Fluctuations in North Atlantic Hurricane Frequency

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ABSTRACT

The annual record of hurricane activity in the North Atlantic basin for the period 1886–1996 is examined from the perspective of time series analysis. Singular spectrum analysis combined with the maximum entropy method is used on the time series of annual hurricane occurrences over the entire basin to extract the dominant modes of oscillation. The annual frequency of hurricanes is modulated on the biennial, semidecadal, and near-decadal timescales. The biennial and semidecadal oscillations correspond to two well-known physical forcings in the local and global climate. These include a shift in tropical stratospheric winds between an east and west phase [quasi-biennial oscillation (QBO)] and a shift in equatorial Pacific Ocean temperatures between a warm and cold phase [El Niño–Southern Oscillation (ENSO)]. These climate signals have previously been implicated in modulating interannual hurricane activity in the North Atlantic and elsewhere. The near-decadal oscillation is a new finding. Separate analyses on tropical-only (TO) and baroclinically enhanced (BE) hurricane frequencies show that the two components are largely complementary with respect to their frequency spectra. The spectrum of TO hurricanes is dominated by timescales associated with ENSO and the QBO, while the near-decadal timescale dominates the spectrum of BE hurricanes. Speculations as to the cause of the near-decadal oscillation of BE hurricanes center on changes in Atlantic SSTs possibly through changes in evaporation rates. Specifically, cross-correlation analysis points to solar activity as a possible explanation.

> ''The hurricanes . . . used to come every seven years, or every five years, but they have become more frequent following the settlement of the Antilles.'' —Jean Baptiste Du Terte

1. Introduction

Fluctuations in North Atlantic hurricane frequency have significant impact on human life and property. The climatology of North Atlantic hurricanes has been the subject of much recent interest as methods have been developed to forecast activity a season in advance (Gray et al. 1993; Elsner and Schmertmann 1993). The skill of these forecast models rests with the association between hurricane frequency and recurrent climate anomalies. For example, a 10-month extrapolation of the 30-mb wind component over the Tropics to September (the peak month of the North Atlantic hurricane season) provides a predictor for the number of hurricanes during the next season. Since the upper-level winds follow a fairly regular cycle of approximately 28–30 months, the extrapolation works well (Gray et al. 1993).

A comprehensive analysis of cycles in the North Atlantic hurricane record is done in Shapiro (1982). He divided the basin into four sectors largely along lines of longitude and analyzed the temporal coefficients of the spatial empirical orthogonal functions of August–October hurricane occurrences in each of the regions. Results, based on data over the period 1899–1978, show that hurricane activity is indeed modulated on the quasi-biennial timescale, with perhaps a linkage to oscillations in sea level pressures over the basin, resulting from shifts in the subtropical high as indicated by Angell et al. (1969). Gray (1984) continued this analysis to show that North Atlantic seasonal hurricane frequencies are correlated to both the quasi-biennial oscillation in 30-mb wind direction [quasi-biennial oscillation (QBO)] and the El Niño fluctuation in SSTs [El Niño–Southern Oscillation (ENSO)].

In addition to natural variability of the climate system, it is possible that global climate fluctuations are responding to changes in external forcing. Oscillations in global climate may influence climate components in the Northern Hemisphere (e.g., Kane and Teixeria 1990). Numerical simulations of the global atmosphere reveal oscillations on the decadal timescale (James and James 1989). For instance, North Atlantic extratropical winter storms track farther south at solar maxima (Tinsley 1988). Solar activity is also hypothesized to be the cause of climate variability in the lower stratosphere (Hood 1997).

One of the primary motivations behind the present work is that there are presently about 20% more hur-

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ricane years to consider than were available for the analyses in Shapiro (1982) and in Gray (1984). More importantly, recent work has shown the utility of considering total North Atlantic hurricane activity as the sum of the frequency of tropical-only (TO) and baroclinically enhanced (BE) hurricanes (Elsner et al. 1996). Results from the present study reaffirm this perspective by showing that these two components of hurricane activity have largely complementary spectral frequencies. Moreover, new clues in understanding the interannual variability of North Atlantic hurricanes are uncovered.

This paper begins with a short description of singular spectrum analysis (SSA) as a tool for time series analysis. In section 3, SSA combined with the maximum entropy spectral method (MEM) is applied to the annual frequency to reveal the leading modes of oscillation in the hurricane record. In section 4, the spectra of TO and BE hurricanes are considered separately. Speculations as to likely and possible causes of the oscillations are discussed in section 5 with the aid of superposed epochs and cross-correlation analysis. A summary of the important findings are given in section 6.

2. Singular spectrum analysis

Time series analysis offers a rigorous approach for extracting underlying cycles in a set of observations. As known, there are several methods available for time series analysis including Fourier decomposition and autoregressive modeling. The method of SSA, which is a special case of principal component analysis, has recently emerged in geoscience as a tool for time series investigations (Elsner and Tsonis 1996). SSA was first used in oceanography by Colebrook (1978), in climatology by Fraedrich (1986), and Rasmusson et al. (1990). It was first introduced as a useful method within nonlinear time series analysis by Broomhead and King (1986) and Vautard and Ghil (1989). Here various aspects of the Atlantic basin hurricane record are examined using the SSA.

SSA begins with the lagged-covariance matrix ($\mathbf{S}$) computed as

$$\mathbf{S}_{ij} = \frac{1}{N_t - m + 1} \sum_{t=1}^{N_t-m+1} x(i + t - 1)x(j + t - 1), \tag{1}$$

where N_t is the length of the time series and m is the window length in years. The value of m represents a compromise between information and statistical confidence. Longer period oscillations, representing additional information, can be resolved only with a larger window length, yet only at the cost of statistical confidence, which increases with decreasing window length. The additional confidence arises from the fact that the higher frequency components are not competing with the lower frequency components for the finite variance. The results presented in this paper are not significantly altered for m in the range of 12–25. The eigenvectors of $\mathbf{S}$ are used to compute the principal components (a^k's) by projecting them onto the original time record. The principal components can be used to reconstruct all or portions of the original time series,

$$x(i + j - 1) = \sum_{k=1}^{m} a_i^k e_j^k, \tag{2}$$

where x is the reconstructed component, a_i^k is the ith term of the kth principal component, and e_j^k represents the jth term of the kth eigenvector. The reconstructed components are limited in their harmonic content and thus can be examined more readily with traditional time series methods. Furthermore, since the time series is a sum of all individual reconstructed components, the removal of one or more components is a form of filtering the time record.

3. Annual hurricane frequency

Data for this study are taken from the so-called best-track dataset,[1] which represents the most complete and reliable source of all North Atlantic hurricane information back to 1886, and is considered the official U.S. National Weather Service record of North Atlantic hurricanes (Neumann et al. 1993). The best-track data records were compiled from various publications and represent a rigorous, postseason analysis of all tropical cyclone intensities and tracks every 6 h. However, prior to 1957 the 6-hourly positions were interpolated from observations made once every 12 h, and prior to 1931, from observations made once every 24 h.

The time series of annual abundance of North Atlantic basin hurricanes is considered first. The time series consists of annual hurricane counts for the period 1886–1996 (Fig. 1). Trends and extremely low frequency oscillations can arise from changes in observing techniques over the years and from natural fluctuations, perhaps induced by changes in sea surface temperatures. Regardless of source, the ultra-low frequency variation is removed prior to the analysis. Following Vautard and Ghil (1989), the SSA can be used as part of an algorithm for removing trends that also includes the nonparametric trend test of Kendall and Stuart (1977). Given a time series $x(t)$, $t = 1, 2, \ldots, N$, count the number K_r of pairs of indices (t, u), with $t < u$ such that $x(t) < x(u)$. In general, if K_r is large there is an increasing trend, and if K_r is small there is a decreasing trend. How large is determined by the test statistic

$$\tau = \frac{4K_r}{N(N - 1)} - 1. \tag{3}$$

The distribution of τ for large N is normal with zero mean and standard deviation given by

[1] The dataset is also known by the acronym HURDAT for hurricane data.

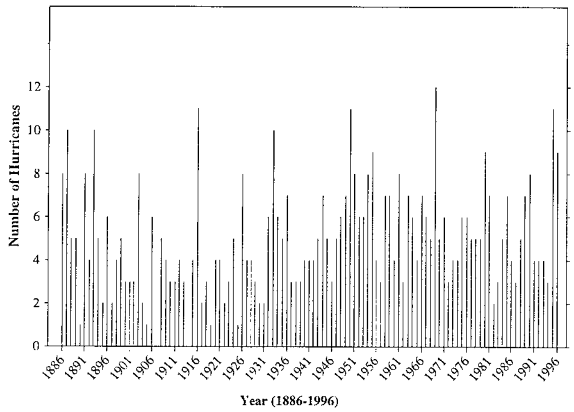

FIG. 1. Time series of the annual frequency of North Atlantic hurricanes over the period 1886–1996. The greatest number of hurricanes in a single season is 12 during 1969. Note the low frequency change in annual abundance over the 111-yr period.

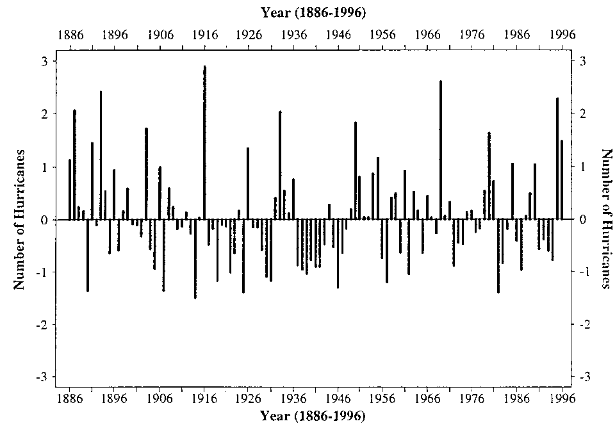

FIG. 2. Time series of annual North Atlantic basin hurricane frequencies over the period 1886–1996 after detrending by removing the leading ultra-low frequency temporal principal component.

$$s = \sqrt{\frac{2(2N + 5)}{9N(N - 1)}}. \quad (4)$$

Allowing for a 5% chance of being wrong, the hypothesis of no trend is rejected outside the interval ($-1.96s$, $+1.96s$).

Here N_t is fixed at 111 yr (1886–1996) and m is fixed at 15 yr, thus $N = N_t - m + 1$. The values $N_t = 111$ yr and $m = 15$ yr are used throughout the present study, except for the analysis of U.S. hurricanes where $N_t = 146$ yr. Only the first principal component contains a large τ indicative of an ultra-low frequency oscillation in the hurricane record. Detrending is accomplished by summing over the reconstructed components leaving out the trend component. Figure 2 shows the detrended hurricane record. The procedure is repeated a second time on the detrended record to ensure against spurious trends resulting from the convolution. This time no principal components are outside the 5% limits. A frequency spectra of the first principal component (not shown) shows no significant decadal or semidecadal signal. This ensures that the retained components are not influenced by the trend removal.[2]

The analysis continues by concentrating on the detrended record shown in Fig. 2. The singular spectrum of the detrended time series is shown in Fig. 3. A strong oscillation in the record, even if it is somewhat irregular, tends to be associated with a pair of nearly equal eigenvalues in the singular spectrum. This observation is only approximately true for records with noise and even in the case of pure waves may not always hold. The first three dominant eigenvalue pairs are inspected further by examining their associated eigenvector pairs (Fig. 4). Each of the three eigenvector pairs is in approximate quadrature (one vector leads the other by a quarter period) further substantiating the implicit claim that they represent meaningful oscillations in the hurricane record. We caution, however, that this does not constitute a rigorous statistical test of significance for oscillations in the data. Indeed, a similar analysis with red noise will reveal pairs of nearly equal eigenvalues and associated eigenvectors in quadrature (Elsner and Tsonis 1996). It is noted that beyond the three leading eigenvector pairs, where the eigenvalues are all less than unity, nearby pairs of eigenvectors are generally not in quadrature.

The harmonic signature of the leading eigenvector pairs is examined by limiting the summation in Eq. (2) to the particular pair. Figure 5 shows the reconstructed components from the three dominant eigenvector pairs. Although these components indicate irregular oscillations (i.e., they are not pure waves), there is a distinct structure to each of them. The reconstructed component from the second eigenvector pair indicates a high-frequency oscillation while the reconstructed record from the third pair suggests a low-frequency intradecadal os-

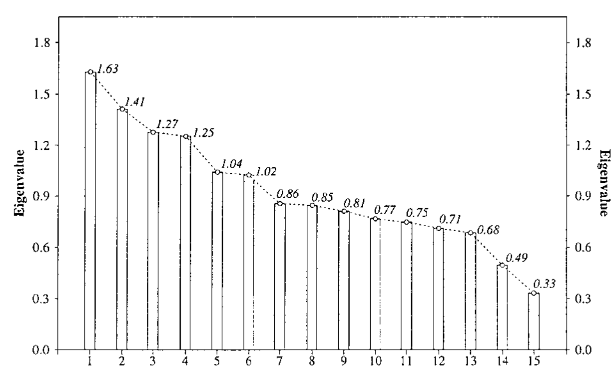

FIG. 3. Eigenvalues of the detrended North Atlantic annual hurricane frequency record using the method of singular spectrum analysis. The first three pairs of eigenvalues are considered above the noise floor.

[2] This check was called to our attention by two of the reviewers.

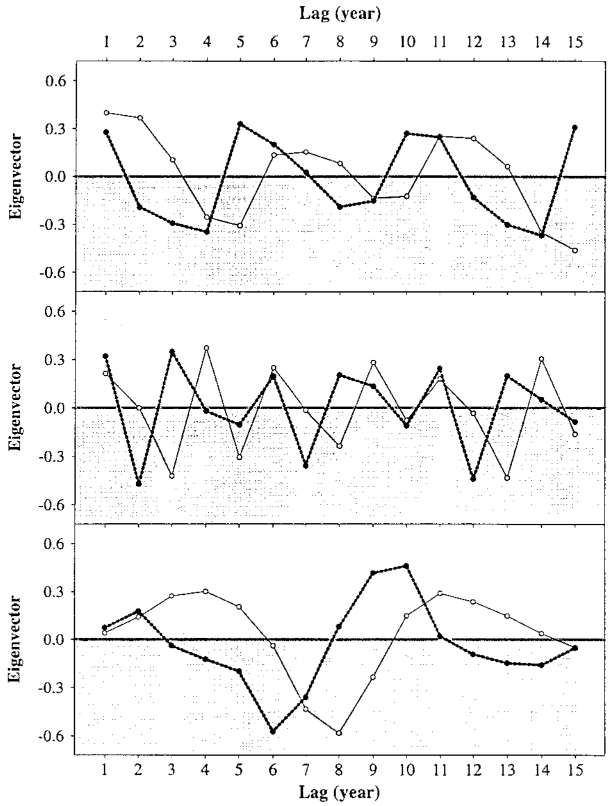

FIG. 4. Three leading eigenvector pairs of the detrended North Atlantic hurricane record. Each pair corresponds to a distinct oscillation in the annual hurricane record.

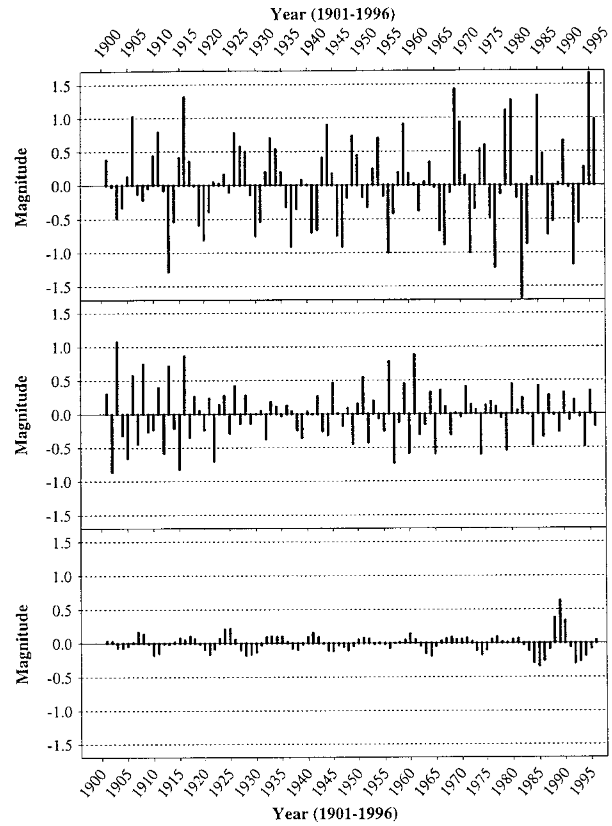

FIG. 5. Three dominant reconstructed components of the detrended North Atlantic hurricane record using the method of SSA. Each reconstructed record corresponds to a distinct oscillation with limited harmonic content.

cillation. The reconstructed components, though having a limited harmonic content show amplitude modulation with different frequencies dominating the variability during different epochs. For example, during the 1950s and 1960s the high-frequency oscillations were relatively robust, however during the middle 1980s until present the highest frequency component (reconstructed component number two) has been somewhat less important.

Due to their restricted harmonic content, the reconstructed components are readily amenable to low-order autoregressive modeling. As such, frequency spectra can be effectively examined using the MEM of spectral analysis. The MEM is capable of high spectral resolution so it is possible to more accurately pinpoint the underlying periodicity in a time record. If the time series has been filtered, MEM can achieve this resolution without the problem of spurious peaks encountered when high-order autoregressive models are required (Penland et al. 1991). Here the MEM is applied to the three reconstructed components using the method of Press et al. (1989) with a maximum order of 15 (see Fig. 6). Each reconstructed component has a distinct MEM spectrum with peaks corresponding to periods of 2.5, 5.6, and 7.4 yr. We note that this two-step method of spectral analysis (SSA followed by MEM) is capable of resolving the low-frequency oscillations into distinct frequencies. This resolution is not possible if MEM is applied to the original detrended record without the careful prefiltering afforded by SSA. The detrended hurricane record can be approximated by simply summing the contributions from each of the six reconstructed components. The approximation is quite good with a Pearson correlation between the two series of 0.78.

The 2.5-yr periodicity reflects the well-established association of hurricane activity with the stratospheric QBO. The stratospheric QBO is a fairly regular fluctuation in stratospheric winds from strong easterlies to weak easterlies (or weak westerlies) that occurs over tropical latitudes at a period between 2 and 3 yr. The semidecadal oscillation is likely tied to the ENSO of the Pacific basin, which has an irregular fluctuation in the range of 4–6 yr and that has been implicated in modulating major hurricane activity over the North Atlantic and elsewhere. It should be noted that ENSO is not strictly periodic. In fact, a significant biennial component to ENSO has been identified by Rasmusson et al. (1990) as well as by others.

Though the stratospheric QBO is close to being periodic, it is not a simple harmonic of the seasonal cycle.

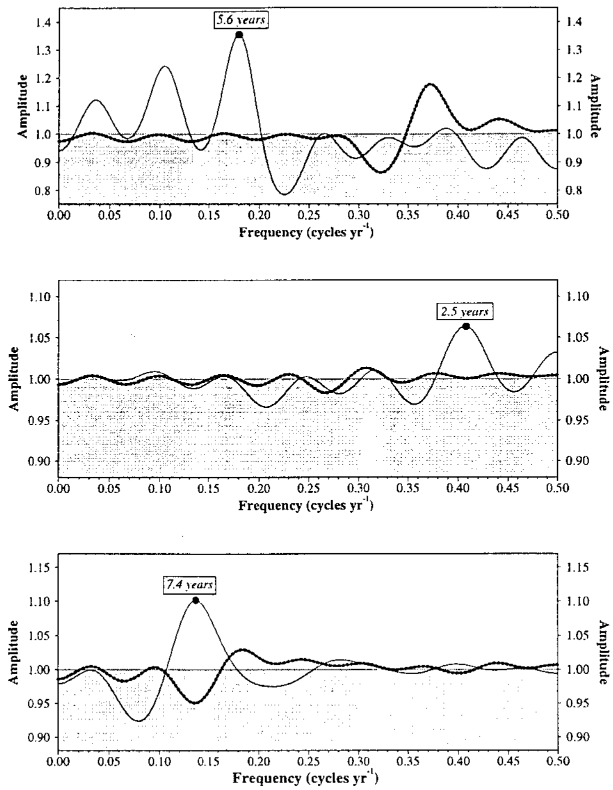

FIG. 6. MEM spectra of the three dominant reconstructed components of the detrended North Atlantic hurricane record using a maximum order of 15. The solid circle indicates the dominant frequency in the record. The thick lines correspond to the MEM of the three dominant reconstructed components of a permuted hurricane record. The ordinate scales are not identical across the graphs.

It is argued that the QBO is related to momentum transfer from the troposphere upward into the stratosphere (Lindzen and Holton 1968). Vertically propagating waves transfer momentum upward, which are absorbed by the horizontal winds blowing largely from east to west. It is believed that the reduction of hurricane activity in east-phase years might be due to increased lower-stratospheric to upper-tropospheric vertical shear of these horizontal winds, which may disrupt the development of tropical cyclones by ripping apart their vertical structure (Gray et al. 1993).

It is suggested that both the QBO and ENSO regulate North Atlantic hurricane activity through changes in upper-tropospheric winds (Gray et al. 1993). When the Pacific ENSO is in its warm (or El Niño) phase, the enhanced convection in the central and eastern Pacific produces upper-tropospheric westerlies (winds blowing from west to east) across the tropical Atlantic. Anomalous westerlies near the equator generate upper-level convergence and sinking air that are detrimental to hurricane development.

The low-frequency oscillation might be forced by sea surface temperature (SST) fluctuations in parts of the North Atlantic Ocean. For example, Kimberlain and Elsner (1998) show that sea surface temperatures in a region to the east of the Lesser Antilles appear to modulate hurricane activity with more hurricanes (see also Elsner et al. 1996) occurring during warm years than cold years and the warm and cold years occurring in roughly 7- to 10-yr intervals. It is widely known that tropical rainfall in the Atlantic basin also varies considerably on this near-decadal timescale (Hastenrath et al. 1984). For instance, rainfall from the northern Nordeste region of Brazil was heavy during the middle 1970s and again in the middle 1980s, whereas during the early 1980s there was drought (Chang et al. 1997).

Explanations concerning the low-frequency oscillation center on the atmosphere's response to observed variations in SST differences between the Northern and Southern Hemispheres (SST gradient). Changes in SST gradients influence changes in sea level pressure gradients, and thus the direction of winds. Assuming hydrostatic equilibrium and weak upper-air thermal anomalies, increases in SSTs are related to decreases in sea level pressures (SLPs). An SST gradient featuring colder temperatures north of the equator will be associated with higher SLPs in the Northern Hemisphere. The anticyclonic (clockwise) flow of air around high pressure in the north will enhance the northeast trades thereby increasing evaporation and keeping the ocean surface relatively cool. Similarly, the cyclonic (also clockwise) flow of air around low pressure (warmer SSTs) in the Southern Hemisphere will restrict the southeast trades implying less evaporation and keeping the SSTs high. One way out of this positive feedback loop is through large-scale changes in ocean circulation aided by changes in atmospheric radiative and turbulent energy fluxes (Chang et al. 1997). Interestingly, Mehta (1998) finds a spectral peak at 8–9 yr in tropical Atlantic SST anomalies and a statistically significant coherence with an index of North Atlantic tropical cyclone activity. The phase difference indicates tropical cyclone activity lags warmer SSTs by a few years. Additionally, Enfield and Mayer (1996) and Penland and Matrosova (1998) show a predictive relationship between El Niño and tropical North Atlantic SSTs.

4. Baroclinically enhanced hurricanes

Baroclinically enhanced hurricanes are tropical cyclones that reach hurricane intensity as a consequence of help from middle-latitude baroclinic dynamics (Elsner et al. 1996). For instance, a hurricane born on the tail end of an old frontal system from the north is considered a baroclinically enhanced hurricane. A tropical wave that receives favorable upper-level outflow due to the proximity of a middle latitude upper-level trough is also classified as baroclinically enhanced upon reaching hurricane strength. Hurricanes that are not baroclinically enhanced are called tropical only. Stratification of North Atlantic hurricanes according to this definition is based on a careful examination of individual storms back to

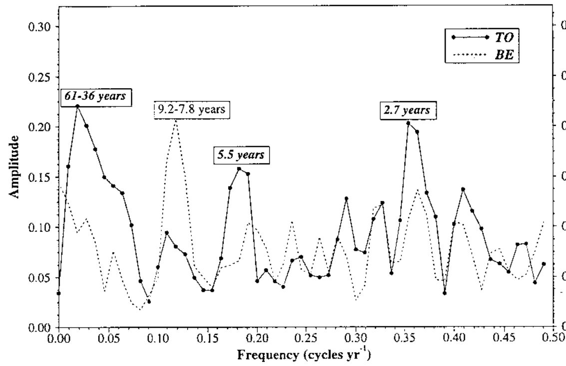

FIG. 7. Blackman–Tukey power spectra of the detrended annual TO and BE hurricane records over the period 1886–1996. The largest peaks are identified with their corresponding period of oscillation. The records have been detrended so confidence is small for frequencies less than 0.05.

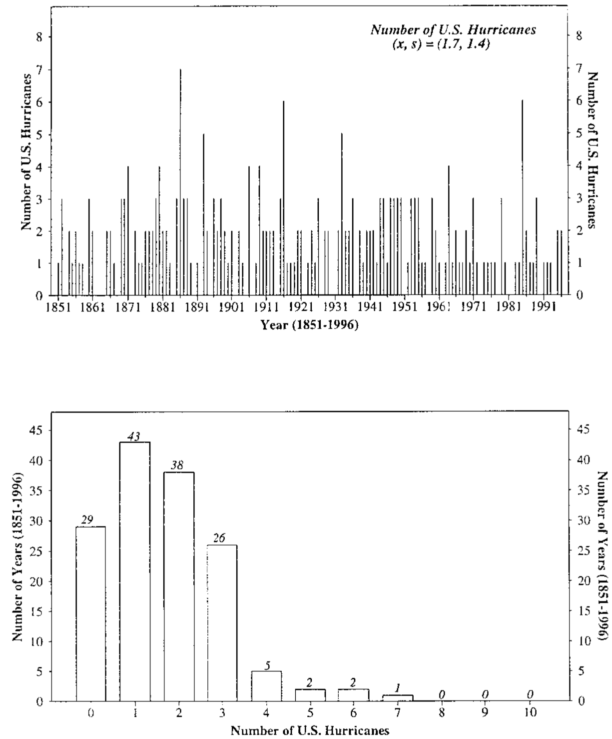

FIG. 8. Time series of the annual abundance of (top) U.S. hurricanes and (bottom) the distribution of annual abundance over the period 1851–1996. Note the lack of a trend in these data over the period. The mean and standard deviation are given in the upper-right corner of the top panel.

1950 (Hess et al. 1995). An objective technique based on the subjective classification is used to stratify hurricanes before 1950 (Elsner et al. 1996).

Changes in incident solar radiation and SSTs might have the most affect on hurricanes that form along the margins of the Tropics. This is because a small warming of the oceans of the deep Tropics will have less influence on the evaporation rate and perhaps the abundance of hurricane activity since the atmosphere there is already conditionally unstable. However, the same small change in SST farther north may cause the atmosphere to become conditionally unstable and thus able to support the development of tropical cyclones. Low-frequency changes in North Atlantic SSTs might thus have the largest impact on BE hurricanes. Figure 7 shows the power spectra, using the Blackman–Tukey method, of the annual number of TO and BE hurricanes. As anticipated the high frequencies are dominated by rhythms corresponding to the QBO and ENSO, especially for the TO component. In contrast, significant periodicity in the range of 7–9 yr is found only in the abundance of BE hurricanes. Our hypothesis concerning the role of Atlantic SSTs in forcing hurricanes hints at this near-decadal timescale. Note that similarity between the Blackman–Tukey spectra and the SSA supports the contention that oscillations uncovered in this study are not artifacts of the chosen analysis method, but are a real part of the hurricane record.

A similar analysis is done for the 146-yr record of the number of U.S. hurricanes, where a U.S. hurricane is defined as one in which makes landfall at least once somewhere along the U.S. coastline from Brownsville, Texas, to Eastport, Maine. Recently, Fernández-Partagás and Diaz (1996) updated and added to the tracks of hurricanes of the North Atlantic for the period 1851–1900 based on careful examination of ship logs, newspaper accounts, and other sources. For instance, *The New York Times*' reports of damage and casualties are often sufficiently detailed to reconstruct the likely location and, to some degree, the likely intensity of the hurricane near, and at, landfall. Arguably this work provides justification to extend the U.S. hurricane landfall record back to 1851. For the years that overlap the best-track data (1886–1900) we refer to the updates explained in Fernández-Partagás and Diaz (1996). A concatenation of the Fernández-Partagás and Diaz dataset with the best-track data is the source for the time series and distribution of annual frequency of U.S. hurricanes shown in Fig. 8. Note the lack of any substantial long-term trend in this record.

Figure 9 shows the maximum entropy spectra of the three leading reconstructed components of the landfall record with N_t = 146 yr and m = 15 yr. The 5–6-yr oscillation in hurricane frequency is clearly reflected in the abundance of U.S. hurricanes. As mentioned, this periodicity is likely associated with the Pacific ENSO. The QBO signal is also apparent in the landfall record. The low-frequency component identified in the annual hurricane frequency is not readily discernible in the frequency of U.S. hurricanes. This is consistent with the fact that only 25% (48/190 from 1886–1996) of all U.S. landfalling hurricanes are BE hurricanes. A relatively large percentage of BE hurricanes originate during the late part of the hurricane season (October) over the western Caribbean and over the western North Atlantic

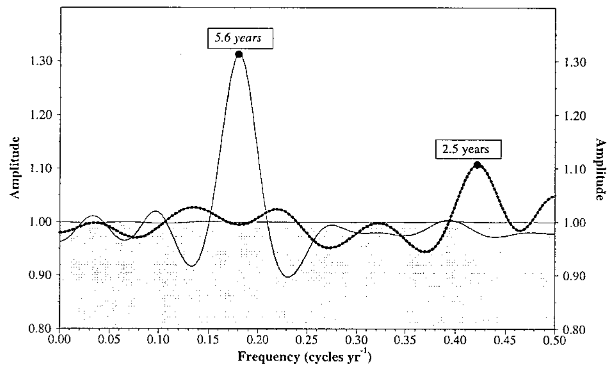

FIG. 9. MEM spectra of the three dominant reconstructed components of the U.S. hurricane record over the period 1851–1996 using SSA. Note that only the first two components show significant oscillations.

TABLE 1. Years of extreme QBO east and west phases over the period 1950–96 as determined by the upper-level (50 mb) zonal winds averaged from stations over the Caribbean from August through October, along with the corresponding components of North Atlantic hurricane activity. Q50 refers to the 50-mb zonal wind anomaly in m s^{-1}.

QBO east phase					QBO west phase				
Year	Q50	All	TO	BE	Year	Q50	All	TO	BE
1952	−11.2	6	6	0	1955	7.5	9	9	0
1954	−13.2	8	5	3	1957	8.5	3	2	1
1956	−7.8	4	3	1	1959	8.5	7	1	6
1968	−9.2	5	1	4	1961	7.5	8	7	1
1970	−10.2	5	1	4	1964	10.5	6	5	1
1972	−9.2	3	0	3	1975	7.5	6	4	2
1977	−12.5	5	1	4	1978	8.8	5	2	3
1984	−13.8	5	0	5	1980	8.2	9	4	5
1992	−9.8	4	0	4	1985	9.8	7	4	3
1994	−13.8	3	1	2	1995	10.8	11	9	2
Avg	−11.1	4.8	1.8	3.0	Avg	8.8	7.1	4.7	2.4

where they travel northeastward away from the United States (see Elsner and Kara 1999). As a consequence, it is not expected that the variability in BE activity will explain much of the variability of U.S. hurricane activity.

5. Physical interpretations

The method of superposed epochs (or composite analysis) is used in many climate studies. It consists of identifying various occurrences of a particular event over time from an independent dataset, then counting (or averaging) the variables from the dependent data at those particular event times. Here the dependent data are the different components of annual hurricane activity. If the independent event is continuous, like SSTs, the event is defined in terms of the upper (and/or lower) fraction of the observed values. The superposed epoch method is used here to examine annual Atlantic basin hurricanes with respect to the QBO, ENSO, and solar activity.

a. QBO and ENSO

As mentioned above, the stratospheric QBO and the Pacific ENSO have previously been implicated in modulating hurricane activity over the North Atlantic basin through changes in upper-air wind patterns. These two signals are also linked to changes in tropical cyclone activity in other parts of the Tropics (McBride 1995). Stratospheric wind data are available for upper-air stations in the Caribbean region back to 1950. The 50-mb zonal wind averaged over the Caribbean stations from August through October provides an index for the QBO relevant to North Atlantic hurricane activity. The average 50-mb winds are from the east, but a particular year experiences a positive or negative departure from the mean for the hurricane season. A positive departure is defined as the westerly phase of the QBO while a negative departure is defined as the easterly phase. The oscillation is nearly biennial, so that easterly and westerly phases alternate approximately every year.

Table 1 gives the average 50-mb zonal wind anomaly (1950–96 base period) for the Caribbean during the hurricane season for the 10 most extreme years of the westerly phase and the 10 most extreme years of the easterly phase, along with the corresponding hurricane activity. The westerly phase is considerably more favorable for North Atlantic hurricanes as the average number of hurricanes for the 10 extreme years is 7.1 compared with 4.8 for the extreme years of the easterly phase. Moreover, the extremes of the QBO discriminate between TO and BE hurricanes as the phase determines which component dominates. The QBO is most strongly related to the frequency of TO hurricanes. This is also reflected in the differences in major hurricane frequencies as the ratio is 3.5–1 in favor of more intense hurricanes during the strong westerly phase (not shown). Statistics for the differences in average hurricane activity between the two QBO extremes indicate that for both all and TO hurricanes the differences are significant (Table 2). The difference in average BE hurricane activity is not statistically significant. Shapiro (1982) notes that a QBO in sea level pressures and other atmospheric variables will regulate both the abundance and tracks of North Atlantic hurricanes.

It is well known that the Pacific ENSO has a significant relationship to North Atlantic hurricane activity

TABLE 2. Statistics of the differences in North Atlantic hurricane activity between the extremes of the stratospheric QBO over the period 1950–96. The mean difference in hurricane activity is denoted by $\delta_{east-west}$, and the *t* statistics and *p* values are based on the null hypothesis of no difference.

Activity	$\delta_{east-west}$	*t* statistic	*p* value
All	−2.3	−2.676	0.0077
TO	−2.9	−2.580	0.0094
BE	+0.6	0.772	0.23

(Gray et al. 1993, 1994). In fact, much of the interannual variability in tropical climate can be traced to ENSO. Moreover, Hess et al. (1995) show that the ENSO signal is more closely related to hurricane activity in the deep Tropics by showing TO hurricanes, which are mostly deep tropical systems, are more predictable (statistically) than all hurricanes. Although ENSO was only included as one of several important variables in the prediction model, its usefulness in predicting TO hurricanes is guaranteed via cross validation. Subsequently, Goldenberg and Shapiro (1996) showed a similar relationship by dividing the hurricanes along a line of latitude. During a typical ENSO event, which usually begins during a Northern Hemisphere spring, an area of anomalously warm surface water appears along the eastern equatorial Pacific, expanding westward during the next several months (Philander 1983). Associated with the warm water in the eastern Pacific are above-average air pressures near the surface in the western Pacific, enhanced precipitation near the equator to the east of 160°E and a weakening, or reversal, of the easterly trade winds in the eastern Pacific.

Changes to the tropical climate of the Pacific have been linked to climate fluctuations in other tropical locations and to portions of the extratropics as well. It is not surprising then that U.S. landfalling hurricane activity appears to be tied to ENSO also. O'Brien et al. (1996) show that if you use the Japanese Meteorological Agency (JMA) index for ENSO, which is defined with respect to SSTs in the central Pacific, then hurricane strikes over the United States are most common during the cold phases over the period 1949–92. The JMA index defines El Niño events based SST anomalies in the region between 4°N–4°S and 150°–90°W. A warm ENSO is observed when the 5-month running average of SST anomalies is above 0.5°C for six or more consecutive months. Additionally, the series of at least six consecutive months must begin before September and must include October–December. Figure 10 shows the probability distributions of U.S. hurricanes for the two opposite ENSO phases (cold and warm). It is based on the additional assumption that the occurrence of U.S. hurricanes is a Poisson process (see e.g., Elsner and Schmertmann 1993). Clearly the cold phase is more conducive to U.S. hurricane activity. Moreover, the average annual number of U.S. tropical-only hurricanes during the cold phase of ENSO is 1.5 compared with 0.2 during the warm phase. Only about half the years can be considered in either a warm or cold ENSO phase.

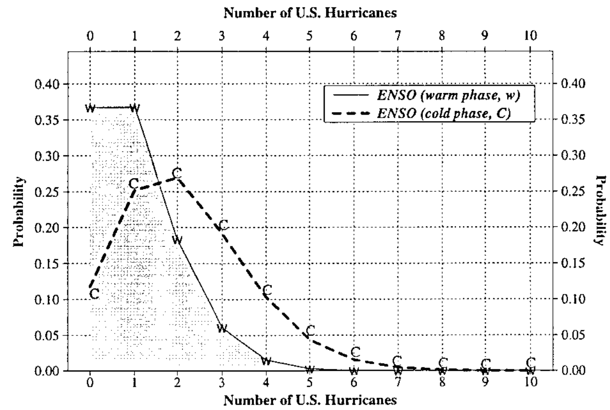

FIG. 10. Probability distributions of U.S. hurricanes with respect to the two phases of ENSO based on the assumption of the occurrence of U.S. hurricanes as a Poisson process. The Poisson parameter is estimated from data over the period 1869–1996. Note that, although overall U.S. hurricanes are more likely during a cold phase, the probability of exactly one U.S. hurricane is higher during a warm phase.

b. Solar activity

Perhaps the most intriguing relationship for North Atlantic hurricanes is found with solar activity. It is fascinating because it represents an extraterrestrial influence and it appears to explain (statistically) only the variability of BE hurricanes. Greater solar activity and higher solar irradiance can be expected to increase the tropical ocean temperatures by a few tenths of a degree Celcius (Hoyt and Schatten 1997) and lead to variations in Northern Hemisphere near-surface temperatures (van Loon and Labitzke 1988). Greater evaporation leading to increased atmospheric moisture and instability might be a consequence of the warmer waters, particularly over the subtropical latitudes where the air is typically subsaturated.

According to Hoyt and Schatten (1997), the first modern account of the influence of the sun on tropical cyclones was reported by Meldrum in 1872. Meldrum (1872) showed sunspot numbers to be strongly correlated (positively) with the yearly number of Indian Ocean tropical cyclones, explaining slightly more than 50% of the year-to-year variation in cyclone activity. Later studies found that the solar–tropical cyclone relationship changed sign during the period 1910–1930. The first to examine the relationship of solar activity to tropical cyclones of the North Atlantic was Poey (1873), who found a correspondence between the solar cycle and Caribbean hurricanes.

It is interesting to note that Willett (1955) used an apparent relationship between North Atlantic hurricane activity and sunspot numbers to predict hurricane activity to the year 2020. His forecast called for an overall decline in activity until 1990 with a tendency for more northerly occurring hurricanes resulting from an increased zonal baroclinic flow in the middle latitudes. It can be said that, in general, his long-range prediction was accurate as an increase in the frequency of the more northerly baroclinically enhanced hurricanes have partially offset the decrease in tropical-only hurricanes since the middle 1960s. This trend may be changing in the middle 1990s as noted in Kimberlain and Elsner (1998).

More recently, Cohen and Sweetser (1975) examined the relationship for the entire North Atlantic basin. They

TABLE 3. Years of extremes in the solar cycle over the period 1886–1996 as measured by the annual-averaged Wolf Sunspot Numbers (R_z) and the corresponding number of North Atlantic hurricanes by type.

10 maximum years					10 minimum years				
Year	R_z	All	TO	BE	Year	R_z	All	TO	BE
1947	151.6	5	5	0	1888	6.8	5	3	2
1956	141.7	4	3	1	1889	6.3	5	4	1
1957	190.2	3	2	1	1901	2.7	3	2	1
1958	184.8	7	7	0	1902	5.0	3	3	0
1959	159.0	7	1	6	1911	5.7	3	3	0
1979	155.4	5	2	3	1912	3.6	4	1	3
1980	154.6	9	4	5	1913	1.4	3	1	2
1989	157.7	7	5	2	1923	5.8	3	2	1
1990	141.8	8	3	5	1933	5.7	10	10	0
1991	145.2	4	0	4	1954	4.4	8	5	3
Avg.	158.2	5.9	3.2	2.7	Avg.	4.7	4.7	3.4	1.3

TABLE 4. Statistics of the differences in North Atlantic hurricane activity between the extremes of the solar cycle over the period 1886–1996. The mean difference in hurricane activity is denoted by $\delta_{max-min}$, and the *t* statistics and *p* values are based on the null hypothesis of no difference.

Activity	$\delta_{max-min}$	*t* statistic	*p* value
All	+1.2	1.207	0.122
TO	−0.2	−0.188	0.427
BE	+1.4	1.772	0.047

offered no explanations as to how variations in the solar cycle influence the frequency of tropical cyclones, but found that spectra of both the number of tropical cyclones and the average length of the tropical cyclone season, when smoothed by a 7-yr running mean, matched the spectrum of the 12-month running mean of sunspot numbers in the periodicity range of 10–11 yr.

Table 3 lists the years and Wolf (or Zurich) Sunspot Numbers (R_z) annually averaged for the 10 yr of peak solar activity and the 10 yr of minimum solar activity. The yearly means of the Wolf Sunspot Numbers are the most commonly used solar index in sun–climate studies. The table also gives the corresponding number of North Atlantic hurricanes by type. Though total basin-wide hurricane activity appears to be only mildly related to the extremes in solar activity (the ratio is 1.3–1 in favor of more hurricanes with more sunspots), it is strongly related to BE hurricane activity where the ratio is 2.1–1. The relationship is statistically significant at the 95% confidence level (Table 4). This relationship is interesting in a physical way because it accounts for cyclical variations in a portion of total hurricane activity not explained by QBO or ENSO effects.

There appears to be no significant relationship between solar activity and U.S. hurricanes as the extremes do not differentiate well between years with many strikes and years with only a few. This is consistent with the fact that only a quarter of U.S. hurricanes are baroclinically enhanced. Note that 4 of the 10 minimum years occur in the reversal period of 1910–30. If these years are replaced by the nonreversal minimum years of 1890, 1900, 1944, and 1964 then the relationship with BE hurricanes increases to 2.7 to 1. Extreme caution must be used in interpreting the significance of this analysis since the 10 yr of minimum solar activity are all before 1955 while the 10 yr of maximum solar activity are all after 1946. Given that a significant portion of the baroclinically enhanced hurricanes occur over the western North Atlantic and track away from land, years before aircraft reconnaissance or satellite images might be biased toward fewer BE hurricanes. However, it is probably safe to conclude that if there is any relationship between solar output and North Atlantic hurricane climate, as this and other analyses hint at, it is likely through BE hurricane activity.

Figure 11 shows the cross-correlation functions for sunspots and several components of North Atlantic hurricane activity. We note that BE hurricane activity is apparently driving the correlation between solar cycle fluctuation and number of hurricanes as these cross-correlation functions are nearly identical for all hurricanes and BE hurricanes.

Peaks in the sun–hurricane relationship occur near 7 and 14 yr. The climate system is nonlinear, and the

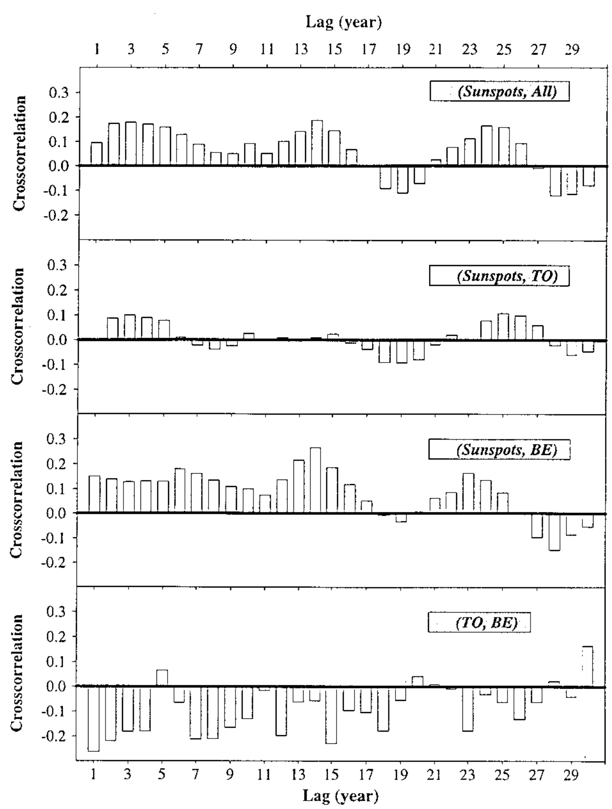

FIG. 11. Cross-correlation functions of sunspots and the various components of North Atlantic hurricane activity over the period 1886–1996, except for the bottom graph that shows the cross-correlation function of TO and BE hurricanes. The lag is in years.

interaction between physical cycles that occur at two different frequencies may generate frequency-modulated sidebands at the sum and difference of these frequencies. The forcing frequencies of the 11-yr and 22-yr solar cycles are 0.091 cycles yr^{-1} and 0.045 cycles yr^{-1}, respectively. The sum produces a frequency of 0.136 cycles yr^{-1} or a periodicity of 7.4 yr (Burroughs 1992). This frequency corresponds to the unexplained periodicity (see Fig. 6) in the hurricane record and to the most pronounced periodicity in the record of BE hurricanes (Fig. 7). As expected, the cross-correlation function between TO and BE hurricane activity is predominantly negative.

The total variation in solar radiant output associated with the 11-yr solar cycle is about 0.15%. Though small, this amount is still climatically significant (Hoyt and Schatten 1997). We speculate that BE hurricane activity might be sensitive to small changes in solar output through increased evaporation at the ocean surface. Increased evaporation would be expected to lead to an atmosphere more conducive to BE hurricanes through an increase in evaporative latent heat transport and a decrease in atmospheric stability. At lower latitudes, where most of the TO hurricanes originate, the atmosphere is typically close to water vapor saturation, so an increase in radiant energy may not significantly increase the evaporation rate or change atmospheric stability depending on whether there are significant corresponding changes in sensible and latent heat fluxes. This hypothesis is the subject of current investigations.

It is also possible to explain the 7–9 yr cycle of BE hurricane activity as a nonlinear interaction between the 11-yr sunspot cycle and the 18–19 yr Saros lunar cycle. Drought occurrences in the western United States also have a significant rhythm of 7–8 yr according to Cook et al. (1997). It is possible that lunar tidal forcing influences atmospheric circulation and pressure fields through the nonequilibrium state of the atmosphere and associated pressure gradients (O'Brien and Currie 1993). We do not propose that the detection of these cycles provides sufficient evidence that they are based upon these or other physical mechanisms. The coincidence of the lunar and solar cycle sideband frequency with BE hurricanes and western U.S. drought frequency is, however, intriguing and merits further study.

6. Summary

The annual record of hurricane activity for the North Atlantic basin was examined from the perspective of time series analysis and physical reasoning. The annual frequency of hurricanes is modulated on the biennial, semidecadal, and near-decadal timescale, accounting for 58% of the total variance in a detrended record. The period of biennial oscillation is 2.5 yr, the period of semidecadal oscillation is 5–6 yr, and the period of near-decadal oscillation is 7–9 yr.

The biennial and semidecadal oscillations correspond to well-known and well-documented signals in the global climate. Both the quasi-biennial shift in tropical stratospheric winds (QBO) and the ENSO have been suggested by others to modulate North Atlantic hurricane activity. The near-decadal oscillation in hurricane activity has not, to our knowledge, been previously uncovered.

Separate analyses on BE and TO hurricanes reveal that the near-decadal modulation is confined to BE hurricane activity. Speculations as to the cause of this modulation center on changes in Atlantic SSTs and evaporation rates. Changes in Atlantic SSTs can arise through alteration in ocean circulation patterns and changes in atmospheric radiative and turbulent energy fluxes. More study is needed here. However, correlation analyses with sunspot numbers suggest that only BE hurricanes are influenced by low-frequency changes in solar activity, perhaps through a modulation involving the 11-yr and the 22-yr solar cycles or the 18–19 yr Saros lunar cycle. It should be kept in mind, however, that solar activity accounts for only a small fraction of the total interannual variability of BE hurricanes. Finally, caution is advised in interpreting some of the results presented here, as a bias in the hurricane record is likely before the middle 1940s (Landsea et al. 1996). The magnitude of this bias is open to considerable debate.

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