Spectral characteristics of Atlantic seasonal storm frequency

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(*Received 8 May 2002, Modified 3 April 2006*)

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सार – वर्ष 1900−2000 की अवधि में अटलांटिक महासागर की तूफानी गतिविधि (जिन्हें तूफान, प्रचंड तूफान, आदि नाम दिए गए हैं) के विभिन्न सूचकांकों के काल श्रेणियों का अनुक्रम विश्लेषण एम.इ.एम.(अधिकतम एनट्रॉपी विधि) द्वारा तथा उसकी आवर्तिता के आयाम एम. आर. ए. (बहु समाश्रयण विश्लेषण) द्वारा प्राप्त किए गए हैं। पिछले कुछ वर्षों के आंकड़ों (वर्ष 1950 से आगे) के अनुसार इनकी महत्वपूर्ण आवर्तिताएँ दशक सहित; द्विवार्षिक कल्प, त्रिवार्षिक कल्प क्षेत्रों तथा इनसे उच्च क्षेत्रों में भी रही। 2.40 वर्षों में 50 मिलीबार के निम्न अक्षांश क्षेत्रीय पवन और 2.40 एवं 2.85 वर्षों के इ. एन. एस. ओ. (एल नीनो/दक्षिणी दोलन) घटना के सदृश द्विवर्षी कल्प दोलन क्षेत्र में (3−4 वर्षों) तूफान सूचकांक 2.40 तथा 2.85 वर्षों के करीब चरम पर रहे। उच्च आवर्तिता वाले क्षेत्रों में तूफान सूचकांक 4.5−5.5., 8−9, 11−12 तथा 14−15 वर्षों में चरम पर रहे जबकि इ. एन. एस. ओ. 7.4 एवं 12−14 वर्षों में चरम पर रहे। बहु दशकीय श्रेणी में 28−34,40,50−53,61−63,~70 एवं ~80 वर्षों में (परन्तु भिन्न सूचकांकों के लिए भिन्न–भिन्न) तूफान चरम पर रहे जो स्थल एवं समुद्री सतह के तापमानों के समान चरम मानों के अनुरूप रहे। कुल सूचकांकों में 90 वर्षों में लगभग 50 प्रतिशत की उर्ध्व प्रवृति रही।

ABSTRACT. The time series of the various indices of Atlantic storm activity (number of named storms, hurricanes, etc.) for 1900-2000 were subjected to spectral analysis by MEM (Maximum Entropy Method) and amplitudes of the periodicities were obtained by MRA (Multiple Regression Analysis). For recent data (1950 onwards), significant periodicities were in the quasi-biennial, quasi-triennial regions and also in higher regions, including decadal. In the QBO region (2-3 years), storm indices had peaks near 2.40 and 2.85 years, similar to 2.40 years of 50 hPa low latitude zonal wind and 2.40 and 2.85 years of ENSO (El Niño/Southern Oscillation) phenomenon. In the QTO region (3-4 years), storm indices and ENSO had common peaks near 3.5 years. In higher periodicity regions, storm indices had peaks at 4.5-5.5, 8-9, 11-12 and 14-15 years, while ENSO had peaks at 7.4 and 12-14 years. In the multi-decadal range, storm peaks were at 28-34, 40, 50-53, 61-63, ~70 and ~80 years (but different for different indices), which matched with similar peaks in land and sea surface temperatures. Some indices had large uptrends, ~50% in 90 years.

Key words – Multiple regression analysis, ENSO, QBO, QTO, Sea surface temperature.

1. Introduction

The Atlantic hurricane basin includes the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico. The region is prone to tropical cyclones, which are large-scale circular flows occurring within the tropics and subtropics but often intruding into middle latitudes, with strongest winds at low levels. Depending upon the magnitude of the maximum sustained winds, these are called Tropical Storms (TS, 17-32 m/s, meters per second), and Hurricanes (H, exceeding 32 m/s). For Hurricanes only, there is the Saffir/Simpson Hurricane scale classification (Simpson, 1974) of speed categories, 1(33-42 m/s), 2(43-49 m/s), 3(50-58 m/s), 4(59-69 m/s), 5(exceeding 69 m/s), where categories 3-5 are called Intense (or Major) Hurricanes (IH). Most of these events are given names in alphabetical order (strictly female from 1953 till 1978 and alternating male/female thereafter) and currently repeating the list of names every six years (for example, Arlene, Bret, Cindy, Dennis ... for 1999). Some 'primarily killer' (deadly) storms have their names 'retired', not to be used again (for example, Hugo of 1989). The events are concentrated in the latter half of the calendar year. The official start and end of the hurricane season are 1 June and 30 November, respectively, but the active part begins only by about 1 August, attains a peak in September and is over by end of October. There is considerable inter-annual variability in the various indices (one value per year), namely, (*i*) NS, number of named storms, (*ii*) NSD, number of named storm days (four 6-hour periods) during which the event occurred, (*iii*) H, number of Hurricanes, (*iv*) HD, number of Hurricane days, (*v*) IH, number of Intense Hurricanes, (*vi*) IHD, number of Intense Hurricane days (Gray *et al*., 1997, 1999).

Hurricanes result in considerable damage in the United States. The National Oceanic and Atmospheric

Administration's National Hurricane Center has kept records of total continental U.S. damages related to hurricanes since 1900 (Hebert *et al.*, 1997). As shown by Landsea (1993) and Pielke and Landsea (1998, 1999), the raw data are inappropriate for climate trend analysis, because large societal changes have resulted in a dramatic growth in recorded losses, even as Hurricane landfalls decreased during the later decades of this century. Nevertheless, it is possible to normalize the dataset to present-day values by accounting for the most significant societal changes.

To normalize past impacts data to 1997 values, Pielke and Landsea (1998, 1999) adjusted losses based on three factors: inflation, wealth, and population. Data on all three factors are kept by the U.S. Government and allow for the creation of a normalized loss dataset for 1925-97. The result of normalization is an estimate of the economic impact of any storm, had it made landfall in 1997. While such estimates are likely conservative for several reasons, it does allow for trend analysis of an underlying climatic signal, as shown by Pielke and Landsea (1998, 1999).

Besides NS, NSD, H, HD, IH, IHD and their average NTC, two more indices are available, namely, Hurricane Destruction Potential (HDP), a measure of a hurricane's potential for wind and storm surge destruction defined as the sum of the square of a hurricane's maximum wind speed (in 10^4 knots^2) for each 6-hour period of its existence, and Maximum Potential Destruction (MPD), a measure of the net maximum destruction potential during the season compiled as the sum of the square of the maximum wind observed (in knots) for each named storm, values expressed in 10^3kt.

Gray (1984a) reported a substantial negative correlation between the storm indices and the phenomenon of El Niño and also when equatorial winds at 30 hPa were from easterly direction and/or were becoming easterly (Shapiro, 1989). Also, a three-to-one ratio was reported in continental U.S. land-falling intense hurricanes, with 0.74 per year striking during non-El Niño years and only 0.25 per year during El Niño years. (Bove *et al.*, 1998; Pielke and Landsea, 1999). Gray (1984b) formulated a forecast scheme for hurricane indices, based on El Niño, stratospheric wind quasi-biennial oscillation (QBO), and regional sea-level pressure data for Caribbean basin meteorological stations. In the present communication, the time series of the various storm indices and the US damage index are subjected to spectral analysis by MEM-MRA (Maximum Entropy Method/Multiple Regression Analysis) and the significant spectral components are synthesized to reproduce the series and use the extrapolations for predictions. The results are compared with the predictions of Gray (1984b)

and their further modifications (Gray *et al.*, 1997, 1999 and references therein). The results are also compared with those of Elsner (1998), who analysed the hurricane activity series (1896-1996) by a combination of (Single spectrum analysis) SSA/MEM, and with those of Elsner *et al.* (1998) who developed an empirical prediction algorithm to assess the potential of useful multi-season forecasts of North Atlantic hurricane activity. Recently, Landsea *et al.* (1999) made a detailed examination of the Atlantic basin hurricane indices for inter-annual trends and multi-decadal variability. Our results are compared with their results.

2.   Methodology MEM-MRA

To obtain quantitative estimates of the characteristics of the interannual variability, the series were subjected to spectral analysis. The method used was MEM (Maximum Entropy Method, Burg, 1967; Ulrych and Bishop, 1975), which locates peaks much more accurately than the conventional BT (Blackman and Tukey, 1958) method. However, the amplitude (Power) estimates in MEM are not very reliable (Kane, 1977, 1979; Kane and Trivedi, 1982). Hence, MEM was used only for detecting all the possible peaks T_k ($k = 1$ to n), using LPEF (Length of the Prediction Error Filter) as 50% of the data length. These T_k were then used in the expression :

$$f(t) = A_\mathrm{o} + \sum_{k=1}^{n}\left[a_k \sin\left(2\pi t/T_k\right) + b_k \cos\left(2\pi t/T_k\right)\right] + E$$

$$= A_\mathrm{o} + \sum_{k=1}^{n} r_k \sin\left(2\pi t/T_k + \phi_k\right) + E$$

where $f(t)$ is the observed series and E the error factor. A Multiple Regression Analysis (MRA, Bevington, 1969) was then carried out to estimate A_o (a_k, b_k), and their standard errors (by a least-square fit). From these, amplitudes r_k and their standard error σ_k (common for all r_k in this methodology, which assumes white noise) were calculated. Any r_k exceeding 2σ is significant at a 95% (a priori) confidence level. For prediction purposes, only the highly significant periodicities were used. This simple method of prediction will be termed as MEM-MRA. There is another, more sophisticated method called SSA-MEM (Single Spectrum Analysis-Maximum Entropy Method) which is employed in many analyses.

3.   Data plots

The data for Atlantic storm indices were obtained from Gray (1984a,b), Gray *et al.* (1999, 2000), Landsea
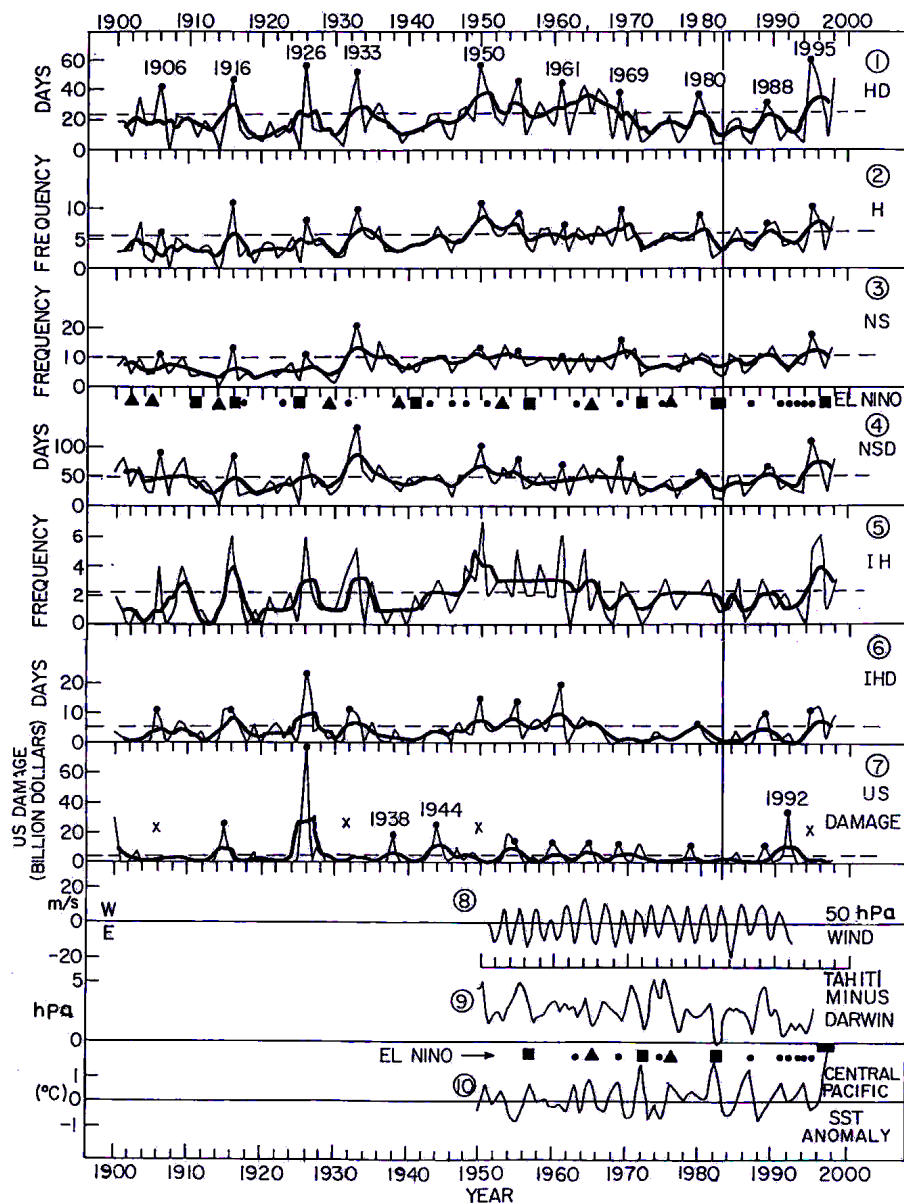
Fig. 1. Plots of one value per year of the Atlantic storm indices (1-7) HD, H, NS, NSD, IH, IHD, US Damage, and two values per year of (8) 50 hPa wind, positive values, westerly, (9) Tahiti minus Darwin atmospheric pressure difference, (10) Central Pacific SST anomalies, for 1900-98. The superposed thick lines are 3-year running averages. The dashed horizontal lines are overall means and the dots indicate high activity years. In panels 4 and 10, El Niños are indicated (Square, strong; Triangle, moderate; Dot, weak). In panel 7, crosses indicate years when storm activity was large but US damage was very small

(1993), Pielke and Landsea (1999), web site of these authors http://typhoon.atmos.colostate.edu/forecast/), and private communications from Dr. Christopher Landsea and Dr. Roger Pielke Jr. Fig. 1 shows plots of some selected series for 1900-98, and Table 1 gives their intercorrelations. The following may be noted :

(*i*) All the series have a large year-to-year variability, indicating a QBO (Quasi-Biennial Oscillation). A considerable variance (~ 50%) is in the 2-3 year band.

(*ii*) If the QBO is minimized by obtaining 3-year running averages, the smooth plots (superposed thick lines) still

TABLE 1

Inter-correlation between the various Atlantic Storm Indices

	Named storms NS	Named storms days NSD	Hurricanes H	Hurricane days HD	Intense hurricanes IH	Intense hurricanes days IHD	US damage	Hurricane dest.poten HDP	Net trop. cycl. activi. NTC	Max.poten destruction MPD
NS	1.00									
NSD	0.87	1.00								
H	0.84	0.81	1.00							
HD	0.71	0.87	0.86	1.00						
IH	0.61	0.73	0.71	0.80	1.00					
IHD	0.46	0.65	0.58	0.80	0.86	1.00				
US Damage	0.10	0.23	0.19	0.32	0.30	0.50	1.00			
HDP	0.67	0.84	0.82	0.98	0.85	0.89	0.38	1.00		
NTC	0.78	0.89	0.86	0.95	0.92	0.88	0.35	0.96	1.00	
MPD	0.87	0.88	0.93	0.89	0.85	0.74	0.25	0.89	0.95	1.00

show considerable variations. For example, named storms (NS, plot 3) showed low activity during 1900-30, a higher level during 1930-70, and a reduced level thereafter. Other indices also showed higher activity during 1930-70. These features have been reported in earlier publications (Gray, 1984a,b; Landsea, 1993; Landsea *et al*., 1999), though these do not support the idea that the whole basin was quieter than usual during these three decades. Incidentally, the low activity during 1900-1930 seems to be substantially due to the lack of observational platforms for monitoring these mesoscale, oceanic phenomena. Without aircraft reconnaissance and satellite imagery, some tropical cyclones were either not counted or were mis-assigned as to their correct intensity (Holland, 1981; Landsea, 1993; Neumann *et al*., 1999; Landsea, 2000). The intercorrelations are not all high (+0.70 or more) probably due to these uncertainties and inaccuracies.

(*iii*) In some years (1916, 1926 etc., marked by a big dot), activity was prominent in all indices and caused heavy damage in U.S.A. In contrast, in certain years (1906, 1933 etc., marked by a cross) the widespread activity had a mild effect on USA land area. On the other hand, there were years (1938, 1944, 1992) in which US damages occurred even when the storm activity was low. However, such statistics could be misleading. As pointed out by Landsea (1999), far more damage can be done by one major Hurricane hitting a heavily populated area than by several major Hurricanes hitting sparsely populated areas. Also, increased activity in any year does not automatically mean increased storm-related damage. In addition, even less intense storms could cause disastrous floods. Thus, a low

correlation between US damage and the other indices is understandable.

(*iv*) In the smooth plots, several peaks have decadal spacings (8-12 years). But the spacing is not always present, indicating its transient nature. Such peaks have been reported earlier, *e.g*., by Elsner *et al*. (1999, and references therein).

Since the correlations are not high, the various indices could have spectral characteristics different from each other. Landsea *et al*. (1999) have pointed out similar facts.

A well-known atmospheric parameter having a QBO (Quasi-Biennial Oscillation) is the stratospheric low latitude zonal wind (Reed *et al*., 1961; Veryard and Ebdon, 1961) at 10-70 hPa. Data were obtained from the Web site (http:/www.cpc.ncep.noaa.gov/data/indices) of the Climate Prediction Center (CPC) of the National Oceanic and Atmospheric Administration (NOAA), Washington D. C. and the 12-month running averages for 50 hPa wind are shown in Fig. 1, plot 8. As can be seen, the 50 hPa wind had 17 westerly maxima during 1950-90, yielding an average peak spacing of 28 months. However, this average spacing has increased with time. Gray (1984a) used 30 hPa QBO wind data (which are very similar to the 50 hPa data) to select years when the winds were easterly or westerly. Presently, Gray's group uses the 30 hPa, 50 hPa and the absolute value of the shear between 50 and 30 hPa.
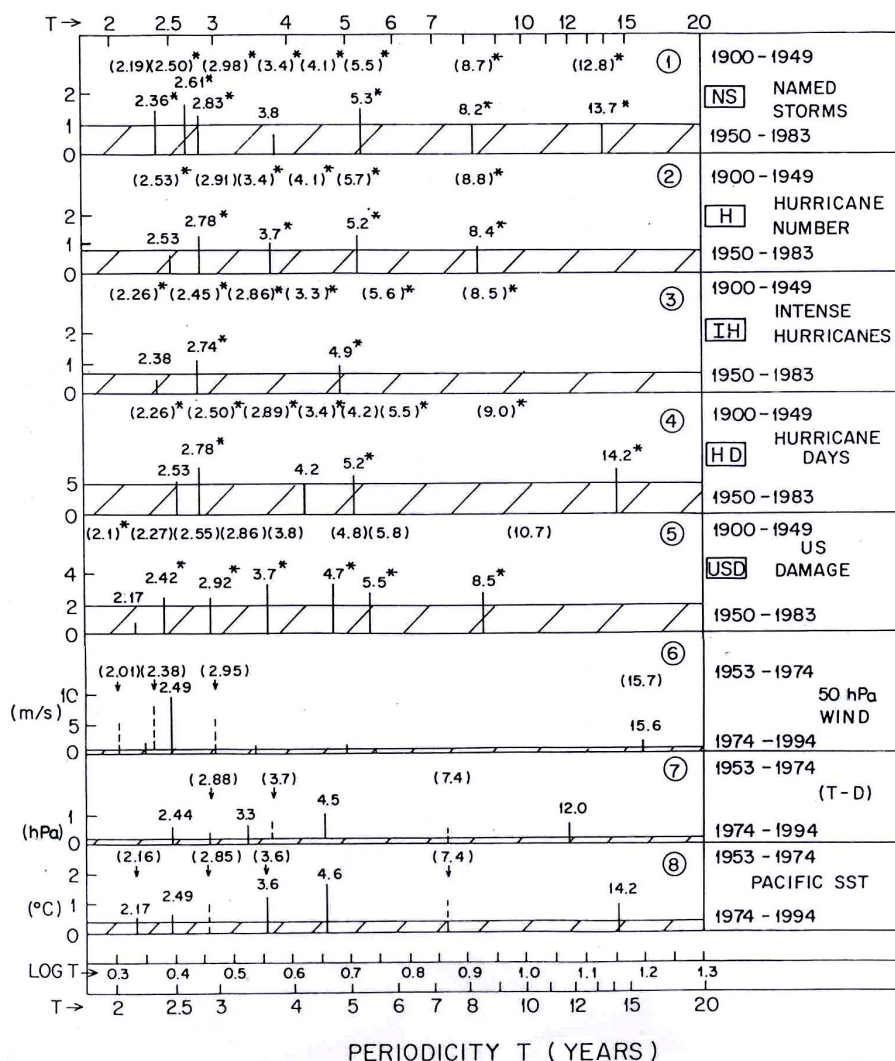
Fig. 2. Amplitudes of the various periodicities (in years) obtained by MEM-MRA. The hatched portions represent the 2σ limits. Values for 1900-49 are shown in parentheses. Values marked with an asterisk (*) are significant above 2σ limits. The abscissa scale is logarithm of periodicity T

Another atmospheric phenomenon having QBO, QTO (Quasi-Biennial and Quasi-Triennial Oscillations) is the Southern Oscillation (SO) Index, simply represented by the Tahiti T (18° S, 150° W) minus Darwin D (12° S, 131° E) mean sea level pressure difference (T-D). Data were available in the Web site mentioned above. The 12-month running averages for (T-D) are shown in Fig. 1, panel 9, for 1950 onward only. The peak spacing is irregular (2-4 years). The (T-D) minima are known to be associated with El Niño events, (defined as warm sea surface temperature anomalies near the Peru-Ecuador coast, South America and listed in Quinn *et al*., 1987) shown by rectangles (strong), triangles (moderate), small circles (weak) in Fig. 1, in-between Panels 3 and 4 for the whole period 1900-99 and in panel 10 for 1950 onward, which also shows a plot of equatorial central Pacific SST

(Niño 3 region) data which were available in the CPC Web site. As can be seen, Pacific SST anomaly maxima are associated with El Niño events occurring at the Peru-Ecuador coast.

4.   Spectral characteristics

4.1. *Small periodicities, up to decadal scale, from MEM-MRA*

Since some series are very well inter-correlated, only spectra for a few selected indices not very well inter-correlated will be shown. The amplitudes of the various periodicities obtained by MEM-MRA for the selected series are shown in Fig. 2, for periodicities 16 years or less. Apart from a study of the periodicities by themselves,

the significant periodicities could be used for reconstructing the series and using the extrapolated values for predictions. To check the usefulness of such predictions, periodicities are obtained by the analysis of data of a limited interval (dependent data), leaving the last few values (independent data, ten values or more) for checking the predictions. In the present cases, only data for 1950-83 are used for periodicity detections and 1984-98 values are predicted by extrapolation and compared with observed values. It has been hinted that the data quality was poor before 1944 when routine aircraft reconnaissance of Atlantic tropical cyclones began, and the greatest reliability started around mid-1960s when satellite detection was begun operationally (Neumann *et al.*, 1993; Goldenberg and Shapiro, 1996). Also, the characteristics might have changed with time. Hence, the series were divided into two parts, 1900-49 and 1950-83, to compare the characteristics. The bifurcation was done at 1950 firstly because data for stratospheric winds and some SSTs (e.g., Niño 1&2 etc.) are available from 1950 onwards only, and secondly, the results for the latter period could be compared with 1951-82, used by Gray (1984a). In each plot in Fig. 2, there are two rows of numbers. The numbers in the upper row (in parentheses) indicate the periodicities for 1900-49, while those in the lower row are for 1950-83 and are shown with a hatched area representing the 2σ limits of 95% confidence. Peaks protruding outside the hatched area are significant above a 95% confidence level and are marked with an asterisk (*). Following may be noted:

(*i*)   In all hurricane index series (1-5), there are many periodicities in the QBO region (2-3 years), much more so in the earlier period 1900-1949. These could be indicative of inaccurate data, but some periodicities stand out prominently in the indices NS, H, IH, HD, for example, ~2.7, 3.8, 5.3 and 8.5 years. Even US damage series shows some of these.

(*ii*)   Plot 6 shows spectra for 50 hPa wind. Here, data were available from ~1950 onwards only. The interval 1953-94 (42 years) was divided into two roughly equal intervals (1953-74) and (1974-94), to check whether the characteristics changed even in such short intervals. In the first part 1953-74, the wind had a prominent peak at 2.38 years (~28.5 months) and two subsidiaries but significant peaks at 2.01, 2.95 years. In the second part 1974-94, there was only one very strong peak at 2.49 years (~30 months). Thus, even though the wind spectra are mostly QBO, the spacing changed from ~28 months to ~30 months. (We have confirmed by using artificial samples as inputs that the MEM-MRA method is very accurate in the QBO region and periodicities can be distinguished with an accuracy of 0.05 years). This change of QBO periodicity with time has already been noticed and reported by

Naujokat (1986) and Pawson *et al.* (1993) who mention that the QBO had a period of ~26 months in the 1960s, which increased to ~27.5 months by 1980s and 28.1 months by 1993 (presently, it is ~30 months, Kane, 1998).

(*iii*)   Plot 7 shows spectra for the Southern Oscillation Index (T-D). Here, 1953-74 had periodicities 2.88, 3.7, 14.0 years, which changed to 2.44, 3.3, 4.5 years during 1974-94. The Pacific SST spectra shown in plot 8 are similar to those for (T-D), with similar changes from 1953-74 to 1974-94. Since both (T-D) and Pacific SST are intimately related to the El Niño events, the changes over time indicate changes in the El Niño timings. It is interesting to note that QBO exists in the ENSO (El Niño/Southern Oscillation) phenomenon too, though to a smaller extent. The main peaks in ENSO are near ~3.5 and 4.5 years.

(*iv*)   For 1974 onwards, 50 hPa wind QBO at 2.49 years is very similar to ENSO (T-D and SST) QBO, namely, 2.44-2.49 years. Thus, there is a possibility that these two phenomena, one related to ocean and the other to stratosphere, may have mutual interaction at this frequency. Rasmusson *et al.* (1990) showed that ENSO had a near biennial component, though its relationship with stratospheric wind QBO was not specifically mentioned. Such a possibility has been indicated in Geller *et al.* (1997 and references therein). However, the 50 hPa wind QBO periodicities are not always similar to those of ENSO. Thus, the relationship between the two may not be the same all the time.

(*v*)   The QBO in Atlantic storm indices has a periodicity at ~2.80 years during 1951-83. This is very different from the 50 hPa wind QBO (2.38 - 2.49 years). Thus, a direct connection between stratospheric wind and Atlantic storms may not exist all the time, or, it could be distorted by ENSO and other effects. The Atlantic storm QBO may as well be a part of the ENSO-QBO at ~2.85 years during 1950-74.

(*vi*)   To get some quantitative measures, the series of storm indices were cross-correlated with the 50 hPa wind series. The correlations were very low at all lags, indicating either a lack of relationship, or distortions due to other effects. The El Niños are individual events, but are well represented by the Southern Oscillation Index (SOI) series (Tahiti minus Darwin atmospheric pressure). A cross-correlation between storm indices and SOI series yielded a positive correlation (storm index values larger for larger SOI, implying La Niña effects), but the correlations were very small (~+0.4 or less), indicating mediocre relationship.
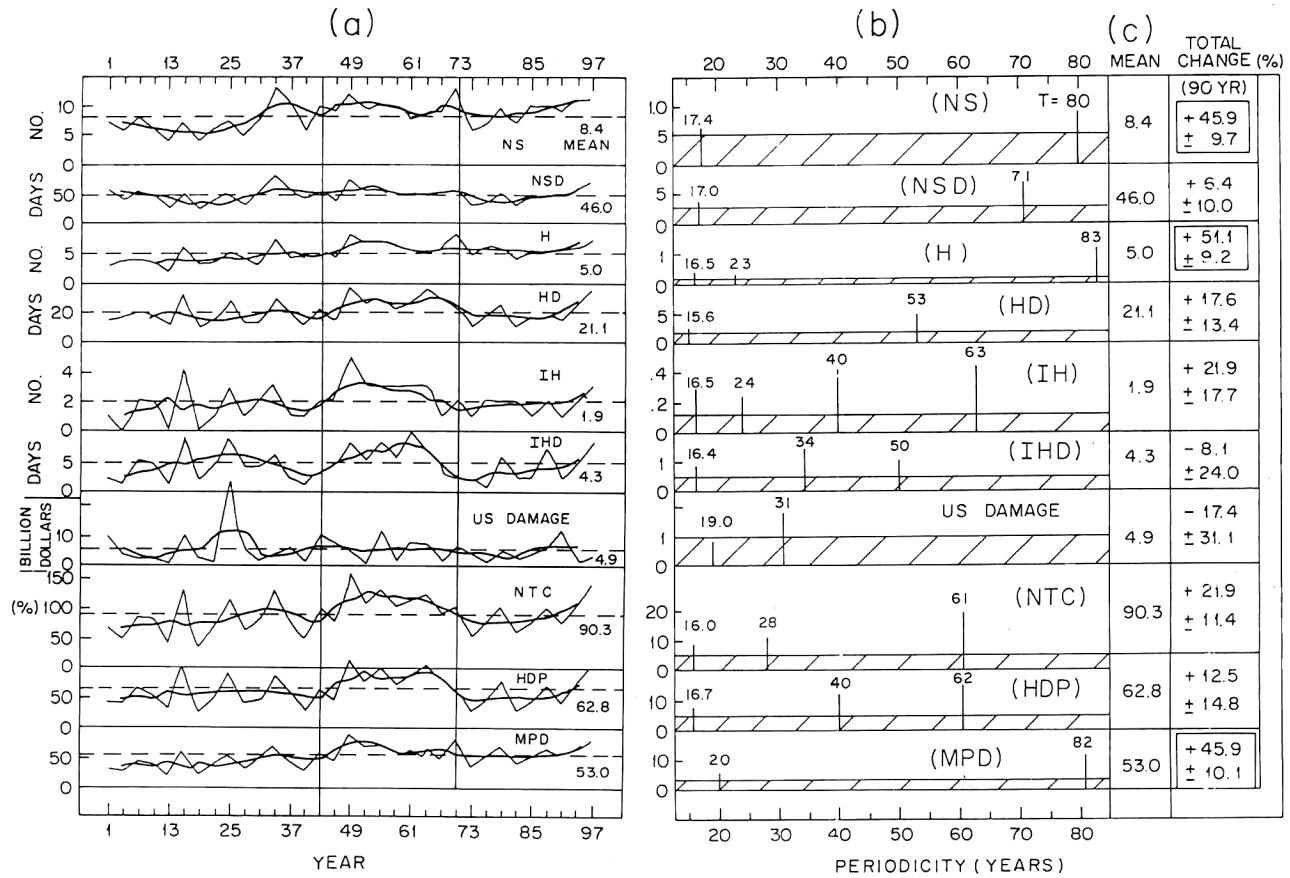
Figs. 3 (a-c). (a)Plots of 3-yearly means (thin lines) and further running means over three consecutive values (thick lines), (b) Amplitudes of the various periodicities (in years) by MEM-MRA, in the 16-80 year interval and (c) Means, and trends (total percentage change in 90 years)

4.2. Trends and large periodicities (multi-decadal scale), from MEM-MRA

Landsea *et al.* (1999) mention that only weak linear trends can be ascribed to the Atlantic hurricane activity and that multi-decadal variability is more characteristic of the region. For studying long periodicities and trends, longer data series need to be used. Hence, even risking the possibility that the earlier hurricane data may not be very accurate, these were used for analysis. A preliminary analysis showed that the long-term characteristics differed considerably from one index to another. Hence all the ten indices were examined. Fig. 3(a) (thin lines) shows a plot of 3-year means, where short-term periodicities (QBO etc.) are expected to be mostly eliminated. However, the thin lines still show some QBO-QTO residues. Hence, further 3 consecutive-value running means were calculated and are shown as superposed thick lines, which are fairly smooth and indicate the following: (*i*) In all the

cases, the activity was high during ~1943-73 (marked by vertical lines) and, in some cases, even about one decade earlier, (*ii*) Some indices show long-period oscillations, or long-term trends, or both.

Fig. 3(b) shows the MEM-MRA spectra, for the higher periodicity range 16-80 years. In almost all indices, a periodicity around 15-20 years (but mostly 15-17 years) is seen. Besides, there are periodicities at 28-34, 40, 50-53, 61-63, ~70 and ~80 years, but not necessarily common to all indices. MEM is very powerful and accurate and detects periodicities even comparable to the data length, though with an error of ~± 10 percent. Hence, in the present case (data length of 90 years), the periodicity of 80 years can be genuine. Fig. 3(c) shows the overall means and the long-term trends (obtained by a linear regression analysis) for each storm index. As can be seen, the trends are very large (almost 50% increase in 90 years) for Named storms NS, Hurricanes H, and Maximum Potential

TABLE 2

Periodicities obtained by MEM-MRA for 1950-83 and used for predictions of values for 1984 onwards.
Asterisks (*) indicate high significance

Index	Periodicities for prediction (years)	Correlation coefficients (±~0.10)			
		Dependent data		Independent data	
		1950-83		1984-98	
		All peaks	Asterisk*	All peaks	Asterisk*
H (No.)	2.78*, 3.70, 5.17*, 8.39	+0.75	+0.61	-0.02	-0.06
NS (No.)	2.36, 2.61*,2.83, 5.29*	+0.74	+0.57	+0.17	+0.14
NS Days	2.34, 2.62*, 2.86, 5.08*	+0.77	+0.56	+0.48	+0.50
H Days	2.78, 5.17, 14.24	+0.61	X	-0.14	X
IH (No.)	2.74, 4.85	+0.63	X	-0.10	X
IH Days	2.70*,3.48, 4.80*	+0.61	+0.53	+0.43	+0.17
US Damage	2.42,2.92,3.68*,4.69*,5.45,8.48	+0.88	+0.56	-0.16	-0.21
NTC	2.42,2.68*,2.91*,3.44,4.97*,6.3,17.4	+0.65	+0.60	+0.47	+0.41

Destruction MPD. As a check, for NS, H, IH and MPD, the uptrends were removed and MESA was redone for the de-trended series. For NS, the 80-year periodicity shifted to ~70 years, and an additional one appeared at ~30 years. For H and MPD also, the periodicities at 83 and 82 years shifted to ~70 years. For IH, the 63-year periodicity shifted to 60. Thus, these large periodicities near ~70 years seem to be genuine and illustrate the multi-decadal nature of Atlantic hurricane activity mentioned by Kimberlain and Elsner (1998) and Landsea *et al*. (1999). Kane and Teixeira (1990) had subjected the annual mean surface temperature series for land masses and sea in the northern and southern hemisphere for 1850-1990 to MEM and obtained, besides a long-term global warming trend of 0.12-0.56° C/century, significant periodicities at 5-6, 10-11, 15, 20, 28-32, 55-60, 64-69, and 78-80 years. Some of these (including the long-term up trends, qualitatively) match remarkably well with the trends and multi-decadal periodicities of the Atlantic storm indices mentioned above, and a cause-effect relationship could exist. Landsea *et al.* (1999) mention that much of the multi-decadal hurricane activity can be linked to the Atlantic Multi-decadal Made – an empirical orthogonal function pattern derived from a global sea surface temperature record, and hint that such linkages may allow for prediction of Atlantic hurricane activity on a multi-decadal scale. However, a word of caution is necessary. The large trends shown in Fig. 3(c) are partly due to the low values during 1900-30. These values are suspect as underestimates due to inadequacy of observing platforms. In that case, the trends could be erroneous overestimates, and the hurricane activities may not have increased so much in reality.

4.3. *Comparison with spectra and predictions reported by other workers*

4.3.1. *Long-term forecasting from extrapolated spectral components (MEM-MRA)*

Only the periodicities obtained for 1950-83 as shown in Fig. 2 were used for predicting further values. Table 2 lists the significant periodicities observed in some storm indices, which were used for reconstruction of the series 1950-83 and for prediction for values for 1984 onwards. As can be seen, the correlation coefficients are reasonably high (+0.6 or more) for the dependent data (1950-83, 34 pairs of observed and expected values), indicating that the selected periodicities give a reasonably good fit. However, for the independent data (1984-98, 15 pairs of observed and expected values), the correlation coefficients are low (occasionally even negative), indicating poor predictions, even when only periodicities with asterisk (*) are used. Thus, the various periodicities seem to be transient, changing amplitudes with time and hence not very useful for long-term predictions, when extrapolated out to 15 years.

The various indices may have their own characteristics different from each other, but there might be some characteristics common to all. These can be seen in the Net Tropical Cyclone Activity (NTC), which is obtained as a mean of the percentages of the long-term (1950-90) averages of the six parameters NS, NSD, H, HD, IH, IHD. The NTC series was subjected to MEM-MRA and yielded several-periodicities. For 1950-83, the

periodicities were: 4.97, 2.68, 2.91, 2.42, 3.44, 17.4, and 6.29 years, in decreasing order of amplitudes; only the first three were significant above a 2σ level. The correlation coefficients for NTC are given at the bottom of Table 2. The results are not very encouraging.

4.3.2. *Short-term forecasting from extrapolated spectral components (MEM-MRA)*

Whereas the predictions for long periods of 15 years are not satisfactory, those for shorter periods (one to three years ahead) could be satisfactory. To check this, the predicted and observed values and their percentage difference for each index for 1984, 1985 and 1986, as obtained in the present MEM-MRA scheme by extrapolating spectral peaks for 1950-83, were compared. It was observed that, even for 1984 (the first independent year), the percentage differences were very large, indicating that the forecasts could be largely in error. The analysis was redone to predict 1985 from 1950-84 data, 1986 from 1950-85 data *i.e.*, forecast only for one year ahead. The forecasts were similar and equally unsatisfactory, mainly because the spectral characteristics for 1950-83 did not change much by adding a year or two to the analysed data.

4.3.3. *Spectral analysis*

Following the works of Shapiro (1982) who showed from data for 1899-1978 that hurricane activity was indeed modulated on the quasi-biennial scale, and the work of Gray (1984a) who showed correlations with both, QBO in 30 hPa wind and ENSO (El Niño/Southern Oscillation), Elsner *et al.* (1999) used the sophisticated SSA-MEM (Singular spectrum analysis combined with Maximum Entropy Method) to analyse the hurricane activity annual record of 1886-1996 (111 years). The three dominant reconstructed components of the de-trended record obtained by SSA were subjected to MEM and showed peaks at 2.5, 5.6 and 7.4 years. The data included the earlier unreliable interval before 1950, but the results are probably valid for all intervals. In the MEM spectra described in the present paper, the extra information missed by Elsner *et al.* (1999) is as follows :

(*i*)   The 50 hPa wind QBO periodicity is different from the QBO periodicities of hurricane indices and ENSO. Elsner *et al.* found only 2.5 years, because of the smoothing involved in SSA-MEM.

(*ii*)   Hurricane indices have a QTO at 3.5 years, similar to ENSO. Elsner *et al.* do not mention this. Hurricane indices have peaks at 4.5 - 5.5 years also. ENSO also has a strong peak at 4.5 years. Elsner *et al.* found only 5.5 years for the hurricane index, again because of smoothing.

(*iii*)   Storm indices have peaks at 8-9, 11-12, 14-15 years. Elsner *et al.* found 7-9 years (near decadal) in the BE component only and also a solar activity effect (10-11 year periodicity) in the BE component.

Elsner *et al.* (1999) suggests that some periodicities like 7.4 years could be due to frequency-modulated sidebands of the 11-year and 22-year solar cycles. However, another interesting possibility mentioned and explored by Elsner *et al.*, is that of association with Atlantic parameters (SST and pressure and wind fields), which have decadal peaks (also shown by Kane, 1997; Kimberlain and Elsner, 1998; Mehta, 1998; Kane, 2000). These seem to be associated with rainfall in NE Brazil and may affect Atlantic hurricane indices also, probably differently for different indices.

4.3.4. *Predictions*

Using the 3 dominant reconstructed components in the de-trended record of North Atlantic hurricane activity as described in Elsner *et al.* (1999), Elsner *et al.* (1998) designed an empirical prediction algorithm to examine the potential for useful multi-season forecasts compared. The predictions do not seem to be very good in recent years (*e.g.*, observed 10, predicted 3, in 1998). For Intense Hurricanes (IH), Elsner (1998) reported that the forecasts were excellent for 1993, 1997, good for 1994, 1995, fair for 1998, and poor for 1996.

4.3.5. *Short-term forecasting based on relationships with El Niño events, wind QBO etc*

As Atlantic hurricanes cause severe damages, attempts have been made since long to link these with large-scale Atlantic wind and pressure field patterns (Ding and Reiter, 1983); but the correlations are rather low and have proved only marginally beneficial for seasonal forecasting. Presently, the scheme is very elaborate, using 16 predictive parameters including stratospheric wind QBO, Gulf of Guinea and West Sahel rainfalls, Pacific and Atlantic sea surface temperatures, sea level pressures, zonal winds in several regions etc. Nine storm parameters (NS, NSD, H, HD, IH, IHD, NTC, HDP, MPD) are forecasted and for each parameter, only some of the 16 predictive parameters are used.

Gray *et al.* (1998) have given the verification of all past forecasts for 1984-98, and the correlations are very good (exceeding 0.75) for NS, HSD, NTC only. The correlation is lowest (0.53) for Hurricane days (HD). Thus, not all indices are predicted satisfactorily.

Landsea *et al.* (1999) have discussed in detail the year-to-year variations of the Atlantic storm indices and

mention that the physical relationships between ENSO, QBO, Caribbean SLP, African rainfall, and Atlantic SSTs are responsible for much of the observed changes and periodicities (including decadal) in Atlantic tropical storm activity and hurricane-related damages. However, in some years, the predictions based on these parameters are unsatisfactory.

5.   Conclusions and discussion

The time series of the various indices of Atlantic storm activity for 1900-2000 were subjected to spectral analysis by MEM-MRA (Maximum Entropy Method/Multiple Regression Analysis). The following was noted :

(*i*)   All indices showed peaks in the QBO, QTO (Quasi-Biennial and Quasi-Triennial, 2-3 year and 3-4 year regions) and higher periodicities, including decadal.

(*ii*)   The data were divided into two portions, 1900-49 (unreliable) and 1950-2000 (reliable). For data for 1950 onwards, only data for 1950-83 were used as dependent data for spectral analysis, using the rest (1984-2000) as independent data for checking predictions.

(*iii*)   In the 1950-83 data, several highly significant (above a 2σ level) peaks were seen. In the QBO region, storm indices had peaks near 2.40 years and 2.85 years. The 50 hPa wind had peaks near 2.40 years, while ENSO indices (Southern Oscillation Index Tahiti minus Darwin pressure difference T-D, and central Pacific SST) had peaks near 2.40 and 2.85 years.

(*iv*)   In the QTO region, storm indices had a peak near 3.5 years, matching with a similar, strong peak in ENSO. The storm indices had prominent peaks in the 4.5 - 5.5 year range, which may be the same as the strong 4.5 year peak in ENSO.

(*v*)   Peaks near 8-9 years, 11-12 years and 14-15 years were seen in some storm indices. The 50 hPa wind had a small peak at 15.6 years, while ENSO had peaks at 7.4 years and 12-14 years.

(*vi*)   The indices NS, H and MPD showed large linear trends, ~50% increase in 90 years. Also, periodicities were seen in all indices in the multi-decadal ranges 28-34, 40, 50-53, 61-63, ~70 and ~80 years, but different for different indices. These compared well with similar peaks in global land and sea surface temperatures.

(*vii*)   When the significant peaks obtained by MEM-MRA were used for reconstruction, the fit was reasonably good (correlations ~+0.6) for the dependent data (1950-83). But for the independent data, the matching was very poor,

with correlations near zero, except in two cases where the correlation reached +(0.40 ± 0.14). The prediction method of Elsner *et al*. (1998) based on SSA-MEM gives better predictions (correlation ~0.5, variance explained ~25%) than MEM-MRA, but still with large errors. For example, in 1998, observed hurricanes were 10 while the ones predicted by SSA-MEM were 3. Professor William M. Gray leads a team of hurricane forecasters at the Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 80523, USA. This team has a forecast scheme, which uses parameters like ENSO, surface pressure and winds etc. in a regression equation and gives forecast with an antecedence of a few months. The forecasts turned out to be reasonably good for NS and H, with correlations exceeding +0.60 for the independent data (1984-98). For other indices, forecasts were not so good.

Forecasting hurricane activity is a hazardous task. To quote Gray *et al*. (1999), "These forecasts are based on the premise that trends in global environmental conditions which preceded comparatively active or inactive hurricane seasons in the past provide meaningful information about trends in future seasons as well. It is important that the reader appreciate that these seasonal forecasts are based on statistical schemes which, owing to their intrinsically probabilistic nature, will fail in some years. Moreover, these forecasts do not explicitly predict specifically where within the Atlantic basin, storms will strike. Landfall probability estimates for any one location along the coast are very low and reflect the fact that in any one season, most US coastal areas will not feel the effects of a hurricane no matter how active an individual season is. And, it must be emphasized, that a low probability does not insure that a hurricane will not come ashore".

Like the Atlantic basin, the Indian Ocean also has storm activity (cyclones). Singh *et al*. (2000) studied the frequency of tropical cyclones over the North Indian Ocean during the 122 year interval 1877-1998. They report increasing trends in the cyclone frequency over the Bay of Bengal during November and May (main cyclone months) but decreasing trends during June and September (transitional monsoon months), and no significant trends in the Arabian Sea. A spectral analysis showed that in the Bay of Bengal, there was a periodicity of 29 years in May and 44 years in November, besides an ENSO signal (2-5 years). Over the Arabian Sea, significant periodicities of 13 and 10 years were observed during May-June and November, respectively.

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