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8B.6

A SNOWFALL CLIMATOLOGY FOR EASTERN NORTH AMERICA

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1. INTRODUCTION

Knowledge of where and in what quantities snow has fallen is important to travel, commerce, water management, safety, recreation, and many other concerns. It is well known that at most locations snowfall varies significantly from year to year. However, for applied purposes, as well as to evaluate potential climate change, it is useful to understand variations in snowfall on annual and decadal time scales.

Previous synoptic-scale, climatological studies of snowfall include the work of Office of Forecast Development (1962), Thomas (1964), Harrington et al. (1990), Leathers et al. (1993), and Groisman and Easterling (1994). While these studies have shown intraseasonal or inter-seasonal variance, no studies have attempted to examine how the annual snowfall cycle has altered on a multi-decadal time frame. Our study explores such potential variations, and whether these changes are functions of alterations in the number of snow events or in snow accumulation per snow event. The examination focuses on comparing two 30-year intervals (1931-60 vs. 1961-90) from the eastern two-thirds of the United States and Southern Canada.

2. DATA SELECTION AND PROCESSING

a. Network selection

The Historical Daily Climatic Dataset provides a quality controlled daily archive from over 1100 cooperative climate observing stations for the United States (Robinson, 1993). The majority of these stations have continuous digitized records that date back to the early 1930's. Fewer than half have digital records prior to 1930, resulting in a network too sparse for the spatial detail of interest here. The Canadian climatological dataset contains over 3000 climate observing stations throughout Canada. Only about 250 of these stations maintain continuous records that date back to the early 1930's.

To insure the quality of the snowfall network selected for this study, only stations with less than 10% of the monthly records missing for snow seasons (Oct.-May) between 1931-90, were selected for this study. A month is considered missing if more than two daily observations were originally unrecorded or absent from the datasets. Some 358 U.S. and Canadian stations within the study region meet this criterion (figure 1). Unfortunately, only 6 stations are located north of 55°N latitude.

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Figure 1. Distribution of stations used in the study.

b. Data processing

The U.S. and Canadian datasets are merged into a single homogeneous network by converting U.S. measurements to metric units and standardizing all snowfall to ruler measurement. Twenty-six of the selected Canadian stations switched from ruler to Nipher gauge snowfall measurements during the 1960's. Differences in snowfall catch between these observing methods have been noted in the work of Goodison (1978) and Goodison et al (1981). The Nipher measurements are adjusted to ruler measurements using geographically-based ratios developed by Ferguson and Pollock (1971).

Of the 358 snowfall stations, only 9 are temporally complete. Missing monthly snowfall values are filled by selecting a surrogate station within 160 km of the primary station. The Pearson correlation between the annual snowfall at the two sites must exceed 0.7. Normality tests on annual values show that many stations, especially in southern locations, have non-guassian distributions of annual snowfall values over the period of study. As a result, a square root transform is applied to the annual snowfall totals to normalize data between the primary and surrogate stations. A linear regression on the square roots of the transformed annual snowfalls is done to obtain the slope (a) and intercept (b) between the two stations. These results are then applied to the monthly and annual means of the primary station and the surrogate's monthly total for the year in which the primary month is missing, using equation 1:

$$Y = ((M/A)a + b\,(X))^2 \qquad (1)$$

where: Y represents the missing monthly snowfall for the primary station, X is the square root of monthly snowfall for the surrogate station, M is the mean monthly snowfall for the primary station, and A is the annual monthly snowfall for the primary station. 97.9% of the filling required only one surrogate. Use of a second and, if necessary, third surrogate leaves only 0.5% of the months without monthly snowfall totals. These months are filled using monthly means of the primary station. The resultant dataset is the most spatially and temporally complete snowfall dataset available to date over Eastern North America.

3. VARIATIONS IN SNOWFALL TOTALS

Mean annual (Oct.-May) and seasonal snowfall totals for the 1931-60 and 1961-90 periods are compared, with several significant differences identified. Increases in 30-year mean values occurred over most of eastern North America, especially the southeast and Great Lakes (figure 2a). This increase reached 30% in the Atlantic Piedmont, lower Michigan, and Wisconsin. The increases in Eastern snow observed in this study agree with the earlier study of Leathers (1993). Stations on the lee side the Great Lakes, which regularly receive lake-effect snow, recorded 10-25% increases in snowfall between the middle and later portions of this century. No consistent pattern of snowfall change is observed in the U.S. Great Plains and in most of Canada. However, over Saskatchewan, a rise of (5-25%) in the 30-year snowfall average occurred. Over the southern U.S., changes range from a 70% increase over Georgia to a 50% decrease over Louisiana. These large and variable results are a function of the infrequent nature of significant snowfall events in the southern United States.

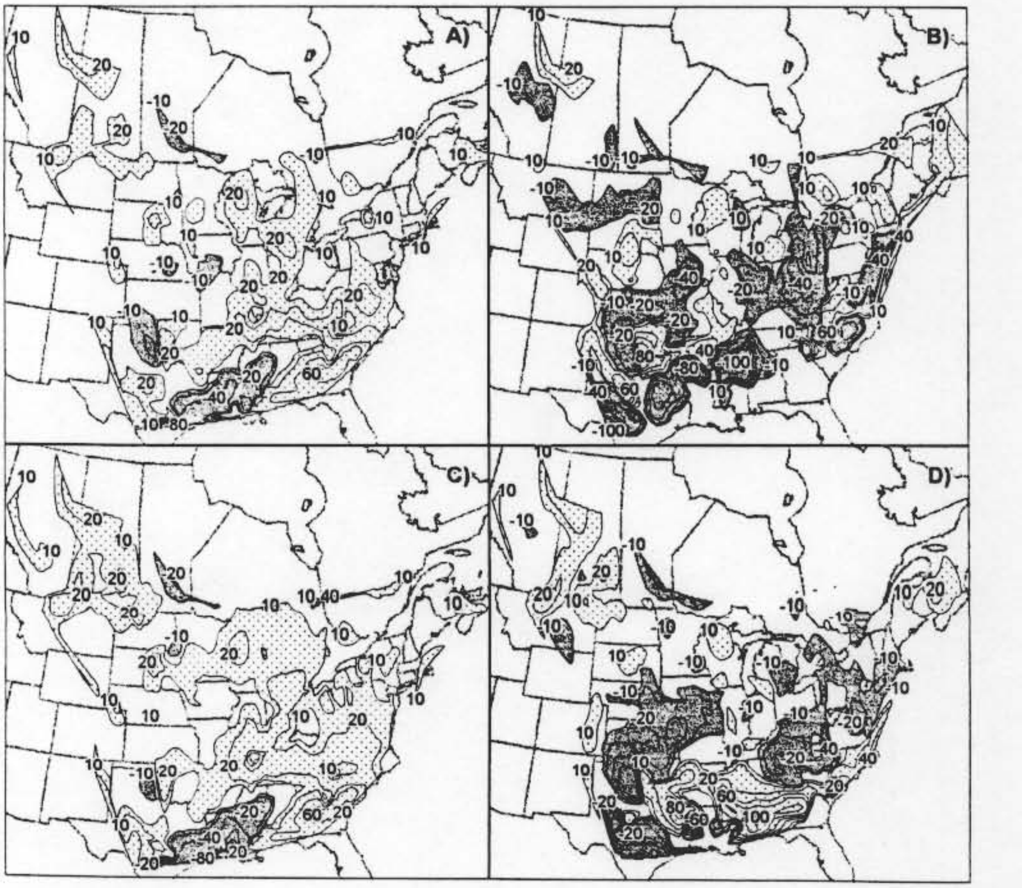

Figure 2. Percent change of the snowfall average between 1931-60 and 1961-90, for A) the annual snowfall season, B) Fall, C) Winter, and D) Spring. Negative percents are represented as shaded areas, while positive percents are represented as stippled.

Figure 2b indicates a decrease the autumn (Oct.-Nov.) snowfall over much of the observing area. Decreases of 10-50% between the first and second thirty-year periods are observed over the Ohio Valley. This is in contrast to Winter snowfall (Dec. - Feb.), which shows increases of 7-30% over the same area (figure 2c). Nearly the entire U.S. east coast and southern Ontario, had winter increases between 5-30%. "Lake effect" stations observed 20-30% increases during the winter months. Increases in these regions have been reported previously by Braham and Dungey (1984) for the western great lakes and Leathers and Ellis (1996) for the eastern lakes. Saskatchewan's snowfall average increased 10-25% from the first to second 30-year interval, with increases of 5-15% in Manitoba and Alberta.

There are no wide-spread differences in spring snowfall between the two 30-year study intervals (figure 2d). However, locally, snowfall in the lower Plains states (Nebraska, Kansas, and Arkansas) decreased by 10-50% from the middle to late century, with a similar decrease observed over the southern Appalachians through the mid-Atlantic states. In contrast, southern Saskatchewan snowfall increased by 5-25%.

4. VARIATIONS IN SNOWFALL PER "SNOW DAY"

In this section, we discuss potential changes that may have occurred in the amount of snow falling per "snow day" (a day with measurable snow reported), between the mid and late century 30-year intervals. Since this variable is not commonly reported, it is worth noting that on average, over the entire 60-year period, stations in central North America average 6-8 cm on a day that snow is observed. Eastern North America stations average 8-10 cm per snow day, while southern areas of the United States, average 12 cm, or more, per snow day.

Changes in the annual average of snow per snow day were limited to the southern United States and southern Canada (figure 3a). The limited number of snow events in the southern U.S. is largely responsible for the sizable values noted over this region. Over Southern Canadian, stations exhibit an increase of 10-25% in the snowfall per snow day. However, with the exception of Saskatchewan, only in the winter is this

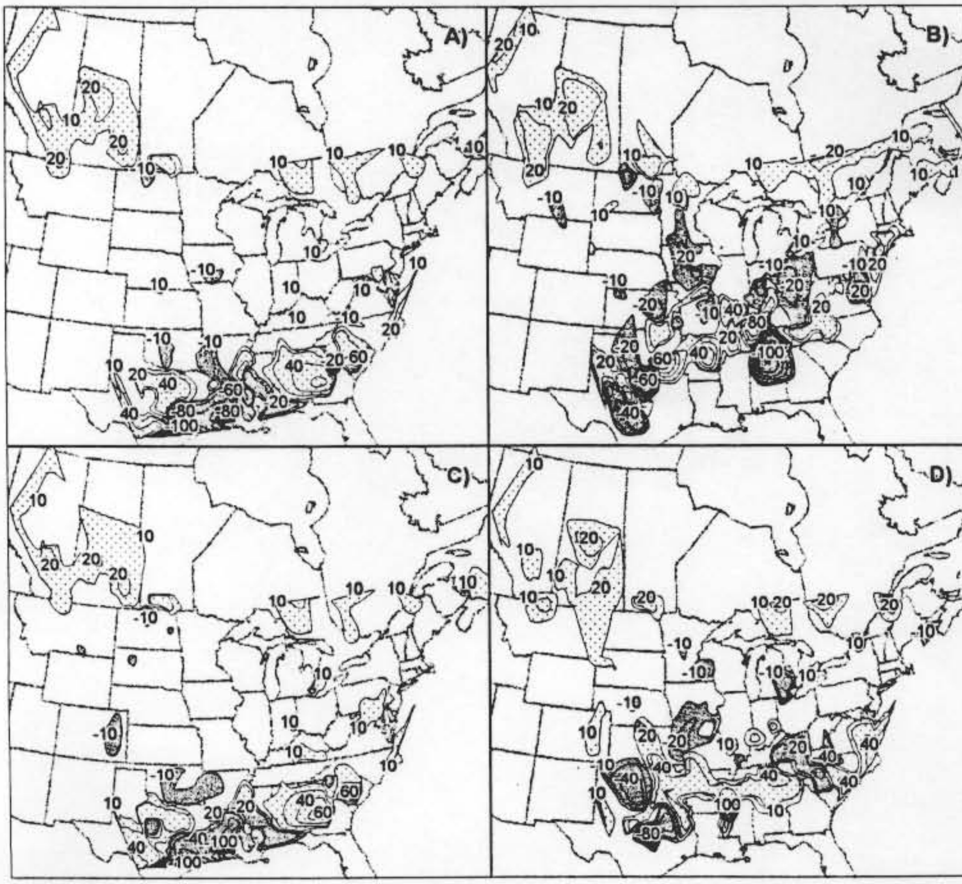

Figure 3. Percent change of the average snowfall per day receiving measurable snow between 1931-60 and 1961-90, for A) the annual snowfall season, B) Fall, C) Winter, and D) Spring. Negative percents are represented as shaded areas, while positive percents are represented as stippled.

increase accompanied by increases in mean snowfall. Other research shows a decrease in southern Canadian snowfall over the 1980's (Karl et al., 1993; Groisman and Easterling, 1994), with no apparent trend in the snowfall record (1951-90) over this area. While past studies do not directly compare to this current study, only Saskatchewan snowfall seems contradictory to previous work. This could be the result of a Nipher adjustment factor that over-corrected Saskatchewan totals from the 1960's, onward. Of the 10 Saskatchewan stations exhibiting more than a 10% increase in the 30-year seasonal snowfall per snow day, 6 stations were corrected using a Nipher factor.

Southern Canada experienced a 10-25% increase in Fall snowfall per snow day from the first to second 30-year intervals (figure 3b). No dominant signal was observed over the U.S. during Fall, although the coastal Mid-Atlantic observed an increase of as much as 45%, with the Ohio Valley values increasing by 10-25%.

Not surprisingly, the winter months resemble results for the entire snowfall season (figure 3c). Much of southern Canada observed an increase in snowfall per snow day in the 1961-90 period compared to the previous 30 years. Little change was observed over the eastern U.S., suggesting the increase in snowfall over this area is a function of more snow events, not larger snow events.

During the spring (figure 3d), fewer snowfall events across the study region result in the mixed southern signal shifting into the lower Plains and the Tennessee Valley. Farther north, but still in the U.S., only minor local changes were noted, suggesting that the decreases in spring snowfall could be the result of less snow falling per day. Southern Canada saw an increase in snowfall per snow day between the two study intervals.

5. CONCLUSIONS

Several characteristics of snowfall over the eastern two-thirds of the U.S. and southern Canada have been analyzed using the most comprehensive and complete dataset available to date. Snowfall amounts and the amount of snow falling on a day with snow have been compared for two 30-year intervals in the middle (1931-1960) and later (1961-1990) portions of this century.

In general, there has been increased snowfall during the Winter (Dec. - Feb.), particularly over Ontario and most of the eastern United States. Autumn (Oct. - Nov.) and Spring (Mar. - May) snowfall underwent overall decreases, with localized decreases scattered throughout the northern U.S.. changes in snowfall were primarily a function of variations in the number of snowfall events, not the magnitude of individual events.

Diagnostic studies are underway in an attempt to understand why the frequency of snowfall events has changed, and why variations in the seasonal distribution of snowfall have occurred. These are employing a number of tropospheric variables from local to hemispheric scales.

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