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# Climatology of Nor'easters and the 30 kPa Jet

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**ABSTRACT**

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Waves generated by nor'easters are responsible for a large portion of the coastal damage and erosion that occurs along the Atlantic coast of North America. Large-scale atmospheric circulations, such as the polar jet stream, are the driving forces behind their occurrence. A regional examination of variations in the 30 kPa (the 300 mb constant pressure level in the atmosphere) polar jet stream is conducted for the east coast of North America for 1942–1992. Jet stream variables of wind speed, latitudinal position, geopotential height, 30 kPa temperature, and flow pattern are obtained from 30 kPa mean monthly maps and correlated with the occurrence, intensity, and synoptic type of non-tropical Atlantic coastal storms. Over eastern North America, the polar vortex was most expanded in the early 1940's and the late 1950's and contracted, but less variable, during the remainder of the time period. Geopotential height displayed an inverse relationship with latitude with an overall decline in the 30 kPa height over the fifty-year period. Zonal (west-east) flow patterns of the polar jet were predominant, and upper tropospheric temperatures displayed an overall warming trend while jet stream wind speed remained stable but highly variable. A jet stream/coastal storm analysis revealed that trough flow patterns in the mean pressure field are associated with increased storm frequency. An examination of the storm origin and tracking frequencies displayed a statistically significant relationship between the most potentially dangerous storm types (Bahamas, Florida, and Gulf Lows) and a southerly position and decreased geopotential height of the jet stream. Knowledge of these relationships will improve our ability to understand and predict the impact of various storm-generated wave climates upon the coastal zone.

ADDITIONAL INDEX WORDS: *Atlantic extratropical storms, coastal storms, wave climate, jet stream, polar vortex.*

## INTRODUCTION

Non-tropical coastal storms that affect the North American Atlantic coast are driven by the mid-latitude westerly winds and are called extratropical storms or nor'easters. These storms generate high winds and large waves that can be devastating to the biotic and abiotic systems residing along the coast. While tropical cyclones, which are smaller and occur less frequently than nor'easters, can cause considerable damage locally, their coastal impact is usually limited to a fairly small area near the point of landfall. Nor'easters, though less intense, affect a much greater area and are responsible for most of the damage to and erosion of the East Coast barrier islands and beaches (MATHER *et al.*, 1964).

The vulnerability of a given coastal region to damage from nor'easters exhibits significant spatial variability. Variations in topography, shoreline orientation to waves, and the extent of human development all act to determine a given area's susceptibility to coastal storm damage. The storm surge and high waves produced by nor'easters can cause extensive coastal flooding, barrier island overwash, and tidal inundation. In addition, a storm's intensity, size, speed of movement, and track will contribute significantly to the length of the coastline affected. Greater knowledge of atmosphere-ocean interactions is therefore necessary to improve our understanding of how the coastal zone environment is affected by these storms. Also, concern over global climate change and its potential impact upon coastal regions highlights the need to establish the physical relationships between the mechanisms responsible for coastal storm development and the annual distribution of nor'easters and their resulting waves. By establishing this linkage, it is possible to evaluate recent trends in storminess in comparison to past variations as well as to more accurately anticipate future conditions based upon theoretical and modeled climate changes.

Waves generated by nor'easters were previously hindcasted for Cape Hatteras, North Carolina on an individual basis using storm locations, tracks, fetches, and durations (BOSSERMAN and DOLAN, 1968; HAYDEN and DOLAN, 1977; DOLAN and DAV-

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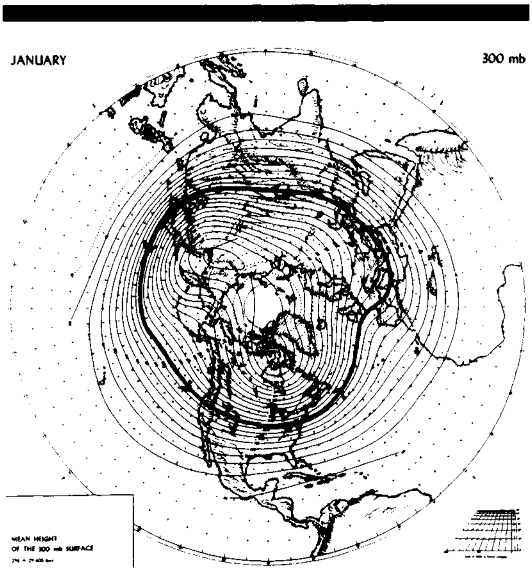


Figure 1. Mean height (in feet) of the 30 kPa (300 mb) surface for January showing the geographical position and extent of the polar jet. The darkened contour indicates the average January position of the polar jet stream over the Northern Hemisphere (after LAHEY *et al.*, 1960).

IS, 1994). A five-stage classification was produced (DOLAN and DAVIS, 1992) that is analogous to the Saffir-Simpson scale for tropical cyclones. Storms were also categorized into eight discrete storm types according to their characteristic regions of formation, tracks, and strength (MATHER *et al.*, 1964; DAVIS *et al.*, 1993).

While the occurrence and intensity of nor'easters has generated several studies of the meteorological and oceanic parameters that serve as their driving forces (*e.g.*, MATHER *et al.*, 1967; HAYDEN and DOLAN, 1977; DOLAN *et al.*, 1988; DAVIS *et al.*, 1993; DOLAN and DAVIS, 1992), to date, there has been a dearth of studies that relate year-to-year changes in the polar jet stream to the spatial and temporal characteristics of nor'easters. Thus, the goal of our research is to examine how the variations in the position and strength of the polar jet stream over eastern North America relate to the seasonality, frequency, strength, and synoptic type of nor'easters off the mid-Atlantic coast of the United States.

### Jet Stream, Cyclones, and Nor'easters

The polar jet stream in the mid-latitudes is associated with frontal discontinuities between air masses. It is defined as a rapid, narrow current of air residing in the upper troposphere that is characterized by very strong lateral and vertical wind shears. In the upper troposphere, at approximately 30 kPa (the 300 mb constant pressure surface at ≈10 km), the mean long waves (meanders) of the jet stream are evident and normally of great length, width, and depth (MCINTOSH, 1972; Figure 1). On upper air charts, a jet stream typically can be found where the wind speeds are greater than or equal to 25 m $sec^{-1}$ (≅50 knots) (HUSCHKE, 1959). Surface cyclones are generally found beneath these upper tropospheric jet wind speed maxima. Changes in wind speed along the direction of flow of the jet causes low-level horizontal mass convergence that is augmented by the presence of horizontal mass divergence at a higher level in the atmosphere (BEEBE and BATES, 1955). Thus, as air is removed from above a low pressure system, the surface pressure declines and the system intensifies. This situation results in vertical motions that create a favorable environment for cyclogenesis (the formation of a low pressure system at the surface). Cyclogenesis is also enhanced along the boundary between cold air masses and the Gulf Stream (DICKSON and NAMIAS, 1976; DOUGLAS *et al.* 1982).

The polar jet stream is contained in the upper air, mid-latitude westerlies which are found in the region of the strongest height and temperature gradients at leading edge of the circumpolar vortex (Figure 1). The vortex is a large-scale cyclonic circulation in the troposphere that is generally centered over the polar regions. Expansions and contractions of the polar vortex are manifested in southward (equatorward) and northward (poleward) movements of the jet stream, respectively. Storm tracks vary in response to these latitudinal migrations of the polar jet stream.

## DATA

For this analysis, the flow pattern, latitudinal position, geopotential height, wind speed, and temperature of the polar jet stream were derived from 30 kPa mean monthly maps for 1942–1992. Although the data were collected from monthly mean maps, which can smooth out meaningful variations at synoptic time scales (DAVIS and BENKOVIC, 1992), the results are useful for examining the seasonal and inter-annual variation of the parameters.

The 30 kPa maps define a constant pressure level in the atmosphere and were chosen because the polar jet commonly occurs at or near that height (RIEHL *et al.*, 1965). Maps for the first 31 years were produced by the National Oceanic and Atmospheric Administration and published in the *Monthly Weather Review* (1942–1958) and the *Climatological Data National Summary* (1958–1972). Contour lines and isotherms for the 1942–1972 maps were generated from radiosonde observations at 0300 GMT (2200 EST), and wind speed observations were generated from pibal (pilot balloon) readings at 2200 GMT (1700 EST). The remaining maps (1973–1992) were contoured from 0500 GMT (0000 EST) radiosonde observations obtained from the National Center for Atmospheric Research and converted to 5° latitude × 5° longitude gridded data.

The position of the polar jet stream is found by manually measuring the steepest height gradient (smallest contour spacing) that occurs along the 75°W meridian, which is roughly parallel with the east coast of North America. The latitudinal position of the jet is then given by the mid-point of this gradient. Air temperature and geopotential height (the height of a point in the atmosphere proportional to the geopotential at that height obviates the necessity of considering spatial variations in gravity when making dynamical calculations) are extracted from their respective mean monthly isoheights found at this latitude. Height on a constant pressure surface is proportional to pressure on a constant height surface; thus, low heights at 30 kPa are associated with an upper-air low pressure area and possible cyclogenesis. In addition, a "flow index" variable is determined by visually inspecting the mean monthly maps for the presence of a ridge, trough, short-wave trough, or zonal pattern in the polar jet stream flow over the east coast of North America between 70°W–100°W longitude (Figure 2). Meridional flow, a ridge or trough in the mean field, is identified when the isoheight defining the position of the jet deviates more than three degrees of latitude, north or south, across the longitude band, respectively, and zonal (west to east) flow occurs when the isoheight does not deviate more than three degrees. A short-wave trough is identified when both north and south deviations of the isoheight are observed across the band. Finally, wind speeds ($V_g$) are calculated using the geostrophic wind equation which utilizes the height gradient in the upper atmosphere and is given by;

$$Vg = \frac{-g}{2\Omega \sin\theta} \frac{dz}{dn}$$

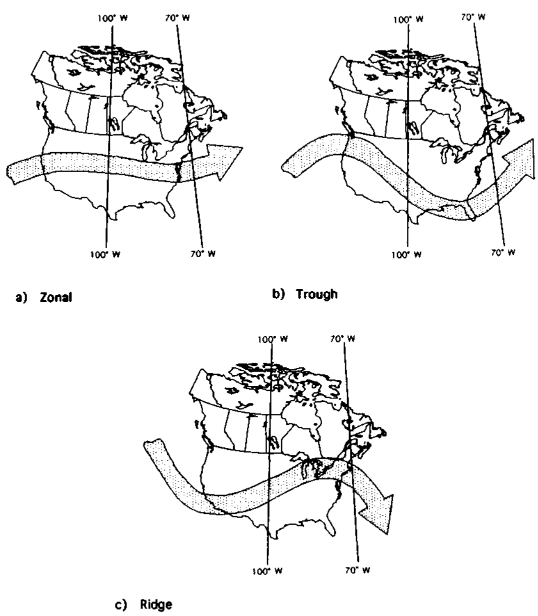


Figure 2. Map of North America depicting the three main flow patterns of the 30 kPa jet as defined over 70°–100°W longitude. (a) Zonal flow. (b) Trough flow. (c) Ridge flow.

where g is the acceleration of gravity (9.8 m sec$^{-1}$), $\Omega$ the angular velocity of the earth (7.29 × 10$^{-5}$ sec$^{-1}$), $\theta$ the latitude, and dz/dn is the slope of the isobaric surface normal to the contour lines. Thus, wind speed increases as the slope, or the height gradient, increases.

BOSSERMAN and DOLAN (1968) developed the original nor'easter data set consisting of all storms that generated 5.0 ft (1.5 m) or higher deep-water waves at Cape Hatteras, North Carolina from 1942 to 1967. Nor'easters were grouped into storm years, July through June, which exhibited a distinct frequency maximum from October through April. The individual storms were then hindcasted using a variation of the Sverdrup, Munk, and Bretschneider method (U.S. ARMY CORPS OF ENGINEERS, 1984) which allows for the estimation of past deep-water wave heights generated by nor'easters from archived surface pressure and wind fields. Although the nor'easters were hindcasted using wave and meteorological data for an individual site, DAVIS *et al.* (1993) show that the results are generally applicable to the mid-Atlantic coast. The data set was later updated through 1984 (DOLAN *et al.*, 1988) and DOLAN and DAVIS

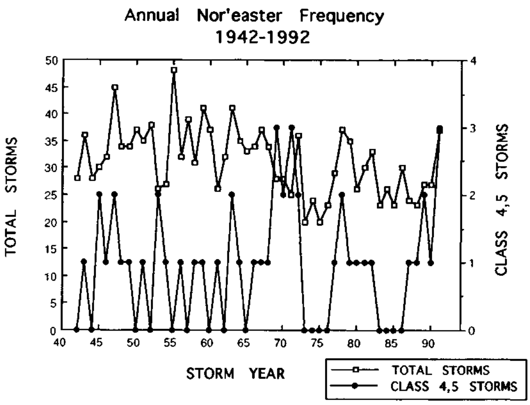


Figure 3. Annual nor'easter frequencies of total storms and Class IV and V storms for 1942–1992.

Table 1. *Mean values of the maximum significant deep-water wave height ($H_{1/3}$), duration, power index, count, and frequency of the Dolan-Davis (a) storm class and (b) storm type for all nor'easters from 1942-1992.*

| | $H_{1/3}$ (m) | Duration (hr) | Power Index ($m^2$•hr) | Count | Frequency (%) |
|---|---|---|---|---|---|
| a. Storm class | | | | | |
| Class I | 2.0 | 8 | 32 | 786 | 50.1 |
| Class II | 2.5 | 19 | 107 | 393 | 25.1 |
| Class III | 3.3 | 35 | 348 | 338 | 21.6 |
| Class IV | 5.0 | 62 | 1,420 | 39 | 2.5 |
| Class V | 7.0 | 97 | 4,332 | 8 | 0.5 |
| b. Storm type | | | | | |
| Bahamas | 3.1 | 36 | 530 | 69 | 4.4 |
| Florida | 3.1 | 30 | 451 | 153 | 9.8 |
| Gulf | 2.8 | 16 | 175 | 220 | 14.1 |
| Coastal plain | 2.4 | 15 | 121 | 77 | 4.9 |
| Hatteras | 2.4 | 15 | 138 | 259 | 16.6 |
| Continental | 2.4 | 14 | 108 | 192 | 12.3 |
| Coastal front | 2.3 | 16 | 115 | 317 | 20.3 |
| Anticyclones | 2.1 | 19 | 104 | 277 | 17.7 |

(1992) have since developed an intensity scale based upon these wave hindcasts. Their intensity scale is based on individual measurements of storm location, track, duration, fetch, and wave heights for 1,347 non-tropical storms. The authors calculated a wave "power index" as the storm's duration times the square of the maximum significant deep-water wave height (average height of the highest third of the waves) and used it as their classification variable. Based on field evidence, a storm was defined to occur if it produced a maximum significant wave height of at least 5.0 ft (1.5 m); this wave height is found to cause some degree of coastal zone alteration to barrier islands along the mid-Atlantic coast (Bosserman and Dolan, 1968). Their scale classifies each storm into one of five classes based upon a cluster analysis of the original 1942–1984 data set which has subsequently been updated through 1992 (Dolan and Davis, 1994). The complete data set now encompasses fifty years and includes a total of 1,564 storms (Table 1a). During the fifty-year period, total coastal storm frequencies have declined, but the most destructive Class IV and V storms have increased in frequency (Davis and Dolan, 1993) (Figure 3).

Based upon earlier work by Mather *et al.* (1964), Davis *et al.* (1993) also classified nor'easters into eight storm types according to their region of formation and preferred tracks (Figure 4). These storm types include Bahamas lows, Florida lows, Gulf lows, Coastal Plain Cyclogenesis, Hatteras lows, Continental lows, Coastal Fronts, and Anticyclones. Of these storm types, the most dangerous and potentially destructive storms form between the Florida peninsula and the open ocean north of the Bahamas and track northward along the east coast of North America (Davis *et al.*, 1993). Bahamas and Florida lows account for 14.2% of all storms and generate the highest mean wave heights and longest durations (Table 1b). For the fifty years of data, only Florida and Hatteras storm types have increased in frequency (Davis *et al.*, 1993).

### Theoretical Relationships Between Nor'easters and the Jet Stream

The development and behavior of nor'easters depend upon the synchronization of different factors throughout the troposphere, with the structure of the polar jet stream being one of the most important. Theoretical relationships between flow patterns and the geopotential height, wind, and temperature fields can help define the dynamic processes associated with nor'easters. Alternating regions of maximum and minimum wind speed, together with long-wave troughs, are known to play an important role in determining the region along the jet where the formation or intensification of nor'easters is likely to occur (Reiter, 1961).

Although cyclogenesis can occur within many environments in the troposphere, a surface low

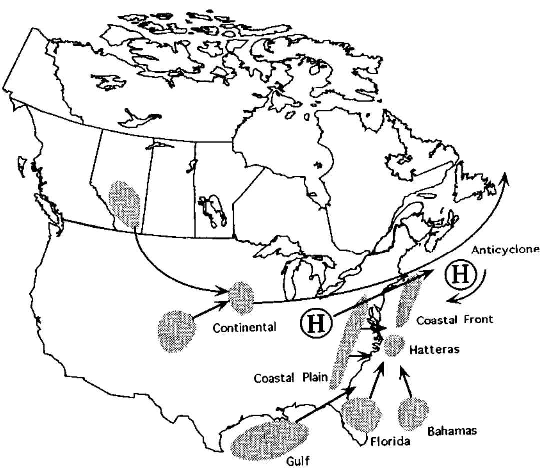


Figure 4. Formation regions for nor'easters and common storm tracks.

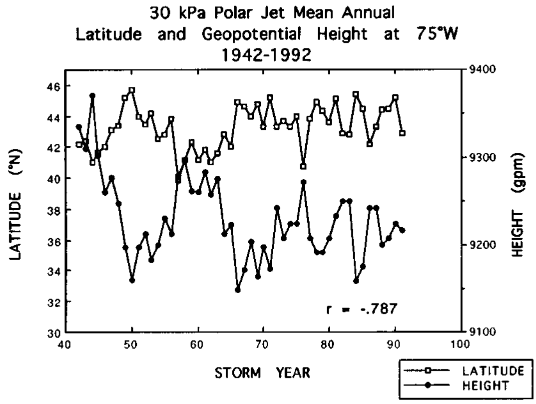


Figure 5. Mean annual latitude (°N) and geopotential height (gpm) of the 30 kPa jet at 75°W for 1942–1992 (r = −0.787).

pressure system is most often associated with a well-defined jet stream maximum in wind speed, occurring downstream of a trough within a region experiencing a deepening of the geopotential height field. Furthermore, a necessary condition for cyclone formation is the thermal contrast between the cold, polar air and the warm, tropical air along the boundary of the polar vortex. Thus, the frequency of nor'easters would be expected to increase within an atmospheric environment marked by upper-level troughs, larger thermal gradients created by a decrease in the 30 kPa temperature, decreased geopotential heights, and higher wind speeds in the mean field of the polar jet stream.

## RESULTS

### Climatological Jet Stream Variations

The mean annual latitude of the polar jet, as referenced to 75°W longitude, varied from 39.9°N to 45.7°N over the period of record (Figure 5). Based upon latitude, there is evidence of a regional circumpolar vortex expansion during 1950–1956 and contractions during the periods 1944–1950 and 1957–1966. With the exception of 1976, the polar jet latitude from 1966–1992 is less variable than previous periods and is generally contracted. The 1957–1966 vortex contraction is in agreement with ANGELL and KORSHOVER (1978, 1983) who determined that the 30 kPa circumpolar vortex was most expanded in the early 1960's. This also shows agreement with a later, updated study by ANGELL (1991) who found the vortex to be most expanded (4.6% larger than average) in 1976 and most contracted in 1989.

The time period's variations in the geopotential height of the polar jet stream display an inverse relationship with latitudinal position (Figure 5, r = −0.787). This relationship reveals that the jet resides at higher heights during periods of equatorward migration and lower heights during poleward movement. Overall, there is a reduction in the geopotential height of the jet that mirrors the general contraction of the circumpolar vortex.

The flow index of the polar jet over the eastern one-third of North America (70°W–100°W) serves as an indication of the prevalence of zonal, trough, short-wave trough, or ridge flow in the mean monthly field. For the time period, zonal flow is the most frequent (occurring 52% of the time), while trough, ridge, and shortwave trough flow types occur 38%, 9%, and <1% in the mean monthly field, respectively. In this analysis, the ridge and short-wave flow patterns display no significant relationship to coastal storm variations and are removed from the data set. The remaining flow conditions, zonal and trough, are "dummy-coded", as zonal = 1 and trough = 2 and have an overall mean of 1.4, indicating that zonal flow is slightly predominant during that time period. Within the time series, the polar jet displays a fluctuating pattern of changes from zonal to trough

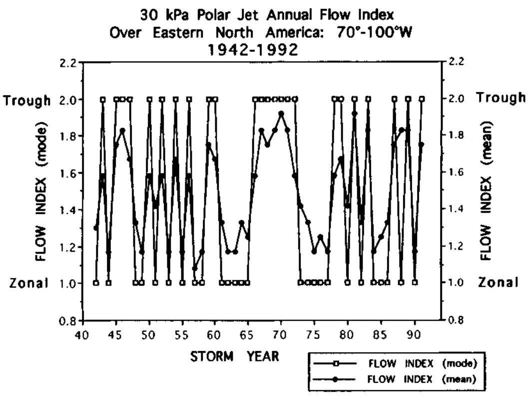


Figure 6. Annual mean and mode of the 30 kPa jet flow index as defined over 70°–100°W longitude for 1942–1992. Zonal (west-east flow) = 1 and trough (north-south flow) = 2.

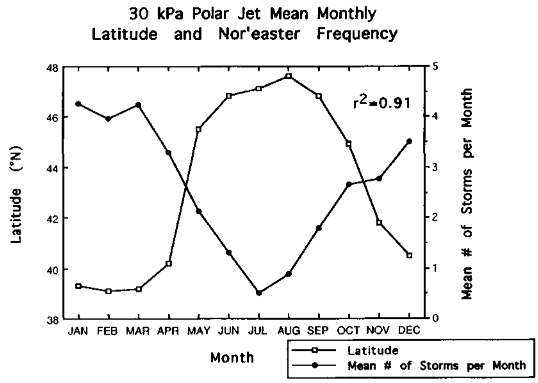


Figure 8. Seasonality of the 30 kPa jet mean latitude and nor'easter frequency ($r^2$ = 0.91).

flow with a period of yearly persistence in both flow types during 1960–1977 (Figure 6).

The temperature of the polar jet stream fluctuated between −41.6°C and −46.9°C with warming trends during 1942–1957 and 1968–1992 and a cooling trend from 1958–1967 (Figure 7). These trends are in agreement with ANGELL and KORSHOVER's (1977) identification of a shift to cooler global upper tropospheric temperatures during the sixties and with ANGELL (1991) who showed a subsequent increase in the 85–30 kPa layer temperature during 1971–1989. The first three observations of the temperature data set could be considered outliers, but an investigation of upper air temperature prior to 1943 suggested that these values are consistent with observations from prior years and therefore have not been removed from the data set.

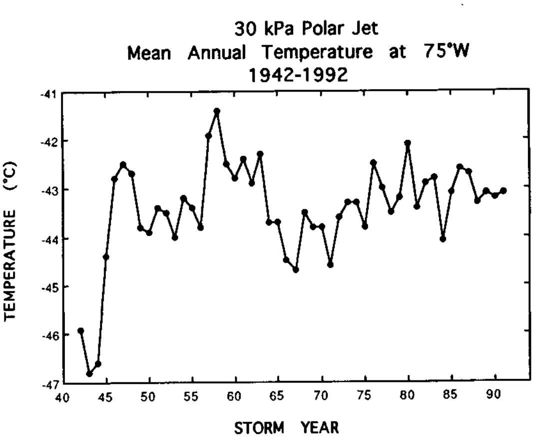


Figure 7. Mean annual temperature (°C) of the 30 kPa jet at 75°W for 1942–1992.

Toward the end of the time period, the mean annual variations of the polar jet stream exhibit a contraction of the vortex, lower geopotential heights, higher temperatures, and a higher frequency of zonal flow. Based upon these observations and theory, it is hypothesized that the mid-Atlantic coast should experience an increased frequency of transient, weaker Class I–III storms and a decrease in the more severe Class IV and V storms. The next step is to examine the relationships between the derived jet stream parameters and variations in strength and frequency of nor'easters during the same time period.

## Jet Stream and Nor'easters Analysis

### Seasonality

The seasonality of nor'easters is apparent (Figure 8), with a distinct storm season from October to April that contains approximately 80% of the total storm frequency (DOLAN *et al.*, 1988). The individual jet stream parameters exhibit statistically significant intra-annual correlations with the mean monthly coastal storm frequency (Table 2). The summer, poleward migration of the vortex correlates with the annual minimum in storm frequency and the winter, equatorward migration coincides with the maximum in storm frequency

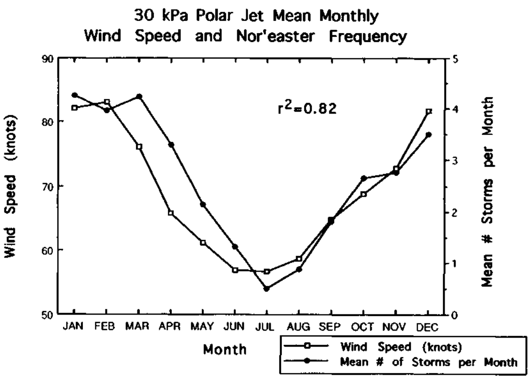


Figure 9. Seasonality of the 30 kPa jet mean wind speed (knots) and nor'easter frequency ($r^2$ = 0.82).

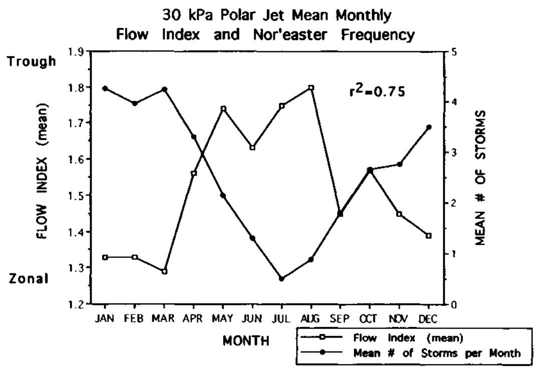


Figure 10. Seasonality of the 30 kPa jet mean flow index and nor'easter frequency ($r^2$ = 0.75).

($r^2$ = 0.91, Figure 8). The graph displays a nearly identical pattern to that of HAYDEN and DOLAN's (1977) 1952–1974 subset of the coastal storm data. Mean wind speeds in the polar jet are highest during the winter and lowest during the summer, mirroring the seasonality of the nor'easters ($r^2$ = 0.82, Figure 9). Again, these results are in excellent agreement with HAYDEN and DOLAN's (1977) kinetic energy versus seasonal storm frequency results for the 1952–1974 time period. The seasonality of the flow index is such that the higher mean storm frequencies that occur during the winter are associated with mean zonal flow patterns ($r^2$ = 0.75, Figure 10). Zonal flow produces more of the weaker Class I and II nor'easters due to a rapid west to east storm track across the continent and the lack of a deep trough formation in the flow. The mean temperature (Figure 11) and geopotential height (not shown) seasonalities are nearly identical with lower temperatures and heights occurring during the winter and at the seasonal maxima in nor'easters ($r^2$ = 0.93 for each).

These results reveal that the winter maximum in coastal storm frequency coincides with the maximum extent of the polar vortex's expansion and concordant decreases in geopotential height and temperature. The seasonal maximum in the strength of the jet stream is concurrent with the increased frequency of nor'easters. The flow index is the least significant seasonal component of the polar jet and shows that zonal flow in the mean pressure field is associated with the period of highest storm frequency.

### Time Series

To examine relationships between the spatial and temporal variations of the jet stream and the relative strength of nor'easters, the coastal storm data set is divided into four groups according to the Dolan-Davis storm intensity scale. The groups are defined as:

Group #1—Σ All storm classes

Group #2—Σ Class II, III, IV, and V storms

Group #3—Σ Class III, IV, and V storms

Group #4—Σ Class IV and V storms.

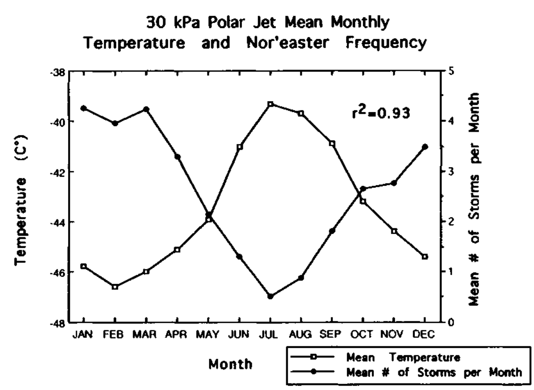


Figure 11. Seasonality of the 30 kPa jet mean temperature and nor'easter frequency ($r^2$ = 0.93).

Table 2. *Stepwise regression statistics of the seasonality of the polar jet versus nor'easter frequency. The number of observations, degrees of freedom, and explained variance are represented by N, DF, and $r^2$, respectively.*

| Analysis | N | DF | F-statistic | Significance Level | $r^2$ | Constant | Coefficient |
|---|---|---|---|---|---|---|---|
| Seasonality | | | | | | | |
| Latitude | 12 | 10 | 98.29 | 0.0001 | 0.91 | 17.87 | −0.35 |
| Wind speed | 12 | 10 | 45.13 | 0.0001 | 0.82 | −5.51 | 0.12 |
| Flow index | 12 | 10 | 30.41 | 0.0003 | 0.75 | 12.26 | −6.34 |
| Temperature | 12 | 10 | 135.29 | 0.0001 | 0.93 | −18.45 | −0.49 |
| Height | 12 | 10 | 136.71 | 0.0001 | 0.93 | 98.33 | −0.01 |

Over the fifty-year time period, the total number of nor'easters has decreased in frequency and the strongest, most potentially destructive storms (Class IV and V) have increased (Figure 3). The data set contains a total of eight Class V and 39 Class IV storms; of these, seven Class V storms have occurred since 1960 and at least one Class IV or V has occurred during each of the last five storm years.

Forward stepwise multiple regression is used to examine the relationship between the five jet stream parameters (independent variables) and the annual frequencies of nor'easters for each group (dependent variables). For the following analysis, a variable is included in the regression equation when the F-statistic exceeds 3.0 and is significant at the $\alpha = 0.05$ level. The analysis for Group 1 reveals that the flow index is the only significant jet stream parameter in describing the variation in total storms but is not statistically significant at the indicated level (Table 3). The analysis for Groups 2 and 3 reveals that the flow index is the only statistically significant predictor, with trough flow associated with an increase in storms ($r^2 = 0.19$ and $r^2 = 0.09$ respectively). The Group 4 analysis indicates that flow index and latitude are the only significant parameters that describe the variation in Class IV and V storms. The results show that trough flow and a southerly jet stream position are identified with an increase in the most destructive nor'easters ($r^2 = 0.19$).

DAVIS *et al.* (1993) found a correspondence between a given storm type's track and the wave heights and damage potential to the mid-Atlantic coast. To examine the relationship between storm track and annual jet stream variations, each of DAVIS *et al.*'s (1993) storm types (Table 1) are grouped into northern and southern classes, based upon the storm's point of origin (this grouping is needed to improve the statistical robustness of the regression analysis). The southern group consists of Bahamas, Florida, and Gulf Lows and the northern group includes Continental Lows, Hatteras Lows, Coastal Cyclogenesis, Coastal Fronts, and Anticyclones. DAVIS *et al.* (1993) identified southerly storm types as the most severe in that they exhibit the greatest mean power index, the longest durations and the highest deep-water waves (Table 1). These southerly storm types also account for 79% of the Class IV storms and 75% of the Class V storms.

Of the eight storm types, Florida and Hatteras lows exhibit increasing frequencies over time, Bahamas lows display no significant trend, and all of the remaining storm types declined in frequency for the time period (not shown). Based on the same forward stepwise multiple regression analysis described earlier, a statistically significant relationship exists between a southern jet stream position, decreased jet stream height, and an increase in the southerly storm types ($r^2 = 0.24$, Table 3). The northerly coastal storm types are shown to increase with trough flow patterns in the polar jet stream ($r^2 = 0.09$).

In summary, the statistical analysis of annual variations in the polar jet reveals that trough flow has the best statistical association with increased Class I through III storm frequency. The strongest Class IV and V storms correlate with an equatorward position and trough flow patterns of the polar jet stream. The most destructive southern storm types (Bahamas, Florida, and Gulf Lows) exhibit increased frequency with the expansion of the polar vortex and decreased polar jet stream heights.

## SUMMARY AND CONCLUSIONS

From the 1942 to 1992, seasonal and annual variations of the physical structure of the 30 kPa polar jet stream were derived from synoptic maps and data. The polar jet stream parameters—temperature, wind speed, geopotential height, lati-

Table 3. *(a) Stepwise regression statistics of the annual variations of the polar jet versus nor'easter groups and storm types (see data section and Table 1 for description). southern storm types consist of lows that form in the Bahamas, Florida, and Gulf regions; Northern types are comprised of Coastal Plain cyclogenesis, Hatteras lows, Continental lows, Coastal Fronts, and Anticyclones. Statistics follow that in Table 3. (b) Regression coefficients and intercept values for the significant variables in each model ($\alpha$ = 0.05).*

| Analysis | N | DF | F-statistic | Significance Level | $r^2$ | |
|---|---|---|---|---|---|---|
| a. Time series | | | | | | |
| Group #1 | 50 | 48 | 3.26 | 0.0771 | 0.06 | |
| Group #2 | 50 | 48 | 11.01 | 0.0017 | 0.19 | |
| Group #3 | 50 | 48 | 4.53 | 0.0385 | 0.09 | |
| Group #4 | 50 | 47 | 11.55 | 0.0014 | 0.19 | |
| Southern storms | 50 | 47 | 7.55 | 0.0001 | 0.24 | |
| Northern storms | 50 | 48 | 4.86 | 0.0323 | 0.09 | |
| | Latitude | Temperature | Height | Wind Speed | Flow Index | Constant |
| b. Coefficients | | | | | | |
| Group #1 | — | — | — | — | 3.15 | 26.62 |
| Group #2 | — | — | — | — | 3.81 | 9.92 |
| Group #3 | — | — | — | — | 1.54 | 5.42 |
| Group #4 | −0.05 | — | — | — | 0.76 | −0.18 |
| Southern storms | −2.15 | — | −0.04 | — | — | 466.15 |
| Northern storms | — | — | — | — | 3.48 | 17.29 |

tudinal position, and flow index—were then analyzed in regard to their relationships with the frequency and strength of nor'easters off the mid-Atlantic coast.

Our research indicates that:

(1) The polar jet stream parameters, as expected, undergo pronounced seasonality and are found to be highly correlated with coastal storm frequency. The seasonal frequency of extratropical storms along the east coast of North America is directly proportional to the mean wind speed of the jet stream and inversely proportional to the mean latitude, 30 kPa temperature, and geopotential height of the jet stream. The seasonal maxima and minima in storm frequency correlate with mean zonal and trough flow of the polar jet, respectively.

(2) The regression analysis on the annual mean of the polar jet variables shows that trough flow patterns are associated with Class I through Class III storm occurrence. Increased trough formations in the mean field, along with deep southerly excursions of the jet stream, contribute to the formation and sustenance of the potentially destructive Class IV and V nor'easters. These results are consistent with the knowledge that surface weather systems tend to form along the leading edge of troughs in the upper air flow.

(3) The most potentially destructive group of storms for the east coast of North America consists of cyclones that form off the southeastern U.S. coast and over Florida. The frequency of these storms has increased during the time period and correlates with an expanded state of the polar vortex and decreased jet stream geopotential heights over the East Coast. Thus, these storms are most common when the polar jet is farther south and cold, polar air masses occupy the eastern United States.

A finer time resolution is necessary to adequately describe the synoptic climatology of Atlantic extratropical storms and the role that the physical properties of the 30 kPa polar jet stream play in initiating and controlling their occurrences. This is because migrating extratropical storms are not discrete entities on mean monthly constant pressure maps and many may not be recognized. Some of the storms could also be attributed to cut-off lows which spin off the main flow of the jet stream. This situation would tend to leave the main body of the jet stream in a zonal flow pattern and north of the migratory surface system. The finer time resolution would allow a much more detailed characterization of the seasonal and annual changes in the large-scale atmospheric circulation.

The lack of explained variance in the regression relationships suggests that other physical aspects of the atmosphere and ocean are responsible for yearly changes in coastal storm frequencies. Further research is needed to explore other influences upon nor'easters. Possible contributing physical parameters include the effect that cut-off lows from the main jet flow have on storm occurrence, the examination of the variation and effects of the 50 kPa steering currents on coastal storm frequency, and a more complete description of the possible feedback mechanisms of the atmosphere and coastal oceans.

Because of the relatively long time period of the coastal storm record, it is possible to use our results to speculate on future coastal storminess in an enhanced $CO_2$ atmosphere. General circulation climate model experiments, when run with an atmosphere containing twice the $CO_2$ and trace gas concentrations of pre-industrial conditions, indicate that most of the resulting warming will occur at night, during the winter, and at high latitudes (*e.g.*, MANABE and WETHERALD, 1975). This predicted polar temperature increase, along with comparatively little tropical warming, should theoretically decrease the pole to equator thermal gradient, weaken the strength of the jet stream, and contract the polar vortex. For the North American Atlantic coastal zone, this predicted warming should also bring about a decrease in the frequency of nor'easters. Our localized results for eastern North America indicate that the polar vortex has contracted over this region and that nor'easters are less frequent than they were from 1942 through the mid-1960s. However, the strength of the polar jet has not decreased over this area, and the number of severe nor'easters has risen substantially in recent years. Thus, these results are inconclusive with respect to evidence of a global warming "signal" from our coastal storm record.

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