Regional Snowfall Intensity and the Great Lakes Anomaly

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ABSTRACT

Snowfall intensity widely varies spatially and temporally within individual storms and within regions. However, regional snowfall intensity has not been mapped or characterized systematically as a climatic phenomenon. Snowfall intensity was compiled and mapped over the continental United States from four years of National Weather Service 6-hour synoptic reports to show general patterns. Intensities are generally greatest in both eastern and western mountain areas and along the East Coast, and are generally lowest in the northern Plains and Great Lakes. The low Great Lakes intensities were unexpected because of the frequent lake-effect storms along their southeast shores. Methodological and meteorological reasons for this pattern are discussed, and methods of resolving whether the Great Lakes patterns are true are suggested.

INTRODUCTION

Snowfall intensity widely varies spatially and temporally within individual storms and within regions. Intense snowfall seriously impacts activities relying upon transmission of electromagnetic radiation through the atmosphere. Heavy intensity snowfall reduces visibility and causes transportation system delays and accidents. If snows are wet and fall rates are heavy, they can reduce transmission efficiency of communications systems. Heavy snowfall rates also reduce the effectiveness of millimeter-wave, infrared and visible target acquisition systems used by the military. Strategic planners, weapons system developers, and battlefield commanders require mapped information on the spatial and temporal potential for encountering intense snowfall. Such maps are also useful for locating facilities such as airports and highways that rely upon visibility for their operation.

Estimates of snowfall intensity made by National Weather Service observers are based on visibility and spot radar estimates (Wasserman and Monte, 1972; Boucher and Wieler, 1985). Snowfall intensity, therefore, is not measured directly in a strict systematic manner because visibility is treated as an analogue of snowfall intensity. Perhaps because of this lack of systematic measurement and the subjectivity of visual estimates, snowfall intensity has not been mapped for large regions. Previous snowfall climatologies include only maps of mean annual snowfall, persistence of snowfall, depth of snow on the ground and snow density (Bates and King, 1966; Foster and Davy, 1988; Bilello, 1967, 1984; Ryerson and Bates, 1989).

Snowfall intensity can be measured with automatic weighing precipitation gauges, which record the water equivalent of snowfall continuously to an accuracy of 0.1 mm. Weighing gauges are "operational" instruments and the data are archived by National Weather Service offices into snowfall amounts in discrete time periods. Various research instruments such as weather radars, Airborne-Snow Concentration Measurement Equipment (ASCME) (Lacombe, 1983; Stallabrass, 1985) and optical snow gauges (Koh, 1987) can also be used to obtain snowfall intensities. However, these instruments are currently research tools only and have not heretofore provided data of sufficient temporal and geographic breadth for mapping. Some of these research instruments could be made operational and might be useful substitutes for discontinued snow surveys and for describing spatial and temporal snowfall rate patterns.

Snowfall intensity can be calculated from archived measurements of snowfall depth at regular intervals. Records of snowfall amounts sufficient for generalized regional snowfall intensity mapping are available from the National Climate Data Center, the Canadian Atmospheric Environment Service, the World Meteorological Organization, and other national and military weather services.

The purpose of this paper is to present maps of generalized continental United States snowfall intensities from archived 6-hour synoptic period snowfall depth data. In addition, one apparent snowfall intensity anomaly, the Great Lakes lake-effect area, will be discussed. Regional snowfall intensity is characterized with regard to topographic patterns and the characteristics of lake-effect storms.

BACKGROUND

Bates and King (1986) have compared storm snowfall intensity measured by four methods: hourly snowfall depth, hourly snowfall water equivalent, airborne snowmass concentration as measured with an ASCME (Lacombe, 1983), and intensity as measured by the National Weather Service using visibility. All measurements were integrated over one-hour time periods. Measurements by the four methods were made during the SNOW experiments at Camp Ethan Allen, Vermont, and Camp Grayling, Michigan.

TABLE 1. Snowfall Intensity Rate System (from Bates and King, 1986).

	Accumulation Rate		Suspended Snow	
Snowfall intensity	Snowfall (mm/hr)	Water equivalent (mm/hr)	Airborne snow concentration (g/m^3)	Visibility by eye (km)
Light (s-)	< 10	< 1	< 0.3	> 1
Moderate (s)	10–20	1–2	0.3-0.7	0.5 and < 1
Heavy (+)	> 20	> 2	> 0.7	< 0.5

Intensities were categorized into equivalent classes of light, moderate, and heavy snowfall (Table 1). Frequencies were then determined from synoptic analysis for each intensity class. In general, the National Weather Service visibility method suggested more frequent heavy intensity snows than did the other methods. This may be because fog or cloud droplet riming, which frequently accompanies heavy snowfall and reduced visibilities, gives the impression that the snowfall is heavy when it may be moderate or light. Any natural or man-made obscurant combined with snowfall will also cause the visibility method to give the impression of greater than true snowfall rates. Use of the visibility method can, therefore, give the false impression of greater snowfall intensities than actually exist. Bates and King (1986) and Bates (1983) recommend mapping snowfall intensity from snowfall water equivalent or snowfall depth measurements.

SNOWFALL INTENSITY MAPPING

Data for mapping snowfall intensity were summarized from TD-3290 *Summary Observation* records from the National Climate Data Center in Asheville, North Carolina. The *Summary Observations* contain 6-hour synoptic period records for maximum and minimum air temperature, precipitation (rainfall and snowfall water equivalent), total snowfall catch over the 6-hour period, and depth of snow on the ground. Total 6-hour snowfall catch data were obtained from the tapes for 286 first-order weather stations in the United States (including Alaska). Data were available on tape (when acquired in the summer of 1988) for only four years, 1984 through 1987. Because of the large volume of data, snowfall data only for the months of November through April were acquired for mapping.

Maps were drafted using snowfall data from 161 of the 286 National Weather Service stations. Some stations did not have complete four-year records, some stations recorded no snow, and some stations were outside the continental United States. Because of these problems, snowfall intensity was not mapped for areas south of 35° north latitude. Synoptic periods recording less than 1 mm of snowfall were not counted as snowfall periods.

Mapping snowfall intensity from the 6-hour records of snowfall catch presents problems of time resolution. Storms significantly shorter than 6 hours in length will have computed intensities that are significantly lower than those of longer storms. For example, a 1-hour-long storm that accumulates 7.6 cm of snow would have the same computed intensity as a 5-hour storm depositing the same amount of snow. All storms less than 6 hours in length will have downwardly biased intensities. Time resolution could be improved with hourly reports of precipitation type, but they could not be incorporated into this report.

MAP ANALYSIS

Snowfall Intensity

Several distinct patterns are apparent on the mean annual snowfall intensity map (Fig. 1). Highest intensity snowfalls occur in the Sierra Nevada, the northern Cascades, the southern Appalachians, and coastal New England, as expected, because of their orographic and/or coastal locations. Northern Maine experiences high intensities because of its northern coastal location along the prevailing winter storm track, and because intense low pressure systems frequently stall in this area, producing prolonged storms advecting abundant moisture from the Atlantic Ocean. The slight mid-Mississippi Valley rise also may be due to the prevailing winter storm track, especially where cyclogenesis is frequent. In addition, this southern location is near the freeze/thaw transition zone much of the winter, encouraging high absolute humidities that produce high intensity snowfalls with the upper air support provided by the Polar Front.

Low intensity snows are found in the northern Plains and Great Lakes region. Low intensities in the northern Plains could be expected because of the dry, polar continental air masses that dominate the winter. However, the Great Lakes region, especially areas to the south and east of the lakes, are noted for intense lake-effect storms. The short 4-year record undoubtedly does not represent long-term trends well, especially for extreme events. However, the lake-effect storms, because they are often short in length (Eichenlaub, 1979), may be mapped as

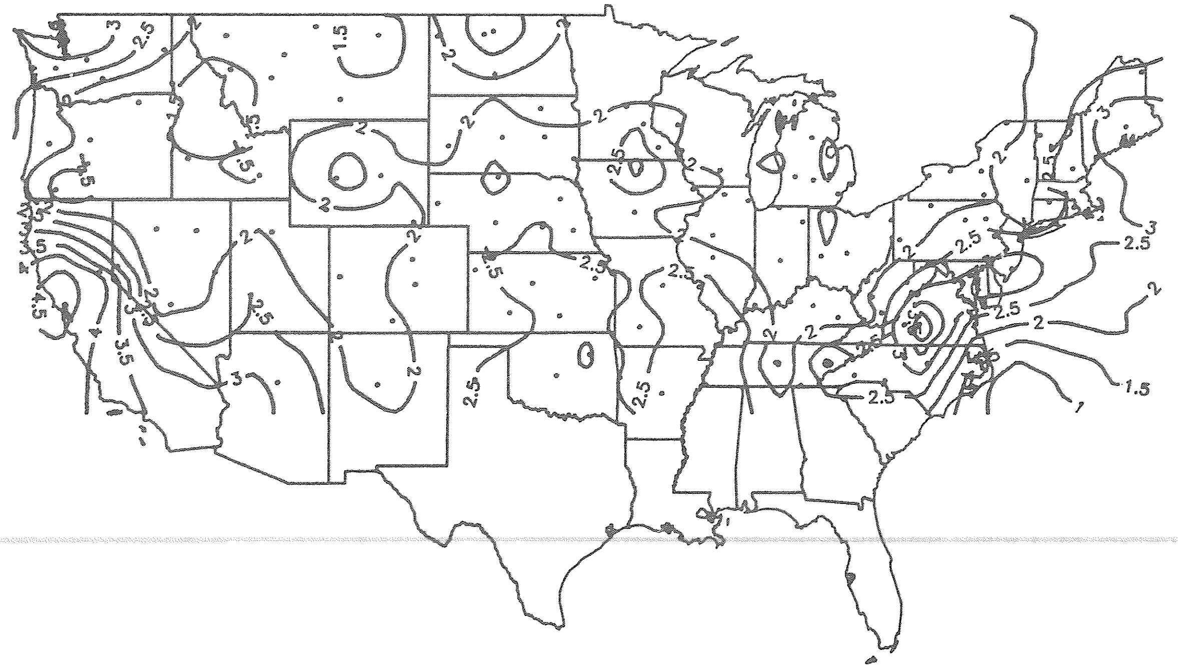

FIGURE 1. Generalized patterns of mean annual snowfall intensity (cm/6 hr, 1984–1987).

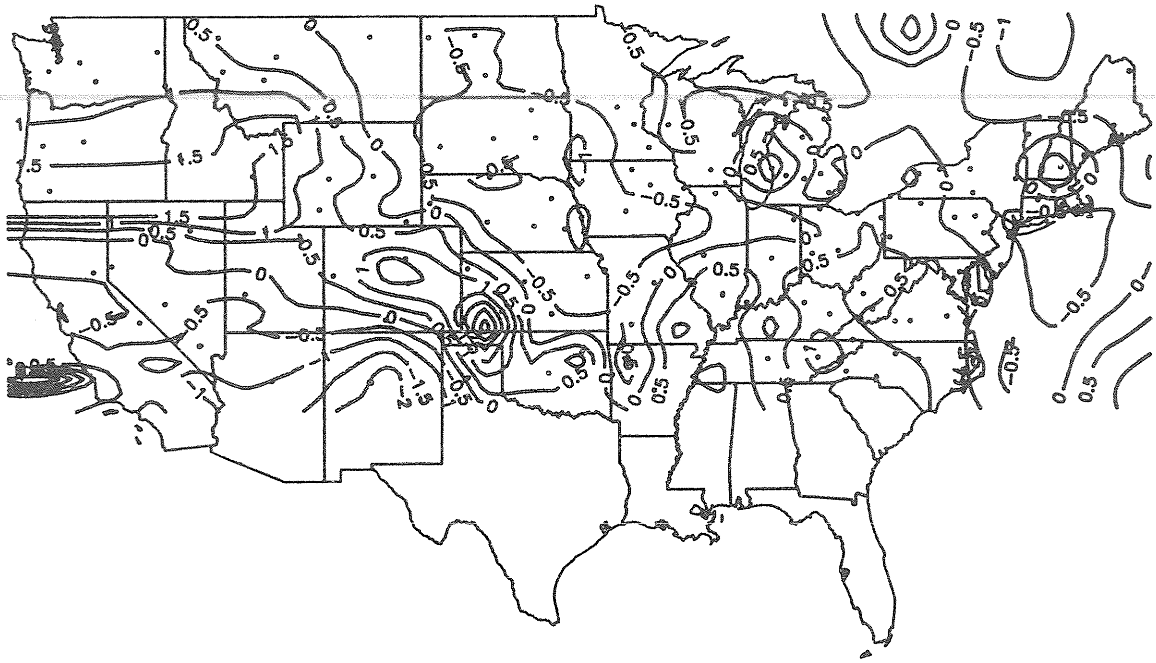

FIGURE 2. Standard deviations of mean annual snowfall intensity (cm/6 hr, 1984–1987). + Above mean, – Below mean.

too low in intensity because of their short duration. The general pattern suggests that light snowfall intensities are found in the most continental areas, with intensities generally increasing near the West Coast, in the southern tier states, and in New England.

The generally low intensity snowfalls in the Great Lakes snowbelts are noteworthy. To determine how anomalous the lake-effect intensities are with regard to intensities elsewhere, standard deviations were mapped (Fig. 2). Standard deviations are near zero in the eastern Great Lakes, indicating that intensities are near the continental mean, and are neither extremely high or low. The only significant deviation from zero in the Great Lakes area is on the eastern shore of Lake Michigan. The 0.5 standard deviation indicates that intensities are slightly higher than the national mean in this small lake-effect area near Muskegon.

Lake effect storms are very seasonal, with most occurring before the Great Lakes freeze over (Eichenlaub, 1979). Fewer lake-effect storms occur after January, especially to the lee of shallow Lake Erie, which freezes earlier and more completely than the other lakes. Maps were produced of snowfall intensity in early winter (November through January) and late winter (February through April) to determine how intensity varied with time.

Snowfall intensity in the Great Lakes region changes little from early to late winter, with mean intensities remaining near 2 cm per 6 hours for the entire year (Fig. 3 and 4). This is true although the length of storms may change seasonally. The predominant types of storms producing snow in lake-effect areas change from short-duration, localized convection phenomena in early winter to large, mid-latitude wave cyclones later in the winter. Residuals of snowstorm intensity between early and late winter indicate that there is little change in Great Lakes region snowfall intensity throughout the winter (Fig. 5).

Standard deviations indicate that early and late winter snowfall intensities in the lake-effect areas are near the national mean or slightly below during both seasons (Fig. 5 and 6). Standard deviations vary from zero to –1.0. However, early winter standard deviations show that intensities are not as depressed in two specific known lake-effect areas: from Gary, Indiana, to Traverse City, Michigan, and from Erie, Pennsylvania, to Watertown, New York (Eichenlaub, 1979). Standard deviations are between only zero and –0.5 in these areas, rather than between –0.5 and –1.0 in the remainder of the Great Lakes. These standard deviations, though low compared to those of the entire nation, suggest that lake-effect areas do have enhanced localized intensities, though overall intensities are somewhat depressed.

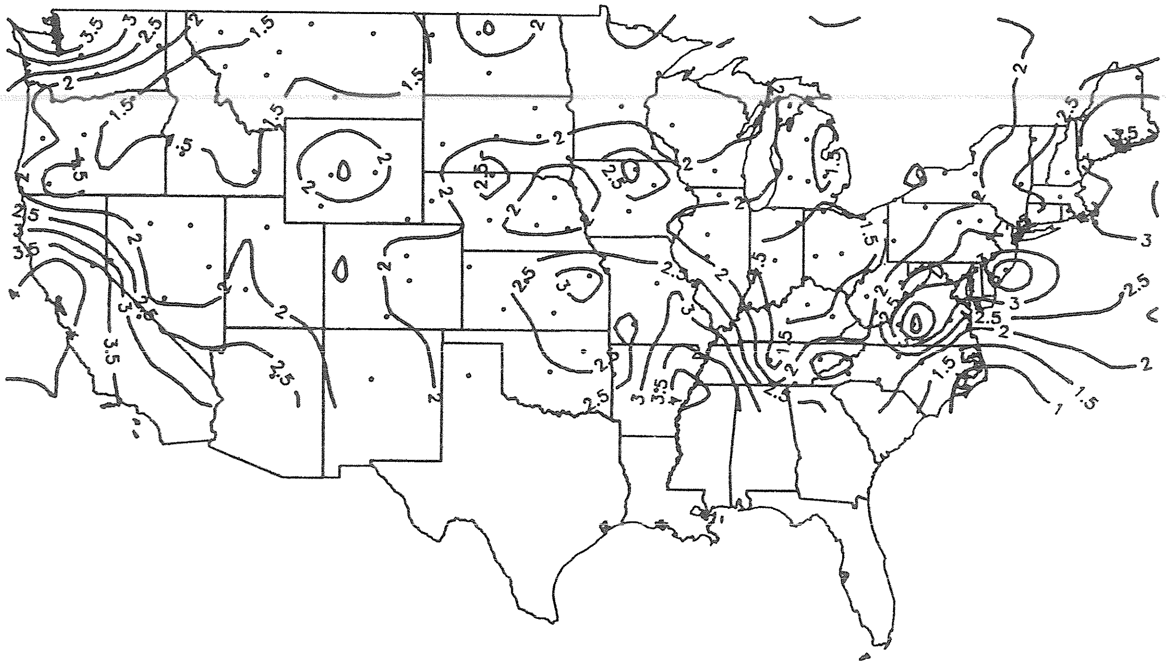

FIGURE 3. Generalized patterns of early winter snowfall intensity (cm/6 hr, 1984–1987).

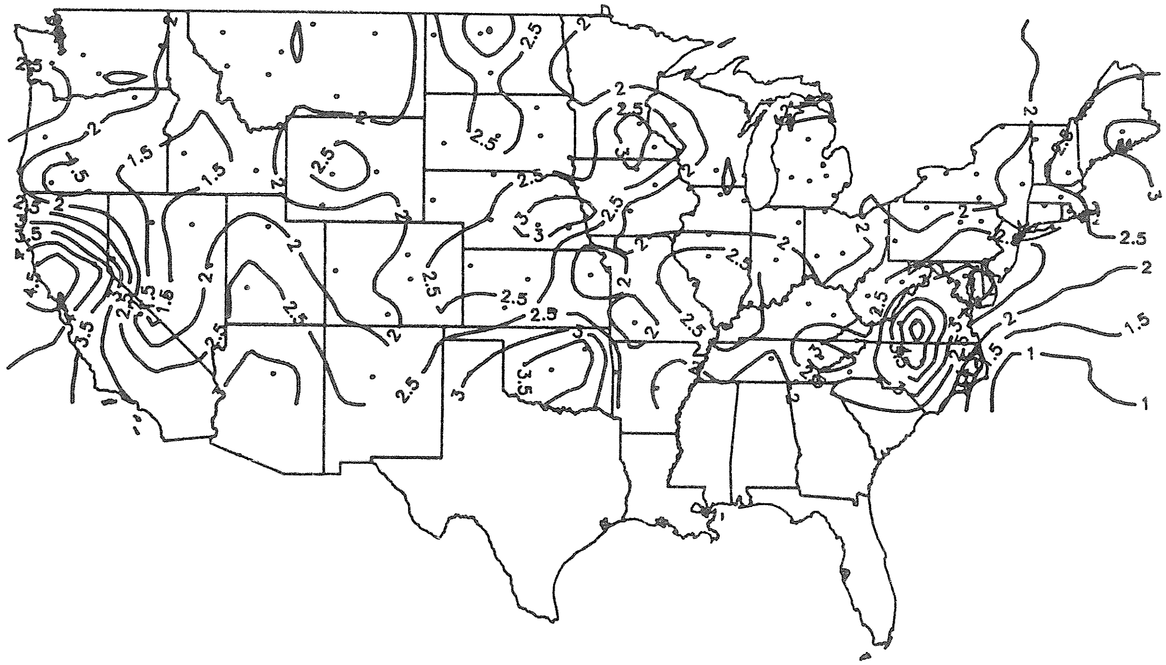

FIGURE 4. Generalized patterns of late winter snowfall intensity (cm/6 hr, 1984–1987).

Late winter, on the other hand, shows slightly depressed standard deviations and thus intensities in lake-effect areas compared to the remainder of the Great Lakes area (Fig. 7). This may be due to greater lake ice cover at this time.

Snowstorm Length

Lake-effect storms are noteworthy for being short, intense squalls with low visibility (Eichenlaub, 1979). Storm length, the mean number of consecutive 6-hour synoptic periods receiving snow at a station, were

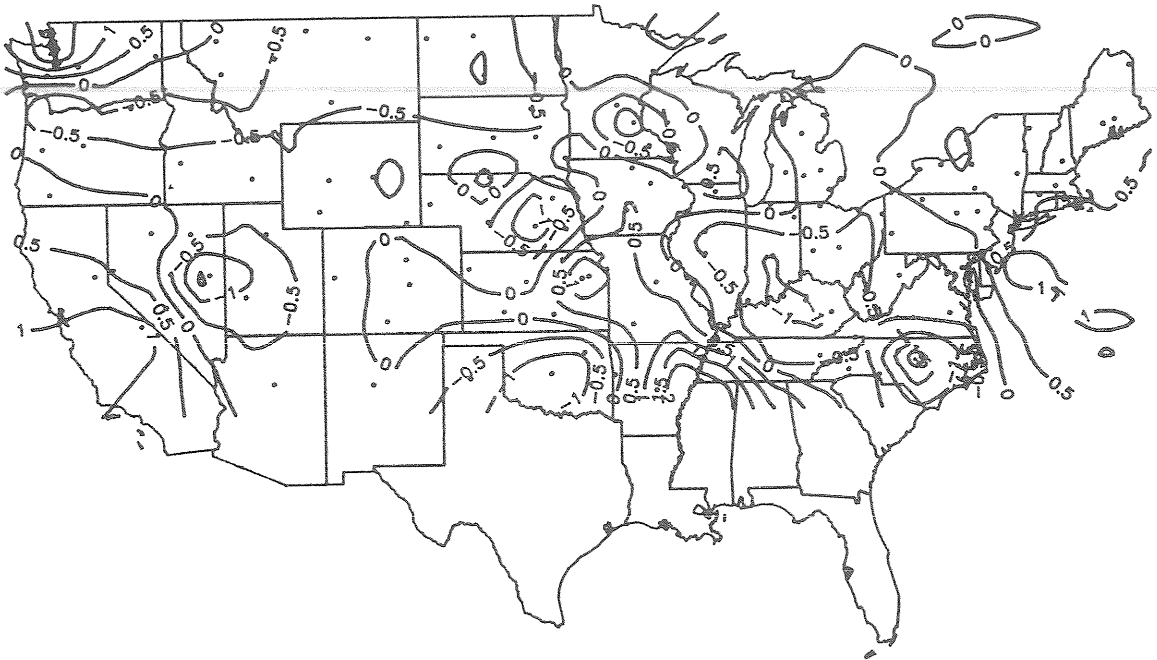

FIGURE 5. Residuals of snowfall intensity (cm/6 hr), early (November–January) to late (February–April) winter (1984–1987). + Early winter larger, – Late winter larger.

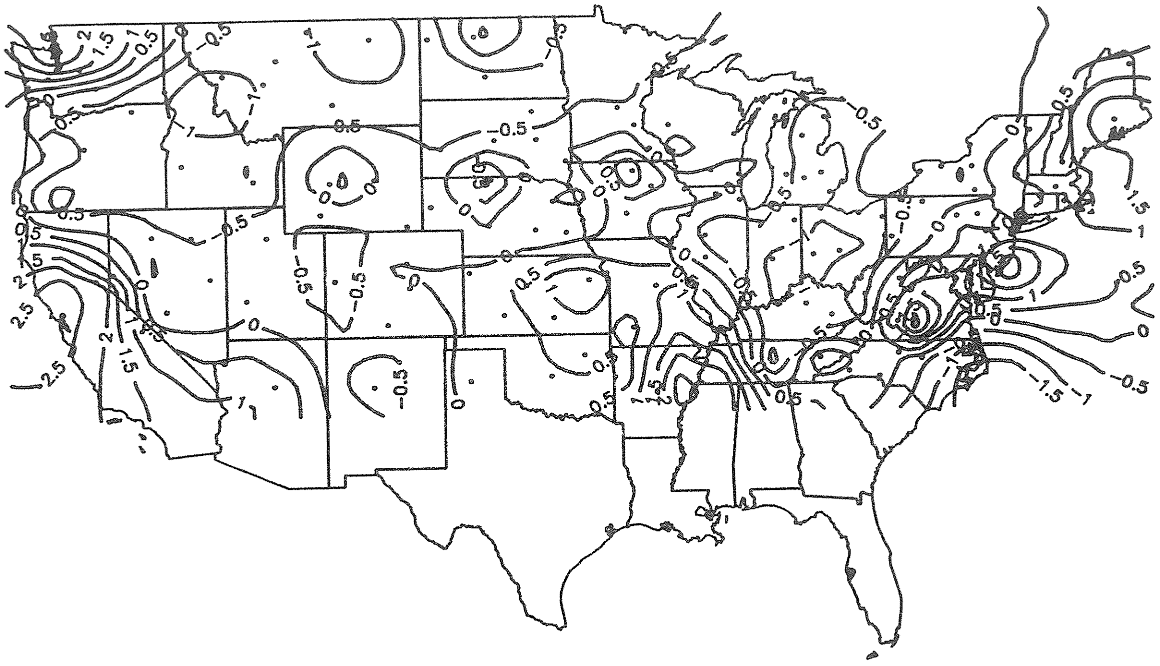

FIGURE 6. Generalized patterns of early winter snowfall intensity standard deviation (cm/6 hr, 1984–1987). + Above mean, – Below mean.

mapped to determine how long snow periods last regionally. In general, the Great Lakes snowbelt areas should record shorter storms, especially early in the winter, if most snowfall is lake-effect in origin. Areas dominated by large-scale cyclonic systems should record longer snowfall periods or more consecutive 6-hour synoptic periods with snow.

Typically, the Great Lakes experience the longest snowstorms of any part of the conterminous United States except for northern Wyoming and southern Montana, which are similar (Fig. 8 and 9). The Great Lakes lake-ef-

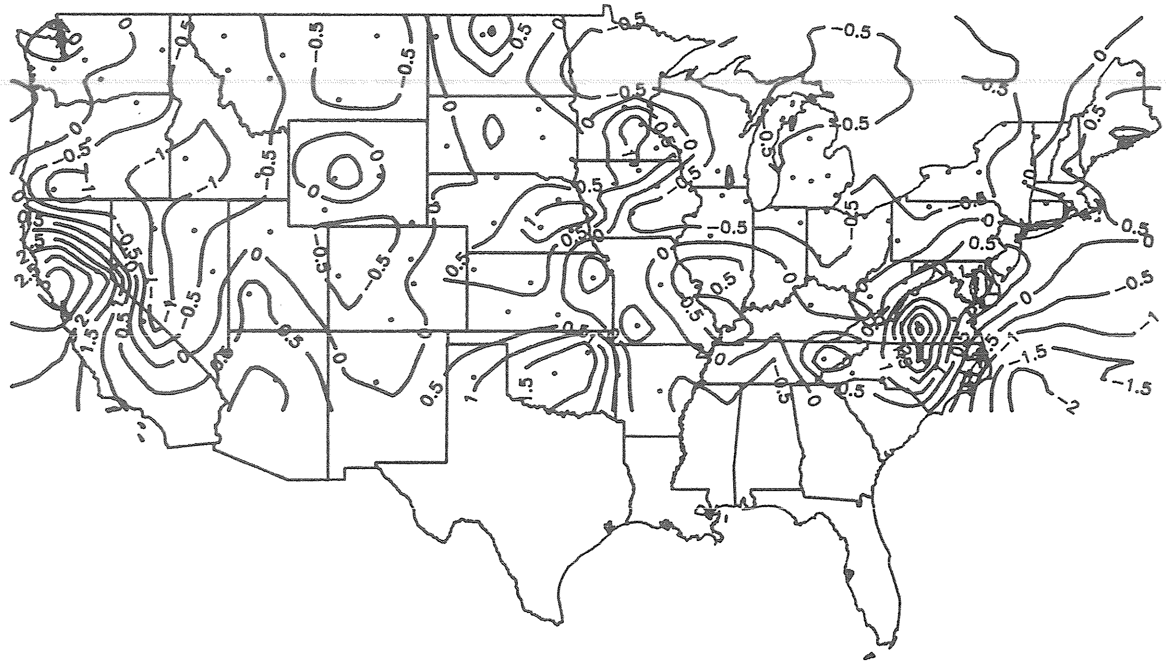

FIGURE 7. Generalized patterns of late winter snowfall intensity standard deviation (cm/6 hr, 1984–1987).
+ Above mean, – Below mean.

fect areas experience storms averaging about 2.5 synoptic periods in length. As with standard deviations of early winter intensities, storms are longest in specific known lake-effect areas from Gary, Indiana, to Traverse City, Michigan, and from Cleveland, Ohio, to Watertown, New York.

There are several possible reasons for the longer mapped storm periods in the lake-effect areas. Since individual lake-effect storms are generally fairly short, several storms occurring in unison due to persistent winds over a long lake fetch could give the appearance of long storms. The long snow periods, however, are more likely a result of the unique synoptic conditions. Wave cyclones traversing the Great Lakes, with their attendant warm and cold fronts, frequently bring significant snows to the area. However, once the cold fronts pass, cold, dry air from following high pressure enters from the west or northwest. With a long fetch over the warm lakes, the cold continental air heats, humidifies, and becomes unstable, creating snow squalls on the lee sides of the lakes. Since these lake-effect snows usually follow the cyclonic snowfall, there is usually little or no break in the snowfall as mechanisms pass from cyclonic to local convective in nature. These combined mechanisms could easily produce snowfalls 12–15 hours in length. When squalls are very active, there may be less than 12 hours separating cyclonic and lake-effect snow systems (Hill, 1971).

Late winter storm lengths are usually similar to those of the early winter in the Great Lakes (Fig. 9 and 10). However, lake-effect areas are no longer enhanced in length except in the Rochester, Syracuse, and Watertown, New York, area. This localized late-winter length enhancement is probably because Lake Ontario is deep and does not completely freeze over, producing lake-effect storms the entire winter (Eichenlaub, 1971).

Snowfall Days

The largest number of days with synoptic periods of snowfall amounts greater than 1 mm do occur in the Great Lakes (Fig. 11). Averaging 40 to 70 days annually, the number of snow days in the Great Lakes snowbelt areas conform more to expected patterns than do the snowfall intensity maps. The high number of snowfall days in the Great Lakes is due to the many short duration lake-effect snowstorms in the region in addition to the wave cyclones traversing the region. Days with snow are high in the Adirondacks, but begin to decrease in the Appalachians. Numbers of snow days are also not as great in the Rockies, the Sierra Nevadas, and the Cascades

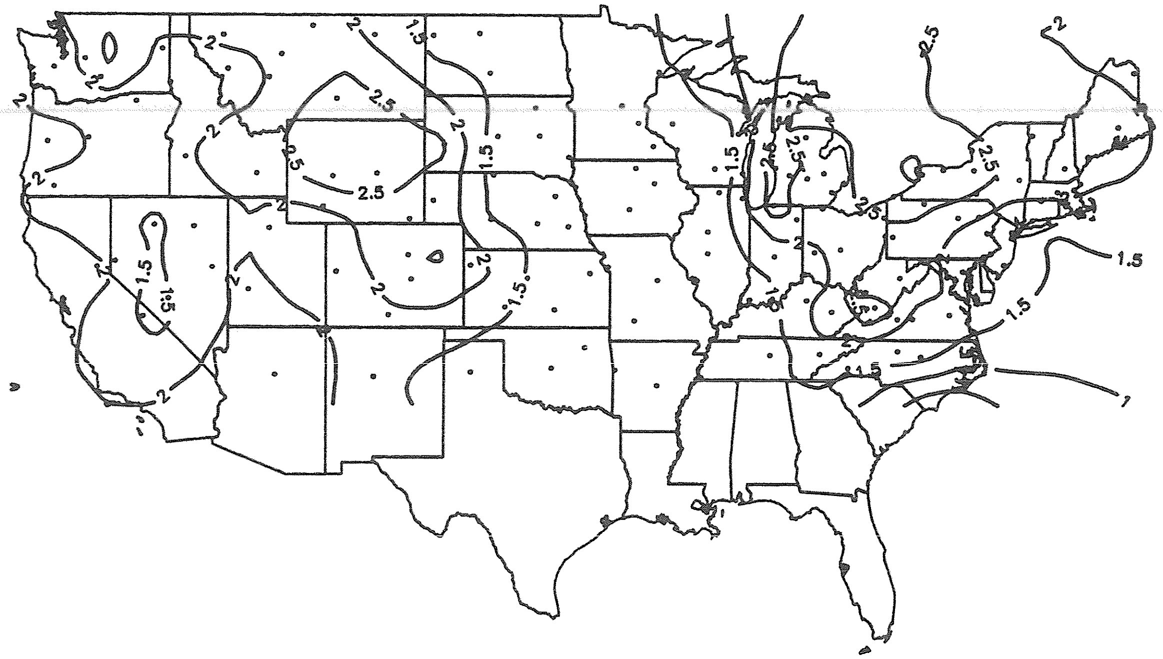

FIGURE 8. Early winter storm length in synoptic periods (1984–1987).

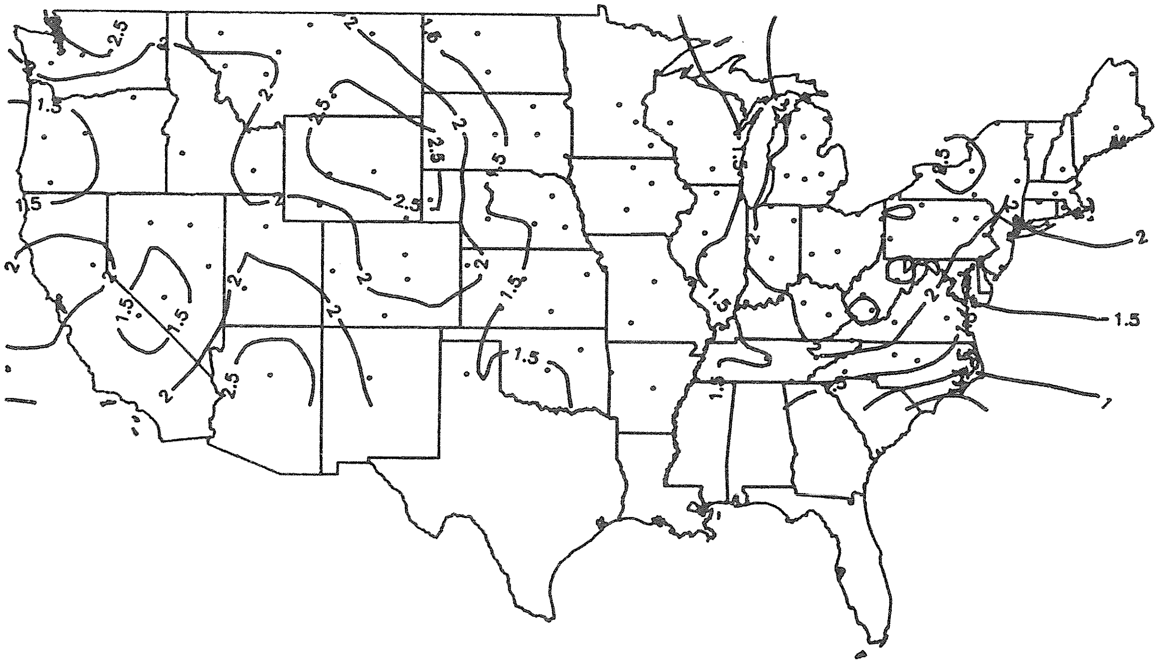

FIGURE 9. Late winter storm length in synoptic periods (1984–1987).

as in the Great Lakes. The western mountains experience fewer days with snow because the storms are cyclonic in origin and do not result from frequent, short-lived, shallow convection systems as do the systems along the Great Lakes. The effects of dry continental air to the north, and warm air to the south, contribute to depressed values in the Great Plains and lower Mississippi Valley.

DISCUSSION

The maps, despite the short period of record, indicate that mountainous regions tend to exhibit higher snowfall intensities, as expected. The Great Plains, dominated by dry, continental polar air for most of the winter,

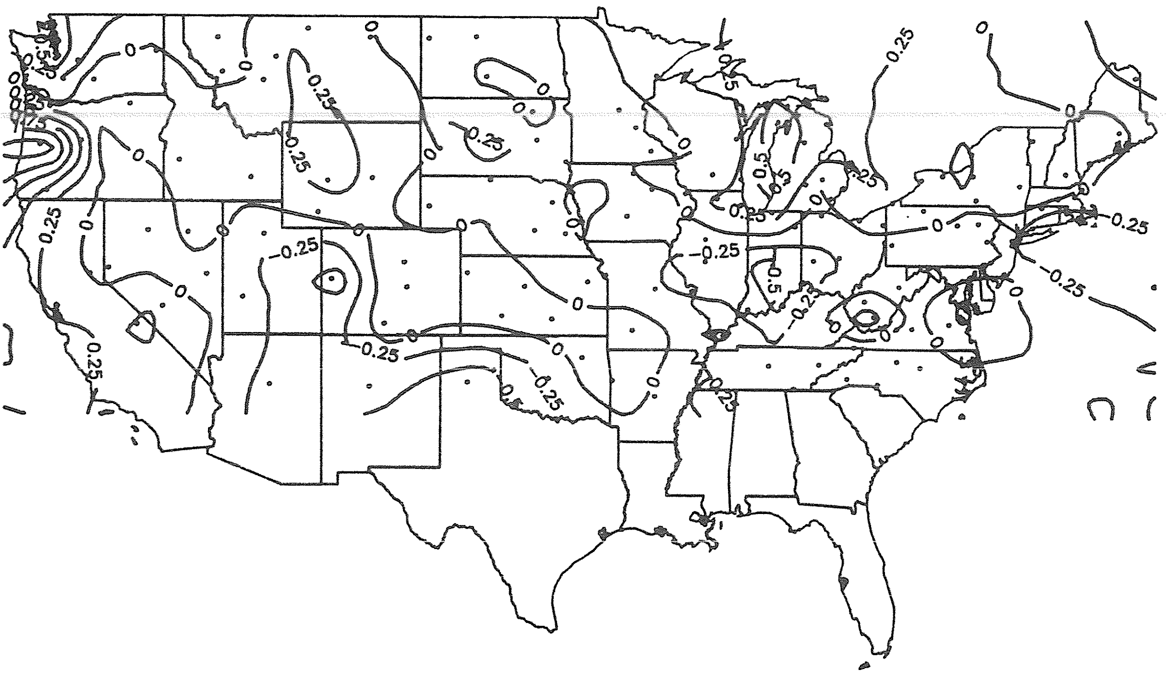

FIGURE 10. Residuals of snowstorm length, early (November–January) to late (February–April) winter (1984–1987). + Early winter longer, – Late winter longer.

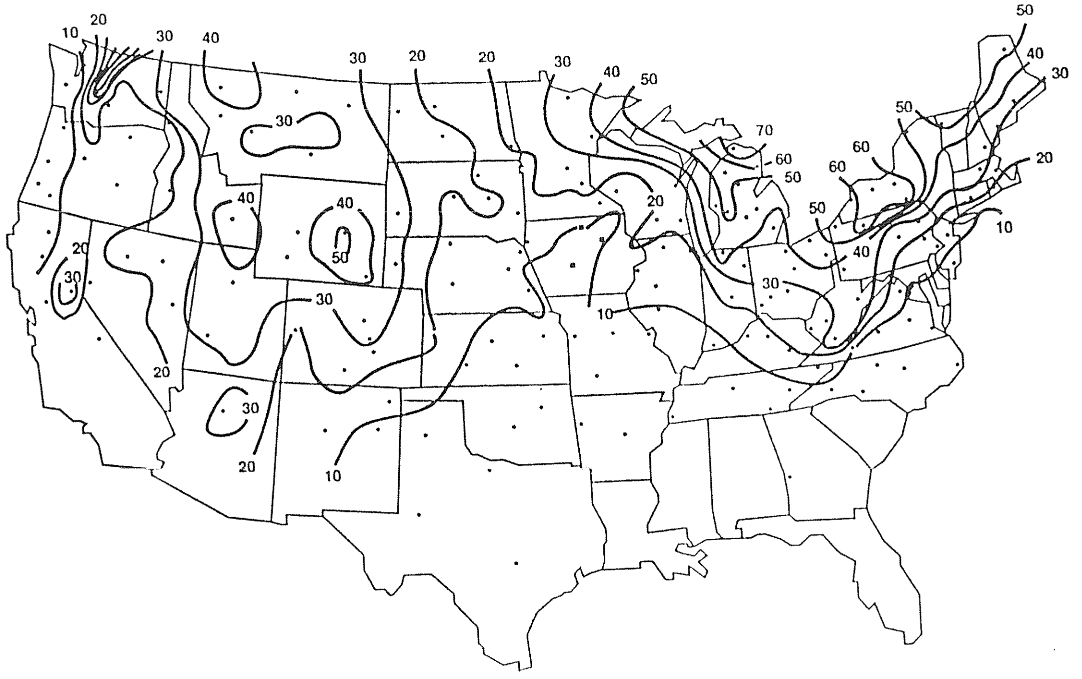

FIGURE 11. Mean annual days with snowfall for 6-hr period with more than 1 mm of snow (1984–1987).

have generally lower snowfall intensities. Coastal regions, and some southern areas, show somewhat higher intensities because of the warmer conditions and higher moisture contents that accompany snowfall in these regions. The primary inconsistency appears to be the Great Lakes snowbelt areas, which show relatively low mean intensities, despite the apparent high snowfall intensities experienced within these short, violent squalls. There are several possible reasons why the lake-effect areas appear to have low snowfall intensities.

The water equivalent of fresh snow in lake-effect storms varies widely. Snow water equivalents range from 6:1 to about 50:1, with 18:1 about average. The low density and thus greater snow depth for a given water content make lake-effect storms appear intense to the eye. When mapped for snow deposited in a given period of time, lake-effect storms are no more intense, and actually less intense, than storms elsewhere in the continental United States that produce denser snowpacks (Weinbeck, 1983; Eichenlaub, 1979; Hill, 1971). This may be due, in part, to the lower fall velocities of crystals producing low-density snows. The lowest fall velocities increase suspended snow volume and the apparent visual snowfall intensity.

Other mechanisms may also cause the lake-effect storms to appear more intense than snow deposited per synoptic period may indicate. Lake-effect storms are strong convective systems with occasional thunder, lightning, and snowdrifting. Strong surface winds produce blowing snow and reduced visibility, giving the appearance of heavier snowfall than is actually occurring. In addition, warm moist air rising from the lake surface produces convection fog in the colder, overlying air, often the precursor to lake-effect storms (Eichenlaub, 1979). Some of this fog could mix with falling snow, further reducing visibility.

A methodological reason for the low snowfall intensities mapped in the Great Lakes region may be the transient nature of lake-effect snows. Lake-effect snowstorms result largely from local instability over warm, humid waters of the unfrozen lakes (Eichenlaub, 1979). The storms are short because they have little or no upper air support and are not organized. As a result, they deposit most of their snow in a short period, and the intensity appears low when averaged over 6 hours. Mapping snowfall intensity from shorter observation time periods may cause the snowbelt areas to appear more significant. However, the length of snowfall periods, as indicated in Figures 8–10, argues somewhat against snowstorm length as a confounding problem. Nevertheless, only additional and more frequent monitoring could determine the intensity of frequent short bursts of snowfall that occur in lake-effect storms.

CONCLUSIONS

The maps presented raise questions about actual versus perceived snowfall intensity, data suitable for mapping snowstorm intensity, and the synoptic conditions producing high intensity storms. Lake-effect storms appear very intense. Whiteouts are common, and drifting snow coupled with large accumulated snow depths provide the impression of very intense storms. However, the total 6-hour snowfall catch of these storms, as indicated by the maps, suggests that these storms are not very intense.

Six-hour synoptic period summaries may not be adequate for mapping snowstorm intensity. Summary periods significantly longer than the event will always result in intensities being computed as smaller than actually occur. Significant and systematic seasonal and geographic variations in snowstorm length produce a confounding situation, because snowfall intensity is no longer a conservative value. It can vary with snowfall amount and with the length of the snowfall event when the summary period is longer than the event. The latter is likely true for the lake-effect areas of the Great Lakes. Mapping snowfall intensity based upon 1-hour summaries might show somewhat different patterns.

The patterns illustrated in the maps, if accurate, raise questions about mechanisms producing snowfall. They provide opportunities to identify regional mechanisms. Understanding of mechanisms allows extrapolation to areas of the globe where snowfall intensity measurements may not be available, but snowfall-producing mechanisms are similar.

The maps presented in this paper can be improved. We will combine hourly precipitation, temperature, and present weather observations to compute a surrogate hourly water equivalent of snow at each weather station. This will enable snowfall intensity to be mapped with greater temporal resolution. The 6-hour data maps provided a first estimate of patterns using actual snowfall data, but the maps may have masked regions experiencing high intensity, short-lived snowstorms, such as the Great Lakes lake-effect areas.

Though Great Lakes lake-effect storms have been studied extensively, much remains to be learned about their intensity, longevity, crystal type, visibility, and surface wind characteristics. The maps presented in this paper were intended to raise questions about the reasons for changes in snowfall intensity geographically, especially in the Great Lakes area.

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