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Mid-Atlantic Coastal Storms

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ABSTRACT

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Waves generated by extratropical storms are responsible for much of the coastal erosion that occurs along the Atlantic Coast. Between 1942 and 1984, 1349 storms producing waves high enough to cause measurable erosion of an open coast beach were investigated to determine their frequency, magnitude, and patterns of occurrence. The 5-month period December through April is the period of maximum storm frequency; 63 percent of all storms occurred during these months. Exploratory analysis of storm frequency and duration data indicates that the occurrence of very stormy months was high relative to a normal distribution. A systematic increase in the number of storms occurring in the months of May and October has resulted in a lengthening of the winter storm season and more abrupt transitions between winter and summer storm regimes. The total number of storms on a mean annual basis has remained unchanged during the period of record, but the average duration of storm waves has undergone a net decline which we attribute to an anomalous shift in the mean winter storm track that occurred during the mid-1970's.

INTRODUCTION

The processes affecting beaches and barrier islands span time scales from hours to decades and include variations in the beach during a single 12-hour tidal cycle, periodic storm surges, shoreline recession in response to long-term alterations in sea level, changes in storm tracks, and island-wide modifications associated with man's activities (U.S. ARMY CORPS of ENGINEERS, 1971; DOLAN *et al.,* 1979; BRUUN, 1962, and MATHER *et al.,* 1964). The processes that result in the most dramatic short-term changes in beaches and barrier islands are, however, associated with waves produced by coastal storms.

Coastal storms as used here refer to any synoptic weather system that produces waves in deep water of at least 1.6 m. Most that affect the Atlantic Coast originate in the middle-latitude westerly wind belt and are generically referred to as extratropical storms, or, more commonly, "northeasters." As a class, these systems are associated with cyclonic (low-pressure) disturbances. There also occur, although much less commonly, "fair weather" or anticyclonic (high pressure) coastal storms that can produce strong northeasterly winds and damaging waves along the shoreline. A second class of coastal storms consists of cyclonic disturbances that develop in warm tropical waters. These are generally referred to as tropical cyclones and include hurricanes and less intense tropical storms. It is virtually impossible for an extra-tropical or tropical storm system to move along the Atlantic Coast without crossing a barrier island or affecting one of them. Between 30 and 35 "northeasters" each year generate wave action with enough force to erode Atlantic Coast barrier island beaches and frontal dunes (BOSSERMAN and DOLAN, 1968.). Over secular time scales a storm will occur that will have a far more significant impact on the barrier islands and on the people who live and work on them. It was such a storm in March of 1962 that now serves as the benchmark for many working in the field of coastal geology and geomorphology. The 5-8 March 1962 storm is now known as "The Great Ash Wednesday Storm of 1962" (BRETSCHNEIDER, 1964; STEWART, 1962).

Along 1600 km of the Atlantic Coast, this storm caused $300 million in damage and resulted in hundreds of injuries and many

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Figure 1. Storm damage along the Outer Banks of North Carolina.

deaths. In Atlantic City, New Jersey, the storm destroyed the famous Steel Pier and damaged the boardwalk. On Fire Island, New York, beach cottages on the ocean front collapsed into the surf (Figure 1). On Fenwick Island, Maryland, the 3-mile long boardwalk was destroyed and much of the resort community of Ocean City was flooded. Also damaged or destroyed were more than 50 homes and apartments, and 150 businesses. Overwash occurred along most of Assateague Island.

It took several days following the Great Ash Wednesday Storm before the changes to the mid-Atlantic beaches and barrier islands became apparent. Beaches were eroded back to the dune lines and, on narrow islands such as Assateague, the vegetation behind the dunes was buried by overwash sand. Along sections of the Outer Banks of North Carolina, the dunes had been eroded back so far that the original sand fences that had been installed 30 years before were exposed. Roads and driveways were buried by overwash sediment, and lagoon channels were choked with sand and debris. The Ash Wednesday Storm of 1962 convinced most coastal scientists that faulty practices had been followed in the development of the Atlantic Coast beaches and barrier islands. It became overwhelmingly apparent that sand dikes and sand dunes could not protect beach-front development from a major storm.

Many learned from the experience of the Ash Wednesday Storm, however, that undeveloped beaches and barrier island systems adjust well to extreme conditions (DOLAN *et al.*, 1973). Moreover, post-storm assessments of the geomorphological changes caused by the storm indicated that the response of a beach or barrier island was not random or happenstance. Indeed, there seemed to be a pattern to the erosion and the large-scale overwash (DOLAN and HAYDEN, 1980).

It also became clear following the March 1962 storm that understanding the natural dynamics of beaches and barrier islands is important not only from an academic standpoint, but it is also the key to recognizing and estimating both the short-term and long-term hazards of living on them (MATHER *et al.*, 1964). There was, soon after, an explosion of new research on beaches and barrier islands; the field of coastal geomorphology moved to a new plateau.

One of the fundamental steps to understanding better the processes that dominate the Atlantic Coast barrier islands is to investigate the characteristics of the storms that produce most of the changes. Extratropical storm frequencies in the United States have been documented for several periods during the twentieth century. HOSLER and GAMAGE (1956), for example, studied the period 1905 to 1954 and found no evidence of trends or periodicities in annual cyclone frequencies, or shifts in the regions of maximum frequency. REITAN (1974, 1979) updated Hosler and Gamage's work and reported a general, although not monotonic, decline in cyclone frequencies during the period 1949 to 1976. ZISHKA and SMITH (1980), in a broader study of the climatology of North American cyclones and anticyclones between 1950 and 1977, noted a significant decrease in both types of systems.

Closer scrutiny of extratropical storm frequency and variability over the Eastern United States and adjacent Western Atlantic Ocean has been given by MATHER *et al.* (1964), RESIO and HAYDEN (1975), COLUCCI (1976), DICKSON and NAMIAS (1976), and HAYDEN (1981). In general, these studies indicate that a notable degree of interannual variability is present in the occurrence of Atlantic Coast storms. Other studies of coastal storminess have focused on the generation of potentially damaging waves and surges. BOSSERMAN and DOLAN (1968) documented monthly storm frequency and magnitude, and hindcasted deep-water wave heights for the years 1942 to 1967 in the vicinity of Cape Hatteras, North Carolina. HAYDEN (1975) updated the Bosserman and Dolan study to 1974 and reported that the duration and frequency of storms generating high waves had increased between 1942 and 1974, as had the length of the winter storm wave season. ALLEN (1981) correlated secular variations of a frequency-magnitude index of storminess at Sandy Hook, New Jersey, with shoreline and sediment budget changes from 1953-78.

In this study we update the Bosserman and Dolan, and Hayden studies, investigating extratropical storms affecting the mid-Atlantic Coast for the 42-year period July 1942 through June 1984. Our objectives are to (1) determine extratropical storm frequency and magnitude for the mid-Atlantic Coast; (2) establish the baseline statistical attributes of the monthly and annual storm occurrences by wave height class; (3) determine the cumulative monthly and annual average hourly duration of waves in each wave height class; and (4) identify trends or recurrent patterns in storm frequency and storm wave duration.

We pursue the last of these objectives using a body of statistics known as exploratory data analysis (EDA). Although not a new subject, EDA has only recently become an important component of statistical analysis (TUKEY, 1977). Its purpose is to search for relationships and structures in a data set and to display the results in such a manner as to make them recognizable (KLEINER and GRAEDEL, 1980). EDA is an iterative process in that each analytical step provides a basis for successive steps in the analysis. It makes extensive use of robust and resistant statistics and relies heavily on graphical display techniques. It also provides a desirable starting point for analyzing a geophysical data set such as the storm data described herein since no prior distributional assumptions about the data are required.

THE STORM DATA

All extratropical storms generating wind fields that resulted in deep-water waves greater than 1.6 m (storm waves) were included in our study because we have found that waves of this height or higher cause some degree of beach change along the Mid-Atlantic Coast barrier islands (BOSSERMAN and DOLAN, 1968; HAYDEN, 1975). Although extratropical storms normally include only low pressure systems that form outside the tropics along cold or stationary fronts, wave generation is a function of wind fields, regardless of the type of weather system. Both cyclones and anticyclones were therefore considered in our study. We excluded tropical disturbances since information about their occurrence along the mid-Atlantic Coast is already well documented (SIMPSON and RIEHL, 1981).

Using a variation of the Bretschneider method now known as the Sverdrup, Munk and Bretschneider (SMB) method (U.S. ARMY CORPS of ENGINEERS, 1984) we calculated (hindcasted) *significant* wave height, which is an index of storm magnitude, and made frequency counts of the number of disturbances occurring in each of seven *deep-water* wave height categories for the mid-Atlantic Coast. The seven wave height intervals are 1.6 to 2.4 m; 2.5 to 3.4 m; 3.5 to 4.3 m; 4.4 to 5.2 m; 5.3 to 6.1 m; 6.2 to 7.0 m, and 7.1 to 9.8 m.

Fetch length was estimated from National Weather Service 12- and 24-hour synoptic weather charts. We obtained wind speed over the fetch area from records of the Cape Hatteras Weather Station, from published logs of ships at sea, and by estimating wind speed from isobaric spacings on weather charts using the geostrophic flow equation with corrections for isobaric curvature (U.S. ARMY CORPS of ENGINEERS, 1984). For the 42-year period of record, 1349 storms were analyzed and found to produce waves in deep water off the mid-Atlantic Coast of 1.6 m in height or higher. The mean track for the storms included in our data base appears in Figure 2.

The raw data on the frequency, magnitude, and duration of the 1349 storms are summarized in Tables 1 and 2. The tables show the number of storms occurring each month during the 42-year period, the number of storms in each wave height category occurring during

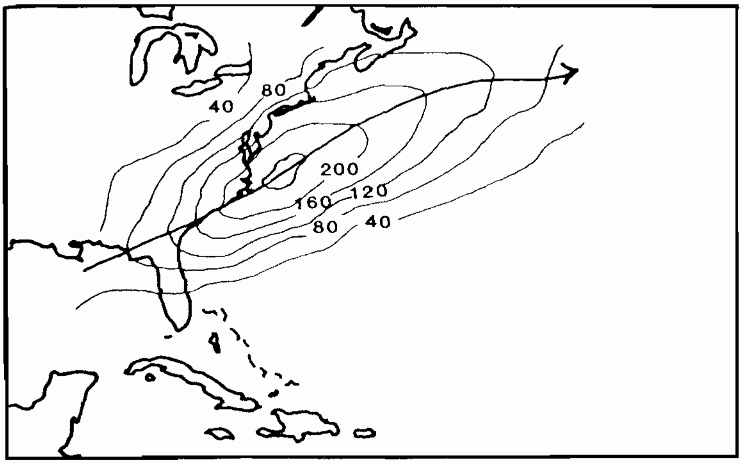


Figure 2. Mean cyclone track and time series for all extratropical storms producing significant waves at Cape Hatteras, North Carolina.

each storm year (July-June), and the duration (in hours) of the storm wave conditions for each category.

Of the 1349 storms generating deep-water waves over 1.6 m, 326 (24 percent) were caused by anticyclones. It is noteworthy that 26 percent of the anticyclones had wind fields of sufficient speed and fetch of sufficient length the generate waves greater than 2.5 m. Cyclones of local origin rarely deepened rapidly enough to result in high waves; only 13 percent of these generated waves greater than 3.4 m. Cyclones that tracked eastward from the continent, especially those crossing the coast to the south of Cape Hatteras, generated the largest waves.

EXPLORATORY DATA ANALYSIS

Prior to performing exploratory analyses of the frequency and duration data contained in Tables 1 and 2, the 6 months of data at the beginning and end of each series were removed (*i.e.*, July through December 1942 and January through June 1984). Thus, the data were aggregated by calendar year forming a consecutive 492-month sequence beginning with January 1943 and ending with December 1983.

The analysis of both data series begins with an assessment of their distributional properties. Theoretical quantile-quantile (probability) plots for monthly storm frequency and monthly storm wave duration are examined first and appear in Figure 3. The figure depicts the distribution of each variable plotted against a theoretical normal distribution. For each variable the normal distribution is specified by the mean and standard deviation of the actual data. The units along the abscissa, normal quantiles, are actually standard deviations for the theoretical normal distribution. The plots for the frequency (Figure 3a) and duration (Figure 3b) data both indicate departures from their respective theoretical normal lines. The most notable misalignments for both occur in the right (upper) tail and the bounded left (lower) tail. This signifies that months with large numbers of storms (7-10) and high storm wave duration times (150-250 hours) occurred more frequently during the 41-year period-of-record than would be expected under the normal assumption. Similarly, months with no storms or storm wave hours were more common than expected. Notably, however, both frequency plots indicate that for the middle range of values (-1 to $+1$ normal quantiles) the theoretical normal generally fits the actual data distributions. RESIO and HAYDEN (1975) compared the SMB data of BOSSERMAN and DOLAN (1968) with the PJN spectral model and found agreement to within 10 percent.

To ensure that both variables were indeed non-normal, the probability plot correlation coefficient test for normality was employed (LOONEY and GULLEDGE, 1985). This test is

TABLE 1. *Extratropical storm frequency by month, year, and wave height category.*

Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	>5′	>8′	>11′	>14′	>17′	>20′	>23′
1983–1984	—	—	2	4	4	3	3	3	3	—	1	—	23	8	1	—	—	—	—
1982–1983	—	1	2	2	1	6	4	6	7	2	1	1	33	13	6	3	2	1	1
1981–1982	1	—	—	3	2	5	5	8	1	5	1	—	31	14	2	—	—	—	—
1980–1981	—	—	1	3	2	4	2	4	2	3	5	—	26	10	3	1	—	—	—
1979–1980	—	—	1	1	2	5	7	4	5	3	4	3	35	11	3	1	1	1	
1978–1979	3	1	3	4	4	4	5	4	2	1	2	4	37	20	2	2	—	—	—
1977–1978	—	—	—	4	—	2	3	2	6	5	4	2	28	12	3	1	—	—	—
1976–1977	—	2	1	4	4	2	1	2	4	2	1	—	23	4	2	—	—	—	—
1975–1976	—	—	1	3	1	2	3	1	2	1	4	2	20	10	5	2	—	—	—
1974–1975	—	2	1	4	3	4	4	2	2	—	—	—	22	8	2	1	—	—	—
1973–1974	—	—	1	—	—	2	2	4	5	1	2	4	21	9	5	—	—	—	—
1972–1973	1	2	1	4	5	5	6	6	2	2	1	—	35	14	7	2	2	1	—
1971–1972	—	—	1	1	2	2	2	4	4	5	3	1	25	14	5	2	—	—	—
1970–1971	—	2	1	3	3	2	4	1	4	4	3	1	28	17	10	3	1	1	
1968–1970	—	—	2	3	3	2	5	5	3	5	1	—	29	18	10	5	1	—	—
1969–1969	—	1	1	2	4	5	6	4	4	4	2	—	33	19	10	4	1	1	1
1967–1968	1	—	2	3	2	5	8	4	3	7	2	—	37	16	9	2	1	—	—
1966–1967	1	—	4	4	3	5	4	5	2	3	1	1	33	17	4	—	—	—	—
1965–1966	1	1	2	5	1	3	6	5	3	1	3	2	33	9	3	1	—	—	—
1964–1965	1	1	—	4	5	3	4	5	6	4	1	1	35	13	4	2	—	—	—
1963–1964	2	2	4	1	3	4	6	8	4	2	3	2	41	18	5	—	—	—	—
1962–1963	—	1	3	—	3	2	6	7	1	4	5	—	32	20	5	2	—	—	—
1961–1962	—	—	1	3	1	2	6	4	4	2	—	3	26	10	3	1	1	1	1
1960–1961	—	2	1	1	2	5	4	9	5	5	2	1	37	16	3	—	—	—	—
1959–1960	—	1	2	4	5	4	4	6	9	4	2	1	42	13	4	1	1	—	—
1958–1959	—	—	2	2	5	5	3	4	7	2	1	—	31	12	6	1	—	—	—
1957–1958	1	3	3	3	6	2	5	2	6	5	1	2	39	9	2	1	—	—	—
1956–1957	1	2	2	4	—	2	6	5	4	4	1	1	32	11	4	—	—	—	—
1955–1956	1	—	4	4	2	2	2	9	7	6	8	3	48	12	3	1	—	—	—
1954–1955	1	1	—	3	2	4	2	5	3	2	4	1	28	8	3	1	—	—	—
1953–1954	2	1	3	1	3	4	2	1	3	3	2	1	26	11	3	2	1	1	—
1952–1953	1	2	5	3	3	5	3	4	4	5	2	2	39	18	2	1	—	—	—
1951–1952	—	3	3	3	4	5	3	4	5	4	—	1	35	14	6	3	2	—	—
1950–1951	1	—	2	2	3	4	3	7	7	5	1	2	37	11	2	—	—	—	—
1949–1950	2	2	2	3	1	3	2	4	8	3	2	2	34	14	2	1	—	—	—
1948–1949	1	—	2	4	3	4	3	3	5	4	3	2	34	15	3	1	1	—	—
1947–1948	1	1	1	2	5	5	10	4	7	6	—	3	45	23	9	3	1	—	—
1946–1947	3	1	1	3	4	3	3	1	5	5	3	2	34	8	2	2	1	—	—
1945–1946	—	—	1	1	3	6	4	3	2	5	4	1	30	14	5	3	1	1	—
1944–1945	—	1	2	3	1	4	7	2	2	3	2	1	28	9	2	—	—	—	—
1943–1944	—	1	3	2	4	3	5	4	8	5	—	1	36	9	3	1	—	—	—
1942–1943	—	3	2	—	4	3	3	1	5	4	3	—	28	13	5	—	—	—	—
Total:	26	40	76	108	141	174	176	176	181	146	91	54	1349	544	178	57	18	8	4
Average:	0.6	1.0	1.8	2.6	3.4	4.1	4.2	4.2	4.3	3.5	2.2	1.3	32.1	13.0	4.2	1.4	0.4	0.2	0.1

based on the fact that the more normal a data set is, the closer it graphs to a straight line on a probability plot. Thus the sample (linear) correlation coefficient between actual data and their normal quantiles can be used to test for normality. As the test is applied, the correlation coefficient (r) is compared to a critical value (r_c) based on the desired confidence level (α) and the sample size (n). To establish that the data are normal, r must be greater than r_c for a given α and n. In this case (where n = 492), for both variables r was less than r_c and we rejected the null hypothesis that the data were normally distributed at the $\alpha = 0.05$ level.

A very informative yet concise characterization of the monthly distributional properties of the two variables can be obtained using boxplots (Figure 4). Boxplots provide a visual summarization of the median, interquartile range, quartile skew, and of extreme values of a data set. As in the present case, they can be put side-by-side to visually compare and contrast data

TABLE 2. *Extratropical storm wave duration (hours) by month, year, and wave height category.*

Year	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	>5′	>8′	>11′	>14′	>17′	>20′	>23′
1983–1984	—	—	45	108	23	24	67	33	18	—	13	—	331	113	4	—	—	—	—
1982–1983	—	3	17	81	25	91	44	88	122	15	1	9	496	218	86	47	27	12	6
1981–1982	11	—	—	165	89	124	81	166	6	53	8	—	703	252	40	—	—	—	—
1980–1981	—	—	35	82	41	130	41	86	35	34	155	—	639	185	48	21	—	—	—
1979–1980	—	—	56	18	34	93	111	38	95	30	48	55	579	148	45	18	14	9	4
1978–1979	35	11	97	106	46	51	65	85	11	20	23	97	647	228	58	8	—	—	—
1977–1978	—	—	—	68	—	24	15	41	64	78	30	20	340	103	30	11	—	—	—
1976–1977	—	49	5	59	19	21	8	13	25	9	12	—	220	51	13	—	—	—	—
1975–1976	—	—	16	36	45	21	34	5	30	28	51	41	317	146	65	6	—	—	—
1974–1975	—	33	19	73	24	42	54	11	18	—	—	—	274	79	10	2	—	—	—
1973–1974	—	—	10	—	—	53	8	71	66	13	37	26	284	108	32	—	—	—	—
1972–1973	27	30	22	75	89	86	91	149	98	14	9	—	692	268	122	66	32	16	—
1971–1972	—	—	26	110	32	82	51	124	66	96	102	1	698	378	151	42	—	—	—
1970–1971	—	54	31	114	65	27	78	18	76	48	51	5	568	338	168	75	14	4	—
1969–1970	—	—	117	214	38	16	71	132	30	32	20	—	714	396	148	30	9	—	—
1968–1969	—	44	16	31	40	90	144	190	66	107	38	—	792	419	254	129	69	44	18
1967–1968	11		29	21	39	88	214	80	51	99	22	—	654	306	111	45	24	—	—
1966–1967	26	—	47	134	140	145	44	64	17	25	69	8	726	277	42	—	—	—	—
1965–1966	26	34	49	44	6	26	110	50	56	11	41	18	458	90	29	4	—	—	—
1964–1965	2	7	—	140	68	40	132	84	46	53	6	19	598	224	40	12	—	—	—
1963–1964	21	3	131	25	48	56	88	82	50	34	124	40	702	292	44	—	—	—	—
1962–1963		4	76	—	40	14	76	186	26	40	157	—	618	246	52	10	—	—	—
1961–1962	—	—	50	34	6	8	74	51	106	24	—	90	442	216	56	38	18	16	12
1960–1961	—	80	124	19	10	88	44	89	98	54	34	45	684	190	16	—	—	—	—
1959–1960	—	18	48	24	158	79	117	39	130	87	46	72	819	252	83	38	1	—	—
1958–1959	—	—	17	90	56	98	40	30	86	81	27		518	216	78	30	—	—	—
1957–1958	24	66	95	91	55	85	77	15	81	86	9	18	702	102	19	2	—	—	—
1956–1957	12	26	12	242	—	9	108	128	40	31	25	32	666	232	38	—	—	—	—
1955–1956	1	—	66	80	7	35	40	98	124	105	122	73	750	182	30	3	—	—	—
1954–1955	19	15	—	44	7	48	18	72	45	19	52	10	350	104	37	22	—	—	—
1953–1954	62	28	77	8	82	39	35	9	54	55	28	9	477	148	43	22	6	2	—
1952–1953	1	57	93	53	32	58	37	54	56	90	28	40	610	178	23	2	—	—	—
1951–1952	—	33	28	192	57	74	63	59	62	14	—	26	608	208	96	46	22	—	—
1950–1951	1	—	65	34	49	60	54	112	97	39	8	13	531	114	16	—	—	—	—
1949–1950	24	26	91	34	10	94	34	44	108	38	22	8	522	156	32	5	—	—	—
1948–1949	13	—	59	46	28	44	41	31	101	66	48	88	602	218	67	32	23	—	—
1947–1948	16	13	62	26	98	52	178	169	124	102	—	22	862	364	156	56	14	—	—
1946–1947	34	2	22	128	95	61	29	17	78	62	31	28	587	129	24	16	10	—	—
1945–1946	—	—	11	32	57	72	104	41	80	106	31	2	536	268	105	28	6	1	—
1944–1945	—	26	16	47	50	108	61	48	7	118	20	3	504	194	48	—	—	—	—
1943–1944	—	30	66	71	72	114	84	62	117	46	—	15	678	174	60	16	—	—	—
1942–1943	—	79	77	—	52	72	69	24	121	37	52	—	584	225	84	—	—	—	—
Total:	336	771	1923	2999	1932	2642	2934	2988	2787	2099	1612	933	24,082	8,735	2,703	882	289	104	40
Average:	8.7	18.4	45.8	71.4	46.0	62.9	69.8	71.1	66.3	50.0	38.4	22.2	573.4	208.0	64.4	21.0	6.9	2.5	1.0

groupings; for example, month-to-month variability. The most prominent feature in the boxplots of both storm frequency and wave duration is a seasonal pattern with high median values in winter and low in summer. The winter season lasts from October to April when a median value of 3 to 4 storms per month (Figure 4a) delivering storm waves for a total of 40 to 75 hours per month (Figure 4b) occurs. The summer, from May to September, is characterized by 0 to 2 storms per month with 0 to 30 hours of storm waves per month. No distinct spring or fall season is evident in either data set. The transition from winter to summer conditions and back again is abrupt, generally occurring within a 1-month period during April-May and during September-October. The absence of spring and autumn periods with wave climate attributes different from either summer or winter was noted earlier (HAYDEN, 1975). This two season winter and summer pattern has been associated with the seasonal climatology of the jet stream and the mid-latitude westerlies (HAYDEN and DOLAN, 1977).

The shape of the monthly distributions of storm frequency and storm wave duration within the central range of values, or interquartile range (denoted by the boxes in Figure 4) is generally symmetric. Asymmetry in monthly storm frequency is most apparent, however, during the winter months of January and March (with positive skew) and April and

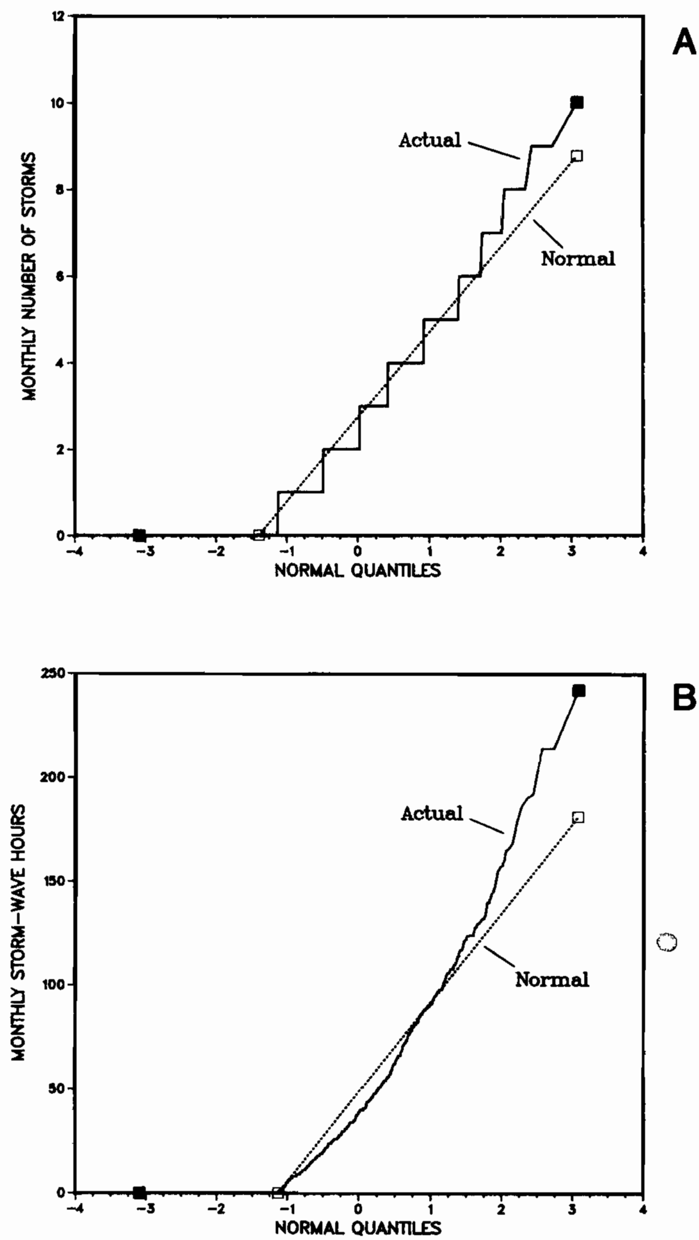


Figure 3. Theoretical quantile-quantile plots of monthly storm frequency (a) and monthly storm wave duration (b) against a normal distribution.

December (with negative skew). Asymmetry in monthly storm wave duration is greatest during the seasonal transition periods, that is in April, September, and October (all with positive skew).

Additional information about the asymmetry of monthly distributions can be obtained from inspection of the vertical lines or whiskers emanating from the top and bottom of the boxes in Figure 4. The lengths of these lines relative to

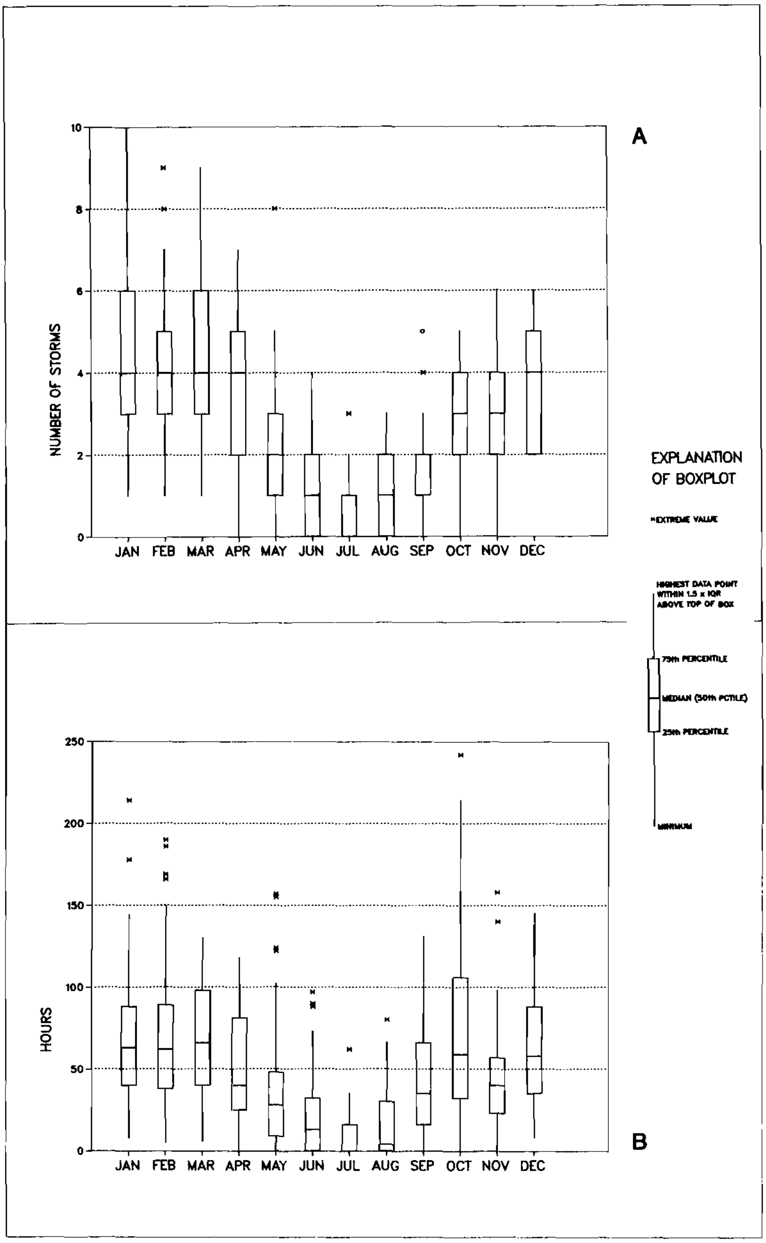


Figure 4. Boxplots of monthly storm frequency (a) and monthly storm wave duration (b).

the box show how stretched the tails of the distribution are. The most distinctive feature of the monthly tails in both variables is a seasonal difference associated with the boundary on the lower end during summer when no tails are present. In June and August, the zero lower bound is the lower quartile of the distribution. That is, 25 percent of the time June and August experience no storms or storm wave hours. Even more striking is July, where the zero bound is the median value for both variables. Lower tails of a relatively common length (~2 storms and ~30 hours of storm waves per month) are characteristic of the winter months. The only notable exception occurs in December where the lower quartile value of two storms per month is also the fewest number of storms to occur in any December during the period of record.

The upper tails of both quantities display a much different pattern. In storm frequency, for example, a seasonal phase shift is evident. The period January through June has the longest upper tails at 2-4 storms per month while the months from July to December generally have a tail only one storm in length. November is the exception with a 2-storm upper tail. Storm-wave duration, on the other hand, exhibits little seasonality in upper tail length. In 10 of the 12 months, the length of the upper tail is between 40 and 60 hours. July, not surprisingly, has the shortest tail (~25 hours). Of more interest, however, is October which has by far the longest upper tail at over 100 hours. Long duration storms, however, may also result when the storms are at a rather low latitude and when they tend to track nearly northeastward. In addition, the relative speed, position, and shape of the jet stream aloft may govern storm speed.

The final point to be made from the boxplots relates to unusual events or outliers. These appear in Figure 4 as small x's beyond the vertical whiskers. The most notable characteristic of the outliers in storm frequency and storm wave duration is that they are not restricted to any particular season. Outliers more commonly occur in the duration distributions than in the frequency distributions. In some months, such as February, May, and July, the outliers in duration can be attributed, at least partially, to those in frequency. In other months, however, such as June, August, October, and November, the duration outliers probably reflect the influence of previously mentioned blocking anticyclones or very slow-moving systems.

The foregoing discussion emphasizes the need for a more thorough analysis of the dependence of storm wave hours on storm frequency. One of the most useful tools for assessing such bivariate relationships is the scatterplot. In this instance, we employ an enhancement of the basic plot, a smoothing scatterplot, to summarize the bivariate distribution of storm frequency and storm wave duration (Figure 5). The three solid lines in Figure 5, from top to bottom respectively, represent the upper, middle, and lower smoothing of the distribution of monthly storm wave hours computed for each discrete value of monthly storm frequency. The smoothings are calculated using robust locally weighted regression, an iterative least squares procedure incorporating the bi-square weight function (CLEVELAND, 1979; CLEVELAND and McGILL, 1984). This procedure minimizes the influence of outliers on the smooth fitted values by downweighting those observations most distant from the original least squares line. The middle smoothing is determined first using the entire bivariate distribution. The upper and lower smoothings are then calculated independently for the positive and negative residuals from the middle smooth line.

The most important conclusion to draw from Figure 5 is that the dependence of storm wave duration on storm frequency is linear (as indicated by the straightness of the middle smoothed curve) and that the distribution of wave duration given storm frequency is asymmetric at nearly all values of storm frequency (as indicated by the unequal distance of the upper and lower smoothings from the middle). We regressed monthly storm wave duration on monthly storm frequency and found that the latter explains approximately 52 percent of the variance in the former. In addition, the broad scatter of points above the upper smoothing (consisting of approximately 25 percent of the total observations) gives the impression of forming a distribution distinct from that existing below the upper curve. In view of this, we interpret the scatter of all observations to represent a mixed distribution.

In addition to the questions of distribution of the storm and storm wave data, we used EDA to consider the data variability through time. Several methods were employed. The first is a combination of statistical and graphical procedures developed by CLEVELAND *et al.* (1979), known as SABL. SABL, unlike power spectrum or harmonic analysis, does not require the assumption of cyclic behavior of the time series. SABL operates by decomposing a data time series (x_m) into trend (t_m), seasonal (s_m), and random (r_m) components. Three sequential elements comprise the SABL approach. First, the original raw data are transformed ($x_m \rightarrow x_m^p$). The transformation used is one that best sta-

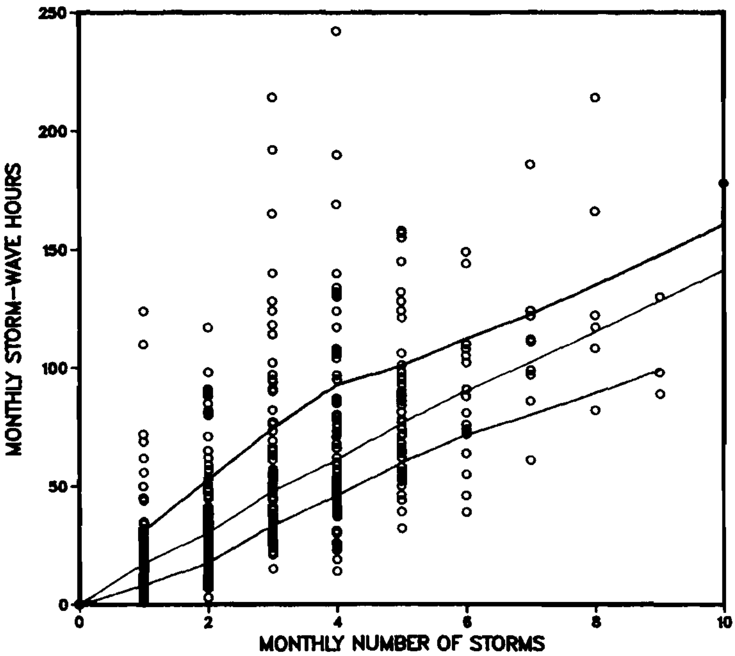


Figure 5. Smoothing scatterplot including the upper, middle, and lower smoothings of monthly storm wave duration given storm frequency.

bilizes the seasonal oscillations, thereby facilitating the subsequent decomposition into additive components; that is

$$x_m^p = t_m + s_m + r_m.$$

We used a log-transformation for both storm data sets. Second, a sequence of robust smoothers is applied that decompose the transformed series into the trend, seasonal, and random components. The smoothers used produce trend and seasonal estimates that are resistant to the effects of outliers. Third, diagnostic graphical plots, useful both for assessing the decomposition's adequacy and for evaluating each component's behavior, are produced.

The process of estimating t_m, s_m, and r_m occurs in six steps. First, an initial estimate of trend is obtained by computing a simple moving average of the original data. In the present study, a 45-month window is used in the trend calculations. A number of smoothing lengths were tested ranging from 7 to 53 months. We found considerable high frequency (intra-annual to biennial) variations attendant to windows less than 30 months and biennial to triennial variations at 30 to 40 months. Little additional damping of 2- to 4-year variations occurred between 45 and 53 months, thus we used the 45-month window in this illustration. Second, an initial estimate of the seasonal term is derived as a series of residuals, *i.e.*, $s_m = x_m - t_m$, and from this series 12 monthly sub-series are extracted. In this instance, each sub-series consists of 41 elements, one for each year of record. Each monthly sub-series is then smoothed using weighted moving least squares regression. We used a 7-element window for seasonal calculations. As with the trend, a number of smoothing lengths were tested. Those greater than 7 tended to remove seasonal detail, those less than 7 seemed not to be general enough. Choosing smoothing windows is clearly a subjective exercise. We emphasize, however, that the basic patterns resulting from this decomposition were relatively invariant to changes in smoothing length over the range of values we tested. We therefore selected values which seemed optimal for visual display. Our third step was to update the trend estimate by subtracting the seasonal estimates (from step 2) from the original data and then applying weighted moving least squares regression to this residual series. Also, an initial estimate of the random component is determined from the estimates in steps 2 and 3 as $r_m = x_m - t_m - s_m$. Fourth, the final seasonal values are computed as $s_m = x_m - t_m$ (using the t_m from step 3) and again 12 monthly sub-series are extracted. The 12 monthly sub-series are then smoothed using robust weighted moving least squares regression where the robustness weights are determined by the size of the random series computed in step 3. Fifth, the final estimate of trend is computed as a new residual series, $t_m = x_m - s_m$, that is smoothed using robust weighted moving least squares regression. The robustness weights for this smoothing come from the size of the random series, computed as $r_m = x_m - s_m - t_m$ (with s_m coming from step 4 and t_m from step 3). Sixth, and finally, the random term is computed as $r_m = x_m - t_m - s_m$ using t_m from step 5 and s_m from step 4.

Examples of component plots computed for the storm frequency and storm wave duration time series appear in Figures 6 and 7. In both sets of plots, the top trace is that of the original data (Figures 6a and 7a; from Table 1 excluding the first and last 6 months of data), the second is the trend estimates (Figures 6b and 7b), the third is the seasonal estimate (Figures 6c and 7c), and the bottom graph is the irregular or random fluctuation (Figures 6d and 7d). The original data series do not appear to exhibit any notable peculiarities, although storm wave durations were comparatively short during the mid-1970's. Identification of a trend in the two time series is difficult to discern.

In an effort to obtain more definitive information regarding the existence or absence of trend in the two data sets we used an alternative, robust nonparametric trend detection procedure, the seasonal Kendall test. This method is designed for use with monthly data exhibiting seasonality, skewness, and serial correlation, although it is not exact in the presence of serial correlation (HIRSCH *et al.*, 1982). An associated procedure, the seasonal Kendall slope estimator, was used to estimate trend magnitude. It is an unbiased estimator of the slope of a linear trend having greater precision than a regression estimator in applications where data are highly skewed.

A problem in applying the seasonal Kendall test and slope estimation procedure arises when using a data series containing values of identical magnitude occurring over consecutive years for a particular month. Such year-to-year monthly observational "ties" typically produce a trend slope estimate of zero, indicating no trend. This condition occurred often in the storm frequency data, but not in the wave duration data. Trend test results for the two data series appear in Table 3. Notice first the aforementioned zero trend slope for storm frequency. Although suspect because of the month-to-month ties, this result in combination with the trend plot in Figure 6b leads us to conclude that there has been no trend in the monthly frequency of storms off Cape Hatteras since 1943. On the other hand, a statistically significant, although shallow downward trend of -0.167 hours (about -10 minutes) per year is indicated in the monthly duration of storm waves. This trend slope corresponds to approximately seven less hours of storm duration in 1983 than in 1943. This value is consistent with that which can be inferred by subjectively fitting a straight line to the trend plot in Figure 7b. It must be pointed out, however, that a reduction of seven hours in the annual duration of storm waves represents a decrease of less than 1 percent. Despite the statistical significance of this value (which is primarily governed by the large sample size, $n = 492$), the physical effect is small. It is probable that the indication of a downward trend results more from the anomalously low monthly wave durations occurring between 1973 and 1977 than from any systematic long-term reduction. Based on this observation, investigators using these or related data from the mid-1970's should exercise caution in making generalizations. The period from 1973 to 1977 was anomalous in terms of the very few cyclonic depressions that tracked along the U.S. East Coast (HAYDEN, 1982). An additional argument for exhibiting care is that the notable lull in wave duration was much less apparent in storm frequency. This indicates that the storms of the middle 1970's were much shorter-lived than was typical during the period-of-record and, therefore, represent a relatively unique set of storms.

The graphs appearing as Figures 6c and 7c represent the seasonal component. As expected, a distinct seasonal pattern of winter maxima

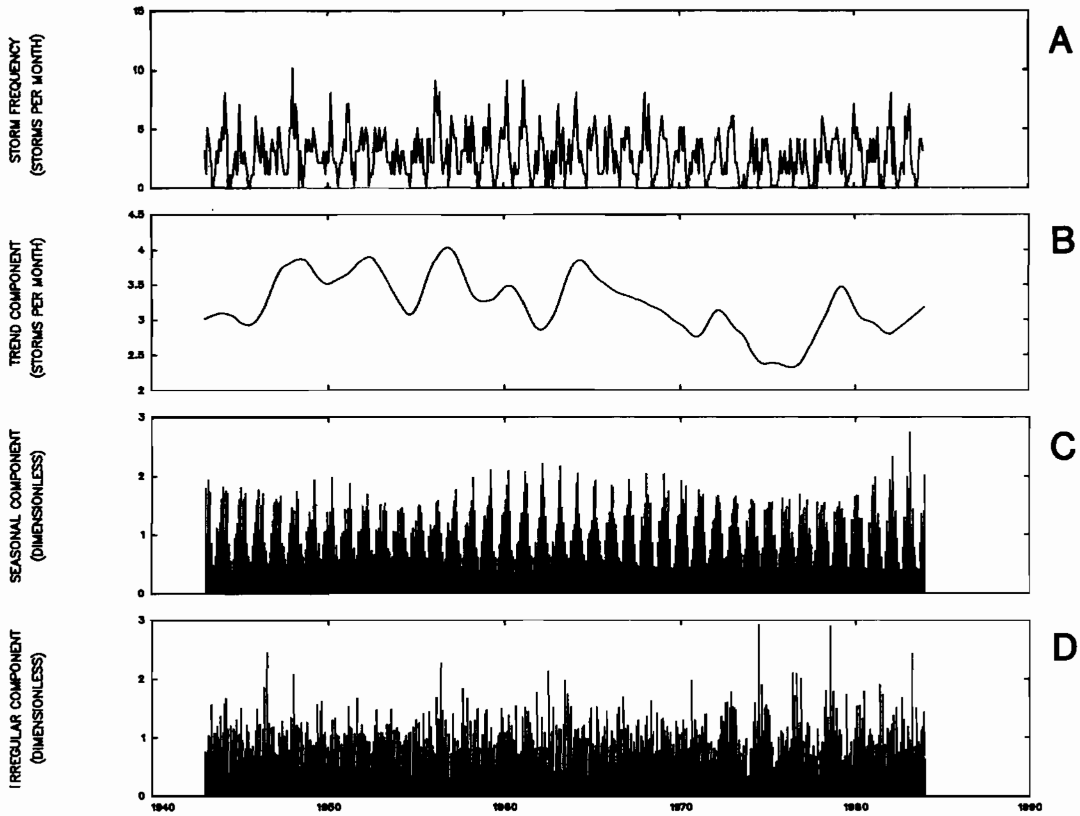


Figure 6. Plot of the raw monthly storm frequency data (a), and its decomposed components: trend (b), seasonal (c), and random (d).

and summer minima is evident in both storm frequency and storm wave duration. This pattern is not, however, stable through the period nor consistent between the two variables. The graph of storm frequency, for example, shows a progressive increase in the length of the winter mid-Atlantic storm season between 1943 and the mid-1970's. This increase was first described by HAYDEN (1975). Since the mid-1970's, however, the length of the winter storm season has decreased. In terms of storm wave duration, the length of the winter season shows a systematic contraction (except during the mid-1970's) through the period. Such a dichotomy in the temporal variation of these storm elements leads us to suggest that a fundamental change in the occurrence and structure of mid-Atlantic winter storms has occurred during the last four decades. The instability in the seasonal component of storm frequency and storm wave duration is also highlighted by the appearance of overlapping and non-uniform wave-like patterns that are apparent when viewing the seasonal graphs from either end of the central axis (*i.e.*, through time) at an oblique angle. These superimposed patterns are indicative of systematic monthly variations in the length of the seasonal transition period, *i.e.*, spring and fall, as well as of interannual variations in individual months. Additional information on these patterns can be obtained from the seasonal sub-series plots in Figure 8. These plots are simply a regraphing into monthly groups of the sequential "Seasonal Component" values appearing in Figures 6c and 7c. The logarithms of the dimensionless seasonal values are used in the sub-series plots to minimize the exaggerated appearance of interannual variations resulting from the wide range of data values, especially in the case of storm wave dura-

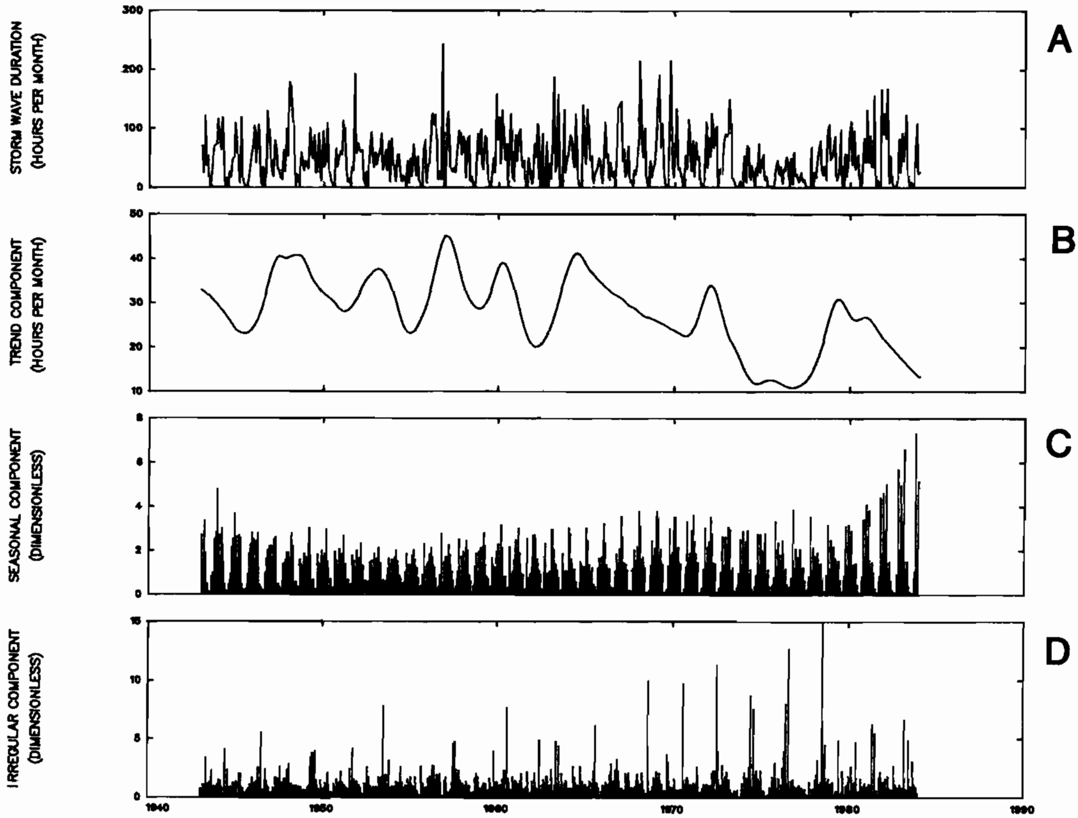


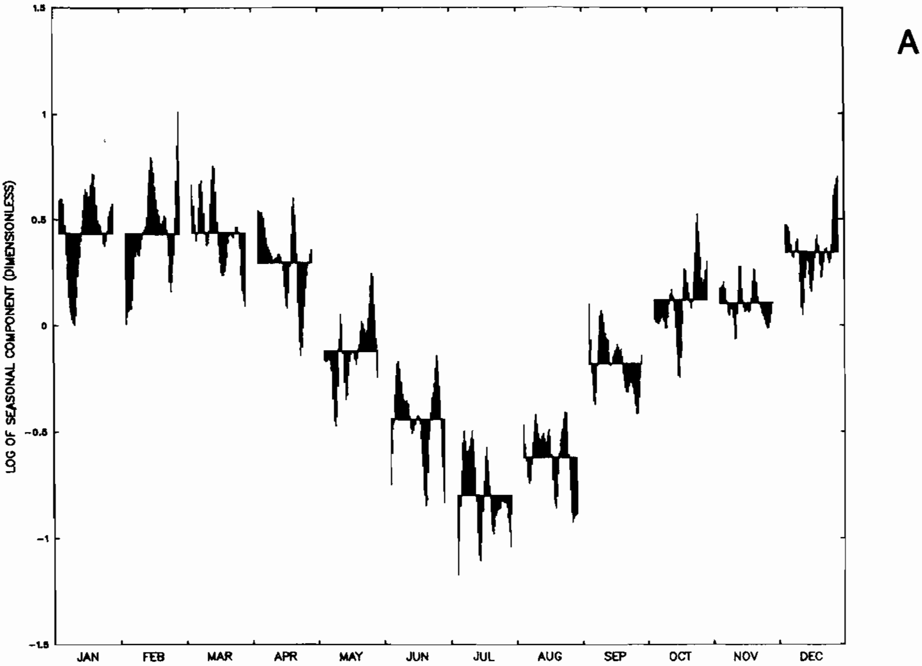
Figure 7. Plot of the raw monthly storm wave duration data (a), and its decomposed components: trend (b), seasonal (c), and random (d).

TABLE 3. *Trend in monthly storm frequency and monthly storm wave duration along the Outer Banks of North Carolina between 1943 and 983.*

Variable	Kendall's tau	P-level	Slope: Actual Units (Δ per year)
Storm Frequency	− 0.088	0.004	− 0.000
Storm Wave Duration	− 0.093	0.003	− 0.167

tion, and the skewed frequency distributions of the variables. The individual values (representing sequential years) for each month are plotted as vertical departures from their respective sub-series mean.

The most obvious aspect of the seasonal sub-series plots is the pronounced seasonality, with high frequencies and durations in winter and low in summer. The shapes of the two sub-series monthly component values compare closely to the shapes of each respective variable's monthly medians that appeared in the boxplots in Figure 4. What the monthly sub-series tells us that the boxplots do not, however, is how the values for each individual month vary from year-to-year in sequence through the period of record. These interannual variations appear as waveforms or oscillations about the monthly component means in Figures 8a and b. A notable feature apparent in these wave patterns is that departures from mean values over just a few years for a given month can be relatively large. Consider, for example, the sub-series plot for February storm wave durations. During the second half of the record there were three large shifts between positive and negative departures from the seasonal mean value. The oscillations differ from month-to-month and these differ-


A
LOG OF SEASONAL COMPONENT (DIMENSIONLESS)
1.5
1
0.5
0
-0.5
-1
-1.5
JAN
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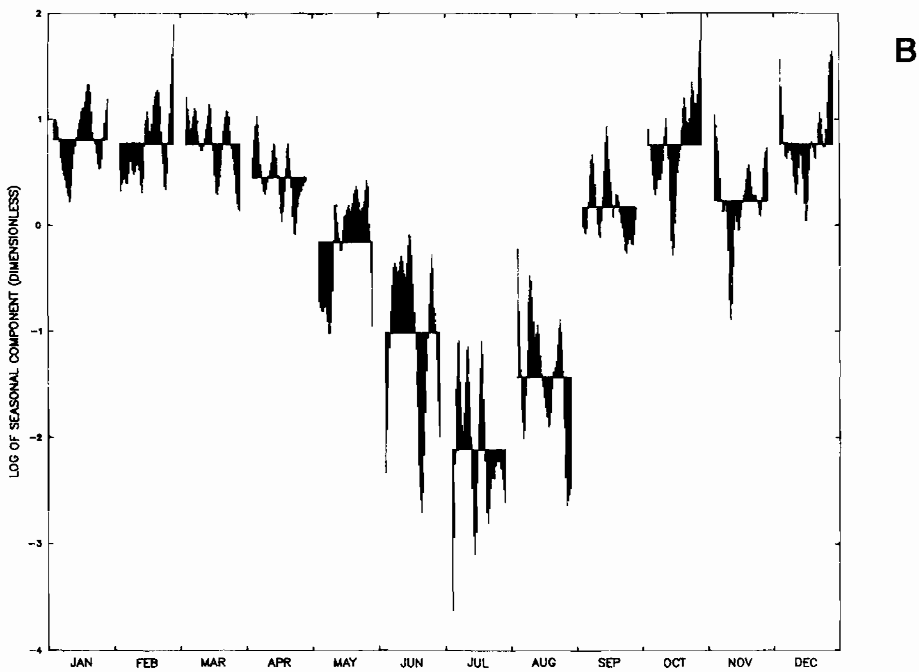
B
LOG OF SEASONAL COMPONENT (DIMENSIONLESS)
2
1
0
-1
-2
-3
-4
JAN
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ences produce the multiple, overlapping wave-like patterns that appear in the seasonal graphs in Figures 6c and 7c.

One of the more significant features of the seasonal sub-series plots relates to interannual variability apparent during the transition seasons. Storm frequencies (Figure 8a) during both October and May, for example. appear to increase through the period of record. Effectively, this represents an extension in the length of the winter storm season. Since, as we have already seen, there has been no overall increase in annual storm frequency, an increase in the number of winter storms must be accompanied by a decrease in summer storms. Indeed, the plots for July through September each show decreasing values during the second half of the record. The result of this pattern in recent years has been the appearance of a distinct two-season (winter-summer) storm frequency regime with abrupt seasonal transitions. Although the change from summer to winter conditions seem to have been sharp throughout the study period, the change from winter to summer storm frequencies has not. During the 1940's and 1950's there appears to have been a considerably more gradual spring transition phase, with May and June frequencies intermediary between the highs of December through April and the lows of July and August.

The temporal variations in monthly storm wave duration (Figure 8b) do not, in general, show an analogous pattern. As with storm frequency, increases have occurred in the duration of storm-generated waves during May and October. These have come, however, concurrent with substantial wave duration decreases in the months of March and April. Thus, a contraction rather than lengthening is apparent in the winter storm wave duration season. Moreover, the seasonal transitions in wave duration are considerably more gradual than for storm frequencies and appear to have been so throughout the period of record.

It is also clear from Figure 8 that there has been no simple annual trend in the two storm variables. Instead, there has been marked non-uniformity in contemporaneous annual variations among months with, in some instances, very large magnitude oscillations and trends within months.

Finally, Figures 6 and 7 also show the residuals, *i.e.*, the random or irregular components. While the random terms are usually left undiscussed, we will comment here on several features of the charts because this kind of output is new to coastal researchers. Since the random term is computed as the residual left from subtracting the trend and seasonal terms from the original data, the largest monthly storm frequency and wave duration values will not necessarily be characterized as the largest random terms in the graphs. An unusually stormy summer month or very calm winter month will more likely produce a large random fluctuation since these conditions are out of phase with seasonal norms. Indeed, in looking at the graphs in Figures 6d and 7d, this situation is apparent. The most anomalous random values in storm frequency (Figure 6d) occurred in June of 1974 (4 storms) and July of 1978 (3 storms). Even though the absolute values of these monthly frequencies were not especially high, they occurred in months where the median values over the period of record were one storm (June) and zero storms (July). They also occurred concurrent with relatively low values in the trend term. Of the next four largest random storm frequency values, two occurred in the summer (July 1946 - 3 storms; and May 1956 - 8 storms) and two in winter (January 1948 -10 storms; and March 1983 - 7 storms).

More straightforward are the random episodes in storm wave duration where the nine largest events all occurred during the summer months. Of these, five took place in August (1960, '68, '70, '74, and '76). In all but one instance the anomalies were associated with above normal conditions. The exception occurred in June of 1972 when a monthly storm wave duration of only one hour produced the large random term. Although this value was well below the monthly median value of 13 hours, its effect was magnified because it came during a period of generally high storm wave duration times and, hence, a relatively large trend component.

Figure 8. Seasonal dependence of storm frequency (a) and storm wave duration (b), for the period 1943-1983. The values plotted are the same as those in Figures 6c and 7c except that the seasonal term is depicted by individual months for successive years rather than as a consecutive 492-month sequence. (*Facing page*).

SUMMARY AND CONCLUSIONS

Monthly storm frequency and storm wave duration, two related and perhaps most significant determinants of physical change along open coast beaches, are non-normal variates exhibiting positive skew and an outlying zero lower bound. This indicates that months having no storms or storm waves, as well as those having numerous storms and storm wave hours, were much more common than would normally be expected along the mid-Atlantic Coast. The numerous months with high storm frequencies likely result from the region's geography which not only lies directly in the path of frontal storms propagating through the westerlies, but also is itself a focus of cyclogenesis. Although linked with the number of storms, the frequent occurrence of months with high storm wave duration times is also attributable to the common appearance of blocking anticyclones southwest of Greenland during the winter season.

Based upon a time series decomposition of the storm data, we find no significant trend in storm frequency and only a modest downward trend in storm wave duration over the period of record. We believe the downward trend in storm wave durations, while statistically significant, resulted primarily from the anomalously brief durations common during the mid-1970's and not from a systematic long-term decline. Between 1973 and 1977 winter storms tracked more eastward than northeastward, and storms following a more eastward trajectory tend to move more rapidly, resulting in fewer storm wave hours.

On a seasonal basis, we confirm the well known annual cycle in storm numbers and storm wave durations. Our analysis also confirms the earlier report of HAYDEN (1975) that the length of the mid-Atlantic Coast winter storm season, on a frequency basis, has increased since the 1940's. We also find, in terms of storm wave duration, that the length of the winter storm season has contracted since the 1940's. This variation between the frequency of storms and the length of time they deliver elevated waves to the beach reflects changes in the tracks of storms relative to the warm waters of the Gulf Stream. Such storm track shifts, especially to the south and east, result in more frequent high magnitude storms (WAYLAND and HAYDEN, 1985).

We believe that our observations confirm the assumption that wave climate statistics should be based on data spanning several decades if a stable estimate is expected. In this regard the U.S. Army Corps of Engineers detailed hindcast records covering a 25-year period should be considered a minimum standard.

Finally, we emphasize that, while the changes in storm climate for the last 4 decades are modest, some scientists are suggesting that climate warming over the next 100 years may be on the order of that experienced over the last several millennia. If this proves to be the case, we should expect consequent changes in the tracks of storms off the U.S. East Coast and with it new regimes of energy delivery to, and patterns of erosion on, Atlantic Coast beaches.

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