

Hurricanes and Snow: A Common Occurrence in Eastern North Carolina?

James D. Jacaruso, Douglas W. Gamble, and Michael Benedetti

Laboratory for Applied Climate Research
Department of Earth Sciences
University of North Carolina at Wilmington

Snowfall is a rare occurrence in eastern North Carolina, yet rain is plentiful in summer and fall due to thunderstorms and tropical systems. The image of hazards created by both hurricanes and snow are uncommon to North Carolinians due to the climate of the region. However, just as recently as 1999, eastern North Carolina was faced with the challenge of responding first to a hurricane hazard (Dennis and Floyd) then record snowfalls the following winter. The purpose of this paper is to create a baseline-climatology, including frequency, probability, and magnitude, for the occurrence of record hurricane seasons followed by record snow seasons in eastern North Carolina. Results indicate that the occurrence of record rainfall created by a tropical systems followed by a record snowfall in the following is actually fairly common, 18 out of 52 hurricane-snow seasons. The conditional probability of a record snow occurring if a record rain occurs in the preceding hurricane season is 0.95. The authors believe that a physical process does not create the high probability of record rain and snow, but is a fallacy created by the database structure. In particular, a relatively short period of record causes record rain and snow to be likely during the hurricane or snow season. Through an increase of the period of record, a more accurate characterization of a record hurricane-snow season may be possible.

Introduction

North Carolina is classified as a Humid Subtropical climate (Koeppen, Cfa) (Critchfield, 1983). This climate type is characterized by a hot, sultry summer similar to the rainy tropics, and mild winters with occasional frost and snow produced by frontal storms (Lutgens and Tarbuck, 2001). Despite this classification, not all of North Carolina closely follows this climate type description (Soule, 1996). In particular, the mountains of western North Carolina experience cool summers and annual snow totals as much as 117 cm. To the east, the Piedmont and the Coastal Plain experience weather closest to the Cfa description. Snowfall is rare in these areas, yet precipitation is plentiful in summer and fall due to thunderstorms and tropical systems.

It is well documented that the tropical systems not only provide plentiful rain to eastern North Carolina but they also represent the leading natural hazard (Barnes, 1995; Hidore and Patton, 1996). An example of this type of hazard occurred in the summer of 1999 when Hurricanes Dennis and Floyd made landfall along the North Carolina coast (NWSILM, 1999). Floyd was the larger of the two hurricanes and caused record rainfalls and flood stages across the

eastern portion of the state (Gares, 1999). Some assessments of the floods created by Hurricane Floyd suggest a 500-year recurrence interval event (Lecce, 2000). The hurricanes and floods caused millions of dollars in damage and disrupted society for months after their passage (NWSILM, 1999).

Given the magnitude and amount of damage created by Hurricanes Dennis and Floyd, many people forget the other weather hazard that occurred the following winter and disrupted society across eastern North Carolina. A total of nine daily snowfall records were set during January 2000. The greatest snowfalls occurred on January 25, 2000 when Raleigh received 17.9 inches and Wilmington received 5.0 inches. These snowfalls required expensive response activities and caused the city of Raleigh to virtually shutdown.

The weather hazards of 1999 indicate that despite a Cfa climate in eastern North Carolina, it is possible for a hurricane to be followed by snow the next winter. Since snow is rare in eastern North Carolina, this rarity causes municipalities in the region, and the entire South for that matter, to be less prepared to respond to a large snowfall event (Bryant, 1991; Suckling 1991). Such an inefficient response can cause an increase in the cost of snowfall hazard mitigation efforts. Thus, if a heavy

snowfall occurs in the winter following a hurricane landfall, municipalities are faced with the problem of responding to not only a costly hurricane hazard response, but also a costly snow response. This cumulative response can cause both financial and organizational stress on emergency management agencies (Alexander, 1993).

It is difficult for government agencies to plan for such of a cumulative hazard because little, if any, research has investigated the occurrence of record snowfalls in a winter following a record hurricane rainfall. Therefore, no basic climate data, including frequency and magnitude of such occurrences, is available for agencies to make plans for response to heavy snows following hurricanes. Accordingly, the purpose of this paper is to create a baseline-climatology for the occurrence of record hurricane seasons followed by record snow seasons in eastern North Carolina. Specifically, this purpose will be supported by determining the frequency and probability of record hurricane-snow seasons in eastern North Carolina 1948-1999, the locations in eastern North Carolina where record hurricane-snow seasons are most likely to occur 1948-1999, the comparative magnitude of record hurricane-snow seasons in eastern North Carolina 1948-1999, and an explanation of why record hurricane-snow seasons occur. Information provided by this study may prove helpful to hazard mitigation activities of emergency management agencies, transportation agencies, and insurance companies. In particular, the characterization of hurricane-snow hazards may allow for agencies and companies to prepare and budget for extended hazard response from July through the following March.

Methodology

Analysis for this study was completed in a total of six steps. The first step was the identification of hurricanes that have made landfall in eastern North Carolina coast. Eastern North Carolina for this part of the study was defined as the portion of the state east of Charlotte. This area approximates the North Carolina coastal plain, the area closest to the coast and most likely to experience a land falling hurricane, and portions of the Piedmont. Portions of the Piedmont were included in the study to allow for the

identification of tropical systems that approach the Coastal Plain from the south or west and produce record rainfall. Tropical systems identified and included in this study were any Tropical Depressions, Tropical Storms, or Hurricanes with a path that entered North Carolina east of Charlotte. The systems were identified from the hurricane track archives produced by the National Hurricane Center as available through the Internet (<http://www.nhc.noaa.gov>).

The second step of analysis was the identification of daily rainfall records in eastern North Carolina associated with these landfall hurricanes. A record rainfall was defined in this study as the greatest rainfall on record at a specific weather station for a given date. The weather stations used in this study are all First Order National Weather Service stations located in the Coastal Plain or Eastern Piedmont, the region most similar to the Cfa climate type in North Carolina. A total of seven stations are used in the analysis, Cape Hatteras WSO, Elizabeth City FAA AIRP, Fayetteville, Greenville, Morehead City 2 WNW, Raleigh Durham WSFO AP, and Wilmington WSO Airport (Figure 1).

The National Climatic Data Center Summary of the Day, as compiled by HydrosphereTM, was used to identify rainfall records associated with tropical systems for the seven weather stations. The period of record used in this study was 1948-1999, except for Cape Hatteras, for which the period was 1957-1999. The rain records included in the study were records set during the time a tropical system's path was in eastern North Carolina.

The third step in analysis was the identification of daily snowfall records following a record rainfall from a landfall tropical system. The daily snowfall records used in this analysis were any daily snowfall record that occurred after a daily record from a tropical system but before the beginning of the next hurricane season. This time period included the fall, winter, and spring, all seasons in which snow has occurred in eastern North Carolina. The Hydrosphere database did not include record daily snowfalls for the year 2000. This data was required to identify snow after tropical system record rainfalls in 1999. So, daily records for January-May 2000 were downloaded from the National During the 52-year period of record, 25 years had at least one tropical system travel into eastern North During the

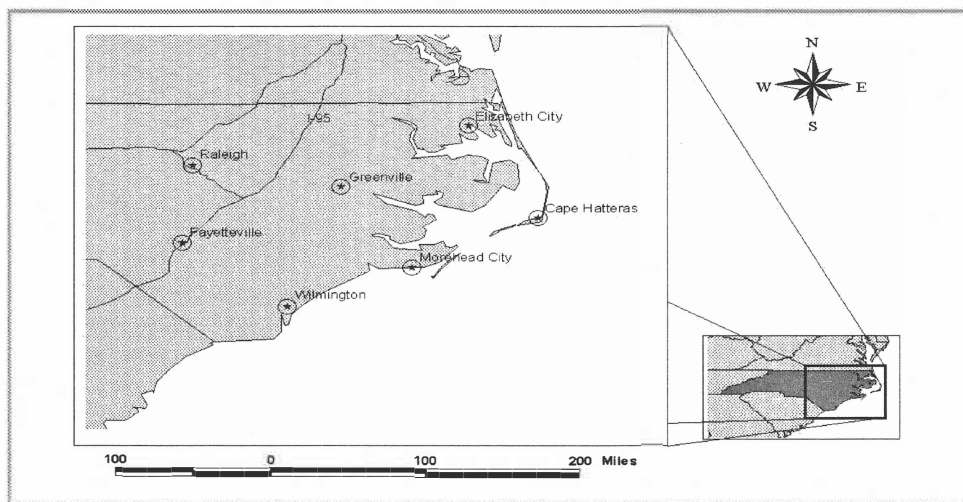


Figure 1. A map of eastern North Carolina displaying the location of weather stations used in analysis.

Climate Data Center's U.S. Daily Surface database available through the Internet (<http://www.ncdc.noaa.gov>), and used to identify daily record snowfalls.

Combination of daily record rainfall and snow data to identify record hurricane-snow seasons was the fourth step in analysis. If one of the weather stations in eastern North Carolina recorded both a daily record due to a tropical system and a record snow the following fall/winter/spring, the year of the tropical system was declared a record hurricane-snow season. Only one weather station with the record rain and snow occurrence was required for the classification but record hurricane-snow seasons can include record rain and snow at multiple weather stations and multiple record tropical systems or multiple record snow events. In fact, many years in the study period contain multiple record rain and snow events that cover multiple weather stations.

Once the record hurricane-snow seasons were identified, the fifth step in analysis, the determination of the location with the most frequent occurrence of record hurricane-snow seasons, was completed. Dividing the total number of record hurricane-snow seasons at a given weather station by the years in the period of record completed this step in the analysis.

The normalizing of the number of record hurricane-snow seasons by the period of record was required since all weather stations did not have the same period of record. Cape Hatteras's period of record was 1957-1999 as compared to 1948-1999 for the remaining weather stations.

The final step in the analysis was the assessment of the magnitude of record hurricane-snow seasons by determining the number of weather station that recorded record rain and snow during a record hurricane-snow season and ranking the amount of rain and snow recorded as records. By counting the number of weather stations observing record rain and snow, the relative size of a storm and the overall impact to eastern North Carolina as a whole can be inferred. A greater number of locations with a record indicates a larger area impacted by the storm. Assigning a numerical rank to the total amount of record rain and snow observed in a hurricane-snow season creates the second measure of magnitude. The total amount of rain and snow were divided by the number of stations receiving record rain and snow before assigning the numerical rankings. This division normalizes the data by area, and thus results are

not biased toward storms causing rain or snow over a large area. The two numerical ranks for rain and snow were then added together to provide an overall rank of magnitude for a record hurricane-snow season. Since the largest amounts of record rain or snow received a rank of 1, the lower the combined ranking the greater the magnitude of the record hurricane-snow.

Results and Discussion

52-year period of record, 25 years had at least one tropical system travel into eastern North Carolina (Table 1). This frequency can be expressed as a 0.48 probability of any year experiencing a tropical system in eastern North Carolina 1948-1999. Of the 25 years, 22 years had record rainfalls at at least one of the seven weather stations included in this study, a 0.88 probability. A total of 18 years between 1948 and 1999 recorded both a record rainfall created by a tropical system and a record snowfall the following fall, winter, or spring. Accordingly, the probability of a record snowfall after a record rainfall created by a tropical system in eastern

North Carolina 1948-1999 was 0.86. Thus, results indicate that once a tropical system causes a record daily rainfall it is highly likely that a record snow will follow in fall, winter, or spring. This is a somewhat surprising result given the description of the Cfa climate, a climate in which heavy snowfall is rare.

The eastern North Carolina locations that observed the most record hurricane-snow seasons for the given period were Raleigh and Wilmington (0.19 record hurricane-snow seasons per year), followed closely by Elizabeth City (0.17 record hurricane-snow seasons per year). Cape Hatteras followed these three stations with 0.11 record hurricane-snow seasons per year. The remaining three stations all had record hurricane-snow seasons per year below 0.10 (Figure 2). The reason for the stations with record hurricane-snow seasons per year above 0.10 is most likely that they are located in areas that either have the greatest annual tropical system frequency or snow frequency. Raleigh and Elizabeth City are located in the northern most portions of the study area, and Luthgens and

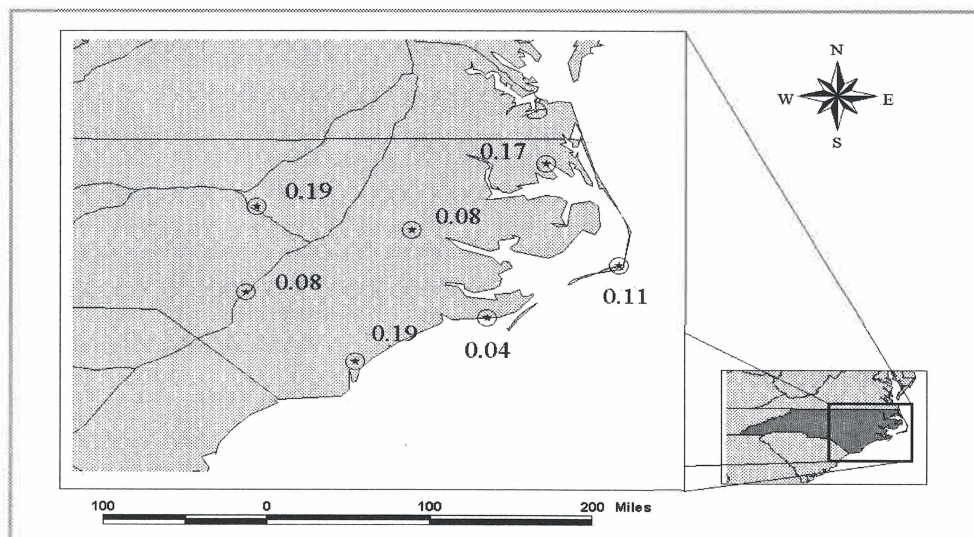


Figure 2. A map of the probability that a record rain-snowfall day will occur during any given hurricane-snow season in eastern North Carolina.

Table 1. Hurricanes making landfall in eastern North Carolina and the associated daily rain and snow records, 1948-1999.

Name	Start Date	End Date	Record Rainfall	Record Snowfall	Weather Station
Able	8/31/52	9/1/52	Y	N	Raleigh Durham WSFO AP
Barbara	8/13/53	8/14/53	Y	N	Elizabeth City FAA AIRP
			Y	Y	Greenville
			Y	N	Morehead City 2 WNW
Carol	8/30/54	8/31/54	Y	Y	Elizabeth City FAA AIRP
			Y	Y	Fayetteville
			Y	Y	Morehead City 2 WNW
Haze 1	10/15/54	10/16/54	Y	Y	Elizabeth City FAA AIRP
			Y	Y	Fayetteville
			Y	Y	Raleigh Durham WSFO AP
			Y	Y	Wilmington WSO Airport
Connie	8/12/55	8/13/55	Y	Y	Elizabeth City FAA AIRP
			Y	N	Greenville
			Y	N	Morehead City 2 WNW
			Y	N	Raleigh Durham WSFO AP
			Y	Y	Wilmington
Diane	8/17/55	8/18/55	Y	Y	Elizabeth City FAA AIRP
			Y	N	Greenville
			Y	Y	Raleigh Durham WSFO AP
Ione	9/19/55	9/20/55	Y	Y	Elizabeth City FAA AIRP
			Y	N	Greenville
			Y	N	Morehead City 2 WNW
			Y	Y	Wilmington WSO Airport
Flossy	9/26/56	9/28/56	Y	N	Fayetteville
			Y	N	Raleigh Durham WSFO AP

Name	Start Date	End Date	Record Rainfall	Record Snowfall	Weather Station
Brenda	7/29/60	7/30/60	Y	Y	Elizabeth City FAA AIRP
			Y	Y	Fayetteville
			Y	N	Greenville
			Y	Y	Raleigh Durham WSFO AP
			Y	Y	Wilmington WSO AIRP
Donna	9/11/60	9/12/60	Y	Y	Elizabeth City FAA AIRP
			Y	Y	Fayetteville
			Y	N	Greenville
			Y	N	Morehead City 2 WNW
			Y	Y	Raleigh Durham WSFO AP
Not Named	9/14/61	9/15/61	Y	Y	Wilmington WSO Airport
Alma	8/28/62	8/29/62	Y	Y	Cape Hatteras WSO
Cleo	8/31/64	9/3/64	Y	Y	Elizabeth City FAA AIRP
Dora	9/13/64	9/14/64	Y	Y	Elizabeth City FAA AIRP
			Y	Y	Fayetteville
			Y	Y	Greenville
			Y	Y	Raleigh Durham WSFO AP
			Y	Y	Elizabeth City FAA AIRP
Isbell	10/16/64	10/17/64	Y	Y	Elizabeth City FAA AIRP
			Y	Y	Raleigh Durham WSFO AP
Not Named	6/16/65	6/17/65	Y	Y	Cape Hatteras WSO
			Y	Y	Elizabeth City FAA AIRP
			Y	N	Fayetteville
			Y	N	Greenville
			Y	Y	Morehead City 2 WNW
			Y	Y	Raleigh Durham WSFO AP
Doria	9/16/67	9/17/67	N	n/a	All Stations
Abby	6/9/68	6/13/68	N	n/a	All Stations

Name	Start Date	End Date	Record Rainfall	Record Snowfall	Weather Station
Alma	5/26/70	5/27/70	N	n/a	All Stations
Not Named	8/17/70	8/18/70	Y	Y	Wilimington WSO Airport
Doria	8/27/71	8/28/71	Y	Y	Elizabeth City FAA AIRP
			Y	N	Morehead City 2 WNW
			Y	Y	Raleigh Durham WSFO AP
Agnes	6/21/72	6/22/72	N	n/a	All Stations
Bob	7/14/79	7/15/79	N	n/a	All Stations
David	9/5/79	9/6/79	Y	Y	Cape Hatteras WSO
			Y	Y	Elizabeth City FAA AIRP
			Y	Y	Fayetteville
			Y	Y	Wilmington WSO Airport
Dennis	8/20/81	8/21/81	Y	N	Cape Hatteras WSO
			Y	N	Elizabeth City FAA AIRP
			Y	N	Greenville
			Y	N	Morehead City 2 WNW
			Y	N	Wilmington WSO Airport
Diana	9/12/84	9/15/84	Y	Y	Cape Hatteras WSO
			Y	N	Fayetteville
			Y	N	Morehead City 2 WNW
Bob	7/25/85	7/26/85	N	n/a	All Stations
Danny	8/18/85	8/19/85	Y	Y	Cape Hatteras WSO
Gloria	9/26/85	9/27/85	Y	N	Greenville
			Y	N	Morehead City 2 WNW
			Y	N	Raleigh Durham WSFO AP
Kate	11/22/85	11/23/85	Y	Y	Raleigh Durham WSFP AP
			Y	N	Wilmington WSO Airport
			Y	N	Wilmington WSO Airport
Charley	8/17/86	8/18/86	Y	N	Morehead City 2 WNW

Name	Start Date	End Date	Record Rainfall	Record Snowfall	Weather Station
Allison	6/5/95	6/7/95	Y	N	Cape Hatteras WSO
			Y	N	Fayetteville
			Y	Y	Greenville
			Y	N	Morehead City 2 WNW
			Y	Y	Wilmington WSO Airport
Athur	6/19/96	6/21/96	Y	N	Cape Hatteras WSO
Bertha	7/12/96	7/13/96	Y	N	Greenville
			Y	Y	Wilmington WSO Airport
Fran	9/5/96	9/6/96	Y	N	Fayetteville
			Y	N	Morehead City 2 WNW
			Y	Y	Raleigh Durham WSFO AP
			Y	Y	Wilmington WSO Airport
Josephine	10/8/96	10/9/96	Y	N	Fayetteville
			Y	N	Greenville
			Y	Y	Raleigh Durham WSFO AP
			Y	Y	Wilmington WSO Airport
Danny	7/23/97	7/25/97	Y	N	Fayetteville
			Y	Y	Raleigh Durham WSFO AP
Bonnie	8/27/98	8/28/98	Y	Y	Wilmington WSO Airport
Earl	9/3/98	9/5/98	Y	N	Cape Hatteras WSO
			Y	N	Greenville
			Y	Y	Wilmington WSO Airport
Dennis	9/4/99	9/6/99	Y	Y	Elizabeth City FAA AIRP
			Y	N	Greenville
			Y	Y	Raleigh Durham WSFO AP
Floyd	9/16/99	9/16/99	Y	N	Greenville
			Y	Y	Raleigh Durham WSFO AP
			Y	Y	Wilmington WSO Airport

Table 2. The number of weather stations observing record rainfall and record snow fall by hurricane-snow season in eastern North Carolina.

Hurricane-Snow Season	Number of Weather Stations	Number of Weather Stations Divided by Number of Storms
1954	7	3.5
1960	7	3.5
1964	7	2.3
1955	6	2.0
1996	5	2.5
1965	4	4.0
1979	4	4.0
1997	4	3.0
1999	4	4.0
1971	2	2.0
1985	2	2.0
1995	2	2.0
1998	2	1.0
1953	1	1.0
1961	1	1.0
1962	1	1.0
1970	1	1.0
1984	1	1.0

Tarback (2001) note snowfall is most frequent in the higher latitudes of Cfa regions. Wilmington is located on the coast in the southeast portion of the state and Cape Hatteras is on the Outer Banks barrier island complex. It has been well documented that both of these locations frequently experience land falling tropical systems (Barnes, 1995, Hidore and Patton, 1996). Given the higher frequency of tropical systems and snow occurrence at these locations there is a greater possibility that these locations will experience both record tropical system rain or record snowfall.

The assessment of hurricane-snow season magnitude indicates that the number of tropical systems in a given year can cause difficulty in determining the area impacted during a hurricane-

snow season (Table 2). The years with the top three number of stations (7, 6, and 5) observing record rain and snow were all years with multiple storms, 1954, 1960, 1964, 1955, and 1996. These numbers don't truly represent the largest area affected in hurricane-snow season because the same weather station can have a record in multiple storms. However, dividing this total number of stations with record rain and snow in a hurricane season by the number of tropical systems, a more accurate measurement of the area impacted by a hurricane-snow season was presented (Table 2). After this division, 1965 and 1979 were the years with the largest area covered by record rain and snow with 4 weather stations followed closely by 1954 and 1960 with 3.5 stations. Combining this with the

Table 3. The ranking of the amount of rain and snow recorded on record days during record hurricane-snow seasons in eastern North Carolina.

Season	Total Rain (in)	Rain Rank	Rain Stations	Number of Stations	Total Snow (in)	Snow/Station	Snow Rank	Overall Rank
1999	31.74	2	7.9	4	59.81	14.95	2	4
1979	20.34	4	5.0	4	67.61	16.90	1	5
1962	10.38	1	10.3	1	1.30	1.30	9	10
1964	18.46	11	2.6	7	39.85	5.69	3	14
1998	11.89	3	5.9	2	0.02	0.01	13	16
1954	17.57	12	2.5	7	27.15	3.87	5	17
1971	5.56	10	2.7	2	5.52	2.76	8	18
1965	9.09	13	2.2	4	14.62	3.65	6	19
1960	21.64	9	3.1	7	8.63	1.23	10	19
1995	6.70	8	3.3	2	2.01	1.00	11	19
1955	21.67	7	3.6	6	3.82	0.63	12	19
1996	20.66	5	4.1	5	0.05	0.01	14	19
1970	1.77	16	1.7	1	4.01	4.01	4	20
1961	1.37	17	1.3	1	3.10	3.10	7	24
1997	11.89	6	3.9	3	0.02	0.01	18	24
1953	1.84	14	1.8	1	0.01	0.01	15	29
1985	3.60	15	1.8	2	0.02	0.01	16	31
1984	1.3	18	1.3	1	0.01	0.01	17	35

rank of record rain and snow magnitudes, it is clear that 1979 was the worst hurricane-snow season, or the season with the largest area impacted with the most amount of rain and snow (Table 3).

Conclusions

Results indicate that a record snowfall occurring in the fall, winter, and spring after a record tropical

system has a relatively high probability or is relatively common in eastern North Carolina. This result is somewhat surprising taking into consideration the general characteristics of the Cfa climate type, hot summers and mild winters with little snow. So, the question remains, what causes record snow to be so common after record tropical system rainfall in eastern North Carolina? The authors believe that the high

probability of record rain and snow is not created by a physical process, but is a fallacy created by the database structure.

The first reason for believing the high probability was produced by the database structure is that there is no clear physical link between hurricanes and snowfall in the following fall, winter, and spring. A literature review by the authors produced no textbooks, articles, or other professional publications linking tropical system activity to snowfall the following fall/winter/spring. This absence of hypotheses as to the link led to a closer examination of the database and methodology used in the study.

This examination led to the realization that the utility of this analysis is related to the length of record used to determine daily rain or snow records. For this study, 52 years is the longest period of record for rain and snow. Thus the probability of a given year to experience a record rain or snow for a given date is 1 out of 52 or 0.02. Using a conservative definition of the hurricane season as July through October, there are 143 days in the hurricane season. Applying the binomial distribution, the probability of one or more days during this 143-day period to record a record rainfall (with a 0.02 probability) is 0.94, very high. Using a conservative definition of the snow season in eastern North Carolina (November through March) and applying the binomial distribution again, the probability of one or more days during the 153-day period to record a record is 0.95, even higher. Calculation of the conditional probability of a record snowfall occurring only if a record rainfall from a tropical system has occurred earlier produces a 0.95 probability. Therefore, based upon the length of record and fundamental laws of probability, a record rain and snow will most likely occur in eastern North Carolina regardless of physical process.

The high probability of record rain and snow in eastern North Carolina due to a short length of record is similar to difficulties in evaluating the 100-yr flood with annual peak flow series (Dunn and Leopold, 1978). The use of a short series of annual peak floods can cause the recurrence interval to be inflated and estimates of a 100-year flood to be unreliable. In fact, Lecce (2001) points out that the characterization of floods created by Hurricane Flood as a 500 yr flood are

inappropriate based upon the relatively short record of annual peak flood series.

The question now remains: since only 50 or so years of data exist, how can agencies accurately assess the risk of a cumulative hurricane and snow hazard? The answer is that it will be difficult. One thing is for sure, that snow and hurricanes in eastern North Carolina, a Cfa region, are not as rare as previously thought. In the last fifty years it has happened at least 18 times and preparation for a cumulative stress to emergency response organization may be worthwhile.

References

- Alexander, D. (1993). *Natural Disasters*. New York: Chapman & Hall.
- Barnes, J. (1995). *North Carolina's Hurricane History*. Chapel Hill: The University of North Carolina Press.
- Bryant, E.A. (1991). *Natural Hazards*. Cambridge: Cambridge University Press.
- Gares, P.A. (1999). "Climatology and Hydrology of Eastern North Carolina and Their Effects on Creating the Flood of the Century," *The North Carolina Geographer*, 7: 3-11.
- Hidore, J.E., and Oliver, J.E. (1993). *Climatology: An Atmospheric Science*. New York: MacMillan Publishing Company.
- Lecce, S. (2000). "Fallacy of the 500-year Flood: A Cautionary Note on Flood Frequency Analysis," *The North Carolina Geographer*, 8: 29-40.
- National Weather Service Forecast Office Wilmington, NC (NWSILM). (1999). *Past Tropical Systems to Affect the Carolinas*. <http://nwsilm.wilmington.net/tropics/tropics.html>
- Suckling, P.W. (1991). "Spatial and Temporal Climatology of Snowstorms in the Deep South," *Physical Geography*, 12(2): 124-139.