SEVERE WEATHER

A RADAR-BASED THUNDERSTORM AND INTENSE THUNDERSTORM DAY CLIMATOLOGY FOR NEW JERSEY

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ABSTRACT

A 5-year radar climatology of summer season (May–Sept.) thunderstorm and intense thunderstorm days for New Jersey was developed using manually digitized radar (MDR) data from four local radar sites. Echo intensity levels equal to 3 or more were determined to be associated with surface reports of thunder in the majority of cases (75 percent). Intense thunderstorm days were arbitrarily defined to occur when echo intensity levels reached 5 or 6. A network of 63 grid boxes located in and around New Jersey was used to tabulate thunderstorm and intense thunderstorm days frequencies over a 5-season period (1978–1982). Frequencies and averages of thunderstorm days were plotted by grid box and isoplethed by month and season. Thunderstorm and intense thunderstorm day frequencies by month were generally highest over interior sections of southeastern Pennsylvania and southwestern New Jersey. When thunderstorm and intense thunderstorm days were averaged over 4 seasons the maximum frequencies were found over southwestern and northern New Jersey and southeastern Pennsylvania. Comparisons to conventional climatologies indicated that despite some similarities, the radar-based climatology provided much finer resolution and indicated frequencies over urban areas to be higher than conventional values.

KEYWORDS: Thunderstorm Climatology Radar Climatology Intense Thunderstorm

I. INTRODUCTION

According to the National Weather Service (NWS) a thunderstorm day is said to occur when thunder is heard at least once at an observing station at any time during a 24-hour midnight-to-midnight period. Court and Griffiths (3) prepared a thunderstorm day climatology for the conterminous United States for the period 1951–70 using first-order stations. The mean frequency of annual thunderstorm days and summer season (Apr.–Sept.) thunderstorm days are shown for the northeastern United States in Figures 1 and 2, respectively. The climatology is obviously strongly dependent upon the distribution of the first-order stations, and may also be affected by observer bias. Such bias may be positive when a thunderstorm is noted although only lightning is observed, or negative when thunder is not audible above local background noise levels or if lightning cannot be observed because of obstructions to vision. The observer also may not record a thunderstorm occurrence because of preoccupation with other duties. Court and Griffiths (3) readily acknowledged these problems with their own and other thunderstorm climatologies, as did Chagnon (4), and errors of up to 25 percent are not uncommon.

Thunderstorm climatologies have also been developed by many authors using various techniques. Frank et al. (5), Bowman and Shulman (6), Boer (7), Sen (8), and Mezgec (9) determined the distribution of thunderstorm frequencies through the examination of synoptic and radar data. Falls (10), Williford and Carter (11), Neumann (12), Falls et al. (13), Carter (14), Sakomoto (15), Yagudin (16), Lugina and Masanova (17), Wallace (18), Tomlinson (19), Litynska et al.

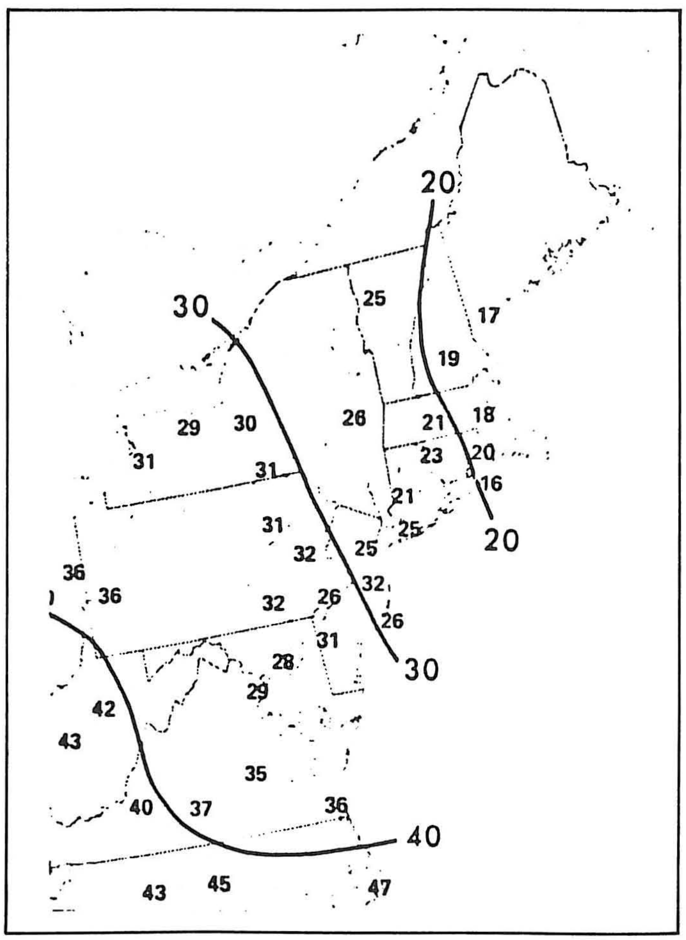

Fig. 1. Mean annual thunderstorm days, 1951–1970 (isopleths are those of original authors, Court and Griffiths, 3).

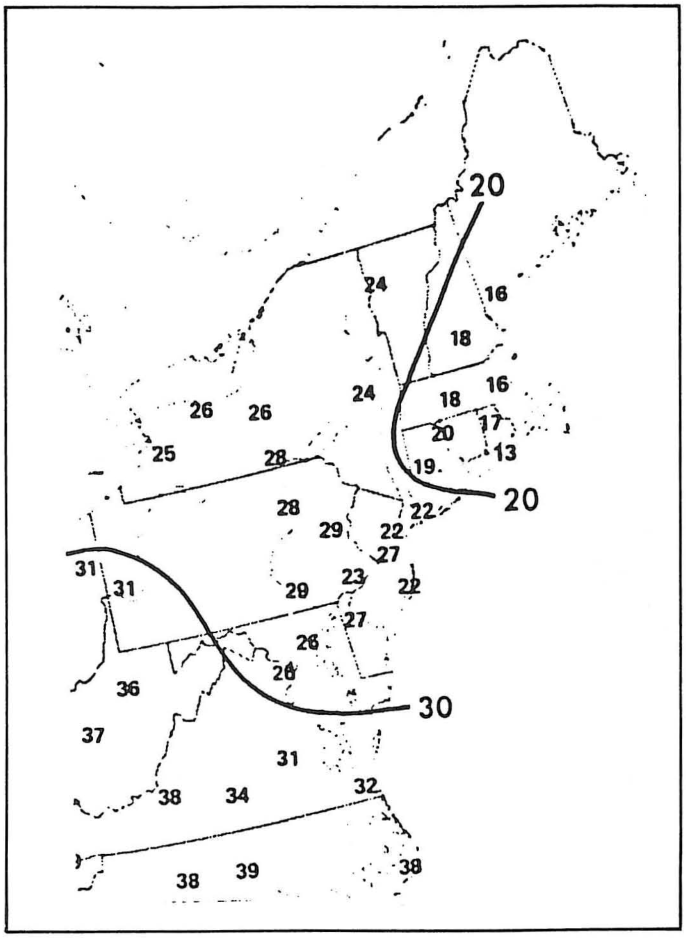

Fig. 2. Mean thunderstorm days April through September, 1951–1970 (Court and Griffiths, 3).

(20), Bradbury (21), McNulty (22), and Michaels and Gerzoff (23) applied various statistical techniques and statistical distributions to characterize thunderstorm frequency distributions.

Recently some authors, such as Easterling and Robinson (24), Robinson and Easterling (25), and Chagnon (4, 26, 27), have examined the temporal and spatial variability of thunderstorm days and thunderstorm events in the contiguous United States using surface observations as the data base.

Weather radar alone has also been used to determine the distribution of thunderstorms and can provide a more detailed thunderstorm climatology in time and space. Thunderstorm frequencies may be evaluated by examination of radar data given an appropriate echo intensity threshold at which thunder can be said to occur. In some cases the resulting frequencies have been combined with statistical techniques to predict thunderstorm occurrence. Such analyses appear in Battan (28), Donaldson (29), Owens (30), Moore et al. (31), Muench (32), Charba (33), Alaka et al. (34), Zak (35), Reap and Foster (36), Alaka et al. (37), and Falconer (38).

More recently, the establishment of the east coast lightning detection network based at the State University of New York in Albany (Orville et al. 39; Orville and Songster, 40; and Shepard, 41), and other planned or operational networks (Newhouse, 42) across the country allow for another method of determining thunderstorm frequency distributions. The relation between lightning occurrence and thunderstorm occurrence is presently being investigated in order to develop a thunderstorm climatology. As yet, the relation is not thoroughly clear, and insufficient data is available for such a climatology. The combined networks cover the majority of the United States and are available in real-time.

Several authors, including Weiss, et al. (43), have questioned the accuracy of radar-based thunder day climatologies. The use of an echo intensity threshold for identification of thunder occurrence is not rigidly defined theoretically, geographically, or seasonally. Differences in VIP intensity level measurements are routinely observed not only between radar observations taken only several seconds apart, but also between radar sites observing the same precipitation cell. The discrepancies are related to the volume "sampled" by the radar, the elevation angle of the beam, and the echo's range from the radar. Radar observations are prone to errors resulting from equipment limitations, spurious signal propagation, and site and observer biases that must be identified and accounted for. It is for these reasons that the NWS stipulates that no VIP intensity levels be assigned to echoes more than 125 n mi. (232 kilometers) from the radar site, although Charba (44) indicates that a maximum range of from 80 to 100 n mi. is probably more appropriate. Smith (45) extensively examined the sensitivity of weather radar as determined by wavelength, signal-to-noise ratio, signal processing, and equipment and design limitations. The reader is referred to this publication, as well as those by Battan (28 and 46), for a full theoretical discussion of radar principles.

2. METHODOLOGY

Local manually digitized radar (MDR) data was used to more precisely determine the thunderstorm day climatology in and around New Jersey. The methodology used here to establish a thunderstorm climatology for the New Jersey area is similar to that of Falconer (38) in which he developed an annual thunderstorm day climatology for New York using MDR data. Falconer used the fine-mesh grid of local MDR grid boxes so that mesoscale features could be identified. The local MDR grid consists of grid boxes 20 to 25 mi. on a side, four of which together compose one national MDR radar grid box (or LFM-II grid box). Based on the work of Reap and Foster (36), all calendar days when a VIP intensity level of 3 or more was observed at least once were considered to be thunderstorm days.

Reap and Foster (36) examined the relationship between radar observations and surface data for the eastern United States. The relative frequency of thunderstorm occurrence to that of no occurrence was maximized at VIP intensity levels of 3 or higher (i.e., 82 percent of all thunderstorms occurred with a VIP intensity level of 3 or more, and 80 percent of all "no thunderstorm reported" occurred with VIP intensity levels of less than 3).

MDR data from the Atlantic City, New Jersey Weather Service Office (ACY WSO), New York City, New York Weather Service Forecast Office (NYC WSFO), Harrisburg, Pennsylvania Weather Service Office (HAR WSO), and the Binghamton, New York Weather Service Office (BGM WSO) were collected for the summer months of May through September for the period 1978–1982. Each radar site is shown in Figure 3. The 5-season data set required manual viewing and interpretation from microfiche. Only summer season (May–Sept.) data was collected as the majority of thunderstorm days occur during that period (Figs. 1 and 2). In addition, observational errors specific to the winter season, such as

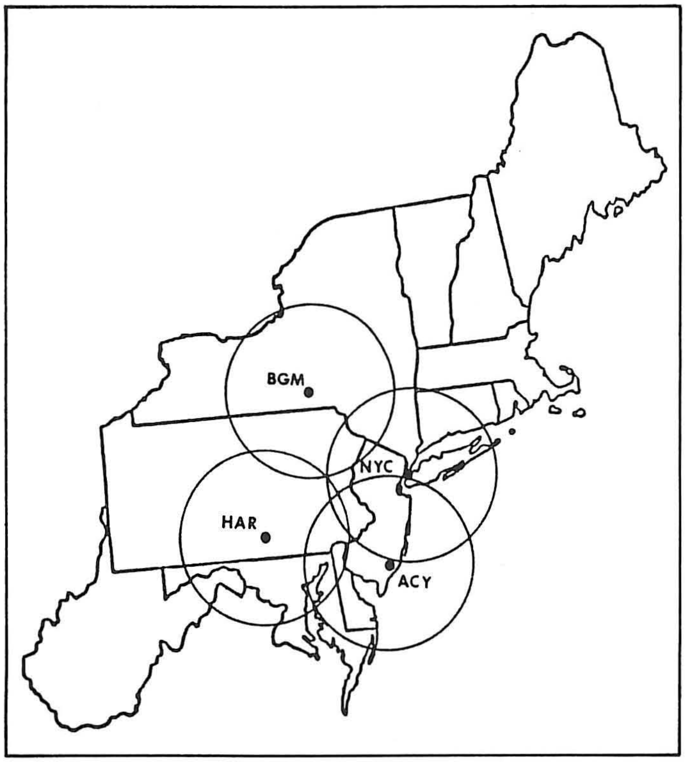

Fig. 3. Radar sites in and around the study area used in data collection. Circles indicate 100 nautical mile observational range of each radar site.

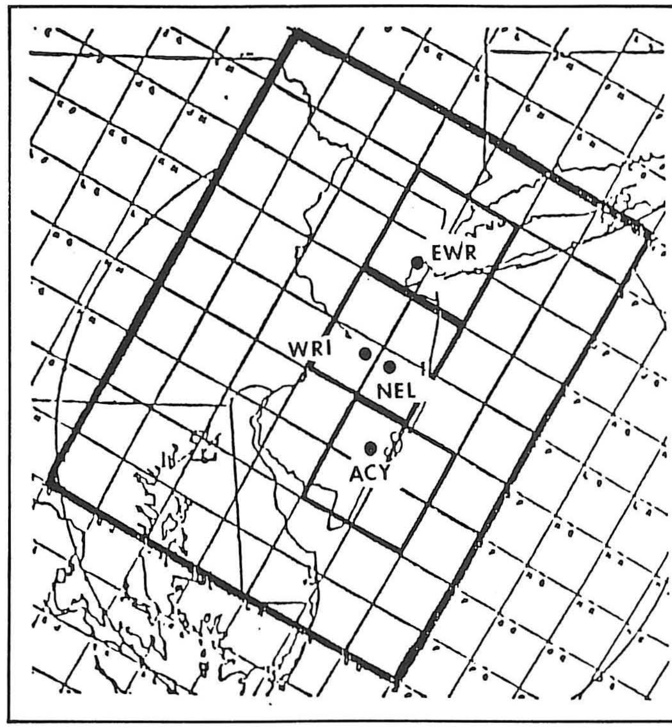

Fig. 4. Grid region and each grid box of the study area. Grid boxes used to determine VIP intensity levels most frequently associated with surface thunder observations at ACY, NEL, WRI, and EWR are shown in bold outline. Note that NEL and WRI share the same grid box set (United States Department of Commerce, 50).

mixed precipitation (which has higher reflectivity than either rain or snow separately) obfuscate the association between echo intensities and surface thunderstorm observations. Each season included 153 days of data (except 1978 where data for May were missing) and 24-hourly radar observations for each day.

A preliminary investigation was conducted to determine the relationship between VIP intensity level measurements and surface thunderstorm observations within the study region using methodology similar to that of Reap and Foster (36). With an appropriate threshold VIP intensity level established specifically for New Jersey, a thunderstorm climatology for the region was developed.

3. PROCEDURES

MDR data from the ACY WSO and hourly surface observations from Atlantic City (ACY), Lakehurst (NEL), and Wrightstown (WRI), New Jersey were collected for the periods Jun–Sept. 1978 and May–Jun 1979. The data were collected so as to include each summer month studied for at least one season.

Depending upon atmospheric conditions, the audible range of thunder is of the order of 25 km, but is highly variable. Acoustic propagation is governed by atmospheric stability, wind speed and direction, background noise, and acoustic barriers, such as hills and buildings (Fleagle and Businger, 47). Therefore, to allow for variations in the audible range of thunder, an area composed of four local MDR grid boxes was considered for each observing station as shown in Figure 4. The size of this area covered a minimum distance of 20 n mi. and a maximum distance of 31 n mi. (57 km) from the observing station when the station was assumed to be located at the juncture of the four grid boxes (although this was clearly not the case). Radar observations were examined for the period from 3 hr before to 3 hr after a surface thunder report to identify those VIP intensity levels most often associated with surface observations of thunderstorms. The 6-hr period allowed for changes in echo intensity and structure, as well as capture of fast-and slow-moving echoes.

For each surface thunderstorm observation at each station, the maximum hourly VIP intensity level that occurred over the four grid boxes during the 6-hr period was determined using the ACY WSO weather radar. The maximum VIP intensity level observed over all four grid boxes for each hour was recorded and used as an estimate of the intensity of the precipitation echo corresponding to the surface thunderstorm observation. All radar echo data were recorded so that the frequency of the "non-occurrence" of thunder reports could be evaluated with regard to VIP intensity level. When radar or hourly data were incomplete or missing during any period examined, no VIP intensity level was assigned to the thunder event, and the event was omitted.

The relative frequencies of each VIP intensity level (as determined by ACY WSO radar) for the investigation period were computed and summed over all stations (ACY WSO, NEL, and WRI) and are shown in Figure 5. The graph indicates that VIP levels of 1 and 2 accounted for three-quarters (76.1 percent) of all echo reports. However, as Table 1 indicates, VIP intensity levels of 1 and 2 each were each associated with a surface report of thunder less than 20 percent of the time. A VIP intensity level of 3 was associated with surface thunderstorm observations 37.5 percent of the time and accounted for 14.4 percent of the total number of echo

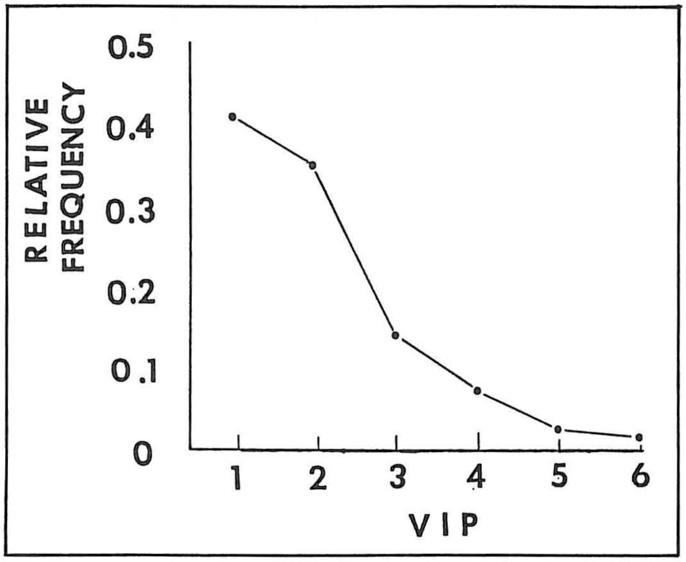

Fig. 5. Relative frequency of VIP intensity levels for ACY WSO, NEL, and WRI combined, based on MDR data from the ACY WSO.

observations. Although low, the percentage of surface thunder observations for this VIP intensity level is much higher than that for intensity levels of 1 and 2. The low percentage of higher VIP intensity levels (greater than 3) associated with surface thunderstorm reports was most likely attributable to observer biases related to thunder audibility, NWS MDR observing criteria (as outlined in *Weather Radar Observations-Parts A and B,* United States Department of Commerce, 48), and the assumption that each observing station was located at the center of its four grid box area.

When only one maximum VIP intensity level over all four grid boxes and for each 6-hour period was considered it was found that VIP intensity levels of 1 or 2 were associated with surface thunderstorm observations only 25 percent of the time. VIP intensity levels of 3 or higher were associated with surface thunder observations 75 percent of the time. The cumulative frequency of the maximum VIP intensity level observed (x), and the cumulative frequency of the maximum VIP intensity level associated with a surface thunder observation (●), appear in Figure 6. The data indicate that the majority of surface thunderstorm observations are associated with VIP intensity levels of 3 or more. Therefore, a VIP intensity level of 3 was considered to be an appropriate

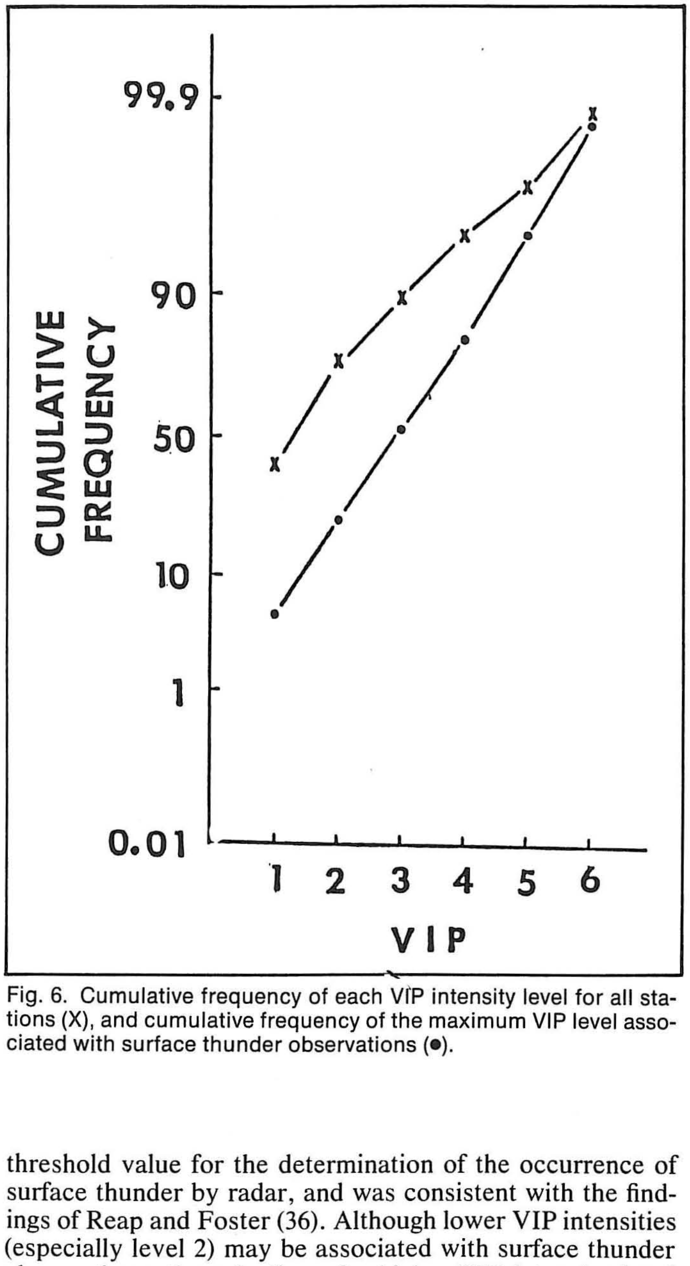

Fig. 6. Cumulative frequency of each VIP intensity level for all stations (X), and cumulative frequency of the maximum VIP level associated with surface thunder observations (●).

threshold value for the determination of the occurrence of surface thunder by radar, and was consistent with the findings of Reap and Foster (36). Although lower VIP intensities (especially level 2) may be associated with surface thunder observations, the selection of a higher VIP intensity level permits a more precise, less "noisy" presentation of thunder activity, as higher VIP intensities occur less frequently.

Table 1. Total and percent frequency of maximum VIP intensity levels observed by the ACY WSO and the total and percent frequency of maximum VIP levels associated with surface thunder reports at the ACY WSO, NEL, and WRI observing stations.

Maximum VIP Level Observed	Total Number of Occurrence of VIP Level	% Freq. of VIP Level	Total Number of Thunder Obsvd. with VIP Level	% Freq. of Thunder Obsvd. with VIP Level
1	1510	41.3	203	13.4
2	1270	34.8	244	19.2
3	525	14.4	197	37.5
4	258	7.1	139	53.9
5	74	2.0	35	47.3
6	17	0.5	6	35.3
TOTALS	3654	100.0	824	22.6

Recall also that in the above analysis each surface station was assumed to be located in the center of its four grid box area. This was clearly not the case and probably caused the maximum VIP intensity level associated with that particular report of surface thunder to be underestimated. For example, in the case of the ACY site, it was possible that if a higher VIP intensity level occurred in a grid box to the northwest (Fig. 4) it would not be reported as the maximum VIP intensity level because it was not within the four grid box area examined. This would result in an underestimate of the actual VIP intensity level encountered near or at the site and associated with surface thunder.

In a similar analysis, MDR data for the ACY WSO and NYC WSFO sites were used to evaluate the maximum VIP intensity levels associated with surface thunder observations at the Newark Weather Service Office (EWR WSO) for the same period (June–Sept. 1978 and May–June 1979). A four grid box area around the EWR WSO was selected (see Fig. 4) and a 6-hr period used. The results indicated that VIP intensity levels of 3 or more were associated with surface thunder 49 percent of the time at EWR, as recorded by the ACY WSO, and 47 percent of the time as recorded by the NYC WSFO. Therefore, ACY WSO and NYC WSFO MDR data were considered comparable in terms of their representation of the echo environment over the same region, and allowed data to be interchanged as needed for missing observations. Note that audibility appears to be a significant problem in this case (the EWR site is located at Newark International Airport) as the percent of thunderstorm observations associated with VIP intensity levels of 3 or more was only 50 percent as compared to 75 percent in the prior analysis.

With the establishment of an appropriate VIP intensity level threshold for thunderstorm occurrence, the 5-season data set was analyzed. A total of 63 local radar grid boxes in and around New Jersey were selected and formed a 9 × 7 grid (9 rows and 7 columns). The grid (shown in Fig. 4) was large enough to cover portions of New York, Connecticut, Pennsylvania, Maryland, and Delaware. Grid boxes were assigned to the radar site to which they were closest to limit the observational range to within 100 n mi. (185 km) of the radar site (as suggested by Charba, 44). More grid boxes were assigned to the ACY site as ground clutter there is less extensive than at the NYC site and therefore less signal attenuation occurs. In cases of missing data, or reports of ROBEPS (Radar Operating Below Performance Standards), backup radar data were used from the BGM WSO and the HAR WSO based on a radar site protocol developed by Croft and Shulman (49). The protocol was designed to minimize the observational range by preferentially choosing backup radar sites with regard to their proximity to the grid box of concern. All MDR data were converted to Eastern Daylight Time (EDT).

A summer season thunderstorm (intense thunderstorm) day climatology was then developed using a VIP intensity level of 3 (5) as the threshold for thunderstorm (intense thunderstorm) occurrence. When a VIP intensity level of 3 or more (5 or more) was recorded in a grid box, at least once during a 24-hour midnight-to-midnight day, a thunderstorm day (intense thunderstorm day) was said to occur (Falconer, 38). Thunderstorm and intense thunderstorm days were summed over each month for each grid box, averaged, plotted, and isoplethed. Thunderstorm and intense thunderstorm days were also analyzed for each season (1978–1982), and for four of the seasons combined. A drawback of the methodology is the inflation of grid box frequencies when an echo is located at the boundary or juncture of two or more grid boxes. The net effect is an increase in the areal coverage of higher thunder frequencies throughout the grid.

4. RESULTS

The average number of thunderstorm and intense thunderstorm days by month appear in Figures 7a–e and 8a–e and show increasing frequencies over the entire grid from May into mid-summer with a drop in frequencies in September (note that May values were computed for only four seasons). Maximum thunderstorm day frequencies were initially located over southeastern Pennsylvania (over the Philadelphia area) and southwestern New Jersey during May. The coastal and oceanic minima, indicated by the east to west gradient of activity, is likely due to the seabreeze phenomenon initiated by large land-sea temperature differences. In June, thunderstorm day frequencies were the same or higher at 52 of 63 grid boxes (83 percent) with maximum frequencies located further east, nearer the coast in Ocean County and further north in Hunterdon County. Maritime influences seem less important in June as higher frequencies extended offshore. In July 37 of 63 grid boxes (59 percent) experienced an increase in thunderstorm activity and 34 of 63 (54 percent) had an average of 6 thunderstorm days. The highest frequencies (8 days) were located over the common border of Delaware, New Jersey, and Pennsylvania. Convective activity again extended offshore, particularly along the northern New Jersey coastline, as land-sea temperature differences continued to diminish allowing cells propagating over the ocean to maintain their intensity. The average number of thunderstorm days increased only slightly from July to August with 8 or more thunderstorm days occurring over northeastern New Jersey (Essex, Hudson, Middlesex, and Union) and southwestern New Jersey. A subtle change was observed in the spatial distribution from July to August as the axis of maximum frequencies moved slightly to the east. For example, 25 of the 27 eastern most grid boxes (93 percent) had higher frequencies in August than in July while 18 of the 27 westernmost (67 percent) experienced lower frequencies. Also, average thunderstorm days over the ocean peaked in August (4 days or more). The average number of thunderstorm days decreased from August to September in every grid box. Highest frequencies were located over south central New Jersey (Burlington, Cumberland, and Ocean counties) and over the ocean waters. Lowest frequencies were observed at each grid corner and were partially a function of radar range as the physical limitations of the radar beam were approached or exceeded. The distribution and frequencies for May and September were similar, except that maximum thunderstorm day frequencies were located closer to the coast and were higher over the ocean in September than in May.

Average intense thunderstorm days by month (Fig. 8a–e) showed distribution patterns similar to those of thunderstorms. In May, June, and September approximately 1 of every 5 thunderstorm days could be considered to be intense. In July and August nearly half of all thunderstorm days could be considered to be intense. Of particular importance is the shift of maximum intense thunderstorm frequencies from northwestern New Jersey southeastward to south central New Jersey with time (from July to August) as it indicates a significant change in the synoptic pattern during that period.

Thunderstorm days were also examined for each season (not shown). We found that thunderstorm days were more

Fig. 7. Average number of thunderstorm days by month: (a) May, (b) June, (c) July, (d) August, and (e) September.

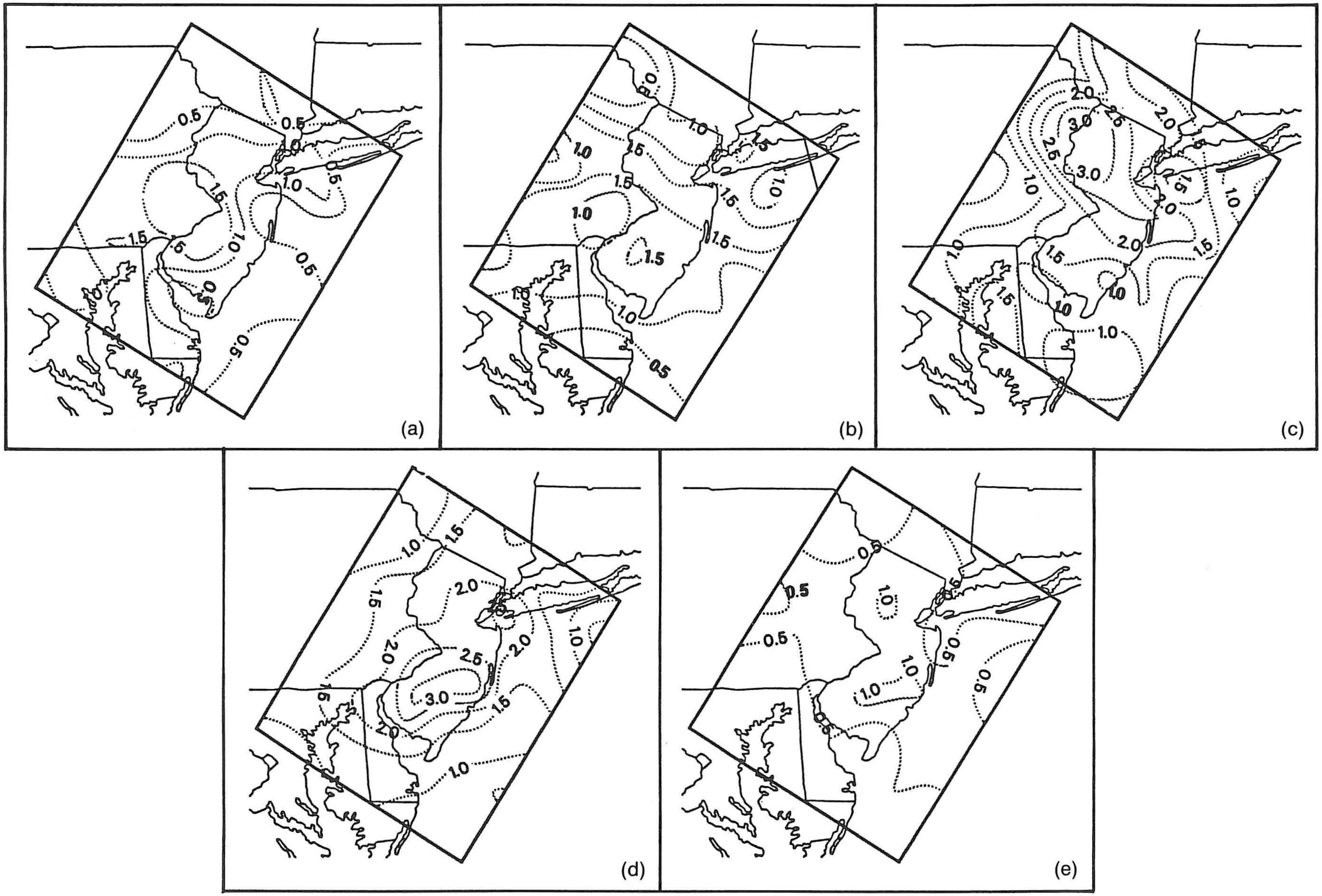

Fig. 8. Average number of intense thunderstorm days by month: (a) May, (b) June, (c) July, (d) August, and (e) September.

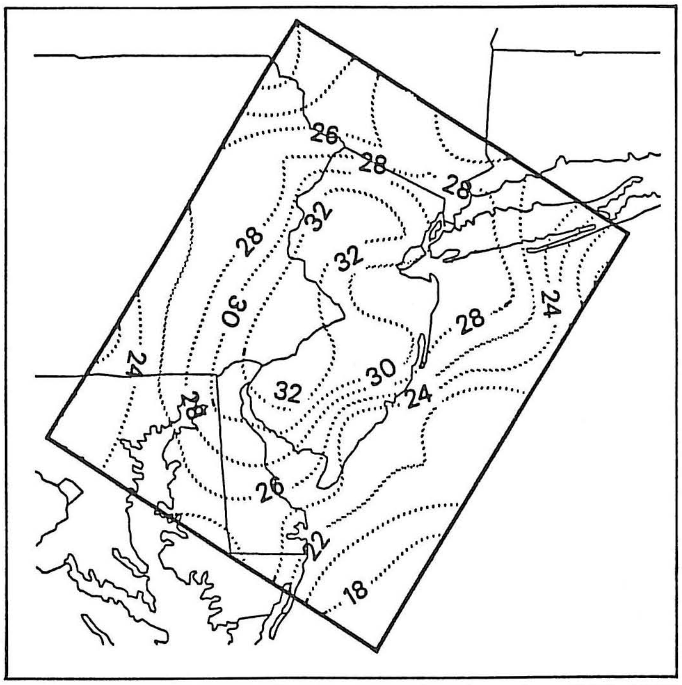

Fig. 9. Seasonal average thunderstorm days based on 1979–1982 seasons.

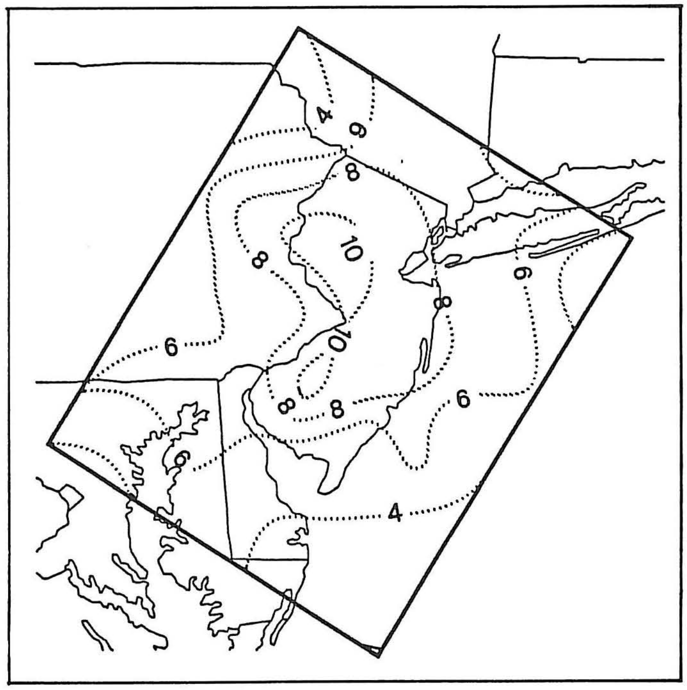

Fig. 10. Seasonal average intense thunderstorm days based on 1979–1982 seasons.

frequent and extensive in 1979 than during any other year with highest frequencies (45 days) over southwestern New Jersey. The lowest seasonal total of thunderstorm days (omitting 1978 as data for May were missing) occured in 1982 with highest frequencies (25 days) over southwestern New Jersey and southeastern Pennsylvania. The distribution of thunderstorm days varied substantially from year to year with maximum frequencies over southwestern New Jersey in 1978, 1979, and 1982, and eastern Pennsylvania and northwestern New Jersey in 1980 and 1981. The annual frequencies and distribution of thunderstorm days were likely determined by each year's prevailing synoptic pattern as put forth by Michaels and Gerzoff (23) and Chagnon (26, 27).

Average seasonal thunderstorm day frequencies were determined using 4 complete years of MDR data (1979–1982). Although this length of record is rather short for a "standard" thunderstorm climatology (e.g., one derived from a 15 or 30 year data set), it is nonetheless a useful short-term study of the thunderstorm distribution. Maximum thunderstorm day frequencies (shown in Fig. 9) were located over both southwestern and northern New Jersey and southeastern Pennsylvania. The state experienced between 28 and 32 thunderstorm days on average during the summer season (May–Sept.). As previously discussed, conventional thunderstorm day climatologies for the same area indicate an average of 30 to 40 thunderstorm days per year with 20 to 25 days in the northern half of the grid and 25 to 30 in the southern half of the grid (Court and Griffiths, 3, see Figs. 1 and 2). Note that despite some similarity, the precision of the radar-based climatology is much better as it depicts the interior maximum and coastal minimum in thunderstorm activity much more clearly. Further, conventional thunderstorm day frequencies for New York City and Philadelphia are 5 to 10 days lower than the radar-derived frequencies. This is most likely due to the audibility and observability problems which prevail in urban areas, and is consistent with Falconer's work (38). Differences between conventional and radar-derived frequencies were very small for central New Jersey and in east central Pennsylvania.

Average seasonal intense thunderstorm day frequencies (Fig. 10) were distributed similarly to thunderstorm days with maximum activity in north central and western portions of New Jersey (Burlington, Camden, Hunterdon, Mercer, and Somerset counties). On average, much of the state experiences 1 intense thunderstorm day for every 3 thunderstorm days.

5. CONCLUSIONS

This study defined a mesoscale thunderstorm and intense thunderstorm day climatology for New Jersey and the surrounding area based on weather radar observations. The highest average frequencies of thunderstorm and intense thunderstorm activity generally occurred over southeastern Pennsylvania, southwestern New Jersey, and occasionally northern New Jersey, but varied by month. This was related to changes in land-sea temperature differences, variations in day length, and changes in the synoptic pattern. Of particular note was the shift of maximum severe thunderstorm activity southeastward from July to August. Thunderstorm activity was least frequent over the ocean throughout the season with a peak in August.

When thunderstorm day totals were averaged over 4 summer seasons the distribution was somewhat similar to conventional climatologies, but contained considerably more detail and showed higher frequencies in urban areas. The results, although from a limited sample, provide a fairly reliable estimate (accounting for radar observational errors) of the thunderstorm climatology for New Jersey and the surrounding area. Operationally, the information can be used to assess climatological probabilities of thunderstorm and intense thunderstorm events. A breakdown of the distribution by synoptic type, and the use of a larger data set, would be desirable to assist the operational meteorologist in prediction of convective activity during the summer season. With the advent of the finer resolution afforded by the NEXRAD system and the east coast lightning detection network, an even more detailed climatology could be developed in the future. This climatological information would be useful in the development of regionalized algorithms necessary at each Doppler radar site.

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NOTES & REFERENCES

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