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Climatology of Rapid Cyclogenesis in the North Atlantic Ocean

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ABSTRACT

Some middle latitude cyclones undergo rapid strengthening, or explosive Cyclogenesis, over the warmer water of the North Atlantic Ocean. Any storm registering a sea-level pressure decrease of at least one "Bergeron" in a twenty-four hour period is treated as undergoing explosive Cyclogenesis.

Using storm data assembled by the National Climatic Data Center (NCDC), the climatology of rapid cyclogenesis for 5 x 5 latitude-longitude squares within the region from 30^0N to 60^0N, 0^0 to 75^0W was compiled. The study period includes the winter months from 1967 to 1993. Explosive marine Cyclogenesis is concentrated in a narrow area just to the south of Newfoundland with yearly probability of about 0.92 per year. This represents 21% of all storms forming or passing though this area. Based on a Chi-Squared analysis, the normality of the deepening and filling rate curves was done for all storms which passed through the box from 1982 to 1993.

1. Introduction

Paul Roebber (1984) performed statistical analysis on storms that occurred in the Pacific, Atlantic, and North America from February 1980 to January 1981. He broke his data up in this manner to minimize the break in data from the Massachusetts Institute of Technology archives where he obtained the data. He found that the storms tended to form to the east of Halifax and south of Newfoundland and explosive Cyclogenesis tended to form to the south-southeast of Newfoundland. Interestingly enough, there was a secondary maximum to the east of Newfoundland. Roebber (1984) also went on the perform statistical analysis on the twelve and twenty-four hour deepening rates of all the storms in his data set. He defined a "bomb" as deepening 19 mb in 24 hours to normalize his data to 42.5^0 N. His data set did not fit one normal curve as would be expected if baroclinic instability were the sole explanation for the rapid Cyclogenesis using the central limit theorem. He found that the mean of the sample deepening rates was greater than the mode of the sample. He then fit two normal curves of different means and standard deviations to the data set and found that the sum of these two curves fit the deepening distributions.

This study involves collecting 25 years worth of data and determining the frequency of storms within 5 x 5 latitude-longitude squares and the frequency of "bombs" within these squares. I used the assumption that a "bomb" was equal to one Bergeron (Sanders and Gyakum 1980) and calculated one Bergeron for every 5 degrees from 30^0 to 60^0 N. Changon et al. (1995) used equal area squares to determine their cyclone frequency. They did this because a 5 x 5 latitude-longitude box would be larger at 30^0 N and smaller at 60^0 N. For simplicity sake, and because the study only goes from 30^0 to 60^0N, I decided to stay with the 5 x 5 boxes.

The data was also used to make histograms for 10 years, based on the deepening rates of the storms within this box. I did these calculations for 6, 12, and 24 hour deepening rates and fit a normal curve to the data and tested for normality using the Chi-Squared test. We would expect our results to be consistent with Roebber's (1984) so our null hypothesis will be that the data is not normally distributed.

2. Background/Data

The data I used in my project was obtained through the NCDC and the National Oceanographic and Atmospheric Administration (NOAA) CD-ROM. The CD contained storm data from 1965 to 1993. I used the data from 1967 to 1993 so that I would have exactly 25 years worth of data instead of an odd number like 27. The storm data included position of the low in degrees latitude and longitude and Sea-Level Pressure (SLP) every six hours. The data used for the theoretical calculations included the years from 1982 to 1993.

The winter months from December to February were chosen as the focus of the study because this is the time of year when non-tropical storms reach their peak intensity. This is due to a peak in the low-level baroclinic instability, especially between Nova Scotia and the Gulf Stream (Hadlock and Kreitzberg 1988).

3. Methodology

First I defined an area of study in the Northern Atlantic to determine the frequency of storms. The area was chosen so that the maximum number of rapidly deepening cyclones would be included. The considerations for the study were to include North American cyclones that would move over the North Atlantic, as well as sub-tropical cyclones moving in from the Gulf of Mexico. The defined area is from 0^0 to 75^0 W and from 30^0 to 60^0 N. The area was further broken down into 5 x 5 latitude-longitude squares and the total number of storms that passed through each 5 x 5 square was determined for the months of December, January, and February for the years 1967 to 1993. A cyclone frequency map was done by taking the number of storms in the square, dividing it by the total number of storms that occurred in the region and multiplying by 100%. The total number of storms occurring in the region was 1891. This frequency was then calculated for all the months combined.

Using the 5 x 5 degree latitude-longitude squares, I determined the number of storms that deepened one Bergeron, considered a "bomb" that passed through each of the boxes using the following equation (e.g., Sanders and Gyakum, 1980):

$$1 Bergeron = \left(\frac{\sin\Phi}{\sin 60^0}\right) \times 24 mb \quad , \qquad (1)$$

in a 24 hour period, where Φ = degrees latitude. Then the number of storms that deepened at least one Bergeron in each of the boxes. A percentage was calculated for the number of "bombs" that passed through a square for the whole period by taking the number of "bombs" in a square and dividing by the total number of storms that passed through the square.

I obtained the 6, 12, and 24-hour deepening rates for 1982 to 1993 using a program which read the data from the NCDC and NOAA CD-ROM. Once the data was collected, a normal curve was plotted on top of the data sets using their respective mean and standard, where negative Bergeron's represent deepening rates while positive values represent filling rates. To determine whether or not the data was normally distributed, the Chi-Squared test was used.

A normal curve was plotted, with a mean of zero and a standard deviation of about 0.8, on top of the 24-hour deepening rate histogram. This represents what would be expected if the storms within the study area deepened to a certain SLP and then filled to its original SLP. The data was tested for normality using the Chi-Squared test. Once again, negative Bergeron's represent deepening rates while positive values represent filling rates.

4. What is a "Bomb"?

The term atmospheric "bomb" was first defined in the Norwegian school and it referred to rapidly deepening marine cyclones. Sanders and Gykum (1980) wrote on the synoptic and dynamical aspects of the "bomb". They defined a "bomb" as a system which deepens at the rate of 1 mb each hour for a 24 hour period. In other words, a storm that deepened 24 mb in 24 hours. Since this term was defined in Norway, which is about 60^0 N, there had to be a way to normalize this value for other latitudes.

By looking at the geostrophic wind equation:

$$V_g = \frac{1}{(2\Omega \sin\Phi)(\rho)} \frac{\Delta p}{d}, \qquad (2)$$

we see that the wind speed is inversely proportional to latitude and directly proportional to changes in the Pressure Gradient Force (PGF). Weinstein and Sanders (1989) showed that the geostrophic wind increases linearly as the PGF increases. They found that a storm, classified as a "bomb", would experience a wind increase of 2 knots per hour as a result. Since the geostrophic wind is inversely proportional to latitude, you would not require as much of a PGF to obtain the same change in wind speed at a higher latitude. With this in mind, it would be impossible to define a storm as a “bomb” at 30^0 N using the same criteria that you would use at 60^0 N. To account for this discrepancy, scientists devised a way to relate the concept of a “bomb” to different latitudes. The equation they created [Eq. (1)] is a way of defining a “bomb” for various latitudes, accounting for changes in the PGF. According to Sanders and Gyakum (1980), a “bomb” is defined as a storm that deepens one Bergeron in a 24 hour period. Within our study area, a “bomb” is defined as a storm that deepens at a rate of 14 mb in 24 hours at 30^0 N and 24 mb in 24 hours at 60^0 N.

5. Cyclone Climatology

While calculating the cyclone frequency I found that most storms occurred during the month of January, followed by February and December. After combining these results, I found that the storms most frequently occurred to the south of Halifax and Newfoundland representing 300 storms (Fig. 1), or a frequency of about 16% (Fig. 2).

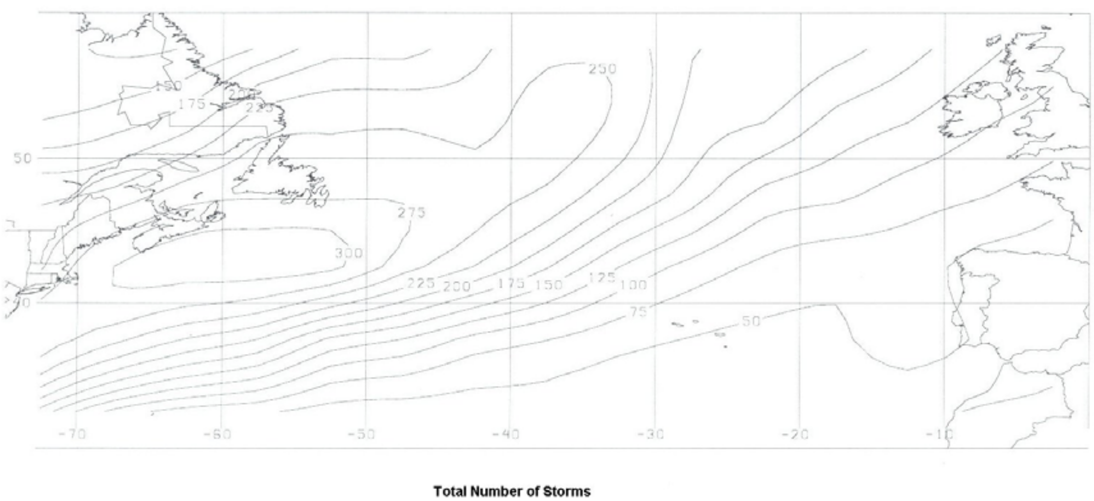

Fig. 1. Total number of storms December to February from 1967 to 1993.

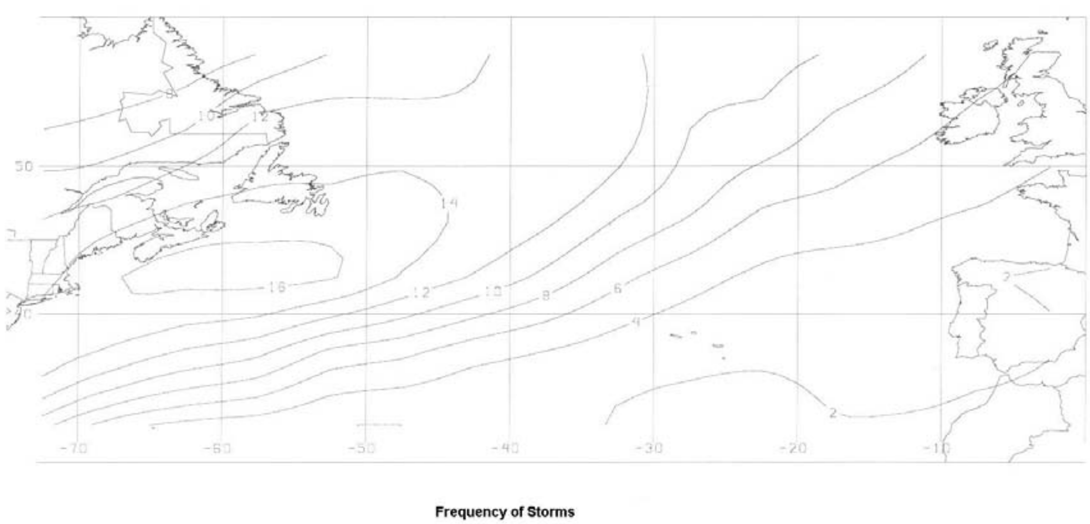

Fig. 2. Frequency of storms December to February from 1967 to 1993.

This is due to the steering flow, which brings most of the storms into this region from the western Atlantic and off the East Coast of the United States. This is also an area where the cold continental air interacts with the warm maritime air, suggesting that baroclinic instability plays a large role in the frequency of cyclones (Hadlock and Kreitzberg 1988).

The frequency for the total number of "bombs" that passed through a square divided by the total number of storms that passed through a square also gave us some interesting results. The most number of "bombs" passed through an area just to the south of Nova Scotia representing 50 storms (Fig. 3) or a frequency of about 16% (Fig. 4).

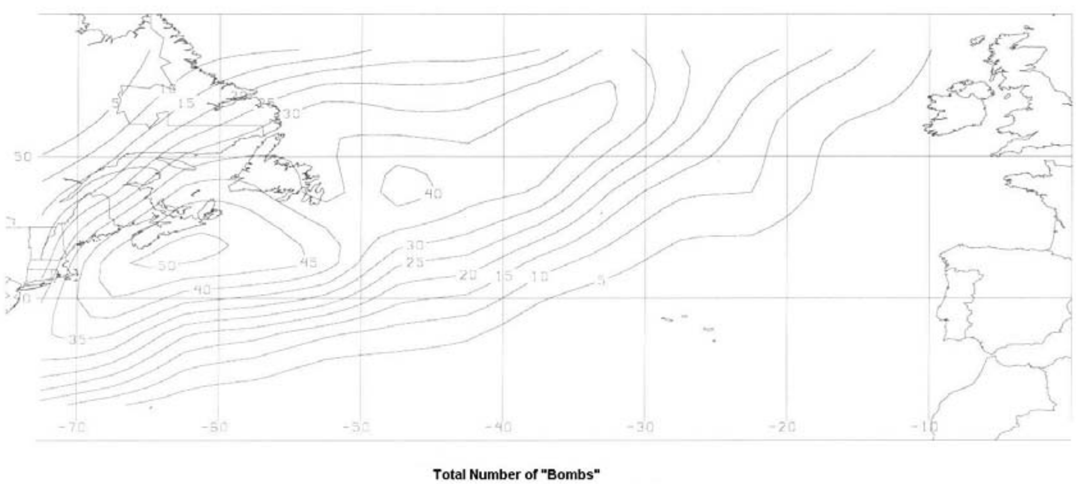

Fig. 3. Total number of "Bombs" December to February from 1967 to 1993.

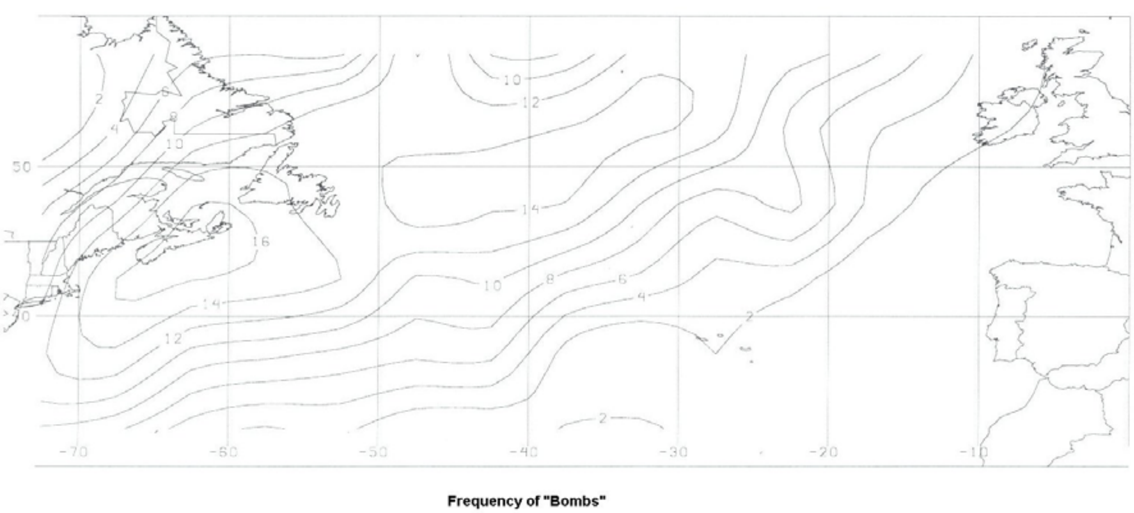

Fig. 4. Frequency of "Bombs" December to February from 1967 to 1993.

This means that 16% of all the storms that pass through this region will be “bombs”. This can be attributed to storms intensifying as they move off the United States East Coast and over the Atlantic Ocean as they experience a decrease in friction, a significant moisture flux, as well as sensible and latent heat fluxes. These results are consistent with the findings of Roebber (1984) as well as the Experiment on Rapidly Intensifying Cyclones of the Atlantic (ERICA), which show this small area of the Atlantic to be a breeding ground for rapidly intensifying cyclones (Hadlock and Kreitzberg, 1988).

A secondary maximum for the number of rapidly deepening cyclones was observed to the east of Newfoundland representing 40 storms (Fig. 3) or about 14% (Fig. 4) of the total storms that passed through this region. This secondary maximum is probably due to the relatively warm waters from the Gulf Stream. Interestingly enough the maximum from the south of Halifax extended into the south of Newfoundland with 40 or more “bombs” being present. This result is also consistent with the findings Roebber (1984) obtained.

The lowest pressure observed for the three months occurred in December and February, while the lowest pressure in January was 10 mb higher. Overall December had a consistently lower pressure than January, with January recording lower overall pressures than February. This may be attributed to greater baroclinic instability and a higher sea surface temperature in December than the other two months. The lowest pressure recorded was 929mb in both December and February. This is important because land based storms over the United States have never reached that intensity unless they were Category 4, according to the Saffir-Simpson scale, hurricanes. This implies that marine cyclones are more intense and occur more frequently than land-based storms. This phenomenon can be explained by taking into effect the large heat and moisture fluxes that the Atlantic has to offer, an effect that is enhanced by the warm waters of the Gulf Stream. The marine environment is also a place where friction has very little effect, allowing higher wind speeds compared to the land-based regime.

In my study it appeared that the 24-hour deepening rate had a bias in what time the deepening began. To test this suspicion I took the data from the 24-hour pressure change histogram and plotted when the deepening began. The results (Fig. 5) show that storms start to deepen at 1200 UTC about 76% of the time, possibly resulting from the time of day when ships report their data. Non-routine observation data usually comes in at 0000 and 1200 UTC to coincide with model runs. Most ships report their data during the daytime (Petty 1995), which corresponds to 1200 UTC in the Atlantic. Therefore the 1200 UTC bias may be a result of that particular hour containing more data than the other three that were used for comparison.

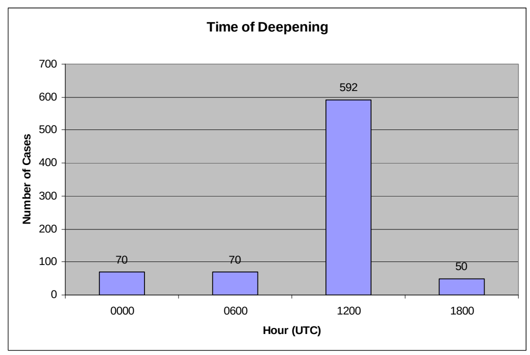

Fig. 5. Time in UTC when storms started deepening, representing 782 total cases.

6. Statistical Analysis

The Chi-Square test is used to examine if a sample of data comes from a particular distribution. Specifically, we will check to see if the data fits a normal curve using sample mean and standard deviation and expected mean and sample standard deviation in the case of the 24-hour deepening rate. To determine if the data will pass the chi-square goodness of fit test we divide the data into two bins, deepening and filling rates, and use the following equation:

$$\chi^2 = \frac{\sum_{i=1}^{k} (O_i - E_i)^2}{E_i} \quad , \qquad (3)$$

where O_i is the observed values for bin i and E_i is the expected value for bin i.

Figure 6 is a histogram representing the 24-hour deepening and filling rates. Overlaid on top of the histogram is a normal curve with a mean of zero and a standard deviation of 0.8011. The histogram shows that the deepening and filling rates are not the same. There are "bombs" in 162 of the cases and less than 50 of the storms filled at the rate of one Bergeron or more. This indicates that the data is negatively skewed with the tail of the curve extending farther into the negative end than the positive end. This data set does not appear to be normally distributed when fitted to this normal curve and the Chi-Squared test verifies this hypothesis. Before we can reject the null hypothesis, we need to fit a normal curve based on the expected data mean and standard deviation.

Figure 7 is also a histogram representing the 24-hour deepening and filling rates. The main difference is that the normal curve that is laid on top of the histogram uses the mean and standard deviation of the original data set (Table 1). Here we see that the data is still negatively skewed but appears to be more normally distributed than Figure 6. Using the Chi-Squared test we find the data is normally distributed so we cannot reject the null hypothesis. These results are not consistent with the results that Roebber (1984) obtained.

Figures 8 and 9 are histograms of the 12-hour and 6-hour pressure changes respectively. The normal curve that is overlaid on the histograms uses the mean and standard deviation of the original data sets (Table 1). The data in each case appears to be normally distributed and the Chi-Squared test verifies this hypothesis for

Length of Pressure Decrease	Mean	Standard Deviation
24-hour	-0.305	0.8011
12-hour	-0.326	0.857
6-hour	-0.321	0.902

Table 1. Mean and Standard Deviation of the 24, 12, and 6 hour pressure decrease.

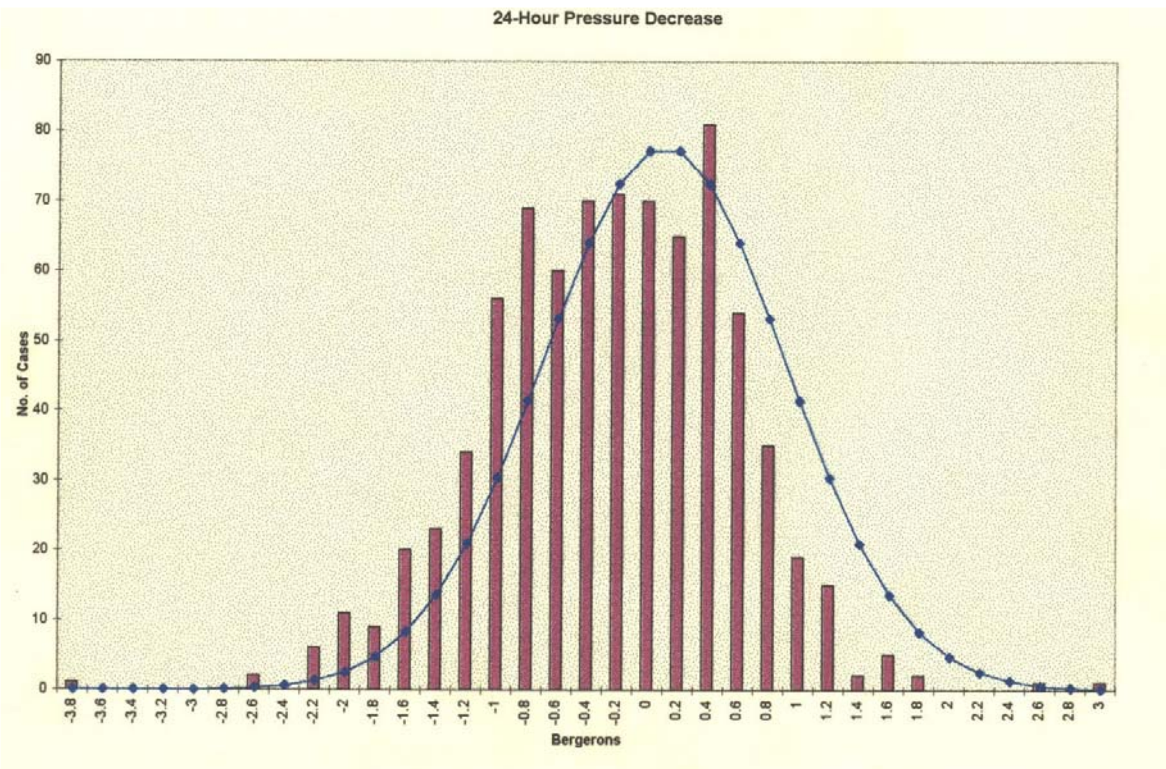

Fig. 6. 24-hour deepening histogram in red and normal curve with a mean of zero and a standard deviation of 0.8011 in blue.

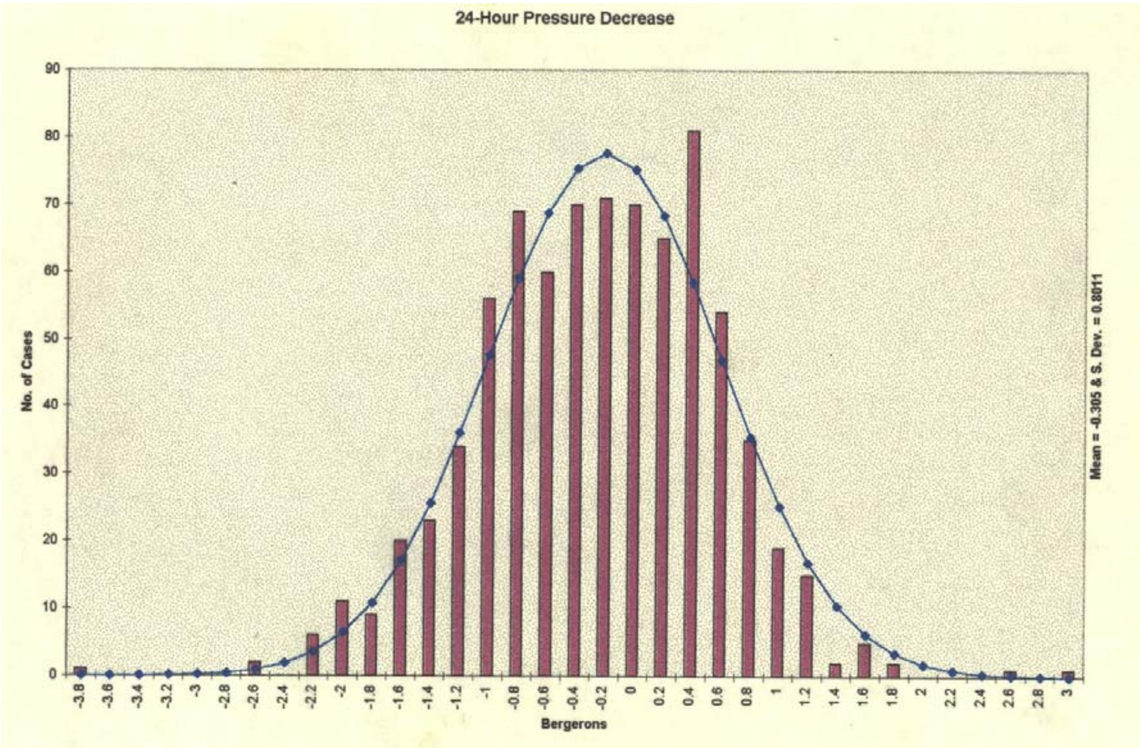

Fig. 7. As in Figure 6 using the mean and standard deviation of the original data set.

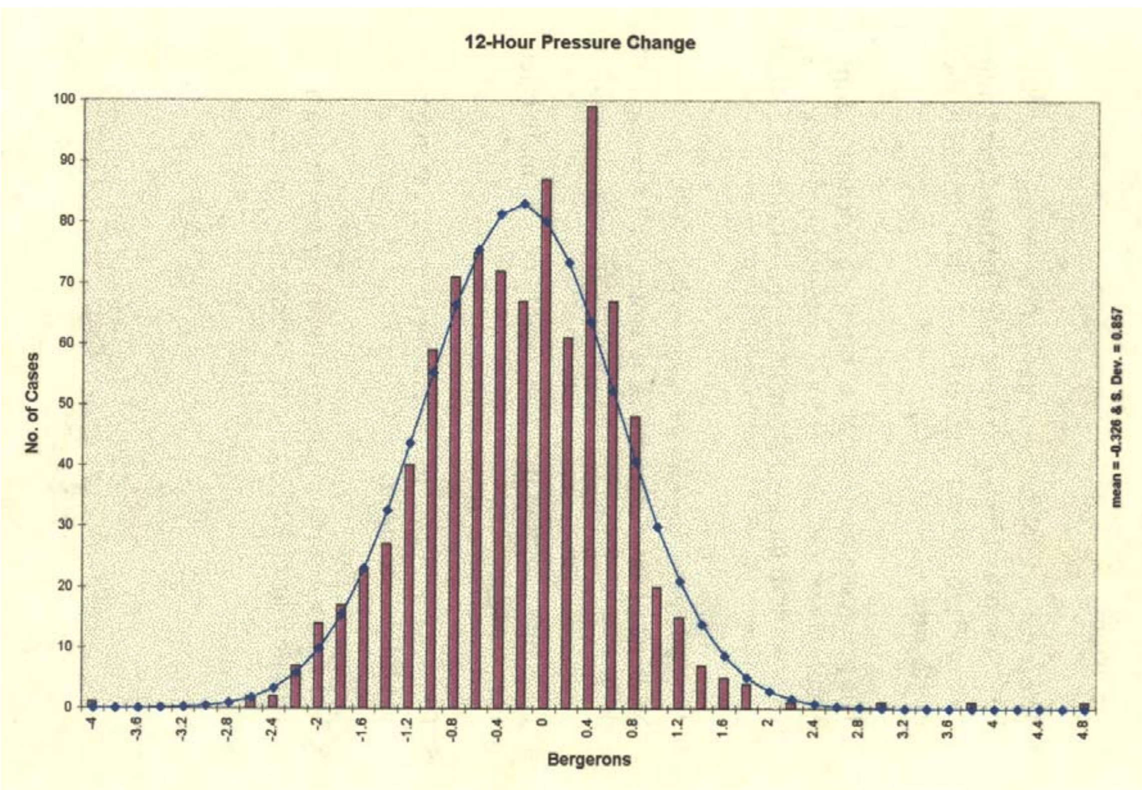

Fig. 8. As in Figure 7 for the 12-hour deepening.

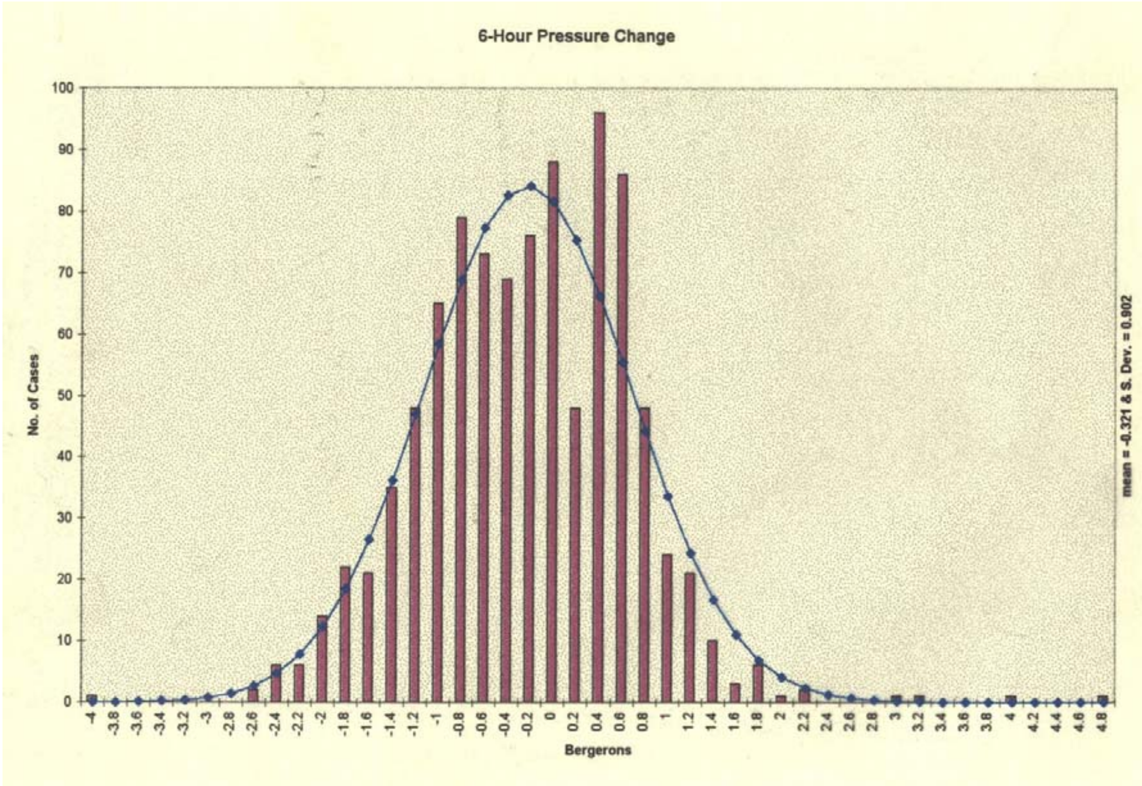

Fig. 9. As in Figure 7 for the 6-hour deepening.

both cases. Once again we cannot reject the null hypothesis and the results are not consistent with the ones that Roebber (1984) obtained.

7. Summary/Conclusions

This study set out to determine where the greatest number of cyclones and “bombs” occurred in the North Atlantic Ocean. Not surprisingly, the two areas are basically the same and represent the northwest portion of the Atlantic, or an area stretching from the south of Halifax to the east of Newfoundland. This phenomenon occurs because baroclinic instability in this region is higher than other regions of the North Atlantic Ocean (Hadlock and Kreitzberg 1988). However, another explanation could be that a different mechanism is involved in the deepening of the storms besides baroclinic instability (Davis and Emanuel 1988), which at this time is not fully determined or understood (Hadlock and Kreitzberg 1988). The storm frequency results are fairly consistent with the ones that Roebber (1984) obtained.

The 6, 12, and 24-hour pressure change histograms (Figs. 7, 8, and 8), which are fitted to a normal curve using the mean and standard deviation from the original data sets show that storms deepen more often than they dissipate. These histograms are normally distributed according to the Chi-Squared test so the null hypothesis cannot be rejected. This is not consistent with the results that Roebber (1984) obtained. This could be the result of the focus of the study, which was a little different than Roebber’s (1984). This study focused on the winter months in North Atlantic Ocean with 10 years worth of data. Roebber (1984) used a full years worth of data for the entire Pacific, Atlantic, and Arctic Oceans as well as the North American continent.

These results indicate a need for further research into this field. However, I would have liked to obtain more data for theoretical calculations to see if my results would have been more consistent with Roebber’s (1984) and not fit the normal curve.

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