An East Coast Winter Storm Climatology

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(Manuscript received 9 July 1999, in final form 16 May 2000)

ABSTRACT

A climatology of East Coast winter storms (ECWS) was developed using an automated procedure. This routine was used along with the NCEP-NCAR reanalysis dataset (1948, 1951–97) to identify storms over the October-April winter season. An array of statistical analyses was used to empirically analyze the interannual variability of these cyclones.

To be classified as an ECWS, an area of low pressure was required to have a closed circulation, be located along the east coast of the United States (within the quadrilateral bounded at 45° N by 65° and 70° W and at 30° N by 75° and 85° W), show general movement from the south-southwest to the north-northeast, and contain winds greater than 10.3 m s^{-1} (20 kt) for at least one time period (6 h). Storms meeting the above criteria were also required to have a closed circulation and be located within the quadrilateral during one additional 6-h period (not necessarily consecutive with the first).

On average, 12 ECWS occurred per season with a maximum in January. Significant trends in storm frequency over the 46-yr period beginning in 1951 are not evident. However, a marginally significant ($\alpha=0.10$) increase in average storm minimum pressure is noted. Spectral analysis of the ECWS time series shows significant cycles with periods of 2.3, 2.8, 3.4, 4.8, and 10.2 yr, which are in agreement with documented periodicities in joint Atlantic SST and sea level pressure data. Average monthly ECWS frequency anomalies are significantly higher during El Niño months when compared to neutral months over the October–April storm season. ECWS show little or no change in frequency anomalies during La Niña months.

1. Introduction

Interest in the occurrence of East Coast winter storms has increased recently, especially following the "Storm of the Century" (1993) and the 1995/96 winter season, in which several major winter storms affected the densely populated urban centers of the eastern United States. Coastal areas had become increasingly sensitive to the impacts produced by these storm systems, given a lull in East Coast winter storm (ECWS) activity, which characterized much of the 1980s (Davis et al. 1993). Despite the severity of the economic, environmental, and societal impacts resulting from these storms, little is known about their climatological variability or the influence that other large-scale events and components of the global atmosphere and oceans exert on their frequency and severity.

Although ECWS are often compared to hurricanes based on their potential to inflict coastal damage, it is surprising that research concerning the climatic interannual variability of these storms has been relatively

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limited. Perhaps the most exhaustive research on these storms was conducted as part of the Genesis of Atlantic Lows Experiment (GALE) in 1986 (Dirks et al. 1988) and the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) in 1989 (Hadlock and Kreitzberg 1988). However, the objectives of these studies addressed the physical mechanisms linked to cyclogenesis, rather than the temporal climatology of these storms.

Numerous authors have developed spatial cyclone climatologies that have included the eastern United States and western Atlantic Ocean. Reitan (1974) compiled one of the earlier climatologies of these storms and showed a broad area of enhanced January cyclogenesis off the southeast U.S. coast along the Gulf Stream. Colucci (1976) showed an area of maximum winter cyclone frequency oriented parallel to the coast, centered on a line from Cape Hatteras, North Carolina, to the easternmost point of Maine, with a width of generally less than 5° of longitude (approximately 550 km). Zishka and Smith (1980) show an area of maximum cyclogenesis off the coast of New Jersey to the west of 70°W for January cyclones. Their areal distribution January cyclone counts showed an elongated area of relatively high cyclone frequency parallel to the coast from South Carolina to the Canadian Maritime Provinces extending about 5° of longitude offshore. Hayden (1981) showed a similar spatial pattern in his climatology of annual cyclone frequency. However, the axis of maximum storm counts tended to be centered along the coast rather than offshore. Whittaker and Horn (1981) used a swath of 5° latitude \times 5° longitude boxes along the East Coast to delineate an area of enhanced cyclogenesis.

The temporal climatology of eastern U.S. cyclones was first analyzed by Mather et al. (1964), who compiled coastal storm counts by studying records of coastal storms and water damage contained in periodicals, newspapers, and weather summaries. They estimated that coastal storms (both tropical and extratropical) of moderate or severe intensity based on damage reports affected the New York and New Jersey coast on average once every 1.4 yr. The frequency of damaging storms was found to increase significantly along the East Coast from 1935 to 1965 (Mather et al. 1967). Although a slight increase in storm intensity was found during this time, Mather et al. concluded that the development of coastal areas was the strongest contributor to this increase. Mather et al. warned against biases in reporting due to the increasing importance of damage-producing storms. The study encouraged further research to characterize the intensity of coastal storms based on readily available parameters such as wind and pressure so that a physical or climatic rather than a socioeconomic evaluation of severity could be obtained.

In the 30 yr following the work of Mather et al., the time-dependent aspects of East Coast storms have received relatively little attention in the literature, although the more general cyclone climatologies (e.g., Reitan 1974; Zishka and Smith 1980; Whittaker and Horn 1981) examined some time-dependent characteristics. Hayden (1981) examined temporal variations in extratropical storm frequencies in an area encompassing the United States east of 100°W long and the western Atlantic east of about 60°W. He found a trend toward increased cyclone frequency over maritime areas and a decline over the land areas during the period from 1885 to 1978. Also, he determined that coastal cyclogenesis increased in the later decades, with a maximum in the 1950s, in agreement with the results of Mather et al. (1967).

More recently, Davis et al. (1993) described the synoptic climatology of extratropical storms using wave heights as a criterion. Deep water waves greater than 1.6 m in height implied that storms caused some degree of beach erosion along the mid-Atlantic coast. Their dataset included storms from 1942 to 1967 (Bosserman and Dolan 1968) but was later extended to 1984 (Dolan et al. 1988). The active period beginning in the late 1980s and continuing into the 1990s was excluded from their study. They examined the annual frequency of eight different storm types and found that most (79%) of the damaging storms occurred from October to April. Davis et al. found that the frequency of Atlantic coast nor'easters declined from a peak in the 1950s to a min-

imum in the mid-1970s before increasing through the mid-1980s.

Collectively, these past studies provide some insight into the climatology of east coast winter storms that are commonly referred to as nor'easters. However, the previous studies either studied grid box storm counts, not individual storms, or have inferred nor'easter occurrence based solely on wind (wave) observations or damage reports. Climatologies presented by Kocin and Uccellini (1990) are limited to a subset of these storms that produced significant snowfall in the major northeastern U.S. cities.

Feasibly, the omission of a synoptic-data-based climatology of individual east coast winter storms stems from the lack of a formal objective definition of "nor'easter." The *Glossary of Meteorology* (Huschke 1959) is vague in its definition of this type of storm, describing it as a cyclone forming within 167 km of the U.S. east coast between 30° and 40°N and tracking north to northeast. Given the lack of such a climatology, it is not surprising that the literature contains little empirical information regarding the possible causes of interannual variations in ECWS frequency. It seems possible that empirical relationships explaining such variations can be developed through a more rigorous statistical analysis and once identified used as a basis for developing physical rationales for these variations.

In this paper, we present a climatology of ECWS using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data. In section 2 (methods), we present a definition for these storms that is based on several of the previously cited studies and discuss the details of an automated ECWS identification routine. Using the resulting cyclone climatology, we analyze the temporal variability of the dataset (section 3) and the relationship between the El Niño–Southern Oscillation (ENSO) and storm frequencies. Finally, a discussion (section 4) including a comparison of our climatology with Davis et al. (1993) is presented.

2. Methods

The climatology of wintertime east coast storms was developed using the NCEP–NCAR reanalysis dataset (1948, 1951–97) (Kalnay et al. 1996). An automated routine identified storms utilizing gridded sea level pressure and u and v component wind data. These data were available four times daily (0000, 0600, 1200, and 1800 UTC) at 2.5° lat \times 2.5° long grid points, with the exception of the period from 1949 to 1950, which was omitted from the study.

Based on these data we have defined an east coast winter storm by four criteria. These specifications are generally a synthesis of previous studies that identify preferred areas of east coast cyclogenesis and areas of maximum storm frequency (e.g., Colucci 1976) and characterize storm impacts in terms of wind data (Davis

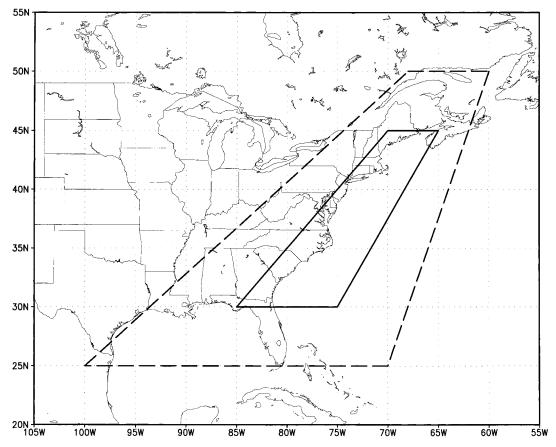


FIG. 1. Boundaries of area used to identify low pressure systems (dashed lines) and potential ECWS (solid lines).

et al. 1993). To be classified as an ECWS, an area of low pressure was required to

- 1) have a closed circulation;
- 2) be located along the east coast of the United States, within the quadrilateral bounded at 45°N by 65° and 70°W and at 30°N by 75° and 85°W (Fig. 1);
- 3) show general movement from the south-southwest to the north-northeast; and
- 4) contain winds greater than 10.3 m s⁻¹ (20 kt) during at least one 6-h period.

Initially, storms were identified by locating the grid point of lowest pressure within the larger polygon shown in Fig. 1 and tracking the movement of this low pressure center through time. Rather than tracking multiple storms at a given time interval t (e.g., Bell and Bosart 1989), the routine identified a unique grid point of low pressure. This method filtered relatively weak areas of low pressure and was also useful in cases that produced redevelopment off the coast. In these latter situations, the deepening coastal storms of interest were preferentially identified and tracked.

Once the storm entered the smaller polygon in Fig. 1, its pressure was compared to that at surrounding grid points to determine if the storm system was closed. Our requirement of a closed circulation was based on the

earlier works of Colucci (1976), Zishka and Smith (1980), and others. To conform with conventional surface weather map analyses, a storm (or grid point of low pressure) was deemed closed if at least 80% of 32 adjacent pressure values were at least 4 hPa greater than the minimum pressure. These 32 grid points composed a square (with sides of length, 20° lat/long), centered on the low pressure. Other routines using different combinations of spacing (8 rather than 32 points), proportion (90% instead of 80%), and shape (circle instead of a square) yielded analogous results.

Each closed low pressure system was required to be within the area stretching from near Panama City, Florida, northeastward to just off the coast of Maine (Fig. 1). This polygon includes many of the major cities of the east coast and the adjacent coastal waters. The southern and northern boundaries of the east coast quadrilateral used to define ECWS is based on the area outlined by Whittaker and Horn (1981) as the primary East Coast cyclogenesis region. The eastern and western boundaries conform with the areal distribution of January cyclogenesis given by Zishka and Smith (1980) and the map of winter cyclone frequencies developed by Colucci (1976).

The movement of each storm was inferred from the location of minimum pressure 6 and 12 h prior to its

current position, t_n (t_{n-1} and t_{n-2}), and 6 and 12 h after t_n (t_{n+1} and t_{n+2}). In the case of newly formed storms, only future movement was considered. Likewise, only past movement was considered for decaying storms. If the low pressure grid point was located within 5 grid units (a value intended to represent the maximum distance a storm could travel within a 12-h period) of t_n at t_{n+1} and t_{n+2} , it was assumed that the storm was in its mature phase and was neither cyclogenetic nor cyclolytic. The direction of storm movement was then calculated using the average storm location at t_{n+1} and t_{n+2} or t_{n-1} and t_{n-2} . Ideally, storm movement from the south-southwest to north-northeast was desired. However, past movement from a compass angle of 169°-259° and future movement to between 349° and 79° satisfied the motion criteria. This array of storm movements encompasses that associated with each of the 23 northeast snowstorms studied by Kocin and Uccellini (1990) as well as that of almost all of the 104 ERICAtype storm tracks plotted in Hadlock and Kreitzberg (1988). Storms showing no movement (identical grid points at two different times) were also retained in the study sample.

The wind threshold criterion was used to imply coastal impacts and gave a measure of overall storm strength. The resultant vector of the wind at each grid point was calculated using the u and v components of wind velocity at the 0.995 sigma level (closest to the surface). If at least 6 of the 26 points within the coastal polygon had winds above the 10.3 m s⁻¹ (20 kt) threshold for a given time period, the wind criteria were satisfied. Mather et al. (1967) found that the lateral extent of damage produced by some coastal storms exceeded 1000 miles. Therefore, no assumptions were made regarding the shape of the wind field or relative locations of the winds meeting the criterion as the storms developed, matured, and occluded. The use of 6 grid points was somewhat arbitrary but was intended to represent the average areal coverage of a storm system, roughly one-quarter of the study domain, while the 10.3 m s⁻¹ threshold was used to indicate potential storm impacts. Thurman (1983) indicates that a 10.3 m s⁻¹ (20 kt) wind on average produces waves heights similar to that used by Davis et al. (1993). Sensitivity analyses also indicated that the 20kt threshold provided a natural break between the relatively constant number of storms that resulted from lower wind thresholds and a rapid decline in the number of storms associated with higher thresholds.

Although these wind criteria were an indication of the potential for storm-related impacts based on storm size and strength, they do not imply the occurrence of coastal erosion or flooding. We are currently investigating the climatology of impact-producing storms using the documented impacts and damage reports associated with each of the candidate east coast storms.

Based on a subjective comparison of daily weather maps from the active winter storm seasons of 1982/83, 1993/94, and 1995/96, our original definition was fine-

tuned to eliminate faster storms that remained in the study area only for a single 6-h period and cyclones that simply brushed the perimeter of the study area. This was achieved by requiring that the first two criteria (a closed circulation and a position within the quadrilateral) be met during one additional 6-h period, not necessarily consecutive with the first. Low pressure centers wobbling in and out of the coastal quadrilateral and those showing temporary weakening (based on the loss of a closed circulation over a 6-h period) were therefore retained in the sample. As a final test, a random sample of storms conforming to our definition were compared against the corresponding daily weather maps. The ECWS identified using the automated procedure were in good agreement with our subjective assessments of the synoptic charts. Furthermore, non-ECWS (i.e., closed low pressure areas within the study domain failing to meet all of the criteria) showed primarily west to east movement, supporting their omission from the climatology.

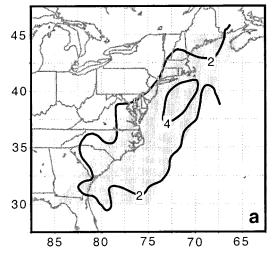
After compiling a list of ECWS occurrences at each 6-h time interval, individual occurrences were combined into daily or multiday storm counts. Successive 6-h storm occurrences were considered different storms if they were separated by at least 24 h (4 time periods) or when they occurred within 18 h of each other but the latter storm occurrence was at a lower latitude than the former. Storms could be separated based on their latitude because a storm traversing north to south would have already been eliminated based on the motion criterion.

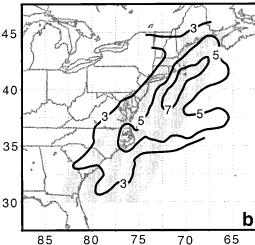
Figure 2c shows the relative percentage of ECWS occurrence at each grid point within the coastal quadrangle. The axis of maximum storm occurrence aligns parallel to the East Coast with maximum storm counts centered within the quadrangle. This pattern is in good agreement with the storm count isopleths presented in Zishka and Smith (1980) (Fig. 2a) and Colucci (1976) (Fig. 2b).

A separate subset of "strong" ECWS was also selected. These storms contained a maximum wind speed in the upper quartile of the distribution of maximum wind speeds associated with all events. Maximum wind speed was defined as the highest wind at any grid point within the coastal study domain during those time periods encompassing the life of the storm. Based on this quartile, a strong storm had a maximum wind of greater than 23.2 m s⁻¹ (45 kt).

Storms were also stratified into those affecting the northern or southern Atlantic coast, or both. Northern (southern) storms impacted the region with a latitude of greater than (less than or equal to) 35°N, or approximately the same latitude as Cape Hatteras, North Carolina. Storms that traversed both the southern and northern half of the quadrangle were termed full coast storms.

This division was chosen based on distinct storm occurrence and cyclogenesis maxima to the north as shown by Zishka and Smith (1980) and Colucci (1976) (Figs. 2a and 2b). In addition to these spatial storm patterns,





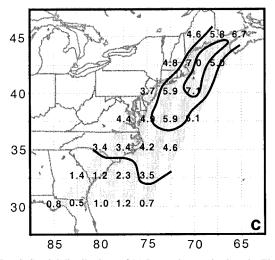


FIG. 2. Spatial distributions of (a) Jan cyclogenesis given by Zishka and Smith (1980), (b) winter cyclone frequency given by Colucci (1976), and (c) the relative percentage of ECWS occurrence at each grid point within the coastal quadrangle used in our storm definition.

this stratification provided a logical division of the storm types presented by Mather et al. (1964), with the Hatteras and Gulf Coast lows grouped into the full coast category. Kocin and Uccellini (1990) show that the majority of their major East Coast snowstorms originate to the south of 35°N before traveling northward along the coast. Physically, the average position of the Gulf Stream veers sharply away from the coast near 35°N. Thus the interaction of cold air over the coastal plain and the warm Gulf Stream waters may promote explosive cyclogenesis to the south of 35°N (Kocin and Uccelini 1990). This is shown as a distinct maximum of deepening cyclones to the south of 35°N by Colucci (1976). The concave coastal shape is associated with a decrease in atmospheric pressure (Godev 1971) and also contributes to enhanced cyclogenesis south of Cape Hatteras (Kocin and Uccellini 1990).

These full coast storms are in distinct contrast with the northern storms, which almost exclusively originate over the Plains or Midwest. In these storms, secondary cyclogenesis generally occurs from the Delmarva Region to Cape Cod, as shown by the area of enhanced cyclogenesis in Fig. 2a. This portion of the coast is characterized by a separate concave profile similar to that south of 35°N.

Southern storms travel through the Atlantic coastal regions south of Cape Hatteras and do not follow either of the classic northeasterly tracks associated with ECWS. They remain in the southern portion of the coastal quadrilateral without having a direct effect on the metropolitan areas of the northeast. The occurrence of these storms in the climatology was rare (about 8% of all storms), providing further support for our storm definition.

Over the 46 seasons, fifteen tropical storms and hurricanes during the months of October and November satisfied the closed circulation and location criteria (conditions 1 and 2). A handful of these tropical systems satisfied all of the ECWS requirements. These fifteen storms were manually eliminated from the climatology. Although weak tropical systems are comparable to strong winter storms in terms of pressure, wind, and potential impacts, our focus on extratropical winter storms required the exclusion of these warm core systems.

Over the 48-yr period including 1948 and 1951–97, 562 low pressure areas were classified as ECWS. An additional 930 low pressure areas had a closed circulation within the study domain but did not satisfy the remaining criteria. All of the 23 snowstorms described by Kocin and Uccellini (1990) as major snowstorms along the northeastern coast of the United States between 1955 and 1987 were classified as ECWS.

Figure 3 compares the distribution of minimum pressures for storms fitting our definition with that of storms failing to meet the motion and/or wind speed requirements. Minimum pressure was defined as the lowest pressure of a system having a closed circulation while

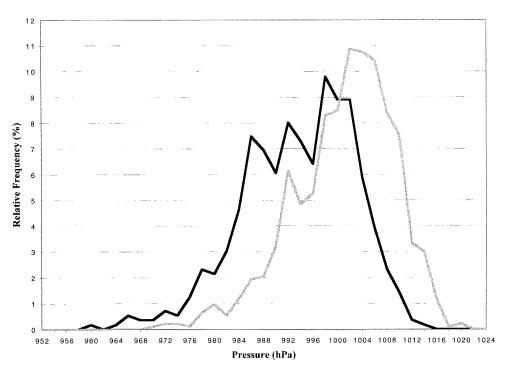


Fig. 3. Distribution of minimum pressures for ECWS (black) and non-ECWS (gray).

traveling within the study domain. The ECWS pressure distribution is shifted toward lower pressure, indicating that the automated procedure successfully filtered relatively weak systems. In no case was the minimum pressure at or above 1013.0 hPa. The overlap between the two pressure distributions is possible because although relatively intense, these storms failed to meet the motion and/or 12-h time criteria.

Similarly, maximum winds were defined as the highest wind at any of the 26 grid points along the coast while a low pressure area had a closed circulation and was located within the study domain. Maximum winds for ECWS averaged 20.5 m s $^{-1}$ (39.8 kt) and were stronger than the 16.7 m s $^{-1}$ (32.4 kt) average for nonstorms. Figure 4 shows this distribution of maximum winds. The ECWS wind distribution is fairly Gaussian and is shifted toward higher winds relative to the nonstorm cases. The highest winds approach hurricane force.

3. Temporal characteristics

a. ECWS climatology

On average, 11.8 ECWS occurred per season (Table 1). Approximately, one of every three closed low pressure areas in the study domain met our East Coast storm criteria.

Figure 5a shows the time series of seasonal (Oct–Apr) storm counts with the *x*-axis years corresponding to October. Generally, seasons with high counts are followed by relative minima in storm frequency leading to high year-to-year variability. Based on the 5-year

running mean, storm counts peak in the early 1960s, early 1970s, and again in the early to mid 1990s. Decreased activity characterizes the mid 1960s and mid 1980s.

Northern ECWS (Fig. 5b) constitute more than half of all storms (Table 1). Similar to Fig. 5a, northern storm counts tended to be high during the early 1960s, early 1970s, and late 1980s to early 1990s. The mid- to late 1960s and early to mid-1980s feature lulls in northern activity.

Most of the remaining storms were classified as full coast (Table 1). An analysis of the 5-yr running mean for full coast storms shows a relatively flat time series with no distinct periods of relatively high or low activity (Fig. 5c). However, the frequency of full coast ECWS declined during the 1970s before reaching a maximum of 12 storms in 1982/83. The lull in full coast activity during the 1970s coincides with a peak in the northern series 5-yr running mean. Relative minima in storm frequency occurred before and after the active 1982/83 season (Table 1 and Fig. 5c). The recent snowy winters of 1993/94 and 1995/96 were both characterized by above-average activity with nine storms occurring in both of those years. A high degree of year-to-year variability is evident in this time series, as indicated by the relatively flat 5-yr running mean and a strong negative lag-1 autocorrelation of -0.295 ($\alpha = 0.02$).

Time series of seasonal average ECWS minimum pressures and maximum winds were computed to analyze the interannual variability of storm intensity (Fig. 6). It is not surprising that an inverse relationship ($r = \frac{1}{2}$)

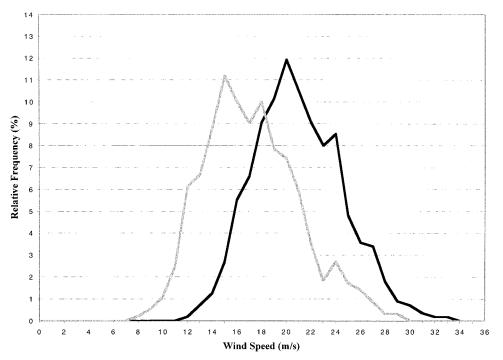


Fig. 4. As in Fig. 3 but for maximum winds.

 \sim 0.55) exits between pressure and wind over the 46-yr time series. Summary statistics for these parameters appear in Table 1.

Five-year running means of minimum pressure were at a minimum during the late 1950s and in the mid- to late 1960s. From the late 1960s to the late 1980s, minimum pressure steadily increased. Since the late 1980s, pressures have dropped, indicating a tendency toward more intense storms. Overall, this produces a marginally significant ($\alpha = 0.10$) increase in minimum pressure through the period based on the nonparametric test of Kendall and Stuart (1997) and the difference series test presented by Karl et al. (1987) (Table 1). The running means for maximum winds generally mirror those of minimum pressure although the variations are more subtle. Thus, significant trends are not indicated for this variable (Table 1). Significant break points (e.g., Solow 1987) are not evident in any of the time series (Table 1).

b. Strong ECWS

As an alternative to choosing arbitrary wind thresholds as a measure of storm strength, those storms producing maximum winds in the top quartile [>23.2 m s⁻¹ (45 kt)] of all ECWS were classified as strong storms. Almost two-thirds of the strong storms were classified as full coast storms while over a third of all full coast storms met the strong criterion. Figure 5a and Table 1 show that strong storm counts increased to a peak of 6 in 1968–69 before dropping off dramatically in the early to mid-1970s. A small but steady increase

took place from the mid-1970s into the early 1980s before storm totals decreased again into the mid-1980s, as indicated by the 5-yr running mean. Another steady increase has taken place since the mid-1980s with five strong storms each occurring in 1992/93 and 1993/94. This leads to an overall decrease in strong storms ($\alpha = 0.10$) through time based on the Kendall–Stuart test (Table 1) that corresponds to the increasing trend in minimum pressure. A marginally significant increase in northern storms is also noted during this period (Table 1).

c. Monthly distribution

Figure 7 shows the monthly distribution of ECWS counts, standardized to a 30-day month. Storm frequency steadily increases through the first 3 months of the season before reaching a maximum in January, when annual temperatures are generally the coldest. Storm counts then decrease in February, March, and April but at a much slower rate than the initial increase. Northern storms occurred most often in December, southern storms in January, and full coast storms in February.

The monthly frequency of strong ECWS (not shown) increases sharply to a maximum in February. An abrupt decrease in storm totals follows in March and April. Although more strong storms occur earlier in the season (as opposed to later), it is not until February that their totals maximize, unlike the original ECWS, which peaked in January. Even after removing the full coast storms, the combined monthly frequencies of strong northern and southern ECWS show a maximum in February.

TABLE 1. Seasonal (Oct-Apr) summary statistics for ECWS. Results from two trend tests (Kendall and Stuart 1977; Karl et al. 1987) and a regression break-point test (Solow 1987) are also included.

Break-points Solow None None None None None = 0.10Increasing $(\alpha = 0.10)$ Increasing (α Karl (None Decreasing $(\alpha = 0.10)$ Increasing ($\alpha = 0.10$) None Kendall-Stuart None (1978, 1984, 1994) Minimum (4 seasons) (1956) (20 seasons) 987.8 (1960) (1962, 1995)ECWS Statistics Maximum (1982)Median Average Min. pressure (hPa) Max. winds (m s⁻¹ Time series Full coast Strong North South

d. Spectral analysis

The maximum entropy method (MEM) of spectral analysis (Marple 1987) was used to analyze the properties of ECWS time series with respect to the frequency domain. Prior to the application of MEM, singular spectrum analysis (SSA) (Elsner and Tsonis 1996) was used to prefilter the series of ECWS counts. SSA is essentially equivalent to principal component analysis of the lagged covariance matrix of a time series. Through SSA prefiltering, the original time series can be decomposed into components that are limited in their harmonic content (i.e., the data are denoised). This allows the frequency domain to be analyzed more readily. Furthermore, the removal of those components that fail to explain relatively large portions of the original series variance provides a means of filtering noise from the record.

Some uncertainty is introduced into SSA by the choice of window length, m, where m is the number of lags that are included in the autocovariance matrix. This value represents a trade-off between the ability to resolve longer period oscillations (more lags) and statistical significance (increases with fewer lags). Elsner and Tsonis (1996) imply that n/4 is a reasonable window length, where n is the number of years in the record. Plaut and Vautard (1994) suggest that oscillations with periods between m/5 and m can often be detected. Throughout this study, window length was set at 12. Thus the SSA of the 46-yr time series is based on a 35 \times 12 lagged covariance matrix, where 35 = 46 - 12 + 1 (Elsner at al. 1999). Although this value is nearly equal to the n/4 value suggested by Elsner and Tsonis (1996), similar results are obtained for window lengths of 7, 10, and 15 yr (Fig. 8).

Pairs of nearly equal eigenvalues in the singular spectrum (i.e., the set of ordered eigenvalues) are associated with strong oscillations in the original record (Elsner and Tsonis 1996). Figure 8 shows the eigenvalues associated with the stationary 1951-97 ECWS series. Using a window width of 12, oscillatory components are identified by eigenvalue pairs 1-2, 4-5, and 7-8 based on their similarity (Vautard and Ghil 1989). Unfortunately, the eigenvalue series do not exhibit distinct noise floors, which can be used to determine the number of eigenvalue pairs to retain (Elsner and Tsonis 1996). This method is similar to the graphical methods for principal component retention described by Wilks (1995). Alternative methods for determining how many eigenvalues to retain are based on the magnitude of these values. Elsner et al. (1999) retained eigenvalues greater than 1.0. Here, a more lenient eigenvalue threshold of 0.7 was used as suggested by Jolliffe (1972).

The oscillation signaled by each eigenvalue pair should be evident in the corresponding eigenvectors, with the phases of each eigenvector in approximate quadrature (i.e., one eigenvector leads the other by a quarter period). For the three retained eigenvalue pairs this is evident in Fig. 9. While this supports the premise

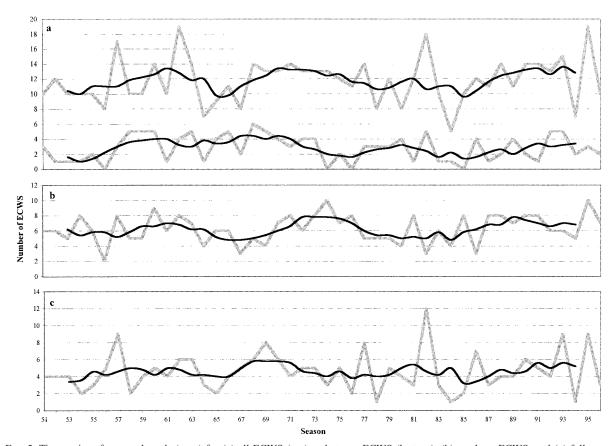


Fig. 5. Time series of seasonal totals (gray) for (a) all ECWS (top) and strong ECWS (bottom), (b) northern ECWS, and (c) full coast ECWS. Data points along the 5-yr moving average (black) correspond to the middle year.

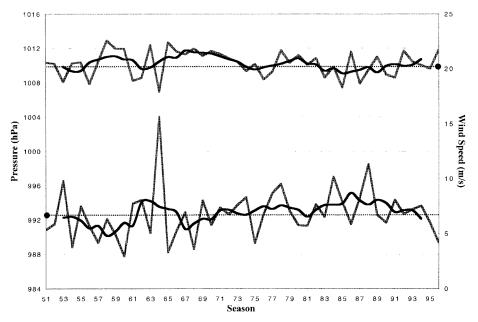


Fig. 6. Time series (gray) and 5-yr running mean (black) of average seasonal ECWS minimum pressure (bottom) and maximum winds (top). The dashed lines represent the average minimum pressure (992.7 hPa) and maximum winds (20.5 m $\ensuremath{\mathrm{s}^{-1}}\xspace$) of all ECWS from 1948 and 1951–97.

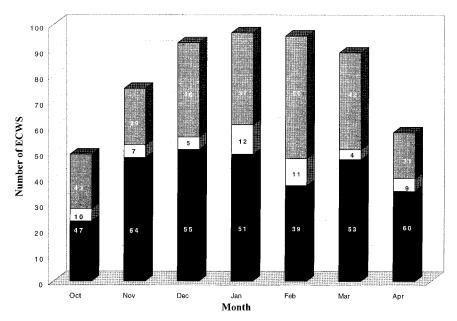


Fig. 7. Monthly distribution of storm totals divided by north (dark gray), south (white), and full coast (gray) ECWS. Relative percentages of each storm type are shown inside each bar.

that these pairs represent real oscillations in the ECWS record, it does not guarantee the statistical significance of the oscillations (Elsner et al. 1999). It should also be noted that quadrature is not apparent between eigenvectors 3 and 4 (Fig. 9d) whose eigenvalues were not judged to be similar.

The eigenvectors associated with the three retained eigenvector pairs (i.e., 1–2, 4–5, and 7–8) were used to compute temporal principal components. This involves projecting the original storm count time series onto the individual eigenvectors. The resulting principal components were then analyzed using MEM spectral analysis (Dettinger et al. 1995) using an order of 10. The MEM spectra of the three dominant reconstructed components are shown in Fig. 10a. Superimposed on each

plot are symbols indicating the significance of the observed spectrum with regard to MEM spectra associated with 5000 bootstrapped ECWS time series. In generating these bootstrapped spectra, the original ECWS time series was resampled. MEM was then applied to the reconstructed components (corresponding to eigenvector pairs 1–2, 4–5, and 7–8) from each resampled time series and the spectral density at each of the n frequencies retained. This allowed a 5000-sample distribution of spectral densities to be formed for each frequency. Each distribution's 95th, 99th, and 99.9th percentiles were identified and compared to the spectral density associated with the original series. Assuming independence between frequencies and the binomial distribution, field significance is attained at the $\alpha = 0.05$

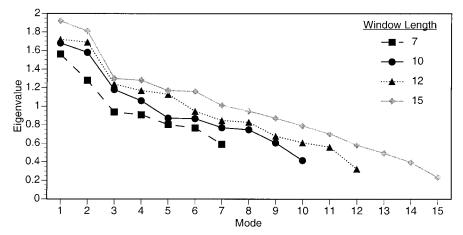


Fig. 8. Eigenvalues of the ECWS time series (storm totals) using the method of SSA with different window lengths.

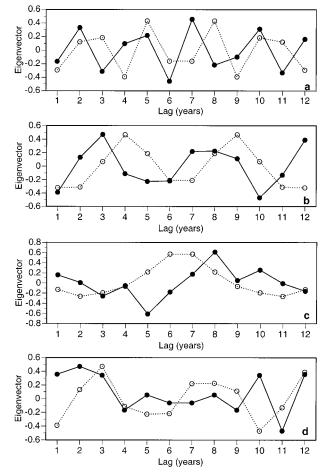


FIG. 9. Eigenvectors of the total ECWS time series associated with similar eigenvalue pairs (a) 1–2, (b) 4–5, and (c) 7–8 using a window width of 12. In (d) the eigenvectors associated with eigenvalues 3 and 4, which were not judged to be similar, do not exhibit quadrature.

level for five exceedences of the 95th percentile, two exceedences of the 99th percentile, and one exceedence of the 99.9th percentile of the resampled distribution. The common occurrence of four exceedences of the 95th percentile in Figs. 10 and 11 is significant at $\alpha = 0.12$ using the binomial distribution.

The combined SSA–MEM analysis was conducted in an analogous manner for the northern, full coast, strong storms, minimum pressure, and maximum wind speed time series. In each case, with the exception of strong storms, a window length of 12 was chosen. In the strong storm case, a window length of 15 was used since the smaller window length produced only one set of similar eigenvalues. For the other series, variations in window length had little effect on the results. The northern, pressure, and strong storm series were detrended prior to spectral analysis since significant trends were evident in these series. In each case, detrending involved reconstructing the original time series with the first eigenvalue (which represents the trend) omitted. Spectral structure was not evident in the omitted components.

The analyzed eigenvalue pairs for each time series are listed in Table 2.

Figures 10a-d show the MEM spectra for the dominant components of the ECWS count series. Similar MEM spectra for the pressure and wind series are given in Figs. 11a,b. These results are strikingly similar to those of Tourre et al. (1999), who reported five significant frequency bands—2.2, 2.7, 3.5, 4.4, and 11.4 yr for joint Atlantic sea surface temperature (SST) and sea level pressure (SLP) data. For each series, with the exception of strong storms, the first component pair is associated with a cycle in the range of 2.2 and 2.7 yr. For strong storms, 2.3- and 2.8-yr cycles are associated with the second and third component pairs, respectively. Field significance ($\alpha = 0.05$) is attained only for the strong storm peaks. However, the field significance of the 2.7, 2.3, and 2.6 year peaks for total storms, minimum pressure, and maximum winds is marginally significant ($\alpha = 0.12$) assuming independence between the tests. The 2.3- and 2.8-year cycles presumably reflect an association between ECWS frequency (and strength) and tropospheric quasi-biennial pulses (Wagner 1971). Angell and Korshover (1974) link these pulses to the displacement of the Icelandic low and Azores high. Elsner et al. (1999) found a similar 2.5-yr cycle in a time series of Atlantic hurricane frequency and attributed it to the stratospheric quasi-biennial oscillation (QBO).

The first pair of strong storm components exhibits a significant spectral peak at approximately 3.4 yr. Likewise the second set of full coast storm components exhibit a sharp peak at 3.2 yr. In both cases field significance is achieved ($\alpha=0.05$). Similar 3.4- and 3.7-yr peaks are also indicated in the northern storm and maximum wind time series (Figs. 10b and 11b). In these cases the level of field significance is given by p=0.06. Tourre et al. (1999) suggest that a similar 3.5-yr cycle in Atlantic SST and SLP data is related to ENSO.

A highly significant (field significance: $\alpha=0.003$) spectral peak emerges at 4.8 yr for all storms (Fig. 10a). A similar cycle is not evident, however, in the other datasets. This spectral peak is near the 4.4-yr peak isolated by Tourre et al. (1999), with the 5-month difference in frequency presumably related to our use of annual data and differences in the spectral analysis techniques. They relate this cycle to local conditions in the Atlantic associated with the position of the intertropical convergence zone (ITCZ) and suggest that the phase of this cycle could influence winter storm activity. Elsner et al. (1999) isolated a somewhat longer 5.6-yr cycle in Atlantic hurricane frequency and attributed this periodicity to ENSO.

A fourth decadal cycle of 10.2 yr is also evident in the total storm series (Fig. 10a) and the maximum wind speed series (Fig. 11b). This cycle is also straddled by a broad spectral peak in the northern storm time series. Such a cycle might be tied to variations in SSTs or preferred atmospheric wave positions associated with the North Atlantic Oscillation (NAO). Tourre et al.

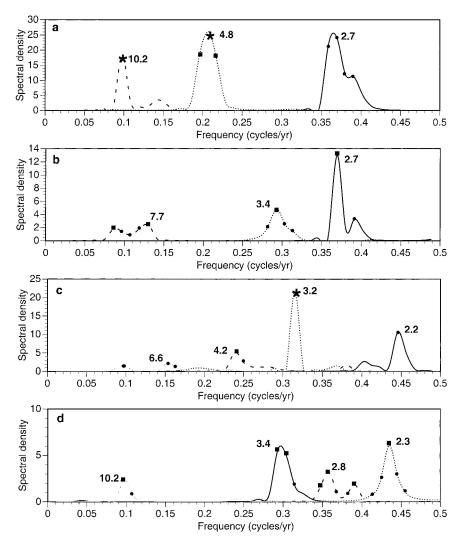


Fig. 10. MEM spectra of the dominant reconstructed component pairs of the (a) total, (b) north, (c) full coast, and (d) strong ECWS time series. Solid black lines represent the component pair explaining the highest proportion of variance, while the less dominant component pairs are given by dotted, dashed, and gray lines, respectively. Symbols represent statistical significance at the $\alpha = 0.05$ (circles), $\alpha = 0.01$ (squares), and $\alpha = 0.001$ (asterisks) levels. The cycle period in years is given numerically for the most significant frequency.

(1999) relate their 11.4-yr cycle to such variations, but indicate that Mehta and Delworth (1995) suggest that SST variability north and south of the ITCZ occurs at timescales between 8 and 11 yr, much like the broad north storm series peak. While this linkage warrants further investigation, such an analysis is beyond the intended scope of this paper.

e. ENSO and ECWS frequencies

On average, El Niño winters (December–February) were associated with over 44% more East Coast storms than ENSO neutral winters, with February storm counts doubling during these winters. Of the four most active winters (highest ECWS counts), two (1957/58, 1982/

83) were characterized by El Niño conditions. In addition, our previous spectral analysis results indicated a significant peak at a period associated with ENSO. Given these results, as well as those of Noel and Changnon (1998) and Janowiak and Bell (1999), it is possible that large-scale circulation changes, such as those attributed to the ENSO phenomenon, influence the formation and the interannual variability of ECWS.

The relationship between ENSO and ECWS was analyzed using the El Niño and La Niña events outlined in Trenberth (1997). The maximum (minimum for La Niña) and average monthly SST anomalies in the Niño-3.4 region (5°N–5°S and 170°–120°W) of the Pacific were calculated for each event using data from the Climate Prediction Center Web site (http://nic.fb4.noaa.

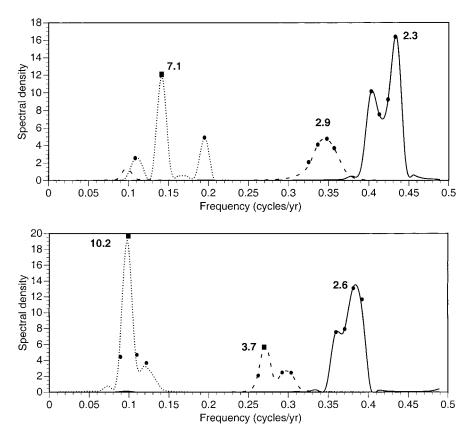


Fig. 11. As in Fig. 11 but for (a) minimum pressure and (b) maximum wind speed.

gov:80/data/cddb/). In addition, the maximum (minimum for La Niña) 5-month running mean was identified. Similarly, this set of three parameters was calculated using the Southern Oscillation index (SOI). If all six of

Table 2. Dominant eigenvalue pairs associated with the SSA of ECWS time series.

Series	Detrending	Eigenvalue pair	Eigenvalues
Total	No	1–2 4–5 7–8	1.7, 1.7 1.2, 1.1 0.8, 0.8
Northern	Yes	1–2 3–4 5–6	2.3, 2.3 0.9, 0.9 0.7, 0.7
Fully coast	No	1–2 4–5 6–7 9–10	2.2, 1.7 1.0, 1.0 1.0, 0.9 0.7, 0.6
Strong	Yes	3–4 5–6 7–8 9–10	1.7, 1.7 1.5, 1.4 1.0, 1.0 0.7, 0.7
Pressure	Yes	1–2 4–5 6–7	1.6, 1.5 1.1, 1.1 1.1, 1.0
Wind speed	No	1–2 3–4 6–7	1.5, 1.5 1.2, 1.2 0.9, 0.9

these values were above the median for all 16 El Niño (10 La Niña) events identified by Trenberth, the given event was considered "strong." Using this method, five El Niño and four La Niña events met the criterion and are listed in Table 3. The 1997/98 El Niño was later classified as a strong event, even though it is not defined by Trenberth. With the exception of the June 1954–March 1956 La Niña, the results are in good agreement with Wolter and Timlin (1998), who used the multivariate ENSO index (MEI) to rank events. Below-median SOI values accompanied this La Niña event.

Hypothesis testing was used to analyze the relationship between ECWS and ENSO. First, standardized frequency anomalies were calculated based on monthly storm counts. Each month was then classified as either a nonevent (neutral) (45%), El Niño (33%), or La Niña

TABLE 3. Subset of Trenberth (1997) ENSO events classified as strong events.

Strong El Niño	Strong La Niña
Apr 1972–Mar 1973 Apr 1982–Jul 1983 Aug 1986–Feb 1988 Mar 1991–Jul 1992 Apr 1997–Apr 1998	Jul 1970–Jan 1972 Jun 1973–Jun 1974 Sep 1974–Apr 1976 May 1988–Jun 1989

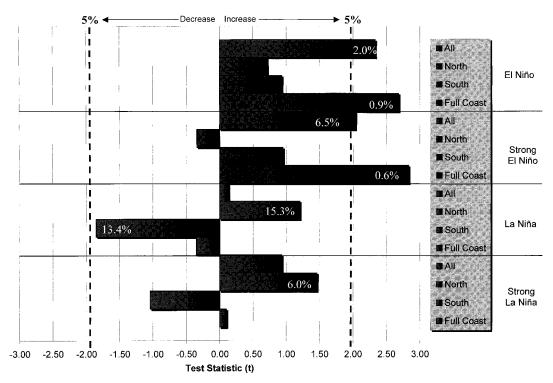


Fig. 12. Test statistics, t, comparing the average frequency anomalies of ECWS during ENSO months to those during neutral months over the Oct–Apr period. Positive (negative) values indicate a(n) increase (decrease) in frequency anomalies. The 5% level of significance based on a two-tailed hypothesis test using the normal distribution is denoted for reference. The p values obtained using resampling appear on selected bars.

(22%), where the parenthetic values indicate the percentage of months in each category. Months were further categorized as strong El Niño (12%) or strong La Niña (12%). Average standardized anomalies, \overline{X} , were then computed for each type of event. A test statistic,

$$t = \frac{(\overline{X}_{\text{event}} - \overline{X}_{\text{non-event}})}{\left(\frac{s_{\text{event}}^2}{n_{\text{event}}} + \frac{s_{\text{non-event}}^2}{n_{\text{non-event}}}\right)^{1/2}},$$
(1)

was used to determine if a significant difference existed in the average monthly ECWS frequency anomalies for events when compared to nonevents over the October-April period. In Eq. (1), s is the standard deviation of the frequency anomalies and n is the number of events. A shorter December-February period was also analyzed, since ECWS frequency was highest during these months. An artificial dataset of 1000 test statistics was created using resampling. Here, the set of 7 (or 3) monthly ECWS frequency anomalies was randomly reassigned to different seasons. This test is advantageous to the traditional methods because no assumptions regarding an underlying theoretical distribution of the dataset are needed (Wilks 1995). The original test statistic was then compared to the artificial distribution to obtain a two-tailed p value.

In general, ECWS frequency increases during El Niño months for all storm types (north, south, and full coast)

as indicated by the positive test statistics over the October–April storm season (Fig. 12). The most significant difference (p = 0.009) occurs for full coast ECWS, indicating that the occurrence of these storms is favored during El Niño. In a practical sense, a 75% increase in full coast storms (about two more storms) occur on average in El Niño winters than is expected during neutral ENSO conditions. For all storms (ECWS totals), positive average frequency anomalies are also large and are significant at a p level of 0.020. This equates to a 25% increase in total storms (about three storms) on average. Similar results are obtained for full coast ECWS when only strong El Niño events are considered. However, when all storms are considered (during strong El Niño events), the significance of the difference decreases slightly (p = 0.065).

It is interesting to note that the frequency anomalies of northern storms decline during strong El Niño events when compared to all El Niño months. Strong El Niño events are often characterized by a very active southern branch of the jet stream. This pattern may be conducive to the development of southern and especially full coast storms at the expense of the frequency in northern ECWS, as shown in Fig. 12.

The relationship between ECWS frequency and La Niña is less consistent. There is no significant difference in storm frequency for all ECWS when compared to

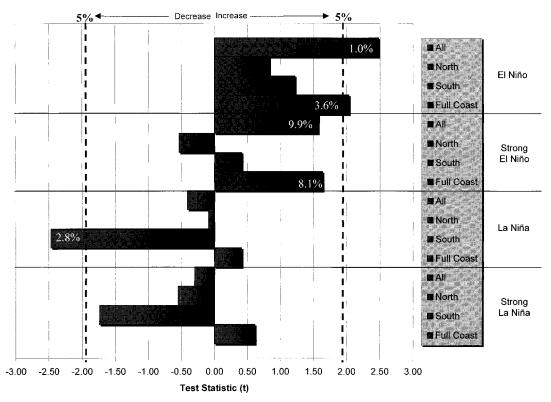


Fig. 13. As in Fig. 12 but for the Dec-Feb period.

neutral months. As expected, northern ECWS show the largest increase in storm counts with a p value of 0.153. During strong La Niña events, this difference is even more significant (p=0.060). This significant increase is possibly due to the active polar jet stream across the northern United States during La Niña events. With this pattern, the frequency of ECWS traveling through the south show a marginally significant decrease (p=0.134) during La Niña events.

The differences in ECWS frequency during El Niño events appear to be more pronounced during the winter season (December-February) (Fig. 13). Values of the test statistic increase for all ECWS, northern ECWS, and southern ECWS when compared to those from October to April. Frequency anomalies indicating an increase in ECWS totals are now significant at the 1% level, with 44% more storms observed during periods characterized by El Niño conditions. All storm types (north, south, and full coast) show an increase in frequency with full coast storms still showing a significant increase (p = 0.036). An overall increase in storms but at significance levels below that for all El Niño events is indicated for strong El Niño events. The positive frequency anomalies for all and full coast storms decline and are now significant at the 90% level.

For all La Niña months and strong La Niña months during December–February, only full coast ECWS show an increase (albeit small) in their frequency anomalies. The marginally significant positive frequency anomaly

of northern storms that was prevalent over the entire season no longer exists. This is due to the low frequency of northern storms during the December–February period. The response to this is an increase in full coast storms, as indicated by a reversal in sign of the full coast anomalies when comparing October–April to December–February for all La Niña events. As in the October–April time frame, southern storms show a decrease in frequency, now significant at p=0.028.

A comparison of the test statistics against the normal distribution shows that the significance values are in good agreement with those found using the randomized resampling procedure.

The findings relating ECWS to ENSO in this study are in agreement with those of Noel and Changnon (1998), who examined winter cyclone frequency in relation to three ENSO parameters (SST intensity, SOI intensity, and location of 28°C SST isotherm). This study also found an overall increase (decrease) of storms off the southeast coast and a small increase (little change) in the frequency of northern storms during El Niño (La Niña) events when compared to nonevents over the December–February storm season.

The results presented here are consistent with those found by Janowiak and Bell (1999). They found an increase in the number of winter days with heavy precipitation (>12.5 mm day⁻¹) along the entire east coast during El Niño events when compared to ENSO neutral winters. Similarly, an increase in northern events and a

statistically significant (5% level) decrease in southeastern precipitation days were indicated for La Niña. Janowiak and Bell attribute this relationship to a westward displaced storm track (to the west of the Appalachians) during La Niña. Thus, it is likely that the decreased frequency of storms during La Niña when compared to El Niño is a result of storms failing to meet the location criteria (positioned outside of the study domain) presented in this paper.

4. Discussion

a. Comparison of ECWS climatology to previous research

The results presented here differ from those reported by Davis et al. (1993). Perhaps the most striking difference is a 62% decrease in annual storm counts. Based on a 12-month storm period, Davis et al. (1993) found that approximately 31.3 Atlantic coast nor easters produced significant waves at Cape Hatteras, North Carolina, per year. Comparatively, the present study indicated that over a 7-month (October-April) storm season, 12 ECWSs can be expected on average.

Although the disparity in storm frequency is partially due to the dissimilarity in reporting periods, the majority of the difference likely results from the Davis et al. manual classification of two storm types that fail to meet the objective criteria of the present study. Clearly, the anticyclonic storm type (Davis et al. type 9) is omitted in the current climatology. Although anticyclones (associated with a strong pressure gradient) are capable of producing high waves along the east coast, high pressure systems are typically not considered winter storms. Strong anticyclones often precede East Coast storms (Kocin and Uccellini 1990). Therefore, it is possible that active seasons produce a higher number of anticyclones. This distorts the Davis et al. storm frequencies and makes the two time series of annual storm counts difficult to compare.

It is also likely that systems identified as continental lows (Mather et al. type 7) are excluded from the ECWS climatology. These low pressure systems show movement to the northeast but often track farther inland (up the Ohio and St. Lawrence River valleys), outside of the study domain used to identify ECWS. These two storm types represent approximately 30% of all storms identified by Davis et al. By eliminating these storm types and excluding storms that develop in the May-September period, the original 31 storms per year reported by Davis et al. (1993) are reduced to approximately 16 storms over the 7-month season. Although still higher than the seasonal frequency of 12 storms reported here, the difference in storm counts between the two climatologies is substantially reduced. Overall, the monthly distribution of nor'easters presented by Davis et al. (1993) is very similar to that presented here.

Given these procedural differences, it is also difficult

to compare the time series of storm counts for both studies. Nevertheless, the time series show some similarities. The Davis et al. time series shows a decline in storm frequency from the mid-1960s to the mid-1970s followed by an increase through to the end of the study period in 1983. Hayden (1981) found a similar pattern with a peak of maritime cyclones in the early 1960s, a decline in storms in the early 1970s, and increase in the late 1970s. The results of this study also show a relative peak in ECWS frequency in the early 1960s. This is followed by a sharp decrease in frequency in the early to mid-1960s and an increase to a relative peak in the early 1970s (based on a 5-yr mean). Like the previous studies, ECWS exhibited a drop in frequency starting in the early to mid-1970s before increasing slightly in the late 1970s.

Hayden (1975) identified an increase in the number of storms producing at least 3.4-m waves from 1955 to 1975. Similarly, Davis et al. (1993) determined that the frequency of strong storms increased in the 1960s and 1970s. Our study also found a steady increase in strong storms over the same period, despite differences in our classification of strong storms.

b. Relationship of ECWS to ENSO

At the present time, it is difficult to say why some years have more ECWS than others. Chaotic fluctuations in storm frequency are natural and inevitably account for some of the variability, but meteorological factors should also play a role.

The large-scale ENSO phenomenon explains a part of the interannual variability of ECWS. El Niño months are clearly linked to increased cyclogenesis along the east coast of the United States. Although the results of the La Niña analysis are less significant, a general decrease in some storm types occurs during these months. Considering the October–April storm season, northern ECWS show an increase (nonsignificant) in frequency during La Niña seasons, reflecting a more active polar jet stream. The early to mid-1970s were characterized by an extended period of La Niña (Trenberth 1997). This correlates well with higher northern ECWS storm counts over this period. Given the results of the pressure and wind climatology, it is also possible that La Niña seasons induce the development of weaker (higher minimum pressure and lower maximum winds) ECWS. The three highest minimum pressures over the 46-year period took place during the La Niña seasons of 1964/65, 1984/85, and 1988/89. The 1964/65 season is an extreme outlier, with a minimum pressure of 1004.0 hPa. Based on the similarities between our spectral analysis and that of Tourre et al. (1999), it appears that SST and SLP anomalies over the Atlantic basin also influence ECWS activity. Further research related to these intriguing findings may produce relationships with predictive ability for East Coast storm frequency.

c. Relationship of ECWS to other meteorological factors

Resio and Hayden (1975) related increased storminess to an increase in blocking patterns at high latitudes. In this study, the relationship between atmospheric blocking (particularly in the Atlantic) and ECWS is also intriguing. The two most active seasons, 1962/63 (19 ECWS) and 1995/96 (19 ECWS), were characterized by frequent blocking in the Atlantic and Pacific (Watson 1999). In addition, blocks were consistently centered near the Greenwich meridian for the three most active seasons (1962/63, 1982/83, 1995/96). Although 1995/ 96 was the most frequent blocking season in the Atlantic (Watson 1999), it was also characterized by weak La Niña conditions (Trenberth 1997). Therefore, it is difficult to attribute the high number of storms in 1995/96 solely to atmospheric blocking. Several large-scale mechanisms may have influenced this season.

Based on the results of spectral analysis, we are currently researching the empirical relationship between the interannual variability of ECWS and events such as the QBO (2.5 yr) and the NAO (decadal cycle). We also plan to explore the effects of tropical storm activity and Gulf Stream SST anomalies on ECWS activity from a climatological perspective. From this, we hope to evaluate the predictive ability of the empirical findings, which will provide a basis for the practical long-range forecasting of ECWS. We are also investigating the relationship between large-scale atmospheric circulation features, such as jet stream strength and location, to ECWS frequencies.

5. Conclusions

A climatology of East Coast winter storms (ECWS) was developed using an automated procedure. The routine was used along with the NCEP–NCAR reanalysis dataset (1948, 1951–97) to identify storms. An array of statistical analyses was used to examine the interannual variability of ECWS and led to the following important conclusions.

- 1) An average of 12 ECWS occur per winter season (October–April). Of the 12 storms, on average, 6 storms remain above 35°N, 1 storm remains at or below 35°N, and 5 storms traverse both the northern and southern portions of the East Coast.
- ECWS deepen to an average minimum pressure of 992.7 hPa.
- 3) ECWS maximum winds average 20.5 m s^{-1} (39.8 kt).
- 4) A maximum of 19 storms took place in 1962/63 and 1995/96. A minimum of 5 storms occurred in 1984/85.
- 5) The monthly distribution of ECWS shows a maximum in January and a minimum in October. Northern storms occurred most often in the month of

- December, southern cyclones in January, and full coast storms in February.
- 6) An average of 3 strong ECWS [maximum winds > 23.2 m s⁻¹ (45 kt)] occur per season, most of which traverse the full east coast. Although strong storms show a monthly distribution skewed to the left (toward the earlier months of the winter season), most strong storms occur in February.
- 7) Two nonparametric trend tests indicated that the frequency of ECWS show a downward tendency over the study period but at insignificant levels. One test found a decreasing trend in strong ECWS significant for $\alpha = 0.10$.
- 8) The trend tests found an increase in minimum pressure (significant for $\alpha = 0.10$) and a decrease in maximum winds (not significant) of ECWS over the 46-yr period.
- 9) Spectral analysis shows significant cycles in most of the series with periods of 2.3, 2.8, 3.4, 4.8, and 10.2 yr. These results compare well with documented periodicities in joint Atlantic SST and SLP data.
- 10) Average monthly ECWS frequency anomalies are higher (p values \sim 2%) during El Niño months when compared to neutral months over the October–April storm season. Storms traversing the East Coast (full coast storms) are the main contributor to this increase with p values \sim 0.9%. ECWS show little or no change in frequency anomalies during La Niña months.
- 11) During December–February, the increase in storms during El Niño months is significant at the $\alpha=0.01$ level. Southern ECWS show a significant decrease (p=0.028) in frequency during La Niña months.

The results of this study suggest numerous topics for further research. It would be interesting to look at the individual effects of the winter storms on the East Coast using *Storm Data*. The ECWS in this study can be further stratified into those producing heavy precipitation (rain and/or snow), wind damage, coastal flooding, and beach erosion. The arbitrary wind threshold can then be adjusted using reports of coastal damage. From this, a practical scale of storm strength, similar to the Saffir–Simpson scale for hurricane intensity, could be developed.

Acknowledgments. This work was supported in part by National Science Foundation Grant ATM-9713572. Partial funding was also provided through NOAA Grant NA76WPO273.

The authors thank Dr. Robert Davis for providing us with his data on nor'easters. These data helped us develop the ideas for this research. We are indebted to Bill Noon for his assistance in reading the reanalysis data files. We are also grateful for the suggestions made by two anonymous reviewers.

Reanalysis data were provided by NOAA-CIRES (Climate Diagnostics Center). The Grid Analysis and Display System (GrADS) provided by COLA was used for mapping. We are grateful to the SSA-MTM Group at UCLA for making their spectral analysis routines freely available.

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