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Long-term variations of North Atlantic tropical cyclone activity downscaled from a coupled model simulation of the last millennium

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[1]   The observed historical record of North Atlantic tropical cyclones (TCs) is relatively short and is subject to potential biases owing to a lack of observation platforms such as aircraft reconnaissance and satellite imagery in earlier decades. Therefore, studies of long-term variability in TC activity are hindered by the limitations and uncertainty within the historical data. An alternative approach is to study long-term Atlantic TC variability within the framework of a coupled ocean-atmosphere climate model simulation. We have taken such an approach using a simulation of the National Center for Atmospheric Research Climate System Model 1.4 forced with estimated natural and anthropogenic forcing over the past millennium. Atmospheric variables from the long-term model simulation are used to drive a recently developed downscaling relationship that simulates TC genesis and tracking over the course of the 1150 year model simulation. This downscaling process generates a long-term synthetic TC track data set, free of observational biases, though subject to limitations in the model climatology. The synthetic TC data are used to perform an analysis of long-term variability in Atlantic TCs, specifically focusing on TC landfalls, within the context of the coupled model simulation. Ultimately, analysis of various TC time series reveals that counts of landfalling TCs and even landfalling hurricanes track relatively well with the total basin-wide TC activity on multidecadal and longer timescales.

1.   Introduction

[2]   Over the past several decades, the scientific community has made significant strides in explaining connections between North Atlantic tropical cyclones (TCs) and the regional and global climate using observational records and a number of other data sets. For example, past studies have established significant connections between Atlantic TC variability and a number of climate variations including, but not limited to, underlying sea surface temperatures or potential intensity [e.g., *Gray*, 1968; *Emanuel*, 1995; *Emanuel*, 2005], the El Niño Southern Oscillation [e.g., *Gray*, 1984; *Bove et al.*, 1998], and the Northern Atlantic Oscillation [e.g., *Elsner et al.*, 2000; *Elsner*, 2003; *Elsner and Jagger*, 2006; *Frank and Young*, 2007].

[3]   Unfortunately, however, analyzing TC variability within the historical record of Atlantic TCs [*Jarvinen et al.*, 1984] is not without its own imperfections. The relatively short observed record only spans the past century and a half (1851 to present), which represents a limitation in assessing long-term trends in TC activity. Recent studies have also argued that the observed record is subject to a potential undercount bias in earlier decades as a result of poorer observations and the absence of measurement techniques such as aircraft reconnaissance and satellite imagery, though the magnitude of this bias is somewhat in dispute [e.g., *Landsea*, 2007; *Chang and Guo*, 2007; *Mann et al.*, 2007a, 2007b]. Such biases potentially limit conclusions regarding trends and low-frequency variations in TC behavior based on analysis of the historical record. Studies of the most destructive tropical cyclone events, such as hurricane landfalls, are particularly difficult because intense hurricanes and TC landfalls represent only a small fraction of the observed record, implying greater sampling uncertainties.

[4]   An alternative approach that can avoid some of these shortcomings in the observed record involves the analysis of idealized millennium-long coupled ocean-atmosphere climate model simulations. Taking such an approach, we have used a millennium-long forced simulation of an earlier version of the National Center for Atmospheric Research's (NCAR) fully coupled Climate System Model [*Boville and Gent*, 1998] as a test bed to analyze long-term tropical cyclone landfall variability. Within the confines of this long-term climate

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simulation, a record of synthetic tropical cyclones may be created using a recently developed statistical and dynamical downscaling relationship [*Emanuel et al.*, 2006; *Emanuel et al.*, 2008]. This process produces an idealized, yet statistically realistic, database of TC genesis, tracking, and intensification across the entire North Atlantic basin over a millennial (A.D. 850–1999) period.

[5] With this synthetic TC record, it becomes possible to examine long-term trends in North Atlantic TCs without the limitations of the existing historical record. The millennium-long synthetic track data set has a larger sample size of TCs and TC landfalls than does the relatively short historical best track record, allowing a more complete analysis of long-term variability of Atlantic storms, albeit within the limitations of the faithfulness of the model-simulated atmospheric environment. This larger sample size is especially useful for examining long-term characteristics of more societally relevant storms, namely landfalling storms, which are less numerous in the observational record. Therefore, the focus of this study will be to examine TC landfalls by analyzing the millennium-long synthetic TC data set and a number of basin-wide and landfall-specific time series derived from the long-term simulation. Ultimately, comparisons of these landfalling series to series of annual basin-wide counts, and various climate state variables, may lead to a better understanding of the most destructive Atlantic TCs within the context of this simulation and beyond.

2. Data and Methods

[6] The coupled ocean-atmosphere climate model used here to generate a synthetic climate of the past millennium is the NCAR Climate System Model, version 1.4 (CSM 1.4) [*Boville and Gent*, 1998], which employs NCAR's Community Climate Model, version 3.0 (CCM 3.0) [*Kiehl et al.*, 1998] run at T31 resolution (3.75° × 3.75°). The CSM 1.4 simulation used here spans the past millennium (A.D. 850–1999) and is forced by both estimated natural (solar and volcanic) and anthropogenic (greenhouse gas and sulphate aerosol) forcings [*Ammann et al.*, 2007].

[7] Noteworthy caveats with regard to the faithfulness of the CSM 1.4's simulated climate over the Atlantic basin include a climatological bias toward too much vertical wind shear in the region and slightly cooler North Atlantic sea surface temperatures (SSTs). These two biases relate to a known issue prevalent in other models in which strong anomalous upper ocean warming is present along the eastern boundaries of the world's oceans [*Large and Danabasoglu*, 2006; *Done et al.*, 2013]. This anomalous upper ocean warming is particularly relevant to Atlantic TC activity because the warming in the eastern equatorial Pacific creates a semipermanent El Niño-like feature [*Done et al.*, 2013] which results in an increase in North Atlantic wind shear and decreased tropical Atlantic SSTs, both of which tend to suppress Atlantic TC activity [*Gray*, 1984]. Additionally, the model simulation analyzed fails to reproduce the observed lower-stratospheric cooling trend in recent decades when compared to recent reanalyses such as NCEP-Department of Energy Reanalysis-2 [*Kanamitsu et al.*, 2002]. The lack of a modern upper-atmospheric cooling trend in the CSM 1.4 could be a result of the fact that simulated ozone concentrations in the model have a varying seasonal cycle but do not vary from year to year.

This bias in the modern era relates to TC activity because cooling in the storm's outflow region results in an increase in potential intensity [*Emanuel et al.*, 2013], meaning that a lack of stratospheric cooling could suppress any tendency for increasing TC activity in recent decades.

[8] Tropical cyclones are generated within the framework of the idealized model simulation using a downscaling method based on large-scale conditions prescribed from the monthly mean thermodynamic state variables of the model, including sea surface temperature and the vertical profiles of temperature and humidity, and daily mean values of interpolated 250 hPa and 850 hPa meridional and zonal winds. The downscaling method [*Emanuel et al.*, 2006; *Emanuel et al.*, 2008] uses these atmospheric variables to produce tropical cyclone genesis, intensities, and tracks. Tropical cyclogenesis is initiated first in this method by randomly seeding warm core vortices with peak winds of 12 m s^{-1} in space and time across the Atlantic Basin, excluding areas poleward of 75°N or equatorward of 3°N. As a result of the random seeding, many of the disturbances suffer from waning intensities at genesis and fail to ever reach maximum sustained winds greater than 20 m s^{-1} because of unfavorable environmental wind shear and/or low potential intensities. Storms that fail to develop are discarded from the synthetic TC data set. To account for a certain number of discarded storms each year, we randomly seed N disturbances ($N \geq 25$) across the Atlantic Basin such that exactly 25 TCs develop annually (peak winds exceed 20 m s^{-1}). Twenty-five storms per year was chosen, as opposed to a more realistic number such as ten, to provide a large enough sample size of storms to properly assess the distribution of each year's TC characteristics (intensity, track, landfalls, etc.). Ultimately, the time series of TC frequencies discussed later in this section are calculated by assessing the distribution of the 25 storms each year and then scaling the relevant parameter (total number of storms, landfalls, etc.) by the ratio of 25 to N and a rate constant calibrated to observed global TC frequency.

[9] Tracks of the tropical cyclones are governed by a beta-and-advection model, driven by the variances and covariances of the 250 hPa and 850 hPa wind components derived from the CSM 1.4. Lastly, storm intensities through each storm's life cycle are generated via the Coupled Hurricane Intensity Prediction System (CHIPS) [*Emanuel et al.*, 2004] with potential intensity, present-day climatology of the upper ocean thermal structure, atmospheric wind shear, temperatures, and humidity all derived from the CSM 1.4 simulation. The intensity of a chosen storm at a given time is calculated by summing its axisymmetric tangential wind speeds (from CHIPS) and a fraction (70%) of the storm's translational speed.

[10] Within the synthetic TC database, it is possible to create annual histories of basin-wide TCs and TC landfalls (Figure 1). The time series that are diagnosed from the downscaling experiments include annual counts of various categories of landfalling TCs: (1) total (i.e., U.S. as well as Canadian/Caribbean/Latin American/African/European) landfalling Atlantic tropical cyclones, (2) total landfalling hurricanes (sustained winds $\geq 33 \text{ m s}^{-1}$; accounts for 33% of all TC landfalls in the simulation), (3) total landfalling major hurricanes (sustained winds $\geq 50 \text{ m s}^{-1}$; accounts for only 7.5% of all TC landfalls in the simulation), (4) United States (For the purposes of these time series, the United States is defined to include the Eastern seaboard and the Gulf Coast,
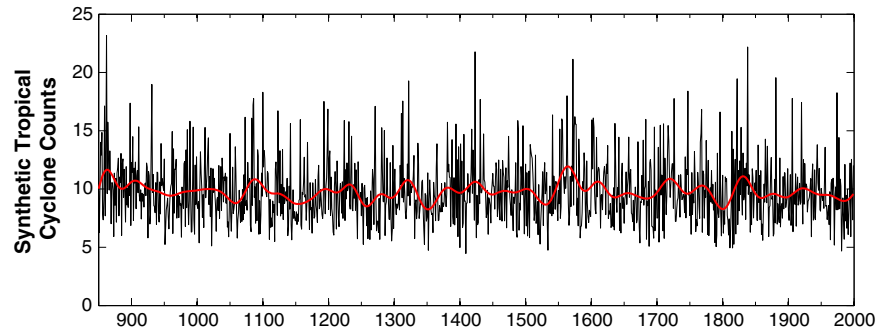
Figure 1. A plot of North Atlantic tropical cyclone counts over the duration of the climate simulation (850–1999). The annual TC counts created within the CSM 1.4 by the downscaling methods described in the text are shown by a thin black line. The thick red line represents the same TC time series smoothed to emphasize multidecadal and longer timescales as described in the text.

but not the United States territories such as Puerto Rico or the United States Virgin Islands.) only landfalling TCs, (5) U.S. landfalling hurricanes, and (6) U.S. landfalling major hurricanes. In addition to the landfalling time series, we computed annual counts of (7) basin-wide tropical cyclones, (8) basin-wide hurricanes, and (9) basin-wide major hurricanes, wherein the intensity of these overall basin-wide counts is classified using the highest maximum sustained wind speed over the course of the life of the TC.

[11] Meanwhile, the landfall-specific time series are obtained from the simulation, such that each landfalling TC is classified by the latitude and longitude at which the storm strikes land for the first time. Therefore, since TCs occasionally make secondary and/or tertiary landfalls, our landfall-related time series represent the number of landfalling TCs rather than the total number of landfall events. The landfall intensities used to classify each landfalling TC are determined by the maximum sustained wind speed at the time of each storm's initial landfall. In this methodology, the landfall positions and intensities are limited in accuracy to within the 2 h time resolution of the synthetic TC data. The dependence on the 2 h step between data points in the synthetic TC record results in slightly underestimated landfall intensities for

many of the simulated storms because they could be weakening over land for as many as 2 h before their landfall intensity is gathered. In addition, the model simulation and landfall detection algorithm is unable to resolve the smaller islands and island chains in the tropical North Atlantic Basin, such as Bermuda, the Bahamas, the Florida Keys, and much of the Lesser Antilles. Therefore, TCs that make landfalls only on these islands will not be included in the landfall series.

3. Analysis of the Millennial Synthetic TC Record

3.1. Basin-Wide Tropical Cyclone Climatology

[12] The simulated annual basin-wide TC series is shown along with its smoothed counterpart in Figure 1. For the purpose of further discussion and comparisons, this and other long-term series have been smoothed to highlight multidecadal and longer timescales using a low-pass filter [*Mann*, 2008] with a half-power cutoff at $f = 0.025$ cycles/year, corresponding to a 40 year period. Substantial multidecadal and centennial-scale variability is observed throughout the millennial-length record, including the modern observational era. There is an average of 9.5 synthetic TCs per year in the North Atlantic basin over the twentieth century, comparable to
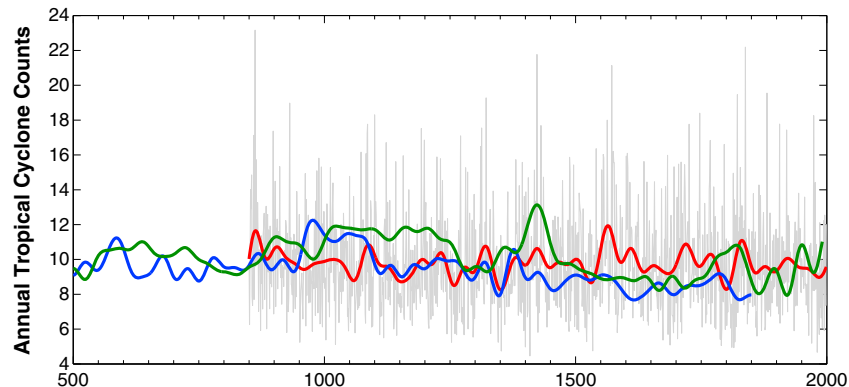

Figure 2. Plot of long-term North Atlantic tropical cyclone counts from the synthetic TC record presented in this study along side of two previously developed long-term reconstructions. The light gray curve and the red curve are the unsmoothed and smoothed synthetic TC counts (850–1999), as presented in Figure 1. The blue curve is a statistical model estimation of long-term Atlantic TC activity (500–1850) from *Mann et al.* [2009a]. The green curve is a reconstruction of landfalling Atlantic Hurricanes based on coastal overwash deposits (500–1991), also from *Mann et al.* [2009a] (the latter record has been restandardized to have same mean and variance as the basin-wide TC series).
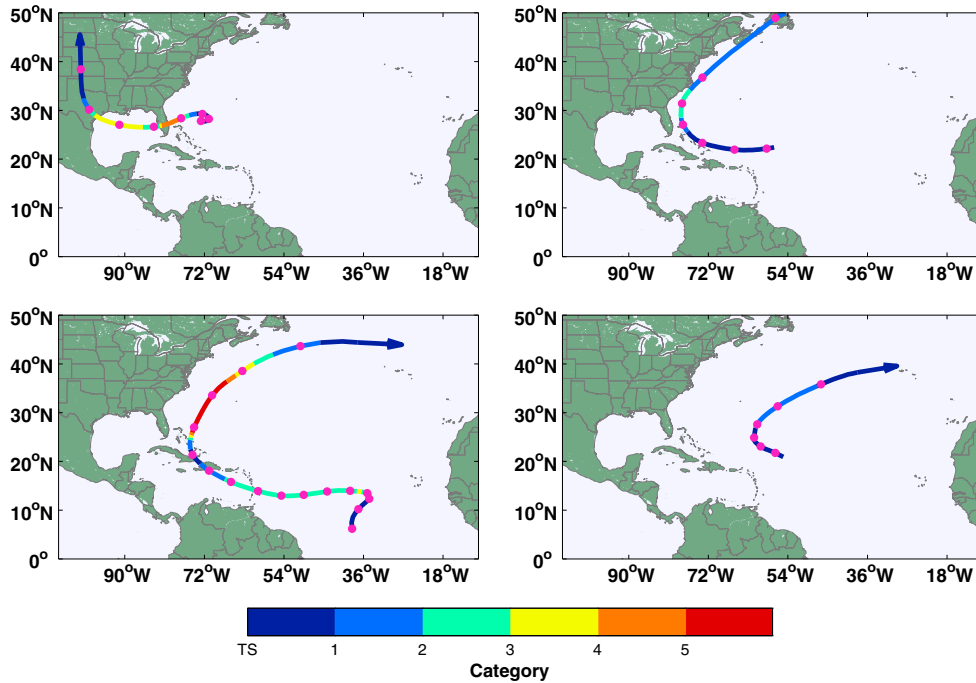
Figure 3. Maps of four synthetic TC tracks within the 1150 year model simulation. The magenta dots on the tracks represent the 00Z positions, and the tracks are color coded by intensity on the Saffir-Simpson Wind Scale. Each of the four storms was selected randomly in order to show the wide variety of storms and storm tracks within our synthetic database. The TC track and intensities are calculated using the downscaling method described in section 2.

the observational twentieth century mean of 9.2 TCs annually and to a lesser extent the mean of 11.7 named storms per year in the post satellite era portion (1966–2012) of the best track hurricane database (HURDAT) [*Jarvinen et al.*, 1984]. This result is to be expected as the downscaling methods are tuned toward current TC frequencies [*Emanuel et al.*, 2008]. Synthetic TC activity during the observational period is below the 1150 year average.

[13] It is possible to reconstruct historical Atlantic TC behavior further back, prior to the modern historical era, albeit with substantially expanded uncertainties. We compare the long-term trends in our millennial synthetic TC data set with reconstructions over the past millennium derived from different types of paleoclimate proxy information. Specifically, we compare with a reconstruction of basin-wide Atlantic TC counts based on a statistical model of TC activity driven by proxy-reconstructed climate indices [*Mann et al.*, 2009a] and an estimate of landfalling hurricane activity based on a composite of coastal overwash sediment records spanning the U.S. East Coast, the Gulf Coast, and the Caribbean [*Mann et al.*, 2009a]. The low-frequency variations in these two reconstructed tropical cyclone histories are compared with the simulated TC record in Figure 2. The series are qualitatively similar in their overall variability, though the two reconstructions exhibit somewhat greater century-scale fluctuations than the synthetic series analyzed here. The simulated and reconstructed series differ in certain key details. Missing from the synthetic series is the peak in activity around A.D. 1000, attributed in the reconstructions [*Mann et al.*, 2009a] to both warm Atlantic SSTs and a La Niña-like pattern at that time. Such discrepancies in the specific features of simulated and reconstructed TC series are expected

given that the features of the CSM 1.4 simulated climate of the past millennium differ substantially in key respects from the features evident in the proxy record. Notably absent from the CSM 1.4 simulation, for example, is the La Niña-like anomaly found in the proxy climate reconstructions [*Mann et al.*, 2009b]. It is possible that some of the differences between the CSM 1.4 climate and other long-term data sets are a result of internal variability, wherein the model-simulated variability cannot be expected to match the phase of the observed internal variability.

[14] In terms of storm motion, the synthetic TCs in our model generally have realistically shaped tracks, despite relying on the simplistic beta-and-advection model for tracking. A random sampling of storm tracks indicates that the synthetic TCs sometimes travel in loops and can make abrupt turns, as is seen in modern observations (Figure 3). Despite the realistic tracks, however, the synthetic TCs do exhibit a significant spatial bias. Figure 4a is a plot of observed TC tracks from HURDAT over the interval 1851–2005, and Figure 4b is a plot of an identical number of synthetic TC tracks in our model simulation during the overlapping time period of 1851 to 1999. A comparison of these two track maps reveals an eastward bias in the synthetic TC tracks. For example, TCs recurve much earlier in the model simulation than storms in the historical record, such that most synthetic storms remain over the open waters of the Atlantic instead of entering the Gulf of Mexico or approaching or striking the Eastern Seaboard of the United States. In some instances, eastern Atlantic storms recurve so rapidly that they unrealistically strike the West African coast.

[15] This eastward track bias likely can be attributed to the model and procedural biases noted in section 2. The randomly
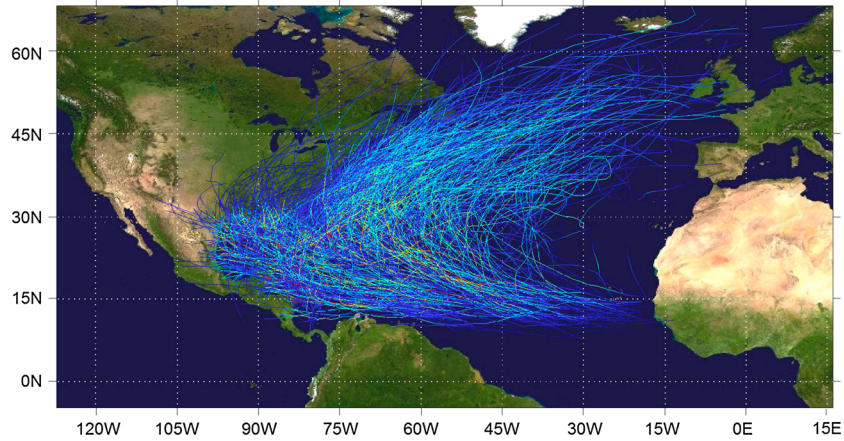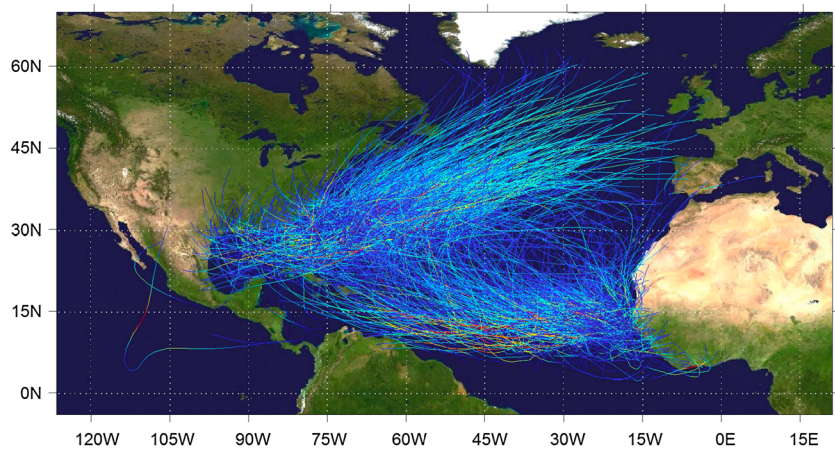
a) Observations

b) Model Simulation

Figure 4. Observed and simulated North Atlantic TC tracks over the modern observational period. (a) The observed tracks from HURDAT over the years 1851–2010. (b) An identical number of synthetic tracks from the climate simulation, which were randomly selected during an overlapping period of 1851–1999. An eastward bias in the synthetic tracks is visible in the comparison of these two plots. As a result, the number of North American landfalls is significantly lower in the model simulation when compared to observations (Table 1).

seeded disturbances require at least marginally favorable conditions to develop; therefore, the environmental biases within the CSM 1.4 are likely to cause biases in TC behavior. Compared to modern reanalysis [*Kanamitsu et al.*, 2002] and observations, the CSM 1.4 has excessive climatological peak-season vertical wind shear between 200 and 850 mbar across nearly the entire basin, especially over the Caribbean Sea and the Gulf of Mexico where these wind shear biases exceed 15 knots. The only region within the Atlantic Basin that has diminished shear on average is near the African coastline south of 15°N, which is an area of enhanced synthetic TC activity. This wind shear bias, in addition to cooler western Atlantic SST anomalies, makes the model environment in the western half of the basin unfavorable for TC development, and as a result, the biases are consistent with the eastward shift seen in the synthetic TC tracks. The downscaling procedures could also contribute to the eastward synthetic track bias to a lesser degree. Specifically, the random genesis mechanism, which does not require incipient disturbances for genesis, may result in more uniformly distributed genesis locations. If all else remains equal, a more uniform genesis distribution would

result in an eastward track bias because observed genesis occurs most often in the western half of the basin.

3.2. Tropical Cyclone Landfalls

[16] As should be expected, the eastern track bias in the long-term simulation has some ramifications on the characteristics of the TC landfall series. For example, the tendency of TCs to recurve too rapidly in the eastern and central Atlantic severely limits the number of Cape Verde-type storms that eventually make a North American landfall (Figure 5). Therefore, as might be expected, the vast majority of synthetic landfalling TCs that strike land west of 40°W originate from regions near the coast, such as the Gulf of Mexico or the extreme western North Atlantic (Figure 5). As a result, most of the U.S. landfalling storms in the simulation also originate from TCs in the western Caribbean Sea and Gulf of Mexico; this is consistent with the observations of *Lyons* [2004], who found that TC numbers in these regions are well correlated to the observed number of United States hurricane landfalls. However, the number of synthetic storms in the western Caribbean Sea and Gulf of Mexico is
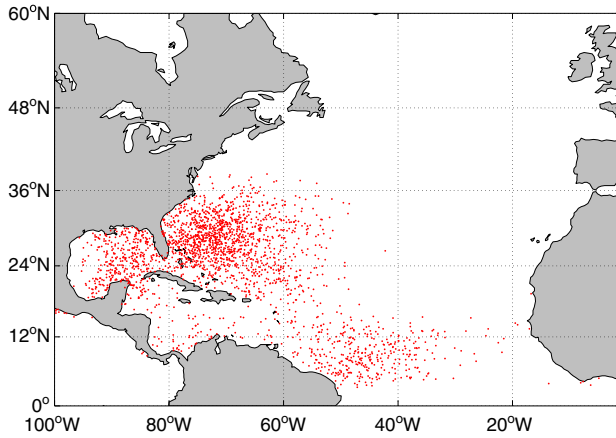
Figure 5. Coordinates of tropical cyclogenesis for all storms within the millennial simulation (850–1999) that would later strike a landmass west of 40°W at hurricane intensity (1 min sustained winds $\geq 33\,\mathrm{m\,s}^{-1}$). The landfall locations for each of these storms are plotted in Figure 9.

underestimated (Figure 4), consistent with the CSM 1.4's wind shear biases discussed in sections 2 and 3.1. The resulting simulated landfall rate also has a significant low-bias between 1900 and 1999 when compared to the observations (Table 1). Although the observed record of basin-wide TCs itself suffers from potential limitations and biases owing to limitations in the observational network [*Landsea*, 2007; *Mann et al.*, 2007b], it is extremely unlikely that the substantial discrepancies between the observed and modeled TC climatologies can be explained by these biases. The fact that between 1900 and 1999 only roughly one third of all basin-wide TCs make landfall in the simulations versus nearly one half in the observations (Table 1) likely results in large part from the greater tendency for recurvature in the synthetic TC tracks due to biases in the large-scale Atlantic climatology in the CAM (Community Atmospheric Model) [see *Emanuel et al.*, 2008] global climate model (GCM) being analyzed. The discrepancy between synthetic and observed landfalling United States hurricanes (6% and 18% of all TCs, respectively) is further affected by a combination of biases in the landfall detection algorithm (e.g., underestimated landfall intensities) and unusually high climatological wind shear in the tropical Atlantic in CAM [see *Emanuel et al.*, 2013]; the CAM's overestimate of the climatological wind shear suppresses the development and strengthening of TCs into hurricanes. Overall, this low bias in North Atlantic TC frequency is consistent with the results of *Emanuel et al.* [2008] for the CAM3.0.

[17] Even given the acknowledged caveats on simulated North Atlantic TC frequency and tracks compared to the modern record, the millennial record afforded by the simulation results in a much greater sample size of landfalling storms than the sample size within the comparatively short observed record. This large synthetic landfall sample allows for robust conclusions regarding the relationships and variability of landfalling events with basin-wide storms in the context of this idealized simulation. Thus, the various smoothed time series of synthetic landfalling storms are compared in Figure 6 (total landfalls, total hurricane landfalls, and total major hurricane landfalls) and Figure 7 (United States landfalls,

Table 1. Observed and Simulated Landfall Statistics During the Twentieth Century[a]

Landfall Statistics (1900–1999)		
Observational Record	Total	Percentage
Basin-wide tropical cyclones	**919**	
United States landfalling hurricanes	**162**	18%
All landfalling tropical cyclones	**509**	55%
Climate simulation	Total	Percentage
Basin-wide tropical cyclones	**948**	
United States landfalling hurricanes	**58**	6%
All landfalling tropical cyclones	**283**	30%

[a]The total number of basin-wide TCs, U.S. landfalling hurricanes, and all landfalling TCs are listed in a bold font. The percentage of U.S. landfalling hurricanes and total landfalling TCs, with respect to the total number of basin-wide TCs, is listed to the right of the total counts. For the sake of consistency, landfall statistics shown for both the observations and the climate simulation does not account for landfalls in smaller islands throughout the basin (Bermuda, Lesser Antilles, etc.).

United States hurricane landfalls, and United States major hurricane landfalls). There is notable correspondence between the multidecadal and longer-term fluctuations in TCs among the various categories. Both total and U.S. landfalling storms (Figures 6 and 7) show the same basic oscillations that arise from a combination of forced and internal climate variability in the CSM 1.4.

[18] Ostensibly, the multidecadal variations within these synthetic landfall series can be primarily attributed to variations in overall storm frequency, genesis locations, and track direction/duration. The United States TC landfalls (Figure 7) and basin-wide storm frequency (Figure 1) are correlated at $r = 0.65$, corresponding to 42% shared variance. In addition, the U.S. TC landfalls are correlated to the mean genesis longitude at $r = -0.50$, corresponding to 25% variance. Since mean genesis longitude and overall frequency are nearly independent ($r^2 < 0.01$), approximately two thirds of the variance in U.S. landfalling TCs can be explained by these two quantities. The remaining unexplained variance (33%) can be attributed to additional storm and environmental factors governing their track and intensity evolution.
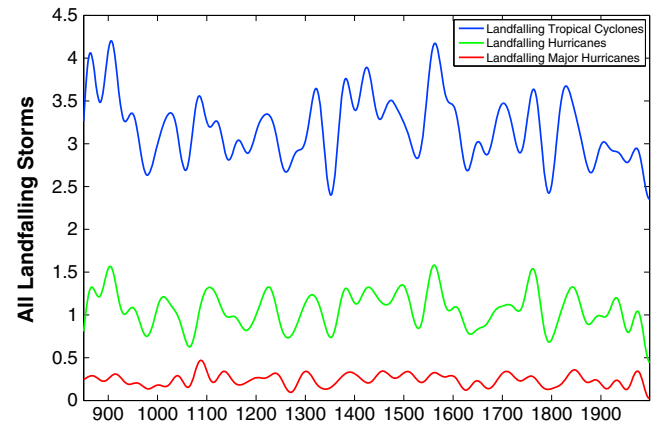

Figure 6. Time series of various TC landfalls (850–1999). A series of all landfalling TCs is indicated by a blue curve. Those storms that made their initial landfall as a hurricane are indicated by the green curve, and TCs that made their initial landfall as a major hurricane are represented by a red curve. The time series have been smoothed as described in the text.
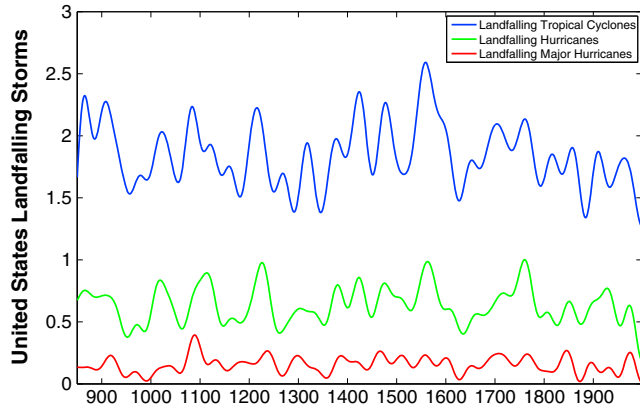
Figure 7. Time series of United States landfalling storms (850–1999). U.S. TC landfalls are indicated by the blue line, U.S. hurricane landfalls are indicated by the green curve, and U.S. major hurricane landfalls are represented by the red curve. These counts include storms that made their first landfall along the continental United States. The time series have been smoothed as described in the text.

[19] To build upon the above discussion, the degree of correspondence between the various categories of TCs and landfalling TCs, shared variance (r^2) is calculated between the various basin-wide and landfall-specific time series (Table 2). These calculations confirm a relatively strong, and statistically significant, relationship among the various categories of basin-wide and landfalling TCs and hurricanes (both U.S. and total) at multidecadal and longer times cales. Indeed, landfalling hurricanes track fairly well with basin-wide TC counts, with many local maxima and minima in common in the two series (Figure 8). The relationship between these two series appears to be slightly weaker prior to 1050; this could feasibly result from the GCM spin-up in the early part of the synthetic time series. Such spin-up issues could affect relationships between TCs and the underlying climate and thus relationships between various TC series in the first century or two of the 1150 year record. Nonetheless, the two smoothed series are correlated at $r = 0.69$ corresponding to 48% shared variance, which is significant well below the one-sided $p = 0.01$ level. The unsmoothed time series of basin-wide TCs and landfalling hurricanes also exhibit significant, albeit weaker, correlations at $r = 0.49$. *Mann et al.* [2009a]

find a similar correlation ($r = 0.44$), between estimates of basin-wide TC activity and landfalling Atlantic hurricanes over the past 1500 years. These results reinforce the hypothesis expressed therein that the two quantities ought to show common patterns of variation on these longer timescales (where sample sizes become more appreciable, particularly with respect to landfalling hurricanes) since they are responding to the same underlying driving climate factors. This interpretation is supported by the fact that the longer-term statistical relationships between the various smoothed series are greater than the corresponding relationships at annual timescales with the unsmoothed series. It is noteworthy, again, that the percentage of TCs that strike land in our synthetic record is lower than that of the observed record because of spatial biases in the simulated tracks (Table 1). It is uncertain how these low landfall rates might affect the relationship between basin-wide TC counts and the landfalling counts in the simulation. One could argue that a lower percentage of landfalls could result in a weaker relationship between basin-wide TC counts and landfall counts. On the other hand, it is also possible that the basin-wide wind patterns and/or track shapes could be less variable in the CSM 1.4, resulting in consistently fewer landfalls in our simulation and an artificially high correspondence between landfall and basin-wide counts. However, this possibility may be relatively unlikely, as standard deviations of surface pressure and 250 mbar zonal winds within the CSM 1.4 are slightly higher across the Atlantic compared to the standard deviations of the same fields in modern reanalyses.

[20] Not surprisingly, categories that are more similar (e.g., landfalling hurricanes and total basin-wide hurricanes) show closer relationships. Conversely, more distantly related quantities (e.g., landfalling United States major hurricanes and basin-wide TC counts) show weaker relationships. For some of the more restrictive quantities (e.g., landfalling United States major hurricanes), sample sizes even on multidecadal timescales (e.g., on the order of one or two storm per decade) may still be too small, making correlations with these series weaker than the correlations between the less restrictive series. Nonetheless, correlations between all of the time series in Table 2 are significant at the $p = 0.05$ level, and the majority are significant at the $p = 0.01$ level.

[21] Additional analyses of the landfall counts reveal that the smoothed time series of total landfalling hurricanes and United States landfalling hurricanes are highly correlated ($r^2 \approx 0.70$); the correlation between the smoothed time series

Table 2. Squared Pearson's Linear Correlation Coefficients (r^2) Between Various Smoothed Tropical Cyclone Counts (All Correlations are Positive)[a]

Squared Pearson Linear Correlation Coefficients (r^2)		Basin-Wide Counts			Total Landfalls			United States Landfalls		
		TC	H	MH	TC	H	MH	TC	H	MH
Basin-wide counts	TC	1.00	0.79	0.60	0.63	0.48	0.18	0.42	0.30	0.14
	H	0.79	1.00	0.74	0.61	0.58	0.24	0.35	0.35	0.20
	MH	0.60	0.74	1.00	0.42	0.43	0.23	0.25	0.26	0.20
Total landfalls	TC	0.63	0.61	0.42	1.00	0.70	0.30	0.67	0.40	0.23
	H	0.48	0.58	0.43	0.70	1.00	0.34	0.47	0.64	0.25
	MH	0.18	0.24	0.23	0.30	0.34	1.00	0.21	0.24	0.69
United States landfalls	TC	0.42	0.35	0.25	0.67	0.47	0.21	1.00	0.55	0.22
	H	0.30	0.35	0.26	0.40	0.64	0.24	0.55	1.00	0.32
	MH	0.14	0.20	0.20	0.23	0.25	0.69	0.22	0.32	1.00

[a]The two different time series of counts used in each calculation are listed in the top row and leftmost column, where "TC" stands for tropical cyclone, "H". stands for hurricane, and "MH" stands for major hurricane. Based on the estimated statistical degrees of freedom in the smoothed series ($N = 29$), r^2 values greater than 0.09 are significant at the $p = 0.05$ level, and those greater than 0.17 are significant at the $p = 0.01$ level.
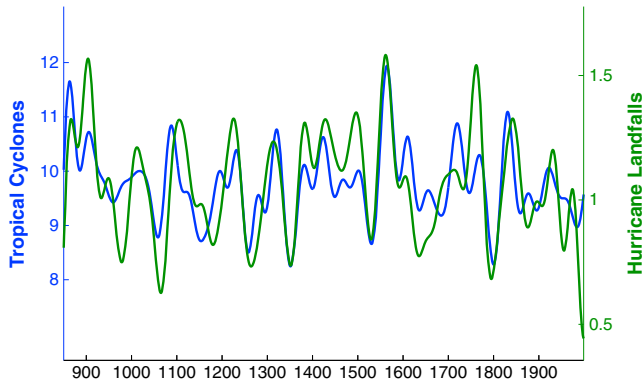
Figure 8. Time series of basin-wide tropical cyclones (blue, left axis) and all hurricane landfalls (green, right axis). Both time series are smoothed as described in the text. The squared correlation coefficient between these two time series of counts is $r^2 = 0.48$.

of total landfalling major hurricanes with United States landfalling hurricanes and major hurricanes is similarly strong ($r^2 \approx 0.70$; Table 1). These close relationships can be ascribed to the expansive nature of the United States' coastline, which spans thousands of kilometers along some of the more active parts of the North Atlantic Ocean and the Gulf of Mexico. In the millennial synthetic track database, 59.7% of all landfalling hurricanes and 64.7% of all landfalling major hurricanes from 850 to 1999 make their initial landfall in the United States (excluding the island nations not detected in the synthetic landfall counts from this comparison, these percentages agree reasonably well with the twentieth century observed climatology).

[22] All of these landfall relationships are of course not constant, as landfall frequencies are a function of both basin-wide storm frequency and track/genesis variability. As a result, landfall frequencies are affected both by random atmospheric variability and, perhaps, modulation of prevailing tracks related to large-scale or regional climate phenomena such as the El Niño Southern Oscillation, the Northern Atlantic Oscillation, and/or the Atlantic Warm Pool [e.g., *Kozar et al.*, 2012; *Wang et al.*, 2011]. On interannual time-scales, random track variability may dominate [e.g., *Frank and Young*, 2007], as was evident during the 2010 Atlantic hurricane season, which experienced near record basin-wide TC counts, but only four landfalling hurricanes, none of which made landfall along the U.S. coast. Yet on longer timescales where sample sizes become larger, the relationships between the landfalling and basin-wide storm counts become more significant, as random variability is filtered out to a certain degree.

3.3. Insights on Paleohurricane Records

[23] As noted above (section 3.2), our millennial simulation of Atlantic TCs exhibits statistically significant correlations between landfalling hurricanes and basin-wide TC counts (Figure 8 and Table 2). The strong relationship between landfalling hurricanes and annual storm counts offers some support for a number of recent studies that have used coastal sediment records to produce long-term TC time series from overwash deposits left by landfalling hurricanes [e.g., *Woodruff et al.*, 2008; *Mann et al.*, 2009a]. Motivated by these

previous studies and the results of section 3.2, an additional "sediment" time series was created from the synthetic TC data set that contains only storms that might have been detected by these sediment-sampling techniques. From this time series, it is possible to determine the appropriateness of using paleohurricane records to assess long-term TC variability within the context of this idealized simulation.

[24] The sediment time series includes the 230 hurricanes in the 1150 year simulation that strike land at hurricane intensity within a 270 km radius of the eight sediment-sampling sites (The sampling sites include the following: Mattapoisett, Massachusetts; Succotash, Rhode Island; Alder, New York; Whales, New Jersey; Brigantine, New Jersey; Singleton Swash, South Carolina; Western Lake, Florida; and Vieques, Puerto Rico.) used in *Mann et al.* [2009a]. The coordinates of each hurricane landfall are plotted in Figure 9, along with the locations of each sediment site. This sediment landfalling hurricane series produces a far more restrictive sample than, for example, landfalling hurricanes alone; not surprisingly, the correlation between the smoothed time series of this sparsely populated data set and the smoothed basin-wide TC count time series is lower ($r = 0.41$), but it is significant at the one-sided $p = 0.05$ level. The correlation is also comparable to that ($r = 0.44$) estimated by *Mann et al.* [2009a] between actual landfalling strong/major hurricanes and basin-wide TCs over the past 1500 years. In comparison, the unsmoothed sediment landfalling hurricane series exhibits a less significant relationship with basin-wide TC counts ($r = 0.28$). Therefore, this simulation offers support for the use of paleohurricane records in assessing long-term multidecadal TC variability; however, paleohurricane records are less appropriate for assessing interannual and higher-frequency TC variability.

[25] Several artificial biases impact the sediment landfalling hurricane series within this idealized climate simulation. First and foremost, there are multiple recognized shortcomings of
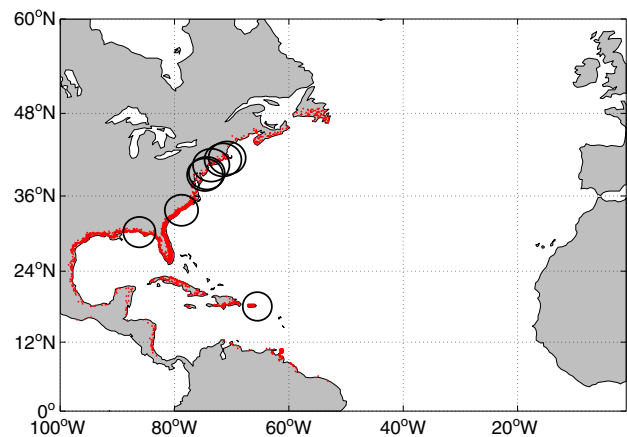

Figure 9. Coordinates of every hurricane landfall west of 40°W during the millennial simulation (850–1999). The black rings represent the eight sediment-sampling sites of *Mann et al.* [2009a] and the 270 km radius around those sites for which the storms are included in the exclusive "sediment" time series discussed in section 3.3. The eight sampling sites include the following: Mattapoisett, Massachusetts; Succotash, Rhode Island; Alder, New York; Whales, New Jersey; Brigantine, New Jersey; Singleton Swash, South Carolina; Western Lake, Florida; and Vieques, Puerto Rico.

the imperfect climatological environment in the CSM 1.4: The previously discussed low bias in landfall counts resulting from eastward track and genesis biases that arise from unfavorable conditions for TC development such as excessively high shear and the semipermanent El Niño feature within the CSM 1.4 discussed in section 2. In addition, the sediment series is affected by the limitations of our landfall tracking methodology, which calculates landfall coordinates and intensities from each storm's first landfall. Many storms that affect the northeastern United States (e.g., Agnes, 1972; Gloria, 1985; Floyd, 1999; Irene, 2011; and Sandy, 2012) strike the Caribbean Islands or the southeastern United States first. An artificially low Northeast U.S. landfalling storm count in particular would likely manifest itself as an underestimation in the "sediment sampling" series, as five of the eight sampling sites are in the Northeast corridor of the United States (Figure 9).

4. Conclusions

[26] The model downscaling experiments presented here provide a useful test bed for examining relationships between various categories of basin-wide and landfalling TCs in the North Atlantic basin within the context of the idealized nature of this model simulation. Despite the spatial track biases and a lower percentage of TC landfalls in our simulation, comparisons between landfalling counts and basin-wide counts reveal that hurricane landfalls within the realm of this downscaled model simulation track total basin-wide counts quite well on multidecadal and longer timescales. This finding provides some model-based support for the use of paleohurricane records to assess long-term changes in TC climatology.

[27] This result may seem intuitive, as an increased population of tropical cyclones, with all other factors being equal, will lead to an increase in hurricanes and likely hurricane landfalls. However, at interannual timescales, hurricane landfalls are somewhat rare events and thus are dominated by random year-to-year variations. As a result, the correlations between landfalling counts and basin-wide activity are small on the interannual scale in the observed record [e.g., *Lyons*, 2004]. However, for multidecadal and longer records, sample sizes are large enough to make meaningful comparisons between categories (e.g., landfalling hurricanes) that are rare on annual timescales. As a result, our analyses show that the longer-term relationships resolvable using smoothed counts over a millennial time frame are closer than the interannual relationships between the same categories of storms.

[28] The percentage of basin-wide synthetic TCs that make landfall at hurricane intensity does nonetheless vary over multidecadal timescales, as it has been shown to do in the modern instrumental record [*Holland and Webster*, 2007]. It is likely that variations in climate, e.g., prevailing steering winds or coastal ocean currents, influence hurricane intensification, and tracks are thereby influencing this ratio of landfalling storms to total storms. Teasing apart the relative importance of such factors will require similar analyses of other model simulations and perhaps other downscaling techniques to insure that the relationships between various categories of storms are not an artifact of a particular model simulation or a particular (e.g., CHIPS and beta-and-advection) downscaling approach.

[29] Correlations between the U.S. landfall counts and the basin-wide activity are all significant at the $p = 0.05$ significance level. Overall, the time series of annual TC landfall counts limited to just the United States do not track basin-wide TC counts quite as well as the "all landfalls" set, but United States landfalling hurricanes and major hurricanes relate quite well to the total number of hurricane and major hurricane landfalls in the basin, respectively.

[30] Ultimately, the analysis of a millennium-long record of tropical cyclone landfalls in the Atlantic Basin produced here provides the groundwork for analyses of landfall variability that were previously impossible using the observational record. Of course, as with any downscaling study, a number of caveats apply to this synthetic TC analysis due to the idealized nature of the climate simulation and the applied downscaling approach. For example, the community model produces far too much shear in the Atlantic Basin, leading to fewer TCs in the western half of the basin. As a result of this particular bias, the CAM3.0 model performed rather poorly with the applied downscaling approach for the North Atlantic Basin in previous simulations of modern TC climatology [*Emanuel et al.*, 2008]. Future studies may thus be able to improve upon the results presented here by employing a different coupled simulation with an atmospheric global climate model that has a better representation of tropical Atlantic climatology. Nonetheless, this study provides an initial proof-of-concept and suggests possible fruitful avenues to pursue in future work. Within this idealized climate model framework, we present some initial results using this synthetic TC data set to address issues in sampling statistics related to basin-wide TC and landfalling hurricane activity. The particular data set used in our analysis should also prove useful for investigating a wider set of questions regarding climate/TC relationships, including behavior in other basins, and the possible assessment of long-term variations in coastal storm surge frequencies and magnitudes [e.g., *Lin et al.*, 2012]. This same framework, applied to other long-term climate model simulations, including the Coupled Model Intercomparison Project Phase 5 state-of-the-art coupled models, should provide a greater variety of synthetic data sets of this sort that can be mined to address fundamental question regarding climate/TC relationships.

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