, and the resolution of its natural variability into components linked with the well-known modes of SST variability in both basins. Interestingly, SST variations related to the above non-stationary SST secular trend exhibit a weaker linear tread in the global-mean (0.39 K/century) than present in the raw SST anomalies (0.53 K/century, e.g., Trenberth and Shea 2006), i.e., about 25% weaker when decadal-multidecadal SST variability is factored in!

It is noteworthy that MDR SST is not the fulcrum but a target of this analysis, albeit a secondary one, after annual TC counts. Another analysis target is the zonal wind shear (200–850 hPa) over the tropical Atlantic, an influential environmental variable for TC activity. A newly developed Atlantic TC count data set that accounts for the increasing number of short-lived ($\leq$2 days) storms in the recent period and potentially missing TCs in the pre-satellite era (Landsea et al. 2010; referred as LVBK2010) is analyzed. We find that

- Annual TC counts can be reasonably reconstructed from the Pacific and Atlantic SST variations; the observed and reconstructed counts are correlated at 0.78, after smoothing, i.e., about 60% of the decadal variance in counts can be accounted using basin-scale SST variability, as compared to 32% using MDR SST variations. Interestingly, the nonstationary SST secular trend explains an insignificant amount of count variance.
- SST natural variability rooted in the Atlantic basin explains a larger fraction ($\sim$55%) of the *natural* decadal variance in counts than corresponding variability in the Pacific ($\sim$35%). The AMO-*Atl* mode of multidecadal variability (GN2009) dominates the Atlantic contribution while the ENSO Non-Canonical and Pan-Pacific decadal modes (GN2008) are the principal Pacific contributors; the latter has significant footprint in the western Atlantic. AMO-*Atl* contributes to the count increase in the 1930s and count-suppression in the 1970–1980s.
- It is noteworthy that multidecadal trends emerge in the TC count record reconstructed from SST natural variability alone: an upward one during the 1920–1930s and a declining one during 1970–1990 (cf. Fig. 2b). Not losing such trends to the secular change component was deemed important for credible characterization of the latter, motivating this analysis.
- *Early-1930s count increase*: a steep increase in counts in the early 1930s and an equally steep decline in the late 1930s suggest a signal in the natural variability realm. Only one-half of the signal was reconstructed (mostly from SST natural variability) but without the steep decline. The absence of this feature in the reconstruction is however not viewed as problematic given the potential undercounting during/preceding World War–II (Vecchi and Knutson 2008). In-phase contributions from the Pacific and Atlantic basins generate the count build-up in the 1920–1930s, albeit only half the signal, as noted earlier.
- *The 1950–1960s decrease*: TC counts decreased significantly in this period but the decrease could not be reconstructed from SSTs. The observation-reconstruction disagreement—the largest in the century-long record—is, interestingly, coincident with the period when global-mean surface temperature leveled off on account of rising aerosols (IPCC 2007, WG1, Mann and Emanuel 2006), leading to the hypothesis that the 1950–60s count decrease resulted from aerosol effects on SST (cooling) and cloud condensation nuclei (increasing), both consequential for TC activity.
- *The early-1990s increase*: TC counts increased from the early 1990s, in part, from the abatement of count suppression maintained by SST natural variability in the preceding decade. Were it not for this suppression, TC counts would have risen since the early 1970s itself, tracking the secular change contribution. The abatement beginning in the early 1990s is coincident with the phase change of the AMO-*Atl* mode (cf. Fig. 3, GN2009).
- *The 1996–2005 increase*: The high *average* count in this period, an additional 3.1 TCs over the long-term average of $\sim$8, is not fully reconstructed using SSTs: of the 2.1 reconstructed counts, 1.5 are linked with the SST secular trend and the remaining (0.6) with SST natural variability. Interestingly, AMO-*Atl* contributes to a 0.9 increase but this is offset by Pacific SST effects, a −0.4 contribution.
- *Main development region SST*: decadal variations of MDR SST can be reasonably reconstructed using basin-scale modes of SST variability (0.72 correlation for total reconstruction, and 0.93 for the natural variability component) but MDR SST does not emerge as a particularly significant influence on TC activity in this analysis: fall-season MDR SST accounts for only 32% of the decadal variance in annual LVBK counts (cf. Fig. 4a) as opposed to 60% by SSTs in the MDR *and* faraway regions! The additional accounting suggests that faraway SSTs influence Atlantic TC activity not only via modulation of MDR SST, i.e., thermodynamically: remotely forced dynamical influences over the tropical Atlantic (zonal-wind shear, static stability, etc.) are, apparently, no less important. Our analysis makes a compelling case for an expansive view of the domain of influential SSTs, in context of Atlantic TC activity.

- *Zonal-wind shear over tropical Atlantic*: the non-stationary SST secular trend is linked with increased zonal-wind shear (200–850 hPa) which should suppress TC activity. It is intriguing that the thermodynamic (SST-warming) and dynamic (increased westerly shear) impacts are offsetting! The net effect is one of count-increase (given the positive correlation in Table 1)—a modest one, thanks to the offset. Pan-Pacific decadal mode (having a warm footprint in the tropical-subtropical north Atlantic) leads to decreased westerly shear, much as the AMO-*Atl* mode in its warm phase. Non-canonical ENSO variability, in contrast, modestly increases westerly shear but mainly southward of the MDR.

Apportioning of the twentieth century record of annual Atlantic TC counts into natural variability and secular change components is clearly more than of academic interest. Our analysis shows that count suppression resulting from SST natural variability buffered the SST secular trend related count increase since the 1970s. It further suggests that as/when SST natural variability related count suppression abates (and augmentation begins)—some evidence for which is present in the preceding decade—Atlantic TC counts could increase rapidly on decadal timescales, perhaps, faster than before. The cold-to-warm phase flip of the Atlantic Multidecadal Oscillation in the mid 1990s is notable in this regard. The SST-unrelated effects on Atlantic counts (TC-Residual in Fig. 2b), which account for a substantial amount of decadal variance (40%) but which are not well understood at this time, will also have to be considered when making count projections.

The undertaken analysis, largely statistical in nature, provides limited insight into how the SST secular trend and decadal-multidecadal variability modes influence Atlantic TC activity. Both lower and upper tropospheric circulation variations (and static stability) associated with these modes will need characterization, for example, as in Vimont and Kossin (2007). Such effort is underway using the twentieth century reanalysis (1908–1958, Compo et al. 2006) and the ERA-40 Reanalysis (1958–2002, Uppala et al. 2005).

The obtained findings are, of course, only as robust as the quality of the Atlantic TC count record. Although a newly developed count data set (LVBK 2010) was analyzed, the count record will, undoubtedly, be further revised to account for the pending sampling concerns related to variation in monitoring efforts and the intensity/duration thresholds for counting.

The TC-count component that is unrelated to SST natural variability or secular trend presents an attractive target for immediate analysis as it accounts for almost 40% of the decadal count variance.

**Acknowledgments** The authors acknowledge support of NSF-ATM-0649666, NOAA NA08OAR4310878, and DOE-DEFG0208ER64548 and DOE-DESC0001660 grants. They thank Alfredo Ruiz-Barradas for updating the SST analyses and the three reviewers for several constructive suggestions. Bin Guan's efforts at Maryland were also supported by the Ann G. Wylie Dissertation Fellowship from the University of Maryland Graduate School.

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