El Niño, Tropical Atlantic Warmth, and Atlantic Hurricanes Over the Past 1500 Years

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Atlantic Tropical Cyclone (TC) activity, as measured by annual storm counts, reached anomalous levels over the past decade[1]. The short nature of the historical record and potential issues with its reliability in earlier decades, however, has prompted an ongoing debate regarding the reality and significance of the recent rise[2-5]. Here, we place recent activity in a longer-term context, by comparing two independent estimates of TC activity over the past 1500 years. The first estimate is based on a composite of regional sedimentary evidence of landfalling hurricanes, while the second estimate employs a previously published statistical model of Atlantic TC activity driven by proxy-reconstructions of past climate changes. Both approaches yield consistent evidence of a peak in Atlantic TC activity during Medieval times (around AD 1000) followed by a subsequent lull in activity. The Medieval peak, which rivals or even exceeds (within uncertainties) recent levels of activity, results in the statistical model from a 'perfect storm' of La Niña-like climate conditions and relative tropical Atlantic warmth.

A number of past studies have attempted to place modern Atlantic TC activity in a longer-term context using regional proxy evidence of past landfalling Atlantic hurricane activity[6-8]. Some studies[4] have sought to infer past changes in activity from plausible local conditioning factors such as wind strength and Sea Surface Temperature (SST), though the interpretations of these studies have been contested[5]. Qualitative comparisons between paleo-hurricane reconstructions appear to show some temporal coherence[8-9]. However, no past studies have attempted to synthesize multiple records from distinct regions into a basin-integrated reconstruction of Atlantic hurricane activity. Moreover, no past studies have sought to quantitatively relate estimated variations in hurricane or TC activity to reconstructions of the key large-scale climate factors known to have a significant influence on modern Atlantic TC activity. Here we produce an empirical record of past landfalling Atlantic hurricane activity by combining information from multiple sedimentary records of TC-induced overwash. Further we compare these resulting estimates to independent statistical model predictions of past TC activity driven by proxy-based large-scale climate reconstructions.

Sediment-based overwash reconstructions of TC landfall are limited in number, but span a wide geographic area across the North Atlantic basin impacted by hurricanes. Our compilation includes (Figure 1) a site from the Caribbean (Vieques, PR[6,9,10]), one from the U.S. Gulf Coast[11], one from the southeastern U.S. coast[8], three from the mid-Atlantic coast (one from New York[9] and two from New Jersey[12,13]) and two from southeastern New England (one from Rhode Island[14] and another from Massachusetts[15]) yielding 5 distinct regional series. We obtained a probabilistic estimate of past basin-wide landfalling hurricane activity using an appropriately weighted combination of the information from these 5 regional series, and incorporating radiocarbon age model uncertainties.

An independent estimate of past tropical cyclone activity was obtained using a statistical model for Atlantic TC counts. This previously developed and validated[16,3] statistical model conditions annual Atlantic TC counts on three key large-scale climate state variables tied to historical variations in Atlantic TC counts: (i) Sea Surface Temperature (SST) over the main development region (MDR) for tropical Atlantic TCs, which reflects favorability of the local thermodynamic environment, (ii) the El Niño/Southern Oscillation (ENSO) which influences the amount of (unfavorable) vertical wind shear, and (iii) the North Atlantic Oscillation (NAO) phenomena which affects the tracking of storms (which influences how favorable an environment they encounter). The statistical model was driven by proxy-based reconstructions[17,18] of these three state variables (Figure 2), yielding a predicted history of Atlantic TC counts for past centuries

We compared the sediment-based record against the above statistical estimate of basin-wide TC activity (Figure 3) guided by a working assumption that an appropriately weighted composite of regional landfalling hurricane activity varies, at multidecadal and longer timescales, in rough proportion to basin-wide TC activity. Though the validity of this assumption can (as discussed further below) be questioned, it is worth noting that the sediment-based record tracks the observed long-term changes in TC count over the historical period remarkably well (inset, Figure 3). On the basis of previously published results the required storm strength required for overwash and deposition varies among sites[19], although qualitatively similar results were obtained assuming uniform sensitivity (category 3 or greater storms) among sites. We down-weighted the Vieques data after AD 1700 to account for an estimated[9,10] artificial inflation of overwash deposit occurrences at the site due to increased sedimentation rates in recent centuries.

Our two entirely independent estimates of past TC activity were found to be statistically consistent (i.e., they overlap within their estimated 95% confident intervals), with certain exceptions, which are discussed below. Jointly, the two independent records suggest periods of high activity (i.e., comparable to current levels) during a “Medieval” era of roughly AD 900-1100. Both estimates also suggest a general decrease in the level of activity after about AD 1200[6,9].

Of particular interest is the aforementioned Medieval peak in activity, which matches or even exceeds current levels of activity within uncertainties for the statistical model. The peak arises in the latter case from a combination of (see Figure 2) La-Niña like conditions during the Medieval era which have been discussed elsewhere[21-23] and relatively warm SSTs in the tropical North Atlantic at this time[24,25], with both of these factors playing a substantial role in the statistical model predictions (Supplementary Information). In contrast, this interval is followed by a combination of relatively cold Atlantic SSTs and more El Niño-like conditions in the tropical Pacific leading to a relative lull in modeled TC activity in subsequent centuries prior to the modern increase. This finding is contrary with other recent work[4], as we do not find activity during the modern decade of the 1970s to be anomalously low in comparison with that over the past few centuries.

There are also some noteworthy discrepancies between the two independent estimates of past Atlantic TC activity provided in this study. There is some independent historical documentary evidence for increased TC activity in the Caribbean during the 1760s-1780s[26], and a modest peak at this time is evident in the statistical model estimate. The sediment-based estimate, however displays a peak that is later (early 19th century), and of considerably greater magnitude. The Medieval peak in the sediment-based record falls slightly later, than in the statistical model estimate, and is of greater duration. The peak in activity indicated by the sediment record in the mid 15th is not seen in the statistical model results.

There are a number of plausible explanations for the differences between the two records. Landfalling hurricanes do not vary in fixed proportion to the total number of storms generated on decadal timescales[1]. A form of the well known ‘ergodic hypothesis’ holds that on increasingly longer averaging timescales (e.g. the centennial timescale variations of interest in this study), variations in totals among the considerably sparser group of landfalling hurricanes will more closely mirror those in the larger group of basin-wide TCs. However, certain predictors, such as the NAO, influence not only the basin-wide activity but also the prevailing regions of landfall, and given an incomplete coastal observing network, a change in the latter could potentially masquerade as a change in the former. The sites used to produce a basin-wide sediment composite record may simply not be representative enough of the true, full basin-wide activity. This caveat applies in particular to the Caribbean, Gulf Coast, and southeast U.S. coast, since we are relying on just one record in each case to estimate past TC activity in these key regions. A jackknife estimate of uncertainty based on the removal of any one of the five contributing regions (Figure 3) nonetheless suggests that the main features of our basin-wide composite are reasonably robust (the individual jackknife surrogates are shown in Supplementary Information).

The sediment record could be contaminated by influences unrelated to hurricane strikes such as alterations to barrier morphology[27,28]. And potential biases in the proxy-based paleoclimate reconstructions[17,18] used to drive the statistical model would of course lead to biases in the statistical model predictions themselves. Finally, there is the possibility that other potential TC influences (e.g. the West African Monsoon[6]) not accounted for in the statistical model (i.e. that are not correlated with the three predictors used), may have had a more important role in the past than is evident during the modern interval.

Such uncertainties and caveats notwithstanding, the striking consistency of certain key features such as the Medieval peak in Atlantic TC activity and subsequent lull using two entirely independent approaches to estimating past activity suggest that these features are real, and provides some degree of additional validation of our current understanding of the primary factors governing long-term changes in Atlantic TC activity. Paths forward that may further improve our understanding include, among other things, development of a more extensive and diverse set of multi-proxy estimates of past landfalling hurricane activity, and improved reconstructions of the past histories of key large-scale climate phenomena influencing Atlantic TCs such as ENSO.

METHODS SUMMARY

Sediment Hurricane Landfall Records. Regional sediment series were weighted with respect to inverse modern return periods for landfalling TCs[19] and summed to yield basin-wide composites of TC activity. We employed a Monte Carlo approach to generate an ensemble of such composites consistent with the event chronologies and age model uncertainties. A basin-wide landfalling hurricane activity series was defined by the maximum rate of activity for each year over this ensemble, i.e. the maximum rate of activity for each year that is consistent with the event chronologies within uncertainties. We examined sensitivity to (i) the contributions of individual regions (issues of reliability have been raised with some events in the Gulf Coast[28] and southeastern U.S. coast[29] records), and (ii) the assumed threshold of the sites to overwash from varying strengths of hurricanes.

Statistical Model. We used a statistical model of TC counts as conditioned on[16,3]: (i) MDR SST, (ii) ENSO (measured by the boreal winter Niño3 SST index), and (ii) the boreal winter NAO index. The TC count series was first corrected for a modest estimated undercount[3] prior to the mid 20th century undercount” though similar results were obtained (Supplementary Information) using the largest[2,20] published estimates of undercount bias. The statistical model, which is trained on the modern historical record, has been shown in independent statistical validation experiments[3,16] to skillfully resolve roughly 50% of the interannual and longer-term variations in Atlantic TC counts. The model, in this study, was driven by decadally-smoothed proxy reconstructions of the three required climate indices to yield predictions of TC activity over past centuries. The MDR SST and Niño3 reconstructions were derived from proxy-based surface temperature patterns spanning the past 1500 years[17]. Though an NAO reconstruction was only available for the past 500 years[18], the NAO influence was found to be very minor (Supplementary Information).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions M.E.M. performed the statistical reconstructions of TC and hurricane activity. J.D.W. and J.P.D. provided the sediment overwash records of hurricane landfall and their uncertainties. J.D.W. provided the landfall return period estimates. Z.Z. provided the climate reconstructions used and their uncertainties. M.E.M. primarily wrote the paper. All authors discussed the results and provided input on the manuscript.

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FIGURE CAPTIONS

Figure 1. Overwash Sediment Records of Landfalling Hurricanes. Event histories are shown for New England (blue), Mid Atlantic (red), southeastern U.S. coast (cyan; gray denotes oyster bay events not used for reasons discussed by ref. 18 and in Supp Info), Gulf Coast (yellow), and Caribbean (green). Horizontal width of shaded rectangles indicates the +/- 1 sigma age model uncertainties. Circles indicate historical events.

Figure 2. Proxy Reconstructions Used in Statistical Model Estimates of Atlantic TC counts. (a) MDR SST[17], (b) Niño3 SST[17] and (c) boreal winter NAO[18]. Positive indices are associated with enhanced (a) and diminished (b,c) TC activity, respectively[16]. The corresponding instrumental series[17,18] are shown for comparison. All series are decadally smoothed[30], and 95% uncertainty intervals are indicated by shading (yellow).

Figure 3. Long-Term Atlantic TC counts. Modern Atlantic TC counts (red) compared both with statistical model estimates of TC activity based on modern instrumental (AD 1851-2006; black) and proxy-reconstructed (AD 500-1850; blue) climate indices and an estimate of basin-wide landfalling Atlantic hurricane activity (AD 500-1991) derived from regional composites of overwash sediments (green). All series were smoothed[30] at multidecadal (>40 year) timescales. The sediment composite record was standardized to have the same mean and multidecadal variance as the statistical model estimates. Uncertainties for the statistical model estimates (gray shading, indicating 95% confidence intervals) take into account the uncertainty in the statistical model itself (light gray shading), and—in the case of the proxy reconstructed indices, (darker gray shading), the additional uncertainty due to the uncertainties in the proxy-reconstructed climate indices.

Uncertainties for the sediment composite record (thin dashed black curves indicating upper and lower limits of the 95% confidence interval) are based on jackknifing of the full composite with respect to each of the 5 contributing regional estimates as discussed in text.

METHODS

Sediment Hurricane Landfall Records

A. Formation of Regional Series and Composites

Regional Landfalling hurricane Chronologies were formed based on combining sediment overwash records that fall within the same distinct (5) regions back through AD 500. The regions and associated records are:

1) New England [2 records: (i) Mattapoisett Marsh, MA (ref. 15 of article), 250 BC-present, lat: 41d 39’ 8”N, lon, 70d 47’ 13” W; (ii) Succotash Marsh, RI (ref. 14 of article), AD 1300-present, lat: 41d 22’ 45”N, lon: 71d 31’ 17”W]

2) Mid-Atlantic [3 records: (i) Alder Island, NY (ref. 9 of article), 238 BC-present, lat 40d 35’ 54”, lon 73d 34’ 45”W; (ii) Brigantine, NJ (ref. 13 of article), AD 600-present, lat: 39d 25’ 14”N, lon 74d 21’ 11”W; (iii) Whale Beach NJ (ref. 12 of article), AD 1300-present, lat: 39d 11’N, lon: 74d 40’ 17”W]

3) Southeast U.S. Atlantic Coast [1 record: (i) Singleton Swash, SC (ref. 8 of article), AD 223-present, lat 33d 46’N; lon 78d 47’ W]

4) Gulf Coast [1 record: (i) Western Lake, FL (ref. 11 of article), 1726 BC –present, lat: 30d 19’ 38”N; lon: 86d 08’ 55” W]

5) Caribbean [1 record: (i) Laguna Playa Grande Lake, Vieques, PR (ref.s 6,9,10 of article), 3461 BC-present, lat: 18 deg 5’ 31” N; 65d 31’ 3”W]

As discussed in the main article, potential biases have been noted with some of the records used, including the Western Lake record[17] and the Singleton Swash record[18]. In the latter case, an explicit attempt was made to deal with certain known problems as discussed in section ‘B’ below.

B. Processing of Individual Sediment Records:

The three oyster bed termination events (AD 223, AD 652, and AD 1283) from the Singleton Swash SC (III) record were not included in our analysis because of the uncertainty regarding the attribution for oyster reef terminations to hurricanes[11,18], as well as potentially significant and undefined age uncertainties related to reservoir effects for the dated oyster shell material. In the absence of such a correction, the chronologies of these events due not meet the age control required for our analyses.

We adjusted the Vieques record PR (V), based on the likelihood of an artificial trend in sensitivity of hurricane landfall at the site owing to a substantial increase in sedimentation rates since AD 1700[9,10]. Following Woodruff *et al*[9,] we assumed that changes in sedimentation rates result in an undercounting of approximately 11% following 1700 AD compared to 32% prior to 1700 AD, and thus down-weighted the post AD 1700 Vieques record by a factor 11%/32% (i.e., approximately one third). Alternatively, we performed an analysis in which the Vieques record was not used subsequent to AD 1700 (Supplementary Information).

C. Formation of Regional Series

In the process of forming regional composites, we attempted to eliminate redundant representation of unique events among multiple contributing records: Multiple events among contributing sites within a region that fell within the 1 sigma age model uncertainties of each other were consolidated to represent a single assumed landfall event. The date and 1 sigma ranges for the consolidated events were defined to have the average of the contributing events. When multiple events from one site fell within the age model uncertainties of an event from another site, the consolidation was done for the event for the first site that was closest in nominal age to that of the second site. This decision was motivated by the fact that known landfall events falling within the modern historical observational period are often recorded at more than one site within an identified region.

D. Formation of a Basin-Wide Event Composite

To attempt to estimate basin-wide hurricane activity from the available regional composites, we normalized each regional event composite by the number of events in that composite, and then weighted the normalized sequence of events by the estimated modern return period for that region (see section 'F' below). This process insures that each site contributes to the estimated basin average in proportion to the modern frequency of landfalling hurricanes for that region, simulating the process by which any underlying basin-wide activity is expressed in terms of regional landfall activity. The results of the analysis were not especially sensitive, however, to whether or not the data were normalized, as shown in Supplementary Figure 1. The basin-wide composite was considered as terminating in the year of the last recorded event. The latest such year in any of the chronologies was 1991.

E. Monte Carlo Ensembles

A nominal chronology of basin-wide landfalling hurricane occurrences is defined by the weighted composite as described in 'D' above. However, this nominal chronology does not take into account age model uncertainties in the chronologies. To take into account the impact of age model uncertainties, we performed Monte Carlo experiments employing ensembles of 2000 realizations where the individual events in the regional chronologies were randomly perturbed within their estimated +/- 1 sigma radiocarbon age model uncertainties. We then defined a probabilistic time series of basin-wide landfalling hurricane rates as the maximum values over this ensemble, i.e. the time sequence of the maximum occurrence rates for each year that are consistent with the event chronologies and their uncertainties.

F. Estimation of Return Periods

We estimated landfall return periods for weighting our sites based on estimated return frequencies for storms striking within a 270 km radius of the site, obtained by the HURISK statistical modeling described by Elsner et al[19]. The radius of 270 km was chosen in order to have a large enough area for obtaining appropriate statistics using the

HurRisk model, yet small enough that the return periods reflect the relative activity at a site compared to the others within the composite. The radius of hurricane impact for each site is likely less than 270 km, and therefore the return periods for overwash at each site would likely be longer than that predicted using this radius. However, these derived return periods are used only to obtain relative weights when assimilating the different records, with actual return frequencies determined by the reconstructions themselves.

It is likely that the various sites differ in the category of storm they are sensitive to. For example, the Alder Island and Mattapoisett sites are likely recording Cat. 2 or greater storms[8,15]. While there are no modern deposits at Western Lake, FL making it difficult to assess the exact sensitivity of the site, Liu and Fearn[7] estimate likely sensitivity to a Cat. 4 or greater storm. The remaining sites are likely sensitive to Cat. 3 or greater storms.

The return periods for storms at each respective site based on the HurRisk model given the above-assumed sensitivities are as follows (parentheses indicate the 5% and 95% uncertainties): (1) Mattapoisett, MA (>=Cat2): 8.52 yrs (6.31,13.09); (2) Alder Island, NY (>=Cat2): 10.15 years (7.35, 16.43); (3) Singleton Swash, SC (>=Cat3): 7.84 yrs (5.90,11.69); (4) Western Lake, FL (>=Cat4): 45.66 yrs (27.69,129.98); (5) Vieques, PR(>=Cat3): 5.37 yrs (4.22,7.39)

Since all distinct events were included in regional composites, the chronologies of the regional composites are dominated by the individual sites with the largest number of contributing events and shortest return periods. Return periods for the regional composites were therefore defined by the most active site contributing to the composite.

The mid-Atlantic composite was accordingly assigned the Alder Island return period, while the New England composite was assigned the Mattapoissett return period.

For comparison, we also examined the case where the HURISK return periods used for weighting were instead assigned based on an assumption of uniform sensitivity to a major hurricane (i.e. Cat 3 or greater storm) passing within 270 km of each site: (1) Mattapoisett, MA: 23.81 yrs (15.5,51.3); (2) Alder Island, NY: 25.71 yrs (16.25,61.45); (3) Singleton Swash, SC: 7.84 yrs (5.90,11.69); (4) Western Lake, FL: 8.78 yrs (6.58,13.16); (5) Vieques, PR: 5.37 yrs (4.22,7.39).

Alternative results from those shown in the main article based on using these latter landfall return period estimates are provided in Supplementary Information. For completeness, we also considered the extreme (and rather implausible) case where all sites are assumed to have equal return periods (Supplementary Information). In all cases, the basic features of the basin-averaged record are preserved (e.g. the elevated activity during the interval AD 900-1100), but the detailed evolution differs.

Finally, an assessment was made of the robustness of the basin-wide composite with respect to the contributions of each of the 5 distinct regions using a traditional jackknife analysis wherein each of the 5 regions (Caribbean, Gulf Coast, Mid-Atlantic U.S. coast, and New England U.S. Coast, and Southeast U.S. Coast, respectively) were one-by-one eliminated, and composites were performed using only the 4 remaining regions. The resulting 5 jackknife surrogates are shown in Supplementary Information. The spread among the 5 jackknife surrogates defines the standard errors shown in Figure 3 of the main article for the sediment composite record.

Statistical Model Estimates

A. Modern Calibration and Validation of Statistical Model

The statistical model was trained over the full (1870-2006) 137 year interval of overlap between the available instrumental climate state variables and historical TC count record as in ref. 3, and the same split calibration/validation procedure, wherein the model was alternatively calibrated and validated over the half-intervals 1870-1938 and 1939-2006, was used. The same instrumental data products were used as in ref. 3, including blended HadCRU/ERSST/Kaplan instrumental SST products for the Aug-Oct MDR SST and Dec-Feb Niño indices, and the CRU Dec-Mar NAO series. Note that the Niño3 index of ENSO (rather than the Niño3.4 index favored in ref. 3) was used, since a paleoclimate reconstruction is available only for the former and not the latter. As noted in ref. 3, however, which Niño index is used has very little influence on the resulting statistical model (statistical model resolved variance is 45%/41% for full calibration/validation, as compared with 50%/43% in ref. 3). For sake of comparison, the instrumental-based statistical model was extended back in time from 1870 to AD 1851 using the longer-term instrumental data provided by ref.s 17 and 18, as shown in Fig. 2 of the main article.

As discussed in the main article, the historical TC record was corrected for an estimated average undercount of 1.2 storms prior to aircraft reconnaissance (pre-1944) as in ref. 3., but the conclusions of our study are insensitive to whether this estimate, or the more sizable undercount bias argued by Landsea *et al* (ref.s 2,19) is used (Supplementary Information). Additional tests performed elsewhere[31] have used an alternative series we term the "MDR residual" (MDR SST-global tropical mean SST during Aug-Oct) which has been argued in certain studies[32,33] as being a preferable predictor of tropical Atlantic TC counts to MDR SST itself. These tests reveal MDR residual to be an inferior predictor to MDR SST itself across all reconstruction skill metrics and, particularly, with regard to the inability of the statistical model to reproduce the positive trend of the past two decades when this alternative predictor is used in place of MDR SST.

The statistical model was examined for adequacy with respect to regression assumptions (i.e. that the assumption of Poisson-distributed regression residuals is met), based on chi-squared and likelihood ratio tests. The statistical model trained over the full 137 year period has a residual deviance of D=107.98 with N=133 degrees of freedom. A $\chi 2$ test indicates α=0.945 (i.e., a 95% chance that we would be incorrect in rejecting the null hypothesis of Poisson distributed residuals). The null deviance (i.e. the residual deviance for an assumed fixed rate Poisson process) is D=196.91 with N=136 degrees of freedom. A likelihood test based on the difference ΔD=88.93 with N=3 degrees of freedom indicates a statistical significance of p=0.0 for the statistical model itself (i.e., a 0% chance that we would be incorrect in rejecting the hypothesis that the model coefficients for the three predictors are all zero).

B. Statistical Prediction of Pre-Instrumental TC counts Using Proxy Reconstructions

Here the model was applied to decadally-resolved reconstructions of MDR SST and Niño3 described by Mann *et al*[17] and the decadally-smoothed winter NAO index of Luterbacher *et al*[18]. For the instrumental interval (1851-present), standard errors due to uncertainties in the model coefficients were calculated from the residual decadal variance diagnosed from the validation residuals (standard errors were averaged for the early and late intervals of the split calibration/validation procedure). For the pre-1851 statistical model estimates which are driven by reconstructed climate indices, there is an additional component of uncertainty due to the uncertainties in the climate indices themselves. This contribution was estimated by Monte Carlo simulations in which the statistical model was driven with an ensemble of 2000 randomly perturbed versions of the statistical predictors consistent with their estimated uncertainties[17], and the additional random term, noted above, due to the uncertainties in the model coefficients.

Finally, to determine the separate roles of the individual predictors, we performed statistical model runs where each of the predictors (NAO, MDR SST, and Niño3) were each kept constant at their modern climatological mean value, while the other two predictors were allowed to vary (Supplementary Information).

31. Sabbatelli, T.A., Mann, M.E. & Miller, S.K. Semi-empirical projections of future Atlantic tropical cyclone activity, *J. Geophys. Res***.** (submitted).

32. Knutson, T. R., Sirutis, J.J., Garner, S.T., Vecchi, G. A. & Held, I. M. Simulated reduction in Atlantic hurricane frequency under twenty-first-century warming conditions, *Nature Geoscience* **1,** 359-364 (2008).

33. Vecchi, G. A., & Soden, B.J. Increased tropical Atlantic wind shear in model projections of global warming, *Geophys. Res. Lett.* **34**, doi:10.1029/2006GL028905 (2007).

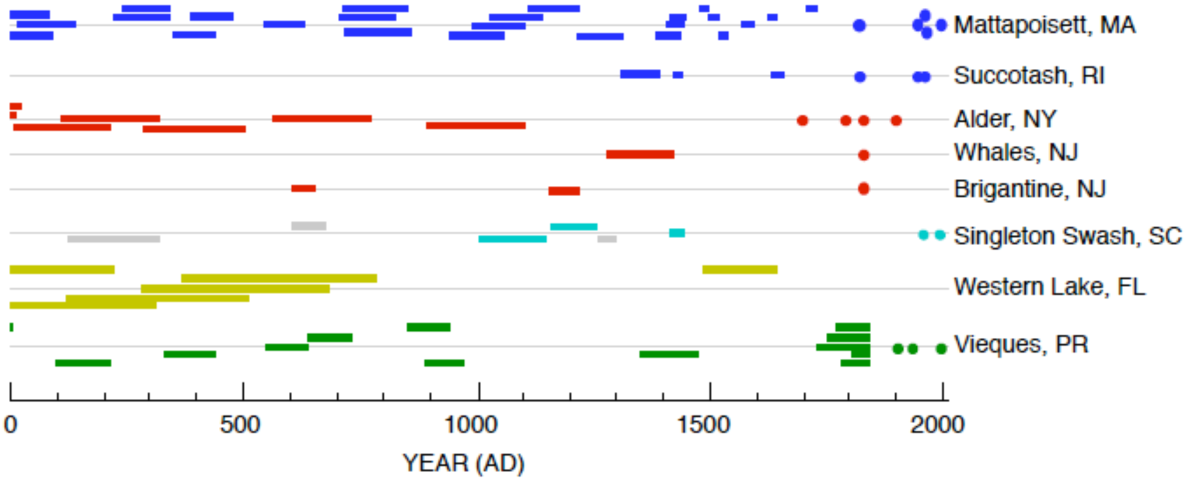
Mattapoisett, MA
Succotash, RI
Alder, NY
Whales, NJ
Brigantine, NJ
Singleton Swash, SC
Western Lake, FL
Vieques, PR
0
500
1000
1500
2000
YEAR (AD)

FIGURE 1

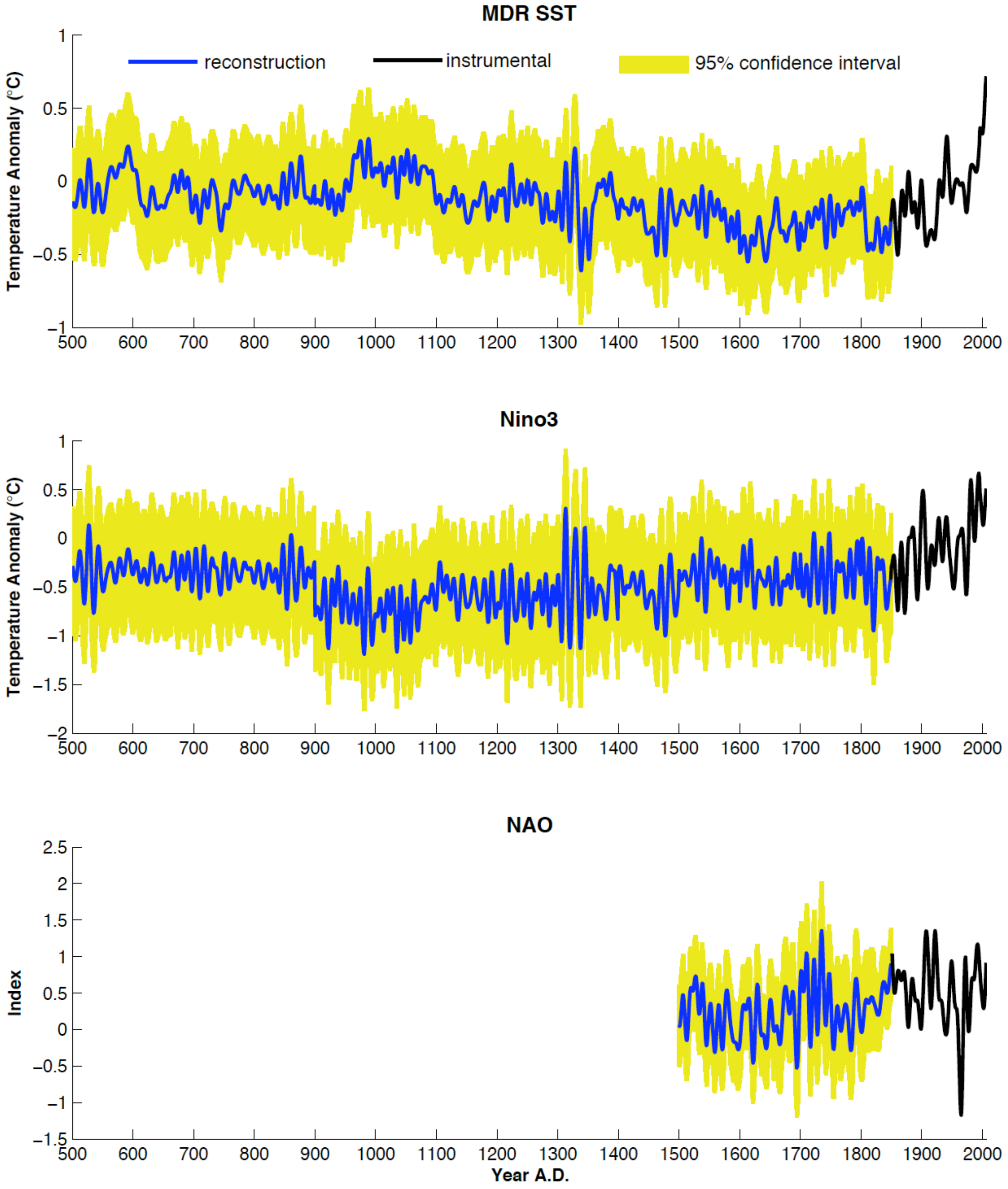
MDR SST
reconstruction
instrumental
95% confidence interval
Temperature Anomaly (°C)
1
0.5
0
−0.5
−1
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Nino3
Temperature Anomaly (°C)
1
0.5
0
−0.5
−1
−1.5
−2
NAO
Index
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
Year A.D.

FIGURE 2

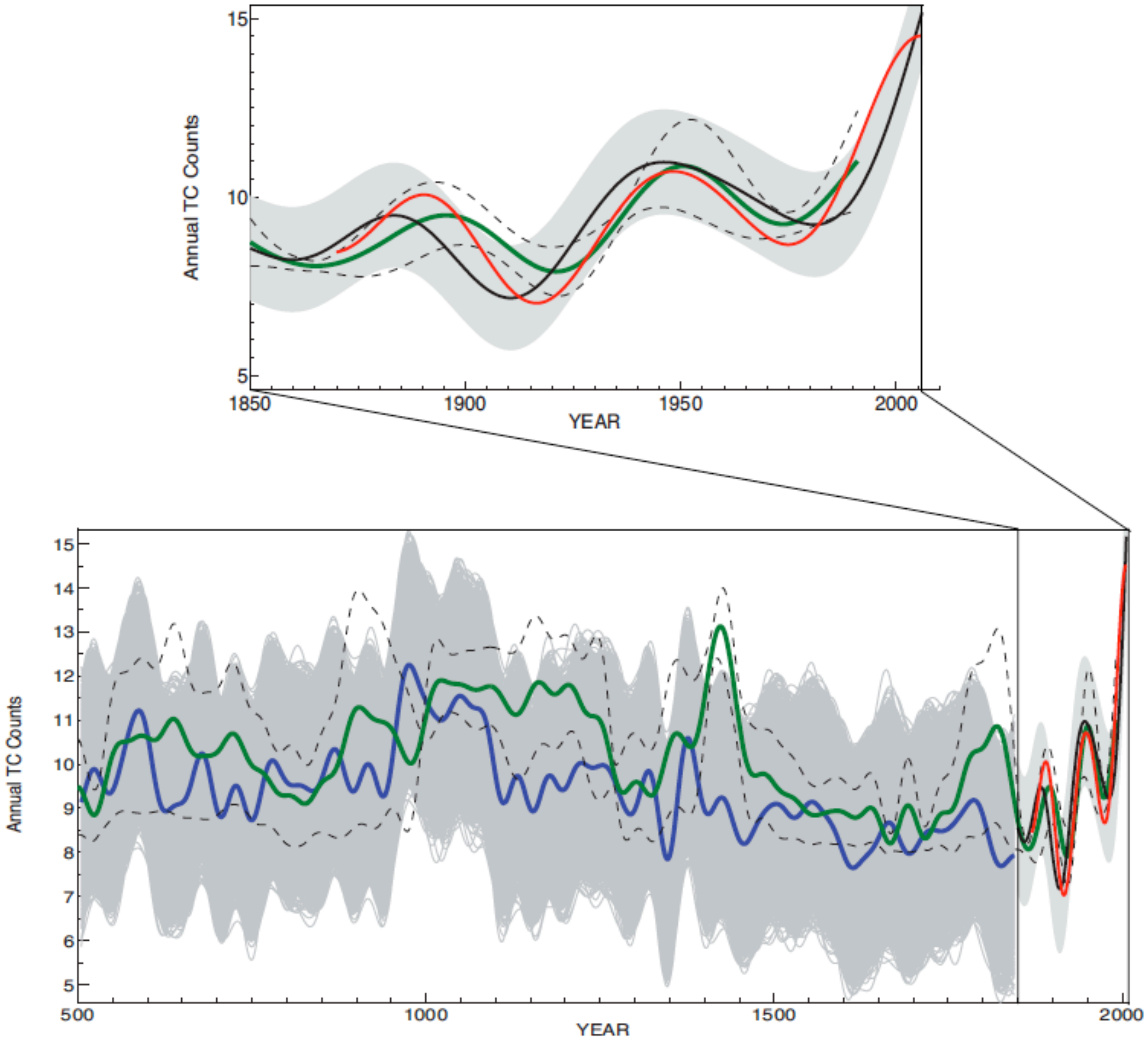
Annual TC Counts
15
10
5
1850
1900
1950
2000
YEAR
Annual TC Counts
15
14
13
12
11
10
9
8
7
6
5
500
1000
1500
2000
YEAR

FIGURE 3